PRESERVATION OF MISSOURI TRANSPORTATION INFRASTRUCTURES

VOL II: Materials and Construction

VALIDATION OF FRP COMPOSITE TECHNOLOGY
THROUGH FIELD TESTING

Strengthening of Bridge X-0495
Iron County, MO

Prepared for:
Missouri Department of Transportation
University of Missouri-Rolla
(Project Code R03MO3-1)

Feb 19, 2004

Strengthening of Bridge X-0495

IRON COUNTY, MODOT DISTRICT 9

EXECUTIVE SUMMARY

This report presents the materials and construction for flexural strengthening of the reinforced concrete (RC) bridge X-0495, Iron County, Missouri, using externally bonded reinforcements. The report makes reference to two other documents: a) Master Materials and Construction Specifications, written in AASHTO language, and b) Manufacturer's Literature, that contains the tech data sheets for the materials used in this research program. This document explains the concrete repairs, surface preparation, materials specification, storage, handling, etc, for the five different technologies used in this research program, namely: manual lay-up carbon FRP laminates; near surface mounted (NSM) carbon FRP bars; adhered pre-cured carbon FRP laminates; steel reinforced polymer (SRP) laminates; and mechanically fastened carbon FRP laminates.

Bridge X-0495 is one of five existing RC bridges, located in three districts, which were strengthened using composite materials. Five different strengthening techniques were used in the entire program but only two were used for bridge X-0495: manual lay-up CFRP laminates and NSM CFRP Bars.

This project was conducted under a joint MoDOT – UMR University Transportation Center – Private Sector funding initiative. The five existing concrete bridges will be monitored twice a year over five years, including repeated load tests. The data, information, and understanding from this validation are used in the drafting of design and construction specifications to be written in AASHTO language for future FRP-related bridge-strengthening projects.

The strengthening schemes were designed in compliance with the ACI 440.2R-02 Design Guide for Externally Bonded FRP Materials where applicable. Both FRP strengthening techniques were easily implemented and showed satisfactory initial performance. The strengthening of this bridge was carried out during seven weeks in July to September of 2003. The structure has three spans, each with three RC girders monolithically cast with a 6 in (15 cm) slab. Lateral spans are *42.5 ft* (12.95 m) while the central span is *52.5 ft* (16 m). The FRP system consisted of manual lay-up laminates and NSM bars. FRP laminates were U-wrapped on all longitudinal girders to anchor the flexural reinforcement and increase the shear capacity.

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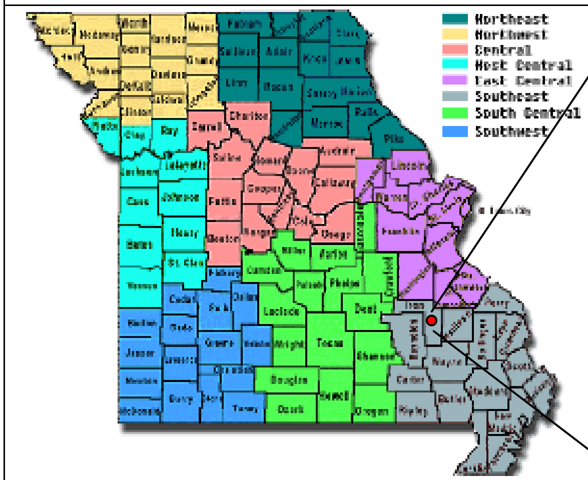
1. INTRODUCTION

1.1 General description

Bridge X-0495 is located in Iron County, MoDOT District 9. The structure has three spans, each with three RC girders monolithically cast on a 6 in (15 cm) slab (see Table 1, Figure 1, Figure 2 and Figure 3).

Table 1- Summary Information

BRIDGE X-0495	
	
District: 9	**County:** Iron
Year Built: 1948	**Feature Intersected:** River
Main Spans Construction: RC T-Beam	**Number of Main Spans:** 3
Total Length: 137.5 ft (41.91 m)	**Rating (Deck/Sup/Sub):** 6/6/7
Load Posting: Trucks over 19 ton (17.23 tons in SI units), 15 mph (24.14 km/hr)on the bridge.	
BRIDGE FEATURES	
Geometry • Height of the bridge is 15 ft (4.6m). Total width of deck is 24 ft (7.32 m) • Deck contains three RC T-beams spaced 9 ft (2.75 m) on centers. The beams in the central span are deeper. All spans have a transverse beam • The thickness of the slab is 6 in (15 cm)	
Concrete Condition before Strengthening • Concrete in the beams is sound and in good condition • Concrete in abutments and piers is in good condition	

The total bridge length is *137.5 ft* (41.9 m) and the total width of the deck is *23.6 ft* (7.2 m). Each span has one transversal beam with the same depth as the main girders (Figure 3). Two FRP system technologies were used for the flexural strengthening of this bridge. The FRP systems consist of FRP manual lay-up laminates and NSM bars for reinforcement of the deck, girders and bents of spans. U-wrapped FRP laminates were installed on all the main longitudinal girders using manual lay-up to hold the flexural reinforcement in place.

Figure 1. Bridge approach

Figure 2. Condition of abutment

Figure 3. Condition of deck

2. MATERIALS

2.1 Material Properties

Two commercially-available external composite systems were adopted: (1) externally bonded CFRP laminates installed by manual wet lay-up, and (2) NSM bars bonded in place with an epoxy-based paste. The main difference between these two techniques is the preparation necessary before the application of the strengthening that in turn depends upon the condition of the concrete substrate on which the fiber sheet and bars are bonded. FRP have been applied following the Master Materials and Construction Specifications.

The properties of the composite materials used in the design are summarized in Table 2 and 3, as reported by the manufacturers (see Manufacturer's Literature).

Table 2 – Properties of CFRP Laminate Constituent Materials

Material	Ultimate tensile strength f^*_{fu} ksi [MPa]	Ultimate strain ε^*_{fu} in/in [mm/mm]	Tensile modulus E_f ksi [GPa]	Nominal thickness t_f in [mm]
Primer	2.5 [17.2]	0.03	104 [0.7]	-
Putty	2.2 [15.2]	0.07	260 [1.8]	-
Saturant	8.0 [55.2]	0.035	440 [3.0]	-
High Strength Carbon Fiber	550 [3790]	0.017	33,000 [228]	0.0065 [0.1651]

Table 3– Properties of NSM CFRP Bars Constituent Materials.

Material	Ultimate tensile strength f^*_{fu} Ksi [MPa]	Ultimate Strain ε^*_{fu} [in/in]	Tensile modulus E_f ksi [GPa]	Cross Sectional Area in^2 [mm^2]	Dimensions in×in [mm×mm]
Epoxy Adhesive	4.5 [31]	0.04	-	-	-
NSM Bars	300 [2,068]	0.017	18,000 [124]	0.1679 [108.3]	4/8 bar size

2.2 Summary Bill of Material (As Built)

Table 4 and Table 5 presents a summary of materials as used. Table 4 shows the break up for the various reinforcement types.

Table 4– Summary of Bill of Reinforcement as Built

<table>
<tr><th>FRP Type</th><th>Reinforcement</th><th>Member Location</th><th>Span</th><th colspan="2">Quantity</th></tr>
<tr><td rowspan="2">NSM Bars</td><td rowspan="2">Flexural</td><td>Interior Girder</td><td>Lateral</td><td>98 ft</td><td>30 m</td></tr>
<tr><td colspan="2">Total</td><td>98 ft</td><td>30 m</td></tr>
<tr><td rowspan="15">Manual Lay-up Laminates</td><td rowspan="3">Flexural</td><td rowspan="2">Slab</td><td>Central</td><td>240 ft^2</td><td>22 m^2</td></tr>
<tr><td>Lateral</td><td>294 ft^2</td><td>27 m^2</td></tr>
<tr><td colspan="2">Total</td><td>534 ft^2</td><td>50 m^2</td></tr>
<tr><td rowspan="5">Flexural</td><td rowspan="2">Interior Girder</td><td>Central</td><td>205 ft^2</td><td>19 m^2</td></tr>
<tr><td>Lateral</td><td>293 ft^2</td><td>27 m^2</td></tr>
<tr><td rowspan="2">Exterior Girder</td><td>Central</td><td>0 ft^2</td><td>0 m^2</td></tr>
<tr><td>Lateral</td><td>128 ft^2</td><td>12 m^2</td></tr>
<tr><td colspan="2">Total</td><td>626 ft^2</td><td>58 m^2</td></tr>
<tr><td rowspan="5">Shear</td><td rowspan="2">Interior Girder</td><td>Central</td><td>231 ft^2</td><td>21 m^2</td></tr>
<tr><td>Lateral</td><td>491 ft^2</td><td>46 m^2</td></tr>
<tr><td rowspan="2">Exterior Girder</td><td>Central</td><td>0 ft^2</td><td>0 m^2</td></tr>
<tr><td>Lateral</td><td>179 ft^2</td><td>17 m^2</td></tr>
<tr><td colspan="2">Total</td><td>901 ft^2</td><td>84 m^2</td></tr>
<tr><td rowspan="2">Flexural</td><td colspan="2">Bent</td><td>231 ft^2</td><td>21 m^2</td></tr>
<tr><td colspan="2">Total</td><td>231 ft^2</td><td>21 m^2</td></tr>
</table>

Table 5– Summary of Bill of All Material as Built

<table>
<tr><td rowspan="2">NSM Bars</td><td>Bar</td><td>98 ft</td><td>30 m</td></tr>
<tr><td>Adhesive</td><td>98 ft</td><td>30 m</td></tr>
<tr><td rowspan="5">Manual Lay-up Laminates</td><td>Sheet</td><td>2,292 ft^2</td><td>212 m^2</td></tr>
<tr><td>Primer</td><td>1,521 ft^2</td><td>141 m^2</td></tr>
<tr><td>Putty</td><td>1,521 ft^2</td><td>141 m^2</td></tr>
<tr><td>Saturant</td><td>3,804 ft^2</td><td>353 m^2</td></tr>
<tr><td>Coating</td><td>1,521 ft^2</td><td>141 m^2</td></tr>
</table>

The detailed compilation for the bill of materials reported in the Tables above is given at the end of this report as Appendix 1.

3. STRENGTHENING

3.1 Substrate Repair

The performance of a composite system depends not only on the quality and strength of the concrete substrate but also on the bond between the composite and substrate. A clean and sound substrate is essential for composite repair systems. No concrete repair was necessary for this bridge.

3.2 Surface Preparation

To promote continuous intimate contact between concrete and FRP, several important issues had to addressed in the surface preparation: concrete surface irregularities, fins, and/or sharp angles that may result in separation and delamination of carbon laminate from the concrete and/or in localized stress concentration. Concrete surface irregularities were removed and smoothed to less than 1 mm. All concrete surfaces to be strengthened were thoroughly prepared according to the minimum requirement defined in the Master Materials and Construction Specification

Rounding of corners using grinders reduces stress concentration and results in improved bond between the FRP and concrete surface. The concrete angles were rounded to no less than 1/2-inch (12.7 mm)

Abrasive sandblasting was used to clean the concrete surfaces of dust, dirt, laitance, oil and any curing substance. Concrete surface roughness was equivalent to CSP 3 (Concrete Surface Profile number 3) as defined by the International Concrete Repair Institute. The sandblasting must be applied prior to CFRP and SRP installation. All loose particles, oil, dust, cement, paint and other contaminants were contained in accordance with State regulation

3.3 Externally Bonded Composite Reinforcement

The three spans were strengthened with manual lay-up laminates and NSM bars. The central slab was reinforced with rectangular (tape) NSM bars. The installation process for each technology will be described in the following sections.

3.3.1 Manual Lay-up CFRP Laminates

The carbon fabric for the manual lay-up system consists of uni-axial carbon fiber sheets for strengthening the positive moment and shear region of reinforced concrete. In this instance, a high strength carbon fiber was used (Table 2)

3.3.1.1 Primer Application to Fill Voids

Two-component epoxy primer (Table 2) was used to fill voids in the concrete surface. All surfaces to receive the carbon fiber fabric were primed with the penetrating primer (Figure 4)

Primer was mixed in accordance with the manufacturer’s recommendations (See Manufacturer’s Literature) using brushes and rollers. The volume of primer to be prepared at one time was such that could be applied within its pot life. Primer was thoroughly mixed with a hardener at the manufacturer’s specified ratio.

Application was uniform in a sufficient quantity to fully penetrate the concrete and produce a non-porous film in the surface after full penetration. A four-way method, application in all four directions, was used. When necessary, a second coat was applied after the first coat penetrated into the concrete.

Figure 4. Filling of voids and defects by primer and putty collocation

3.3.1.2 Epoxy Filler/Surfacer

Remaining minor surface irregularities and defects were corrected using epoxy filler/surfacer or putty. It is not desirable that the epoxy putty filler cover the entire concrete surface.

A trowel was used to apply the putty in order to fill any surface defect (Figure 4). The material properties of the primer and putty that were used are listed in Table 2.

3.3.1.3 Application of Carbon Fiber Sheets

The carbon fiber sheets were cut beforehand into prescribed sizes using scissors and a simple made-in-place device (Figure 5)

A saturant coating (Table 2) was applied with a medium nap roller after application of the primer and putty (Figure 5). Afterward, the pre-cut fiber sheets were attached according to Contract drawings.

The carbon fiber sheets were installed by manual lay-up method (Figure 6). The sheets were properly aligned and set into the surface saturant. The fiber plies were aligned on the structural member according to the Contract Documents. Any deviation in the alignment more than 5˚ (approximately 87 mm/m or 1 in/ft) was not acceptable. The sheets were saturated by rolling out the external surface. This operation also removed excess of saturant and bubbles (Figure 7). After appropriate time (10 minutes), a second saturant application over the carbon fiber sheets were applied to a complete impregnation.The saturant was applied in strict accordance with the manufacturer’s recommendations (Manufacturers Literature).

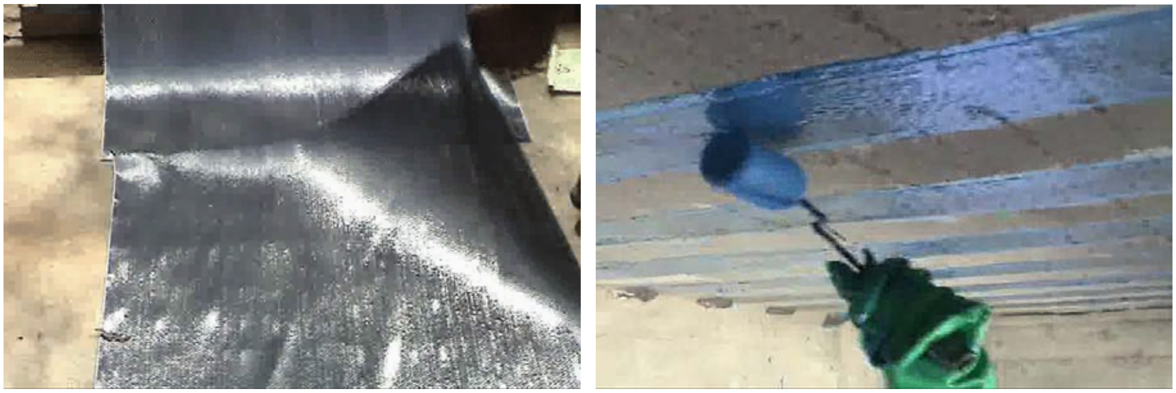


Figure 5. Cutting process and saturant application

Figure 6. Manual lay-up CFRP sheet installation.

Figure 7. Squeezing of air bubbles

The process must allow sufficient working time for the rolling of the carbon fiber sheet and saturant to produce a uniform system that is completely free of voids and trapped air. It must be completed within the limits of saturant pot-life.

Because saturant is susceptible to temperature, special care shall be taken to minimize the elapsed time between mixing and application of the saturant. This must be applied to the sheet at least 15 minutes prior to any thickening.In order to avoid vibrations during the installation, traffic control was used. Speed of the car was limited to 15 mph (24.14 km/hr). Finally, a topcoat was applied to the sheet to provide a cosmetic finish and environmental protection (Figure 8).

Figure 8. Topcoat protection

3.3.2 Near Surface Mounted (NSM) Bars.

The carbon/epoxy CFRP Bars are pultruded carbon fiber reinforced epoxy. These bars are reinforcing elements for positive moments. The material properties of the bars and epoxy paste used are listed in Table 3.

Installation of the bars was achieved first by grooving the concrete surface. The grooves have square cross section, 5/8 inch per side, to allow embedment. This value is equivalent to the diameter of the bar plus one eighth of an inch per side). Concrete was grooved making parallel saw cuts of 5/8 in depth and spaced at 5/8 in. The groove is created by chipping out the concrete between the two cuts. The system included a primer/sealer for the concrete surface

A high modulus, high strength and high viscosity epoxy adhesive was used (Table 3). This epoxy paste is chemically compatible with the individual properties of the primer and bars, so a solid bonding can be developed.

Figure 9. Bar installation

The NSM bars were then placed into the grooves and lightly pressed to force the paste to flow around the bar. The bars are sometime placed with the help of wedges. Excess material was removed manually and the surface was leveled (Figure 9).

The NSM FRP technique does not require any surface preparation work and requires minimal installation time compared to FRP laminates. Nevertheless, the grooving work can take more time and cost than the normal surface preparation of in-place-cured or pre-cured laminates.

4. ACCEPTANCE TESTING.

A direct pull-off test based on ASTM D 4541-93 was used by the contractor in this project. This test allows to check the quality of the installation of the FRP. It consists in gluing an aluminum square plate on the strengthened part to be checked; afterwards, a core is drilled close to the aluminum plate through the laminate strip into the concrete substrate, providing an isolated test location for attachment of the pull-off tester. A tension device is then loaded to failure during the test (Figure 27). The tester records the force causing the failure, which, if divided by the core cross sectional area, will result in tensile strength (psi). Upon failure of the core specimen, a visual examination of the failure plane location reveals whether the failure occurred at the bond line or within the substrate. Failure of the concrete and not at the bond line was the only acceptable failure. The tensile bond strength must be more than 200 psi (1.4 MPa)

One pull-off test was performed every 200 ft^2 (20 m^2) of area strengthened with carbon fiber strip system or once every deck span.

The results of single tests made on the three spans were values of tensile bond strength bigger than the minimum required. Based on these results and that all failures occurs in the concrete and not at the bond line, installation of FRP was considered successful.

APPENDIX 1.

1 NSM Bars

1.1 FLEXURAL REINFORCEMENT

1.1.1 Interior Girder

1.1.1.1 Central Span

0ft

1.1.1.2 Lateral Span

$(2)\cdot(2)\cdot 24.5\text{ft} = 98\,\text{ft}$

2 Manual Lay-up

2.1 FLEXURAL REINFORCEMENT

2.1.1 Slab

2.1.1.1 Central Span

$(2)\cdot(16 + 21)\cdot(6\text{in})\cdot(6.5\text{ft}) = 240\,\text{ft}^2$

2.1.1.2 Lateral Span

$(2)(2)\cdot(9 + 12)\cdot(6\text{in})\cdot(7.0\text{ft}) = 294\,\text{ft}^2$

2.1.2 Interior Girder

2.1.2.1 Central Span

$(32.0\text{ft} + 27.0\text{ft} + 24.0\text{ft} + 23.0\text{ft} + 17.0\text{ft})\cdot(20\text{in}) = 205\,\text{ft}^2$

2.1.2.2 Lateral Span

$(2)(27.0\text{ft} + 26.0\text{ft} + 25.0\text{ft} + 19.0\text{ft} + 13.0\text{ft})\cdot(16\text{in}) = 293\,\text{ft}^2$

2.1.3 Exterior Girder

2.1.3.1 Central Span

0ft^2

2.1.3.2 Lateral Span

$(2)\cdot(2)(11.0\text{ft} + 13.0\text{ft})\cdot(16\text{in}) = 128\,\text{ft}^2$

2.1.4 Bent

$(2)(10.0\text{ft} + 11.0\text{ft} + 12.0\text{ft})\cdot(42\text{in}) = 231\,\text{ft}^2$

2.2 SHEAR REINFORCEMENT

2.2.1 Interior Girder

2.2.1.1 Central Span

$$(2)(31in + 21in + 31in)(2 \cdot 1.0ft + 1 \cdot 10.67ft + 4 \cdot 1.0ft) = 231ft^2$$

2.2.1.2 Lateral Span

$$(2)(2)(25in + 17in + 25in)(4 \cdot 1.0ft + 2 \cdot 6.0ft + 2 \cdot 3 \cdot 1.0ft) = 491ft^2$$

2.2.2 Exterior Girder

2.2.2.1 Central Span

$$0ft^2$$

2.2.2.2 Lateral Span

$$(2)(2)(2)(25in + 17in + 25in)(4 \cdot 1.0ft) = 179ft^2$$

3 SATURANT APPLICATION

3.1 FLEXURAL REINFORCEMENT

3.1.1 Slab

3.1.1.1 Central Span

$$(2) \cdot (16 + 21) \cdot (6in) \cdot (2 \cdot 6.5ft) = 481ft^2$$

3.1.1.2 Lateral Span

$$(2)(2) \cdot (9 + 12) \cdot (6in) \cdot (2 \cdot 7.0ft) = 588ft^2$$

3.1.2 Interior Girder3.1.2.1 Central Span

$$(2 \cdot 32.0ft + 27.0ft + 24.0ft + 23.0ft + 17.0ft) \cdot (20in) = 258ft^2$$

3.1.2.2 Lateral Span

$$(2)(2 \cdot 27.0ft + 26.0ft + 25.0ft + 19.0ft + 13.0ft) \cdot (16in) = 365ft^2$$

3.1.3 Exterior Girder

3.1.31 Central Span

$$0ft^2$$

3.1.3.2 Lateral Span

$$(2) \cdot (2)(2 \cdot 13.0ft + 11.0ft) \cdot (16in) = 197ft^2$$

3.1.4 Bent

$$(2)(10.0\text{ft} + 11.0\text{ft} + 2\cdot 12.0\text{ft})\cdot(42\text{in}) = 315\,\text{ft}^2$$

3.2 SHEAR REINFORCEMENT

3.2.1 Interior Girder

3.2.1.1 Central Span

$$(2)(31\text{in} + 21\text{in} + 31\text{in})(2\cdot 2\cdot 1.0\text{ft} + 2\cdot 10.67\text{ft} + 2\cdot 4\cdot 1.0\text{ft}) = 461\,\text{ft}^2$$

3.2.1.2 Lateral Span

$$(2)(2)(25\text{in} + 17\text{in} + 25\text{in})(3\cdot 3\cdot 1.0\text{ft} + 3\cdot 6.0\text{ft} + 2\cdot 4\cdot 1.0\text{ft}) = 782\,\text{ft}^2$$

3.2.2 Exterior Girder

3.2.2.1 Central Span

$$0\text{ft}^2$$

3.2.2.2 Lateral Span

$$(2)(2)(2)(25\text{in} + 17\text{in} + 25\text{in})(2\cdot 4\cdot 1.0\text{ft}) = 357\,\text{ft}^2$$

4 PRIMER AND PUTTY APPLICATION

4.1 FLEXURAL REINFORCEMENT

4.1.1 Slab

4.1.1.1 Central Span

$$(2)\cdot(16 + 21)\cdot(6\text{in})\cdot(6.5\text{ft}) = 240\,\text{ft}^2$$

4.1.1.2 Lateral Span

$$(2)(2)\cdot(9 + 12)\cdot(6\text{in})\cdot(7.0\text{ft}) = 294\,\text{ft}^2$$

4.1.2 Interior Girder

4.1.2.1 Central Span

$$(32.0\text{ft})\cdot(20\text{in}) = 53\,\text{ft}^2$$

4.1.2.2 Lateral Span

$$(2)(27.0\text{ft})\cdot(16\text{in}) = 72\,\text{ft}^2$$

4.1.3 Exterior Girder

4.1.3.1 Central Span

$$0\text{ft}^2$$

4.1.3.2 Lateral Span

$$(2)(2)(13.0\text{ft})\cdot(16\text{in}) = 69\,\text{ft}^2$$

4.1.4 Bent

$$(2)(12\text{ft})\cdot(42\text{in}) = 84\,\text{ft}^2$$

4.2 SHEAR REINFORCEMENT

4.2.1 Interior Girder

4.2.1.1 Central Span

$$(2)(31\text{in} + 21\text{in} + 31\text{in})(2\cdot 1.0\text{ft} + 10.67\text{ft} + 4\cdot 1.0\text{ft}) = 231\,\text{ft}^2$$

4.2.1.2 Lateral Span

$$(2)(2)(25\text{in} + 17\text{in} + 25\text{in})(3\cdot 1.0\text{ft} + 6.0\text{ft} + 4\cdot 1.0\text{ft}) = 290\,\text{ft}^2$$

4.2.2 Exterior Girder

4.2.2.1 Central Span

$$0\text{ft}^2$$

4.2.2.2 Lateral Span

$$(2)(2)(2)(25\text{in} + 17\text{in} + 25\text{in})(4\cdot 1.0\text{ft}) = 179\,\text{ft}^2$$