SMAR 2015

The Effects of Environmental Exposure on Polyurethane-based GFRP Bridge Deck Panels

Hesham Tuwair[1], Jeffery Volz[2], Mohamed ElGawady[3], K. Chandrashekhara[4], Victor Birman[5]

[1] Ph.D. Candidate, Missouri University of Science and Technology, Rolla, USA
[2] Associate Professor, The University of Oklahoma, Norman, USA
[3] Associate Professor, Missouri University of Science and Technology, Rolla, USA
[4] Curators' Professor, Missouri University of Science and Technology, Rolla, USA
[5] Professor, Missouri University of Science and Technology, Rolla, USA

ABSTRACT: The performance of polyurethane foam-infill bridge deck panels (PU sandwich panels) were investigated after being exposed to various environmental conditions. These panels were constructed with woven E-glass fiber/Polyurethane facesheets. These facesheets were separated by a trapezoidal-shaped, low-density, polyurethane foam. Corrugated web layers were introduced into the core to enhance the panel structural characteristics. An experimental program was undertaken to simulate their in-situ environments. The environmental conditions included 350 different thermal cycles through a computer-controlled environmental chamber. The thermal cycling consisted of 50 freeze-thaw cycles that simulated the effects of winter season. Then followed by alternating 50 high temperature cycles and 50 high relative humidity cycles to simulate the summer season effects for a total of 150 cycles each. The conditioned panels were then tested in four-point loading tests. The strength, stiffness, and failure modes were each compared to those specimens that were not conditioned (the control). The results of this study revealed that degradation in strength does exist to a certain extent. These results will be used on determining design factors using polyurethane-based GFRP materials in bridge construction under the expected wreathing exposure in the mid-west United States.

1 INTRODUCTION

Over half of the 607,000 bridges currently in use across the United States were built before 1940 (Kirk and Mallett 2013). Thus, these bridges have reached the end of their useful service lives. In study recently conducted by Ellis (2011) for the Federal Highway Administration (FHWA) estimated the annual direct cost of repairing corrosion on highway bridges to be between $6.43 and $10.15 billion. This estimate includes the $1.07 to $2.93 billion needed each year to maintain the concrete bridge decks. In an effort to address these sobering statistics, transportation agencies have been trying to identify new, cost-effective, and reliable construction materials that can be used to not only fabricate but also rehabilitate bridge decks. Advanced composites made of fibers embedded in a polymeric resin, also known as fiber-reinforced polymer (FRP) materials, have received considerable attention as a strong candidate to replace deteriorating concrete and steel structures. These composites, commonly used for civil engineering applications, are reinforced with fiberglass due to its low relative cost. The advantages of FRP composites have been widely recognized and include their low weight, ease of installation (reducing traffic delay), resistance to both environmental and chemical attacks, and resistance to fatigue loads.

Extensive durability studies have been conducted on FRP composites for aerospace and marine applications. However, all of these applications have been manufactured in highly controlled factory environments using autoclave-based fabrication under strict specifications. Cheaper manufacturing processes have been used in the civil market (e.g., wet layup, vacuum assisted resin transfer molding [VARTM], and pultrusion), resulting in lower temperature cure epoxies. The FRP composites used in the field for rehabilitation purposes are cured under ambient temperatures. Thus, these composites are more vulnerable to moisture damage and plasticization than those used for aerospace and marine applications. Accordingly, it is impossible to interpret the results of those studies established by the Department of Defense for civil engineering applications (Karbhari 2007).

Polyurethane resin has better properties in comparison with traditional resin systems (e.g., polyester and vinyl ester resin systems; Connolly et al. 2006). The pultrusion process is typically used to manufacture polyurethane composites. The process, however, is limited to the manufacture of constant cross-section profile composite parts. The VARTM process is a low-cost composite manufacturing process that is widely used throughout the composite industry. This process has been developed over the last two decades for applications in commercial, military, and marine composite structures (Karakuzu et al. 2010). The polyurethane resin's viscosity and pot-life limitations, however, have prevented its use with the VARTM process until recently where a major development in novel catalysis chemistry was developed by Bayer MaterialScience. This dual catalyst system extended the pot life of mixed resins at room temperature (Bareis et al. 2011). The resin itself was developed quite recently. Thus, the durability studies of polyurethane composites, manufactured using the VARTM process under harsh environmental conditions, for infrastructure applications, has not been reported in the literature.

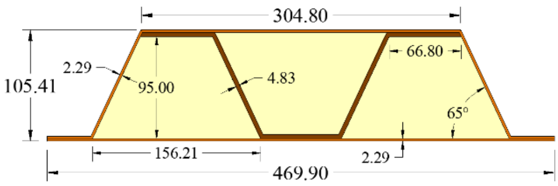
This study was conducted as an attempt to investigate the effects of environmental exposure on the behavior of PU sandwich panels originally proposed by Tuwair et al. (2014). The prototype PU sandwich panels were comprised of two woven E-glass fibers/polyurethane facesheets that were separated by a trapezoidal-shaped, low-density, polyurethane foam (see Fig. 1). The foam core was comprised of web layers that served as a truss structure between the facesheets.

2 EXPERIMENTAL PROGRAM

Testing the entire sandwich panel under different environmental conditions is essential to determine the full stiffness and strength degradation, and mode of failure of the panel. The conditioning regimens conducted in this study consisted of thermal cycling (a series of freeze-thaw, mid-high temperatures, and mid-high relative humidity cycles) in a computer-controlled environmental chamber.

A schematic of the PU mid-scale sandwich panel cross-section is given in Fig. 1a. Both the top and bottom facesheets were constructed with three plies of 0º/90º, biaxial, E-glass, plain weave, woven fabric (WR18/3010); they were manufactured by Owens Corning. The diagonal webs, manufactured by VectorPly, consisted of three plies of +45º/-45º, double-bias, E-glass, stitch-bonded fabric (EBXM1715) that was integrated with the facesheets. The foam was matted with two plies of +45º/-45º, E-glass, knitted fabric to enhance bonding between the foam core and facesheets.

The VARTM process was used to manufacture the PU sandwich panels. The panels used a two-part, thermoset polyurethane resin system that was manufactured by Bayer MaterialScience. The specimens were post-cured for 1 hour at 71.1°C and for 4 hours at 82.2°C in a walk-in oven. A total of four mid-scale prototype panels were manufactured with the cross-section shown in Fig. 1b. Each had an overall length of 1193.80 mm. Two of the panels were subjected to a predetermined sequence of thermal cycling conditioning while the remaining panels was designated as the control panels.



(a)

(b)

Figure 1. Mid-scale PU sandwich panels: (a) schematic of panel cross section, and (b) four prototype panels.

2.1 *Test procedure and conditioning regimen*

The thermal cycling conditioning, in terms of a series of freeze-thaw, mid-high temperatures, and mid-high relative humidity cycles, was designed to simulate in-situ environments. ASTM C666 standard (2003) was followed for the conditioning cycling test. This standard was originally designed for testing concrete's durability; it was used here as a guide for measuring the composite structure's durability. The computer-controlled environmental chamber used in this study (Model WR-1750) was manufactured by B-M-A, Inc.; it is pictured in Fig. 2a. It had a temperature range of between 82.2°C and -34.4°C and an extensive range of cycling capabilities. Table 1 illustrates the environmental cycle regimen that was used to cycle both temperature and humidity. This regimen was based on weather data accumulated in the Midwest United States over the previous 30 years.

Prior to the conditioning of the PU sandwich panel specimens in the environmental chamber, the specimens were prepared by protecting their ends with supplemental epoxy coating and waterproof tape (see Fig. 2b). This step was necessary because the actual bridge deck panels would completely encapsulate the foam core. The specimen's actual weight and dimensions were taken before the environmental exposure was begun. The panels were elevated within the environmental chamber to allow air circulation on all sides (see Fig.2b). The conditioning procedure was comprised of three main phases: a 50-cycle freeze-thaw phase followed by 150 cycles of mid-high temperatures. Those phases were then followed by a phase consisting of 150 cycles of mid-high relative humidity, for a total of 350 cycles, as presented in Table 1. The panels were removed, thoroughly inspected for signs of damage, instrumented with strain gauges, and then placed into the static loading test setup after the required number of days within the chamber was achieved. The examination included a comparison between the flexural strength, stiffness, and failure mode of the conditioned specimens and the control specimens.

(a)

(b)

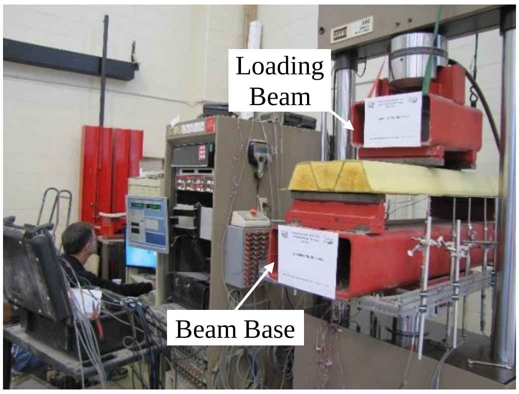
Figure 2. Thermal cycling: (a) environmental test chamber, and (b) PU sandwich panels within environmental test chamber.

Table 1: Thermal Cycling Regimen

Cycles	Freeze-Thaw	High Temperature	High Relative Humidity (60-95%)		
Temperature Range (ºC)	-15 to 10	20 to 50	20	25	40
Number of Cycles	50	150	50	50	50
Total Number of Cycles			350		

2.2 *Four-point bending flexural test*

Characterization of the durability behavior of the PU sandwich panels was accomplished by testing the PU sandwich panels under the four-point bending tests. A picture of the test-setup is illustrated in Fig. 3. This test was performed according to the ASTM C393 standard (2011). The objective of this test was to determine the flexural stiffness and the strength of the panels. Each panel was tested in one-way bending with a span of 1092.20 mm, under two equal point loads applied at 393.70 mm from each support. The specimens were loaded up to failure using an MTS880 testing machine at a load rate of 1.27 mm/min.



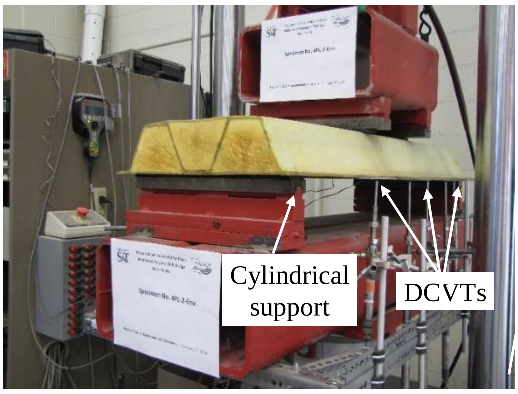
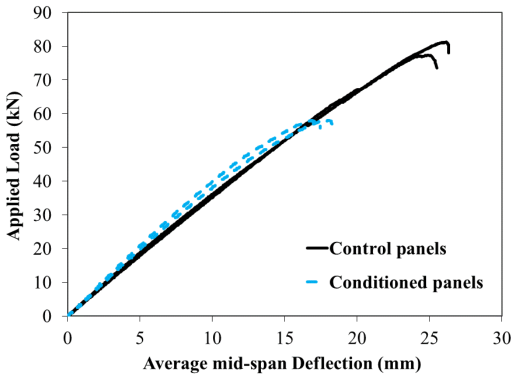


Figure 3. Four-point bending test setup.

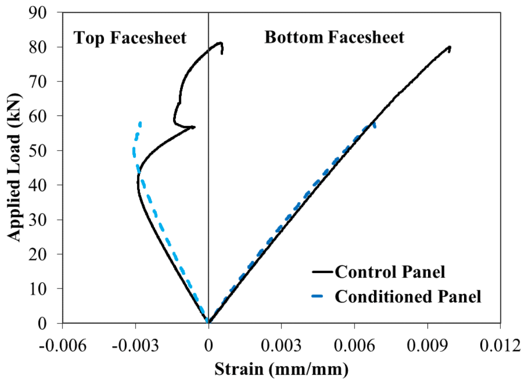
Four strain gauges monitored the strain; two each were attached in the compression and tension areas at the specimen's mid-span. Eight direct current variable transformers (DCVTs), two at the mid-span, two at each loading point, and one at each end were used to monitor displacement at five locations.

3 EXPERIMENTAL RESULTS

The PU sandwich panels were removed and thoroughly inspected for signs of damage after they had been in the chamber for the required number of days. Visual inspection revealed that the outer surface had lost some of its brightness. The sectional dimensions of each conditioned panel did not change. The weight, however, did increase by approximately 0.5%. The PU panels were then instrumented with strain gauges and placed into the static loading test setup (Fig. 3). The applied load versus the mid-span deflection of both the conditioned and the control PU sandwich panels is illustrated in Fig. 4a. All of the panels exhibited nearly the same tendency; they behaved almost linearly up to failure. The control and the conditioned PU panels failed at an average load of approximately 79.2 kN and 60.1 kN, at a mid-span deflection of approximately 25.65 mm and 17.53 mm, respectively. Accordingly, the average ultimate load of the environmentally conditioned PU panels indicated a noticeable decrease in static flexural strength by approximately 24 % compared to the control PU panels. The average stiffness exhibited by both of the conditioned PU panels was approximately 11% higher than that exhibited by the control PU panels. These results are summarized in Table 2.



(a)



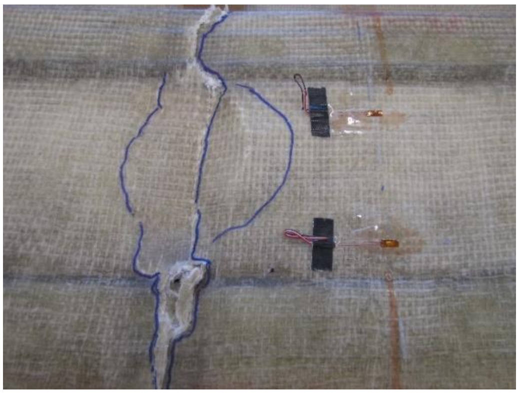
(b)

Figure 4. Test results: (a) applied load vs. mid-span deflection, and (b) applied load vs. mid-span strain.

Failure of the two control panels occurred by two failure phases: an initial failure mode occurred by the outward skin wrinkling on the top facesheet (see Fig. 5a), followed by an ultimate failure mode that occurred due to excessive compressive stresses in the top facesheet under the loading points, as shown in Fig. 5b. In the case of the conditioned PU panels, failure occurred only by excessive compressive stresses in the top facesheet under the loading points as shown in Fig. 5b. Outward skin wrinkling did not occur compared to the control panels, as the static flexural load that causes wrinkling was not reached due to the load reduction (see Fig. 4b).

The curve's linearity was tested by measuring the strain gauges that were bonded to the bottom and top faces at the mid-span of the panels. The load versus strain curves for both the control and the conditioned PU sandwich panels are illustrated in Fig. 4b. The average maximum tensile strain recorded (bottom facesheet) for the control PU panels was 0.00907 mm/mm at an average load of approximately 79.2 kN, and that for the environmentally conditioned PU panels it was approximately 0.006782 mm/mm. Thus, the strain was reduced by nearly 25%. The wrinkling phenomena that occurred in the control PU panels can be observed in the response of the top strain gauge's curve (see Fig. 4b). The reading exhibited both nonlinearity and a reversal of direction before it reached the ultimate load. The top strain gauge readings in the environmentally conditioned PU panels had a linear response up to failure, confirming the previous observation that outward skin wrinkling did not occur.

(a)



(b)

Figure 5. Failure modes: (a) outward skin wrinkling in the control panels, and (b) compression failure in the control and conditioned panels.

Table 2. Structural behaviors of four-point bending flexural results

Condition	Control Panels			Conditioned Panels		
	Ultimate Load Capacity (kN)	Flexural Stiffness (kN.m^2)	Failure Mode	Ultimate Load Capacity (kN)	Flexural Stiffness (kN.m^2)	Failure Mode
Mean	79.2	7,525	Wrinkling + compressive failure	60.1	8,353	Compressive failure
S.D	1.91	214.8		0.44	249.6	
C.V (%)	2.41	2.86		0.74	2.98	

4 DISCUSSION AND SUUMARY

The stiffness of the thermal cycling conditioned PU sandwich panels was increased by between 8 and 14%. This increase is likely due to the extended curing of the polyurethane resin during high temperature sequences. It was assumed that the elevated temperatures could enhance the curing of the resin because the GFRP composites are seldom fully cured (due to insufficient time). Thus, exposure to elevated temperatures that is higher than the curing temperature can facilitate the linking of these polymers, causing additional curing. This additional curing will increase the stiffness of the GFRP material.

In contrast, the thermal cycling conditioning regimen negatively affected the material property of the composite in terms of its flexural strength. This loss of strength (24%) could be related to the freeze-thaw cycles. Due to the mismatch of the coefficient of thermal expansion (the polymeric resin coefficient is generally an order of magnitude higher than that of the fiber), microcracks and voids in the polymer matrix and in the matrix-fiber interface occurred, causing progressive damage within the fiber materials due to the expansion and contraction cycles (thermal fatigue) of the entrapped water. This reduction is consistent with the FHWA guidelines on composite deck designs. These guidelines recommend an environmental durability factor of 0.65 to account for the degradation of properties over time and represents a 35% decrease in strength.

Yet again, the design of FRP bridge deck panels is often controlled by stiffness rather than strength. Therefore, such structures tend to be designed as small as 10-15% of their ultimate strength (Karbhari and Seible 1999).

5 CONCLUSION

This study presented an experimental work that investigated the effects of environmental conditioning on the behavior of PU sandwich panels. The environmental exposure included thermal cycling (a series of freeze-thaw, mid-high temperatures, and mid-high relative humidity cycles) in the environmental chamber. Following the exposure regimen, four-point loading tests were performed on the PU sandwich panels. The degradation was determined in terms of ultimate strength, stiffness, overall behavior, and modes of failure of the sandwich panels. The following conclusions were drawn from this study:

- The panels displayed linear-elastic behavior throughout the majority of their response during the static flexural testing, with only a slight decrease in stiffness near failure.
- The environmental exposure resulted in a 24% degradation in ultimate strength but a slight increase in stiffness. The ultimate failure of the environmental panels under the subsequent static loading occurred in the same manner as the control panels.
- The strength reduction is consistent with the FHWA guidelines on composite deck design, which recommends an environmental durability factor of 0.65 to account for degradation of properties over time and represents a 35 percent decrease in strength.

Considering the sustained stresses during the environmental regimen may accelerate mechanical degradation of FRP composites. However, the expected in-service stress levels maintain the ability for long-term durability without considering the sustained stresses. This is due to the visco-elastic behavior of the resin, which prevents the formation of micro-cracks (Devalapura RK et al., 1997).

For future work, it is suggested that the durability of FRP composites should be tested with coupling effects. Due to coupling effects (for example; moisture and elevated temperatures), the degradation could be accelerated by high diffusion rates. Additionally, different environmental regimens can be applied concurrently to see how the combinations of the influential parameters affect the degradation of the FRP specimens.

REFERENCES

American Society of Testing and Materials. 2003. *ASTM Standard Test Method for Resitance of Concrete to Rapid Freezing and Thawing (C666/C666M-03)*. West Conshohocken, Pennsylvania: ASTM International 2003.

American Society of Testing and Materials. 2011. *ASTM Standard Test Method for Flexural Properties of Sandwich Constructions (C393/C393M-11e1)*. West Conshohocken, Pennsylvania: ASTM International.

Bareis, D, Heberer, D, and Connolly, M. 2011, Advances in Urethane Composites Resins with Tunable Reaction Times. *American Composites Manufacturers Association Ft*. Lauderdale, Florida. Huntsman Polyurethanes Auburn Hills, MI: 1-7.

Connolly M, King, J, Shidaker, T, and Duncan, A. 2006, Processing and Characterization of Pultruded Polyurethane Composites. *Huntsman Enriching lives through innovation*.

Devalapura RK, Gauchel JV, Greenwood ME, Hankin A and T., Humphirey. 1997. Long-term durability of glass-fiber reinforced polymer composites in alkaline environments. *3rd International Conference on Fibre-Reinforced Plastics for Reinforced Concrete Structures* FRPRCS-4, Baltimore, MD.

Ellis, Z. 2011. *Corrosion Cost and Preventive Strategies in the United States.* FHWA-RD-01-156.

Kirk, RS, and Mallett, WJ. 2013. *Highway Bridge Conditions: Issues for Congress*. Congressional Research Service, Report to congress. Contract No. R43103.

Karakuzu, R, Erbil, E, and Aktas, M. 2010. Impact Characterization of Glass/Epoxy Composite Plates: An Experimental and Numerical Study. *Composite Part-B*, 41: 388-395.

Karbhari, VM. 2007. Durability of Composites for Civil Structural Applications. *Woodhead Publishing Limited*, Cambridge England.

Karbhari, VM and Seible, F. 1999 .Fiber-reinforced Polymer Composites for Civil Infrastructure in the USA. *Structural Engineering International*, Volume 4.

Karbhari, VM and Pope. G. 1993, Effect of Cold Region Type Environment on Impact and Flexure Properties of Glass/Vinyelester Composites, *ASCE Journal if Cold Regions Engineering.* 8(1), 1-20.

Tuwair, H, Volz, J, ElGawady, M, Mohamed, M, Chandrashekhara, K, Birman, V. 2014. Testing and Evaluation of Polyurethane-Based GFRP 2 Sandwich Bridge Deck Panels with Polyurethane Foam Core. Journal of Bridge Engineering, ASCE. 10.1061/(ASCE)BE.1943-5592.0000773.