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Economic Analysis of Fiber-Reinforced Polymer Wood Beams

Noel D. Stevens

and

George K. Criner

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Noel D. Stevens
Former Assistant Research Scientist, Advanced Engineered Wood Composites Center, University of Maine

and

George K. Criner
Professor of Resource Economics and Policy

Department of Resource Economics and Policy
University of Maine
5782 Winslow Hall
Orono ME 04469-5782

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INTRODUCTION

This study assesses the costs of producing an innovative structural beam developed at the University of Maine that employs Maine's underutilized timber resources. The new beams are composite beams that are made by reinforcing glue-laminated timber beams, commonly known as *glulam*, with fiber-reinforced polymers (FRP) in the tension region of the beam. Research has shown that the FRP-reinforced beams are stronger than non-reinforced glulam beams because the reinforcement absorbs some of the most damaging tension stresses endured by conventional wooden glulam beams. By reinforcing the beam in this manner, researchers at the University believe lower-quality wood species that are found in Maine can be substituted for the high-quality wood that is commonly used in glulam production. This could potentially create a cost advantage for a local manufacturer and provide a value-added use for Maine's lumber.

The University has provided extensive scientific evidence demonstrating that FRP glulam represents a structural improvement over non-reinforced beams. However, research concerning the economics of producing the beams has been limited. Therefore, the purpose of this study is to conduct an investigation into whether FRP-reinforced glulam beams are cost-competitive alternatives to non-reinforced glulam beams.

Research Objectives

This study focuses on the cost of producing FRP-reinforced glulam relative to the cost of producing non-reinforced beams with equal strength. While it is possible to produce stronger glulam beams using FRP than non-reinforced beams, the present study does not address this further complication. If consumers are assumed to be indifferent between structurally similar beams (i.e., beams with the same dimensional and strength properties), then price governs their decision to purchase one beam over the other. Assuming competitive market conditions, beams with production cost advantages can be priced lower in the market, providing them with a competitive advantage.

The current study addresses the following research objectives: (1) developing cost models for a range of FRP-reinforced eastern hemlock and non-reinforced southern pine glulam beam alternatives; and (2) conducting sensitivity analyses on key cost parameters. While the second objective examines uncertainty about the cost parameters identified in the first objective, it does not focus on potential changes to the production processes. The primary focus of this study is on cost changes that result from changes in the material inputs. Examining specific production process changes is beyond the scope of this analysis.

BACKGROUND

Glulam beams are engineered wood products composed of many different pieces of wood. The beams consist of pieces of *dimension lumber* (i.e., two-by-four, two-by-six, or two-by-eight) that vary in length. The width of the lumber will depend upon the width of the beam that is being made. Individual pieces of lumber are carefully graded and then *finger-jointed* together to make a longer plank called a *lamination*. Figure 1 illustrates a lamination composed of three pieces of lumber finger-jointed together.

Laminations are glued together in a stack to form a beam. The process of applying glue to the surfaces of the laminations is referred to as *face-gluing*. The glue that is used for both finger-joints and face-gluing varies among *laminators* (manufacturers of glulam beams). However, most laminators currently use an adhesive known as *phenol-resorcinol*, which must be mixed at the facility prior to application. The number of laminations glued together determines the beam's depth. Figure 2 illustrates a glulam beam.

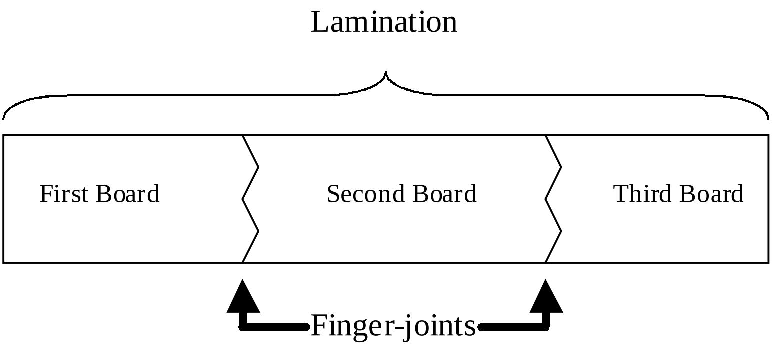

Figure 1. Lamination produced by finger-jointing smaller peices of lumber (top view).

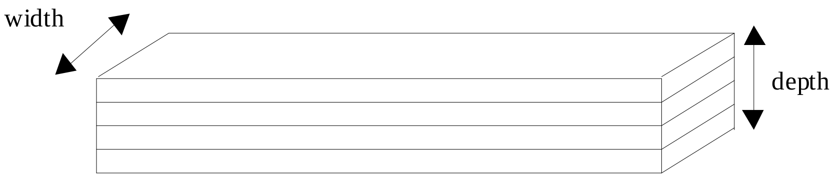

Figure 2. Glulam beam (side view).

Design Considerations for Glulam Beams

The lumber that makes up a glulam beam is carefully graded and strategically placed in the beam to take advantage of known properties of wood. By distributing strength-reducing defects (i.e., knots and pitch pockets), evenly throughout the beam's volume, it is possible to produce beams that possess much greater strength properties than the individual pieces of lumber or solid-sawn wood beams. The American Plywood Association writes "Pound for pound, they are stronger than steel" (APA 1995:3). Figure 3 illustrates two of the major stresses endured by a beam that is subjected to a load. These are *compression*, the stress caused by pushing fibers together, and *tension*, the stress caused by pulling fibers apart.

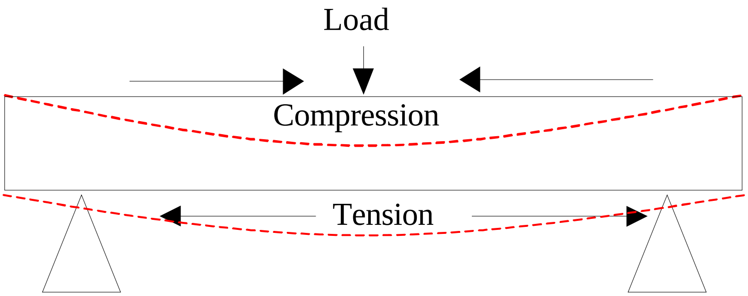

Figure 3. Tension and compression stresses on a glulam beam (side view.

The individual laminations must endure the stresses encountered within the glulam beam. Therefore, when designing a beam it is necessary to consider the mechanical properties of those wood laminations. An important property of wood accounted for in the engineered design of a glulam beam is stress level under which the wood fails in either tension or compression. Referring to Figure 3 again, if a load is placed on top of a wood beam, it will bow downward and snap quickly from the bottom up due to a tension failure, or crack and yield slowly from the top down due to a compression failure. This is because wood is more *brittle* when subjected to tensile stress, which causes it to break rapidly (or snap) once the maximum tensile stress is reached. However, wood that is subjected to compressive stress will fail slowly because wood is more *ductile* in compression. Consequently, tension failures in wood tend to be rapid and compression failures tend to be slow. The direction a glulam beam will fail depends upon the strength of the material on either side of the beam. Therefore, the quality of lumber used in each lamination of the beam determines the strength of the beam.

Figure 4 illustrates the cross-section of a glulam beam on the left and the corresponding distribution of stresses to the right. Notice that the beam is divided into five zones, which must be considered when determining the layout of a glulam beam. The zones are *outer compression, inner compression, inner tension, outer tension,* and the *core*. These are the zones a laminator must take into account when designing and *laying-up* (the process of gluing laminations together) beams.

The stress diagram in Figure 4 shows that the greatest compression stress is experienced by the top of the beam, and lessens toward the center. Similarly, the greatest tension stress occurs at the base of the beam and lessens toward the center. While the number and quality of laminations will vary according to the beam’s strength, stiffness, depth, and lumber species, knowing how the stress is distributed throughout a beam provides valuable information regarding matching lumber quality with known stress. The material that makes up the outer tension zone must be high quality lumber because this region is most susceptible to failure. Although the stresses on the compression side of the beam can be equally high, lower quality lumber is typically weaker in tension than compression. The inner tension and compression zones are under less stress and do not require laminations of such high quality. The core of the beam undergoes the least compressive or tensile stress and can be the lowest quality lumber in the beam.

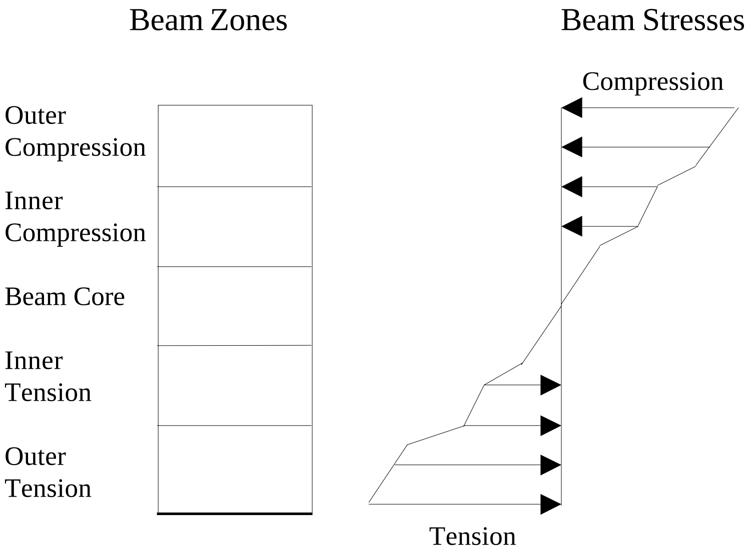

Figure 4. Stress zones of a glulam beam (cross section).

Because the placement of high-quality lumber is essential to the engineered design of a glulam beam, it is essential for laminators to have standardized methods of identifying the quality of a piece of lumber. Fortunately, lumber is a commodity that is bought and sold within a mature marketing channel that separates lumber with different qualities according to grades. Although the grading restrictions used in making glulam beams are more stringent than for ordinary lumber, it is useful to understand the way lumber is graded before considering glulam grades.

Lumber grades are set by a number of regional grade associations. Each regional grade association sets grade requirements on lumber species that are cut in that region of the country. For example, the Southern Pine Inspection Bureau is the primary grading agency for southern pine species. Southern pine grades include select, #1, #2, #3. Select lumber is the highest quality and highest priced grade listed and #3 lumber is the lowest. While it is not mandatory that lumber mills belong to a grading agency, it is in their interest to follow these grade requirements because grades provide a standard norm on which consumers can base their purchase decisions.

Laminating stock (lamstock) is lumber used to produce laminations, which is subjected to more stringent grading requirements than standard lumber grades. These requirements are set by one of the glulam trade associations, either the American Institute of Timber Construction (AITC) or the American Plywood Association (APA). Again laminators are not required by law to belong to either the APA or AITC, but it is in their best interest to do so if they wish to sell their product. A manufacturer does not receive APA or AITC approval for their products unless those products meet all of the specifications set by the respective organization. The specifications describe the recipes for making different size beams of a given strength and stiffness. In addition to specifications set to assure beam strength and stiffness, there are also specifications for appearance grade requirements, fire requirements, production technologies, and requirements on the connections that can be used to fasten beams into place. It is important to note that the AITC and APA are concerned with setting specifications that standardize production in the glulam industry and not the mill industry. Therefore, it is the responsibility of the laminator to verify that the lumber grades they receive from mills meet either AITC or APA regulations.

Generally speaking, the quality of a piece of lamstock will depend on the size of any knots, the location of those knots, the overall slope of the grain, and the species of wood used. Lamstock that is made from species that come from the western U.S., such as Douglas fir, can be purchased from mills according to actual laminating grades. However, laminating grades are not commodity items for all species that are used in glulam production. Southern pine, which is used in the South and East to produce glulam beams, cannot be purchased according to laminating grades. As a result, manufacturers of southern pine glulams must purchase lumber according to lumber grades. Consequently, the AITC specifications for southern pine laminations are set according to Southern Pine Inspection Bureau grades to facilitate the design of southern pine beams. However, these specifications still restrict the lumber quality beyond commodity level. While the rules for identifying the grades used for laminating stock are standardized, lumber mills do not typically separate and sell lumber according to these more stringent grade requirements. Laminators must order southern pine lumber according to lumber grades then further separate the lumber to meet certain additional restrictions.

As the use of forest resources increases, the cost of acquiring the high-quality lamstock used in the tension laminations increased. As Dagher et al. (1996:207) explain “With recent changes in availability of forest resources, high quality laminations necessary for glulam design have become increasingly difficult to procure, and more expensive as well." As a result, the glulam industry has sought innovative techniques of replacing the tension laminations of glulam beams with other materials.

Fiber-reinforced Glulam

Responding to the need for a substitute to the high-quality tension laminations typically used in glulam beams, researchers in the Advanced Engineered Wood Composites Center at the University of Maine have developed a reinforcement technology capable of reinforcing the tension zone of a glulam beam. Recently, research at the University of Maine, led by Professor Habib J. Dagher, has developed a method of producing stronger glulam beams by combining glulam with FRP. The new technology eliminates the need for relatively expensive tension laminations required by non-reinforced glulam. Additionally, reinforcing the beams makes it possible to produce stronger beams from wood species found in Maine. These local wood species may be available at lower prices than species traditionally used to make glulam, which could provide a local laminator with a production cost savings.

The technology uses a FRP that consists of a resin matrix reinforced with glass fibers. It is also possible to use other types of fibers such as carbon or kevlar, but glass fibers are the least expensive. The resulting material has a greater tensile strength than mild steel. More importantly, the research has developed a strong and durable bonding material to bond the wood beam and the FRP. By placing a thin strip of FRP at the base of a beam, Dagher et al. (1996) have shown that the bending strength of a glulam beam can be increased up to and exceeding 100%. Figure 5 illustrates a FRP glulam beam.

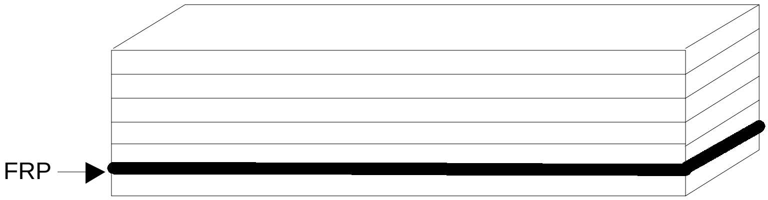

Figure 5. Fiber-reinforced glulam beam (side view).

The FRP is placed at the base of the beam to reinforce the tensile region of the beam. The lamination on the bottom of the beam (below the FRP) acts as a bumper strip, which provides a nailing surface, protection to the FRP, and facilitates the manufacturing process. The amount of FRP shown in Figure 5 is exaggerated for illustrative purposes. Only 1% to 3% of the volume of the beam needs to be FRP. The FRP takes on most of the tensile stress, and the wood is utilized primarily for its compression strength.

FRP reinforcement in tension is a particularly beneficial property for beams made from species such as eastern hemlock that are stronger in compression than in tension (Dagher et al. 1996). (The remainder of this bulletin will refer to eastern hemlock as hemlock.) Because hemlock is relatively week in tension, it is not currently used to make glulam. Consequently, there are no standard specifications for producing hemlock glulam beams. However, designing FRP-reinforced glulam beams cannot be done using standard glulam design methodology because adding the FRP to the beam changes the behavior of the wood beam.

The design of FRP-reinforced beams requires the use of a computer model called ReLam, which was developed by the AEWC at the University of Maine. ReLam uses information on the stiffness and compression and tensile strength of the wood members and the stiffness and tensile strength of the FRP plus the percentage of FRP used to make the beam to design a FRP-reinforced glulam beam. Using ReLam, it is possible to determine the strength and stiffness of a beam using any wood species or fiber reinforcement type (i.e., glass, carbon, kevlar), provided the necessary data are available. For further information on the design of FRP-reinforced glulam beams using ReLam see AEWC (1998).

METHODOLOGY

This bulletin develops an economic-engineering model to estimate partial production costs for two separate glulam facilities. One facility is assumed to produce non-reinforced glulam beams using southern pine lumber and the other produces FRP-reinforced glulam beams using hemlock lumber. Both facilities are assumed to produce a range of structurally similar glulam beams using their corresponding technology. Structurally similar beams possess identical strength and dimensional characteristics. The model is designed to determine which technology provides producers with unit-cost savings in the production of structurally similar FRP-reinforced and non-reinforced glulam beams.

Relevant Literature

The production cost model developed in the foregoing analysis draws on arguments first made in Sammett and French (1953), which discussed the need to coordinate engineering and economic information in the development of production cost models. Engineering information is used to define the production process in terms of distinct stages, which can themselves be thought of as subproduction processes. Each stage is responsible for the production of a partial product, using its own material, capital, and labor inputs. The final product is the sum of the partial products. Similarly, the production cost of the final product consists of the sum of the production costs from the individual stages. Viewing the production process in terms of stages allows for the analysis of changes to certain inputs in a part of the process without considering changes to the whole process. This facilitates the effects of changes such as material substitution, replacing labor with capital inputs, and analyzing the returns to size of a process. Because of the coordination between economic (cost) and engineering (process) information, the modeling approach developed by Sammett and French is often referred to as Economic-Engineering Analysis (or EEA).

After the stages of a production process have been identified, it is necessary to assign the appropriate costs to each stage. When assigning costs, it is important to for the analyst to consider three factors:

- partial verses complete cost reporting;
- the time value of money; and
- inflation.

Casler et al. (1984) describe the difference between partial and complete cost reporting as the level of detail required for the analysis. A complete cost analysis lists all of the relevant costs for each stage of an EEA to provide the total cost of production for each alternative. A partial cost analysis lists only those costs expected to change between the alternatives. If the analyst is only concerned with the incremental cost difference between alternatives and does not need a full cost description of the process, then a partial analysis is all that is required. However, if the total cost of production is needed, for budgetary or other administrative purposes, then full cost reporting is required.

Regardless of whether the analysis includes either full or partial costs, it is necessary to be consistent in the reporting of costs in terms of their value over time. To ensure that costs are reported on a consistent basis, both the time-value of money and inflation must be considered. Most production decisions involve spreading costs (and benefits) over a number of years. This presents a number of issues important to the analysis of production decisions.

First, capital inputs are assets that have a useful life of greater than one year. Investing in a capital item requires the firm to lock up resources for the life of the equipment. This loss in liquidity presents a cost because resources are prevented from earning a rate of return elsewhere (e.g., interest paid by a bank). Amortization is a method incorporating the capital acquisition cost plus the interest cost into equal annual payments over the capital item's useful life.

Second, when considering the cost of goods over time, it is important to account for the affects of inflation, which is a general increase in all prices over time. An analysis that includes inflation is referred to as a "nominal analysis," while an analysis that removes inflation is referred to as a "real analysis." Whether nominal or real, the analyst should be certain that all costs are reported on a consistent basis. If inflation is included in cost estimates, then the analyst should use a nominal interest rate to account for the time value of money. Conversely, if inflation is not included in cost estimates, then the analyst should use a real interest rate to account for the time value of money.

General Production Cost Model

This study develops an economic-engineering model to compare the production costs for FRP-reinforced glulam beams and non-reinforced glulam beams. The model identifies costs for a range of glulam beams using both FRP-reinforced and non-reinforced glulam technologies. The model is a partial analysis because only costs that are expected to vary between alternatives are included in the analysis. Because the primary focus of this study is to determine cost differences that result from changing the material inputs to the beams, all costs are expressed in terms of the cost per linear foot of lamstock used in each beam. The final unit costs of the beams are expressed in terms of linear foot of beam produced.

The model compares the production costs for two separate production processes, both manufacturing a line of structurally similar beams. One process manufactures FRP-reinforced glulam beams using hemlock lumber and the other manufactures structurally similar non-reinforced glulam beams using southern pine lumber. Both plants are assumed to have a production capacity of 5,000,000 board feet (bdft) of lamstock per year. A board foot is a measure that corresponds to the amount of wood that makes up a one-inch-thick piece of wood that is a 12x12-inch square. This volume is based on the market projection provided by Price et al. (1996).

The production facilities for the two plants are assumed identical. This assumption is reasonable because the facilities have essentially the same production volumes and product lines. Thus, it is possible to eliminate facility costs from the analysis because no cost differences will be reflected between the alternative plants. Furthermore, while plants could be located at various locations throughout the U.S., to simplify the analysis, it is assumed that both facilities are located in Maine. The model was developed in the four general steps listed below. These steps are discussed in detail in the following four sections.

- Identify product
- Identify the stages of the production processes.
- Identify costs centers for each stage.
- Allocate costs to each product.

Products

Each of the competing technologies is assumed to be produced in facilities that split production equally among five different beam strengths, which are listed in Table 1. Beam (bending) strength is measured in pounds per square inch (psi). Therefore, each plant is assumed to attribute 1,000,000 bdft of lamstock processed to 1600-psi, 2000-psi, 2400-psi, 2600-psi, and 3000-psi beams for a total of 5,000,000 bdft. Aside from its bending strength, each beam has a corresponding stiffness, which is measured by the modulus of elasticity (MOE or “e”). Stiffness measures the amount a material will move when subjected to a stress. Selecting the structurally similar beams used in the study required accounting for the design-performance of the two beam technologies. To identify the possible range of FRP-reinforced-glulam beams the ReLam software program designed by the AEWC was used. ReLam is a stochastic model that determines the strength and stiffness of FRP-reinforced beams. Using data on the strength properties of the species used to make the beams, ReLam design a beam that maximizes the benefits of a given set of strength and stiffness properties by optimally distributing them throughout the beam. Moreover, ReLam can account for strength and stiffness properties of FRP to optimize the properties of all the materials used in FRP-reinforced glulams.

Table 1. FRP-reinforced and non-reinforced beam alternatives ($5^1/_8$ inches wide).

FRP-Reinforced Hemlock Beams			Non-Reinforced Southern Pine Beams		
Strg (psi)	MOE (e)	Dpth (in)	Strg (psi)	MOE (e)	Dpth (in)
1600	1.4	12	1600	1.4	12
1600	1.4	24	1600	1.4	24
1600	1.4	36	1600	1.4	36
1600	1.4	48	1600	1.4	48
2000	1.5	12	2000	1.5	12
2000	1.5	24	2000	1.5	24
2000	1.5	36	2000	1.5	36
2000	1.5	48	2000	1.5	48
2400	1.7	12	2400	1.7	12
2400	1.7	24	2400	1.7	24
2400	1.7	36	2400	1.7	36
2400	1.7	48	2400	1.7	48
2600	1.8	12	2600	1.8	12
2600	1.8	24	2600	1.8	24
2600	1.8	36	2600	1.8	36
2600	1.8	48	2600	1.8	48
3000	1.9	12	3000	1.9	12
3000	1.9	24	3000	1.9	24
3000	1.9	36	3000	1.9	36
3000	1.9	48	3000	1.9	48

Because there were no published sources for data reporting the tensile and compressive stress of hemlock, primary data had to be collected. This required physically testing 100 pieces of #2 and better hemlock lumber in compression and tension. Due to time and budgetary restrictions, data could only be collected on nominal 2x6 pieces of lumber. Therefore, all beams are made from nominal 2x6 lamstock. Finished beams made from nominal 2x6 lamstock are $5^1/_8$ inches wide due to width reductions caused by surfacing.

To identify structurally similar non-reinforced southern pine beams, AITC-117-93, Manufacturing Standard Specifications for Structural Glued Laminated Timber of Softwood Species was used. The model includes the highest and lowest strength beams listed in AITC 117-93. Those strengths are 1600-psi and 3000-psi. Three additional strength beams were also selected: 2000-psi, 2400-psi, and 2600-psi. All beam designs used in the study correspond to the lowest visual grades listed in AITC 117-93.

Because all beams designed in the model are manufactured from nominal 2x6 lamstock, one board foot of lamstock translates directly into one linear foot. A linear foot is a foot-long piece of 2x6 lumber. The remainder of the study will use linear feet rather than board feet. The model determines all production costs according to the amount of material used in each beam (i.e., linear feet of lamstock used in a beam). Each plant can choose to produce 12-, 24-, 36-, or 48-inch deep beams for each of the five strengths, but these are not regarded as separate products because producing a deeper beam simply requires adding more layers of lamstock.

Production stages

The second step in creating the model is to define different stages of production. The model divides the production processes for both FRP-reinforced and non-reinforced glulam beams into four stages: grading, finger-jointing, gluing, and finishing. These stages are listed in Table 2 along with a brief description of the processes that occur within each stage.

It is important to note that the analysis presented in this study is a preliminary cost comparison to acquire a general understanding of the cost competitive position of FRP-reinforced glulam beams. While there are many possible changes that could be made to a production facility to accommodate the use of FRP reinforcement, this analysis assumes that production processes are essentially identical, with the exception that FRP is used in one of the facilities. There is insufficient evidence at present to make definitive statements about what changes should be expected. Fortunately, both types of beams can be produced in a small-scale, low-technology plant without any changes to technology. Therefore,

Table 2. Description of the stages for the production of glulam beams.

Stage	Description
Grading	Receives lumber and visually grades lumber
Finger-jointing	Produces laminations from lamstock by finger-jointing smaller pieces together
Gluing	Produces unfinished beams from finger jointed laminations; FRP is affixed to the beam in this stage for FRP beams
Finishing	Unfinished beams are planed, rough ends are removed, and final carpentry work provides the beam with its finished appearance

both production processes are assumed to consist of the same four stages with only minor alterations to production processes.

Cost centers

The third step in constructing the model is to identify the general cost categories. Three cost categories (or cost-centers) are identified for this model: material, labor, and equipment. Figure 6 illustrates the reporting of cost centers for each stage of production.

Cost categories are general classifications of costs. Each cost category actually includes a number of specific cost items that function as inputs to the production of either FRP-reinforced or non-reinforced glulam beams, or both. Material costs include lumber and glue for non-reinforced glulam, lumber, glue, and FRP for FRP-reinforced glulam. The non-reinforced beams are made with southern pine lamstock, while the reinforced beams are made using hemlock lamstock. Labor includes employees that perform the various jobs within each plant. Because job descriptions vary, the skill level required to perform each job varies as well. This is reflected in wage differentials between workers.

Equipment costs require special attention because these reflect capital costs, which require the investment of resources for periods

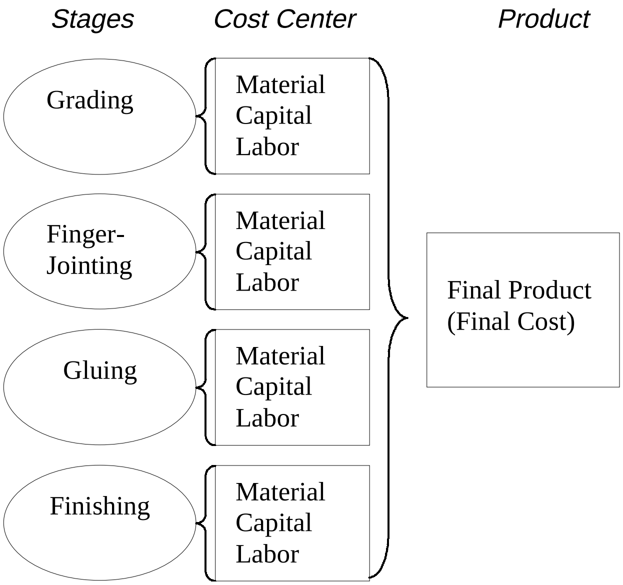

Figure 6. Cost center, production stage, product relationship

longer than one year. As was discussed earlier, amortization calculates equal annual payments, which reflect principal and interest costs for each capital item based on its useful life and the interest rate. The useful life of each capital item was determined through interviews with machine manufacturers. A 10% salvage value was assumed for all capital items. The salvage value was incorporated into the model by subtracting its present value from the purchase price of the item, then the difference is amortized using an interest rate of 6%. This consists of a real risk-free rate of 3% plus an additional 3% that is added for risk. Finally, a charge of 2% of the initial equipment cost is added to amortized values as an estimate for annual maintenance and repair costs.

Costs within each cost category are expressed in terms of their cost per linear foot of lamstock processed by each plant. The price of lamstock is expressed in price per linear foot without any adjustment. The price of FRP is also expressed in terms of price per linear foot for each layer of FRP used in a beam, but it should be noted that most beams require more than one layer of FRP. Glue costs can be easily translated into cost per linear foot because glue prices are based upon a spread rate. Labor costs are expressed in terms of linear feet of lamstock processed by dividing each employee's annual compensation by the production capacity. Finally, because equipment costs are expressed in equal annual terms, expressing these costs in terms of the cost per linear foot of lamstock simply requires dividing the adjusted equipment cost by the production capacity.

Allocation of costs among products

The final step in distributing costs is to divide the cost categories within each production stage among the beams produced in the two plants. Each plant is assumed to process 5,000,000 lnft of lamstock per year, which they split equally among the five strength beams. Therefore, they will each attribute 1,000,000 lnft of lamstock to each of the five beam strengths.

Production costs are based on linear feet of lamstock processed. Therefore, determining production costs for each beam can be done in two steps. First, the cost of material, labor, and equipment per linear foot of lamination are added together which provides the total cost for one lamination in that beam. This cost is multiplied by the number of laminations in a one-foot section of each particular size beam, which yields the cost per linear foot for the beam.

Once the stages of the production process are defined, the appropriate costs from each of the cost categories are assigned to each stage. Most costs allocated to their appropriate production stage represent direct costs (i.e., costs that apply directly to the specific operations of that stage and no other stage). Allocation of these is straightforward. Some costs are indirect costs, and cannot be attributed to only one stage. These indirect costs include compensation for the quality control and production managers, shop equipment, and maintenance equipment. These costs are divided equally among the four stages.

While the production process does not require the FRP until the gluing stage, its cost is attributed to the grading stage. This was because it is easier to keep track of the lamstock requirements for FRP-reinforced beams by simultaneously considering wood and FRP requirements. It is assumed that the FRP passes through the production system with no additional cost until it reaches the gluing stage. A linear foot of FRP is accounted for the same as a linear foot of lamstock, but it has a different price and the number of layers will vary depending upon the beam strength and depth. If the thickness of the FRP used in any given beam surpasses 1.5 inches, one piece of lamstock is removed from the wood portion of the beam.

Production Cost Data Assumptions

The wood species used to make the FRP-reinforced beams is (eastern) hemlock. However, there are no published sources for hemlock prices. Interviews with hemlock lumber mills indicate that hemlock prices are roughly equal to spruce prices. When spruce prices rise or fall, hemlock prices follow. Therefore, this study uses kiln dried eastern spruce-pine-fir prices, reported in Random Lengths (1998a) and converted to 1997 dollars to represent hemlock prices. The prices reported are for lumber delivered to Boston. The average price for 1995 to 1997 of spruce-pine-fir is $418/thousand bdft, which is used as the price of hemlock.

The price of southern pine lumber was identified using Random Lengths (1998a). Material requirements for non-reinforced glulam beams correspond to AITC 117-93, indicating the distribution of the specific laminating grades throughout the zones of each strength beam. However, through telephone interviews with southern pine laminators and AITC's chief inspector, it was determined that laminators primarily order #1 southern pine and regrade the lumber in-house to identify various laminating grades. Laminators indicated that an order of #1 southern pine will contain material ranging from select to #3 grade.

Only one laminator contacted reported ordering select or #2 southern pine. This was done for two reasons. First, the laminator manufactures high-performance 3000-psi glulam beams that require material with exceptional strength properties. Up to 40% of the lumber contained in these 3000-psi beams must have an MOE of 2.3. The highest commodity grade, select, has an average MOE of 1.9, so these laminators must order excess lamstock and grade out the quality material providing them with a surplus of high-quality material. In order to balance the surplus of high quality lumber, the firm orders #2 southern pine. Nevertheless, this laminator also reported ordering #1 southern pine for the majority of its inventory.

Random Lengths (1998a) reports annual free on board (FOB) prices for kiln dried, #1 southern pine lumber for 2x4 dimensions. The prices required for the analysis must be for 2x6 lumber and delivered to Boston to be comparable to the hemlock prices. Fortunately, Random Lengths (1998b) publishes weekly prices that include both 2x4 and 2x6 lumber. Annual prices are adjusted to account for the dimensional difference using an index from the weekly prices. The annual prices are preferable because there is a great deal of variation in weekly prices. Telephone interviews with southern pine lumber mills were conducted to determine a delivery charge to Boston. Based on these conversations, prices are adjusted upward by $55/thousand bdft to account for delivery. The average price for the past three years is $544/thousand bdft, which is used to reflect the cost of southern pine lamstock.

Relative price difference between species

Figure 7 charts the price of southern pine and spruce-pine-fir over the past ten years. It appears from the graph that recently the price of southern pine has increased relative to the price of spruce-pine-fir.

Because of the apparent divergence in the two prices, the model considers three price differences between southern pine and spruce-pine-fir in the sensitivity analysis. These are presented in Table 3. All differences are based on current prices of hemlock to keep the analysis in real terms. The first set of prices assumes the current prices for southern pine and hemlock, which indicates that southern pine is 30% greater than hemlock. The second set of prices assumes that there is no difference between the two prices. The third set of prices assumes that the difference between the two prices is twice the current difference, or 60%.

Distribution of lumber acquisition costs

The distribution of lumber acquisition costs is a concern for laminators producing non-reinforced beams. The acquisition

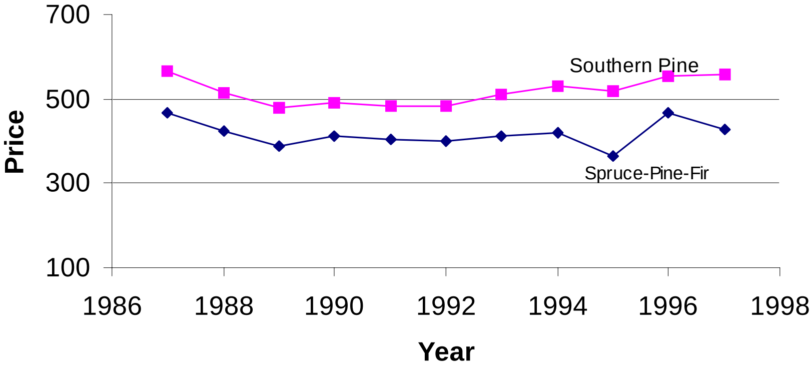

Figure 7. Average price/mbdft for southern pine and spruce-pine-fir from 1987 to 1997.

Table 3. Lumber prices used in sensitivity analysis to account for differences between southern pine and hemlock prices.

Price difference	Price proportion	Price southern pine	Price hemlock
Current difference	$Price_{sp} = 1.30P_{hem}$	$0.54	$0.42
No difference	$Price_{sp} = P_{hem}$	$0.42	$0.42
Twice current difference	$Price_{sp} = 1.60P_{hem}$	$0.67	$0.42

and resulting inventory costs arise because laminators buy wood to meet the grade requirements of each strength beam. Higher strength beams require a greater proportion of high-quality lumber.

Laminators contacted during the course of this study reported various methods to handle inventory imbalances. Some sell the lower-grade lumber as framing lumber. Others produce lower valued products, such as finger-jointed planks and laminated poles. The model assumes that low-grade lumber is used to produce two low-strength beams, 2000-psi and 1600-psi beams. Nevertheless, it is still necessary to identify the value of each laminating grade to correctly attribute costs to each of the different strength beams. Since no laminators contacted during the study could provide such figures, and there are no public sources of this information, some additional assumptions were made.

The model accounts for inventory costs by adjusting lumber costs to reflect higher wood acquisition costs for stronger beams because they require higher quality wood. Even though southern pine laminators are assumed to order only one grade of lumber (#1), they must grade out this high-quality wood from that material. An adjustment is made to the price of lamstock used in each beam to reflect inventory costs. The inventory adjustments for the different strength beams are illustrated in Table 4.

Table 4 is read in the following manner. If inventory acquisition costs are not reapportioned to account for differences in laminating quality requirements among different strength beams, then each strength beam accounts for 20% of the costs. This is shown in the “No Apportionment” case. However, lumber acquisition costs must be reapportioned to appropriate inventory costs to stronger beams. The model uses the “Medium” apportionment, which assumes that the firm attributes 30% of its lumber acquisition costs to the strongest beams even though 3000-psi beams only account for 20% of the total output. Similarly, the firm attributes 25% of its lumber acquisition costs to 2600-psi beams even though they also account for only 20% of total production. The plant attributes no additional lumber acquisition costs to 2400-psi beams. Since, it is relatively easy to acquire material for the two lowest strength beams, which could be made using lower grade lumber or the unusable material from each of the highest strength beams, there is a reduction in the lumber acquisition costs for these beams.

Table 4. Apportionment of lumber inventory costs for the five beam strengths.

Inventory Acquisition Cost Apportionment	-------------- Beam strength (psi) --------------				
	3000	2600	2400	2000	1600
	------------------------- % -------------------------				
No apportionment	20	20	20	20	20
Medium	30	25	20	15	10
Low	25	22.5	20	17.5	15
High	35	27.5	20	12.5	5

The table also shows two additional cases for inventory adjustment. The "High" apportionment scenario charges the greatest cost for the inventory used in the strongest beams. These low and high apportionment scenarios are used to analyze the sensitivity of cost estimates to changes in the distribution of inventory costs. The inventory cost distributions listed in Table 4 can be expressed in terms of lumber price mark-ups. In essence, each inventory cost apportionment is the same as marking up or down the price of lamstock by the percentage of inventory costs attributed to each strength beam. Therefore, the inventory distributions in Table 4 are translated into average price mark-ups seen in Table 5.

Table 5. Lumber price adjustments to account for inventory costs apportionment to stronger beams.

Lumber Price	-------------- Beam strength (psi) --------------				
Adjustment	3000	2600	2400	2000	1600
Medium	1.50	1.25	1	.75	.50
Low	1.25	1.125	1	.875	.75
High	1.75	1.375	1	.625	.25

FRP material costs

Material requirements for FRP-reinforced glulam beams were identified using the ReLam software program and the hemlock data discussed above. The ReLam model determined the percent volume of a beam that is taken up by FRP, when the remainder of the beam is composed of a random lay-up of #2 and better hemlock. The AEWC at the University of Maine provided the price for FRP.

Currently, there is only one manufacturer of FRP, who is licensed by the University to supply FRP only to the University for research purposes. This requires the FRP producer to interrupt its regular production process to provide the University with a relatively small amount of product. Logic would suggest that larger production runs would decrease costs and lower the FRP price. The price used in the analysis is $1,250/thousand lnft (or 1.25/lnft), which is based upon a study performed by the AEWC that projected the reduction in price resulting from increasing the volume of FRP produced.

While the results of the study have been confirmed with the current FRP producer, this study did not account for any markup established by the FRP producer. Therefore, the sensitivity analysis uses three different prices for FRP to account for expected price changes that may result from increased competition. The first price assumes current price estimates without any adjustment to account for competitive market conditions. The second price assumes that the competitive market price is 80% of the current price, or $1,000/thousand lnft. The third price assumes that the competitive market price is 60% of the current price. The FRP prices used in the analysis are listed in Table 6.

Table 6. FRP prices used in sensitivity analysis to account for competitive price adjustments.

FRP Price	Price
Current	$1.25 lnft
80% of Current	$1.00 lnft
60% of Current	$0.75 lnft

Equipment and labor costs

Equipment for each facility is assumed to meet quality code requirements that are specified in AITC 200-92. While the use of FRP in manufacturing glulam beams is likely to reduce or eliminate the need for many quality control procedures, such changes would require altering codes that govern the industry. Moreover, because FRP-reinforced glulam currently is not available in the market, it is likely that a producer of FRP-reinforced glulam will also produce non-reinforced glulam. Therefore, major alterations in production equipment are not anticipated. Equipment requirements are identified to determine the extent of equipment changes that may occur in the production of FRP-reinforced beams without violating AITC 200-92.

The equipment requirements were identified through extensive telephone interviews with AITC officials, laminators, and equipment manufacturers. In addition, two different glulam facilities were visited. Equipment prices were obtained from leading equipment manufactures.

Labor requirements for the two facilities were identified through plant visits. Telephone interviews with equipment manufacturers and laminators were used to confirm the estimated labor requirements for all operations. All laborers are assumed to work 48-hour weeks. This is in accordance with information gathered on plant visits and through conversations with equipment manufacturers. Labor costs are derived from the Census of Maine Manufacturers, which reports annual compensation for general occupations in the lumber and wood products industry. However, this does not identify wages for specific jobs required by each glulam plant. Therefore, the general wage categories are adjusted according to wage differences identified through conversations with local lumber manufacturers. Because fringe benefits are not include in the wages reported in the Census, 20% is added to all wage estimates.

Production Costs

The material requirements for non-reinforced southern pine glulam beams consist of southern pine lamstock and glue. The lamstock requirements for each beam are identified using AITC 117-93. Table 7 lists the lamstock requirements and the associated prices for each of the beams considered in the analysis. Using the current price of southern pine of $544/thousand bdft for example, the cost per linear foot of lamstock can be found by dividing this price by 1000 and adding 10% for a loss from grading and moisture. The loss figure is based on data reporting actual losses provided by a manufacturer of southern pine beams. Then, this price is multiplied by the appropriate inventory price adjustment factor to yield the cost of lamstock for that particular beam. Determining the lamstock cost per linear foot of each beam is done by simply multiplying the price per linear foot of lamstock times the number of laminations used in the beam.

Material costs for FRP-reinforced beams include hemlock lamstock, FRP, and glue. The ReLam model provided the hemlock and FRP requirements for each of the beams analyzed in the study. The FRP is purchased in strips that are $^1/_8$ inch thick and $5^1/_8$ inches wide. Table 8 lists the lamstock and FRP costs for the reinforced hemlock beams.

The cost per linear foot of hemlock lamstock is found by dividing $400 by 1000, and adjusting for loss. Because layouts provided by the ReLam model are based on random lay-up of #2 and better hemlock, as graded by the lumber mill, no additional grading is necessary. However, loss is still expected from moisture. Therefore, a 10% loss is still added to the estimated price. Similarly, the price of FRP/lnft is found by dividing $1250 by 1000. To determine the lamstock costs/lnft of each of the reinforced beams, it is necessary to multiply the number of required laminations of each times its respective price.

Table 7. Southern pine lamstock costs for $5^1/_8$-inch-wide beams.

Strng (psi)	MOE (e)	Depth (inches)	Num of Lams	Price per lnft	Cost per lnft
1600	1.4	12	8	$0.28	$2.24
1600	1.4	24	16	$0.28	$4.48
1600	1.4	36	24	$0.28	$6.72
1600	1.4	48	32	$0.28	$8.96
2000	1.5	12	8	$0.42	$3.36
2000	1.5	24	16	$0.42	$6.72
2000	1.5	36	24	$0.42	$10.08
2000	1.5	48	32	$0.42	$13.44
2400	1.7	12	8	$0.56	$4.48
2400	1.7	24	16	$0.56	$8.96
2400	1.7	36	24	$0.56	$13.44
2400	1.7	48	32	$0.56	$17.92
2600	1.9	12	8	$0.70	$5.60
2600	1.9	24	16	$0.70	$11.20
2600	1.9	36	24	$0.70	$16.80
2600	1.9	48	32	$0.70	$22.40
3000	2.0	12	8	$0.84	$6.72
3000	2.0	24	16	$0.84	$13.44
3000	2.0	36	24	$0.84	$20.16
3000	2.0	48	32	$0.84	$26.88

The cost of glue is also a material cost that must be considered for both types of beams. Manufacturers provided a price of $0.80/lb. Glue comes in a two-part mixture, a resin and a hardener, and is applied according to a spread-rate. The spread-rate is dependent upon the proportion of each part used in the mixture as well as the properties of the substance to which the glue is being applied. A spread rate of 60lbs/square foot is used in the analysis. Again, because all lamstock consists of nominal 2x6 inches, one square foot is equal to one linear foot. A charge of 10% is added to the glue required for face gluing to account for finger-jointing and loss due to waste. Therefore, each linear foot of lamstock incurs a glue cost of $0.0528.

Labor

The labor requirements and their associated costs for the non-reinforced southern pine beam plant are presented in Table 9. Through conversations with personnel at laminating plants and

Table 8. FRP-reinforced hemlock lamstock beam costs for $5^1/_8$-inch-wide beams at $0.44/lnft for hemlock and $1.25/lnft for FRP.

Strng (psi)	MOE (e)	Depth (inches)	Num Wood Lams	Num FRP Lams	Cost per lnft
1600	1.4	12	8	1	$4.77
1600	1.4	24	16	2	$9.54
1600	1.4	36	24	3	$14.31
1600	1.4	48	32	4	$19.08
2000	1.5	12	8	2	$6.02
2000	1.5	24	16	4	$12.04
2000	1.5	36	24	6	$18.06
2000	1.5	48	32	8	$24.08
2400	1.7	12	8	3	$7.27
2400	1.7	24	16	6	$14.54
2400	1.7	36	24	9	$21.81
2400	1.7	48	32	12	$29.08
2600	1.8	12	8	4	$8.52
2600	1.8	24	16	8	$17.04
2600	1.8	36	24	12	$25.56
2600	1.8	48	31	16	$33.64
3000	1.9	12	8	5	$9.77
3000	1.9	24	16	10	$19.54
3000	1.9	36	23	15	$28.87
3000	1.9	48	31	20	$38.64

lumber mills, it was learned that the highest paid individual in the plant, aside from plant manager and quality control (QC) supervisor, is the grader because of the high level of skill required. The next most skilled employee is the finger-joint operator due to the precision required to operate the saw properly to avoid improperly cut finger joints that can backlog the entire system.

Employees are paid 150% of their hourly wages for the eight hours they work over 40 each week. The labor requirements for the FRP-reinforced glulam facility are not expected to differ greatly from the non-reinforced beam facility because it is assumed the reinforced beam facility will be subjected to the same quality control codes as the non-reinforced beam plant. However, FRP-reinforced beams are designed with random placement of #2 and better hemlock, so it is not necessary to regrade the lumber. The grading stage is still required to eliminate moist material and

Table 9. Labor costs for non-reinforced southern pine beams.

Position	Num Worker	Wage/ hour	Hour/ week	Annual comp
Grading				
Forklift Operator	1	$ 9.00	48	$ 28,080
Grader	1	$ 12.00	48	$ 37,440
Laborer	1	$ 8.00	48	$ 24,960
Finger Jointing				
Finger Joint Operator	1	$ 11.00	48	$ 34,320
Laborers	1	$ 8.00	48	$ 24,960
Gluing				
Meter Mix Glue Operator	1	$ 10.00	48	$ 31,200
Laborers	7	$ 8.00	48	$ 24,960
Finishing				
Skilled Carpenter	1	$ 10.00	48	$ 31,200
Laborers	9	$ 8.00	48	$ 24,960
Forklift Operator	1	$ 9.00	48	$ 28,080
Shipping Manager	1	$ 10.00	48	$ 31,320
Indirect Labor				
Quality Control Supervisor	1	$ 15.00	48	$ 46,800
Plant Manager	1	$ 18.00	48	$ 56,160

defects, but the grader can be replaced with an unskilled laborer at a lower cost. No additional labor is included for handling the FRP, over and above time spent on handling the wood laminations. While recent test runs of producing FRP-reinforced beams have utilized excess labor time, it is assumed that handling the FRP will not incur additional labor for large-scale production. The difference in labor is shown in Table 10, where labor costs for the grading stage of the non-reinforced southern pine beam plant are the labor costs for the grading stage of the FRP-reinforced hemlock beam plant.

Equipment

The equipment requirements for the non-reinforced southern pine beam facility are listed in Table 11. The unit cost for each item is found by amortizing the acquisition cost adjusted for the 10% salvage value, dividing this by the production capacity and adding an annual repair and maintenance costs of 2% of the original cost.

Notice that the grading stage includes a machine stress rating (MSR) grading system. This machine is necessary to identify the highest quality lamstock used to make the 3000-psi beams. It is not

Table 10. Labor costs for grading stage of FRP-reinforced hemlock beams.

Position	Num Worker	Wage/ hour	Hour/ week	Annual comp
Grading				
Forklift Operator	1	$ 9.00	48	$ 28,080
Laborer	2	$ 8.00	48	$ 49,920

Table 11. Equipment costs for non-reinforced southern pine beams.

Item	Units	Price/Unit	Cost
Grading Forklift	1	$23,450	$23,450
Lumber conveyer system	1	$75,953	$80,132
MSR grader system	1	$171,250	$171,250
Defecting saw system	1	$120,700	$120,700
Moisture detector-linear flow system	1	$8,500	$8,500
Finger jointing line			
Finger joint system	1	$765,000	$765,000
Proof loader	1	$38,000	$38,000
18" planer and cutterhead	1	$101,900	$101,900
Beam gluing line			
Meter mix glue system	1	$95,095	$95,095
Cold clamp rack	1	$26,441	$26,441
Overhead cranes	2	$10,500	$21,000
Finishing			
Beam surfacer system	1	$223,000	$223,000
Overhead cranes	6	$10,500	$ 63,000
Band saw	2	$13,900	$27,800
Forklift	1	$23,450	$23,450
Indirect			
Quality control equipment	NA	$50,000	$50,000
Shop equipment	NA	$100,000	$100,000
Maintenance equipment	NA	$50,000	$50,000

possible to visually grade material for the specific properties required by AITC 117-93 for that strength beam. Lamstock used in all other strength beams can be visually graded. Through conversations with the only laminator that produces 3000-psi beams, it was confirmed that the charge for this machine should only apply to the 3000-psi beams. Therefore, unit costs for the MSR equipment are determined by dividing the amortized cost by 1,000,000 lnft rather than 5,000,000 lnft, and this cost is only applied to 3000-psi non-reinforced beams.

Because the equipment in both plants is assumed to be restricted by AITC 200-92, changes in finger-jointing and testing equipment are not permitted. Finger-jointing equipment is restricted to ensure the tensile strength of the joints. While this may not be necessary in FRP beams because the FRP absorbs the majority of tensile stress endured by a beam, codes prohibit changes in finger-jointing. One item that may be unnecessary but is required is the defecting saw, which removes knots that affect finger-joint strength. Further, the finger-joint line itself may be replaced by a different type of joint system, such as a scarf joint, which provides lower tensile strength but may be a less expensive type of joint. Similarly, quality control testing will remain unchanged until the codes are changed. However, such changes require more evidence demonstrating strength properties and reliability of the FRP beams, and the optimal production process design for the beams.

The MSR grading system is not necessary for the production of 3000-psi FRP-reinforced beams. Since no additional grading is necessary for FRP-reinforced beams, the MSR equipment is not needed. The change in equipment costs for the grading stage of the FRP-reinforced beam production process is shown in Table 12.

Table 12. Equipment costs for grading stage of FRP-reinforced hemlock beams.

Item	Units	Price/Unit	Cost
Grading Forklift	1	$ 23,450	$ 23,450
Lumber transfer system	1	$ 75,953	$ 80,132
Defecting saw system	1	$ 120,700	$ 120,700
Moisture detector system	1	$ 8,500	$ 8,500

RESULTS

This bulletin is concerned with identifying the cost competitiveness of producing FRP-reinforced glulam beams. Using the production cost model outlined in the previous chapter, the unit costs of producing FRP-reinforced hemlock beams and non-reinforced southern pine beams have been identified. Cost estimates that assume the medium inventory price adjustment as well as the current lumber and FRP prices define the base case scenario. The key findings from the base case are discussed, and the results from a sensitivity analysis on inventory costs, the relative difference in price between the two wood species, and the price of FRP are presented. For a full presentation of the results see Appendix B.

Base Case Results

The results indicate that the production of FRP-reinforced beams is only cost competitive for the two deepest and strongest beams under consideration. Table 13 reports the cost difference for FRP-reinforced and non-reinforced beams. These beams appear in bold type. They have a bending strength of 3000 psi and are 36 inches and 48 inches deep. For all other beams, the production of non-reinforced southern pine beams provides the lower cost production alternative.

These results indicate that given current price conditions and the medium inventory price adjustment, the added cost of FRP in the production of glulam beams will be absorbed by cost savings on materials for high-performance beams only. As beam strength increases, the cost of southern pine lamstock also increases according to the inventory distribution costs. It becomes increasingly more expensive than hemlock lamstock, which maintains a constant price. For less deep beams (i.e., 12 inches and 24 inches), there

Table 13. Difference in cost of 3000-psi FRP-reinforced and non-reinforced glulam beams under the base case.

Beam depth (inches)	Cost difference $\text{cost}_{\text{frp beam}} - \text{cost}_{\text{non frp beam}}$
12	$ 2.93
24	$ 5.86
36	**$ (2.41)**
48	**$ (3.05)**

Negative number in parentheses imply cost advantage for FRP-reinforced beams.

are insufficient laminations to create a cost savings large enough to offset the added expense of the FRP. However, in the deepest beams, there are enough laminations so that the sum of the savings on each one offsets the added expense of the FRP. Given the assumptions of the base case, the production of 3000-psi beams that are 36 inches and 48 inches deep are \$2.41/lnft and \$3.05/lnft less costly to produce using FRP-reinforced hemlock than non-reinforced southern pine. Expressed as a percentage, the differences are 6% of the total unit cost of each FRP-reinforced beam.

Sensitivity Analysis

Sensitivity analysis was used to account for uncertainty in cost estimates. Based on the assumptions identified in previous sections, lumber price, inventory cost, and the FRP price were varied to identify the effects on the relative cost advantage of each beam. This provided 26 additional scenarios. The cost parameters used in the sensitivity analysis are summarized in Table 14.

The sensitivity analysis shows that the competitive position of FRP-reinforced glulam beams is sensitive to changes in material cost parameters. While none of the scenarios provided 1600-, 2000-, or 2400-psi FRP reinforced glulam beams with a competitive advantage, changing the assumptions about cost parameters does effect the competitive position of both 2600- and 3000-psi FRP-reinforced glulams. This section identifies some of the key findings of the sensitivity analysis. Appendix B contains the cost differences for beams that show a competitive advantage, which are discussed in this section.

The most significant changes in the competitive position of FRP-reinforced glulam result from changing the relative position of lumber prices. In only three of the nine scenarios that assume equal lumber prices are any of the FRP-reinforced beams cost competitive. While the results are responsive to changes in the

Table 14. Assumptions on cost parameters used for sensitivity analysis

Inventory price adjustment	Lumber prices	FRP price
Medium*	$P_{SP} = 1.3P_{Hem}$*	Current*
Low	$P_{SP} = P_{Hem}$	80% of Current
High	$P_{SP}=1.6P_{Hem}$	60% of Current

* = Assumptions used for base case.

other two cost parameters, there must be substantial changes in the other two costs to provide FRP-reinforced beams with a competitive position. When lumber prices are equal, given the medium inventory apportionment, FRP prices must fall to 60% of their current level to provide any FRP beams with a competitive advantage. Assuming the high inventory apportionment, FRP prices must still fall to 80% of their current level.

Conversely, if the relative hemlock price drops to $P_{sp} = 1.6P_{Hem}$, FRP-reinforced beams always have a competitive advantage for 3000-psi 36- and 48-inch-deep beams. Again these results are sensitive to changes in the other two cost parameters. Given reductions in the price of FRP and either the medium or high inventory cost apportionment, both 3000-psi and 2600-psi beams have a competitive advantage. Assuming the medium inventory apportionment and a 40% reduction in FRP price, all 3000- and 2600-psi beams become competitive. Further, assuming the high inventory cost apportionment, all 3000- and 2600-psi beams are competitive at both 40% and 20% reduction in FRP price.

Changing the FRP price alone does not alter the competitive position of any beams without altering one of the other cost parameters. Decreasing the price of FRP from $1.25/lnft to $0.75/lnft does strengthen the cost advantage of both beams that are found to be competitive. In the base case cost savings is only 6% of the total unit cost of each beam, but with 60% of the FRP price the cost savings is 35% of the total unit cost of the either beam.

The effects of altering the distribution of inventory costs are also substantial. If the low inventory cost distribution is appropriate, then substantial cost savings in the production of FRP-reinforced beams only result if the difference in lumber price increases and FRP prices decrease. Relative to the other inventory distributions, the high inventory price adjustment attributes the highest inventory costs to southern pine lamstock used in making the strongest beams and the lowest cost to lamstock used to make low strength beams. This provides FRP-reinforced glulam with the most favorable cost position in the production of high-strength beams. Consequently, cost savings on high-strength beams are the strongest using the high inventory price adjustment.

The most favorable scenarios for the production of FRP-reinforced beams assume the high inventory price adjustment and lowest relative hemlock price. Assuming the current price of FRP, the cost savings for either 36-inch and 48-inch 3000-psi beams amounts to roughly 46% of their total unit costs. Assuming 60% of current FRP price, the savings on 2600-psi beams amount to roughly 16% on 2- ,3-, 4-feet-deep beams. Savings on the 3000-psi beams amount to 30% for the one and two foot deep beams and 86% for the three and four foot deep beams.

CONCLUSION

The analysis demonstrates that ability to produce FRP-reinforced glulam beams with production cost advantages over non-reinforced glulam beams is limited to relatively deep beams with high bending strength. Since wood used in high-strength beams is more difficult to procure, it costs more. Savings on each wood lamination used in FRP-reinforced beams are greater for these high-strength beams. This offsets the added cost of FRP in the deeper beams, providing the stronger FRP-reinforced beams with a production cost advantage. Therefore, the FRP appears to offer an alternative to high-strength tension laminations used in these beams. However, it is unlikely that a product line consisting of only 3000-psi glulam beams that are 36 inches and 48 inches deep would constitute a large enough production volume to justify maintaining a production facility. Moreover, the competitive position of these beams is sensitive to current cost conditions. Therefore, there is insufficient evidence to support the production of FRP-reinforced beams in Maine under current market conditions.

The findings indicate that changes in cost parameters could hinder or help the potential of FRP-reinforced beams in the future depending upon the actual changes that occur. The relative price of materials for the two beams impacts the cost advantage of high-strength FRP-reinforced beams considerably. First, the price of lumber used to make FRP-reinforced beams relative to the price of lumber used in non-reinforced beams significantly influences the competitiveness of FRP-reinforced beams. Moreover, these results are sensitive to the price of FRP and inventory management costs.

Using a less expensive wood fiber to produce FRP-reinforced beams would increase the competitiveness of this product. This would be particularly true if there was a substantial decrease in the price of FRP and/or if inventory costs increase for quality laminations. A fall in the price of FRP could result from competitive market conditions. Increased inventory costs would result from the relative difficulty in procuring high-quality laminations for non-reinforced beams.

While this bulletin does provide a preliminary analysis of the competitive position of FRP-reinforced beams, further research is necessary. First, due to time restrictions, cost savings that may result from the increased strength attributes of FRP-reinforced beams were not considered. Second, the optimal wood fiber source for FRP beams was not explored. Third, the possibility grading the wood resource to optimize the strength properties of both the wood and FRP was not examined. Finally, this bulletin did not take into account market considerations to identify the appropriate market for this product. Further research is necessary to explore these issues.

REFERENCES

American Institute of Timber Construction (AITC). 1993. AITC 117-93: Standard Specifications for Structural Glued Laminated Timber of Softwood Species. Englewood, CO: AITC.

American Institute of Timber Construction (AITC). 1996. AITC 200-92: Inspection Manual for Structural Glued Laminated Timber. Englewood, CO, AITC.

American Plywood Association (APA). 1995. Glulams: Product and Application Guide. Tacoma, WA: American Wood Systems.

Casler, G.L., B.L. Anderson, and R.D. Aplin. 1984. *Capital Investment Analysis Using Discounted Cash Flows,* 3rd ed. Columbus, OH: Grid Publishing, Inc.

Dagher, H.J., T.E. Kimball, S.M. Shaler, and B. Abdel-Madid. 1996. Effects of FRP Reinforcement on Low Grade Eastern Hemlock Glulams. in *Proceedings, National Conference on Wood in Transportation Structures*. Madison, WI: October 23–25, 1996: 207–14.

Maine Department of Labor. 1994. Census of Maine Manufactures.? Augusta, ME: Bureau of Labor Standards. 120-40.

Price, W., L.C. Irland, R.B. Anderson, A. Potter, M. Rivard, and W. Skinner. 1996. Review of Commercialization opportunities for Fiber Reinforcement in Glulam Beams and Patent and Licensing Options. Augusta, ME: Report to Maine Science and Technology Foundation.

Random Lengths. 1998a. *1997 Yearbook*. Salem, MA: Random Lengths Publications, Inc.

Random Lengths. 1998b. The Weekly Price Report on North American Forest Product Markets. Salem, MA: Random Lengths Publications, Inc.

Sammet, L.L., and B.C. French. 1953. Economic-engineering methods in marketing research. *J. Farm Economics*: 35(5): 924–30.

APPENDIX A: GLOSSARY

American Institute of Timber Construction (AITC)—national trade association for glue-laminated timber beams.

American Plywood Association (APA)—national trade association for engineered wood products.

beam core—zone of a glulam beams that is subjected to least stress and contains the lowest quality lamstock.

board feet (bdft)—a measure that equal to the amount of wood contained in a section that is 12 inches wide by 12 inches long by 1 inch thick.

brittle—a physical property of a solid substance that causes it to snap or break rapidly once its maximum stress is reached.

compression—a stress characterized by forcing particles of matter together.

deflection—the vertical distance a material moves when subjected to a load from above.

depreciation—the reduction in the value of a firm's capital assets through time.

dimension lumber—lumber cut to standard dimensions such a 2 inches by 6 inches; framing lumber.

ductile—a physical property of a solid substance that causes it to react plastically when subjected to a stress; elastic.

face-gluing—gluing together of individual laminations of a glulam beam.

finger-joints—joints used in a glulam beam to combine individual pieces of lamstock to produce a lamination.

fiber-reinforced polymer (FRP)—polymer (fiberglass) that is reinforced with either glass or carbon fibers.

glass fibers—tiny pieces of glass used to reinforce fiberglass.

inner compression zone—the zone of a glulam beam subjected to compressive stress, but less intensely than the outer compression zone.

inner tension zone—the zone of a glulam beam subjected to tensile stress, but less intensely than the outer tension zone.

laminating stock—lumber used in making glulam beams.

lamination—a long plank that constitutes one layer of a glulam beam.

laminator—a glulam manufacturer.

lay-up—(n.) the design of a glulam beam (v.) the process of gluing together laminations in a glulam beam.

linear foot (lnft)—a measure that is equal to a one foot long section of any width or depth.

machine-stress-rating machine (MSR)—a machine used to mechanically grade lumber.

neutral axis—the section of a glulam beam that receives offsetting compressive and tensile stresses. It is also the shear plane of the beam.

outer compression zone—the zone of a glulam beam subjected to the greatest compressive stress.

outer tension zone—the zone of a glulam beam subjected to the greatest tensile stress.

phenolic-resin—resin used in producing FRP.

phenol-resorcinol—glue used to make glulam beams.

tension—stress characterized by the pulling apart of fibers.

APPENDIX B—COST ESTIMATES

Table B1. Cost per lnft of producing FRP-reinforced beams and non-reinforced glulam beams (base case).

Strng (psi)	Depth (inch)	Cost of Frp beams	Cost of non-reinforced beams
1600	12	$6.96	$4.36
1600	24	$13.93	$8.72
1600	36	$20.89	$13.08
1600	48	$27.85	$17.44
2000	12	$8.27	$3.17
2000	24	$16.53	$6.34
2000	36	$24.80	$9.52
2000	48	$33.06	$12.69
2400	12	$9.57	$6.74
2400	24	$19.14	$13.47
2400	36	$28.70	$20.21
2400	48	$38.27	$26.94
2600	12	$10.87	$7.92
2600	24	$21.74	$15.85
2600	36	$32.61	$23.77
2600	48	$42.97	$31.70
3000	12	$12.17	$9.24
3000	24	$24.35	$18.49
3000	36	$36.01	$38.42
3000	48	$48.18	$51.23

Table B2. Cost per lnft of producing FRP-reinforced beams minus cost per lnft of producing non-reinforced glulam beams (medium inventory price adjustment).

Lumber Cost	Beam Strng (psi)	Beam Depth (inch)	Current FRP Price	80% Current FRP Price	60% Current FRP Price
$P_{SP} = 1.3P_{Hem}$	3000	12	$2.93	$1.68	$0.43
	3000	24	$5.86	$3.36	$0.86
	3000	36	$(2.41)	$(6.16)	$(9.91)
	3000	48	$(3.05)	$(8.05)	$(13.05)
$P_{SP} = P_{Hem}$	3000	12	$4.51	$3.26	$1.84
	3000	24	$9.03	$6.53	$3.68
	3000	36	$4.71	$0.96	$(3.29)
	3000	48	$6.46	$1.46	$(4.23)
$P_{SP} = 1.6P_{Hem}$	2600	12	$2.09	$1.52	$(0.66)
	2600	24	$4.18	$3.03	$(1.32)
	2600	36	$6.27	$4.55	$(1.98)
	2600	48	$7.87	$5.55	$(3.13)
	3000	12	$1.84	$1.21	$(1.46)
	3000	24	$3.68	$2.43	$(2.92)
	3000	36	$(3.29)	$(10.14)	$(18.14)
	3000	48	$(4.23)	$(13.34)	$(24.03)

Note: Negative values in parentheses.

Table B3. Cost per lnft of producing 3000-psi FRP-reinforced beams minus cost per lnft of roducing non-reinforced glulam beams (low inventory price adjustment).

Lumber Cost	Beam Depth (inch)	Current FRP Price	80% Current FRP Price	60% Current FRP Price
$P_{SP} = 1.3P_{Hem}$	12	$4.12	$2.87	$1.62
	24	$8.24	$5.74	$3.24
	36	$2.93	$(0.82)	$(4.57)
	48	$4.08	$(0.92)	$(5.92)
$P_{SP} = 1.6P_{Hem}$	12	$2.69	$1.44	$0.19
	24	$5.38	$2.88	$0.38
	36	$(3.50)	$(7.25)	$(11.00)
	48	$(4.50)	$(9.50)	$(14.50)

Note: Negative values in parentheses.

Table B4. Cost per lnft of producing FRP-reinforced beams minus the cost per lnft of producing non-reinforced glulam beams (high inventory price adjustment).

Lumber Cost	Beam Strng (psi)	Beam Depth (inch)	Current FRP Price	80% Current FRP Price	60% Current FRP Price
$P_{SP} = 1.3P_{Hem}$	3000	12	$1.74	$0.49	$(0.76)
	3000	24	$3.49	$0.99	$(1.51)
	3000	36	$(7.76)	$(11.51)	$(15.25)
	3000	48	$(10.18)	$(15.18)	$(20.18)
$P_{SP} = P_{Hem}$	3000	12	$3.59	$2.34	$0.91
	3000	24	$7.18	$4.68	$1.83
	3000	36	$0.56	$(3.19)	$(7.45)
	3000	48	$0.91	$(4.09)	$(9.77)
$P_{SP} = 1.6P_{Hem}$	2600	12	$0.78	$(0.22)	$(1.40)
	2600	24	$1.56	$(0.44)	$(2.79)
	2600	36	$2.34	$(0.66)	$(4.19)
	2600	48	$2.61	$(1.39)	$(6.08)
	3000	12	$0.26	$(1.51)	$(2.94)
	3000	24	$0.52	$(3.02)	$(5.87)
	3000	36	$(16.77)	$(20.52)	$(24.78)
	3000	48	$(22.19)	$(27.19)	$(32.87)