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Novel type engineered structural beams from pine lumber

Maisaa Kakeh

NOVEL TYPE ENGINEERED STRUCTURAL BEAMS FROM PINE LUMBER

By

Maisaa Kakeh

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NOVEL TYPE ENGINEERED STRUCTURAL BEAMS FROM PINE LUMBER

By

Maisaa Kakeh

Approved

Rubin Shmulsky
Professor of Forest Products
Department Head/Graduate Coordinator
Director of Dissertation

Sheldon Q. Shi
Assistant professor of Forest Products
Committee Member

R. Dan Seale
Professor of Forest Products
Committee Member

Donald L. Grebner
Associate professor of Forestry
Committee Member

George M. Hopper
Dean of College of Forest Resources

Name: Maisaa Kakeh

Date of Degree: August 7, 2010

Institution: Mississippi State University

Major Field: Forest Resources

Major Professor: Dr. Rubin Shmulsky

Title of Study: NOVEL TYPE ENGINEERED STRUCTURAL BEAMS FROM PINE LUMBER

Pages in Study: 95

Candidate for Degree of Doctor of Philosophy.

The intersection of decreasing resource size and increasing population and its associated demand creates a pressing need to develop products that act as alternatives to solid sawn lumber. Engineered composite lumber is one such alternative.

The product described herein utilizes a modified form of sawn lumber as the raw material.

The objective of this research was to manufacture, mechanically test, and evaluate a novel type of engineered lumber. Non destructive evaluation of raw materials and finished beams, and final mechanical testing to determine mean strength and stiffness values as per ASTM 5456 were used. The mechanical property data was converted into design values for fiber stress in bending (F_b) and stiffness (MOE). These design values was compared to those published by the U.S. (NDS) for wood construction. Pine logs were reduced into cants and further processed into matched symmetrical trapezoids. Symmetrical trapezoids were then non-destructively evaluated via E-computer and Director, and sorted by results. Next, the sorted trapezoids were matched into pairs and assembled into bowtie beams. Polyvinyl acetate adhesive was used throughout. Stiffness of the manufactured beams was nondestructively evaluated too. Then the beams were mechanically tested.

The information from the E-computer was correlated to the strength and stiffness for each beam. The design strength and stiffness was compared to the values of sections of equivalent depth and maximum width as shown in the NDS. Also, non destructive test values were compared and correlated to those from the destructive tests. Finally, the design strength and stiffness values were respectively multiplied by the sectional area or the moment of inertia. This produced a strength efficiency factor and a stiffness efficiency factor. These factors were compared to factors derived from multiplying the design strength or design stiffness values (from the NDS) times the area or the moment of inertia of a rectangular section of equivalent depth and maximum width. It is found that the mechanically efficient bowtie section produced an increased strength and stiffness efficiency as compared to that of solid sawn material.

Key words: beams, non-destructive test, engineered lumber.

DEDICATION

I would like to dedicate this research to my parents in my country, Syria, and my kids, Nour, Mohammed, Bayan, and Shaimaa, and all my friends who I have met in U.S.A.

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I would like to express my sincere gratitude to all people who had been helping and assisting me to perform this dissertation.

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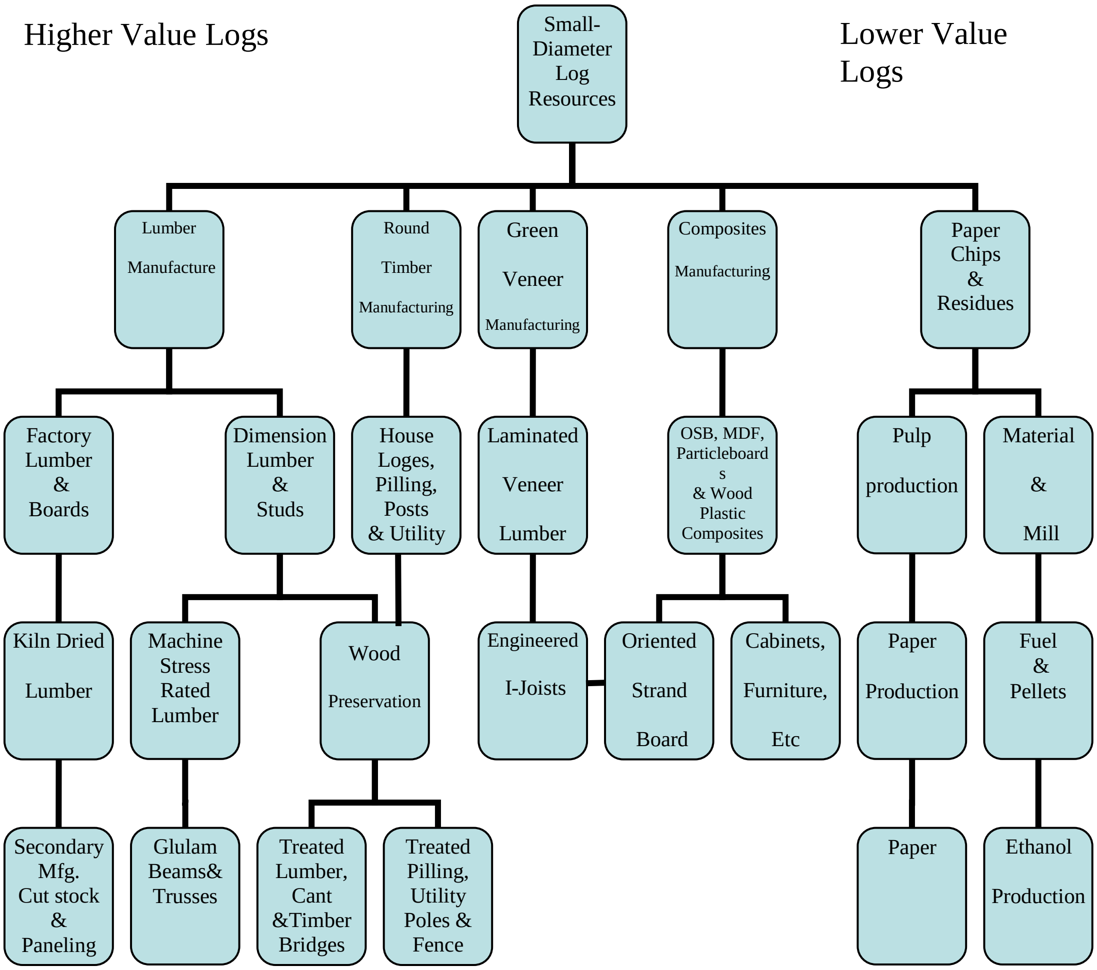
CHAPTER 1

INTRODUCTION

During the past several decades, the average tree diameter for commercial softwood sawlogs going into production has declined. Tree rotation periods are being minimized in an effort to accelerate income production for timber owners. This trend often causes trees to be harvested at younger ages and associated smaller diameters. Harvesting trees at relatively young ages can provide a large amount of woody biomass during a short time as a renewable resource for wood industries. Trees with larger diameters however can be used for a larger number of industrial choices as compared to smaller diameter trees. Harvesting small diameter trees, such as via a plantation thinning operation, is a common silivicultural practice. Thinning may also reduce the risk of forest fire. It also releases the diameter growth of the rest of the trees in the forest. This allows these residual trees to grow rapidly to bigger diameters. Demand for long, straight, strong, and stiff structural material from wood continues. Given the economic pressures on plantation forests, it is imperative that new markets be developed for small diameter timber. Many wood products can be manufactured from small diameter logs (Figure 1.1). Despite cyclical economic events, the demand and consumption of these wood products continues to increase annually. This demand is driven by the increasing population, especially in the U.S. (Table 1.1).



. Figure 1.1 Potential products for small- diameter utilization (Dramm, 1999)

Table 1.1 United States' population growth by decade

Year	Population (million)
1900-1910	16.3
1910-1920	14.1
1920-1930	16.6
1930-1940	9.00
1940-1950	20.1
1950-1960	28.4
1960-1970	24.2
1970-1980	22.2
1980-1990	22.2
1990-2000	32.7

(Note). Source of the table is NumbersUSA.com

The intersection of decreasing resource size (not necessarily total volume) and increasing population and its associated demand creates a pressing need to develop products that act as alternatives to solid sawn lumber. In one of FAO report in 1999, it was expected that the increasing demand for industrial round wood at 2010 in developed countries will be at a rate of about 1.7% per year because of the technological improvement in wood processing to increase the efficiency of using raw material (Youngquist & Hamilton, 1999) Figure 1.2.

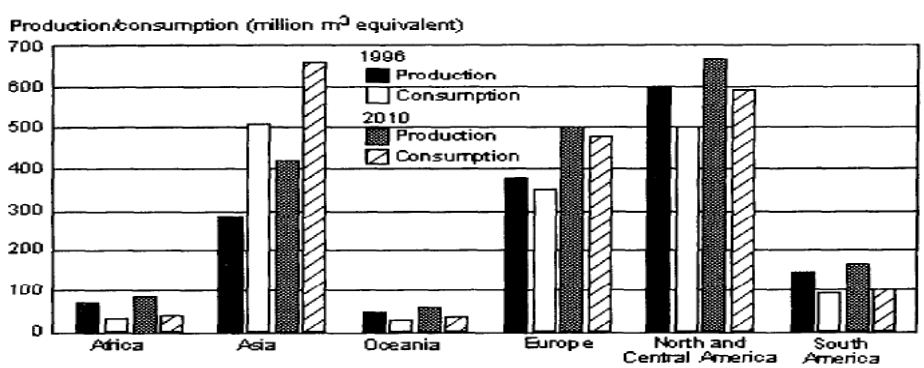


Figure 1.2 Forecast industrial round wood production and product consumption in 1996 and 2010 (From FAO 1999)

Howard reported in the USDA, U.S. Forest Products Annual Market for 2004-2008 and 2005-2009 the economic indicators for wood consumptions during 2003-2007 and 2005-2009 (Table 1.2).

Table 1.2 Selected U.S. economic indicators, 2005–2009

Indicator	Actual						Forecast
	2003	2004	2005	2006	2007	2008	2009
Gross domestic product (billion 2000 dollars)	10,301	11,704	11,049	11,415	11,524	11,652	11,547
New housing starts (thousand units)	1.848	1.956	2.068	1.801	1.046	0.622	0.718
Mobile home shipments (thousand units)	131	131	147	117	96	82	85
Nonresidential investment in structures (billion 2000 dollars)	243.5	248.7	251.5	298.1	304.6	338.8	325.7
Total industrial production (Index: 2002 = 100)	100.6	104.7	108.2	107.5	111.4	109.6	107.4
Furniture and related products (Index: 2002 = 100)	101.3	101.9	100.7	104.7	101	90.4	88.4
Paper products (Index: 2002 = 100)	102.3	104.8	105.4	101.6	95.9	92.1	90.2

(Note).Source of the table is USDA. U.S. Forest Products Annual Market Review and Prospects, 2004-2008

Table 1.3 shows the global forest production and consumption as it was reported by FAO 1999:

Table 1.3 Current and forecast global forest production/ consumption by product category, 1996 and 2010

Product	Production/ Consumption		Total growth 1996-2010%	Annual growth 1996-2010%
	1996	2010		
Industrial roundwood (million m^3)	1,490	1,872	26	1.7
Sawnwood (million m^3)	430	501	17	1.1
Wood-based panels (million m^3)	149	180	20	1.3
Pulp (million tones)	179	208	16	1.1
Paper/paperboard (million tons)	284	394	39	2.4

Engineered composite lumber is one such alternative. It can provide relatively long-span high strength and stiffness structural products from a relatively underutilized forest resource. Engineered composite products increase the efficiency of using small diameter logs as a raw material. These products often have more flexibility with respect to the type and quality of raw material as compared to solid lumber.

Engineered composite lumber seeks to retain and improve many of the desirable properties of wood as a structural material. It touts the environmental sustainability and energy efficiency of all forest products, can produce higher mechanical design values, and generally incorporates lower value raw material. Additionally, engineered composite lumber improves product performance, remains cost competitive, and extends the forest resource (Youngs & Hammett, 2001) since these products can realize high production yield from small diameter logs. Tables 1.4 and 1.5 display the production and the consumption of engineered composite lumber in 1999.

Table 1.4 Production statistics for selected engineered lumber products, 1999

Wood Products	North America	Percent share	Outside North America	Total
Glulam (million board feet)	331	30%	770	1,101
I-joists (million board feet)	895	95	61	956
Laminated veneer lumber (million board feet)	52	86	8	60

(Note). Source of the table is Schuler and Adair (2000)

Table 1.5 Consumption of sawnwood, wood panels, and engineered lumber products,1999

Wood Products	Sawnwood (billion cubic feet)	Wood panels(billion cubic feet)	Engineered lumber products(billion cubic feet)
Europe	3.67	1.83	0.05
North America	6.35	1.95	0.14
Japan(1998)	1.15	0.43	0.04

(Note). Source of the table is ECE-FAO (2000): Russ Taylor and Associates (2000).

During 2004-2007 and 2005- 2009, USDA reported the production and consumption for wood products during 2005- 2009. The prospects of wood products production and consumption are displayed in table 1.6.

Table 1.6 Wood products production and consumption in U.S.A as in U.S Forest Products Annual Market Review and Prospects

Wood products	2005 Production	2005 Consumption	2006 Production	2006 Consumption	2007 Production
Sawn softwood	69,187	125,189	65,549	117,078	59,511
Coniferous logs	165,976	161,486	157,259	152,271	163,748
Sawn hardwood	27,355	26,468	25,986	24,750	24,811
Hardwood logs	57,254	55,189	56,593	54,640	56,883
Coniferous plywood	12,682	14,461	11,884	13,144	10,835
Non-coniferous plywood	1,767	5,543	1,602	5,912	1,566
OSB	13,262	24,592	13,240	23,689	13,065
Particleboard	7,276	8,466	7,414	8,549	6,271
MDF	3,257	4,499	3,400	4,313	3,343
Insulation board	2,755	2,914	2,755	2,914	2,755
Roundwood pulpwood	144,555	142,730	145,567	143,730	142,230
Hardboard	1,282	2,377	1,131	2,183	977

Wood products	2007 Consumption	2008 Production	2008 Consumption	2009 Production	2009 Consumption
Sawn softwood	88,929	49,438	69,255	42,319	62,147
Coniferous logs	157,915	137,062	131,008	135,716	129,386
Sawn hardwood	23,680	23,454	22,077	15,062	13,783
Hardwood logs	54,940	51,730	49,907	50,002	48,240
Coniferous plywood	11,320	9,060	9,182	8,608	8,661
Non-coniferous plywood	4,846	1,218	3,427	1,198	3,229
OSB	18,957	11,508	14,395	10,907	13,563
Particleboard	6,943	5,161	5,618	4,865	5,321
MDF	4,130	3,021	3,390	3,110	3,572
Insulation board	2,914	2,755	2,914	2,600	2,704
Roundwood pulpwood	140,349	135,062	133,083	133,077	131,085
Hardboard	1,802	860	1,237	849	1,265

(Note). Source of the table is USDA. U.S. Forest Products Annual Market Review and Prospects, 2004-2008 and 2005-2009

There is a wide variety of types of engineered lumber. These range from glue laminated timber, which utilizes sawn lumber as a raw material, to medium density fiber board which utilizes refined fiber as the raw material. Structural composite lumber (SCL) is one of these products. SCL acts as a sawn lumber substitute. It includes laminated veneer lumber (LVL), parallel strand lumber (PSL), and oriented strand lumber (OSL). In addition to some other products such as, I-joists, glue laminated timber (Glulam), machine stress rated lumber (MSR), open web metal plate wood trusses, and finger-joined structural lumber (Nelson, 1997).

Background

In general, larger raw material forms require less technological processing for manufacture of engineered lumber while smaller raw material elements require more processing technology. Engineered lumber is particularly useful in beam applications.

A beam can be defined as a mechanical device in which the ratio of length to breadth and depth is relatively high (Brown et al, 1952) and which is used to bear bending or “flexural” loads. Among other materials, beams can be made from sawn lumber or engineered composite lumber such as I-joists and glue laminated lumber.

The product described herein utilizes a modified form of sawn pine lumber as the raw material. As such, should this engineered product prove commercially viable, a manufacturing facility could likely be constructed with a relatively small amount of capital and processing will require only limited amounts of technology. This product is a type of an engineered composite lumber. Due to its symmetrical double-trapezoidal shape, it is colloquially called a “Bowtie-Beam”. For manufacture, symmetrical trapezoids per MSU invention disclosure titled Structural Bowtie Beams authored by Rubin Shmulsky, are glued together. The result is a cross section that is widest at the extreme fibers (beam edges or flanges) and narrowest at the center line or neutral axis.

Loblolly pine (*Pinus taeda*.L) is the raw material that is used in this research, however other tree species can readily be used. Loblolly pine is a native species in North America and it is the most widely planted forestry species in the world (Frederick et al 2008). The rotation time for loblolly pine saw timber application is often 23 years (Hinchee et al, 2007). Loblolly pine is intensively managed in pine plantations, where thinning, fertilization and prescribed fires have all shown improvements in the growth and volume of the stand. Loblolly pine pulpwood and saw timber products can be grown in relatively short rotations, compared to other pine species, under these intensive regimes (A southern pine management guide, 2004).

In 1990, one-third of the South's pine timberland consisted of plantations. These plantations are projected to comprise 50% of the total pine harvest volume by the year 2000. As a result, increasing amounts of lumber are being cut each year from young, small-diameter trees (Wu & Smith, 1997).

Residential building construction is the single biggest market for structural pine lumber. The housing industry in USA is facing increasing competition from domestic sources, and is adopting many organizations strategies, like Just in Time (JIT) supply and Design for Manufacture and Assembly (DFMA). The adaptation of these types of waste reducing and cost saving programs improves the productivity and the quality of the production (O'Brien et al., 2000). The advances in the housing industry include the use engineered lumber products instead of solid wood.

Purpose

The objective of this research was to manufacture and evaluate a new type of engineered lumber beams, by using minimally processed sawn lumber. This raw material and process requires minimal processing technology. Once produced, this novel type of lumber was mechanically evaluated. Key variables were measured and or documented throughout. These include secondary manufacturing, non destructive evaluation of raw materials and finished beams, gluing characteristics, and final mechanical testing to determine mean strength and stiffness values as per ASTM 5456. The mechanical property data was then converted into design values for fiber stress in bending (Fb) and stiffness (MOE). These design values were then compared to those published by the U.S. National Design Specification (NDS) for wood construction. As such, this intended product of this work is research and development of a new engineered composite wood product from initial manufacture, through testing and evaluation, through final comparison to solid sawn material of the same species group. The product manufactured herein is environmentally friendly with respect to both tree production and manufacturing efficiency.

CHAPTER 2

REVIEW OF THE LITERATURE

Engineered wood composite

During the past 300 years, the population of the world has increased approximately 10-fold. During the 20th century the world population increased at a rate of approximately one-half percent per year (Keyfitz 1973). Even at these modest rates, models suggest a much larger world population at the end of the 21st century (Lutz et al. 2004). Increased population has lead to the increased demands for wood as a raw material in many industries and declines in wood resources and forests areas. According to the World Resources Institute, the world lost about half of its forest cover until the year 2000 with an average of nine million hectares per year deforested during 1990-2000 (FAO 2001). Despite a number of initiatives to stop forest decline, the world continues to lose some 15 million hectares of forests every year. The major causes of forest decline are displayed in Figure 2.1 (CIFOR 2000). Not only the degradation in forest area but also the degradation in timber quality in forests which has led to changes in timber production because of the decreasing log diameters that are available for industry applications. The FAO (The United Nation's Food and Agriculture Organization) had estimated that total global round wood production increased from 2,463 million m^3 in 1970 to 3,358 million m^3 in 1994 with 1.3% increasing per year (Buehlmann et al. 2000).

Based on these changes in wood supply, declines in the availability and quality of wood resources, and changes in lumber prices, alternatives to solid lumber are actively sought. These changes have lead to the use of wood composite in some wood industries instead of using sawnwood. The engineering wood and wood composite industries have grown rapidly during the past two decades and further growth and development is expected to continue in the future. The continued success and growth the forest products industry depends on this industry's ability to produce competitive composite products from various types of woody resources (Hsu 1997).

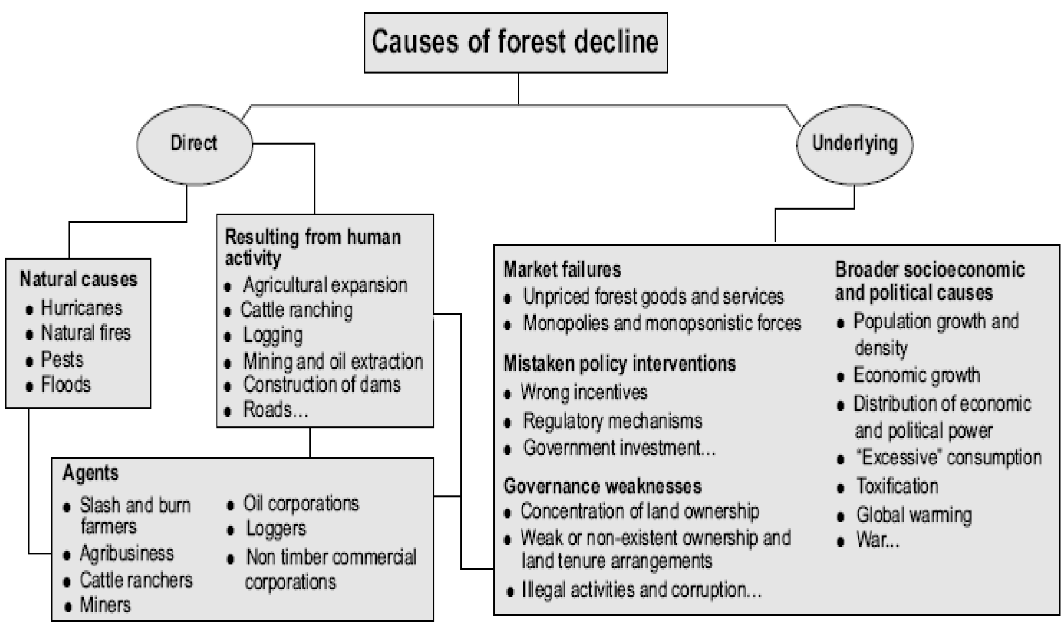


Figure 2.1 Major causes of forest decline. resource: CIFOR 2000

Wood composites are small distinct wood elements or materials bonded together. Wood materials that used in manufacturing wood composites are many and varied. These include wood residues, co-products, lumber, small diameter logs that can not be used in wood industry as sawn timber, etc. The composite concept is used to describe any wood material adhesive-bonded together. Composite products range from fiberboard to laminated beams as structural and nonstructural applications in product lines ranging from panels for interior covering purposes to panels for external uses, support structures, furniture, etc. The basic wood elements that can be used in wood composite industries are small diameter logs, lumber, veneer, wood chips, wood flakes, wood strands, wood particles, wood fiber, wood flour, and wood cellulose (Figure 2.2) (Wood handbook 1999).

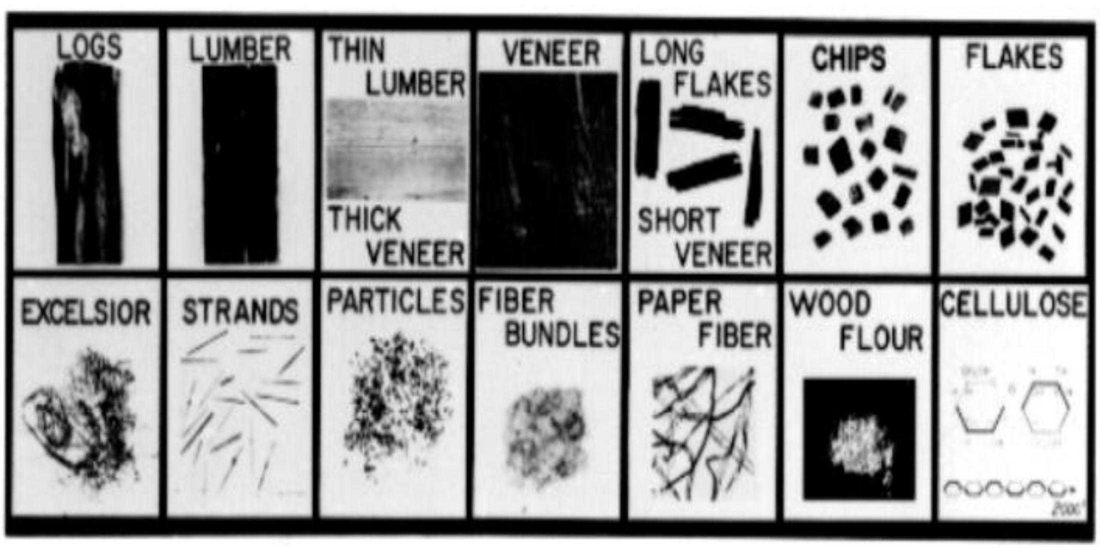


Figure 2.2 Basic wood elements, from largest to smallest (Marra 1979)

Currently, there are many kinds of commercially viable wood composite products (Figure 2.3) including: wood panel, molded products, inorganic-bonded products (cement or gypsum), laminated panel, oriented strand board (OSB), plywood, laminated veneer lumber (LVL), laminated strand lumber (LSL), particleboard, laminated beams, edge glued panels, I-joists beam, T-beam panels, stress-skin panels, in addition to engineered wood products (EWP) such as, plywood, structural panels or structural composite lumber (SCL), glued laminated timber (glulam), particleboard and medium density fiber (MDF) (Maloney 1996). Wood plastic composites are a type of wood composite that contains ground wood residues and thermoplastics (such as PVC). This industry is date to the early 1960s (Clemons 2002 and Wood Handbook 1999).

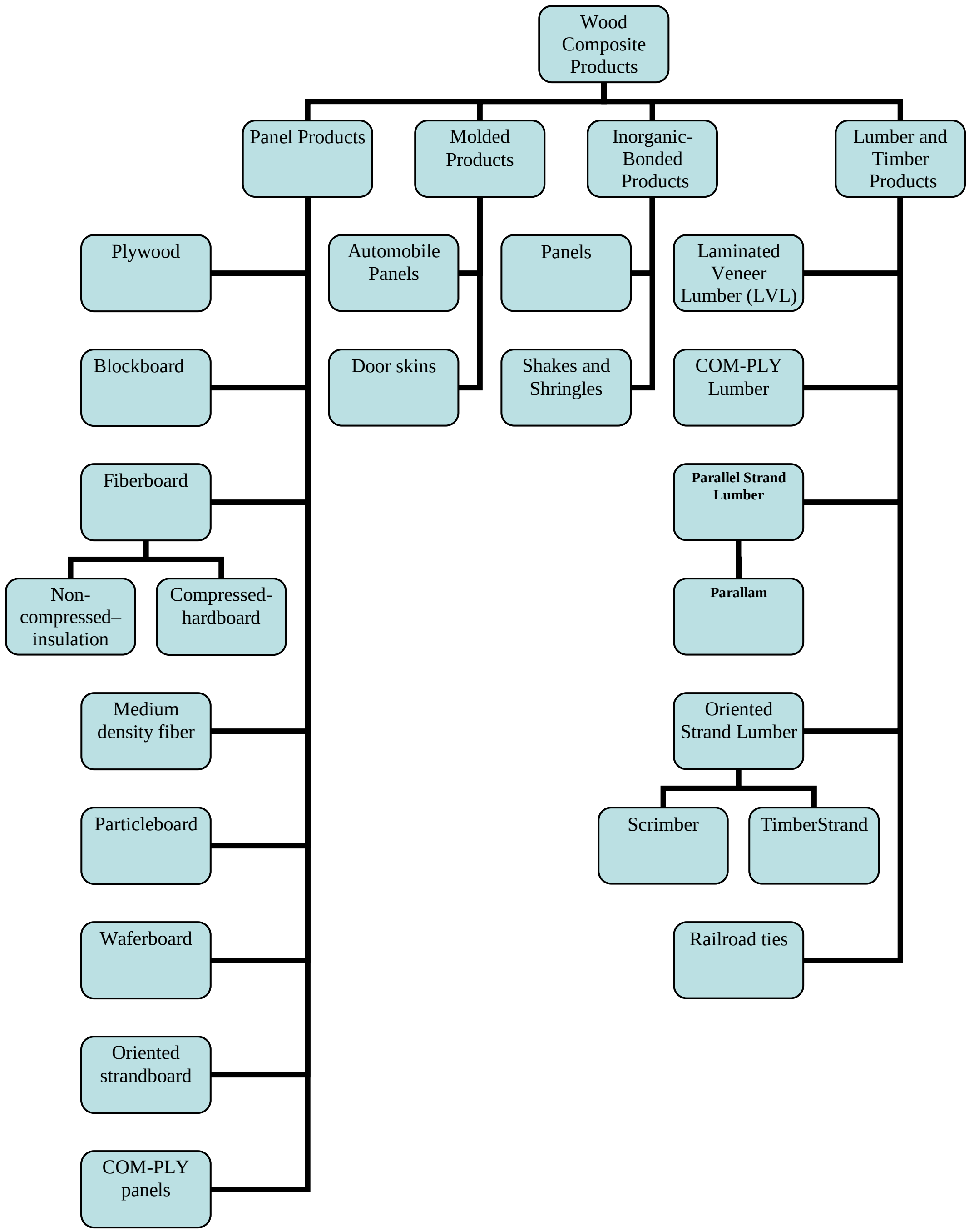


Figure 2.3 Wood Composite Products

(Note). Source: From Maloney 1996 with some edits

Wood Panel

Wood panels are relatively thin, flat sheets used by the manufacturing and construction industries to produce a variety of products (Figure 2.4). Plywood, oriented strand board (OSB), medium density fiberboard (MDF) and particleboard are examples of such materials. According to FAO, the annual growth for this production from 1970 to 1994 was 2.9% annually, and this rate of growth is expected to stay above the 2.0% during the 2010 decade and the estimated consumption during 2010 will be 172.6 million m^3 due to the increasing demand for these materials (Buehlmann et al. 2000).

Figure 2.4 Wood Panel

Inorganic-Bonded Products

Inorganic-bonded materials consist of a wood fiber or particle component that is bonded within an inorganic mineral matrix such Portland cement or gypsum to make wood-cement board or wood-gypsum board (CWC 2002) (Figure 2.5).

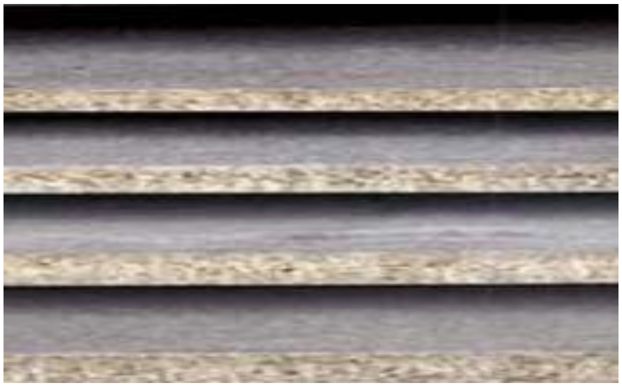


Figure 2.5 Wood-Cement Board

Oriented Strand Board (OSB)

OSB is a type of engineered structural-use panel manufactured from thin wood strands bonded together with waterproof resin under heat and pressure. It is used primarily for roof, wall, and floor sheathing (Wood Handbook, 1999) (Figure 2.6). The consumption of this product increased strongly during the past two decades because of the good mechanical properties related to the specific gravity, its resource efficiency, and it's relatively low cost. In 1997, the production of OSB in North America was 14 million m^3 (Kruse et al. 2000)

Figure 2.6 Oriented Strand Board (OSB)

Plywood

Plywood has been in use for thousands of years. Early examples have been found in Egyptian tombs. Plywood production was more fully mechanized and industrialized during 1930s. Plywood is composed of a number of thin layers of wood veneers bonded together with an adhesive and with the grain direction of adjacent layers perpendicular to one another (Sellers 1985) (Figure 2.7).

Figure 2.7 Plywood

Laminated Veneer Lumber (LVL)

Laminated veneer lumber is produced by gluing relatively thick wood veneers together in the same direction (Figure 2.8). The primary use for this product is as a structural composite lumber substitute. A significant amount of this product is also used in the furniture industry (Eckelman 1993). The LVL production in North America exceeds 1 million m^3 per year for specialized lumber, I-joist flanges, headers, and glue laminated arches and beams (Sellers 2001).

Figure 2.8 Laminated Veneer Lumber (LVL)

Laminated Strand Lumber (LSL)

Laminated strand lumber is a composite structural material consisting of relatively long parallel-oriented wood flakes that are glued together under heat and pressure. LSL can have mechanical properties that are similar to or stronger than solid lumber (Figure 2.9). Small diameters trees of generally low quality can be used for producing this kind of wood product (Moses 2003).

Particleboard

Wood based particle board is manufactured from small pieces of wood such as chips, splinters, small flakes, shavings, and strands that are bound together by adhesive. In 1994, the consumption of wooden particle board panels reached 46.6% of all wood panel consumption (Buehlmann et al. 2000) (Figure 2.10).

Figure 2.9 Laminated Strand Lumber (LSL)

Figure 2.10 Particleboards

Glue Laminated Timber

Glue laminated timber (glulam) beams are large section members consisting of two or more layers of the raw material bonded together using structural adhesive. Laminated beams as a type of engineered wood provide high strength and stiffness as well as large sections that can cover long spans (Figure 2.11). Structural glued-laminated timber was first used in 1893. It a material glued up from pieces of wood with the grain of all pieces parallel to the longitudinal axis of the member. This kind of production allows using different grades of lumber within the same member (Moody & Hernandez 1997)

Figure 2.11 Laminated beams

Edge Glued Panels

Edge glued paneling was developed to produce high value products from small diameter and low quality logs (Araman et al. 1982). The panels are made by edge-gluing narrow clear cuttings into panels that can be used for making furniture and cabinets (Armstrong & Sneckenberger 1991) (Figure 2.12).

I-Joist Beams

I-joists were first produced during late 1960s (Leichti et al. 1990). These are a unique type of I-beam that can be used in floor and roof applications. Plywood or OSB is used for the web material and lumber or SCL for the flanges (Wood Handbook 1999) (Figure 2.13).

T-Beams

Commercially available wood T-beams were first introduced in 1988 in bridge construction in Virginia (Taylor 1990). The T-beam is a beam resembling a “T” in cross section (Figure 2.14). Prior to its use with wood, this type of beam has been used successfully with pre-stressed concrete in highway bridge applications. Several side-by-side T-beams acting as a unit form floor for increasing the stiffness (APA the engineered wood association glossary)

Figure 2.12 Edge Glued Panels

Figure 2.13 I-Joist beams

Figure 2.14 T-beam flooring

Stress-Skin Panels

Stress- skin panels were developed in the early 1930's. This kind of panel is the most efficient structure for walls, floors, ceilings, and roofs. These panels made of framing members with plywood facing that are bonded by using glue and pressure (Figure 2.15). The glued skin and framing members act as integral unit under loading. The use of the skin allows a reduction in size of the framing material. The panel can be used as a structural unit in exterior or interior applications (U.S. Forest Service Research Paper 1964).

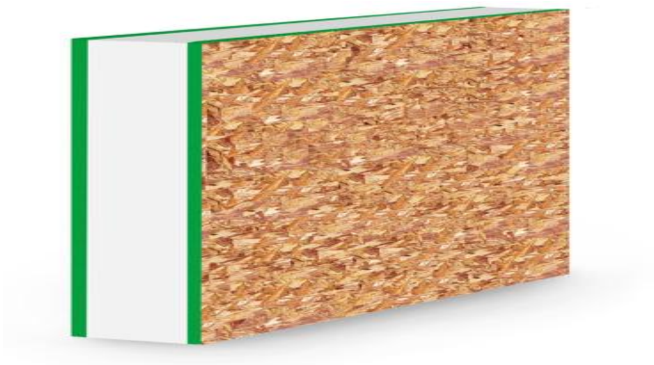


Figure 2.15 Stress Skin Panel

Medium Density Fiber (MDF)

Medium density fiber board is engineered wood products manufactured by adding wax and adhesive to the wood fibers and makes a wood panel by applying high pressure and temperature (Figure 2.16).

Figure 2.16 Medium Density Fiber boards

United States produces approximately 21 million tons per year of composite products from the residues and unusable raw materials, and this production is expected to be increased because of the minimizing of the number of larger forest trees resources (Maloney 1996). The production of these products declined during 2000-2010 because of the economic crises which is expected to start recovering in 2012 (USDA 2010). In 2008 the production of MDF reached to 3,021,000 cubic meters (equivalent to approximately 1,067 million tons), 10,278,000 cubic meters (3,630 million tones) of plywood, 11,508,000 cubic meters of OSB (4,064 million tons) and 5,161,000 cubic meters of particleboard (1,823 million tons) (Howard 2009).

In 1975, it was estimated that 50 percent of wood fiber could be saved by using wood composite structures (Nelsons 1975). Since 1971 laminated veneer lumber (LVL) has been available (Faherty & Williamson 1999), and the first composite I-beam was invented in early 1920 when was used in wooden aircraft (Robins 1987). Composite structural beams have been used in roof supports, floor joists, garage door headers, framing components, and numerous other applications (McNatt 1980). However, I-beam members with mechanical fasteners and elastomeric adhesive can be difficult to design properly, and environmental factors such as rain during the construction phase can significantly reduce strength and stiffness (Leichti 1989).

For the future, there is ongoing research in Canada that uses nanotechnology in extracting cellulose from wood as the raw material for aircraft made of wood composite materials (Turner 2009). Wood–plastic composite, wood polymer composite and wood composite fencing are some of the other types of wood composite products that have been developed and commercialized during this century.

With respect to resource efficiency, environmental stewardship, cost effectiveness, and architectural design freedom, engineered lumber products (e.g. plywood, floor joists, beams, LVL, etc.) represent technological advances. According to Trus Joist MacMillian one of the companies that specialized in U.S. based engineered lumber manufacturing, only seven percent of all the trees the company uses are greater than 21 inches in diameter, and 50% of the used trees are less than nine inches in diameter. This fact occurs because the industry in general and this company specifically, depends on small diameter logs. With these small diameter log it is stated that nearly 70% of the tree is used when the lumber is engineered (Davis 1999).

Incorporation of engineered wood in building gives the efficient, stable uniform and consistent use of wood by placing stronger and uniform components in their suitable areas. The ease of handling and flexibility in shape and size are the other positive properties of using engineered lumber because of the lower weight that engineered lumber has compared to solid sawn lumber weight. The strength and durability of engineered lumber is the major positive characteristic. Cost is very attractive factor because incorporation of engineered lumber in building systems often results in lower overall cost, reduced waste, and higher performance. There are many applications for all kind of engineered wood such as flooring, roofing, beam headers, and frame construction (Figure 2.17).

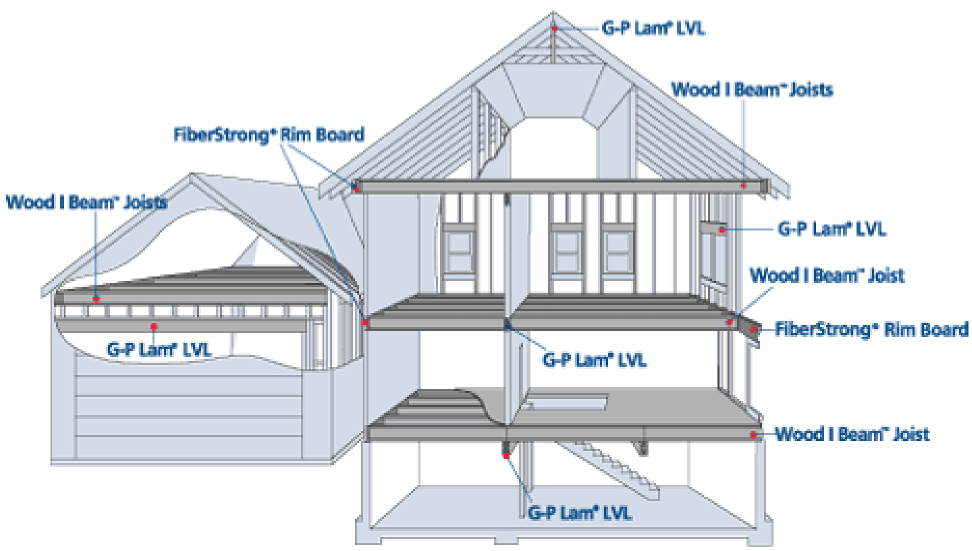


Figure 2.17 Engineered lumber application in wood industries

(Note): Source is Georgia Pacific web site: http://www.gp.com/build/productgroup.aspx?pid=1063

In the United State of America, there are approximately 100 major wood species but not all of them are available with sufficient quality, size, and of sufficient quantity to be of commercial significance. Of these 100 species, approximately 60 have major importance for commercial purposes. An additional 30 species, approximately, are imported as logs, cants, veneer or finished products (Faherty & Williamson 1999).

Softwood lumber is the most important lumber class or group that is used for structural applications in the United States. Softwood timber consumption and production and the imported timber in the United State for the years of 1989, 1995, and 2001 are displayed in Figure 2.18.

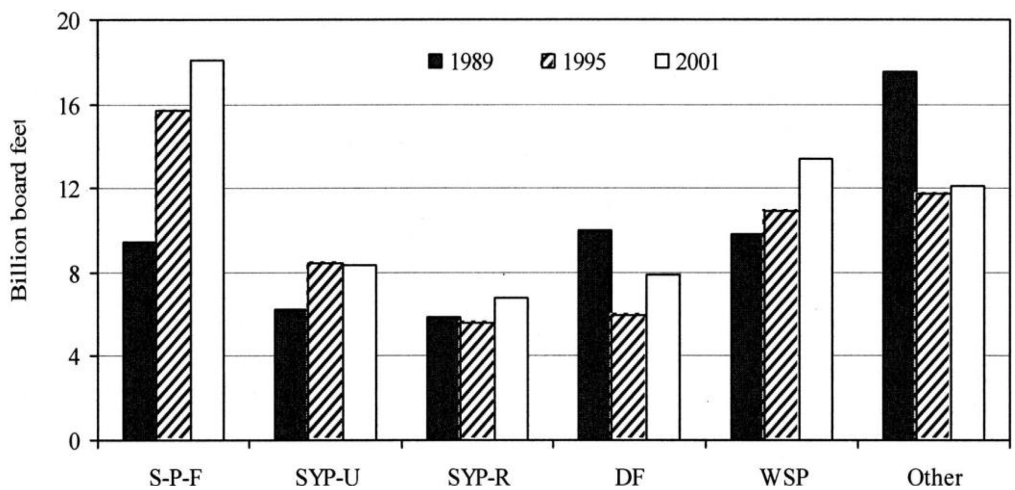


Figure 2.18 Softwood products consumption, production, and imports in the United States during 1989, 1995, and 2001.

Where S-P-F is Spruce Pine Fir lumber, SYP is southern yellow pine. Source: Society of American Foresters 2004.

Southern pine wood properties

Southern pine is a name of a commercially important group of pine species including primarily: longleaf pine (*Pinus palustris*), shortleaf pine (*Pinus echinata*), loblolly pine (*Pinus taeda*), and slash pine (*Pinus elliottii*) from the family *Pineaceae*. Once the trees are processed, the wood of this group of pines is very similar in appearance with wide yellowish sapwood and reddish heartwood, and it has similar mechanical and physical properties. In these trees, the heartwood starts to form at approximately 20 years of age. All of these species have moderately high shrinkage and stable dimensions once dried (Table 2.1). Due to the high strength and the density of southern pine species wood (Table 2.2), they can be used in construction, building, railroad crossties, etc. (Wood Handbook 1999). Loblolly pine is one of the most commercially important timber species in North America. It is grown for both solid wood and pulp and paper products (Sewell et al. 2002). The desirable industrial characteristics of this species are it favorable physical, chemical and mechanical properties of wood such as lumber strength, stiffness and dimensional stability (Megraw 1985).

Table 2.1 Shrinkage (%) from green to oven dry moisture content for Southern pine wood

Species	Radial shrinkage (%)	Tangential shrinkage (%)	Volumetric shrinkage (%)
Loblolly pine	4.8	7.4	12.3
Longleaf pine	5.1	7.5	12.2
Shortleaf pine	4.6	7.7	12.3
Slash pine	5.4	7.6	12.1

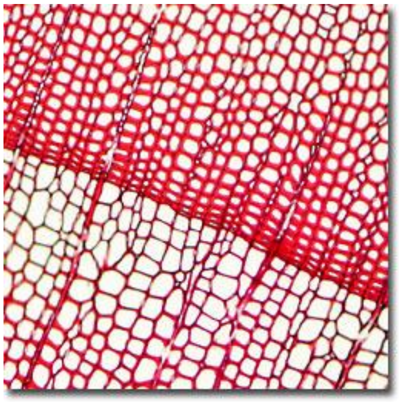
(Note).Source of the table is Wood Handbook 1999

Table 2.2 Mechanical properties for Southern pine wood

Species	MC%	SG	MOR (lbf/in^2)	MOE ($\times 10^6 lbf/in^2$)	Compression Parallel to grain (lbf/in^2)	Shear Parallel to grain (lbf/in^2)
Loblolly pine	G	0.47	7,300	1.40	3,510	860
	12	0.51	12,800	1.79	7,130	1,390
Longleaf pine	G	0.554	8,500	1.59	4,320	1,040
	12	0.59	14,500	1.98	8,470	1,510
Shortleaf pine	G	0.47	7.400	1.39	3,530	910
	12	0.51	13,100	1.75	7,270	1,390
Slash pine	G	0.54	8,700	1.53	3,820	960
	12	0.59	16,300	1.98	8,140	1,680

(Note). Source of the table is Wood handbook 1999. Where: MC% is the percent moisture content. G is the green moisture content. SG is the specific gravity. MOR is the modulus of rupture.MOE is the modulus of elasticity.WML is the work to maximum load.

Anatomically, southern pine wood is identified as hard pine (Figure 2.19). Its anatomical qualities include such things as: medium to high density, hard, uneven-grained, abrupt early wood/latewood transition with large, numerous, mostly solitary, and evenly distributed resin canals, thin-walled epithelial cells, dentate ray tracheids, and windowlike or pinoid cross-field pits, and absence of longitudinal parenchyma (Hoadley 1990).



Cross section

Radial section

Tangential section

Figure 2.19 Loblolly pine (*Pinus teada*) microscopic identification**.**

(Note) the picture is taken by: Michael W. Davidson . Florida State University© 1995-2010

Engineered wood adhesive types

Wood as an anisotropic, porous material has interconnected lumens in cells that can provide pathways for the flowing of the liquids-phase resin. When resin is added to the surface of wood, interconnecting pits are often adequate to permit resin flow (Frederick & Lee 2007).

Until 1920s, the only available adhesives were manufactured from animals and plants, and those adhesives were not water resistant. Thus, at that time, composites were limited to dry interior applications only. After that time a variety of waterproof structural adhesives, largely based on petro chemicals, were developed. In 1998, more than 1.78 million metric tons of solid resins were consumed in North and Central America (Table 2.3) to bond about 58 million cubic meters of composite products (Table 2.4) (Sellers 2001).

Table 2.3 Estimated consumption of major wood-based adhesives in North America

Polymer Type	North America Consumption	
	Kt	%
Amino	1060	59.5
Phenolic	568	31.9
Isocyanate	90	5.1
Polyvinyl acetate	50	2.8
Resorcinol type	7	0.4
Soy-modified casein	5	0.3
Total	1780	100.0

(Not).Source of the table is Society of plastics industries, industry sources, and other calculations

Table 2.4 Estimated 1998 production of wood-based and other fiber- based composites in North America

Glued Composite Type	USA Consumption (million m^3)
Plywood	15.730
OSB/OWB	9.935
Oriented flake-strand lumber	0.051
Parallel veneer strand lumber	0.200
Hardwood plywood	1.770
Particleboard	8.127
Agrifiber (wheat, straw, etc.)	0.159
MDF	2.480
Hardboard	1.903
Insulation board	1.454
LVL	1.161
Wood I-joist	0.547
Glulam	0.677
Inorganic panels	0.932
Total	45.126

(Note). Source of the table is Society of plastics industries, industry sources, and other calculations

The chemicals present in the adhesive (adhesive type) and the interaction of the adhesive with wood surface affect the gaseous emission during panel manufacture (Pizzi 1983). Adhesive penetration into wood can be categorized into: gross penetration, and cell-wall penetration. First the resin fills the cell lumen of the wood, and then the resin diffuses into the cell wall and micro fissures (Marra 1992).

According to Pizzi (1994) in his book (Advanced Wood Adhesive Technology) and Pizzi & Mittal (2004) in their book (Handbook of Adhesive Technology), there are many types of adhesives used in engineered wood applications. These adhesives include primarily: urea-formaldehyde adhesives (UF), melamine-formaldehyde adhesives (MUF), phenolic resin wood adhesives (PF), tannin-based wood adhesives, lignin-based wood adhesives, resorcinol adhesives, Isocyanate wood adhesives, polyvinyl acetates (PVA) and ethylene vinyl acetates (EVA), and Polyurethane adhesives.

Urea-Formaldehyde Adhesives (UF)

Urea-formaldehyde resins are the most widely used. These have favorable water solubility, hardness, nonflammability, thermal, and color properties. Additionally, these adhesives are easily adaptable to various curing conditions. These kinds of adhesive are used just for interior applications because of their bond deterioration under the effect of water and moisture (Pizzi 1994).

Melamine-Formaldehyde Adhesives (MF)

Melamine- formaldehyde resins and melamine-urea-formaldehyde resins are used for exterior and semiexterior wood panels (Plywood and particleboards). They are high resistant to the water and weather. MF adhesives are used for the impregnation of paper sheet in the production of self-adhesive overlays for the wood-based panel products' surface (Pizzi & Mittal 2004).

Phenolic Resin Wood Adhesives (PF)

Resol-type resins are the only commercial types of phenolic resins. They are water resistant adhesives that used for exterior applications, plywood and particleboard that used for exterior applications (Pizzi 1994).

Tannin-Based Wood Adhesives

Tannin-based wood adhesives have been used in many countries in wood panels industries (Pizzi 1983, 1994). These adhesives are capable of minimizing formaldehyde emissions. Commercial tannin resins are based on some plant tannin extracts. Tannin-based resins cure quickly and can thus increase production (Pizzi &Trosa 2001).

Lignin-Based Wood Adhesives

Since 1925, some hardboard industries depend on using natural lignin as a binder. In 1981, lignin modified PF resins remained in use as a means of reducing cost as a wood binder (Sellers 2001).

Isocyanate Wood Adhesives

Isocyanate resins have many advantages for wood composite. These adhesives have been in use since the 1970s. They are especially well suited for OSB production. Isocyanates are colorless, cure rapidly, and can tolerate more water than PF type adhesives (Pizzi & Mittal 2004).

Polyurethane Adhesives

The first application of this resin was in 1940 when it was applied for bonding elastomers to fibers and metals. Then the application expanded to bonding glass, wood, fabric, ceramics, and rubber composite in 1950s. The polyurethane adhesives provide durability, flexibility, and fast curing for all applications (Pizzi & Mittal 2004).

Polyvinyl Acetates Adhesive (PVA)

These adhesives are typically suspensions in water or alcohol. They provide good cohesion and adhesion to the jointed surfaces. These have a glass transition temperature of about 30 ℃. The estimate production of this kind of adhesive in the United States was 715,000 tons in 1986. These are generally low cost, low toxicity, low flammability, and cold set. As such, they are relatively easy to use (Pizzi 1989).

Non-destructive tests

Non-destructive testing of wood provides a means to identify mechanical and physical properties of wood without altering their end-use capabilities. This kind of test is used to define relationships between properties and performance of wood or any other material. During the past 40-45 years, non destructive tests have been developed for using in-place evaluation of wood member structures. This type of testing is valuable in industrial applications to evaluate the raw material used in some industries, such as machine stress rating of lumber and ultrasonic veneer grading for laminated veneer lumber manufacture. It is also very important for evaluating the ability of wood to withstand use characteristics as in buildings and historic structures, for assessing decay in wood, and for stimulating the awareness and interest of the public in the wood preservation of historic structures in an effort to help to conserve forests as a natural resource.

Acoustic emission and acoustic velocity techniques have been used as a means of non-destructively assessing wood decay (Ross 1992). Dunlop (1983) used the acoustic velocity and vibration techniques for evaluating wood poles by measuring the response vibrations of a wood pole after tapping it. Additional techniques that can be used as non-destructive tests include things such as: radiography, acoustic emission, thermal, and optical and vibration methods (Summerscales 1987). Non-destructive test include some methods that relay on the ability of wood to transmit waves in the form of x-rays and microwaves, such as sonic and ultrasonic stress waves, acoustic emission and acousto-ultrasonics, optical scanning, electrical resistance; and some other methods rely on the ability of wood to transverse vibrations. The particular geometry of the wood has sound influences on the propagation of different frequencies of sound or vibrations (Falk et al. 1990).

The ultrasound based methods have been developed during the last decade. These are based on the relation between the propagation velocity of the longitudinal ultrasound waves and the wood elastic properties (Sandoz et al. 1999).

Carter and other researchers in 2004 used non destructive testing via the Director HM200 for sorting logs according to stiffness.

Therefore, in the case of any of new products, it can be beneficial to use nondestructive methods for process control, quality assurance measurements, and grade classification during and after processing (Falk et al. 1990).

CHAPTER 3

MATERIALS AND METHODS

Introduction

The primary raw material for this work was pine logs. Logs were scaled and sawn into cants at the Forest Products Department. Cants were further reduced into rectangular sections of approximately 3x4 inches. These sections were further processed into matched similar trapezoids. Trapezoids were further processed into symmetrical trapezoids per MSU invention disclosure titled Structural Bowtie Beams authored by Rubin Shmulsky. Symmetrical trapezoids then were then air dried to approximately 10 percent moisture content and jointed. Symmetrical trapezoids were then none destructively evaluated for stiffness (via E-computer) and acoustical velocity (via Director Machine) and sorted by results. Next the sorted trapezoids were matched into pairs and assembled into beams. 22 beams were produced. Stiffness of the composite beams was nondestructively evaluated via E-computer. Then the beams were mechanically tested via ASTM 5456

Logs preparation

Loblolly pine (*Pinus taeda*) was used exclusively for manufacturing of the bowtie beams. Logs were taken from the College of Forest Resources' John Starr Memorial Forest (Figure 3.1) in July of 2007. Approximately one month prior to harvest, a windstorm had damaged the forest stand. Many trees were completely broken off at a height of approximately twenty to thirty feet. As such, logs were taken as part of the salvage and recovery operation. All material for this study was taken from butt logs that remained standing on the stump. Butt logs measured from approximately 9 to 16 inches diameter at breast height, that is, 4.5 feet. Twelve logs were harvested, bucked to a maximum length of approximately 15 feet, and returned to the Department of Forest Products at Mississippi State University.

Figure 3.1 College of Forest Resources' John Starr Memorial Forest

(Note). Source of the table is www.cfr.msstate.edu/bulldogforest/star.htm

Cants development

The logs were slabbed into rectangular cants on a Wood-Mizer horizontal band sawmill. The target product from the sawmill was small timbers that were approximately 3.4 inches by 4.4 inches in cross section. Thus, cants were sized in multiples of these dimensions in an effort to maximize yield. Cants were then resawn accordingly into the rough green 3.4 inches by 4.4 inches timbers (Figure 3.2). Approximately 25 cants were recovered.

Figure 3.2 Cant dimensions

Trapezoids processing steps

Cants were then resawn on a vertical band saw into two similar trapezoids. For this processing step, the bandsaw platen was tilted approximately 15 degrees from the horizontal. Trapezoids were then resawn on the vertical band saw in an effort to make each one symmetrical about its central axis (Figure 3.3).

Following final resawing, trapezoids were stacked on drying stickers and air dried in a climate controlled facility at approximately 70 ° degrees Fahrenheit and 60 percent relatively humidity until the boards reached a constant weight. These conditions corresponded to an equilibrium moisture content of approximately 10 percent. Following drying, the trapezoids were trimmed back to a finished length of 12 feet. Some of the trapezoids were culled. Culling was due primarily uncontrolled warp, excessive wane, and shear splits that could not otherwise be trimmed off. After drying, trimming, and culling, 45 trapezoids remained in the pool for further processing (Figure 3.4). Each of these was numbered with indelible ink such that they could be tracked and sorted throughout testing and processing.

Trapezoids non-destructive tests

Next, the trapezoids were numbered and non-destructively evaluated via acoustic velocity (Director HM200) (Figure 3.5) and vibrational stiffness analysis (E-computer) (Figure 3.6).

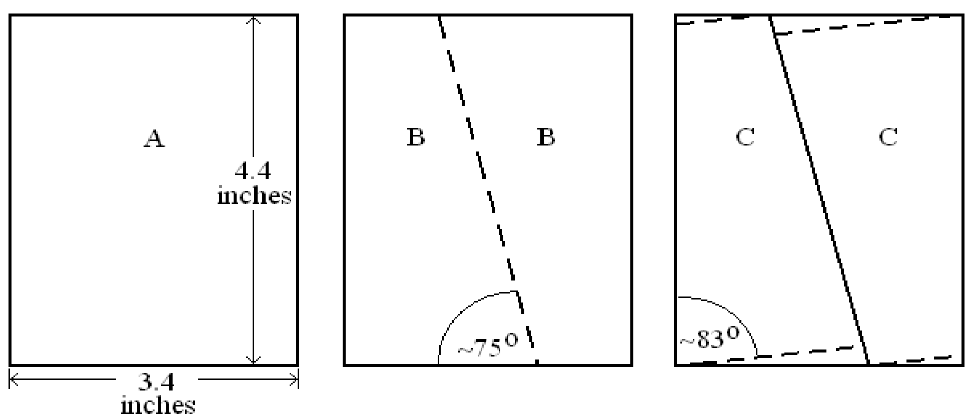


Figure 3.3 Three processing steps from solid rectangular cant (A), to similar trapezoids (B), to symmetrical trapezoids (C).

(Note) waste in this process is limited to the resaw kerf and the small triangular portions that were removed during the conversion from similar trapezoids to symmetrical trapezoids.

Figure 3.4 The 45 trapezoids

Figure 3.5 Director HM200

Figure 3.6 E-computer trapezoids test

E-Computer trapezoids evaluation

E-computer used as a non destructive test to test the stiffness of the trapezoids. The E-computer machine consists of a Metriguard Model 340 E-computer, two sensitive tripod knife-edge stands, and monitor.

Prior to use, the E-computer equipment was calibrated by using weight 8.01 pounds. Next, the wood trapezoids were first measured and marked at their respective points of mid length. Each trapezoid was spanned across the E-computer stands. The stands were spaced such that approximately one inch of overhang was present at each end (Figure 3.7). When the wood sample was ready to be tested, all the information regarding the length, depth, and width was input into the E-computer to calibrate the vibrational program. For all of the trapezoids, the input length was 12 feet, 1.5 inches width, with 4 inches depth. These measurements are for a rectangular section. Thus, it was not anticipated that the E-computer would produce completely accurate stiffness measurements for the trapezoidal sections. It was however hypothesized that the results would be consistent and thus they could be used for sorting of trapezoids, for determining correlation to acoustic velocity, and for correlation to final mechanical properties as per destructive mechanical testing.

After the program was set, each wood sample was tapped at midspan in an effort to induce a vibration at the natural frequency. Transferred vibrational waves and respective information then appeared on the computer screen. Based on the size parameters of the trapezoids and the vibrational characteristics, the computer calculated an estimated density and stiffness value for each trapezoid (Figure 3.8).

Figure 3.7 Trapezoids E-computer set up

Figure 3.8 E-computer monitor shows the strength and the density

Trapezoids acoustic velocity (Director) evaluation

This portable equipment requires only minimal set up. Workpieces can be tested while on the ground. Prior to testing the length of the sample workpiece must be input. The equipment then uses the time required for an acoustical wave to travel the sample's length and return along with the sample's length to determine the inherent acoustic propagation characteristics of each particular piece of wood.

With respect to use, the equipment has a sensitive large button on the top which must be pressed in to end of the wood sample. Next, the wood sample is hit with a hammer on the end, near the Director equipment, in an effort to induce a vibration in the wood sample. The Director equipment then provides an audible signal to indicate that the reading is complete and it displays a calculated value of acoustic velocity on its display screen (Figure 3.9).

Figure 3.9 Director testing of trapezoids

Trapezoids sorting

Trapezoids were then sorted based upon their stiffness as given in E-computer test. Next, trapezoids were arranged in matched pairs based upon their stiffness rankings. Matched pairs were designated for the manufacture of the composite bowtie beams.

Jointing of trapezoids for Bowtie-Beam manufacture

After the non destructive E-computer results were sorted, each matched pair was grouped in order to maximize the potential correlations between the non-destructive test results and the ultimate performance of the beams. Immediately prior to gluing, each trapezoid was jointed along its glue edge in order to make the edge straight, true, and suitable for adhesive bonding. Commercial polyvinyl acetate adhesive (PVA) (Figure 3.10) was applied to the jointed edge of each trapezoid. Once glued, these edges became the neutral axis of the bowtie beam. PVA adhesive was chosen based on its cost, ease of clean up, strong performance in interior applications, and ability to cure at ambient temperature conditions. The trapezoids were clamped into the bowtie shape after adhesive application. Once clamped, each beam remained under pressure for 24 hours at the ambient conditions until the glue cured (Figure 3.11).

To minimize variation, a consistent amount of adhesive was applied during the manufacture of each bowtie beam. Approximately 85 grams of glue was added to make each bowtie beam.

Once pressed together, each bowtie section beam was 12 feet long, approximately 7.5 inches deep, two inches wide at the flanges, and one inches wide at the neutral axis (Figure 3.12). After gluing, 22 beams were produced (Figure 3.13). Each bowtie beam was assigned an ID number.

Non destructive testing of the Bowtie-Beams

The bowtie beams were tested in the same manner as the trapezoids had been. That is, bowtie beams were subjected to non destructive testing by both E-computer and acoustic velocity.

Figure 3.10 The used adhesive

Figure 3.11 Bowtie-Beams during clamping and ambient temperature curing

Figure 3.12 The Bowtie-Beam immediately after the glue was cured and the clamps were removed

Figure 3.13 The completed 22 Bowtie-Beams

E-Computer evaluation of Bowtie-Beams

For these tests, each bowtie beam was re-measured, and a visible point at midlength was marked. Next, the equipment was calibrated to a standard weight of 8.01 pounds. Each bowtie beam was then set up on the E-computer stands, again with one-inch of overhang at each end. Next, the information related to the length, depth, and width was input to the E-computer in order to set up the program. The input length was 12 feet, 1.5 inches width with 7.5 inches depth. Next each bowtie beam was tapped at midspan in an effort to induce a vibration at its natural resonant frequency. Transferred vibrational waves then appeared on the computer screen. The stabilized waves were used by the computer to calculate an estimated stiffness and density for each sample. The results were displayed on the computer monitor (Figure 3.14).

Figure 3.14 Bowtie-Beam E-computer evaluation test

Acoustic velocity (Director) evaluation of Bowtie-Beams

Immediately following E-computer testing, bowtie beams were tested for acoustic velocity by the director, the Director equipment was programmed for a Bowtie Beam length of 12 feet. At the same end of the bowtie beam that the Director equipment was applied; the beam was hit with a hammer. Two readings were taken from each bowtie beam; one from each of its trapezoids. The average of the two readings was used as a predictor value of the mechanical properties of each bowtie beam.

All the values from E-computer and director were correlated to the strength and stiffness for each bowtie beam.

Destructive testing

After all bowtie beams were nondestructively tested, mechanical test was applied to all bowtie beams to find the value of maximum load, the modulus of elasticity (MOR), and the modulus of rupture (MOR).

All values were compared to non-destructive values to evaluate using nondestructive test in wood evaluation. Then the values for mechanical properties were converted into engineering design values. These design values were then compared to those of structural pine lumber of similar depth.

An Instron universal testing machine was used for mechanical testing. All beams were tested in third-point bending per ASTM 5456 (D-143) (ASTM, 2000). Beams were loaded in edgewise bending at a constant displacement rate of 1.5 inches per minute. Maximum load values, MOE, and MOR were obtained from the testing program for each beam. MOR and MOE values were then adjusted to account for the section modulus of the bowtie beam.

The design strength and stiffness values were respectively multiplied by the sectional area or the moment of inertia. This action produced a strength efficiency factor and stiffness efficiency factor. These factors were compared to factors derived from multiplying the design stiffness values from National Design Specification (NDS) times the area or the moment of inertia of rectangular section of equivalent depth and maximum width.

Beam mechanical test

Before mechanically testing the bowtie beams, two solid sawn rectangle beams with actual dimensions of 1.5 inches by 7.25 inches by 12 feet length were tested. Their respective values of maximum load, MOE, and MOR were recorded. Figure 3.15 illustrates the mechanical testing of the solid sawn beams.

Bowtie-Beam mechanical test

For mechanical testing of the bowtie beam, the universal testing machine software was programmed for a rectangular beam of 1.5 inches of width and 7.5 inches depth. During subsequent analysis, the section properties of this virtual beam were then corrected for those of each actual beam. The span was 126" and the rate of loading was 1.5 inches/minute (Figure 3.16).

Figure 3.15 Mechanical testing of solid sawn beams

Figure 3.16 Bowtie-Beam mechanical test

Parametric design strength

The design strength and stiffness were compared to the values of sections of equivalent depth and maximum width (that is the width at the flanges or light frame construction lumber) as shown in the National Design Specifications (NDS 1997). Also, non destructive test values were compared and correlated to those from the destructive tests.

F_b (psi) was calculated as:

$$F_b = \frac{\overline{MOR} - (Stdev \times k)}{2.1 \times 0.96} \quad (1)$$

Where:

$\overline{MOR}$ = Average modulus of rupture
Stdev = Standard deviation of the MOR
2.1 = The safety factor.
k = Statistical value associated 5^{th} percentile for given sample size. For 22 pieces:
k = 1.916.
0.96 = Load concentration factor to convert from 4-point bending in the universal testing machine to uniform loading as shown in the National Design Specification.

MOR was calculated as

$$MOR = M \times Z \quad (2)$$

Where:

M = Maximum bending moment (pound inches):

$$M = \frac{PL}{6} = \frac{P}{2} \times \frac{L}{3} \quad (3)$$

P = Maximum load (pounds)
L = Clear span (inches)
Z = Section modulus:

$$Z = \frac{I}{c} \tag{4}$$

Where:

I = Moment of inertia (inches^4)
c = Half of the sectional depth (inches)

$MOE_{apparent}$ psi was calculated as:

$$MOE = \frac{Pa}{24\Delta yI} \times (3L^2 - 4a^2) \tag{5}$$

Where:

P = Change in load, in the linear deflection range (pounds)
a = 1/3 span (inches)
Δy = Maximum change in deflection associated with change in load in the linear deflection range (inches)
I = moment of inertia (inches^4)
L = clear span (inches)

Design stiffness: MOE design value:

$$MOE_{true} = MOE_{apparent} \times 1.05 \text{ (as per APA)} \tag{6}$$

Prior to testing, the bowtie beams were measured. Maximum width at the flange edge was measured in two locations, to the nearest one hundredth of an inch, and these values were averaged. This average value was used as the maximum width for each beam. The minimum width at the neutral axis was measured in two locations, to the nearest one hundredth of an inch. This average value was used as the minimum width for each beam. The depth of each beam was measured in two locations and these values were averaged. This average value was used as the beam depth. These values were used in computing the moment of inertia of the bowtie section.

Calculation of the moment of inertia occurred in three steps. First, the moment of inertia of a full rectangular section was calculated, using the beam depth and maximum width (Figure 3.17). The formula used in this calculation was:

$$I_{rectangle} = \frac{b_f h^3}{12} \tag{7}$$

Where:

$I_{rectangle}$	=	The moment of Inertia of the rectangular section
b_f	=	The maximum beam width at the extreme fiber of the section
h	=	The beam depth

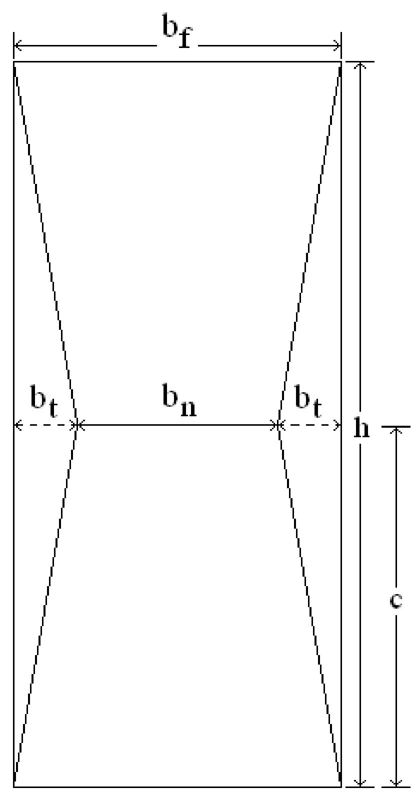


Figure 3.17 Approximation of the Bowtie-Beam section used for mechanical property calculation.

Next, the moments of inertia of the triangular sections, about the neutral axis, that were removed, were calculated. For reference, in the case of Figure 38, there were four triangular sections. Each had a base measurement value of b_t and each has a depth of c. The formula used to calculate the moment of inertia of a triangular section, about its base was:

$$I_{rec\tan gle} = \frac{b_t c^3}{12} \text{.(John \& Harold 1983)} \quad (8)$$

Where:

$I_{triangle}$ = Moment of inertia, about the basal axis, of a triangular section of base b_t and height of c.

b_t = The base width of each triangle. This value was equivalent to the maximum beam width, b_f minus the minimum beam width at the neutral axis, b_n, divided by two.

c = The height of each triangle and was equivalent to h/2.

Finally, the moment of inertia of the missing wood was subtracted from the moment of inertia of the full rectangular section to determine the moment of inertia of the bowtie section. Note that the moment of inertia of the missing wood was equivalent to the four times the moment of inertia of the triangular section. Thus:

$$I_{bowtie} = I_{rec\tan gle} - 4I_{triangle}. \quad (9)$$

Then, during analysis, the MOR and MOE values were adjusted by the proportional difference between the section modulus of the virtual rectangular beam, as programmed in the testing machine software as compared to the section modulus of the actual bowtie beam.

Failure mode

According to ASTM standards (D-143) (ASTM, 2000) the bowtie beam static bending failures were classified in accordance to the type of wood failure (Figure 3.18). Failure mode type for bowtie beams were compared with that for the regular beams that tested at the beginning of this test (Figure 3.19).

Figure 3.18 Regular beam failure mode

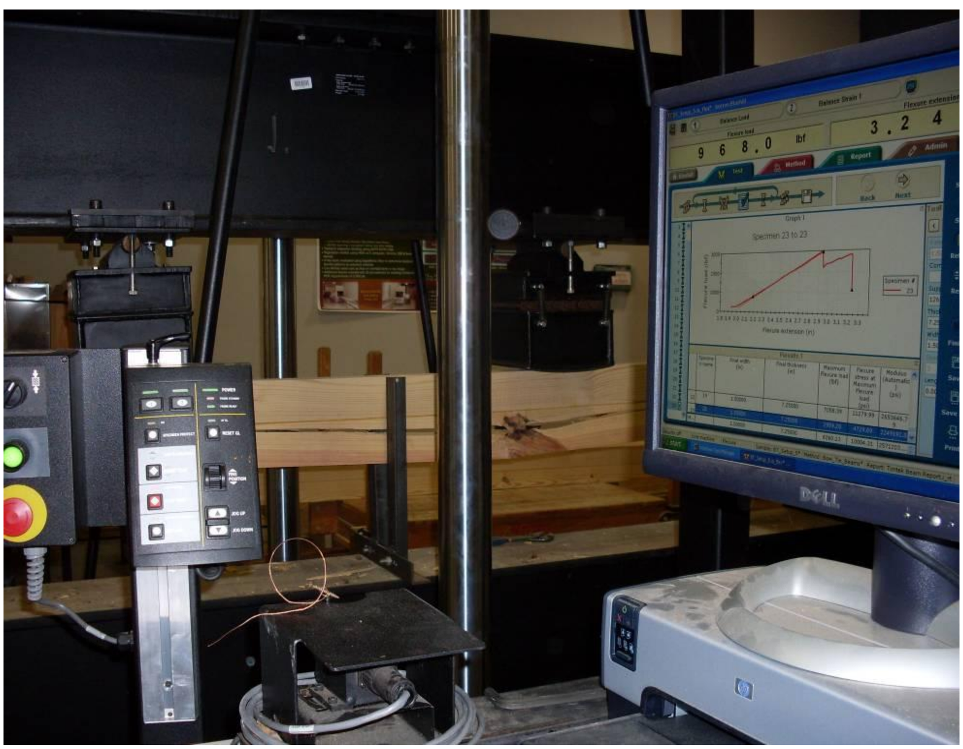


Figure 3.19 Bowtie-Beam failure mode

CHAPTER 4

RESULTS

Introduction

From the non destructive evaluation, the information from the E-computer and the acoustic velocity testing was correlated to the ultimate strength and stiffness of each beam. Correlations were reported. From the mechanical testing evaluation, design strength and stiffness were calculated and reported. The design strength and stiffness were compared to the values of sawn lumber sections of similar depth and maximum width (that is the width at the flanges or light frame construction lumber) as shown in the NDS. Also, non destructive test values were compared and correlated to those from the destructive tests. Finally, the design strength and stiffness values were respectively multiplied by the sectional area or the moment of inertia. This produced a strength efficiency factor and a stiffness efficiency factor. These factors were compared to factors derived from multiplying the design strength or design stiffness values (from the NDS) times the area or the moment of inertia of a rectangular section of equivalent depth and maximum width. It was found that the mechanically efficient bowtie section produced an increased strength and stiffness efficiency as compared to that of solid sawn material.

Non destructive tests results

Data from the E-computer and the Director were recorded during evaluation of both the trapezoids and bowtie beam tests.

Non destructive trapezoids results

Both the results from E-computer and Director were recorded. The range of the stiffness values for trapezoids per the E-computer was between 1.49 million psi and 3.34 million psi. The average stiffness for all trapezoids was 2.30 million psi. The range of the specific gravity between 0.43 and 0.66, and average specific gravity of trapezoids was 0.54. These values are based on rectangular sections of approximately the same area as the trapezoids. As such, the primary utility value of these results is for relative sorting among the trapezoids. The range of acoustic velocity of trapezoids was between 14,961 feet/sec and 19,587 feet/sec with the average acoustic velocity for all trapezoids 17399.44 feet/sec. Table 4.1 displays the non destructive test results from the E-computer and the Director tests for each of the trapezoids.

The relation between the E-computer results and Director results as nondestructive tests is displaying in figure 4.1. According to the results, trapezoid which has high value stiffness (E-computer value) has high acoustic velocity (Director value).

Table 4.1 Trapezoids stiffness, specific gravity results from E-computer and Director

ID	stiffness(E-computer)	SG(E-computer)	Acoustic velocity(Director)
1	2.83	0.641	17651
2	3.03	0.573	18570
3	3.23	0.602	19587
4	3.13	0.630	18340
5	2.57	0.561	17651
6	1.84	0.581	15846
7	2.40	0.491	17782
8	1.91	0.506	17881
9	2.41	0.495	17881
10	2.17	0.537	17782
11	2.88	0.616	17224
12	2.42	0.653	15978
13	2.81	0.538	18570
14	2.46	0.520	17552
15	1.98	0.517	15650
16	2.17	0.467	18012
17	2.02	0.522	17093
18	2.12	0.531	16535
19	2.62	0.548	19127
20	1.94	0.658	16634
21	1.49	0.463	14961
22	1.84	0.550	16765
23	2.72	0.572	18110
24	2.28	0.509	18110
25	2.06	0.476	17224
26	2.60	0.529	18340
27	2.54	0.543	17224
28	3.34	0.628	19455
29	2.42	0.542	17881
30	2.10	0.568	16306
31	2.28	0.570	17815
32	2.07	0.516	16437
33	1.55	0.432	16207
34	2.28	0.499	16535
35	2.11	0.457	18012
36	2.08	0.538	17487
37	1.89	0.463	16864
38	1.98	0.495	17224
39	2.25	0.467	18438
40	1.99	0.526	15650
41	2.28	0.516	17323
42	2.22	0.543	17621
43	2.38	0.502	17782
44	1.68	0.476	16207
45	2.19	0.512	17651
Ave	2.30	0.54	17399

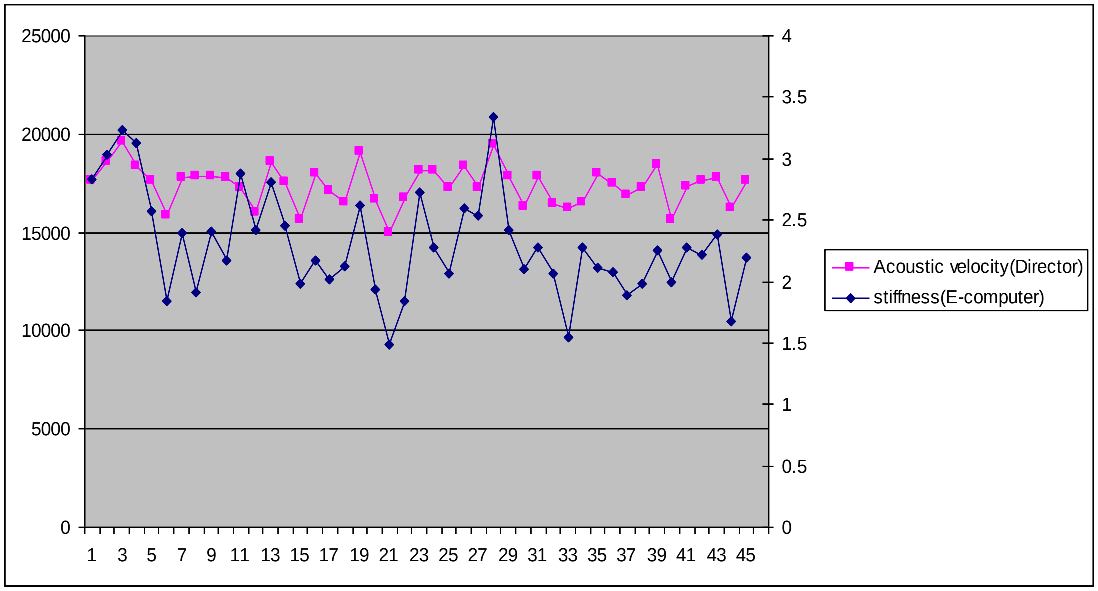


Figure 4.1 The relationship between E-computer and Director values

Trapezoids sorting results

According to non-destructive results, all trapezoids were sorted from lowest to highest. The sorted trapezoids were then paired, lowest to highest. This pairing was performed in an effort to better account for variation among beam results (Table 4.2). As a means of comparing the non destructive evaluation methods, simple linear regression was used. A linear formula and correlation coefficient was determined for the relationship between E-computer and Director results (Figure 4.2 & 4.3). The relatively strong correlation between these two techniques suggests that one can be used to predict the other and perhaps that either can be used to predict mechanical performance. Following sorting and pairing, trapezoids were jointed to form bowtie beams and each beam then received a new and unique sequentially numbered ID (Table 4.2).

Table 4.2 Sorting trapezoids depending on their strength given from E-Computer

ID	stiffness(E-computer)	Density(E-computer)	Acoustic velocity(Director)
21	1.49	0.463	14961
33	1.55	0.432	16207
44	1.68	0.476	16207
6	1.84	0.581	15846
22	1.84	0.550	16765
37	1.89	0.463	16864
8	1.91	0.506	17881
20	1.94	0.658	16634
15	1.98	0.517	15650
38	1.98	0.495	17224
40	1.99	0.526	15650
17	2.02	0.522	17093
25	2.06	0.476	17224
32	2.07	0.516	16437
36	2.08	0.538	17487
30	2.10	0.568	16306
35	2.11	0.457	18012
18	2.12	0.531	16535
10	2.17	0.537	17782
16	2.17	0.467	18012
45	2.19	0.512	17651
42	2.22	0.543	17621
39	2.25	0.467	18438
24	2.28	0.509	18110
31	2.28	0.570	17815
34	2.28	0.499	16535
41	2.28	0.516	17323
43	2.38	0.502	17782
7	2.40	0.491	17782
9	2.41	0.495	17881
12	2.42	0.653	15978
29	2.42	0.542	17881
14	2.46	0.520	17552
27	2.54	0.543	17224
5	2.57	0.561	17651
26	2.60	0.529	18340
19	2.62	0.548	19127
23	2.72	0.572	18110
13	2.81	0.538	18570
1	2.83	0.641	17651
11	2.88	0.616	17224
2	3.03	0.573	18570
4	3.13	0.630	18340

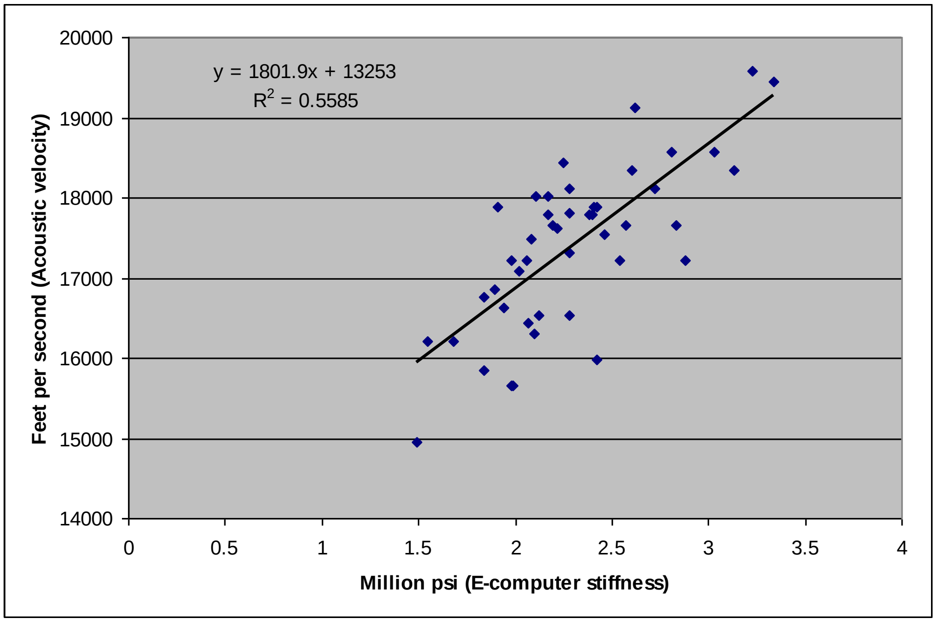


Figure 4.2 The regression plot with the correlation coefficient for E-computer stiffness and acoustic velocity results for trapezoids

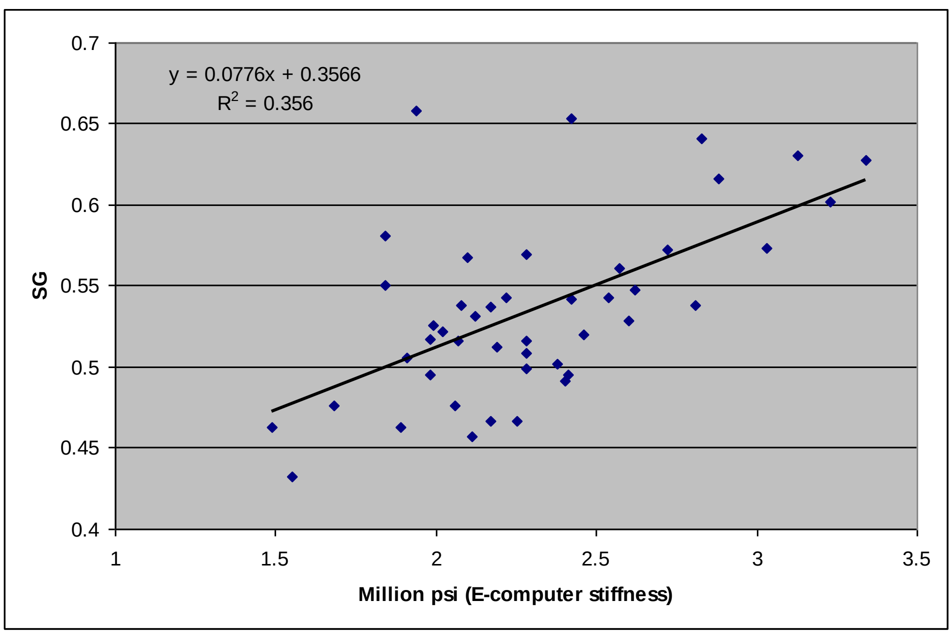


Figure 4.3 The regression plot with the correlation coefficient for stiffness and density for trapezoids

Table 4.3 Compilation of the matched pairs of trapezoids those were used to manufacture each Bowtie-Beam.

ID	Beam ID	ID	Beam ID
21	2	39	9
33		24	
44	6	31	7
6		34	
22	1	41	4
37		43	
8	22	7	21
20		9	
15	20	12	12
38		29	
40	17	14	13
17		27	
25	14	5	5
32		26	
36	8	19	10
30		23	
35	18	13	11
18		1	
10	19	11	16
16		2	
45	3	4	15
42		3	

Non destructive Bowtie-Beams results

Both results from E-computer and Director were recorded. The range of the stiffness values for Bowtie beams was between 1.39 and 2.75 million psi. The average stiffness for all Bowtie beams was 2.10 million psi with range of the specific gravity between 0.35 and 0.45, and average specific gravity of bowtie beams was 0.42. The range of acoustic velocity of bowtie beams was between 15,435 feet/sec and 19,092 feet/sec with the average acoustic velocity for all Bowtie beams was 17,536 feet/sec. Table 4.4 displays all the finding results that had recorded from Bowtie beams E-computer and

Director tests. The acoustic velocity test applied twice for each Bowtie beam, once on each of the two trapezoids from which the beam was manufactured. Most of the trapezoids of each beam gave the same value of acoustic velocity for each of the trapezoids. This behavior suggests that the beams were acting as a single composite section. Two beams (#2 & 14) however showed different acoustic velocity values for each of the two trapezoids. For these two beams, the average value of these two readings was recorded. Simple linear regression was then used to correlate E computer and acoustic velocity results in the bowtie beams. The prediction equation and the correlation coefficient were determined and are shown (Figure 4.4& 4.5). High correlation coefficient value which gives strong positive linear correlation relationship between the E-computer stiffness values and acoustic velocity values from the Director was found. The reasonably high correlation between these two techniques suggests that one can be used to predict the other and perhaps that either can be used to predict mechanical performance

Table 4.4 Bowtie-Beams results from E-computer and Director

Beam ID	E-computer	Density	Acoustic velocity
1	2.22	0.400	17224
2	1.39	0.355	15435
3	2.22	0.413	17881
4	2.10	0.410	18012
5	2.42	0.448	18110
6	1.54	0.414	16207
7	2.00	0.420	17421
8	2.15	0.441	16995
9	2.16	0.383	18438
10	2.36	0.447	18570
11	2.53	0.485	18209
12	2.39	0.486	17093
13	2.09	0.421	17421
14	2.06	0.395	17044
15	2.75	0.496	19029
16	2.54	0.474	18116
17	1.56	0.404	16437
18	2.12	0.398	17323
19	2.10	0.392	18209
20	1.57	0.404	16864
21	2.09	0.385	18209
22	1.88	0.381	17552

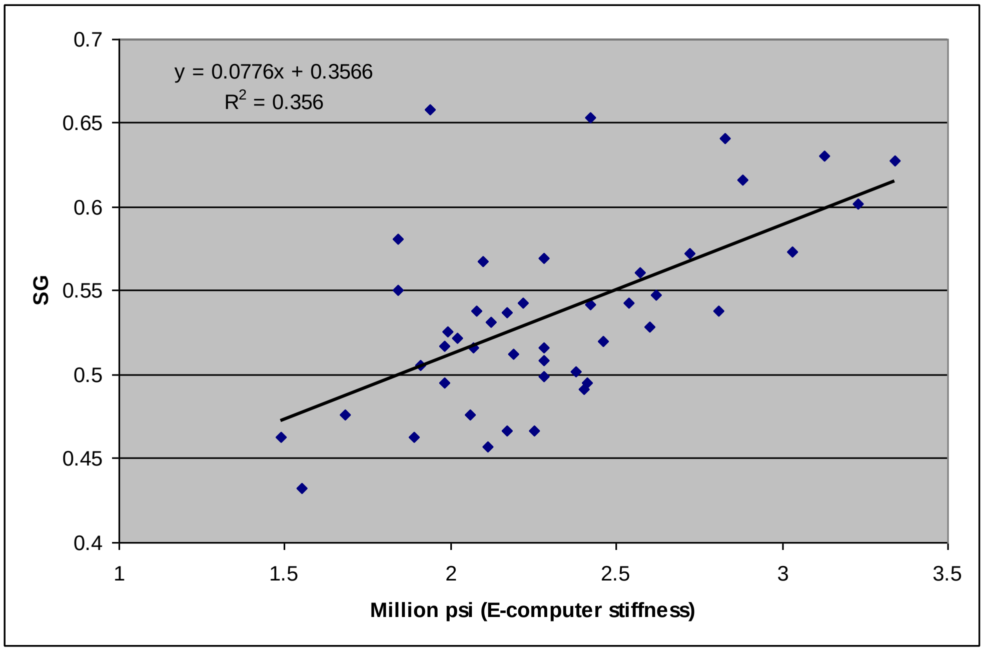


Figure 4.4 The regression plot with the correlation coefficient for stiffness and density for Bowtie-Beams based on E-computer testing.

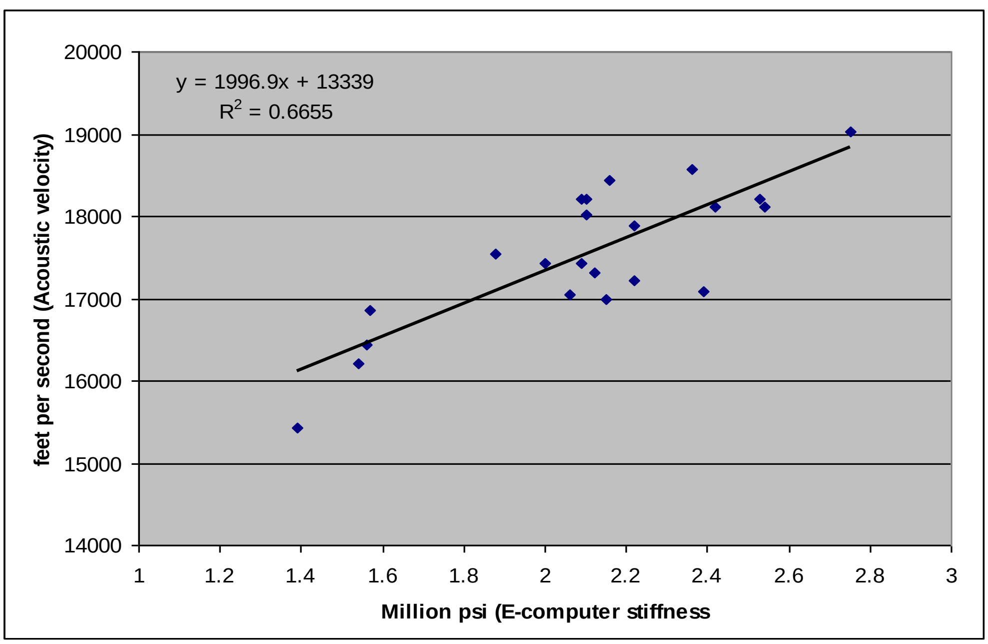


Figure 4.5 The regression plot with the correlation coefficient for E-computer stiffness and acoustic velocity results for Bowtie-Beams

Destructive test results

Bowtie-Beams measurement results

All bowtie beam dimensions (width at flanges, width at the neutral axis, and depth) were measured and recorded using a digital caliper. Many reading were taken for each critical point of each beam and the average of these readings were recorded (Table 4.5). From the results, it was determined that the average maximum flange width for the all bowtie beams was 2.01 inches. The minimum width at the neutral axis was 1.18 inches. The average beam depth was 7.67 inches. The percent of the minimum width at the neutral axis to the maximum flange width was: 1.18 / 2.01 = 0.587.

Bowtie-Beams mechanic test results

Maximum load, MOE, and MOR were recorded from mechanical testing machine. Maximum moment value (M_{max}) was calculated according to the maximum load and the load configuration. In this case, third point bending was used. As such, $M_{max}=PL/6$. Where P is the maximum load (pounds) and L is the span (126 inches) (Table 4.6). Maximum stress or MOR_{actual} is equivalent to $M_{max} \times c/I$ .Where is M_{max} is the maximum moment in pound inches, c is one half of the depth of the beam, that is, the distance from the extreme fiber to the neutral axis, and I is the moment of inertia. As a standard, the value of I $(1.5 \times (7.5)^3)/12 = 52.73$ inch^4, was input into the machine for every beam. This is the value that the machine used to calculate MOE. The machine ran its calculations with the notion that it was testing rectangular beams. To figure out the corrected MOE, the calculated MOE value was multiplied by ($52.73/ I_{actual}$) (Table 4.6).

In this case, the actual I values were larger, thus the actual E values were lower and were adjusted accordingly. A design value for stiffness of E=2.25 Million psi was calculated. The design value for E is the numerical average of the sample.

$$Adjusted = E \times \left(\frac{I_{bowtie}}{I_{fullrec\tan gle}} \right) \tag{10}$$

A design value for maximum allowable bending stress was also calculated. The design Fb was calculated as the parametric 5th percentile, divided by a 2.1 safety factor and by a 0.96 load configuration factor. The 5th percentile was calculated as the mean, adjusted for the appropriate section modulus, minus the standard deviation times the specific k-factor for the 22 member sample.

Table 4.5 Bowtie-Beams dimensional measurements results. All results are as measured in inches.

Beam Id	Width1(b1)		mean b1	Width 2 (b2)		mean b2	(b1-b2)/2	Depth(h)		mea n h
1	1.93	1.89	1.91	1.18	1.11	1.15	0.38	7.52	7.75	7.64
2	1.84	2.22	2.03	1.15	1.27	1.21	0.41	7.62	7.75	7.69
3	1.95	2.08	2.02	1.13	1.21	1.17	0.42	7.52	7.52	7.52
4	2.04	1.99	2.02	1.15	1.12	1.14	0.44	7.75	7.75	7.75
5	1.95	1.91	1.93	1.11	1.15	1.13	0.40	7.75	7.75	7.75
6	1.96	2.08	2.02	1.04	1.28	1.16	0.43	7.75	7.75	7.75
7	1.96	2.04	2.00	1.12	1.29	1.21	0.40	7.62	7.60	7.61
8	2.02	2.02	2.02	1.19	1.18	1.19	0.42	7.60	7.75	7.68
9	1.88	1.95	1.92	1.22	1.04	1.13	0.39	7.62	7.75	7.69
10	1.93	1.89	1.91	1.11	1.15	1.13	0.39	7.75	7.76	7.76
11	2.27	2.06	2.17	1.44	1.19	1.32	0.43	7.62	7.52	7.57
12	2.2	1.99	2.10	1.34	1.23	1.29	0.41	7.75	7.52	7.64
13	1.93	2.07	2.00	1.15	1.19	1.17	0.42	7.75	7.62	7.69
14	1.99	2.02	2.01	1.13	1.18	1.16	0.43	7.62	7.73	7.68
15	2.1	1.87	1.99	1.32	1.13	1.23	0.38	7.50	7.60	7.55
16	2.02	2.14	2.08	1.29	1.41	1.35	0.37	7.75	7.75	7.75
17	2.03	2.26	2.15	1.09	1.25	1.17	0.49	7.61	7.62	7.62
18	1.99	1.92	1.96	1.06	1.13	1.10	0.43	7.60	7.75	7.68
19	2.05	2.02	2.04	1.33	1.00	1.17	0.44	7.72	7.60	7.66
20	2.27	2.04	2.16	1.26	1.14	1.20	0.48	7.62	7.62	7.62
21	1.94	1.91	1.93	1.17	1.11	1.14	0.39	7.60	7.90	7.75
22	1.93	1.88	1.91	1.19	1.04	1.12	0.40	7.66	7.75	7.71
2x8# 1			1.50							7.25
2x8# 2			1.50							7.25

(Note) Width 1 is the average maximum width of flange, Width 2 is the average minimum width of the beam at the natural axis. For reference, the dimensions of two exemplar solid sawn pine two by eights is also shown.

Table 4.6 Maximum load, adjusted MOR and adjusted MOE for all tested beams

Beam Id	Maximum load (pounds)	Maximum stress (MOR, psi)	Stiffness (MOE, million psi)	Beam Id	Maximum load (pounds)	Maximum stress (MOR, psi)	Stiffness (MOE, million psi)
1	8410	10576	2.49	12	5354	6115	2.44
2	2238	2616	1.44	13	7525	8956	2.19
3	7079	8744	2.56	14	7467	8911	1.94
4	3922	4584	2.15	15	9673	11912	3.10
5	8911	10805	2.36	16	9670	10691	2.39
6	5012	5825	1.82	17	4062	4642	1.80
7	5563	6719	1.91	18	7584	9323	2.28
8	8465	9997	3.34	19	7058	8340	2.05
9	7616	9453	2.40	20	2959	3351	1.68
10	8928	10907	2.83	21	5298	6429	1.98
11	8486	9556	2.57	22	5872	7299	1.94

Summary statistics for the testing are shown below (Table 4.17).

Calculation of design Fb was performed as:

$$5^{th} \text{ percentile} = \text{mean} - (\text{st dev} \times k) \text{ and } Fb = 5^{th} \text{ percentile} / (2.1 \times 0.96) \qquad (11)$$

Where:

MOR mean = 7,989 psi
St dev = 2624 psi
k = 1.916 (based on 75% confidence level)
Safety factor = 2.1
Load configuration factor to adjust third point bending to uniform loading
= 0.96
5^{th} percentile = 2,961 psi
Fb design = 1,469 psi

Table 4.7 Summary statistics for destructive testing

	Max load (pounds)	MOR (psi)	MOE (million psi)
Mean	6,689	7,989	2.26
Stdev	2,150	2,624	0.46

The regression plots for the relationships between E-computer and actual MOR (Figure 4.6), E-computer and corrected MOE (Figure 4.7), acoustic velocity (director) and corrected MOE (Figure 4.8), and acoustic velocity and actual MOR (Figure 4.9) are presented along with the correlation coefficient for each. It was found that there are strong positive linear correlations among many of these relationships.

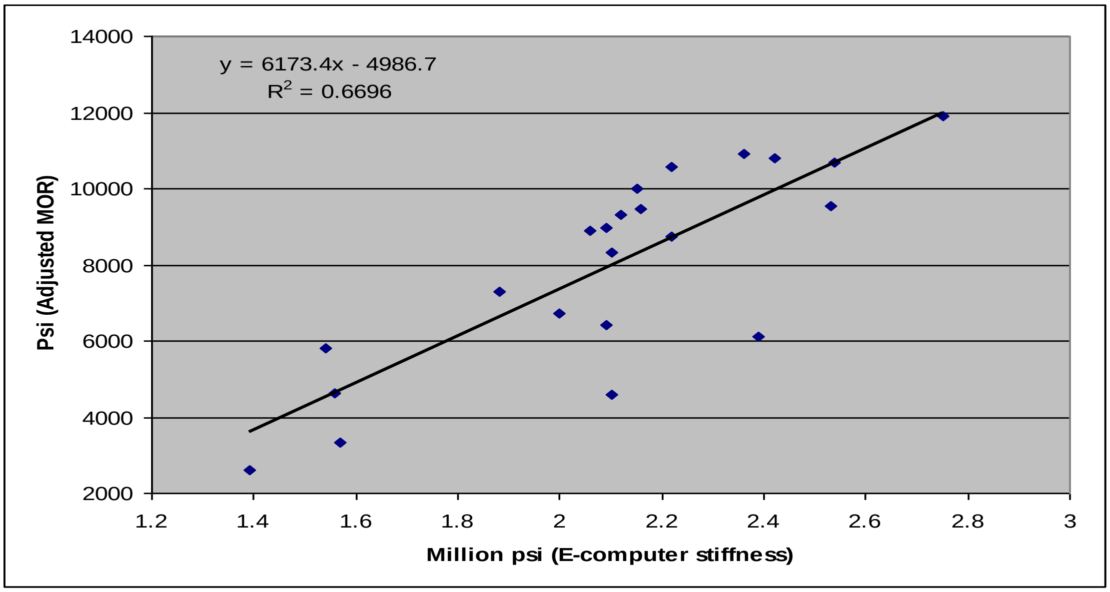


Figure 4.6 The regression plot with the correlation coefficient for the relationship between E-computer and MOR

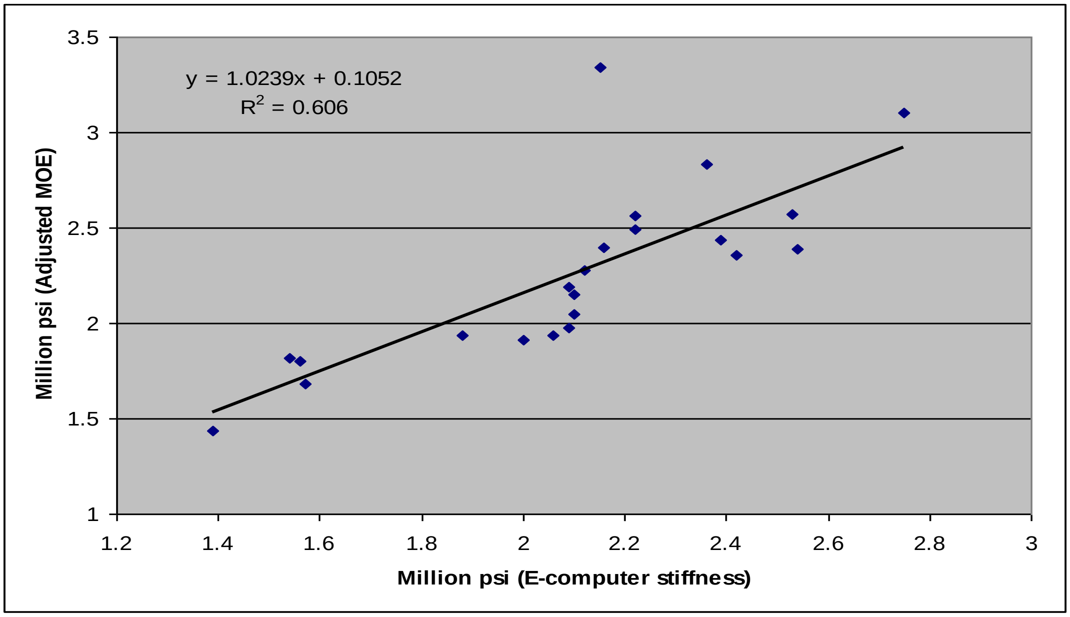


Figure 4.7 The regression plot with the correlation coefficient for the relationship between E-computer and MOE

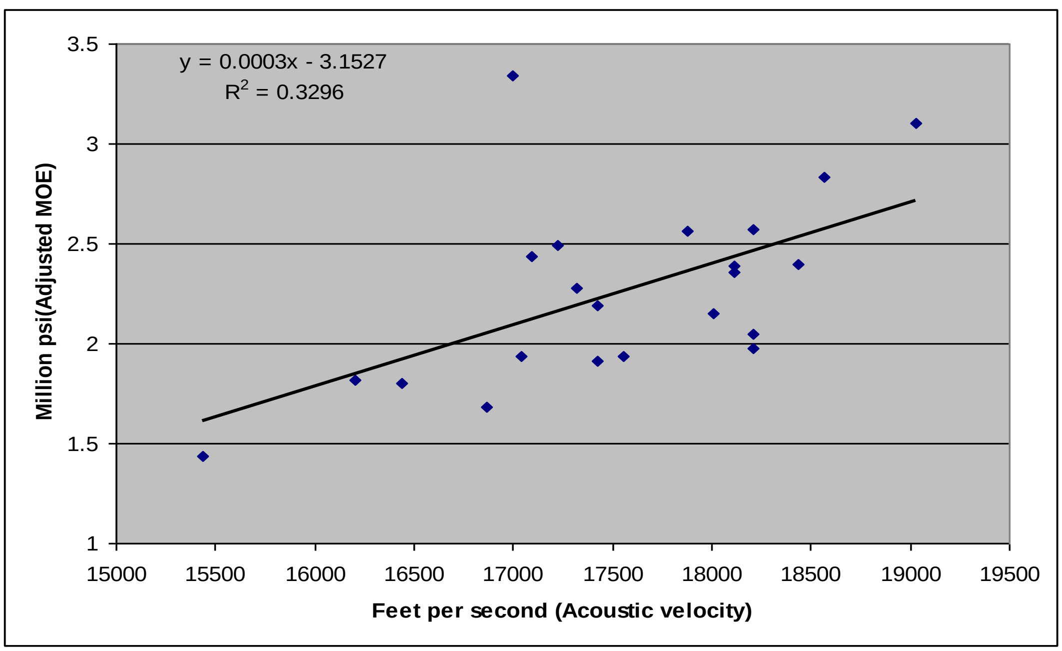


Figure 4.8 The regression plot with the correlation coefficient for the relationship between Acoustic velocity (Director) and MOE

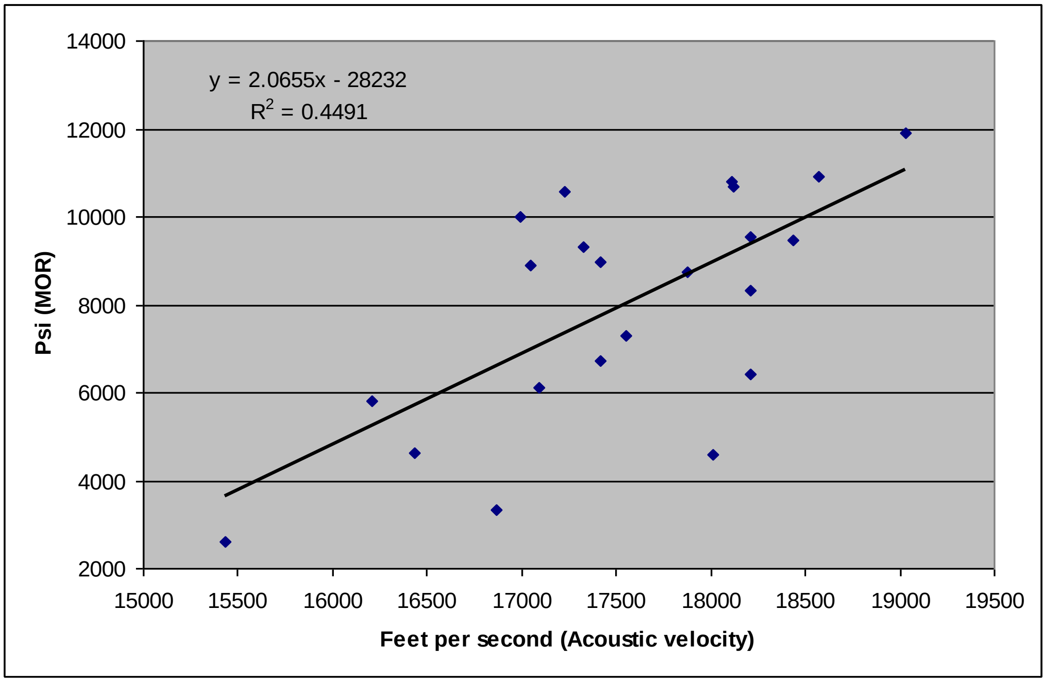


Figure 4.9 The regression plot with the correlation coefficient for the relationship between Acoustic velocity and MOR

Re-testing wood moisture content

Because of the differences in the non-destructive test results between the trapezoids before jointing and the Bowtie beams after it, moisture content were tested via the oven dry method, after testing, in an effort to verify previous results.

Eight random samples were selected from the beams and cut in to $1 \times 3 \times 35$ inches. A digital caliper was use to measure the dimensions of each sample. The dimensions for moisture content wood sample are displayed in Table 4.8. Samples were measured, weighed, and put in the oven with the temperature of 103 ℃ for 24 hours. Then samples reweighed and the moisture content was determined according to the formula:

$$MC\% = \frac{W_g - W_d}{W_d} \times 100 \qquad (12)$$

Where:

MC% = the percent of moisture content in wood sample.
W_g = the weight of the sample before drying (in the test condition) in grams.
W_d = the weight of the sample after drying in grams.

The average moisture content for the wood was 9% (Table4.8).

Specific gravity for wood samples was determined depending on the formula:

$$SG = \frac{W_d}{V \times 62.4} \tag{13}$$

Where:

Sg = the specific gravity.
W_d = the dry weight in pound.
V = the volume of the wood sample in the test condition in feet.
62.4 = the specific gravity of water.

The average specific gravity for the wood sample was 0.53 (Table 4.8).

Table 4.8 Moisture content and specific gravity test results

#	W (in)	W (f)	L (in)	L (f)	H (in)	H (f)	V f^3	W_g g	W_d g	W_d (lb)	Mc %	SG
3	1.1	0.09	34.8	2.9	3.24	0.27	0.07	1367	1254	2.76	9	0.61
4	1.11	0.09	34.9	2.91	3.29	0.27	0.07	1237	1136	2.51	9	0.55
13	1.09	0.09	35.5	2.96	3.28	0.27	0.07	1240	1142	2.52	9	0.56
16	1.13	0.09	35.7	2.98	3.35	0.28	0.08	1086	999	2.2	9	0.45
19	1.2	0.10	35.6	2.97	2.3	0.19	0.06	1016	940	2.07	8	0.59
27	1.14	0.10	35.5	2.96	3.27	0.27	0.08	1232	1132	2.5	9	0.53
42	1.15	0.10	36.1	3.01	3.25	0.27	0.08	1178	1089	2.4	8	0.49
45	1.11	0.09	36.1	3.01	3.23	0.27	0.08	1152	1064	2.35	8	0.50
										Ave	9	0.53

Failure mode results

According to ASTM standards (D-143) (ASTM, 2000) the specimens' static bending failures were classified in accordance to the type of wood failure simple. Most bowtie beams had similar failure modes, these being, tension failure and gross grain tension failure. Occasionally, the beams spit in horizontal shear.

All the tested bowtie beams, except two, had failure initiate on the tensile face. The two abhorrent failures appeared to be the result of warped trapezoids caused failure initiation at the glueline wherein a horizontal shear failure followed.

Data analyses

According to the trapezoids non-destructive test using E-computer and Director, both machines gave very similar results for evaluating the trapezoids and evaluating the bowtie beams. However, using the Director is simpler than using E-computer because of the smaller size, easier information input, and faster taking the results. From the regression plot for E-computer trapezoids test and Director results, it is found that there is a high correlation coefficient (r= 0.75), which means strong positive linear correlation and high relationship between both results. At the same time there is a strong positive relationship between the E-computer stiffness results and the wood density given by E-computer (r=0.60).

Testing the Bowtie-Beams nondestructively (Figure 4.10) gave higher correlation coefficient value for the relationship between both results from E-computer and Director machines (r=0.82). Additionally, there was high correlation between stiffness and density based on E-computer (r=0.75). The relationship between E-computer stiffness and

Bowtie beams MOR, and between E-computer stiffness and MOE was very strong (r=0.8), and the relationship between acoustic velocity results and Bowtie beams MOE, and between acoustic velocity results and MOR was also strong (r=0.6 for MOE and r=0.7 for MOR).

Figure 4.10 Bowtie-Beam has high elasticity property

By comparing the Bowtie beams design strength values to Southern pine species with 2x8 inch design strength values (bending F_b values and E values in NDS) (Table 4.9), it was found that Bowtie-Beam design strength value is between that of Number 1 and Number 2 grade pine 2x8s.

Table 4.9 Design values for visually graded Southern pine dimension lumber as in NDS

Species and commercial grade	Size classification	Design values in pounds per square inch(psi)						
		F_b	F_t	F_v	$F_{c\perp}$	F_c	E	Grading Rules Agency
Dense Select Structural	2”-4” thick 8” wide (depth)	2450	1350	90	660	2050	1,900,000	SPIB
Select Structural		2300	1300	90	565	1900	1,800,000	
Non-Dense Select Structural		2100	1100	90	480	1750	1,700,000	
No.1 Dense		1650	875	90	660	1800	1,800,000	
No.1		1500	825	90	565	1650	1,700,000	
No.1 Non-Dense		1450	725	90	480	1550	1,600,000	
No.2 Dense		1400	675	90	660	1700	1,700,000	
No.2		1200	650	90	565	1550	1,600,000	
No.2 Non-Dense		1100	600	90	480	1450	1,400,000	
No.3 and Stud		700	400	90	565	875	1,400,000	

(Note).F_b is bending strength design value.
F_t is tension parallel to grain.
F_v is shear parallel to grain.
$F_{c\perp}$ is compression perpendicular to grain.
F_c is compression parallel to grain.
E is modulus of elasticity

CHAPTER 5

DISCUSSION

Based on observation of the plotted results it appears that there may be some outlier values that strongly influence the relationship between various factors. Such outliers potentially negatively impact coefficient correlation values. Omitting those outliers from the data leads to stronger relationships between those factors such as:

Omitting the two outlier values: SG= 0.653 and SG=0.658 from the data for the relationship between E-computer stiffness and the wood density gave higher value of coefficient correlation (R=0.7) which suggests a very strong relationship between these factor. The revised relationship would be SG = 0.0832 × (E-computer stiffness) + 0.3376. In this case, if the wood stiffness has a value of 1.7 million psi the density of this wood sample will be 0.48, and when it is 3.2 million psi the density of this wood will be 0.60. This relationship seems somewhat reasonable based on existing data and experience for pine but does need further refinement at the upper end of the density scale (Figure 5.1).

Omitting the two outlier values: E=3.1 and E= 3.34 from the data of the relationship between E-computer stiffness and adjusted MOE gave very high value of coefficient correlation (R= 0.9) (Figure 5.2). Such elimination is potentially reasonable because E-values of 3.1 and 3.34 are extraordinarily high and realistically unreasonable

In this case, the value of the MOE will be given based on the value of stiffness of E-computer generated equation: MOE= 0.9246 × (E-computer stiffness) + 0.2499. In that case, if the E-computer gave the value of 1.7 million psi for the tested wood sample the MOE for the same sample will be 1.82 million psi, and when the value of E-computer is 2.6 million psi the value of MOE will be 2.7 million psi. These correlations seem to be improved over the ones that are based on the entire data set.

Omitting the two outlier values: E=3.1 and E= 3.34 from the data of the relationship between acoustic velocity and adjusted MOE gave very high value of coefficient correlation (R=0.7). This change improves the MOE value from the acoustic velocity tests. The new relationship would be: MOE = 0.0003 × (Director Acoustic velocity) - 3.2734. Thus, if the Director gave the acoustic velocity of the wood sample equal to 15,500 feet per second the MOE for the wood sample will be 1.4 million psi, and if the acoustic velocity is 18,500 feet per second the MOE 2.3 million psi. These prediction values agree very well with actual MOE ranges (Figure 5.3).

To compare the accuracy between the results of the two devices (E-computer and acoustic velocity), randomly, one of the beam sample was chosen and the revised equations were applied. Sample number 7 which has the value of the E-computer stiffness 2 million psi, and the value of acoustic velocity of 17,421 feet/sec, and the coefficient correlation equations applied for this beam sample.

The MOE value for this sample calculated by using the E-computer coefficient correlation equation is 2.1 million psi, and for the Acoustic velocity director coefficient correlation equation is 2.0 million psi. The calculated results for both devices are displayed in table 5.1. By comparing the MOE value calculated from both devices, it is found that either of the non destructive devices can provide very good results.

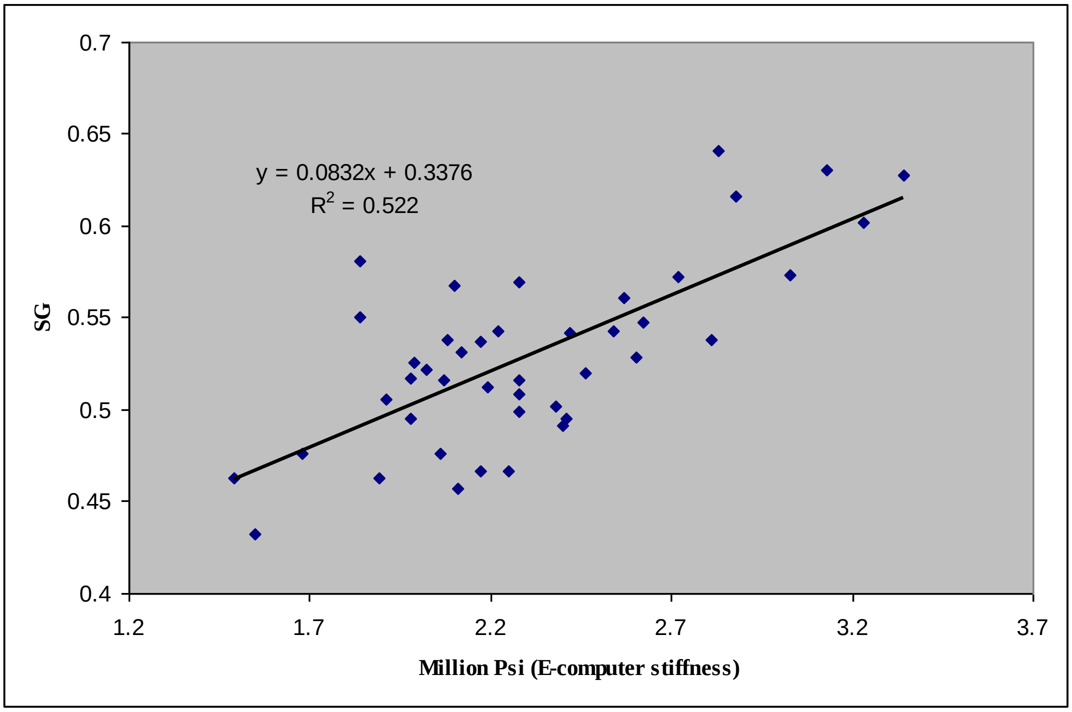


Figure 5.1 The regression plot with the correlation coefficient for stiffness and density for trapezoids after omitting potential outlier values

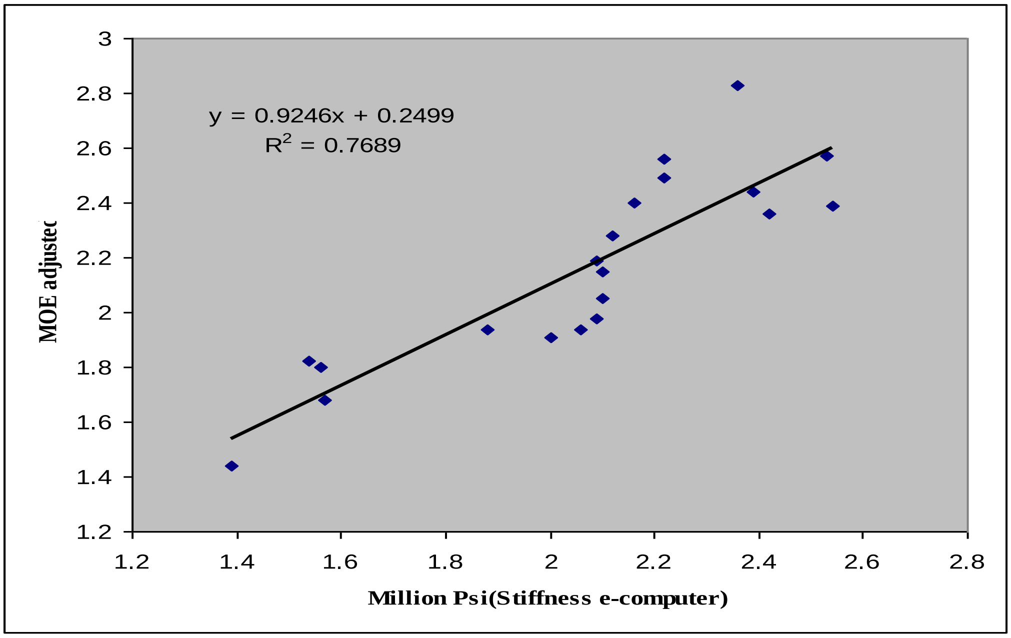


Figure 5.2 The regression plot with the correlation coefficient for the relationship between E-computer and MOE after omitting two potential outlier values

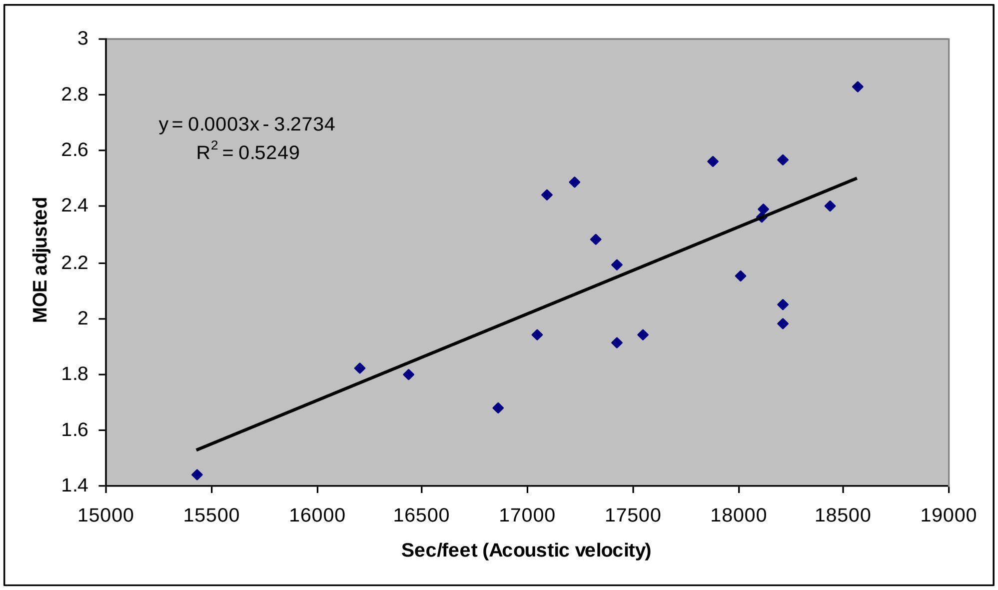


Figure 5.3 The regression plot with the correlation coefficient for the relationship between acoustic velocity and MOE after omitting two potential outlier values

Table 5.1 The calculated MOE values from the results of the E-computer and Director

Beam ID	E-computer	MOE (from E-computer)	Acoustic velocity	MOE (from director)
1	2.22	2.3	17224	1.9
2	1.39	1.5	15435	1.4
3	2.22	2.3	17881	2.1
4	2.1	2.2	18012	2.1
5	2.42	2.5	18110	2.2
6	1.54	1.7	16207	1.6
7	2	2.1	17421	2.0
8	2.15	2.2	16995	1.8
9	2.16	2.2	18438	2.3
10	2.36	2.4	18570	2.3
11	2.53	2.6	18209	2.2
12	2.39	2.5	17093	1.9
13	2.09	2.2	17421	2.0
14	2.06	2.2	17044	1.8
15	2.75	2.8	19029	2.4
16	2.54	2.6	18116	2.2
17	1.56	1.7	16437	1.7
18	2.12	2.2	17323	1.9
19	2.1	2.2	18209	2.2
20	1.57	1.7	16864	1.8
21	2.09	2.2	18209	2.2
22	1.88	2.0	17552	2.0

From the results of the acoustic velocity, it was found that the acoustic velocity values from the trapezoid evaluation differed from those results from the bowtie beams. The input data was the same in both tests (the length of the trapezoids equal to the length of the bowtie beams), and they were tested under the same conditions. From the moisture content results, it was found that no moisture content changes occurred during the entire research. These results suggest that other factors may affect the results. One potentially significant other factor is the affect of the adhesive. Because the director measures the acoustic velocity of the sound wave inside the wood, this velocity may be changed when the material changes. Adding glue to the beams (even there is very small amount of glue was added) will lead to penetrate some of this glue in to the wood, and this may affect the velocity of the sound waves inside the wood and this may lead to these differences between the acoustic velocity trapezoids values and acoustic velocity bowtie beams values.

From the results of the specific gravity test, it was found that there is a difference between the specific gravity given by E-computer and the calculated specific gravity, by oven and scale method after moisture content test. This result suggests that the specific gravity results from the E-computer are not highly accurate. This inaccuracy can largely be traced to the fact that there is no provision to enter a bowtie section or a trapezoid section in the E-computer. Rather a surrogate rectangular shape was entered. The E-computer device would be significantly improved if it had a provision for alternate sections such as trapezoids, bowties, I-sections, etc.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

Conclusion

Continual decreases in average tree and log diameters to accelerate income production for timber owners, increases in population, and its associated demand for material goods creates an urgent and pressing need to develop low cost, high performance products that act as alternatives to solid sawn lumber. The bowtie beam as detailed herein is one of these alternatives. It can be developed from small diameter trees, with little additional cost over and above sawn lumber, and a minimal amount of adhesive as compared to other structural products. Bowtie beams can be used for many structural applications such as flooring and ceiling supports.

The bowtie beam improves many of the desirable properties of wood as a structural material such as strength and stiffness properties, with minimal additional amounts of raw materials (sawn wood and adhesive) which make this product friendly to the environment.

Non-destructive tests such as vibrational stiffness (E-computer) or acoustic velocity (Director) are likely sufficient in evaluating the mechanical properties of both the raw wood materials and the finished bowtie beam product. Beam stiffness is very often most important property for wood industry. Results of this study demonstrated strong relationship between the bowtie wood beams properties given by E-computer, acoustic velocity as non-destructive tests, and static bending properties techniques as destructive test.

Recommendations

The research detailed herein illustrates that new engineered wood products have great potential as alternatives to sawnwood. Engineered wood can often provide better quality and uniformity than sawn lumber. For manufacturing, small diameter trees can be used for manufacturing engineering wood of large sectional properties such as depth, instead of using large tree diameters. In this manner, small diameter trees and forests can potentially enhance the economy and provide the market with great quality products.

Using non-destructive tests for quality evaluation of wood is highly promising because of the highly correlated relationships among vibrational stiffness, acoustic velocity, stiffness, and strength. With respect to the environment, engineered products such as this can protect and enhance both forest resources and commercially viable market demand driven solutions and products. As compared to other engineering wood beams such as glue laminated timber and laminated veneer lumber, bowtie beams are most likely less expensive and relatively easy to manufacture. As compared to engineered wood I-joists which incorporate a very thin web material, the thicker bowtie beam is likely significantly more durable in fire resistance performance.

The E-computer provides an important means of nondestructive evaluation for strength and stiffness but it is not highly accurate with respect to measuring wood density/specific gravity. The E-computer technology would be improved if it were able to account for material sections other than rectangles, such as, I beams, trapezoids, bowties, etc.

This research will likely lead to future research on similar fields of study such as testing of other types of adhesive in manufacturing, other species, and use of other types of wood composite products instead of sawn lumber. It will be particularly interesting to see this concept applied to other construction species. While it could be applied to low value hardwoods, it can perhaps most readily be applied to small diameter softwoods such as beetle killed pine in the upper Midwest and other thinning that are prevalent on national forest lands. Additionally, the strong relationship between non destructive testing and ultimate destructive testing suggests that this technology and be further developed and readily applied in commercial situation.

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