RAPID REPAIR AND RETROFIT OF TIMBER PILES USING UHPC

Quarterly Progress Report
For the period ending March 01, 2023.

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1. Background and Introduction

Timber piles are often in bridge substructure in rural areas and in coastal touristic piers (such as Santa Monic Pier) and are subject physical agents (mechanical damage, steel corrosion contact, etc.) as well as to damage from surrounding water stream or due to biological effects (bacteria, fungi, insects, etc.). Nowadays preservative as well as retrofitting techniques are applied to old timber structures for maintenance and repair. For preservation, Creosote, Chromated Copper Arsenate and other chemical products are available to treat timber and extent durability. For repair and retrofit concrete/steel jacketing, besides other methods, had been proved effective. The cost of repairing/retrofitting timber piles would be much cheaper compared to replacing them. The best repair technique should restore the load-carrying capacity of the timber piles and at the same time should be cost-effective. In this research, we propose the use of UHPC as repair/retrofit material for timber piles. Our research approach includes the investigation of bond strength between timber as substrate material and UHPC as repair material in addition to studying the load-carrying mechanism of repaired/retrofitted timber piles using UHPC. The proposed research will be conducted experimentally in two phases: 1) small-scale testing including push-out test to evaluate the bond strength between timber and UHPC and compressive tests to evaluate the load-carrying capacity of the repaired timber specimens; 2) large-scale testing where repaired timber piles using UHPC will be tested under axial and lateral load schemes. Numerical modeling using finite element models will be conducted on the tested specimens to better understand the behavior of repaired timber piles using UHPC.

2. Problem Statement

One of bridge substructure system utilizes a pier consists of a beam supported over timber piles. This substructure system is common practice in county bridges. Many reasons can lead to the deterioration of these timber piles over an extended period of time such as biological damage caused by fungi, termites, powderpost beetle, carpenter ants, and bacteria or physical damage due to floating in water, overload, failure of adjacent piles, and firs. (A. Mohammadi, 2014). Figure 1 shows some possible locations for the damage in timber piles and proposed partial or full UHPC encasement.

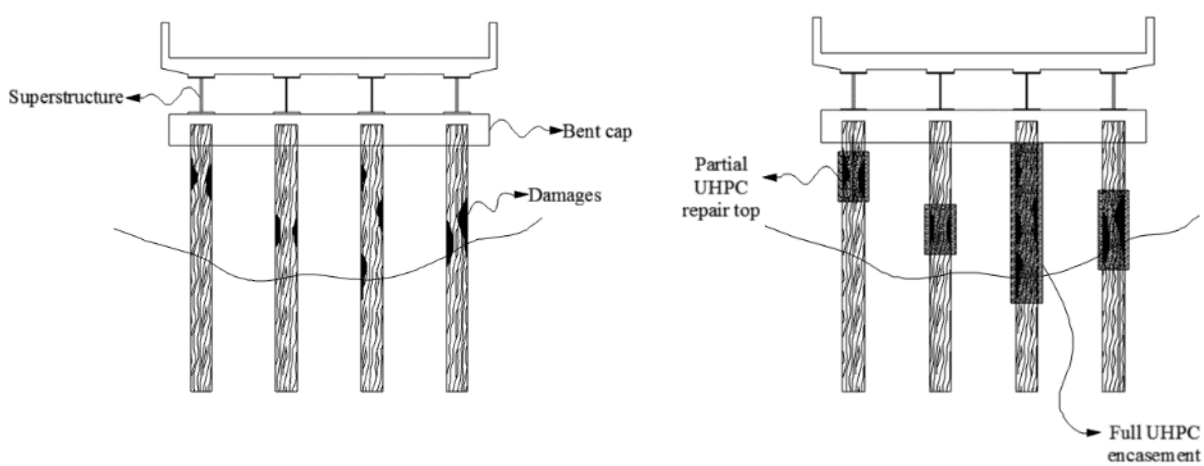


Figure 1. Common damages in timber piles (left) and proposed UHPC repair/retrofit (right).

Replacing the damaged timber pile may be considered an obvious option to address the damage; however, the cost of an effective repair and retrofitting of timber piles can be much cheaper. Different repair and retrofit techniques are available for the timber piles and some of the retrofit options failed to result in the expected performance levels. (J. H. Gull, 2015)

The superior mechanical properties of UHPC, such as high compressive strength, high tensile strength, and higher durability make this material a perfect solution to repair and retrofit timber piles. This study proposes the use of UHPC as repair and retrofit material for timber piles. The proposed repair method suggests the removal of the damaged portion of timber piles and filling the resulted cavity with UHPC in addition to an outer UHPC enhancement with a wall thickness which can restore the entire timber pile capacity (i.e. UHPC thickness of ½ in. can restore the capacity of timber pile with diameter of 8 in.), as shown in Figure 2. However, many research questions should be answered such as the bond strength between timber and UHPC, the surface preparation for timber piles to enhance the bond strength with UHPC, the effect of UHPC thickness of repair/retrofit. These questions, among others, will be addressed under this project.

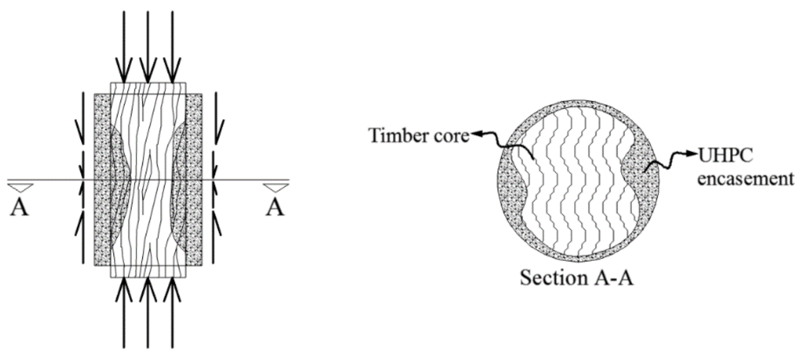


Figure 2. Force transfer sketch (left) and cross section (right) of repaired/retrofitted timber pile.

3. Objectives and Research Approach

The main objectives of this project are:

a) Studying the bond strength between timber and UHPC as repair/retrofit material.
b) Defining the best surface preparation for timber piles to enhance the bond strength
c) Studying the load carrying mechanism of timber piles repaired or retrofitted using UHPC.
d) Conducting small scale testing to study the bond strength and load carrying mechanism between timber and UHPC.
e) Conducting large scale component testing of timber piles repaired/retrofitted using UHPC under realistic axial and lateral loading schemes.
f) Studying repair methods for in service weathered piles.
g) Developing detailed finite element models for both small scale material testing and large scale component testing for better understanding of the local and global behavior of timber piles repaired/retrofitted using UHPC.

4. Description of Research Project Tasks

The following is a description of tasks carried out to date.

Task 1 – Conducting literature review on current practice of repair and retrofit of timber piles

In this task, a comprehensive literature review will be conducted including the current repair and retrofit practices for timber piles, bond strength between timber piles and repair materials, and load carrying capacity of repaired/retrofitted timber piles.

Progress: This task is completed. Many reports and publications are collected and studied.

Task 2 – Small scale experimental work

In this task, experimental work will be conducted on small scale level specimens to study the bond strength of UHPC as repair/retrofit material for timber with different surface preparation. In addition, compressive tests will be conducted on cylindrical shape timber with UHPC shell to study the load carrying mechanism between timber piles and UHPC.

Progress: This task is complete. Small scale samples were constructed in the laboratory by shaping timber into prisms and cylinders.
For bond strength study, timber prisms were cut with a dimension of 4”x4”x8” (width x length x height) to form a push-off test specimen. The push-off test specimens consist of intermediate timber prism and outer UHPC prisms with a dimension of 4”x4”x8” (width x length x height) as shown in Figure 3, the intermediate timber prism was then placed inside timber formwork, as shown in Figure 4. Different surface preparations were selected to enhance the bond between timber and UHPC including smooth surfaces, rough surfaces, horizontal nails, inclined nails, horizontal holes, and inclined holes, as shown in Figure 5 and Figure 6. A total of 14 specimens were tested under push-off test setup, as shown in Figure 7. Tables 1 and 2 lists the specimen notations, failure load of each specimen, and the average bond strength of each surface preparations.

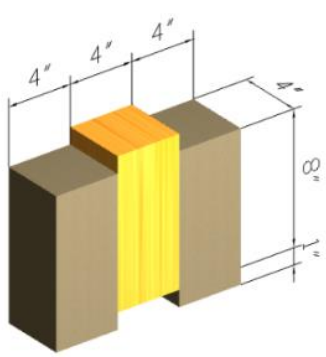


Figure 3. *Construction for push-off specimens*

Figure 4. *Formwork for pull-off specimens prior to casting UHPC.*

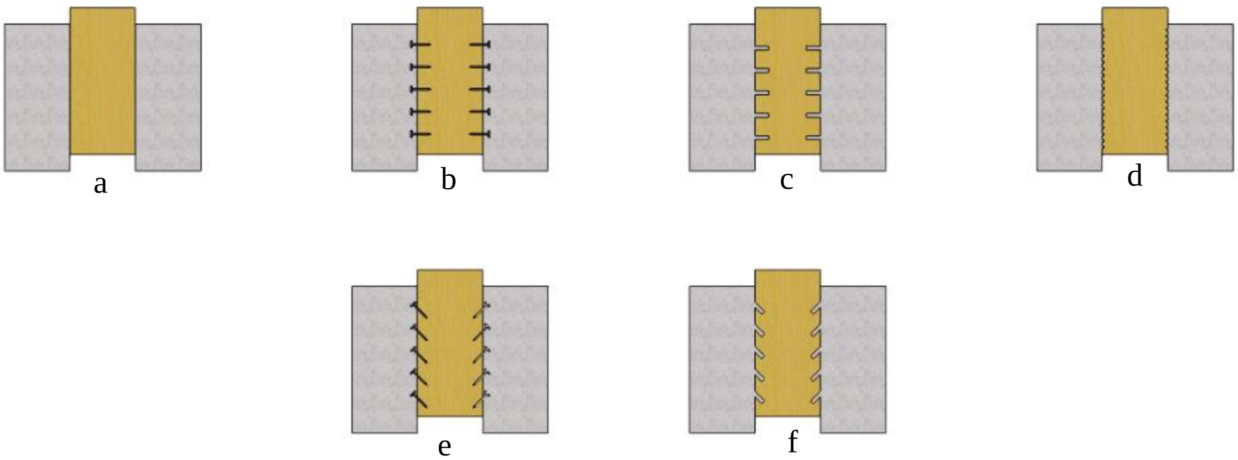


Figure 5. *Schematic for pull-off test specimens different surface preparation between timber (inner) and UHPC (outer), (a) plain, (b) horizontal nails, (c) horizontal holes, (d) rough surface, (e) inclined nails and (f) inclined holes.*

Figure 6. *Different surface preparation for timber prisms*

***Figure 7**. Push-off test setup.*

Table 1. *Specimen notation and description for push-off shear samples.*

Specimen notation	Description
P	Timber's plain surface
R	Timber's rough surface
H90	Holes in timber perpendicular to bonding surface
H45	Holes in timber inclined 45 degrees to bonding surface
N90	Nails inside timber perpendicular to bonding surface
N45	Nails inside timber inclined 45 degrees to bonding surface

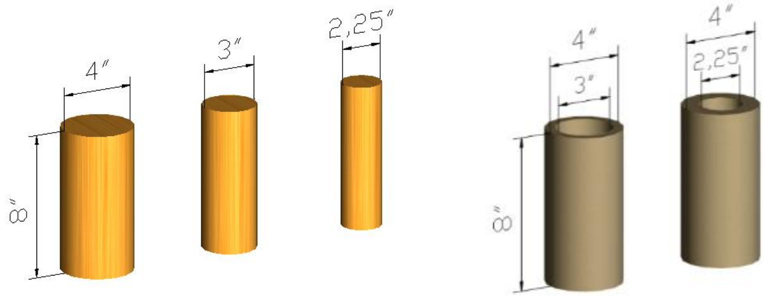
Table 2 *Push-off shear test results.*

Specimen notation	Max load (kip)	Stress (psi)	Average per type	Standard deviation
H90-1	3.3	53.7	69.3	13.6
H90-2	4.4	75.5		
H90-3	4.8	78.7		
H-45	2.7	47.1	47.1	-
R-1	3.8	62.5	73.8	16.9
R-2	5.1	93.3		
R-3	3.9	65.7		
N90-1	9.8	159.3	168.8	8.3
N90-2	9.6	171.7		
N90-3	10.1	175.2		
N-45	4.5	76.6	76.6	-
P01	0.8	13.9	-	-
P02	0	0.0*		
P03	0	0.0*		

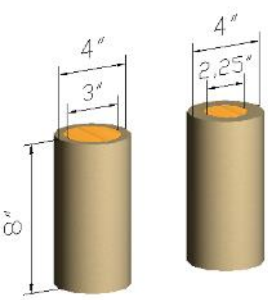
For load-carrying capacity, timber cylinders were cut by woodturning as shown in Figure 8, some of them were cast with an outer UHPC shell and other specimens were just UHPC shells molded by the use of cylindrical inner cylindrical styrofoams, as shown in Figure 9. Two diameter-to-thickness ratios between the inner timber cylinder and outer UHPC shell (d/t) of 6 and 2.57 were selected in this test as shown in Figure 9. All the specimens required cylindrical plastic molds for forming UHPC, as shown in Figure 10. Same surface preparations as bond strength specimens were replicated in the load-carrying capacity test as shown in Figures 11 and 12. Figure 13 shows the compression test setup and Figure 14 shows the final damage of one specimen. It should be noticed that two timber moister preparations were conducted by (1) soaking timber in a water tank prior to casting UHPC (2) by spraying timber with water prior to casting UHPC. Tables 3 and 4 lists all specimen notations, failure load, and average failure load for each group. New specimens were cast as shown in Figure 15.

(a) *(b)*

Figure 8. Timber cylinders. (a) hexagons as cut form large timber pile, (b) cylindrical shape using wood turning.



(a) *(b)*



(c)

Figure 9. Specimens for load-carrying capacity. (a) Timber cylinders, (b) UHPC shells, (c) timber cylinder with UHPC enhancement.

Figure 10. Sample for final timber cylinders with UHPC encasement.

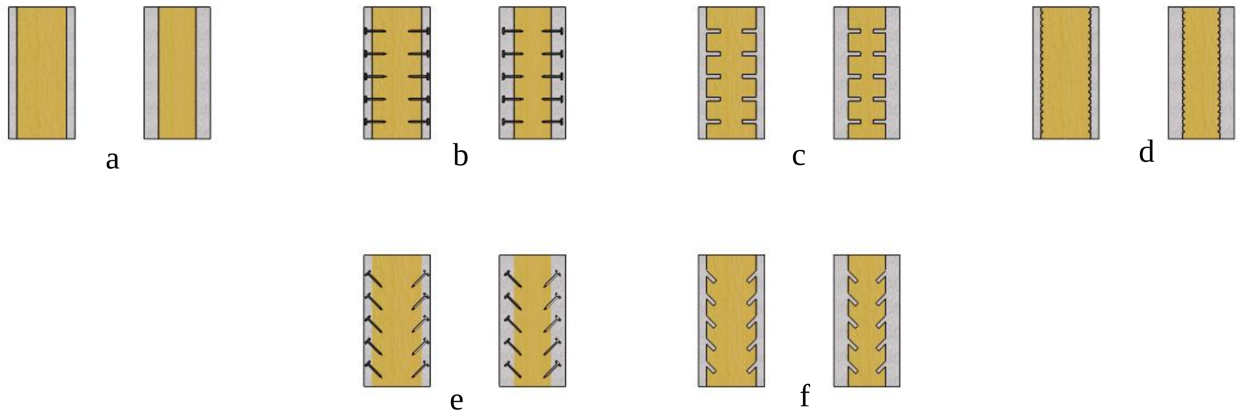


Figure 11. *Schematic for load-carrying capacity test specimens different surface preparation between timber (inner) and UHPC (outer), (a) plain, (b) horizontal nails, (c) horizontal holes, (d) rough surface, (e) inclined nails and (f) inclined holes.*

Figure 12. *Different surface preparation for timber prisms*

Figure 13*. Test setup for load-carrying capacity. (a) timber specimen, (b) timber cylinder with UHPC encasement.*

Figure 14. *Failure mode of one of tested specimen.*

Table 3 *Specimen notation and description for small scale compression samples*

Notation Level	notation	Description
Level 1	T	Timber only
	TC	Timber core (reduced section)
	V	Void due to internal foam in UHPC shell
	P	Plain (smooth) surface of timber core
	R	Rough surface of timber core
	H	Holes at timber´s surface
	N	Surface with nails
Level 2	4.0	Timber Diameter in inches
	3.0	
	2.25	
Level 3	01	Repetitions ID
	02	
	03	
Level 4	sk	Soaked timber when casting UHPC
	sp	Sprayed timber when casting UHPC

Table 4 *Load-carrying capacity results*

Specimen notation	Max load (kip)	Average per type	Standard deviation
T-4.0-01	53	53.0	3.0
T-4.0-02	56		
T-4.0-03	50		
TC-3.0-01	34	35.3	2.3
TC-3.0-02	38		
TC-3.0-03	34		
TC-2.25-01	13	14.3	5.1
TC-2.25-02	10		
TC-2.25-03	20		
V-3.0-01	96	94.7	17.0
V-3.0-02	77		
V-3.0-03	111		
V-2.25-01	210	200.3	9.5
V-2.25-02	191		
V-2.25-03	200		
P-3.0-01-sp	68	68.7	8.0
P-3.0-02-sp	77		
P-3.0-03-sp	61		
P-3.0-01-sk	97	96.0	11.5
P-3.0-02-sk	84		
P-3.0-03-sk	107		
R-3.0-01-sp	46	50.0	7.8
R-3.0-02-sp	59		
R-3.0-03-sp	45		

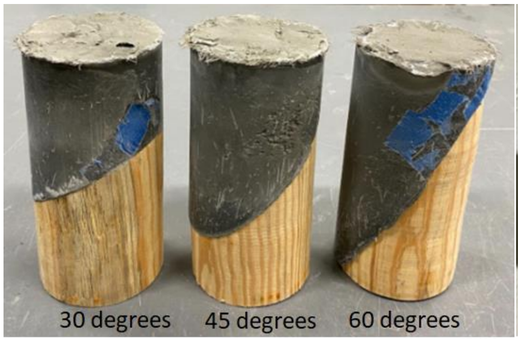
Cont. ***Table 4*** *Load-carrying capacity results*

Specimen notation	Max load (kip)	Average per type	Standard deviation
H-3.0-01-sp	42	45.7	6.4
H-3.0-02-sp	42		
H-3.0-03-sp	53		
N-3.0-01-sp	66	59.7	5.5
N-3.0-02-sp	57		
N-3.0-03-sp	56		
N-3.0-01-sk	134	124.3	8.0
N-3.0-02-sk	114.3		
N-3.0-03-sk	125		
P-2.25-01-sp	74	99.3	23.0
P-2.25-02-sp	105		
P-2.25-03-sp	119		
P-2.25-01-sk	218	195.7	22.5
P-2.25-02-sk	196		
P-2.25-03-sk	173		
R-2.25-01-sp	96	81.7	17.6
R-2.25-02-sp	87		
R-2.25-03-sp	62		
H-2.25-01-sp	83	72.3	9.5
H-2.25-02-sp	69		
H-2.25-03-sp	65		
N-2.25-01-sp	73	79.3	23.2
N-2.25-02-sp	60		
N-2.25-03-sp	105		
N-2.25-01-sk	189	188.3	8.0
N-2.25-02-sk	180		
N-2.25-03-sk	196		

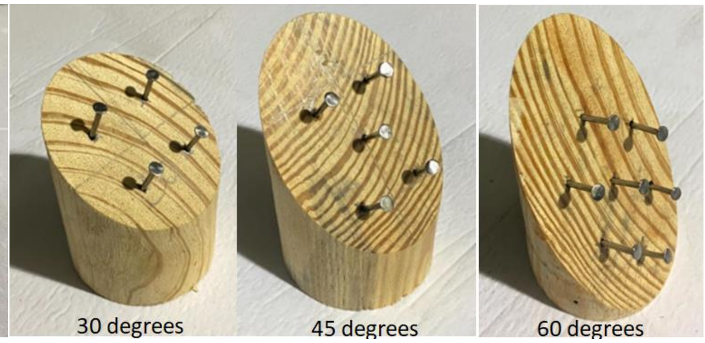
Figure 15. *New specimens to replace the ones that turned out deficient.*

During this reporting period, additional material testing was added to study the interaction between shear and axial loading since the damage in timber piles is more random in direction than straight vertical surfaces. Composite timber-UHPC specimen were cast and tested under

Slant Shear test setup with different inclinations of 30, 45, 60 degrees as shown in Figure 16. Table 5 shows summary of the slant shear test.



a)



b)

c)

Figure 16. *Slant shear test. a) different surface inclination, b) nails crossing the inclined surface between UHPC and timber, c) specimen prior to testing.*

Table 5 *Slant shear test results.*

Surface Inclination	Repetition	Maximum Axial Load			Bond Strength		
		Value (kips)	Average (kips)	SD (kips)	Value (psi)	Average (psi)	SD (psi)
30 degree	1	29.97	26.72	2.13	1,872	1669.0	133.2
	2	26.18			1,635		
	3	26.70			1,668		
	4	24.01			1,500		
45 degree	1	23.48	22.01	1.44	1,722	1614.0	105.7
	2	23.12			1,695		
	3	19.83			1,454		
	4	21.60			1,584		
60 degree	1	4.18	4.08	0.11	255	249.0	6.70
	2	4.18			255		
	3	3.92			239		
	4	4.03			246		

After this stage, design was performed to study the capacity of different types of nails (4D, 6D, 8D, and 10D) in order to minimize the number of required nails. According to NDS-2015 for timber, the lateral strength for nails was calculated. It is concluded that 10D nails might be the ones that best fit our requirements (larger lateral shear capacity). So, three more push-off specimens were cast to find the maximum lateral shear strength for these nails and comparing them with NDS-2015 limits. Figure 17 shows the intermediate timber segment with 10D nails. Figure 18 shows the testing of the three specimens with 10D nails.

Figure 17. *Timber block with 10D nails.*

a) *b)* *c)*

Figure 18. *Push-off test with 10D nails. a) Original samples, b) Sample tested up to complete failure, c) Detail of bent nails at the interface after failure.*

The push-off results for the specimen with 10 D nails are shown in Table 6 with comparison with the lateral capacity according to NDS-2015. It should be noted that Table 6 also show comparison between experimental results for 4D nails as mentioned in Table.

Table 6 *Push-off tests with 10D nail results.*

ID of Samples	Nail Type	Total load (lb.)	Load by nail (lb.)	NDS capacity (lb.)	Safety Factor
A	10D	18200	607	138	4.4
B	10D	18210	607	138	4.4
C	10D	20020	667	138	4.8
N90-1	4D	9800	327	62	5.3
N90-2	4D	9600	320	62	5.2
N90-3	4D	10100	337	62	5.4

The small-scale testing was expanded to include cylinder timber sampled encased with UHPC and tested under push-off test for better understanding of the combined behavior. A ¾" gap was created between the bottom of the UHPC encasement and the bottom of the timber cylinder to allow timber cylinder to slide as shown in Figure 20. This setup will allow to study the frictional strength when timber begins to move.

Three types of surfaces were suggested to the timber surface to study the surface preparation effect. The types were plain ('P' type), nailed ('N' type), and zigzag ('Z' type) surfaces as shown in Figure 19. It should be noted that Z-type specimen could be difficult to obtain in the field but was suggested to obtain the maximum bond between the two materials. For N type we had 3D nail (1.25 inches long) were distanced at 1.5 in.

a) *b)* *c)*

Figure 19. *Timber cylinders for encased push-off test. a) Plain surface ('P' type), b) Nailed surface ('N' type), c) Zigzag surface ('Z' type).*

Figure 20. *Encased timber cylinder. Left: front view, Right: bottom view*

Figure 21 shows the behavior of 'P' and 'N' type specimens. First, when tested, the friction between timber core and UHPC encasement is provoked allowing the sliding of the timber core inside the encasement. Second, once the timber core touches the bottom base plate, it started to be compressed. It should be noted at this stage the UHPC encasement was still uncracked. Finally, the loading plates touches both timber core and UHPC encashment that caused and increase in load carrying capacity since the UHPC enhanced is fully loaded.

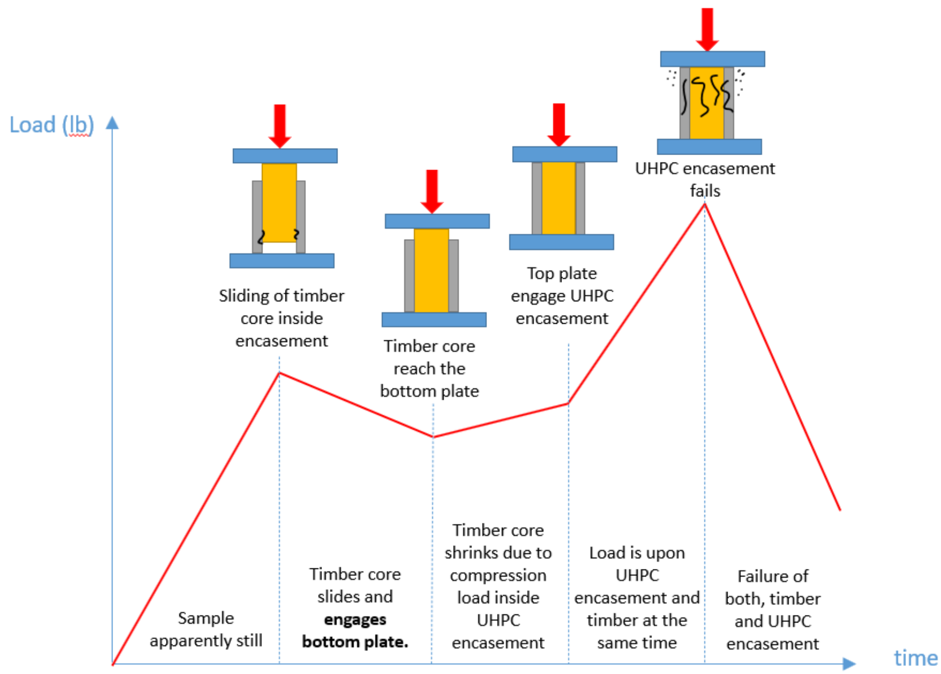


Figure 21. *Behavior for types plain and nailed surfaces in timber.*

Figure 22 shows the behavior of 'Z' type specimens. For this case, the timber core never slipped through the UHPC encasement due to the high friction between timber core and UHPC encasement which was induced by the corrugated surface preparation. Instead, the timber core was compressed completely until the loading plate touched the top surface of UHPC encasement and started to be loaded. Even though, this surface preparation is hard to be obtained for in-service timber, it may be a good idea in new timber piles that may require UHPC protection for aggressive environment.

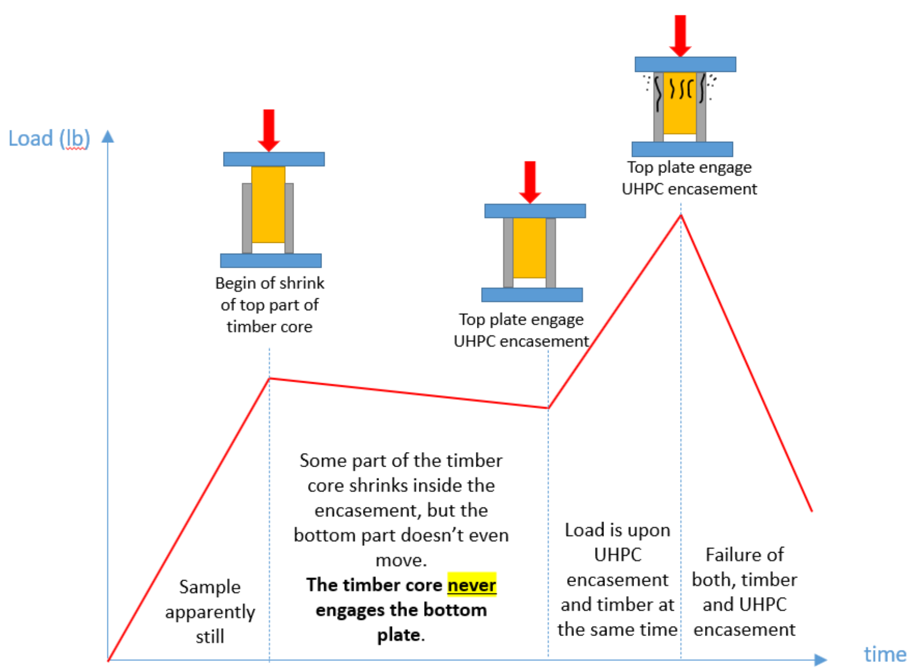


Figure 22. *Behavior for zigzag type surfaces in timber.*

Table 7 and Figure 23 shows the load values for each stage of loading for the three examined surfaces preparation.

Table 7. *Load values for each stage of loading of the three different surfaces preparation.*

	Load to provoke slide or shrink timber (first peak of previous plots) (kips)		Final load after timber compressed into UHPC shell (ultimate peak of previous plots) (kips)	
	Specimen	Type Average	Specimen	Type Average
P1	16.2	14.2	49.0	54.5
P2	13.0		63.2	
P3	13.3		51.4	
N1	14.9	15.2	52.4	50.4
N2	15.7		47.5	
N3	15.1		51.2	
Z1	33.2	31.4	58.8	53.4
Z2	32.6		47.9	
Z3	28.5		- *	

* Thin encasement crushed (failed) due to inclined timber core and not as expected.

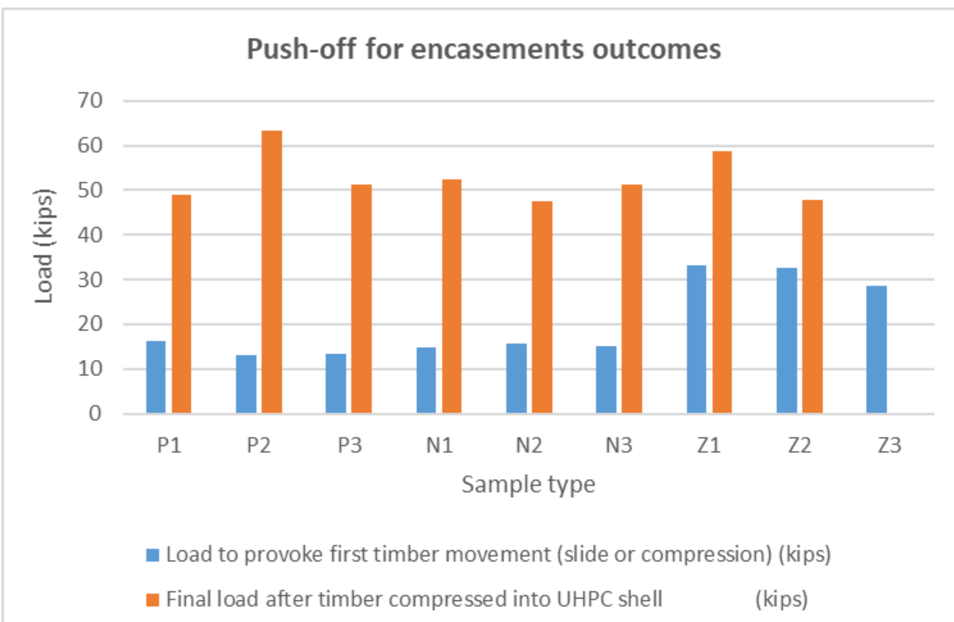


Figure 23. *Behavior for zigzag type surfaces in timber.*

Task 3 – Large scale experimental work

In this task, experimental work will be conducted on the first specimen. The column will be tested under constant axial and lateral cyclic loads.

Figure 24. *Test setup for large-scale specimens*

After the first test, it was noticed that local failure occurred at the ends of the timber at the contact with the loading steel beam, so it was decided to cast concrete caps for a proper stress distribution at testing.

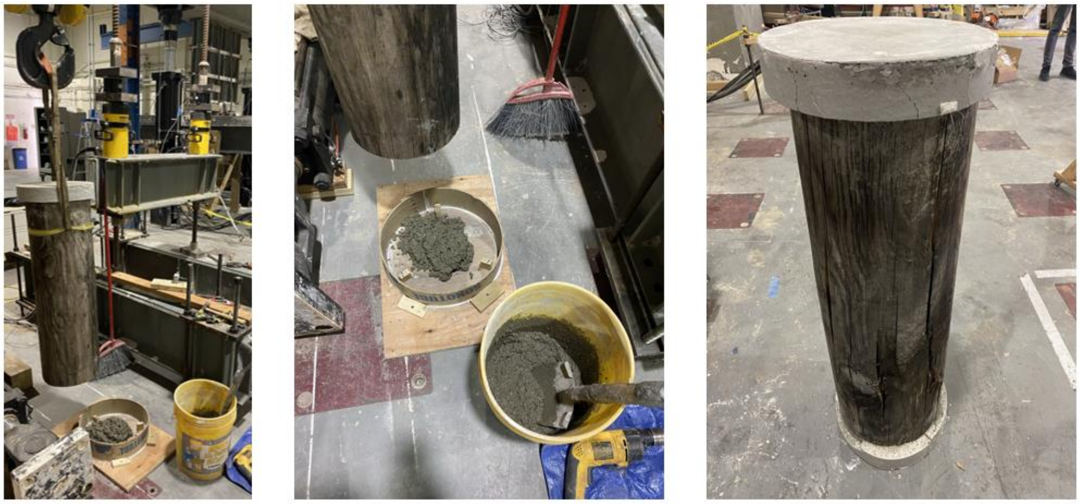


Figure 25. *Casting end concrete caps*

For the axial load, many alternatives were studied. Because of the stiffness of the system the smallest hydraulic rams couldn't reach the desired force to break the specimens. So, bigger hydraulic rams were used to provide higher forces.

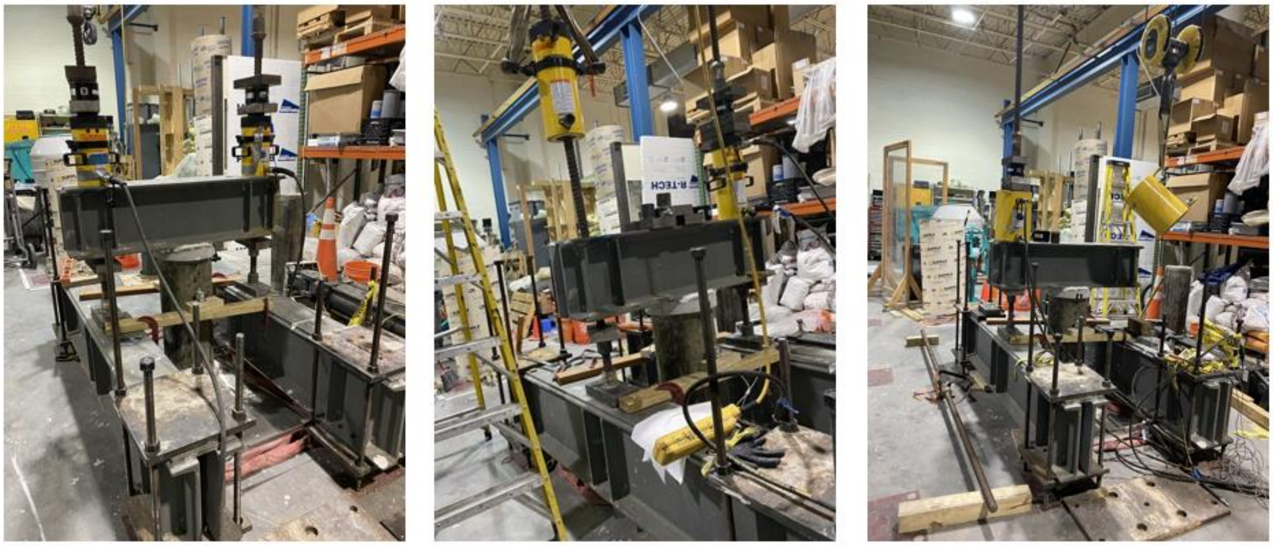


Figure 26. *Different hydraulic cylinder used in the test.*

The first five specimens (test 01 to test 05) were tested with decayed timber and additional two specimens using newly purchased timber (tests 06 and 07). Table 8 shows details of each specimen along with summary of maximum load achieved.

Table 8. *Summary of large-scale tests of timber*

Large-scale test ID	Material	End preparation	Timber Diameter (in)	UHPC Encasement (in)	Total Height (in)	Max Load (kip)
test 01	decayed timber	flat ends	9	-	33.75	19.3
test 02	decayed timber	flat ends	9	-	37.06	9.0
test 03	decayed timber	flat ends	9	-	41.00	16.7
test 04	decayed timber	concrete caps	9	-	39.00	27.7
test 05	decayed timber	concrete caps	12	-	41.00	23.5
test 06	new timber	concrete caps	12	-	33.50	Not broken
test 07	new timber	concrete caps	9	-	31.00	345.0
test 08	decayed timber with UHPC	flat ends	12	1" all heigh	33.00	Not broken
test 09	new timber with UHPC	flat ends	8.5	0.75" at middle	33.00	154
test 10	new timber with removed part	flat ends	10.5 (-1.25 at middle)	-	31.00	110
test 11	new timber with removed part	flat ends	8.1 (-0.75 at middle)	-	29.00	150

Figures 27 and 28 show steps of retrofit technique that involved the application sprayed foam in a thin layer to provide a gap between timber and UHPC shell to allow the volumetric changes of timber piles without affecting UHPC encasement. After that a chicken wire mesh is installed and mounted using to provide reinforced UHPC encasement against radial stress. Finally, UHPC was cast.

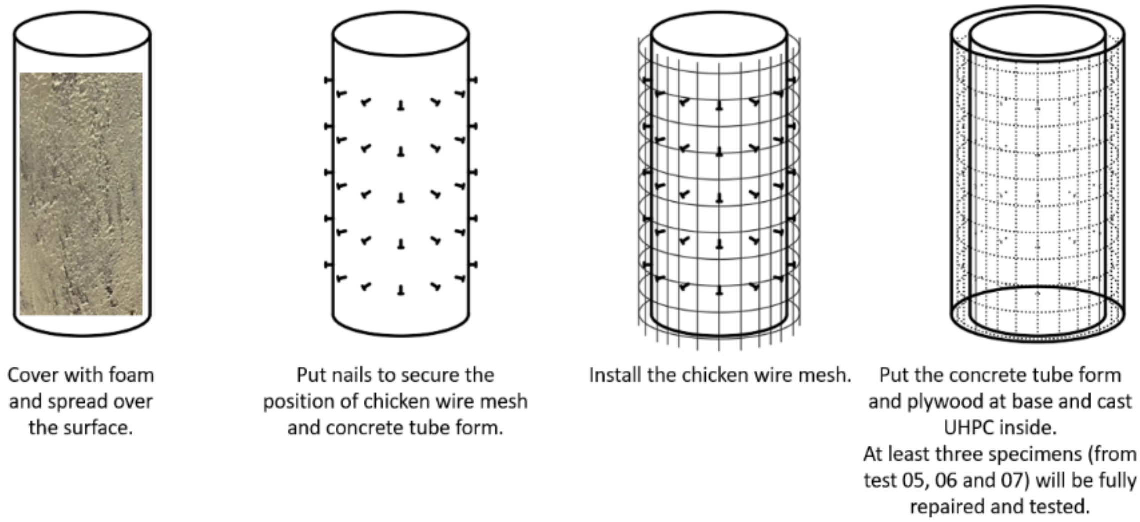


Figure 27. *Steps to retrofit tested timber specimens.*

Figure 28. *Construction process for complete shell encasement.*

The next large-scale are specimens for partial repair. Figure 29 shows the construction of the dog-bone like specimen to examine the constructability. The specimens will be tested, and additional specimens will be added during the next quarter.

Figure 29. *Construction process for partial shell encasement.*

Figure 30 to Figure 40 show photography of every tested specimen mentioned in Table 8.

Large-scale test 1:

Figure 30. *Large-scale specimen 01 – Max. Load: 7.7 kips*

Large-scale test 2:

Figure 31. *Large-scale specimen 02 – Max. Load: 2.5 kips*

Large-scale test 3:

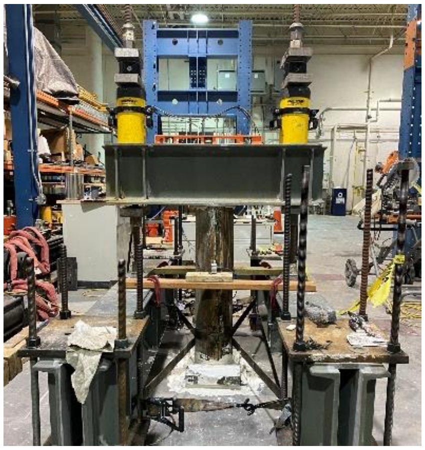


Figure 32. *Large-scale specimen 03 – Max. Load: 6.7 kips*

Large-scale test 4:

Figure 33. *Large-scale specimen 04 – Max. Load: 11.0 kips*

Large-scale test 5:

Figure 34. *Large-scale specimen 05 – Max. Load: 19.0 kips*

Large-scale test 07:
Loaded but not broken. Will be tested in bigger setup

Figure 35. *Large-scale specimen 07 – Max. Load: 87.0 kips*

Large-scale test 08:

Figure 36. *Large-scale specimen 08 – Not broken – test 14 will repeat this specimen*

Large-scale test 09:
Loaded but not broken. Will be tested in bigger setup

Figure 37. *Large-scale specimen 09 – Not broken – test 20 will repeat this specimen*

Large-scale test 10:

Figure 38. *Large-scale specimen 10 – Max. Load: 150 kips*

Large-scale test 11:

Figure 39. *Large-scale specimen 11 – Max. Load: 110 kips*

Large-scale test 12:

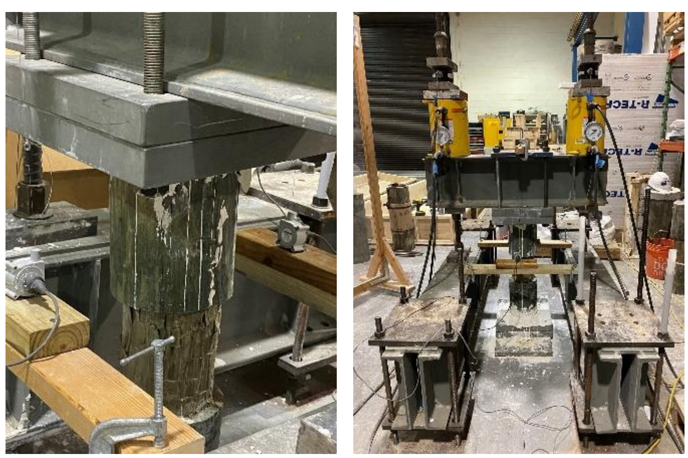


Figure 40. *Large-scale specimen 12 – Max. Load: 150 kips*

Large-scale test 13:

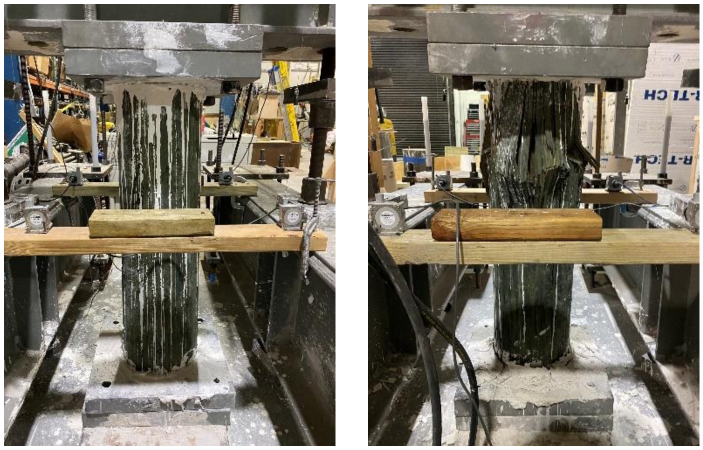


Figure 41. *Large-scale specimen 13 – Max. Load: 345 kips*

Large-scale test 14:

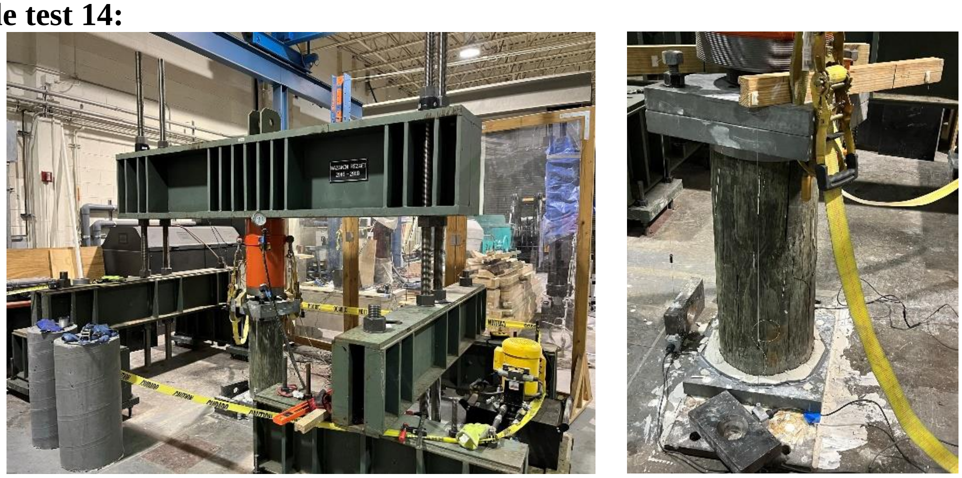


Figure 42. *Large-scale specimen 14 – Max. Load: 450 kips*

Large-scale test 15:

Figure 43. *Large-scale specimen 15 – Max. Load: 216 kips*

Large-scale test 16:

Figure 44. *Large-scale specimen 16 – Max. Load: 318 kips*

Large-scale test 17:

Figure 45. *Large-scale specimen 17 – Max. Load: 215 kips*

Large-scale test 18:

Figure 46. *Large-scale specimen 18 – Max. Load: 378 kips*

Large-scale test 19:

Figure 47. *Large-scale specimen 19 – Max. Load: 692 kips*

Large-scale test 20:

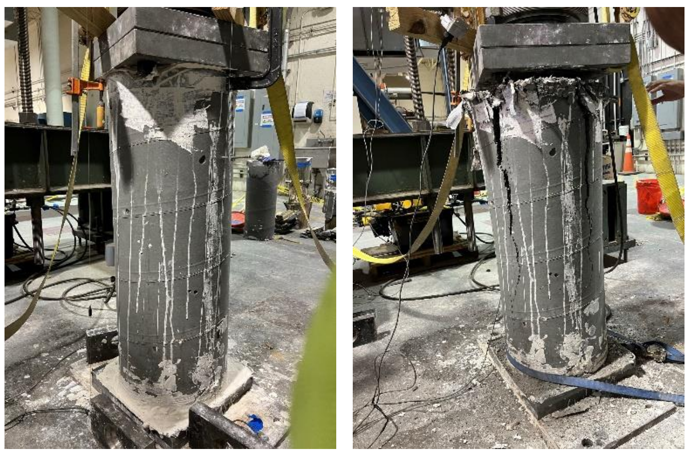


Figure 48. *Large-scale specimen 20 – Max. Load: 664 kips*

Large-scale test 21:

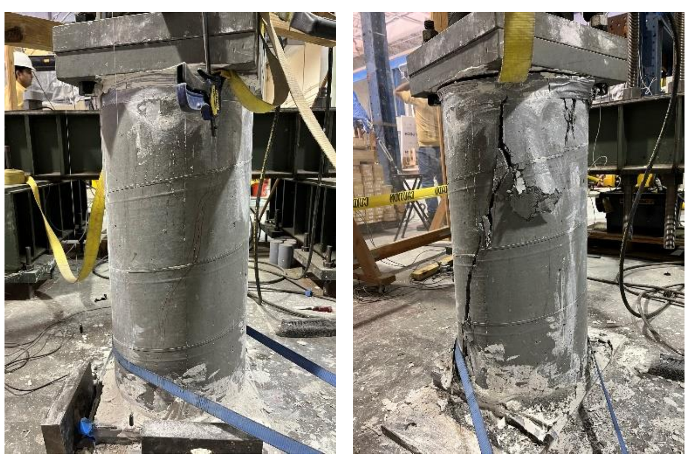


Figure 49. *Large-scale specimen 21 – Max. Load: 752 kips*

After test #21 it was decided to prepare more specimens. Some were meant to study the retrofitting effectivity for tested specimens and others were meant to study the effect on larger specimens and some of them with steel reinforcement.

The repairing process started by applying a thin foam layer to allow a small gap between timber surface and concrete encasement.

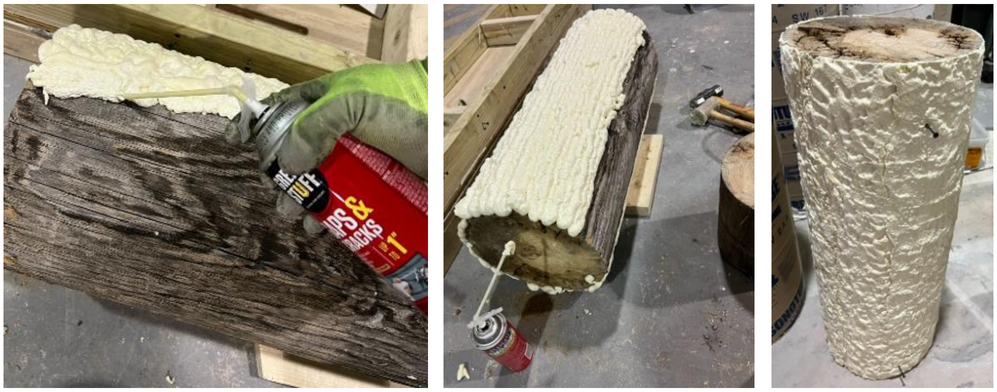


Figure 50. *Foam installation around timber.*

After that the form tube was placed providing a uniform space all around the timber.

Figure 51. *Uniform gap between timber and tube form.*

After that formwork was properly prepared and placed into position to cast non-proprietary UHPC inside.

Figure 52. *Specimens after casting.*

Two week after casting, the top surface was chipped away to expose some cavities due to bubbles and supports. Finally, one thin layer of non-proprietary UHCP was placed on top to provide a uniform top surface.

Figure 53. *Top surface, after and before putting thin non-proprietary layer.*

Three weeks after casting the form tube was removed.

Figure 54. *Removal of tube form*

In the following pages the new specimens to be used in tests 22 through 31 are shown.

Preparation of specimen for Large-scale test 22:

This specimen is the one used in test 14. It is 28 inches high and 14.5 inches in diameter. No steel rebar was used for retrofitting.

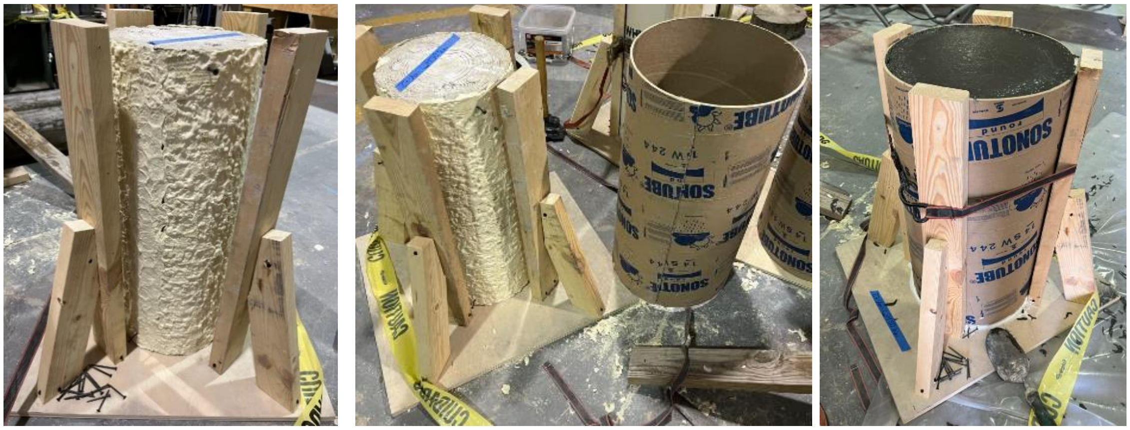
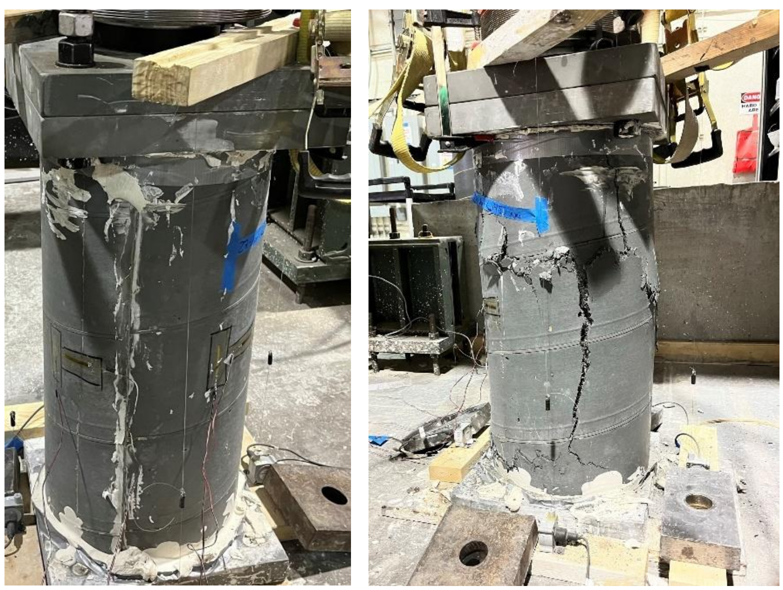


Figure 55. *Preparation of specimen for test 22*

Results for Large-scale test 22:



(before) *(after)*

Figure 56. *Large-scale specimen 22 – Max. Load: 705 kips*

Preparation of specimen for Large-scale test 23:

This specimen is the one used in test 16. It is 32.5 inches high and 13.75 inches in diameter. No steel rebar was used for retrofitting.

Figure 57. *Preparation of specimen for test 23*

Results for Large-scale test 23:

(before) *(after)*

Figure 58. *Large-scale specimen 23 – Max. Load: 709 kips*

Preparation of specimen for Large-scale test 24:

This specimen is the one used in test 18. It is 33.25 inches high and 12 inches in diameter. No steel rebar was used for retrofitting.

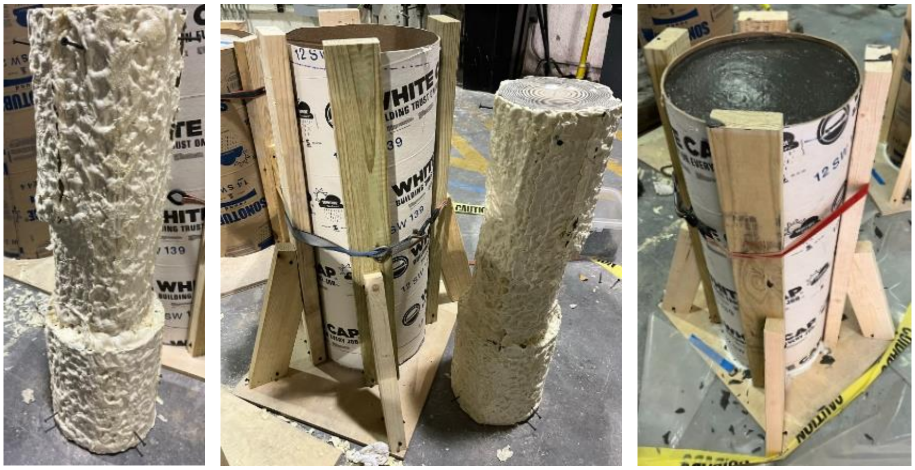


Figure 59. *Preparation of specimen for test 24*

Results for Large-scale test 24:

(before) *(after)*

Figure 60. *Large-scale specimen 24 – Max. Load: 550 kips*

Preparation of specimen for Large-scale test 25:

This specimen is completely new. It is 31.25 inches high and 12.25 inches in diameter. Steel rebar was used for retrofitting. Four longitudinal #3 bars were used, and #3 stirrups spaced 3 inches on center.

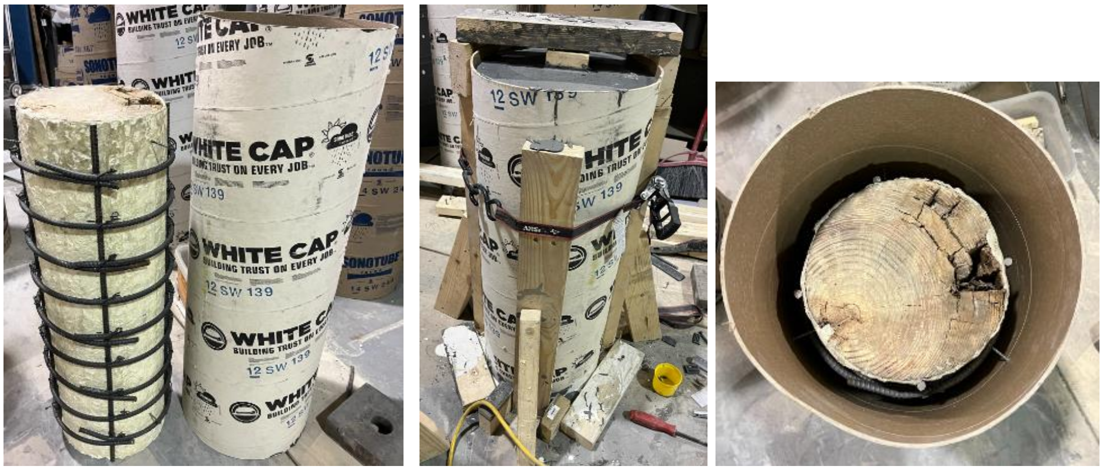


Figure 61. *Preparation of specimen for test 25*

Results for Large-scale test 25:

(before) *(after)*

Figure 62. *Large-scale specimen 25 – Max. Load: 715 kips*

Preparation of specimen for Large-scale test 26:

This specimen is completely new. It is 31.75 inches high and 14.5 inches in diameter. No steel rebar was used for retrofitting.

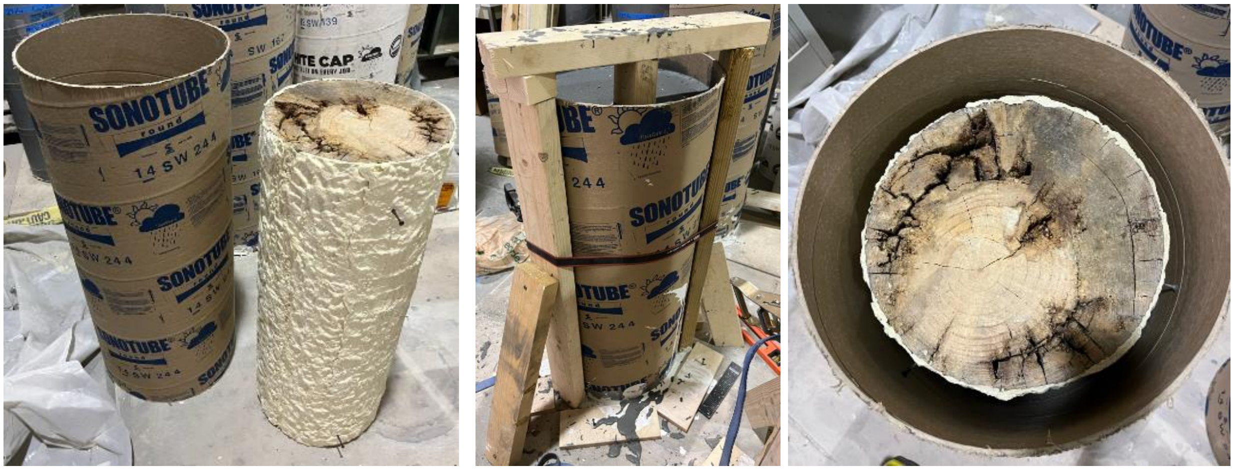
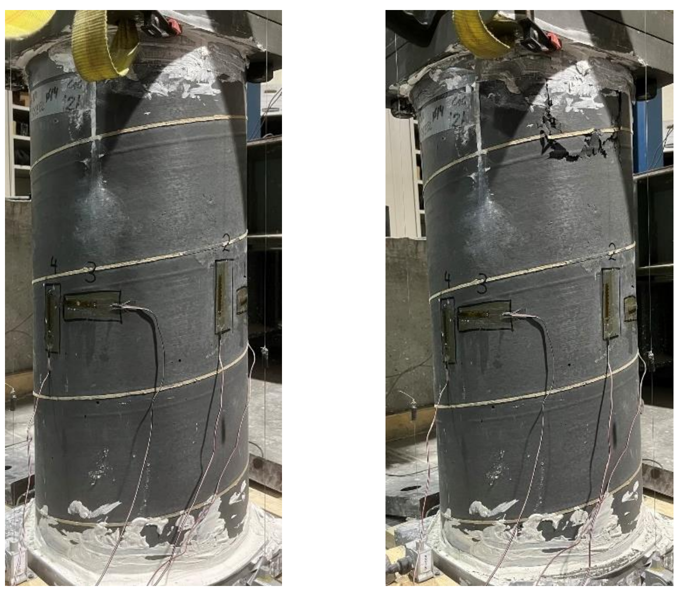


Figure 62. *Preparation of specimen for test 26*

Results for Large-scale test 26:



(before) *(after)*

Figure 63. *Large-scale specimen 26 – Max. Load: 718 kips*

Preparation of specimen for Large-scale test 27:

This specimen is completely new. It is 31.75 inches high and 14.5 inches in diameter. Steel rebar was used for retrofitting. Four longitudinal #3 bars were used, and #3 stirrups spaced 3 inches on center.

Figure 64. *Preparation of specimen for test 27*

Results for Large-scale test 27:

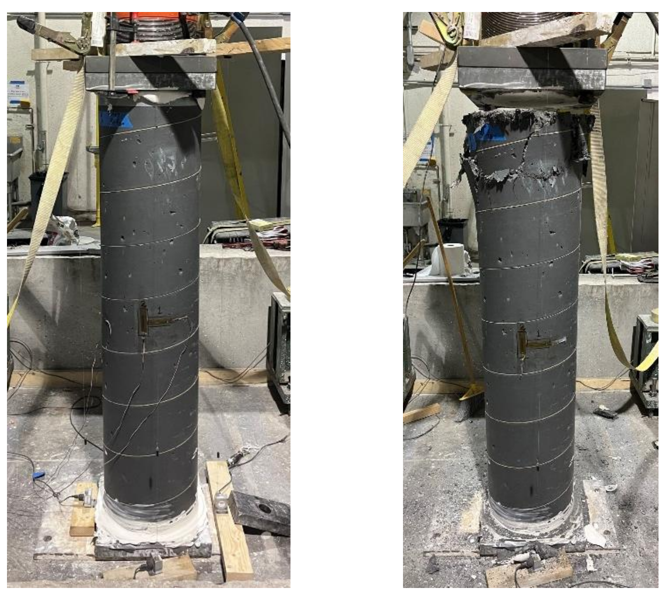
(before) *(after)*

Figure 65. *Large-scale specimen 27 – Max. Load: 783 kips (**but never failed**)*

Preparation of specimen for Large-scale test 28:

This specimen is completely new. It is 60.75 inches high and 12 inches in diameter. No steel rebar was used for retrofitting.

Figure 66. *Preparation of specimen for test 28*



(before) *(after)*

Figure 67. *Large-scale specimen 28 – Max. Load: 300 kips (top local crushing)*

Preparation of specimen for Large-scale test 29:

This specimen is completely new. It is 61 inches high and 12 inches in diameter. Steel rebar was used for retrofitting. Four longitudinal #3 bars were used, and #3 stirrups spaced 3 inches on center.

Figure 68. *Preparation of specimen for test 29*

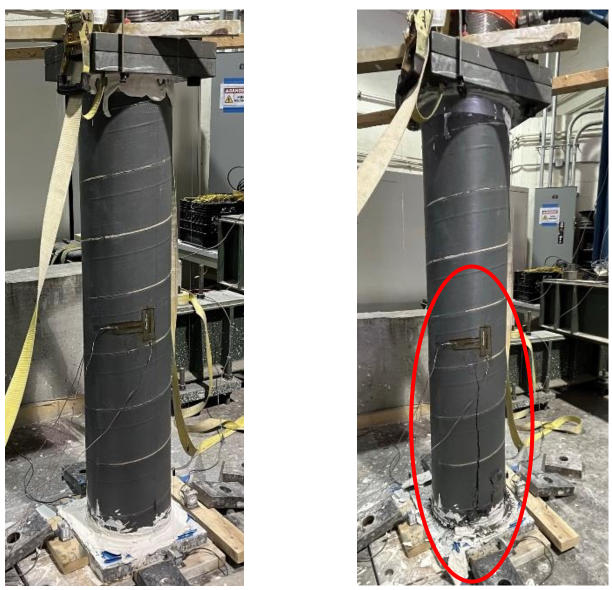
(before) *(after)*

Figure 69. *Large-scale specimen 29 – Max. Load: 783 kips (**but never failed**)*

Preparation of specimen for Large-scale test 30:

This specimen is completely new. It is 61.25 inches high and 14 inches in diameter. No steel rebar was used for retrofitting.

Figure 70. *Preparation of specimen for test 30*



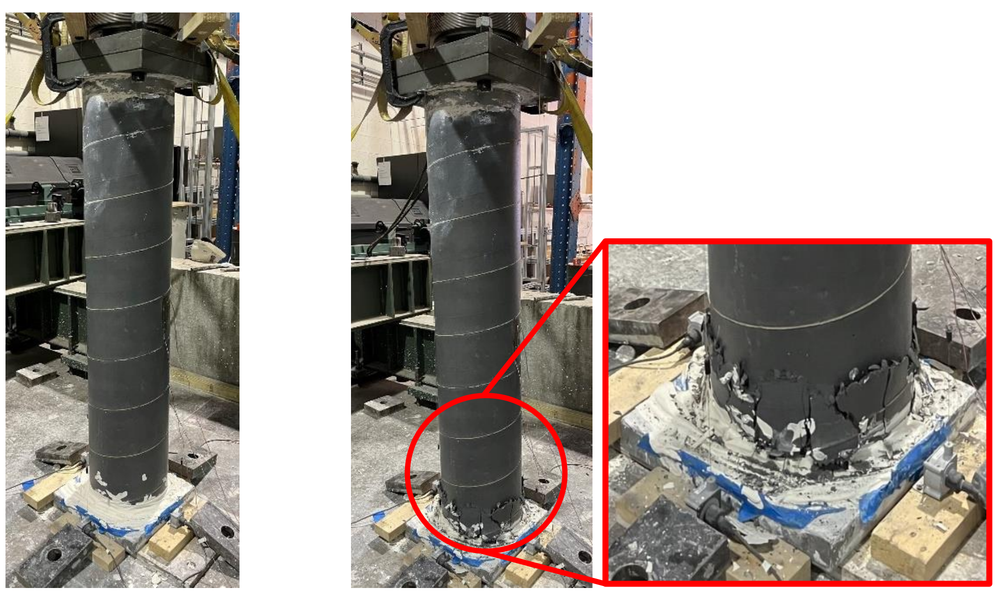
(before) *(after)*

Figure 71. *Large-scale specimen 30 – Max. Load: 637 kips*

Preparation of specimen for Large-scale test 31:

This specimen is completely new. It is 60.5 inches high and 14.5 inches in diameter. Steel rebar was used for retrofitting. Four longitudinal #3 bars were used, and #3 stirrups spaced 3 inches on center.

Figure 72. *Preparation of specimen for test 31*



(before) *(after)*

Figure 73. *Large-scale specimen 31 – Max. Load: 660 kips*

Finally, all specimens are ready to be tested.

Figure 74. *All specimens ready for tube form removal*

Task 4 – Numerical model verification through finite element analysis

In this task, numerical models will be developed to calibrate the test results from Task 2 and Task 3 to better understand.

Using the results from small-scale tests numerical models are being prepared using ATENA software as shown in Figure 50.

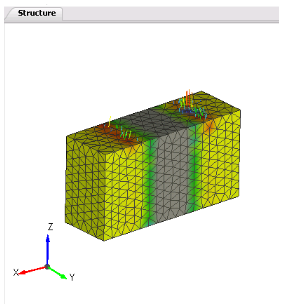


***Figure 75**. Numerical model of push-off tests using ATENA software.*

By using ANSYS, numerical model was performed for the following cases as shown in Figure 42 through Figure 44:

Figure 51 shows the FEM for the small-scale specimen with timber core and UHPC encasement. In this specimen the only restriction is the base of the UHPC encasement to allow the timber to slide down. Figure 51 also shows the stress distribution in UHPC encasement.

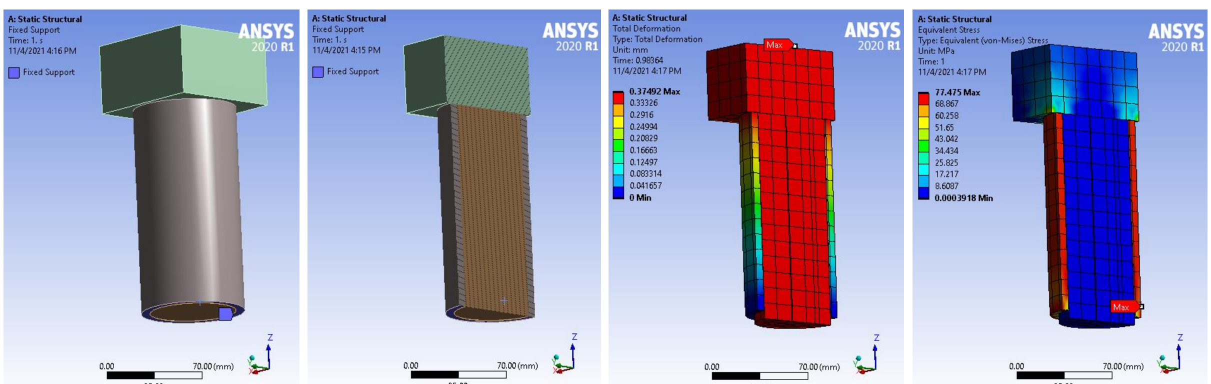


***Figure 76**. Numerical model of push-through tests using ANSYS software.*

Figure 52 shows the FEM for the large-scale sample. In this model, the specimen was modeled with gap element between the timber core and UHPC encasement. Figure 42 also shows the stress distribution in both timber and UHPC encasement.

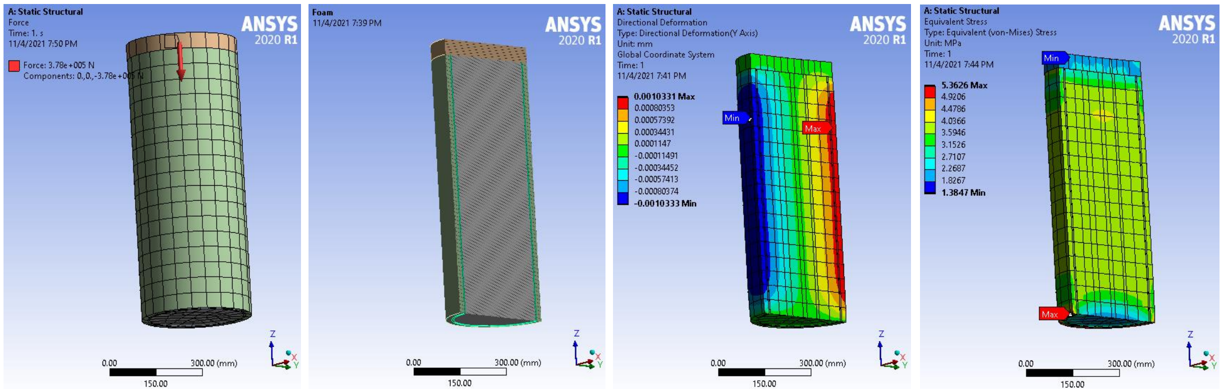


Figure 77. *Numerical model for complete repair encasement using ANSYS software.*

Figure 53 shows the FEM for specimen with partial repair. As depicted, the timber pile had reduced section in the middle representing damage and the UHPC encased the reduced section. Figure 53 also shows the stress distribution in both timber and UHPC encasement.

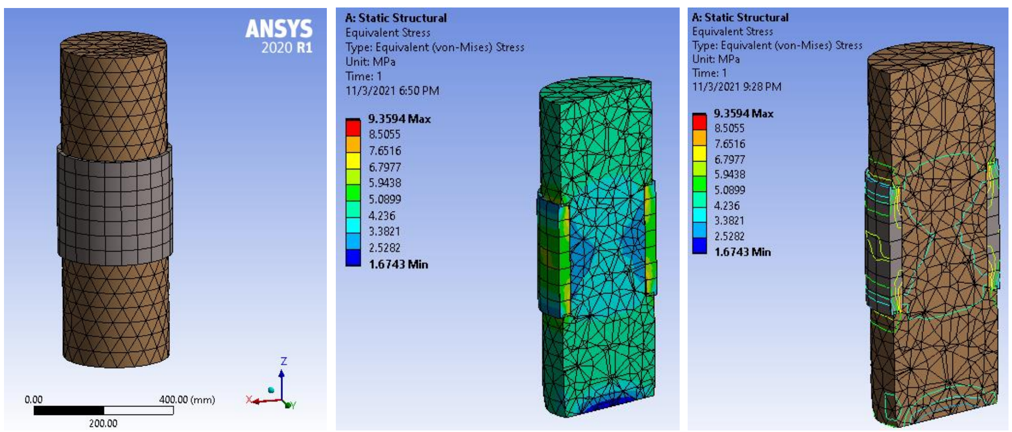


Figure 78. *Numerical model for partial repair encasement using ANSYS software.*

Task 5 – Final Report

In this task, full assessment of the findings from Task 1 throughout Task 4 will be conducted and a report will be published including design recommendations of repairing and retrofitting timber piles using UHPC.

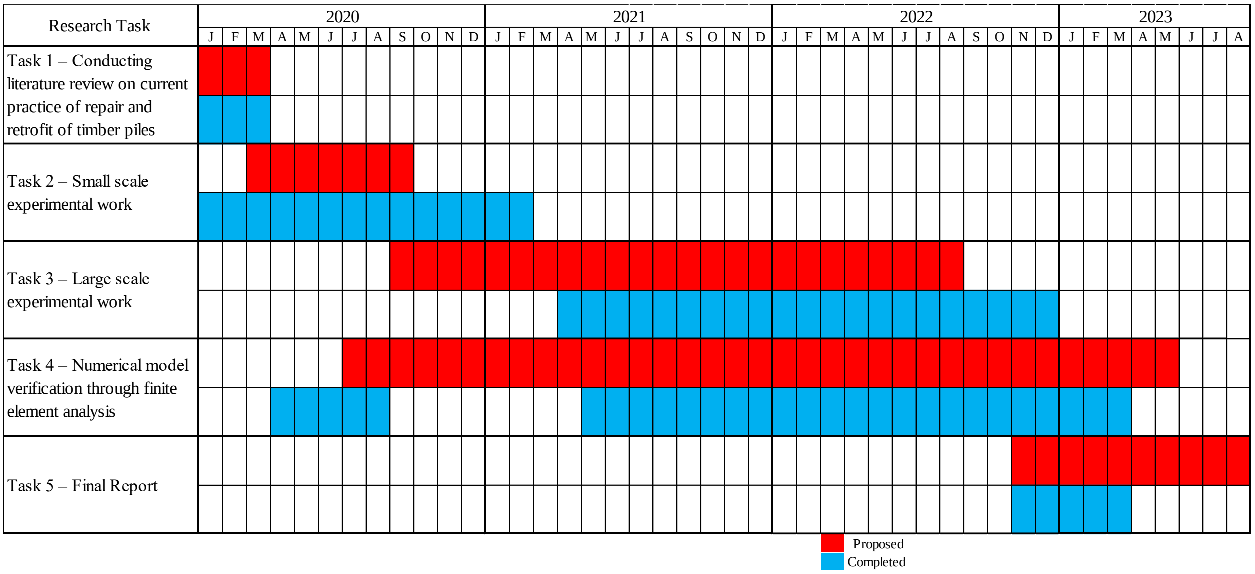
Progress: Researchers are building up this report for the final report.

5. Expected Deliverables

The final report, journal articles, design guidelines, and a five-minute video presentation will be the expected deliverables.

6. Schedule

Item	% Completed
Percentage of Completion of this project to Date	94%



7. Reference

J. H. Gull, A. Mohammadi, R. Taghinezhad, and A. Azizinamini, "Experimental evaluation of repair options for timber piles," *Transp. Res. Rec.*, 2015.

A. Mohammadi, P. D. Jawad H. Gull, R. Taghinezhad, and P. D. P. E. Atorod Azizinamini, "Assessment and Evaluation of Timber Piles Used in Nebraska for Retrofit and Rating," 2014.

Timber Piling Council, and American Wood Preservers Institute, "Timber Pile Design and Construction Manual" 2002.