Introducing the First Recycled Plastic Bridge In the World

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ABSTRACT

Designed for an AASHTO H-15 truck loading, the first fiber reinforced recycled plastic bridge was completed on October 28, 2000. This is the first time that the primary load carrying structure of a bridge has been composed of fiber reinforced recycled plastic "lumber" (FRPL). An introduction to the recycled plastic lumber material will be presented, as well as the results of an extensive testing program which consisted of flexural and tensile testing of the FRPL members, and tensile testing of bolted connections along with monitoring the bridge structure's behavior for deflection and creep.

INTRODUCTION

With the relatively recent development of recycled plastic lumber and recycled plastic composites, these materials have been successfully engineered for use in residential/commercial decks, platforms, floating docks, and decking for small pedestrian/vehicular bridges. Public agencies, private developers, and the individual homeowner are all becoming increasingly aware of the tremendous potential these materials offer as a viable alternative to traditional materials. This gradual acceptance is igniting an interest not only in a progressive segment of the architectural and engineering communities, but also with public and governmental agencies.

The New York State Department of Economic Development, through its Environmental Management Investment Group, has sought and funded demonstration projects to construct and test the use of these materials for more robust installations. The world's first recycled plastic lumber bridge is a result of this program.

This interest, as fueled by market needs for material life cycle alternatives, energy conservation, and environmental awareness, is presently realized through continuing research and development in improving manufacturing processes and material mechanical properties. The material used in the construction of this bridge represents the effective recycling of 70,000 one-gallon milk jugs.

The recycled plastics industry is compelled to define, and ultimately adopt, an appropriate methodology for its design. If the use of recycled plastic is to be readily accepted by the design community, a successful design approach must be familiar, simple, and statistically accurate, whereby behavior can be predicted through a basic understanding of the material's unique mechanical properties. Furthermore, a familiar design philosophy must be used to allow for simplified design procedures.

In consideration of this, these materials can be understood through standardized laboratory testing and in-situ live load monitoring. Limited information regarding the former is available, allowing the design community to develop the skeletal framework of a rational design procedure. With this limited understanding, this paper presents the engineered use of a glass fiber reinforced recycled plastic composite material, referred to as a fiber reinforced plastic "lumber" (FRPL), in the structural design of the world's first recycled plastic bridge. Also presented are the initial results of a laboratory testing program for verification of structural elements and connections used in the design.

The first fiber reinforced recycled plastic bridge was completed on October 28, 2000. Designed for an H-15 truck loading, the bowstring truss structure is located along the Hudson River Interpretive Trail in the Town of New Baltimore, New York. The single lane bridge is approximately 11 ft wide with a 30-ft span crossing a tidal estuary of the Hudson River adjacent to Hannacroix Creek. The recycled plastic superstructure consists of two parallel bowstring trusses with transverse floor beams framing into panel points. This is the first time that the primary load carrying structure of a bridge has been composed of recycled plastic lumber.

To verify the member proportions used in the design, laboratory testing of structural elements and connections was implemented, including flexural and tensile testing of the FRPL truss members, and tensile testing of bolted connections used on the bridge. Flexural testing was performed on ten (10) 2x8 FRPL specimens in accordance with ASTM D6109 to establish viscoelastic characteristics. Tensile testing on 2x8 FRPL specimens was conducted in accordance with ASTM D198-99 and stress-strain curves were generated. Finally, tensile testing of FRPL bolted connections with a varying number of bolts and edge distances was performed. This paper will summarize the key results from the testing program, and their correlation to design parameters used.

In order to confirm theoretical predictions, an in-situ load monitoring program is presently underway on the bridge. The program is designed to measure the bridge's structural behavior under live load using a vehicle with axle loads equivalent to an AASHTO H-15 truck. Elastic deflections as well as long term creep will be monitored.

BRIDGE SUPERSTRUCTURE TYPE – Several superstructure types were considered for the crossing in an effort utilize the materials most effectively. With a charge to provide a live load capacity of AASHTO H15, deflections and stresses eliminated a stringer type solution. Several trusses were examined, but the inefficiency of a Warren or Pratt type truss became obvious during schematic designs. Consideration was given to a two-hinged arch, but the dependence on fixed abutments, a very low dead to live load ratio (creating significant bending moments) and movements due to thermal expansion/ contraction made this solution impractical.

A most favorable application for FRPL is a bowstring truss. This allows the designer to make an advantage of the material's primary disadvantage- it is significantly less stiff than wood, although its strength is similar. Laminating several plies of 2 x 8 FRPL into a curved configuration is relatively simple. The chords carry axial loads and the curved top chord reduces the amount of material used for verticals and diagonals. A span to depth ratio of 4 provides a reasonable curvature to construct, while providing efficient member forces. Because such a through truss must be a pony truss by necessity, it was decided to brace the top chord by means of outriggers at each vertical. The selected six panel bowstring truss is represented in Figure 1.

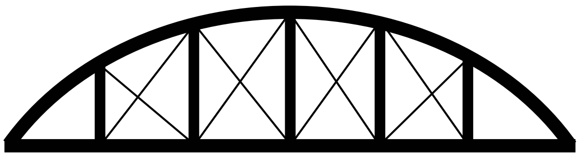


Figure 1 – Bowstring Truss

DESIGN PHILOSOPHY - Historically, use of an allowable stress design philosophy (ASD) has been successful for metals and timber, largely because of the following:

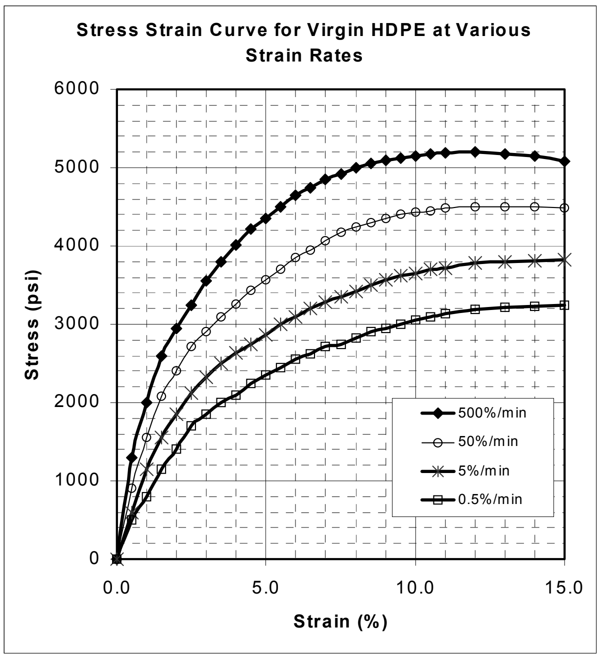
1. Metals typically exhibit a large linear elastic range in their stress-strain diagrams for small strains;

2. Stress-strain diagrams, as affected by the time rate of loading for both metals and timber, are relatively insensitive to variations in temperature, as may be practically encountered during service.

If the familiar and simple ASD philosophy is to be successfully applied to recycled plastics, the resulting design equations must not only account for the mechanical nonlinearities inherent with recycled plastic's stress-strain diagrams, but it must also account for the variation of these diagrams as affected by rate of loading, time duration of loading, and temperature. These considerations are largely neglected in the design of metals and are given some minor influence in timber materials. The material used in this bridge, and typical of the products available as recycled plastic lumber are primarily High Density Polyethylene (HDPE) in content (approximately 80% in this application) and therefore the properties of HDPE must be understood.

Figure 2, below, shows stress-strain curves for virgin HDPE tested at various strain rates.

Figure 2 – Stress Strain Curve for HDPE



In the case of this bridge, creep is expected to be negligible due to the inherent stiffness realized through the glass fiber reinforcement content of the material. These assumptions were borne out during the testing phase. Furthermore, the design incorporated conservative allowable stresses to account for high temperatures during hot summer months.

The basic design equation used is given by

$$F_a = F_{base} \times C_t \times LDF \qquad \text{Eq. (1)}$$

where

F_a is the allowable stress,
F_{base} is the base design value,
C_t is a temperature correction factor, and
LDF is the Load Duration Factor.

The LDF factor provides the necessary adjustments to account for variations in the stress-strain diagram due to rate of loading and time duration of loading, while the C_t factor makes the necessary adjustments for temperature. Since the design of recycled plastics must account for long term creep, the base design value should be selected for the "permanent" loading condition at a conservatively high temperature, whereby strains may be limited to an acceptable level.

The allowable stress used in design was F_a = 750 psi, as determined by Eq. (1), where

F_{base} = 600 psi (0.3 x 2,000 psi ultimate strength per previous test data)
The factor 0.3 normalizes the test load rate against the truck application rate, and provides a factor of safety of 2)
C_t = 1.0 (50°C)
LDF = 1.25 (3 month DL+LL)

Again, based on test data available prior to this design, a modulus of elasticity, E = 300,000 psi was used, after correcting for a temperature change from 23°C to 50°C; that is, a correction factor of .71 was applied to the base modulus of 350,000 psi at 23°C. Lastly, a coefficient of thermal expansion of 5.5×10^{-5} in./in./°F was used in the design of connections, and the accommodation of differential thermal expansion between dissimilar materials.

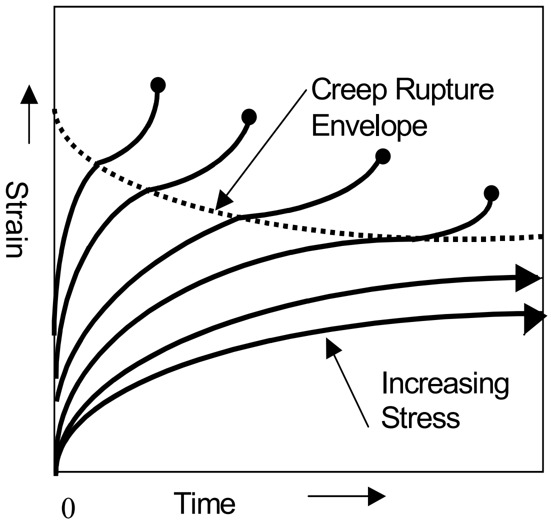
The derivation of Eq. (1), and the development of the above coefficients are outside the context of this paper. Suffice it to say that the values used are conservative for FRPL. The above values were used in proportioning the truss members and predicting initial elastic deflections for live loads.

Creep. An important consideration in the design of thermoplastic polyolefins is the viscoelastic behavior created by the slippage of weak polymeric bonds. This results in two phenomena, which require attention.

Long-term deflection. Because live loads are transient and temporary, only the dead load of the structure will tend to exhibit long term increases of deflection. Accordingly, stresses under dead load were limited to 250 psi, which places the material in a region more nearly approximating elastic, rather than viscoelastic behavior.

Figure 3 – Creep Rupture Envelope (Ductile Plastics)

Creep rupture. Plastics fail under sustained stresses at an upper limit which defines their creep rupture limit. This effect is dependent upon time and temperature. At lower temperatures and longer time periods the creep rupture limit diminishes. Figure 3, below, shows a typical creep rupture curve for a ductile plastic.



FINAL DESIGN -The final design of the bridge superstructure requires the use of 11,000 lb. of FRPL; 5,400 lb. of steel for connection plates, diagonal tie rods and flitch plates, along with 18 pieces of precast hollow core concrete plank to create its abutments.

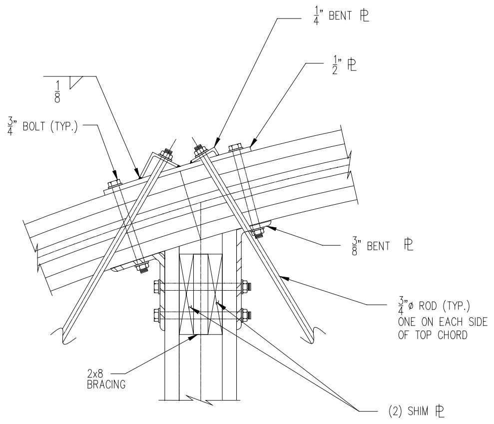
The final design of the bridge consists of four levels of framing. The primary truss structure has been explained. Because it was determined that the most efficient truss structure should have no bending, a floor beam system was required to load the truss at panel points. With a 5 ft spacing of panel points, it is now incumbent upon each individual floor beam to carry a full axle load of the H15 truck. Conservatively allowing a bending stress of only 750 psi would require impractical plastic member for the floor beams. It was decided to use steel flitch plates to augment the floor beam strength.

Figure 4 – Connection Detail

Table 1 – Bridge Composition

Stringers are rather conservatively designed for the anticipated wheel loads, with a spacing of only 7.5 inches. Thicker planking would have diminished this requirement, but these were not immediately available for delivery to meet the schedule of construction.

Verticals are bolted 2 x 8 pairs, with blocking and spacers to accommodate the bracing outriggers. All connections are made with bent or flame cut steel plates, galvanized to resist corrosion.



Diagonals made of plastic lumber would have been difficult to frame or connect, so it was decided to use rods for these elements. An effort was made to locate either carbon or fiberglass rod to maintain the polymeric or organic theme, but neither was readily available. Steel rod was used by default. Because of the transient loads and negligible dead loads, a single panel diagonal would necessarily alternate between compression and tension. Rods, in such a configuration, would buckle. It was therefore decided to use opposite pairs of rods, forming an X in each panel. Transfer of loads between diagonals and the primary truss is performed by the detail shown in Figure 4.

TESTING PROGRAM

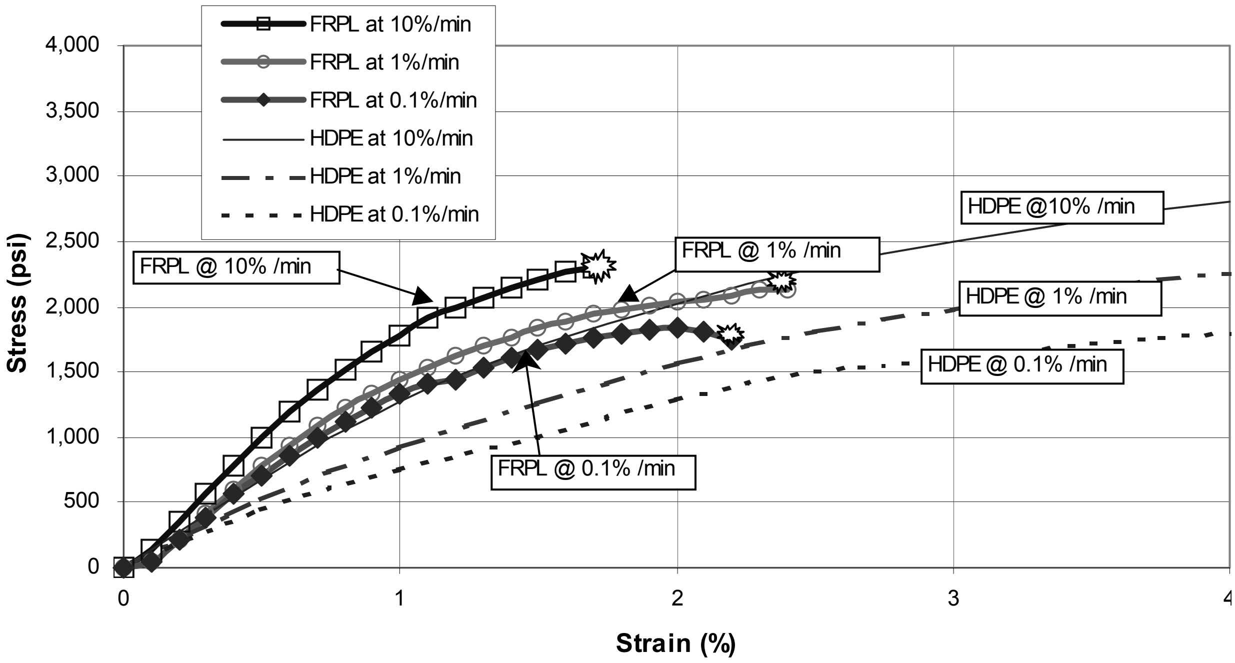
The testing program consisted of four distinct tasks:

1. Flexural testing of plastic lumber members
2. Tension testing of plastic lumber members.
3. Tension testing of bolted connections.
4. Bridge structure monitoring.

Table 2 – Flexural Testing Table

The flexural and tensile tests were conducted at Washington State University in Pullman, Washington. The testing was performed in a climate-controlled environment where the ambient air temperature was held at a constant temperature of 73°F ± 5°F. The objective of the testing program was to predict, monitor, and evaluate the behavior of recycled plastic lumber that is used in the truss bridge. A description of each task and the corresponding test results are presented below.

Figure 5- FRPL 2 x 8 Tension Tests - Comparison with 100% HDPE



FLEXURAL TESTING OF PLASTIC LUMBER MEMBERS - The proposed bridge, consisting of a truss configuration, contains plastic lumber members loaded in tension. The objective of this task, however, is to first determine the viscoelastic characteristics of the material. This was accomplished by conducting flexural tests on ten (10) 2x8 specimens. The flexural test set-up and procedures was conducted in accordance with ASTM D6109. Five (5) specimens were tested at a constant outer fiber strain rate of 0.1 in./in./min. (10%/min), and the remaining five (5) specimens were tested at a constant strain rate of 0.001 in./in./min. Table 2 presents the mean results of these tests.

Outer Fiber Strain Rate (%/min)	Density (pcf)	Modulus of Elasticity (psi)	Modulus of Rupture (psi)
0.1	51.1	358,723	3131
10.0	51.6	448,924	4059

TENSION TESTING OF PLASTIC LUMBER MEMBERS – Nine specimens with 2 x 8 cross-sectional dimensions (1.5″ x 7.5″ actual) were subject to full section tensile testing per ASTM D198-99 under different constant strain rates to determine the stress, strain and strength of the material. The strain rates were 0.1 in/in/min., 0.01 in/in/min., and 0.001 in/in/min. Three samples were tested for each strain rate. The average results are shown in Table 3.

2x8 Tension Tests			
Strain Rate (%/min)	Density (pcf)	Modulus of Elasticity (psi)	Ultimate Tensile Stress (psi)
0.1%	52.8	285,810	1852

1.0%	52.9	326,217	2079
10.0%	52.6	363,447	2276

Table 3 – Tension Test Results

TENSIONS TESTING OF BOLTED CONNECTIONS - Thru-bolt connections were utilized in the bridge design to transfer loads between truss members. Two types of connections were tested at a constant rate of 0.01 in/in/min. with varying end distances (L = 2d, 4d, and 7d). These connections are represented in Fig. 6. The test results are shown in Table 4 for the single and two-bolt tests.

Tension Bolt Tests (Double shear w/ 2 x 8 on each side)						
Member	Bolt Size	No. Bolts	Edge Dist	Yield Load (lb)	Ult. Load (lb)	Allowable by NDS (Wood)
2 x 8	3/4"	1	2D	4596	4910	494
2 x 8	3/4"	1	4D	4620	8634	988
2 x 8	3/4"	1	7D	4986	10493	1730
2 x 8	3/4"	2	2D	9324	9684	2224
2 x 8	3/4"	2	4D	10205	14783	2718
2 x 8	3/4"	2	7D	9716	15230	3460

Table 4 – Bolt Tests in Double Shear

A single test of the bottom chord tension splice was performed at the laboratory as well. Limitations of testing fixtures and equipment precluded testing to failure. The (4)- 1 inch bolts with steel side plates (the bottom chord splice) were tested to a force of 38,500 lb without any indication of yield. This is more than twice the design force anticipated in the bottom chord under application of the H15 truck.

BRIDGE STRUCTURE MONITORING - Monitoring of the bridge is currently underway to determine the response of the structure to live load. A minimum of ten (10) elevation targets and one reference monument were placed at specific points along the bridge and at the site. The elevation targets are to remain on the structure for a period of one year. Using a reference point, the elevation of these targets will be determined using total station surveying equipment. The deflection of the bridge elements can then be determined by the differential change in elevation of the targets.

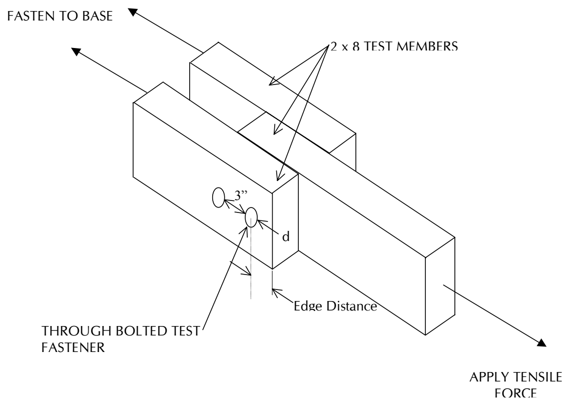


Figure 6 – Bolt Test Setup

On April 25, 2001, an AASHTO H-15 design vehicle, supplied by the New Baltimore Conservancy through the New York State Thruway Authority, was driven across the span as elevation measurements were recorded. The vehicle was stopped at five specific locations along the bridge. For each vehicle location elevation measurements were recorded and compared against unloaded elevations. In addition, the ambient air temperature (55°F), and duration of load were recorded. Maximum bottom chord deflection was measured at 1.28 inches for a truck with wheelbase 0f 12.75′, front axle weight of 10,580# and rear axle weight of 21,340#. Four live load monitoring events will be conducted at three-month intervals over a one-year period.

EVALUATION OF TEST RESULTS

EFFECTS OF FIBERGLASS REINFORCEMENT. Figure 5, which shows the superposition of stress/ strain curves for FRPL and HDPE provides an indication of the effect of the fiberglass. Three effects are noteworthy:

1. The modulus of elasticity (or stiffness) is improved. Note that the slope of each of the three FRPL curves, independent of the rate at which strain is applied, indicates a greater slope than the corresponding HDPE curve. This varies from a 40% improvement at high rates of strain to 75% at low rates of strain.

2. The material is much less ductile. Virgin or pure HDPE can reach strains in excess of 15% at room temperature (23°C) before fracture. The FRPL fractures at strains between 1.5% and 2.5%. This is more ductile than wood, which fails at approximately 0.7% strain, but it is a significant departure from the properties of HDPE and pure polyolefins. Because of this characteristic, the effects of creep rupture must be given serious consideration in future research.

3. The FRPL has a lesser tendency to creep. The curves for FRPL are much more closely packed than the curves for HDPE. Note that at a stress of 1000 psi, the HDPE has a strain of 0.7% for the 10%/min strain rate, while it strains to 1.5% at the 0.1%/min rate. This is a 115% increase in strain.

Conversely, FRPL is not as greatly affected. At 10%/min, strain is 0.5%, and at the slower rate of 0.1% the strain increases only to 0.7%, a 40% difference.

Bolted Connections. The results given in Table 4 indicate that the material is as good or better than timber in similarly bolted configurations. One difference is significant. Material yield appears to be independent of the edge distance. The "yield" is defined by a 5% strain at the bolt, and this occurred at the same magnitude of force independent of edge distance. Failure levels, however, vary in a fashion similar to wood.

RECOMMENDATIONS

Innovative designs are often handicapped by the amount of precedent information available to the designer, and this is no exception. There is a great deal of additional work necessary before construction with FRPL becomes commonplace. Some of the area requiring further research and definition are the following:

1. The phenomenon of creep rupture must be studied in much greater detail for fiberglass reinforced plastics. The significant reduction in ductility indicates that creep rupture failures will occur above certain stress levels. These must be identified through experimentation.
2. Optimization of the material matrix must be studied. A 20% fiberglass content was produced for this application, but it has not been determined if this represents the optimal proportioning as it affects ductility, strength, and stiffness. More fiberglass will make the material stiffer, less likely to creep and probably stronger, but the loss of ductility, and the increased probability of creep rupture may offset these gains.
3. Plastic lumber is presently produced in dimensions to replace or replicate those of sawn lumber. There is no engineering reason for this. Optimization of sizes will necessarily be a by-product of advances in design. Because extrusions can be made to any dimension, lumber sizes may become product specific in the future.

CONCLUSIONS

It would appear that the use of fiber reinforced plastic lumber offers a viable and economical alternative means of constructing short span bridges. There are many inherent advantages to the material that may indicate its use. Foremost is its stability and sustainability. It is not biodegradable, nor does it corrode, spall or deteriorate in any significant fashion. Materials tested after service of ten years have shown improvement in stiffness and strength. Use of recycled plastic material not only is environmentally responsible, but when life cycle costs are considered, the economics are very competitive. The material is very easy to work with, as standard woodworking tools can be utilized.

To its detriment, the material is subject to viscoelastic behavior, which may lead to creep and/ or creep rupture in the long term. More knowledge is needed on this subject. Additionally, the material is quite flexible, with stiffness approximately 20% to 30% that of wood. This can be overcome by design, but it represents a psychological barrier.

In any prototype design such as this, the completion of the task is always followed by the question, what would we have done differently? There are a few of these. One, the use of steel connection plates made the field drilling of connections quite difficult. Aluminum might have been a better choice. We also would have provided a more aesthetic solution to the connection plates by tapering them. Thicker planking (3x) and stringers would have reduced the number of pieces, and, a single tension splice in each bottom chord would be an improvement.

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