

THERMOPLASTIC COMPOSITES AS DEGRADATION-RESISTANT MATERIAL SYSTEMS FOR TIMBER BRIDGE DESIGNS

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ABSTRACT

Plastic lumber made primarily from recycled high-density polyethylene first emerged on the United States marketplace in the early 1990's. Plastic lumber is an attractive substitute for natural wood because it diverts waste plastic from landfills and is inherently resistant to moisture, rot, and insects without the need for chemical treatments. However, while as strong as an equivalent-sized piece of wood, these original plastic lumber products had an elastic modulus (stiffness) at least an order of magnitude less than even the most common wood species used in construction. Eventually manufacturers started incorporating fibers into the formulation to produce a reinforced thermoplastic composite lumber with a higher elastic modulus. The first plastic vehicular bridge using reinforced thermoplastic composite lumber (in typical rectangular shapes) was built at a mid-west Army Installation in 1998. This bridge has not had any maintenance done to it since its completion and still looks like new. Due to its no-maintenance needs, when viewed on a lifecycle basis, this bridge has now more than paid for its higher initial material costs. However, first costs are still most often the deciding factor whether these type materials are or are not used over traditional treated-wood. Since 1998, researchers and engineers have looked at arch and I-beam designs as a means to reduce the

material and installation costs for a given load capacity in order to come up with a design that is cost competitive to traditional wood designs on a first cost basis. The latest demonstration of this sort is a thermoplastic composite I-beam bridge being constructed at an east coast Army Installation designed to cross an M-1 battle tank. This innovative design is cost competitive to a wood timber bridge to carry the same load and virtually maintenance-free from the degradation effects of moisture, rot, insects, and weather. This paper will describe the evolution of these materials, their durability, and the design factors that make these materials attractive sustainable alternatives to chemically treated-wood for timber bridges and many other outdoor structural applications where treated wood is traditionally used.

Keywords: degradation, thermoplastic composite, plastic lumber, timber, bridges, U.S. Army.

INTRODUCTION

The plastic lumber industry originated in Japan and Europe during the early to mid-1970's where new equipment was being developed to make large cross-section thermoplastic polymer products.^{1,2,3} A lower abundance of wood than the United States and the possibility of these products as wood lumber substitutes drove development of the industry. The early plastic lumber products were made mainly from post-industrial plastic waste that was the only resin material available at a reasonable price at that time.

In the United States, a few small entrepreneurs were entering the field by the mid-1980's. Their efforts and those of others worldwide were hindered by: 1) the limited and uncertain supply of raw materials, 2) a lack of certifiable performance, 3) a significantly lower modulus as compared to wood along the growth axis, and 4) a plentiful supply of wood. The two main advantages of plastic lumber that are most apparent when compared to chemically treated wood are that the material is benign to the environment and that it will not degrade readily when used outdoors.⁴

As recycling efforts started to gain momentum, experts in the United States were considering plastic lumber processes as a possible alternative to landfilling the abundance of available post-consumer waste plastic containers.⁵ More than 8 billion pounds of plastic containers are produced each year in the United States with the majority being landfilled due to the lack of demand for their resins.⁶ The commercial viability of the plastic lumber industry in the United States is now being driven by the economic and logistical need to reduce disposal quantities of waste plastics and the development of more cost-effective designs and construction methods.

INITIAL APPLICATIONS OF PLASTIC LUMBER

The first applications of plastic lumber as a substitute for treated wood were in non-critical, outdoor applications. The substitution of any traditional material with a new material must take into account the required performance for the product and particular application in mind. At first, plastic lumber was considered for relatively low stress applications. Picnic tables and park benches have been successfully produced from plastic lumber, and are performing satisfactorily. Some of the earliest designs had the product performing well when new but sagging over time. Since then, manufacturers have learned to design these structures

with lower stress on the elements to reduce the time dependent properties affect on the overall shape.

Many manufacturers found that they could produce decking boards to be fitted atop chemically treated wooden frames. This application typically has fairly low values of dead load stress, and the time-dependent properties do not play a very important role in most cases. The biggest problem in these applications seems to be the much larger thermal expansion coefficient of plastic lumber as compared to wood. Since just the decking boards are plastic lumber, one cannot claim that the whole structure will not biologically decay, or that it is not treated with hazardous materials. To make these claims, the entire structure must be made from plastic and/or polymer composites.

Various types of treated woods are used in outdoor applications. Chemically treated yellow pine is typically used in the Eastern United States for decks and creosote-treated oak is used for railroad ties. Despite the use of chemical treatments or protective coatings, wood eventually rots and must be replaced. The fact that wood has properties that cause it to deteriorate when left outside unprotected as well as imperfections such as knots, complicate its performance.

MATERIAL PROPERTY CONSIDERATIONS

According to the USDA Wood handbook, pines and oaks typically have moduli of at least 1 million psi (6,900 MPa) and strengths of 2,400 (17 MPa) and 3,500 psi (24 MPa) respectively, when measured along the axis.⁷ Virgin polyethylene has a modulus of only 160,000 psi (1,100 Mpa) and an ultimate strength of 3,500 psi (24 MPa).⁸ Polyethylene-based, unreinforced plastic lumber has upper-bound properties similar to virgin polyethylene due to the manufacturing process. Cooling a large cross-section of a semi-crystalline polymer product leads to voids in the interior cross-section due to thermodynamic and physical chemistry reactions occurring during the cooling process. These voids possess an apparently random size and shape. Impurities in these materials represent material inclusions also reducing mechanical properties.⁹ To reduce the size of the voids, manufacturers have added small amounts of foaming agents without significantly affecting the properties. However, a high level of foaming can significantly reduce stiffness and strength, while increasing the thermal expansion coefficient.

The two basic problems that unreinforced plastic lumber has in structural applications for wood are: 1) lower modulus, and 2) even lower modulus when loaded over a long time. A comparison of mechanical properties of wood along the grain with plastic and plastic lumber indicates that the lower modulus of plastic is a much bigger issue than any strength comparison.¹⁰ Incidentally, wood is several times less stiff and strong when measured orthogonal to the growth axis as compared to along the growth axis. Most any plastic lumber compares rather favorably in terms of both stiffness and strength in this situation.

The materials that are typically used in plastic lumber are viscoelastic in terms of their mechanical properties. This means that there is a time-dependence to their mechanical properties.¹¹ For example: if a structure is loaded to a certain load level and the deflection of that structure is measured right after the load is applied, the deflection is expected to increase by some value for each increment of time as the load remains applied. To further complicate

matters, the deflection will increase more during the first day than the second day. The deflection will occur each day at ever decreasing rates, unless a crack opens up in the material. This effect can be minimized by designs with lower levels of stress.

The two key advantages of plastic lumber over wood are that it is not subject to degradation (perhaps unless filled with a high percentage of wood material), and it does not leach harmful chemicals into the soil or groundwater. Successful applications for unreinforced plastic lumber types of products have been developed for which concrete or other materials are the traditional material used. Among others, these include construction curbs, removable speed bumps, parking lot wheel stops, and bollards.

DEMONSTRATION OF STRUCTURAL APPLICATIONS

More structurally demanding applications have been attempted, and all have met with some level of success. Applications have included joists, railroad ties, marine pilings, and vehicular bridge sub-structures. These all required the use of reinforced plastic materials in order to achieve the necessary structural properties at a reasonable cost. The development of ASTM test methods to evaluate and compare the properties of plastic lumber has opened up real possibilities to engineer structures with these materials.¹²

The first all-plastic lumber civil structure of major significance was the Tiffany Street Pier located at the end of Tiffany Street in the Bronx in New York City. This roughly 125 meter (410 ft) long by 15 meter (49 ft) wide recreation pier was designed by the New York City Department of General Services. The structure incorporates recycled-plastic pilings, timber joists, decking, and railings.¹³

Plastic Lumber Bridge at Fort Leonard Wood, MO

While the Tiffany Street Pier showed that a large all-plastic structure could be built, the structural design of the pier was not very optimal in materials usage. With the help of funding from the U.S. Environmental Protection Agency, an existing wood timber bridge at Ft. Leonard Wood, MO, was selected to demonstrate applications of “structural-grade” plastic lumber.¹⁴ The 25-ft (7.6-meter) long by 26-1/2-ft (7.8-meter) wide plastic lumber bridge sits on six steel girders that had supported the original wooden bridge. Although the bridge is used primarily for pedestrian traffic, the replacement plastic lumber bridge was designed to carry light vehicular traffic. Figure 1 shows an Army HMMWV (High Mobility Multipurpose Wheeled Vehicle) crossing the plastic lumber bridge.

M. G. McLaren Consulting Engineers, New York, designed the bridge structure using protocol developed for plastic lumber as part of the ASTM standards development for these products. The safe capacity of the new bridge is more than 30 tons over the entire structure. Structural-grade plastic lumber 3x12 boards that incorporated polystyrene for added stiffness were used as the main support joists over the steel girders.¹⁵ The decking was also 3x12 plastic lumber but a standard-grade material. In all, products from four different manufacturers were used in the structure. The bridge was constructed with standard woodworking power tools and fasteners.¹⁶



Figure 1. The first plastic lumber bridge built in the summer of 1998.

Plastic lumber expands and contracts to a greater extent with changes in temperature than does wood or steel. Design features were, therefore, incorporated to allow the plastic lumber bridge structure to move differentially relative to the steel members and the bridge abutments during such changes in temperature. These features included slotted connections between the plastic lumber joists and the steel girder to which they were attached to accommodate side-to-side movement, and a floating deck at the bridge abutments to accommodate end-to-end movement.

A typical treated wood bridge structure at this site would need to be replaced every 15 years with biannual inspections and maintenance to replace deteriorated boards and loose fasteners. The plastic lumber bridge is expected to last 50 years with minimal maintenance. While the plastic lumber products cost more than double what they would be for a replacement treated wood bridge, a lifecycle cost analysis showed the plastic lumber bridge would begin to pay for itself in less than 8 years. An added benefit is the fact that the plastic lumber bridge used some 13,000 lb (5,900 kg) of waste plastics that had otherwise been destined for landfills. This amount is equivalent to approximately 78,000 one-gallon (3.8-liter), high-density polyethylene (HDPE) milk jugs and 335,000 8-oz (237-milliliter) molded polystyrene coffee cups. The bridge will not require any application of protective coatings or preservatives that can emit environmentally damaging volatile organic compounds into the atmosphere.

Laminated Arch-Truss Designed Bridge in NY

One way that wooden structures are designed involves “laminated beams” where smaller dimensional lumber such as 2x6’s or 2x8’s are used to make “built-up” beams and arches resulting in a more efficient and cost-effective use of materials.¹⁷ Therefore, a 30-foot (9-meter) span bridge was used as a demonstration project to investigate if reinforced plastic lumber may be used to construct laminated beams and arches. The arched top chord of the bridge consists of laminated 2x8 curved members while the bottom chord is a standard

dimensional 8x8 glass fiber reinforced plastic lumber. Although the bridge only needed to be designed for H-10 [10 ton (9,070 kg)] emergency vehicular loading, it was designed and tested for H-15 loading [15 ton (13,600 kg)]. As seen in Figure 2, a loaded dump truck weighing almost 32,000 lb (14,500 kg) was used for testing the bridge. The maximum deflection was only 1.2 inches (30 mm), which is more than acceptable for such structures. The bridge was designed and built by M. G. McLaren Consulting Engineers in a remote area using no heavy equipment.



Figure 2. Load testing the plastic lumber, arch-truss bridge in Albany, NY.

I-Beam Bridge at Wharton State Forest, NJ

In 2003 another all-plastic lumber bridge was built using I-beam plastic lumber structural members. This bridge, located in the Wharton State Forest, New Jersey, was designed for a Class H-20 rating [18,100 kg (20 ton)] since it must be able to support a fire truck which might be needed to answer a call within this part of the forest. Figure 3 shows the I-beam design bridge under construction. The I-beam design reduced the construction time and materials needed to build a bridge structure with the same load capacity using conventional joist and beam construction. The design and construction was a collaborative effort between M. G. McLaren Consulting Engineers and Rutgers University, NJ. While the costs were not fully analyzed and documented, because of the reduced labor time to complete the bridge, this I-beam design appears to be competitive on a first-cost basis with conventional treated-wood with life-cycle considerations making the design even more advantageous.

Innovative I-Beam Bridge at Fort Bragg, NC

An opportunity to demonstrate and validate the performance and benefits of the I-beam design on an Army Installation presented itself in 2008 as part of the Deputy Under Secretary of Defense's Corrosion Prevention and Control (CPC) Program and the Army Chief of Staff for Installation Management's (ACSIM's) Installation Technology Transition Program (ITTP). Both



Figure 3. I-beam designed bridge being constructed at Wharton State Forest, NJ

of these Programs focus on validating emerging technologies and processes that show a potential for cost savings to the Army and the rest of the Department of Defense (DoD) through the use of more durable and cost effective materials and processes. Cooperatively, these two Programs funded the design, construction, and performance monitoring of an innovative thermoplastic composite bridge to replace an existing dilapidated wooden timber bridge at Fort Bragg, NC. Figure 4 shows the original wooden bridge at Fort Bragg that was to be replaced. This bridge had a load limit of 4.7 tons (4,300 kg).

The original intent was to build and evaluate a thermoplastic composite bridge as a replacement for a conventional wood timber bridge with an American Association of State Highway and Transportation Officials (AASHTO) load rating of H-20. To accommodate future training requirements, Fort Bragg asked if the new thermoplastic bridge could be designed to cross a 71-ton (64,000kg) M-1 Abrams tank. The research team proceeded to design, build, and test such a bridge that would provide the required load capacity at a cost competitive to the first cost of a traditional wood timber bridge to carry the same load but with the durability that would require minimal maintenance over its 50-plus year life.

The bridge was designed by M.G. McLaren Consulting Engineers basically using traditional timber bridge design methodology but with slightly lower allowable stresses for the thermoplastic composite materials. The material properties utilized in the design are shown in Table 1.



Figure 4. Original wood timber bridge at Fort Bragg to be replaced with thermoplastic composite bridge.

Table 1
Design Values for Thermoplastic Composite Bridge

Elastic modulus for live load (short duration)	$E = 350 \text{ ksi (2,400 MPa)}$
Ultimate compression parallel to grain*	$f'_c = 3,500 \text{ psi (24 MPa)}$
Allowable compression parallel to grain*	$f'_c = 1,000 \text{ psi (6.89 MPa)}$
Ultimate flexural strength	$F'b = 2,300 \text{ psi (15.9 MPa)}$
Allowable flexural strength	$F'b = 600 \text{ psi (4.1 MPa)}$
Ultimate shear strength parallel to grain*	$F'v = 1,100 \text{ psi (7.58 MPa)}$
Allowable shear strength parallel to grain*	$F'v = 350 \text{ psi (2.4 MPa)}$
Self weight	$\omega_p = 0.032 \text{ pci (8,686 N/m}^3\text{)}$
<u>Coefficient of thermal expansion</u>	<u>$\epsilon = 0.000052/^{\circ}\text{F / } 2.88889\text{E-}05/^{\circ}\text{C}$</u>

* For the flow molded thermoplastic composite members, grain is considered to be the direction of material flow in the mold during fabrication.

The design incorporates heavy-duty I-beam members up to 18 inches (46 cm) high. The piles are made from the same glass-fiber reinforced polymer material as the I-beams and decking. Figure 5 shows an I-beam pile cap on a set of piles. Stainless steel and other corrosion resistant bolts and screw fasteners were used in the bridge construction.



Figure 5. Construction of thermoplastic composite I-beam bridge at Fort Bragg.

The bridge was completed in late May 2009 and, during the week of 8 June, load tests were conducted by the Army's Bridge Inspection Team and their contractor, Bridge Diagnostics, Inc. The bridge was instrumented with 64 strain transducers, 8 displacement sensors (LVDTs), and 6 functional rosette strain gages on the beam webs. Initial load tests were conducted using a heavy dump truck (dual axles in the rear) empty and loaded with rock. On 11 June 2009, an M-1 tank crossed the bridge (Figure 6). With the 36 ton (32,700 kg) dump truck, the deflection at mid-span was 0.216 inches (0.55 cm) including pier deflections. With the M-1 tank, the deflection at the mid-span was 0.525 inches (1.3 cm) including pier deflections.

The elastic modulus, E , used in the design calculations was 350 ksi (2,400 MPa). The load test results indicate that E is closer to 400 ksi (2,760 MPa). Assuming E equals 400 psi (2,760 MPa), the maximum recorded strain and stress with the 36 ton (32,700 kg) dump truck was 637 micro-strain and 255 psi (1.9 MPa). For the M-1 tank, the maximum recorded strain and stress was 740 micro-strain and 296 psi (2.0 MPa). The data is still under analysis.

While data is still being collected and analyzed, initial cursory estimates indicate the cost of the thermoplastic composite bridge is actually less than a conventional treated wood timber bridge designed to carry the same load. Previous bridge demonstrations and studies on the durability of the thermoplastic composite materials used in this bridge, indicate that it will need minimal maintenance over its projected 50-plus year lifetime.

The bridge has now been instrumented with a series of deflection and strain gauges to remotely monitor the performance of the structure on a real-time basis. This monitoring will continue over the next couple of years with the results recorded in future publications.



Figure 6. M-1 tank crossing the thermoplastic composite bridge during initial load testing

CONCLUSIONS

Thermoplastic composite lumber materials are resistant to moisture, rot, insects, and degradation that occurs with natural wood when exposed to the outdoor environment, chemically treated or not. Because it does not use toxic chemical treatments, it is a viable alternative material to treated-wood. While there certainly are property differences between thermoplastic composite materials and natural wood, appropriate design considerations and material formulation (i.e., unreinforced versus reinforced) enable these materials to be used in high load bearing applications for all-types of structures such as the subject bridge at Fort Bragg.

Not only can these bridges be cost competitive on a first-cost basis but are clear winners on a lifecycle basis considering the low-maintenance requirements of these materials. The innovative thermoplastic composite I-beam bridge at Fort Bragg shows that this design and materials should be considered for replacement of the thousands of wood timber bridges that exist on Army Installations and Federal and State Parks and Forests throughout the U.S.

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REFERENCES

1. "The Klobbie." REHSIF Bulletin No. 400. Rehsif S. A., Switzerland.
2. Klobbie, Edward, U.S. Patent 4 187 352, 1974.
3. "The Reverzer," REHSIF Bulletin No. 300, Rehsif S.A., Switzerland.
4. Forster, R., "The Ultraviolet Degradation of Polyethylene and Poly(ethylene Carbon Monoxide) under Simulated Environmental Conditions," Ph.D. Dissertation, Rutgers University, 1994.
5. Ehrig, R.J., ed., *Plastics Recycling - Products and Processes*, Chapter 9, "Commingled Plastics," Munich, Germany: Carl Hanser Verlag, 1992, p.197.
6. Lampo, R., and T. Nosker, "Development and Testing of Plastic Lumber Materials for Construction Applications." USACERL Technical Report 97/95, pp.22-23.
7. *Wood Handbook: Wood as an Engineering Material*, USDA Agriculture Handbook 72, Chapter 4, Table 4-2.
8. *Modern Plastics Encyclopedia '96*, 72, 12, pp. B-185, B-186.
9. Reference 5, p. 198.
10. Reference 6, pp. 35-39.
11. Nosker, T., et.al, "Predictive Techniques- Commingled Plastic Properties." Proceedings, SPE Second Annual Recycling Conference, Akron, OH, November, 1995.
12. *Ibid.*, p. 80.

13. Lampo, R., "What's New in Building Materials," Proceedings 2004 Watchable Wildlife Conference, Dubuque, IA, 2004
14. Nosker, T. and R. Lampo, "Recycled Plastic Composite Structures for Civil Use," Proceedings, Chesner Engineering Conference, New York, 2000.
15. Nosker, T., et.al, "Improvements in the Properties of Commingled Waste by the Selective Mixing of Plastics Waste," Proceedings, SPE Recycling RETEC, Charlotte, NC, Oct. 1989.
16. Gregorski, T., ed., October 1998. "Bridge Advances Plastic Lumber Use," Roads & Bridges, Des Plaines, IL: Scranton Gillette Communications, p 58.
17. Nosker, T. and R. Lampo, "Innovative Structural Design Concepts for Plastic Lumber Materials," Proceedings, Society of Plastics Engineers, 1996 ANTEC Conference, Indianapolis, IN, May, 1996.