FRP Repairs to Steam Tunnel

By Richard R. McGuire and William J. Gold

The University of Missouri (MU), Columbia, MO, wanted a structural assessment performed of its more dated, arterial steam tunnels running throughout this large university complex. MU was founded in 1839, as the first public university west of the Mississippi River. Most of these older steam tunnels were constructed of reinforced cast-in-place concrete of varying cross-sectional sizes.

The original campus area, known as the Quad, is served by very old brick-arch steam tunnels. It was in this area that a pronounced lateral bulge projecting inward was discovered on the multi-wythe brick unreinforced masonry wall (URM) during field surveys of the study tunnels (refer to Fig. 1).

Upon completion of the formal study for MU in September 2004, and following discussions with the university's consultant, it was decided that the highest repair priority must be given to the 100+ year old brick-arch steam tunnels in the Quad area. The consultant prepared a system of repair priorities, identified as "Priority A, B, C, or D," with Priority A being the most critical due to the potential for personnel injury and/or operational disruption.

The MU steam tunnels provide both heating and cooling energy through a complex system of live steam and condensate pipes inside the various tunnels, together with many other communications lines, to the entire MU campus. Ironically, the most critical Priority A repair area was a 30 ft (9.1 m) long lateral bulge on a section of tunnel wall, which was under a busy campus sidewalk and directly in front of the original Engineering Hall.

Fig. 1

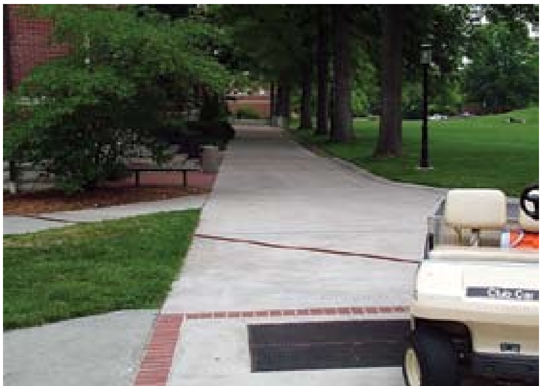

Fig. 2

Repair Accessibility and Options are Limited

The structural engineer considered several options from open excavation to expose the steam tunnel and reconstruct the deteriorated section of the masonry wall half-section, to several repair schemes within the tunnel. As noted, the section of steam tunnel requiring the structural strengthening or replacement repairs was under the Quad sidewalk in front of an older academic building, and open excavation of this area was ruled out due to concern for student safety, building access, temporary drainage control, and a construction cost premium (refer to Fig. 2).

Further investigation and discussions with the MU Energy Management engineering staff helped the engineer to narrow down the best repair method and cost options. Repair options were further narrowed to conventional structural steel bracing of the masonry wall bulge and the possible use of fiber-reinforced polymer (FRP) in a below-grade URM wall application.

Steam tunnels present owners, engineers, and contractors with a myriad of technical repair and maintenance challenges. Aside from the obvious confined, restricted space and movement in most of the tunnels (thankfully, the lateral bulge repair was on the opposite wall from the steam pipes), temperatures ranged from about 100 to 135 °F (38 to 57 °C), humidity was always very high, standing water was common, hazardous gases needed to be continually monitored (that is, CO and H_2S), pipe burns and dehydration were always looming, and there were some interesting diversions from various insect species as well.

As solution options were being investigated, the engineer consulted the leading manufacturers of FRP composites and attempted to find industry and academic research in URM strengthening-bracing applications for steam tunnels. There was little to be found on similar repairs to URM steam tunnels. This pointed us toward a difficult choice, because we initially had moved toward the more conventional repair using structural steel members to create a lateral bracing frame to check the bulge and transfer loads to the tunnel's masonry walls and floor. The steel bracing frame solution, however, presented installation challenges and associated costs, coupled with an undesirable maintenance traffic impact that made the FRP low-profile, faster installation solution even more attractive to the project team.

Working jointly toward the FRP repair solution, the engineering consultant received welcomed engineering assistance from Dr. Antonio (Tony) Nanni, PE, of the University of Missouri-Rolla, School of Engineering, who had researched the use of FRP in reinforcing and strengthening applications, including URM repairs. Dr. Nanni's concrete research lab and years of work in FRP-reinforcing applications for concrete structures provided significant insight and confidence into the solution methodology. With a better understanding of the FRP design variables and the tunnel bracing conditions, we could now proceed with the details.

Design Parameters for the FRP Application on the Steam Tunnel Wall

In pinning down the design criteria and repair details, the engineer focused on the use of high-strength carbon-fiber reinforced polymer (CFRP) reinforcing bands in the lateral bulge area of the steam tunnel's brick wall. In consultation with the selected CFRP manufacturers, specifically the Engineering Services Manager, calculations verified that these CFRP bands could perform the required strengthening, even given the very adverse environmental conditions.

It was estimated that the lateral deflection or bulge in the wall of the tunnel (refer to Fig. 3) was created by a 70,000 lb (31,750 kg) horizontal force from soil pressure acting along a 30 ft (9.1 m) length of the tunnel (2000 lb/ft [2975 kg/m] of tunnel). The unreinforced masonry wall alone was not capable of safely sustaining this level of load. Therefore, the FRP system was designed to counteract this force with a minimum factor of safety of 2.0.

Based on an analysis of the masonry wall reinforced with the FRP system, the ultimate bending failure of the wall was determined to be compressive failure of the masonry on the exterior face of the wall. As such, the maximum strain level in the FRP was limited to 0.006 in./in. (0.015 cm/cm), and the

SCHEMATIC CROSS SECTION OF THE TUNNEL WALL SHOWING THE DEFLECTION OR BULGE AT MID-HEIGHT OF THE WALL

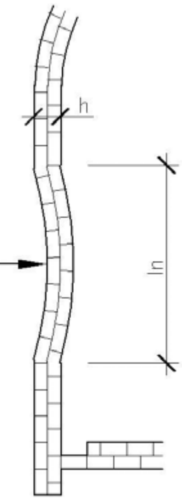

Fig. 3

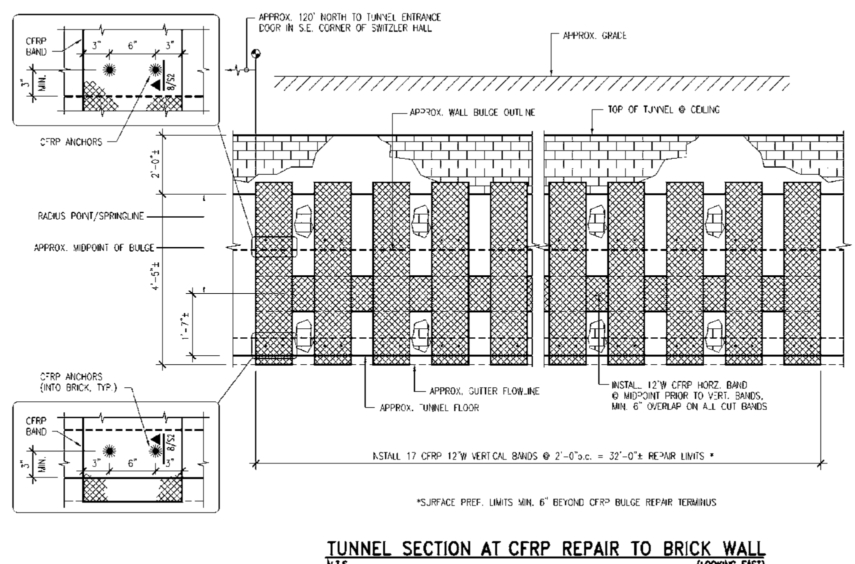

Fig. 4

maximum stress that could be developed in the FRP was 198 ksi (9.48 MPa) (roughly 35% of the FRP system's 550 ksi [26.3 MPa] tensile strength). At this level of stress, the FRP does contribute substantially to the bending capacity of the wall. The analysis indicated that the maximum bending moment that the FRP reinforced wall can resist is 5200 lb-ft/ft (720 kg-m per 0.3 m) of wall. This bending moment is 2.1 times larger than the anticipated moment in the wall from soil pressure of 2500 lb-ft/ft (345 kg-m per 0.3 m) of wall.

To satisfy the design conditions, two layers of CFRP fabric bands were installed. First, a horizontal band centered on the midpoint of the wall bulge was applied, and then vertical strips 12 in. (30.5 cm) wide and spaced at 24 in. (61 cm) on-center were used over the length of the wall repair area. The FRP system consisted of a high-strength carbon fiber fabric (9 oz, unidirectional) that was applied directly to the prepared surface of the masonry wall and was encapsulated using a high-strength, high-chemical/temperature-resistant, 100%-solids epoxy (refer to Fig. 4).

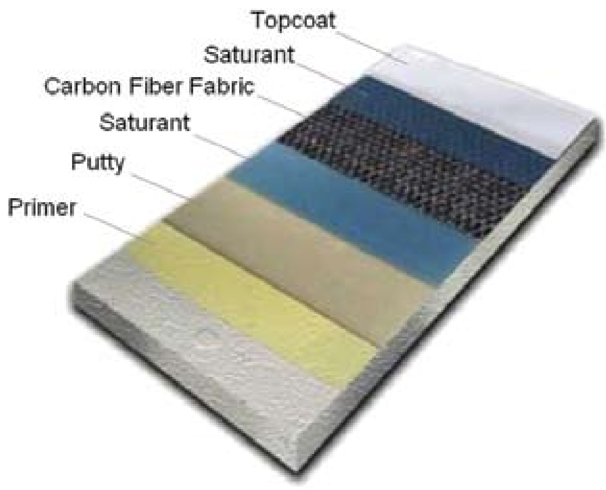

Fig. 5


Fig. 6

The FRP system was installed by first applying a low viscosity epoxy primer to the surface of the masonry after preparing the surface of the masonry to an ICRI CSP 3 profile. Surface irregularities were then filled using an epoxy putty. The encapsulation resin or saturant was then applied directly to the surface of the masonry, the fabric is placed into the saturant, and a second coat of saturant was applied to completely encapsulation the carbon fiber fabric (refer to Fig. 5).

Because all of the epoxy components of the FRP system used were 100% solids and very low volatile organic compounds (VOC), the system could be placed in the tunnel without the need for respirators or supplemental oxygen. Due to the elevated temperature inside the tunnel, however, all of the components of the system had to be placed quickly. Because the epoxy putty had to fill a number of surface irregularities, it was best to apply the system "wet-on-wet," meaning that the saturant was applied before the putty cured. In this way, the irregularities in the putty did not need to be ground flat. Because the epoxy putty cured very quickly in the elevated temperature of the tunnel, it was necessary to work in small sections to apply each component in a relatively short period of time.

In general, FRP systems installed to resist horizontal forces in walls function best when the bond surface is smooth and flat. Neither condition was the case with the tunnel walls. The mortar joints and variations in brick placement resulted in a very rough surface condition. This was addressed by using a paste epoxy filled with silica flour as a leveling material to provide a smooth bond surface. The greater challenge, however, was the fact that the tunnel wall was not a flat surface. The large permanent deflection in the tunnel wall created a severe surface undulation (refer to Fig. 6).

Furthermore, it was determined that, to provide sufficient bond length for the FRP system, the FRP system would need to extend up onto the arched ceiling of the tunnel. These undulations in the surface result in very high out-of-plane or pull-off bond stresses in the FRP. To ensure that the FRP system would not debond in these high stress areas, strategically located mechanical anchors were also installed, that is, a belt-and-suspenders approach (refer to Fig. 7, 8, 9, and 10).

Advantages of FRP Strengthening of Existing Concrete and Masonry Structures

FRP composites have been employed for over 30 years in various aerospace and manufacturing applications. In recent years, FRP has evolved into a proven structural strengthening tool as an externally bonded reinforcement system for both shear and flexural capacity increases. FRP composites can have tensile strengths up to 10 times that of steel. High strength and durability, coupled with a low profile, non-corrosive material and accelerated installation time, made this repair solution attractive to all parties on this project.

In considering the use of FRP composites for concrete (or masonry) strengthening, it is important to consult the American Concrete Institute (ACI) guideline on FRP systems, ACI 440.2R, "Guide for Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete." ACI 440.2R was first published in October 2002, and is the second publication from ACI's Emerging Technology series. This informative guideline offers general information on the history and use of FRP strengthening systems;

Fig. 7

Fig. 9

Fig. 8

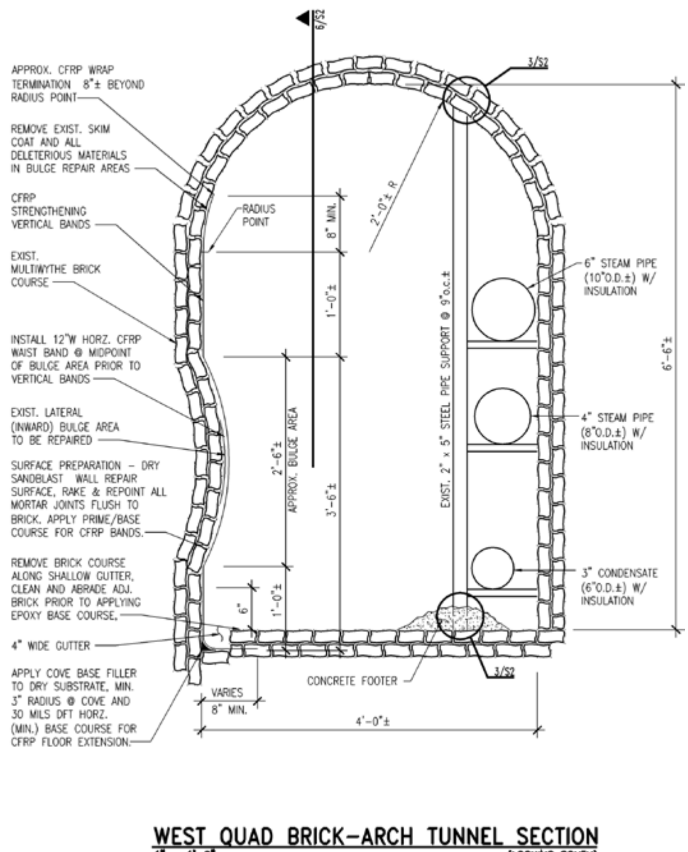

Fig. 10

material properties of FRP; and ACI Committee 440 recommendations on engineering, construction, and inspection of FRP systems used to strengthen concrete structures.*

The Repair Contractor Selection and Qualifications are Critical to Success

Equally important to evaluating the application of FRP composites for shear and/or flexural strengthening applications and the requisite calculations and details is the selection of the qualified FRP-certified repair contractor. For these steam tunnel repairs, MU decided to pre-qualify and invite "short-listed" repair contractors for the competitive bidding process. A mandatory Pre-Bid Conference was conducted at the MU site with the owner's project manager and energy management engineering staff, the consulting engineer, and the invited contractors. This also provided the contractors with an opportunity to discuss issues on tunnel accessibility, safety, surface preparation, FRP technical issues, and the project schedule. In addition to the FRP strengthening of the tunnel wall bulge area, there were numerous steam pipe anchorage/support repairs (from corrosion), brick repointing, concrete washes in the tunnel floor, and installation of a new tunnel sump pump and force main.

MU awarded the project to the contractor who offered the owner a proposal that was within the project budget and with an aggressive construction schedule. As with most educational facilities, especially colleges

*For URM strengthening applications, the author recommends that the design professional contact the leading manufacturers in FRP composites, as well as academic researchers in FRP.

and universities, the construction "window of opportunity" tends to be from mid-May to mid-August. The contractor finished the steam tunnel repairs on time and on budget, with no job-related injuries.

Ted Jacques, the President of the contracting firm, stated, "The structural repairs on the steam tunnels were extremely difficult, to say the least, due to the limited access, confined space, utilities, and elevated operating temperatures. Thanks to our team of engineers, manufacturers, skilled craftsmen, and the close support of the university's energy management and project management staff, this project was completed safely and on time with great success." Given the spatial and environmental factors that confronted the project team, beyond the challenge of this somewhat unique FRP strengthening application, this was another success story.

FRP Strengthening is Evolving Technology—Stay Tuned and Do Your Homework

As consultants, we were able to apply, after careful research and consideration, a CFRP banding solution to strengthen a failing steam tunnel wall that minimized installation cost and schedule, eliminated live steam and condensate piping downtime, and achieved the need for minimal profile in a very tight and hostile space.

FRP strengthening and reinforcing can be applied to concrete and masonry structural elements to resist loads from wind, soil pressure, increased/superimposed framed level loading, fluid pressure, and blast loading. Research is underway to develop FRP reinforcing bars that could eventually replace conventional reinforcing steel in some applications, providing greater tensile strength and smaller cross-sectional solutions in reinforced concrete structures.

As we seek opportunities to apply developing technology to give owners safe and cost-effective solutions, together with increased service life for their facilities, we must continue to apply sound judgment with good science on all projects. We found that there was much to be learned by engaging in proactive dialog with engineering academia and the FRP manufacturer to ensure we were "tuned in" to the best approach and current design methodology. As with all repair and/or restoration projects, do your homework and assemble the right team.

MU Steam Tunnels

Owner
University of Missouri
Columbia, MO

Structural Engineer and University Consultant
Structural Engineering Associates, Inc. (SEA)
Kansas City, MO

Repair Contractor
JACOR Contracting, Inc.
Kansas City, MO

Material Supplier
BASF Building Systems
Beachwood, OH

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***William J. Gold**, PE, is the Engineering Services Manager for BASF Building Systems, Cleveland, OH. Gold has nearly 10 years of experience in the use of advanced composite materials in the construction industry. He has had extensive involvement in the design, installation, and testing of FRP systems for strengthening numerous existing structures. Gold has also been involved in research on FRP systems at the University of Missouri-Rolla and The Pennsylvania State University. He completed his bachelor's degree in architectural engineering at the University of Kansas. As an active member of ACI and ICRI, he has served as Chair of an ICRI committee on strengthening concrete structures, and is Past Chair of ACI Committee 440F, FRP Repair-Strengthening.*