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Behavior of Inflatable Rigidified Composite Arch Bridges

by

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Abstract

Researchers at the University of Maine have developed a novel system for short span arch bridge construction that utilizes tubular fiber reinforced polymer (FRP) composite arches that act as both formwork and structural reinforcement for concrete. The inflatable rigidified composite arch (IRCA) system is designed for field rigidification allowing for tailorable arch geometry as well as rapid field construction. The system is being explored for military applications where construction time, component weight, and equipment requirements are of great importance.

Arches have been manufacture and subjected to load tests at the AEWC Center's structural testing laboratory. The IRCA system exhibits a nonlinear response due to both the stress-strain relationship of confined concrete in compression and progressive cracking of concrete in tension. A finite element model was developed to predict the ultimate capacity and load-deflection response of the IRCA specimens. The structural model predictions correlated well with the experimental results.

Background

Cast-in-place (CIP) concrete is used extensively in the construction of highway bridges in the United States. While CIP concrete offers the benefits of being readily available and inexpensive, the processes of formwork construction and shoring and reinforcing bar installation are very time and labor intensive. With the rapidly increasing cost of labor in the United States, an ideal solution would combine the benefits of CIP concrete construction with a rapidly constructible formwork and reinforcement system.

In recent years, FRP composites have seen increasing use as reinforcement for concrete. Applications of FRP to concrete include FRP reinforcing bars, external fabric wraps for longitudinal and shear reinforcement in beams, and column encasing using bonded FRP sheets. FRP composites do not corrode and, therefore, they have a durability and maintenance advantage over conventional steel reinforcement

Researchers at the University of Maine have developed a novel system for short span arch bridge construction that uses inflatable tubular FRP arch members that act as both a stay-in-place formwork and structural reinforcement for concrete. The system is designed such that the arch members may be rigidified onsite, placed quickly using light construction equipment, and filled with concrete to form the entire bridge superstructure in one hour. Additionally, the FRP arch tubes fully encase the concrete providing confinement as well as protection from environmental conditions. The result is a truly high-performance structure.

Applications

The IRCA system is currently being explored for military applications where reduced time and equipment needs are critical. Potential uses include buried arch bridges, bunkers, tunnels, or hangers, all of which could potentially be constructed very quickly and with little to no heavy equipment.

Current manufacturing capabilities include arches with cross section diameters of 6.5 in. and 12 in., and FRP wall thickness up to ½ in. Continuous tubular reinforcing fabrics are used in production allowing for rapid manufacture of arch tubes of virtually any geometry or size. Arch tubes have been manufactured with spans up to 60 ft.

Manufacturing of FRP Arch Tubes

The IRCA members are manufactured using a patent pending process developed at the University of Maine that combines industry standard composites manufacturing procedures with several application specific techniques to create an efficient, effective, and highly repeatable process.

The hollow arch tubes are assembled, infused with a thermoset resin, and allowed to cure. This process is deemed "primary rigidification".

Due to the light weight of the hollow arch members, installation can be completed quickly by two to three laborers with little to no heavy equipment (Figure 1). After installation is complete, the arches undergo secondary rigidification, which consists of filling the IRCA members a cementitious concrete mix

IRCA System Characterization

In order to effectively carry out structural design using the IRCA members, it is necessary to thoroughly understand the system's behavior. This includes the ability to accurately predict load carrying capacity, failure modes, and deflections. In order to characterize the behavior of the IRCA system, a three-phase comprehensive testing and modeling program has been completed.

In the first phase, a material nonlinear finite element model was developed to predict the behavior of arch members. The second phase consisted of material level testing of the constituent materials to determine model input parameters. The third phase consisted of full scale structural testing for model validation on two levels. The model was validated on an elemental level through testing of straight concrete-filled FRP beam specimens, and on a system level through full scale structural testing of concrete-filled FRP arch specimens.

Phase I: Development of Finite Element Model Overview

Analysis of the IRCA system presents a complex problem due to the presence of material nonlinearities, concrete cracking, interaction of axial and flexural response, and load history dependent properties. The analysis is carried out using a nonlinear model developed using the finite element method. The finite element method allows for analysis of a complex structure such as the IRCA by dividing the structure into a number of smaller elements whose behavior can be modeled more easily, then connecting these elements at nodes and enforcing the appropriate compatibility conditions [1].

The model addresses material and geometric nonlinearities, load-history dependent material properties, and the interaction of axial and flexural forces.

Phase I: Development of Finite Element Model Flexural Behavior

The nonlinear flexural response of reinforced concrete is well documented in literature. In general, concrete is assumed to behave linear-elastically up to the point of cracking. The first occurrence of cracking is assumed to take place when the extreme tension fiber reaches the modulus of rupture, defined by ACI-318 as:

$$f_r = 7.5\sqrt{f_c'} \qquad \textbf{[2]}$$

where f'c is the 28-day compressive strength of concrete in psi. At the onset of cracking, the section exhibits a nonlinear response to failure, defined as the point at which concrete reaches its crushing strain of 0.003.

The flexural response of FRP reinforced concrete varies from that of steel reinforced concrete due to the relatively low modulus of elasticity of the FRP material and lack of yielding behavior in FRP. Additionally, the FRP tube provides a level of confinement for the concrete which varies with laminate properties, and axial force in the member. Several researchers have published moment-curvature relationships for concrete filled FRP tubes, two examples are the publications by Fam [3], and Burgueño [4]. Both present methods for predicting the moment-curvature relationship of concrete filled FRP tubes using an iterative approach that accounts for confinement of concrete in compression and cracking of concrete in tension.

Phase I: Development of Finite Element Model Axial-Flexural Interaction

When subjected to generic loads, each section of an arch must carry both axial and flexural forces. In the case of the concrete filled FRP arch system, the flexural behavior is directly coupled to the level of axial force in the member. In general, a greater axial force results in a greater bending stiffness. Additionally, each section of the arch experiences a different combination of axial and flexural loads under any given load.

In order to address the interaction of axial and flexural forces and deformations, a three-dimensional axial-flexural interaction domain was defined for the member. At each step in the analysis the curvature, axial force, and moment must be solved for simultaneously in each element in order to satisfy equilibrium conditions.

Phase I: Development of Finite Element Model Arch Discretization

The arch is discretized using 2-dimensional plane frame elements of equal length placed along the center line of the arch geometry. The plane frame element is chosen as it is the simplest of elements that can undergo both flexural and axial deformations. Symmetry about the arch centerline is assumed for computational efficiency.

The number of elements used to discretize the arch structure is determined by first analyzing the structure using a coarse mesh, then refining until results show convergence within an acceptable tolerance. For the purpose of developing the arch model, the arch was discretized using a number of elements ranging from 6 to 800. It was seen that less than 1% error could be obtained in deflections and developed moments by using 25 elements, 35 elements were used for all further analysis to result in an even member length.

Phase II: Model Input Parameters Shell Laminate Testing

The behavior of the IRCA system is highly dependent on the mechanical properties of the shell laminate. In order to determine mechanical properties of the laminate, representative panels were manufactured using the same layup of braided fabric as in IRCA members, and infused using a similar resin chemistry and VARTM process. From these panels, coupons were manufactured and tested in tension using two test methods.

Tension tests were performed in accordance with ASTM D-3039 [5] to determine the elastic properties E_1 (longitudinal modulus), E_2 (transverse modulus), and ν_{12} (Poisson's ratio). The FRP exhibits a response that is linear elastic very nearly up to the point of failure. The slight nonlinearity before failure was considered an artifact of the test method and not a material response and therefore a linear elastic behavior was assumed for the laminate for all further analysis.

Tensile strength of the laminate was determined using a test method developed at the University of Maine specifically for laminates reinforced with symmetric off-axis braided fabrics. The test method uses a 2 in wide specimen notched horizontally at the middle of the gage section. The specimen geometry and notch size and location maintain fiber continuity between grip sections effectively reducing free edge effects and resulting in an accurate representation of laminate tensile strength. The mechanical properties determined for the FRP laminate are given in Table 1.

Phase II: Model Input Parameters Concrete Testing

Concrete strength was determined in accordance with ASTM C-39 [6]. Using the concrete compressive strength, a stress-strain curve was predicted using the model developed by Mander [7], and elastic and strength parameters were calculated in accordance with the equations of ACI 318.

Phase III: Experimental Validation of Model Flexural Testing of Concrete-Filled FRP Beams for Elemental Level Validation

In order to validate the flexural behavior of the concrete-filled FRP beam element used in the finite element modeling, three straight beam specimens were manufactured and tested in 4 point bending. The first of the three specimens was tested using an uncalibrated load cell. Results from this test, while consistent with those obtained from the remaining two specimens, will not be included in this paper.

Beams specimens were tested in four-point bending with a span of 144 in. Load was applied to specimens at the third points using a 110 kip servo-hydraulic actuator. The test setup is shown in Figure 2.

For all specimens, vertical displacement was measured at the load points, midspan, and supports using linear variable displacement transducers (LVDT). Rotation of the specimen or apparatus in plane was measured by installing LVDT's on both sides of the cross section at the load points and midspan. Strains were measured at the top face, mid height, and bottom face of the specimen at two sections within the constant moment region using 1" resistance foil strain gages. In order to measure any differential movement of the concrete core relative to the FRP shell, string potentiometers were installed horizontally at each end of the specimen. No differential movement was observed in any specimens.

From the experimental data load-deflection plots were created for all specimens. The nonlinear flexural behavior of the beam specimen is seen in the load-deflection response. Figure 3 gives the experimental and model predicted load vs. midspan deflection. Localized buckling of the FRP shell on the compression face was observed in all specimens at approximately 80% of the failure load. This can be seen in the load deflection diagram given in Figure 3, as a slight softening occurs at approximately 45 kips.

All specimens ultimately failed due to tensile rupture of FRP within the region of maximum moment at a mean moment of 1304 in*kip (6.6% COV), 5.7% below the predicted failure moment of 1378 in*kip.

Phase III: Experimental Validation of Model Flexural Testing of Concrete-Filled FRP Arches for System Level Validation

In order to provide system level validation for the IRCA finite element model, full scale structural testing was carried out on three concrete-filled FRP arch specimens. All arch specimens had a cross section diameter of 12 in, a constant centerline radius of 13 ft, and a span of 22 ft, and were tested under a single patch load applied vertically at the crown. The arch test setup is pictured in Figure 4.

Arches were subjected to two quasi-static tests. In the initial test specimens were loaded until FRP tensile failure occurred at the crown, the maximum load from this test corresponds to the ultimate strength of the arch. After failure has occurred, the arch maintains stability along with a significant portion of the initial strength. The post-damage behavior was investigated by carrying out a secondary quasi-static test in which loading was continued until complete failure of the specimen occurred. Failure during the secondary test was due to tensile rupture of FRP on the outside face at a location approximately half the distance between the crown and support. At the point of secondary failure, stability is lost and complete failure of the specimen occurs.

Specimens were instrumented with strain gages at the top face, mid-height, and bottom face at two sections along the span to measure strain and curvature of the section. Deflections of the specimen were measured using string potentiometers at the crown and two sections along the span, while deflection of one half of the arch was measured using and a digital image correlation (DIC) system. Support rotations were measured using string potentiometers mounted to the bases of the specimens.

The undamaged load-deflection response of the IRCA is characterized by an initial linear region up to the point at which tensile cracking of concrete first occurs followed by a nonlinear region of softening in which concrete cracking occurs progressively throughout the arch. Figure 5 gives the model predicted and experimental load-deflection response. Model predictions were in very good agreement with experimental load-deflection response.

Deflections were monitored in three dimensions for half of the arch specimen using a DIC system. Using the DIC data, the deflected shape was plotted for the arch specimens at various levels of applied load ranging from 0 to 85% of the failure load. This data was plotted against model predictions and in general showed very good correlation. Figure 6 gives the model predicted and experimental deflected shape at various levels of applied load, (deflections magnified 15X).

The mean failure load for arch specimens was 71.1 kip (0.2% COV), while model predicted failure load was 69.0 kip. The model underpredicted specimen capacity by approximately 3%. The failure mode for all specimens was tensile rupture of FRP at the location of maximum moment, consistent with model predictions (Figure 7).

Initially, the two-pinned arch is a single degree statically indeterminate structure. At the point of initial failure, a hinge is developed at the crown of the arch. At this point, one degree of freedom is released and the result is a statically determinate structure that maintains stability. The three-hinged arch also maintains a significant portion of the initial strength. In order to asses the post-damage behavior of the arch, a secondary quasi-static test was carried out by loading the arch specimen until complete failure of the specimen had occurred. Secondary failure occurred in all specimens due to tensile rupture of FRP on the outside face approximately half the distance between the crown and the support (Figure 8). Secondary failure occurred in specimens at a mean load of 56.7 kip (10.4% COV), approximately 80% of the undamaged strength. During secondary tests, significant deflection is achieved, with deflections to failure of 2.5-3.0 times that observed in initial load tests.

In order to predict the post-damage behavior of the arch specimen, a three-hinged arch model was created by modifying the boundary conditions in the undamaged arch model to allow free rotation at the crown. The model predicts strength of specimen very well, with a prediction of 57 kip, however significantly underpredicts stiffness of the three hinged arch. This suggests that after FRP failure has occurred at the crown, fully pinned behavior does not occur; rather some amount of rotational stiffness is retained at the joint contributing to overall the stiffness of the system.

Conclusions

A novel system has been developed for short span arch bridge construction that uses inflatable composite arch tubes that act as both formwork and structural reinforcement for concrete. The system is designed for reduced construction time over conventional CIP concrete, and can be constructed using little to no heavy equipment.

The unique manufacturing method allows for onsite rigidification of the FRP composite arch tubes allowing for design versatility. The FRP composite shell provides both longitudinal and hoop reinforcement for concrete, increasing strength and ductility over unconfined concrete. The exterior FRP reinforcement also provides protection from environmental conditions.

A finite element model has been developed to predict the behavior of the arch specimens. The model has shown to very accurately predict capacity, deflections, and failure modes for arches during initial load tests.

At the point of initial failure, the IRCA develops a hinge at the crown resulting in a stable, statically determinate structure. The arch maintains approximately 80% of the initial undamaged strength after failure and achieves significant deflection to failure in post-damage testing. The result is a safe structural system that provides significant warning prior to failure.

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Figures:

Figure 1. Installation of 22’ Span Arch Tubes by Three Laborers

Table 1. Shell Laminate Properties

Property	Mean Value	Number of Specimens	COV	Source
Shell Thickness	0.101 in (2.566 mm)	17	2.6%	ASTM D-3039
Longitudinal Modulus	6195 ksi (42.71 GPa)	8	5.7%	ASTM D-3039
Transverse Modulus	2068 ksi (14.26 GPa)	9	4.3%	ASTM D-3039
Poisson's Ratio	0.429	8	9.5%	ASTM D-3039
Ultimate Strain	0.0174	8	6.5%	Notched Tension

Figure 2. Beam Test Setup

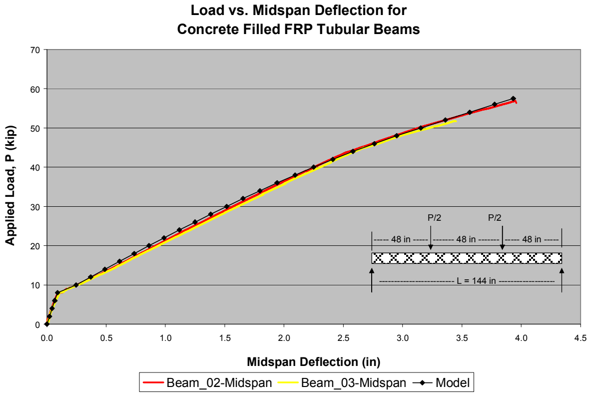

Figure 3. Experimental and Model Predicted Load vs. Midspan Deflection

Figure 4. Arch Test Setup

Figure 5. Arch Specimen Load-Vertical Deflection at Crown

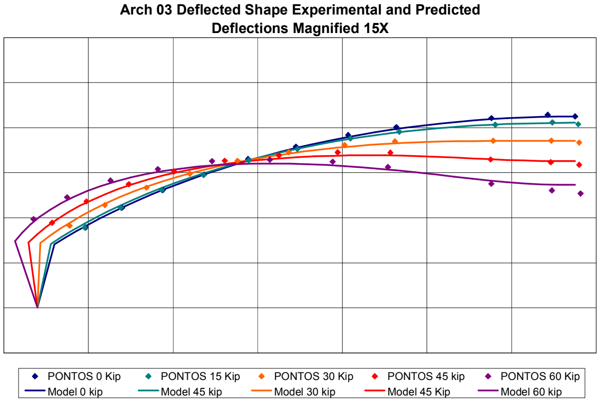

Figure 6. Arch 03 Deflected Shape Experimental vs. Model Prediction

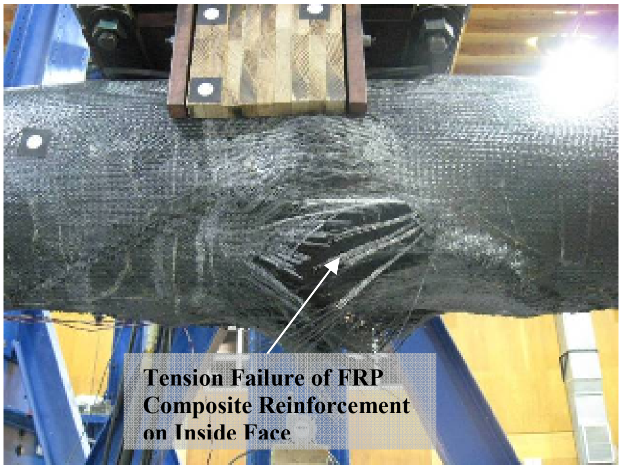

Figure 7. Arch Initial Failure Mode

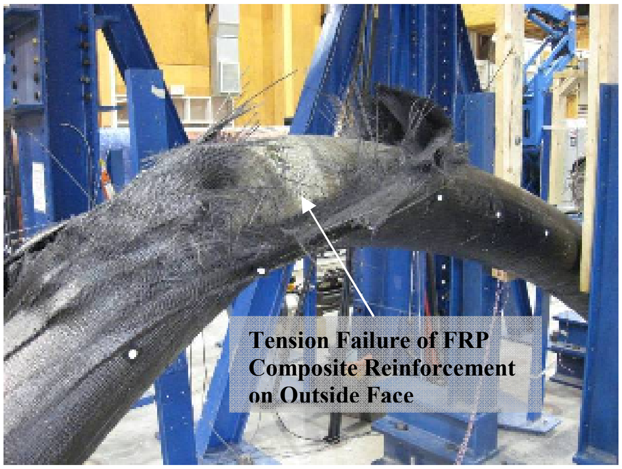

Figure 8. Arch Secondary Failure Mode