Suitability of Salvaged Timber in Structural Design

by

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ABSTRACT

Increased demand for timber construction in the United States has placed a strain on the American timber reserve. At the same time, the annual demolition of thousands of buildings and wood structures results in thousands of tons of waste earmarked for incineration or landfill disposal. There exists a great potential to reuse most of the wood already standing in today's structures for tomorrow's construction. Identifying alternatives for virgin timber can create economic opportunity and help to mitigate an expensive and environmentally sensitive landfill problem.

This thesis describes the opportunities, barriers, and benefits of using reclaimed lumber and timbers in new construction. Factors affecting the mechanical properties of wood are examined and changes in strength over time are quantified. Utilizing current research, various sources of reclaimed timber are studied and recommendations are made as to their potential for reuse in structural design.

Thesis Supervisor: Jerome J. Connor
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I. INTRODUCTION

For centuries, wood has been a favorite building material due to its availability, workability, and overall strength. Even as the world gravitates toward steel and concrete construction, wood remains a popular material of choice. Although wood is a highly available and renewable resource, it is not an unlimited one. The United States is the world's largest producer and consumer of timber products, including both softwood and hardwood lumber. In 2008, the United States produced 49.4 million cubic meters of sawn softwood and 19.1 million cubic meters of sawn hardwood.[1] Diminishing reserves of American sawtimber have led to an increased reliance on imported foreign lumber and a competitive demand on forest ecosystems.

As a result, alternative sources to virgin timber are being explored for use in structural design. Recently, salvaged timbers have been popular for their aesthetics and reuse as value added wood products such as flooring, paneling, and siding. Some recycled wood members, such as barn timbers, are used in new construction, but are more desirable as an architectural feature than a structurally integral member. Little technical information exists on the residual engineering properties of these reclaimed wood timbers. Identifying alternatives for virgin timber can create economic opportunity and help to mitigate an expensive and environmentally sensitive landfill problem.

This thesis will quantify how the strength properties of wood are affected over time by a number of conditions experienced during the life cycle of a structural wood member. Three prospective reclaimed timber sources – dimensional lumber from deconstructed buildings, timber from industrial buildings, and utility poles removed from service – will be examined using current research and recommendations will be made as to their practicality for reuse in structural design.

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[1] Howard, James L. and Westby, Rebecca. *U.S. Forest Products Annual Market Review and Prospects, 2005–2009.*

Factors Affecting the Mechanical Properties of Wood

In order to examine the structural integrity of salvaged timber, it is first important to understand wood as a building material and some of the factors that affect its bending strength (Modulus of Rupture, MOR) and stiffness (Modulus of Elasticity, MOE). The *Wood Handbook: Wood as an Engineering Material*, published by the U.S. Department of Agriculture Forest Service[2], is an excellent reference for natural occurring characteristics that affect the mechanical properties of wood, such as specific gravity, knots, shakes and checks, and grain orientation. For the purpose of this report, emphasis is placed on characteristics that affect wood's strength over time. The most common of these conditions are listed below. More specific strength conditions will be examined as they apply later in this report.

1. Moisture Content

Moisture content is the percentage of water that exists in completely dry wood. All green wood contains moisture that can vary from 30% to more than 200% of the wood's weight. For most construction purposes, wood must be dried to a moisture content of 19% or less. Dimensional lumber is often air-dried or kiln-dried, a process that heats the wood until excess moisture has evaporated and the wood maintains a constant weight. The amount of water retained in the cell walls after drying is defined as moisture content.

In general, strength properties are considered to decrease as the moisture content increases. This is true only until the wood reaches its fiber saturation point (FSP), between 25-30% moisture content for most species. Saturation after this point is not maintained within the cell walls, but rather the cell cavities and does not affect the mechanical or physical properties of the wood. Wood will continue to adjust to the relative humidity of its surroundings. As such, it is generally good practice to

[2] USDA. *Wood Handbook: Wood as an Engineering Material, Centennial Edition.*

install wood with similar moisture content to the environment in which it will serve. Beyond a change in the mechanical properties, variations in the moisture content of wood can lead to dimensional changes, insects, or fungus attack.

2. Duration of Loading

Wood is capable of withstanding higher loads for a shorter period of time than it can for a longer time period. In the 1940's, the Forest Products Laboratory (FPL) attempted to quantify the load duration effect of wood. Standard bearing tests on clear Douglas fir members were conducted to establish baseline strength. A second test was then conducted on identical members at a pre-selected percentage of strength and the time to failure was observed – in some cases, more than five years. The results of this experiment are shown in Figure 1. A hyperbolic curve fitted to the data points predicts that the strength of the member after fifty years is equal to 9/16 of the short term strength.

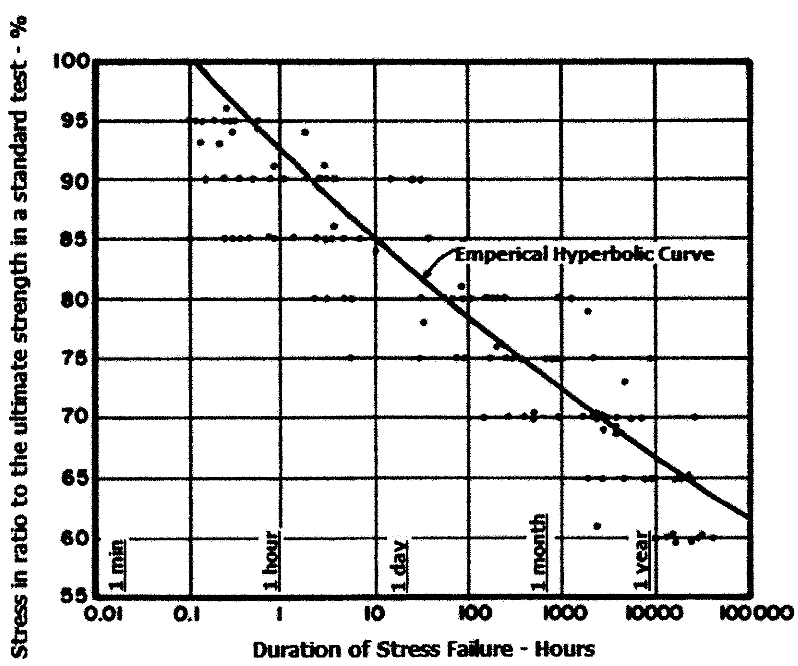

Figure 1: Relation of duration of constant stress to level of stress in long time loading [3]

[3] Wood, Lyman. *Relation of Strength of Wood to Duration of Load.*

More recent studies, however, show that strength degradation may not be as severe for commercial lumber as reported in clear wood. Additionally, the failure mode exhibited in the FPL experiment was one of compression. Due to the localized slope of the grain caused by knots, the most commonly observed failure mode in commercial lumber is one of tension. Figure 2 shows the results of an experiment conducted on commercial lumber by the University of British Columbia in comparison to the FPL results (Madison Curve).

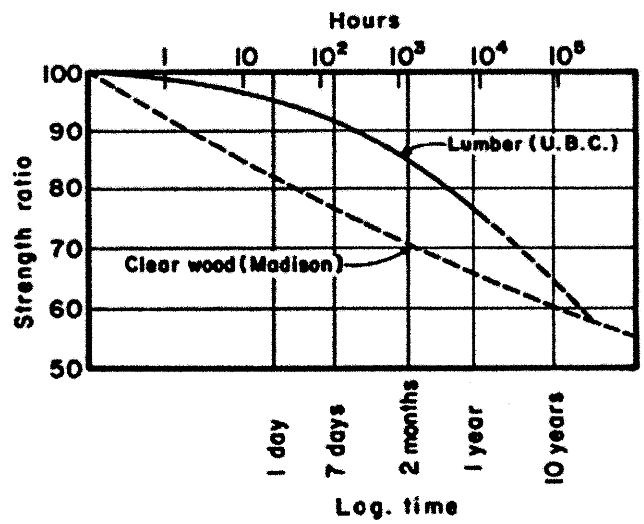

Figure 2: Comparison of load duration trend lines [4]

For structural design purposes, the National Design Specification (NDS) for Wood Construction lists a load duration factor as one of fourteen adjustment factors required to be applied as necessary to tabulated design values. The load duration factor is applicable to all allowable stresses except compressive stress perpendicular to grain and modulus of elasticity. Listed in Table 1, the load reduction factor clearly reduces capacity for permanent structures versus an increase in capacity for shorter loading durations. [5]

[4] *Evaluation, Maintenance and Upgrading of Wood Structures.* American Society of Civil Engineers.
[5] *National Design Specification for Wood Construction, 1991 Edition*. American Forest & Paper Association.

Loading Condition	Adjustment Factor, C_d	Example
Permanent Load	0.90	Load exceeding ten years
Normal Duration	1.00	Typical building occupancy
2 Months	1.15	Snow loads
7 Days	1.25	Construction loads
10 Minutes	1.60	Wind and earthquake loads
Impact Loads	2.00	Dropped weight

Table 1: Load duration factors used in structural design

An additional concern for wood members under prolonged loading is creep. Wood structures deflect immediately when loaded; any increase beyond the initial deflection is known as creep. Figure 3 shows the stages of creep. Primary creep, segment AB, is the continued deflection after the initial load. During secondary creep, segment BC, little deflection occurs. Tertiary creep, segment CD, may occur if the load is maintained long enough and may result in failure. Figure 4 demonstrates how wood members subjected to varying amounts of stress react to creep. Members 3 and 4 are under high stress; tertiary creep occurs rather quickly leading to failure. Member 2 is under less stress and only beginning to reach tertiary creep. Member 4 is under low stress and has not, and may never, reach tertiary creep. If the stresses are kept low enough, failure due to creep will never occur during the expected lifetime.[6]

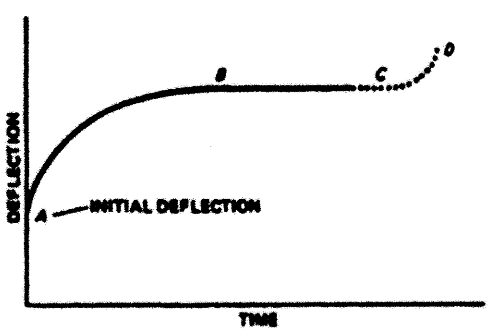

Figure 3: Stages of creep deflection

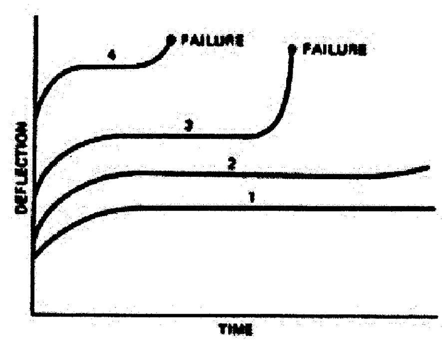

Figure 4: Creep at various stress intensities

[6] Stalnaker, Judith J. and Harris, Ernest C. *Structural Design in Wood, 2nd Edition.*

3. Temperature

Prolonged exposure to extreme high or low temperatures can have immediate and permanent effects on structural wood members. Table 2 shows the effects of temperature on the mechanical properties of wood at various moisture contents.

Property	Moisture Condition	Relative change in mechanical property from 20°C (68° F)	
		At -50° C (-58° F)	At +50° C (122° F)
	%	%	%
Modulus of elasticity parallel to the grain	0	+11	-6
	12	+17	-7
	> FSP	+50	–
Modulus of elasticity perpendicular to the grain	6	–	-20
	12	–	-35
	≥ 20	–	-38
Modulus of rigidity	> FSP	–	-25
Bending strength	≤ 4	+18	-10
	11 to 15	+35	-20
	18 to 20	+60	-25
	>> FSP	+110	-25
Tensile strength parallel to the grain	0 to 12	> -10	> -4
Compressive strength parallel to the grain	0	+20	-10
	12 to 45	+50	-25
Shear strength parallel to the grain	> FSP	–	-25
Tensile strength perpendicular to the grain	4 to 6	–	-10
	11 to 16	–	-20
	≥ 18	–	30
Compressive strength perpendicular to grain at the proportional limit	0 to 6	–	-20
	≥ 10	–	-35

Note: Dashes reflect no information on the property.

Table 2: Effects of temperature on mechanical properties of clear wood [7]

[7] Gerhards, C.C. *Effects of Moisture Content and Temperature on the Mechanical Properties of Wood: An Analysis of Immediate Effects.*

With the exception of tensile strength parallel to the grain, all measured strength properties increase when exposed to lower temperatures. Conversely, all properties decrease when exposed to higher temperatures. Thermal degradation may occur at temperatures less than 68° F, but is presumed not to occur until hundreds of years have passed. In this case, the time dependency effects are considered fully reversible. Alternatively, thermal degradation from prolonged exposure to temperatures above 68° F may result in irreversible changes. This is most likely to occur in steam heated exposure where hot, moist environments cause a higher rate of degradation.[8]

4. Weathering

The weathering of structural wood members creates an aesthetic change that has been a source of demand for salvaged timber. Exposure to water, light, and heat force wood to undergo chemical changes resulting in a gray outer layer most often associated with aged wood. This layer only penetrates the wood up to 2mm. Physical decomposition of wood also occurs, causing surface erosion of approximately 3 - 6mm per 100 years.[9] These chemical and physical changes are the most noticeable and dominant changes due to weathering, and the amount of each varies with the type and length of exposure. Under favorable conditions, wood can last for centuries. Exposed to adverse climate, such as the tropics, it may only last a few years.

Surprisingly, weathering has very little effect on the structural properties of wood. In 1975, researchers at the Institute for Wood Biology and Wood Protection in Hamburg, Germany examined wood members between 900 - 4400 years old to determine the effects of weather. The results showed weathering to be essentially a surface effect with structural properties being only slightly effected.[10] Figure 5 shows the effects of weathering on round and square timbers. Note that the cutaway shows the interior wood relatively unchanged.

[8] *Evaluation, Maintenance and Upgrading of Wood Structures.* American Society of Civil Engineers.
[9] Feist, William C., *Weathering and Protection of Wood.*
[10] Borgen, K. et. al. *The Effect of Aging on the Ultrastructure of Wood.*

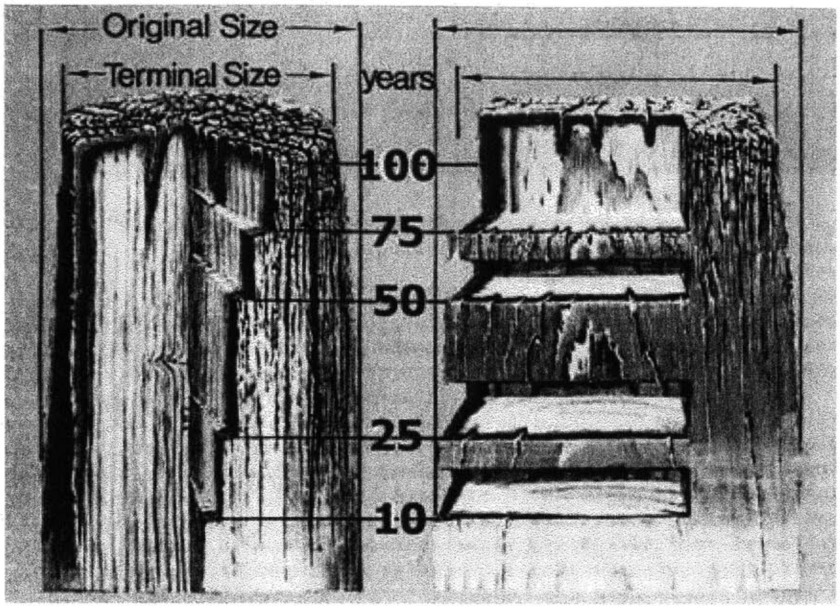

Figure 5: Weathering process of timbers [11]

5. Chemicals

Chemicals affect the strength of wood in two general types of action. In the first type, chemicals such as alcohols and other polar solvents cause swelling in air-dry wood. The removal of the swelling liquid returns the wood member to its original dimensions. In this case, the effect of the chemical is almost completely reversible and no reduction in strength occurs. The second type of action is caused by chemicals classified as acids, alkalis, salts, and oxidants. Each of these chemicals reacts with the wood in a different way causing permanent strength loss that can be fast or slow depending on the concentration of the chemical, the pH, and the temperature. In general, softwoods are more resistant to chemicals than hardwoods, and heartwood is more resistant than sapwood. Table 3 shows the strength retention of ¼ x ½ x 6 inch wood samples soaked in acidic solutions at 120°F for one week as a

[11] Feist, William C., *Weathering and Protection of Wood.*

percentage of water soaked control samples. Note that Douglas fir is a softwood, naturally more resistant to chemicals than white oak, a hardwood.[12]

Species	Concentration %	Nitric %	Sulfuric %	Acetic %	Caustic %
Douglas	2	80	92	90	22
Fir	6	60	89	88	0
White	2	44	80	101	20
Oak	6	13	60	101	0

Table 3: Strength retention after chemical exposure

6. Decay due to fungi and insects

There are three categories of wood decay fungi: white rot, which bleaches the affected wood; brown rot, which produces a crumbling decay; and soft rot, a process which soften the wood's surface. A greater propensity for fungal growth exists in wood that is in contact with soil, a major source moisture. Both hardwoods and softwoods are attacked by brown and white rot fungi when in contact with the soil. In above ground construction, white rot fungi are more common in hardwood than softwood lumber and products, where brown rot is prevalent. Consequently, brown rot is the most common type of decay in above ground construction due to the predominant use of softwood lumber. Soft rot is more prevalent in hardwoods and has a greater tolerance for low oxygen levels; therefore, soft rot is more exclusively found in saturated environments such as cooling towers.[13]

Brown rot causes a more rapid decrease in the strength properties of wood than white rot due to deeper penetration and faster consumption of the cell walls by the mechanical degrading mechanisms of brown rot fungi. Table 4 shows the percentage of strength reduction in southern pine

[12] *Evaluation, Maintenance and Upgrading of Wood Structures.* American Society of Civil Engineers.
[13] Ibid.

species due to brown and white rot fungi. Serious reductions in strength are noted in the presence of brown rot.

	Loblolly Pine		Slash Pine	
Property	L. saepiaria (brown rot) %	P. gigantae (white rot) %	L. saepiaria (brown rot) %	P. gigantae (white rot) %
Specific Gravity	6	8	7	7
Modulus of Rupture	46	15	57	12
Modulus of Elasticity	14	8	33	7
Maximum Crushing Strength	18	15	22	11

Table 4: Strength reduction due to brown-rot and white-rot fungi [14]

The presence and damage due to insects is highly variable dependant on the species. Varieties of termites and boring beetles can infest and feed on lumber of various moisture content, ranging from very damp to very dry, and reduce sawn wood products to sawdust. Carpenter ants and carpenter bees do not feed on wood. Rather, they burrow into timbers creating nests and chambers throughout the wood member. Immediate removal of wood products containing these insects is the best protection against future infestation.

Organisms that cause wood decay – both fungi and insects – require oxygen, a favorable temperature, moisture, and food. While exposure to oxygen and temperature are difficult variables to control, the effects of moisture can be mitigated through the use of water repellant preservatives. Building codes often require a minimum clearance above ground for wood construction. Site sanitation and insecticide soil treatments are the principal methods for preventing insect damage. Best practice typically dictates that wood exposed to decay not be reused for structural purposes.

[14] Richards, C.A. and Chidester, M.S. *The effect of Peniophora gigantae and Schizophyllum commune on strength of southern yellow-pine sapwood.*

Current Grading Process

One of the common barriers that exist for salvaged timber, regardless of source, is the lack of a proper grading system. Unlike steel or concrete which can be tightly controlled and monitored during production to ensure quality, wood is a natural product whose quality is dependent on its response to environmental conditions and variability between tree species. For structural lumber, there are two types of grading – visual and mechanical. The most common method, visual grading, involves a grader examining each piece for defects that may affect the structural strength. A grade and stamp is then assigned to the piece allowing the user to determine its probable strength. Mechanical grading is used only for thinner material up to four inches in nominal thickness. After visual grading, the lumber is passed through a grading machine which bends the member to a predetermined curvature and measures the force required to deflect it. The member is then be assigned a flexural modulus of elasticity, E.

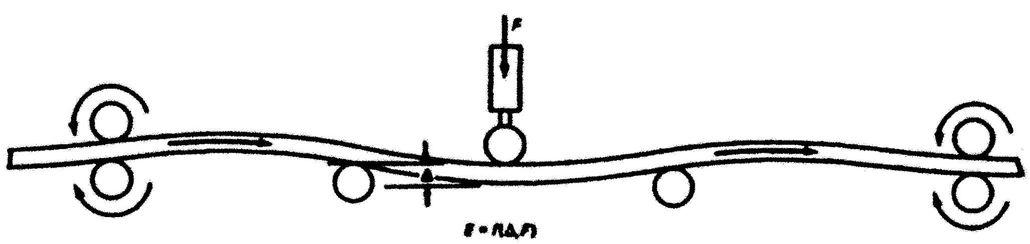

Figure 6: Exaggerated schematic of a lumber grading machine [15]

These grading methods are used only for virgin lumber and are not applicable to salvaged timber. More information must be known about the effects of stress over time and defects on the structural properties of salvaged timber in order to certify it for structural use.

[15] Stalnaker, Judith J. and Harris, Ernest C. *Structural Design in Wood, 2nd Edition.*

II. SALVAGED DIMENSIONAL LUMBER FROM RESIDENTIAL DECONSTRUCTION

Availability

Residential construction accounts for over one third of new construction in America and is the largest consumer of softwood lumber. In 2008, the United States built 622,000 new, single-family homes; this number followed a decreasing economic trend from 2005 when annual home production peaked at 2,068,000 units.[16] Conversely, the U.S. Environmental Protection Agency estimates that 245,000 residential homes are demolished annually, of which as much of 85% of the waste is discarded in landfills.[17]

Additionally, hundreds of military bases are being closed, realigned, or converted to civilian uses. Many of the existing buildings on these bases, primarily barracks and warehouses, date to World War II and have become obsolete, are inconsistent with reuse plans, or no longer meet current codes for public safety. According to a 1995 estimate by the U.S. Army Corps of Engineers, over 250 million board feet of lumber was available from World War II era buildings then slated for demolition.[18] These buildings, and more from other military branches, government agencies, and the private sector are prime candidates for deconstruction.

Barriers

Current grading standards for fresh cut dimensional lumber do not take into account the characteristics commonly found in reclaimed lumber which has been subjected to a lifetime of use. The effects of long term loading, damage from installation and deconstruction, and multiple nail holes have not been properly quantified and may lead to reclaimed lumber being unnecessarily downgraded.

[16] Howard, James L. and Westby, Rebecca. *U.S. Forest Products Annual Market Review and Prospects, 2005–2009.*
[17] EPA. *Characterization of Building-Related Construction and Demolition Debris in the United States.*
[18] Falk, Bob. *Wood-Framed Building Deconstruction: A Source of Lumber for Construction?*

Lumber in older buildings also has the increased potential of having been in contact with materials such as lead based paint, PCBs, and asbestos.

Furthermore, the deconstruction process required to harvest reclaimed lumber is a much more time and labor intensive process than demolition, though proceeds from reclaimed materials may help offset the associated costs. Reclaimed lumber must also overcome marketability and perception of quality. Even if proven to be structurally adequate, a fiercely competitive market of fresh lumber is often more readily available at a cheaper price.

Current Research

Limited research has been conducted on reclaimed lumber. Small specimens cut from 85 year old roof trusses were examined by Fridley et. al to determine the compressive and parallel-to-grain properties; comparison to historic research values showed no difference in material strength.[19] Lanius et. al. used non-destructive techniques to evaluate the elastic modulus of in-place floor joists and suggested the values be used to determine strength using existing elastic modulus-strength relationships.[20] Neither of these studies utilized destructive tests on full-sized reclaimed members.

The first, in-depth study conducted with full-size, reclaimed dimensional lumber was published by the Forest Products Laboratory in 2008. Over 1,000 2x6-10 foot, 2x8-12 foot, and 2x10-14 foot were collected from deconstructed buildings at four locations: (1) Fort Ord, Marina, California – barracks and warehouse; (2) Oakland Naval Supply Center, Oakland, California – warehouse; (3) University of Washington Campus, Seattle, Washington – university (former military) housing; (4) Twin Cities Army Ammunition Plant, New Brighton, Minnesota – warehouses. All buildings were wood framed and built in the early 1940s in preparation for World War II. The 1,078 pieces tested – consisting of reclaimed

[19] Fridley, K. J. et.al. *Effect of 85 years of service on mechanical properties of timber roof members. Part 1. Experimental Observations.*
[20] Lanius, R.M. et. al. *Strength of old joists.*

wall studs, floor joists and stringers, roof joists, and roof rafters – were visually graded as either Select Structural (SS) or No.2. Over 90% of the lumber collected was Douglas fir. Table 5 shows a summary of the pieces tested.[21]

		Location				Total
Size	Grade	Fort Ord	UW[a]	TCAAP[b]	Oakland	#
2 x 6	No. 2	98	20	--	16	134
	SS	12	36	--	47	95
2 x 8	No. 2	220	167	--	--	387
	SS	40	2	--	--	42
2 x 10	No. 2	--	--	53	53	106
	SS	--	--	117	197	314
Total	#	370	225	170	313	1078

[a] University of Washington

[b] Twin Cities Army Ammunition Plant

Table 5: Size and grade of reclaimed lumber tested

A total of 662 1x1x16 inch small clear specimens were cut from full size members and tested in order to verify the assumption that the properties of wood do not change appreciably with time. Standard center point bending tests were conducted and member stiffness and strength was compared to historical averages. Additional observations included the time until failure and the type of failure. Blocks cut from the specimens after failure were used to calculate specific gravity and moisture content. The results show that bending strength (MOR) was only slightly lower than historical data. Stiffness (MOE) was greater than the historical average by nearly 11%. Attention was also given to the geographical location from which the members were harvested. The minor variances in modulus of elasticity were attributed to the difference in specific gravity and not necessarily the geographical location. Results from the small clear bending tests can be seen in Table 6 and Figure 7.

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[21] Falk, R. et. al. *Engineering Properties of Douglas-Fir Lumber Reclaimed from Deconstructed Buildings*.

Property	Reclaimed No.	Reclaimed Mean	Reclaimed COV[a]	Historical Mean[b,c]	Difference Mean (%)[d]
MOR (x 10^3 psi)	622	13.59	16.3	13.7	0.7
MOE (x 10^6 psi)	622	2.06	18.4	1.86	10.8
Specific Gravity	582	0.48	11.1	0.49	2.0
Moisture Content (%)	586	11.4	8.9	12.0	5.0

[a] Coefficient of variation is standard deviation/mean

[b] Average of Coast, Interior West, and Interior North regions

[c] Percentage difference is (historical average - reclaimed average)/historical average

[d] As reported in the *Wood Handbook* (FPL 1999)

Table 6: Reclaimed and historical small clear data for Douglas fir [22]

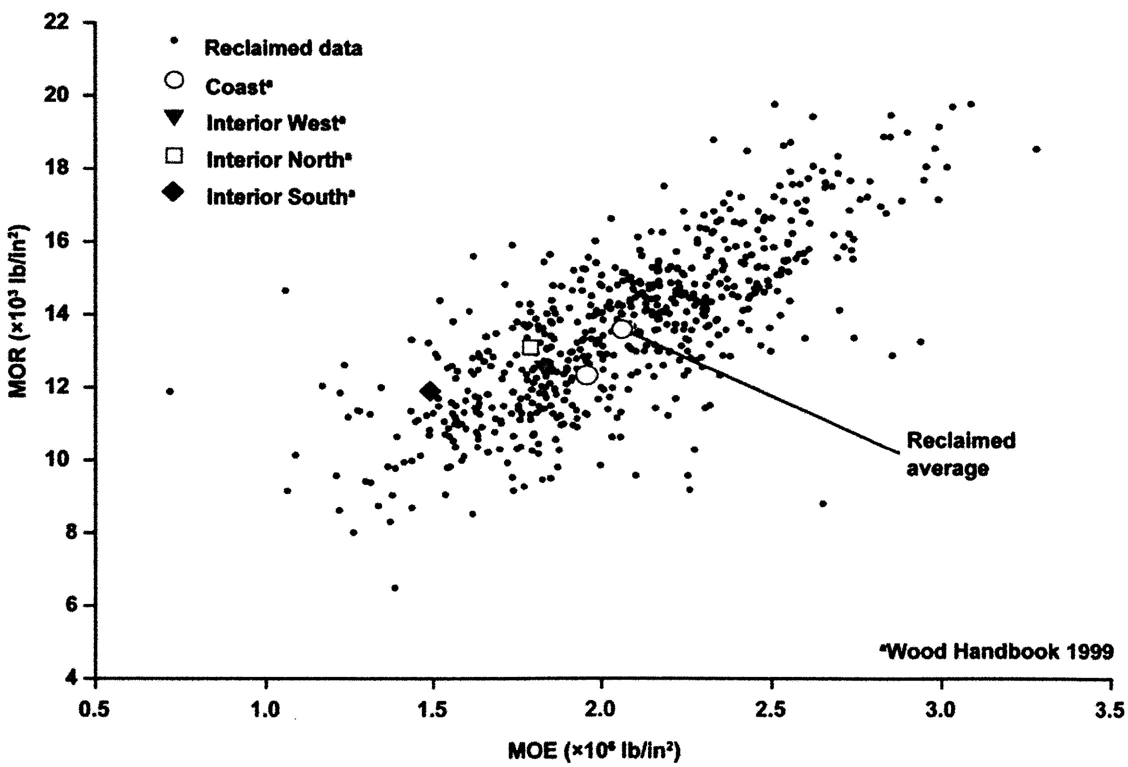

Figure 7: Comparison of small clear data to historical averages of MOE and MOR [23]

[22] Ibid.
[23] Ibid.

After determining the performance of small clear specimens, similar destructive testing was conducted on full size Douglas fir members. Within a single grade, the modulus of elasticity is statistically the same for 2x6 and 2x10s. Interestingly, the modulus of elasticity is the lowest for both grades in the 2x8 size. Falk et. al. attribute this disparity to the lower specific gravity found in the 2x8s from Washington driving down the group stiffness. The modulus of rupture, as expected, increases with the depth of the member. This data is graphically represented in Figure 8. The raw data collected for both No.2 and Select Structural grades are shown in Tables 7 and 8, respectively.

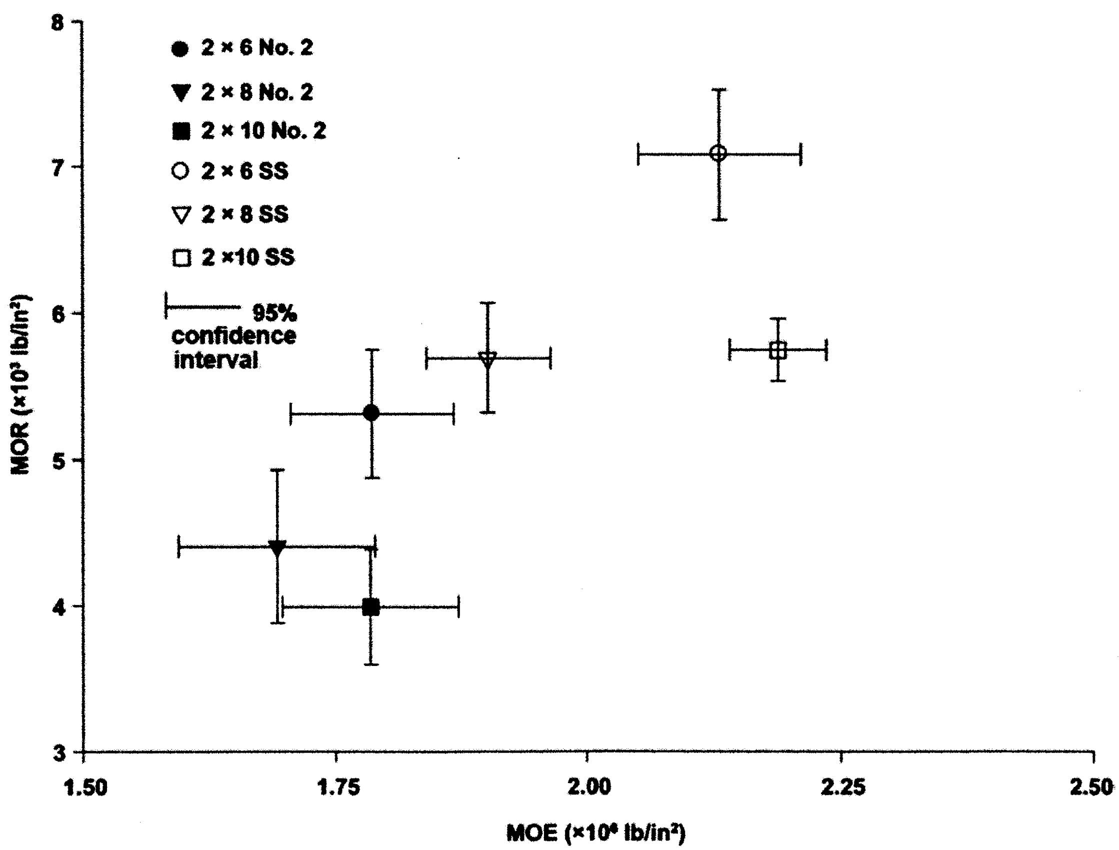

Figure 8: Comparison of average size and grade to MOE and MOR [24]

[24] Ibid.

	2 x 6			2 x 8			2 x 10		
Property	No.	Mean	COV	No.	Mean	COV	No.	Mean	COV
MOR (x 10^3 psi)	107	5.28	41.7	241	4.79	43.4	93	4.04	42.4
MOE (x 10^6 psi)	103	1.79	23.3	43	1.69	18.8	78	1.78	21.9
Specific Gravity	107	0.50	11.3	241	0.48	10.7	93	0.49	12.9
Moisture Content (%)	107	12.3	7.6	241	9.7	10.1	93	11.4	11.5

Table 7: Statistical summary for reclaimed No. 2 lumber [25]

	2 x 6			2 x 8			2 x 10		
Property	No.	Mean	COV	No.	Mean	COV	No.	Mean	COV
MOR (x 10^3 psi)	96	7.03	31.5	163	6.11	37.1	291	5.65	31.8
MOE (x 10^6 psi)	94	2.13	18.3	125	1.9	18.2	254	2.19	17.5
Specific Gravity	96	0.52	10.9	163	0.49	13.2	291	0.51	10.8
Moisture Content (%)	96	11.8	8.5	163	13.2	5.7	291	10.4	9.9

Table 8: Statistical summary for reclaimed Select Structural (SS) lumber [26]

Unlike small clear specimens, no historical data exists for destructive testing of full size Douglas fir members. Instead, the data is compared to existing data using the in-grade program outlined in *Mechanical properties of visually graded lumber.*[27] Comparisons show that the modulus of rupture is approximately 26% lower in the reclaimed lumber. Additionally, the higher graded lumber exhibits a larger difference than the lower grade. This is markedly different than the small clear results in which minimal difference was experienced on the microscopic level. The decrease in bending strength in the full size members may be due to damage from drying, nail holes, or deconstruction. Conversely, the modulus of elasticity is an average of 9% higher in the reclaimed lumber than the in-grade. This is consistent with the results from the small clear testing. The complete comparison of strength and stiffness between reclaimed and in-grade lumber is located in Table 9.

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[25] Ibid.
[26] Ibid.
[27] Green, D.W. and Evans, J.W. *Mechanical properties of visually graded lumber: Volumes 1–8.*

Size	Grade	Property	Reclaimed			In-grade			Percentage Difference
			No.	Mean	COV	No.	Mean	COV	Mean
2 x 8	No. 2	MOR (x 10^3 psi)	241	4.79	43	1964	6.25	42.7	23.4
		MOE (x 10^6 psi)	43	1.68	19	1964	1.62	25.1	-4.1
	SS	MOR (x 10^3 psi)	163	6.11	37	493	8.48	30.4	28.0
		MOE (x 10^6 psi)	125	1.9	18	493	1.91	20.7	0.4
2 x 10	No. 2	MOR (x 10^3 psi)	93	4.04	42	388	5.45	46.3	25.9
		MOE (x 10^6 psi)	78	1.78	22	388	1.59	24.7	-12.2
	SS	MOR (x 10^3 psi)	291	5.65	32	414	7.84	29.8	27.9
		MOE (x 10^6 psi)	254	2.19	18	414	1.92	20.0	-13.9

Table 9: Comparison of full size reclaimed and in-grade Douglas fir lumber [28]

A final consideration is the effect of damage due to nail holes, splitting, and other mechanical damage such as drilled holes, gouging, and cuts or notches. Almost all reclaimed lumber has nail holes – either in the face, from bridging or hardware, or along the edge, from the prior attachment of cladding. Boards with edge nails were tested in two orientations – nail edge up (nail holes in the compression zone) and nail edge down (nail holes in the tension zone). In general, boards with the nail edge down resulted in a lower bending strength. Nail holes in a board's face did not become influential on the bending strength unless they were closely spaced or created further splitting, primarily in the tension zone. Other mechanical damage reduced the modulus of rupture only in the select structural graded boards. Otherwise, the No. 2 boards were more likely to fail as a result of the grade determining defect – such as knots, slope of grain, and splits – rather than the mechanical damage.

Benefits

The potential supply of reclaimed lumber in the United States is vast. Much of the three trillion board feet of lumber and timber sawn in the last century still stands in existing buildings today. It is

[28] Falk, R. et. al. *Engineering Properties of Douglas-Fir Lumber Reclaimed from Deconstructed Buildings.*

estimated that "if only 2 percent of wood buildings now standing were decommissioned each year, and 25 percent of the lumber in them were reclaimed, it would supply up to one-fourth of the overall lumber market in this country for over 50 years."[29] Despite years of service, reclaimed wood does offer some performance advantages. Many of today's building use virgin lumber cut from second and third growth forests, resulting in lumber with a looser grain and more knots than wood cut from old growth forests. Additionally, lumber in older buildings is often oversized and may be available in sizes and species no longer available in virgin timbers.

Case studies have shown deconstruction to be a cost effective solution to reduce demolition waste and recycle as much as 90% of building materials. Building 901 at the Presidio of San Francisco was a 9,200 square foot wood frame warehouse built in 1942. It was deconstructed in 1996 by a five person team over four weeks at a total expense of $53,000 for labor, equipment, waste disposal, and administration. Income from the sale 65,000 board feet of reclaimed Douglas fir and Port Orford cedar equaled $43,600. The $9,340 net cost of deconstruction was 45% less than the demolition bid of $16,800 and 87% of the building's materials were recycled.[30]

Uses and Recommendations

Reclaimed lumber from deconstructed buildings offers the largest potential for reuse of any method discussed in this report. However, specific grading standards are needed to address the unique conditions of reclaimed lumber. Using current grading standards would often disallow reclaimed lumber on the basis of visual defects commonly found in recycled lumber, even though it may be dimensional and structurally stable. Because every board is unique and species mixing often occurs, it is essential that every recycled member is individually graded.

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[29] Horne-Brine, Preston and Falk, Robert. *Knock on wood: Real recycling opportunities are opening up.*
[30] Leroux, Kivi and Seldman, Neil. *Deconstruction: Salvaging Yesterday's Buildings for Tomorrow's Sustainable Communities.*

Preliminary data shows that bending strength may be as much as 25% less in reclaimed wood members than in virgin lumber. Further testing must be conducted to determine more consistent engineering properties and the effect of age, exposure, and defects on the structural performance of reclaimed lumber. It may be necessary to downgrade a reclaimed wood member one or two grades below that of its virgin counterpart. If reclaimed members with edge nailing are to be allowed, grading should specifically mandate that the edge nail holes be placed in the compression zone.

III. SALVAGED TIMBER FROM INDUSTRIAL BUILDINGS

Availability

Opportunity to reclaim building material increases as America's infrastructure continues to age. Between 1800 and the mid 1900s, many industrial structures, such as warehouses and sawmills, were constructed using solid timber. Larger, old growth timbers from these buildings are in increasing demand for reuse as structural framing in new timber frame construction. Currently, 24% of the wood used by the timber frame industry is recycled.[31] The aged character that may deter the reuse of some dimensional lumber is often valued by the customer for aesthetic reasons as well as the recycled nature of the material. For this reason, another popular source for recycled timbers has been post and beam barns built prior to the 20th century.

Barriers

Unlike dimensional lumber, structural timbers are often left uncovered, exposed to the effects of climate. Most timbers are installed green and, therefore, condition over time to the surrounding environment. The most common barrier confronted with old timbers is severe drying checks or splits. For timbers containing the pith, heart checks are a common result of stresses set up by the difference in tangential and radial shrinkage of wood around the pith (Figure 9). Typically, heart checks are confined to one side of the member, rather than a continuous split down both sides.

The nature of the building may have exposed the timbers to excessive heat or moisture, or to various industrial chemicals such as solvents, machine oil, or fertilizer. Depending on the use and age of the timber, metal fasteners, bolt holes, or notches may be present as well.

Finally, the grading process and criteria is significantly different than that of dimensional lumber. Visual grading is used almost exclusively for timbers due to the lack of availability in commercial

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[31] O'Connell, T.D. and Smith, P.M. *The North American timber frame housing industry.*

mechanical graders capable of supporting wood members thicker than two to four inches. Additionally, timbers are graded exclusive to their species and intended use. For all species except for southern pine, timbers are graded as either post and timbers or beams and stringers. Post and timber applications involve axial loading, and the grading criteria is uniform along the entire length of the member. Beams and stringers are intended for use in bending and receive more stringent grading criteria for the middle third of the member than for the outer two thirds.[32]

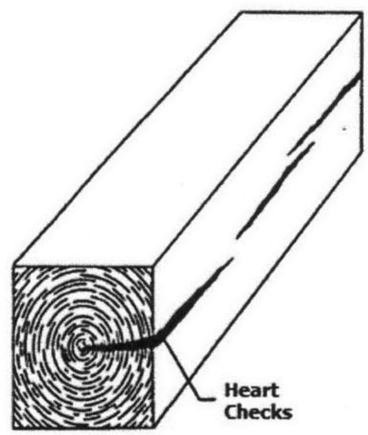

Figure 9: Typical heart check in pith-centered timbers

Current Research

In addition to the research discussed in Section II, two independent evaluations were conducted using reclaimed large timbers from the Twin Cities Army Ammunition Plant. The first study examined the engineering properties of 8x8-12 foot Douglas fir columns after 55 years of service.[33] Sixty 8x8 timber columns were collected for the first experiment and tested for residual column capacity. Each timber was assigned a visual grade (Table 10). Forty percent of the reclaimed timber columns qualified as select structural.

[32] Green, D., Falk, R., and Lantz, S. *Effect of Heart Checks on Flexural Properties of Reclaimed 6 by 8 Douglas-Fir Timbers.*
[33] Falk, R., Green, D., Rammer, D., and Lantz, S. *Engineering Evaluation of 55-Year-Old Timber Columns Recycled from an Industrial Military Building.*

Reason	Select Structural	No. 1	No. 2	Utility	Reject	Total (no.)	Total (%)
Met Highest Grade	24	--	--	--	--	24	40
Checks, Splits	--	--	5	5	2	12	20
Knots	--	11	4	--	--	15	25
Damage	--	--	--	8	--	8	13
Wane	--	--	1	--	--	1	2
Total	24	11	10	13	2	60	100

Table 10: Reasons for visual grades of reclaimed 8x8 timber columns [34]

Damage in the members was mostly confined to the ends; consequently, 12 inches were cut from either end prior to testing. All columns were testing in direct compression with no intermediate lateral support. Lateral displacement was monitored at mid-span for buckling, and the ultimate compressive stress was calculated from the maximum load achieved for each column. Table 11 shows the measured test results compared to the current allowable design values found in the National Design Specification (NDS) for Wood Construction. The modulus of elasticity in the columns graded for structural reuse was greater than the NDS design values. The mean compressive strength of the tested columns was a minimum of 40% greater than the mean compressive strength from the design equations. A comparison of the tested column strength with the design values over a range of (length/depth) ratio is shown in Figure 10.

	NDS Derived Values		Measured Test Results		Comparison	
Grade	(1) Modulus of Elasticity (MOE)	(2) Column Strength (f_c)	(3) Modulus of Elasticity (MOE)	(4) Column Strength (f_c)	MOE Ratio (3/1)	f_c Ratio (4/2)
	(x 10^6 psi)	(psi)	(x 10^6 psi)	(psi)		
Select Structural	1.65	2,640	1.91	3,830	1.16	1.45
No. 1	1.65	2,380	1.90	3,320	1.15	1.40
No. 2	1.34	1,680	1.68	2,890	1.25	1.72

Table 11: MOE and column strength of NDS values and tested Douglas fir columns [35]

[34] Ibid.
[35] Ibid.

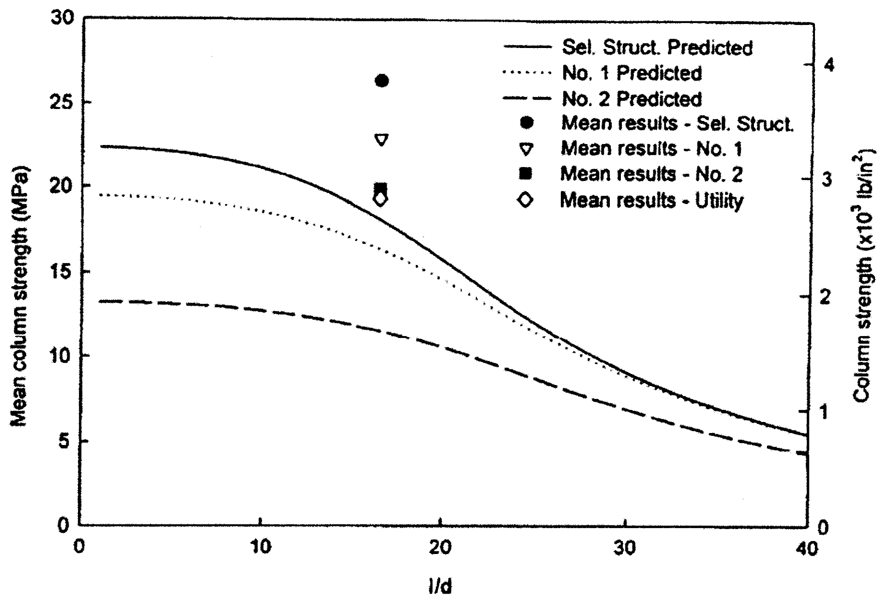

Figure 10: Graphical comparison of NDS design equations and test results of Douglas-fir columns [36]

A second comparison was made between checked and unchecked columns to determine the effect of checks on column capacity. An average of all columns tested revealed that there is no significant difference in the column capacity of checked versus unchecked columns. With the exception of the utility grade, the strength of the checked columns is at least as high as the unchecked columns. The test results are displayed in Table 12 and a plot of all compressive strength and modulus of elasticity for all tested columns is found in Figure 11.

Grade	(1) Checked Columns		(2) Unchecked Columns		Ratio (2/1)
	(no.)	(psi)	(no.)	(psi)	
All grades	35	3,340	23	3,340	1.00
Select Structural	12	3,950	12	3,700	0.94
No. 1	5	3,340	6	3,310	0.99
No. 2	6	3,240	4	2,360	0.73
Utility	12	2,790	1	3,060	1.10

Table 12: Column capacity of checked and unchecked Douglas fir columns [37]

[36] Ibid.
[37] Ibid.

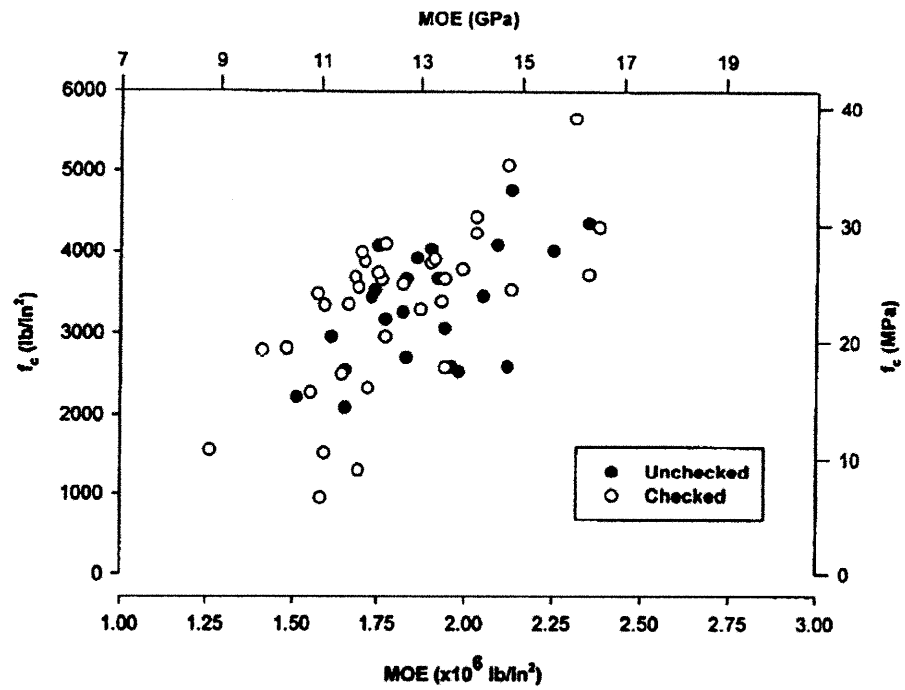

Figure 11: MOE and column strength of checked and unchecked Douglas fir columns [38]

The second study on reclaimed timbers focused on the effects of heart checks on the flexural properties of 6x8-16ft Douglas fir beams and stringers. Ninety-one members were selected, twenty-eight of which had large checks located down to the center of the member. These checks were not considered when visually grading the timbers (Table 13).[39]

Reason	Select Structural	No. 1	No. 2	Utility	Total (no.)	Total (%)
Met Highest Grade	70	--	--	--	70	77
Splits	--	--	3	--	3	3
Knots	--	10	3	1	14	15
Damage	--	--	2	1	3	3
Wane	--	--	1	--	1	1
Total	70	10	9	2	91	100

Table 13: Reasons for visual grades of reclaimed 6x8 timber beams

[38] Ibid.

[39] Green, D., Falk, R., and Lantz, S. *Effect of Heart Checks on Flexural Properties of Reclaimed 6 by 8 Douglas-Fir Timbers.*

Modulus of elasticity and modulus of rupture were recorded for each member by conducting third point bending tests. Data sets for the unchecked (Figure 12) and checked (Figure 13) testing results show identical slopes for the MOE-MOR regressions. The plots suggest that checks have little effect on the modulus of elasticity but cause a slight reduction in the modulus of rupture.[40]

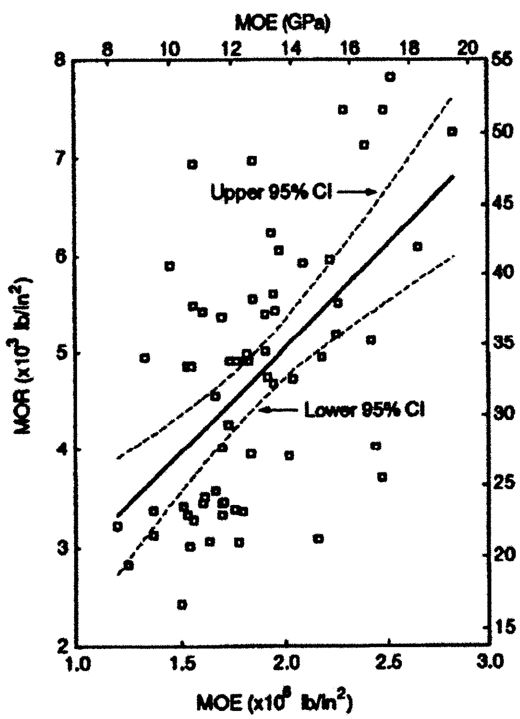

Figure 12: MOE and MOR for unchecked Douglas fir 6x8 timbers

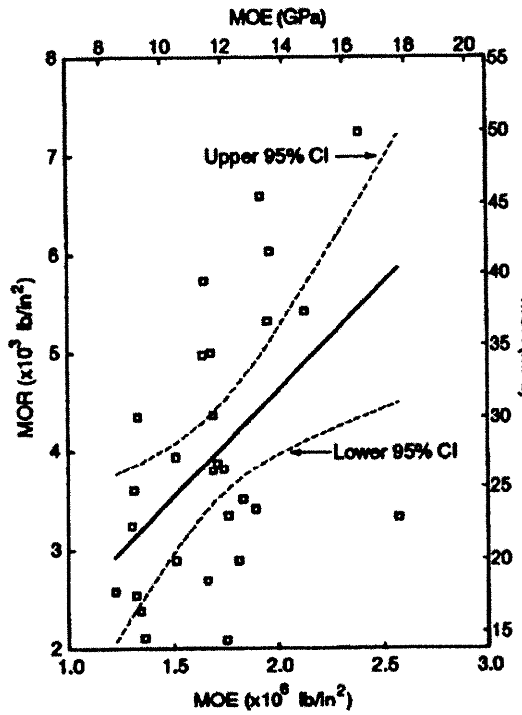

Figure 13: MOE and MOR for checked Douglas fir 6x8 timbers

While there is no significant reduction in stiffness between the checked and unchecked members, the modulus of elasticity is actually about 10% higher in the reclaimed members than for NDS design values. The bending strength of the checked members is about 20% lower than the unchecked members. The modulus of rupture for the unchecked members is about 90% of the design value and the checked members are about 75% of the design value. These numbers can be found in Table 14.

40 Ibid.

			Measured Test Results			NDS Derived Values[a]			
				MOR				MOE	MOR
Beam	Grade	no.	(3) MOE[b]	Mean	(4) 5th%	(5)MOE	(6) MOR[c]	Ratio (3/5)	Ratio (4/6)
			($x\ 10^6$ psi)	($x\ 10^3$ psi)	($x\ 10^3$ psi)	($x\ 10^6$ psi)	($x\ 10^3$ psi)		
Unchecked	Select Structural	48	1.85	4.87	3.06	1.60	3.36	1.16	0.91
(1)	No. 1	8	1.78	4.20	–	1.60	2.84	1.11	–
	No. 2	5	1.57	4.18	–	1.30	1.84	1.21	–
Checked	Select Structural	22	1.72	4.14	2.54	1.60	3.36	1.08	0.76
(2)	No. 1	2	1.29	2.99	–	1.60	2.84	0.81	–
	No. 2	4	1.51	3.49	–	1.30	1.84	1.16	–
Ratio	Select Structural	–	0.93	0.85	0.83	–	–	–	–
(2/1)	No. 1	–	0.72	0.71	–	–	–	–	–
	No. 2	–	0.96	0.83	–	–	–	–	–

[a] NDS values are for green, unchecked 6x8 timbers

[b] MOE reduced 2% for green values

[c] MOR is 5th % MOR

Table 14: Comparison of checked and unchecked timber beams to NDS values [41]

Benefits

There is strong evidence that high quality timbers can be recovered from salvaged structures. The preliminary studies discussed have shown that these timbers may be stronger than virgin timbers when used in axial compression. They also have the advantage of being dry and stable when erected into a frame.

Recycling timbers offers many of the same benefits as discussed earlier for recycling dimensional lumber. This includes a reduced strain on timber harvesting and less overall construction waste. However, salvaged timber may be most prized for its aesthetic value. Many timbers are available in species that are difficult to find on the commercial market. Reclaimed timbers also offer unique characteristics such as patina and hand hewn markings that cannot be reproduced in virgin

[41] Ibid.

timbers. Depending on the use of the timber, defects that may take away from the structural integrity of the member – bolt holes, notches, splits, and checks – may bring additional value that can garner a high price on the reclaimed timber market.

Uses and Recommendations

Despite 55 years of service, 75% of both columns and beams were classified as No. 2 or better, resulting in a great potential for reuse. Even members that are rejected from structural reuse can be prized on the value added lumber market. Prior to structural reuse, all members require regrading. In addition to the research discussed, non-destructive, stress wave measurements were used to calculate the modulus of elasticity for the timber beams. There was good correlation between the static and stress wave modulus of elasticity measurements. Thus, it appears feasible to establish mechanical grading systems for reclaimed timbers.

It is recommended, however, that reclaimed timbers are reinstalled in a similar fashion to their previous use. Compression members are best used as columns and bending members are best used a beams or stringers. The most damage found in old timbers is present in the ends; therefore, it is recommended that at least 12 inches be cut from either end prior to reuse.

IV. SALVAGED TIMBER FROM UTILITY POLES

Availability

Wood utility poles in North America can range from 25 foot distribution poles to 65 foot transmission poles. Diameters can vary from 6 inches at the top to 16 inches at the bottom. It is estimated that between 160 and 180 million wood utility poles are currently in service in the United States. A 2002 survey of 261 North American utility companies (representing 25% of total service) revealed that between 0.5 and 0.7 percent of utility poles are being replaced annually. This equates to a staggering one million wooden utility poles being removed from service each year, the majority of which are incinerated or placed in landfills.[42]

Barriers

Utility poles are unique because they carry very little axial load. Instead, they behave like a cantilever and take the majority of loading in bending action, possibly introducing stresses not commonly found in structural framing members. However, the most prevalent barriers for utility pole reuse is exposure to chemical preservatives, weathering, and nails and metal fasteners.

Utility poles are treated with a variety of chemicals to prevent the effects of weathering, insect attack, and fungal decay. A survey of North American utility companies showed that pentachlorophenol (Penta or PCP), chromated copper arsenate (CCA), and creosote are the three most widely used chemicals used to treat utility poles in the United States (Figure 14). Respondents to the same survey indicated that the service life for most species of poles is between 30 and 50 years, while cedar poles – naturally resistant to decay – can remain in service for over 100 years.[43]

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[42] Mankowski, M., Hansen, E., and Morrell, J. *Wood Pole Purchasing, Inspection, and Maintenance: A Survey of Utility Practices.*
[43] Ibid.

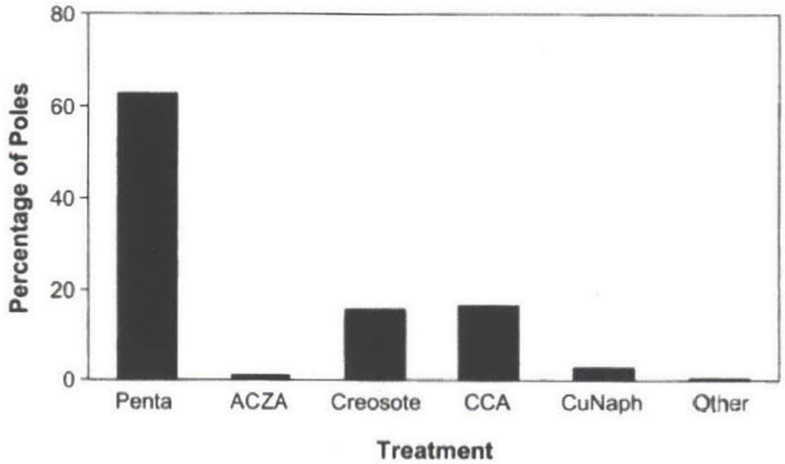

Figure 14: Frequency of initial preservative treatment in wood utility poles

Penetration of preservatives is generally limited to the first inch of the pole's sapwood. Deeper penetration may occur if traditional or deep incising – a procedure that drives 12-75 mm teeth into the sapwood to increase penetration – is used. The heartwood remains preservative free (Figure 15) while the mechanical properties go essentially unchanged. As discussed earlier, the effects of weathering are also limited to the exterior of the wood and are further limited due to the use of preservatives.

Figure 15: Cross-section of CCA treated pole [44]

[44] *Protocols for recycling redundant utility poles and bridge timbers in New South Wales.*

Current Research

In 1996, the Faculty of Forestry at the University of Toronto released a study on the potential for reuse of preservative treated utility poles. In all, 456 poles of various species, size, age, preservative, and condition were collected and tested to determine the most suitable form of reuse. Specific criteria for reuse are listed in Table 15, with priority going to reuse as a utility pole.[45]

Priority or Rating	Proposed Use	Criteria
1 (Highest)	Re-use as is as a pole	Less than 10 years old, good condition, greater than 35 feet long
2	Cedar roof shakes or shingles	Western red cedar only, top diameter 12 inches or greater, few knots
3	16 foot saw log	Top diameter 6 inches or greater, sound, minimal hardware
4	8 foot saw log	Top diameter 6 inches or greater, sound, minimal hardware
5	Round building poles or posts	6 feet or longer, sound
6	Firewood	Untreated northern white cedar or western red cedar
7 (Lowest)	Landfill disposal	Excessive rot or mechanical damage, excessive hardware, heavy preservative, bleeding

Table 15: Hierarchy of preferred uses for poles taken out of service

Results of the study yielded a larger percentage of sawn products than any other end use. 37% of the wood was assigned to the production of dimensional lumber and timbers, while another 20% was suitable for round posts (Table 16). Further testing was conducted to determine if long term exposure to weathering and chemicals had any effect on the structural suitability of dimensional lumber cut from preservative treated poles. 1x1-16 foot clear specimens were cut from representative poles and subjected to traditional bending tests according to ASTM D143 procedures.[46] Measurements for

[45] Cooper, Paul et al. *The potential for re-use of preservative treated utility poles removed from service.*
[46] American Society for Testing and Materials. *Standard Methods of Small Clear Specimens of Timber.*

bending strength (MOR) and stiffness (MOE) were recorded. In comparison to published values, the data showed similar properties to new lumber and suggests that no great reduction in strength occurs (Table 17).

	Species				
End use	Cedar	Red Pine	Jack Pine Lodgepole Pine	Southern Pine Douglas Fir	Total
Re-use ad pole	1.0	4.6	1.9	0.3	7.8
Shingles	14.7	-	-	-	14.7
Lumber and timbers	7.7	18.3	10.0	1.3	37.3
Posts	4.5	9.3	5.7	0.8	20.3
Firewood	10.0	-	-	-	10.0
Landfill	2.6	3.9	3.0	0.4	9.9
Total	40.5	36.1	20.6	2.8	100.0

Note: Values are given as percentages of total sample volume

Table 16: Distribution of wood for various end uses by pole species

Pole Species	Description	Sample Size	MOR (MPa) Mean	MOR (MPa) Std .Dev.	MOE (MPa) Mean	MOE (MPa) Std. Dev.
Red Pine	Creosote	14	79.2	13.1	9,051	1,743
	Pentachlorophenol	15	77.5	10.2	9,850	1,820
	Published Values		76.0	8.3	10,200	2,020
Jack Pine	Creosote	14	88.6	13.1	10,613	1,267
	Pentachlorophenol	15	84.2	11.1	10,800	1,320
	Published Values		77.9	8.8	10,900	1,560

Table 17: Bending strength of specimens cut from used poles

Benefits

With one million poles being removed from service each year, there is the potential of 80,000 wood poles being returned to service each year in the United States. For poles unsuitable for re-service, the potential value for lumber alone is about $12 million annually. Finally, widespread reuse of existing wood utility poles can lead to as much as a 90% reduction in poles earmarked for incineration or landfill disposal.

Uses and Recommendations

Based on current research, recycled utility poles can serve as a supplemental source for structural timbers and lumber. There is potential for almost half of the volume of recycled poles to be sawn into lumber of No. 2 grade or better. Limited testing suggests, but does not prove, that lumber from recycled utility poles is as strong as fresh cut lumber.

There are plenty of non-structural uses for utility poles as well. The most logical option is to return a serviceable pole to operation after it has been retreated. The Environmental Protection Agency encourages that the reuse of treated poles be consistent with the intended use of treated wood. Common examples of reuse include landscaping timbers, retaining walls, fence posts, and decks.[47] There is also a large potential for value added wood products such as shingles and flooring.

Perhaps the largest barrier that remains in reusing utility poles is the time and expense involved in washing the poles and removing metal hardware. The use of a metal detector is not uncommon to find fragments that can easily damage or destroy saw blades. Additional precaution must also be taken by the handlers of any wood material containing chemical preservatives. A more efficient milling process must be developed in order to make reusing utility poles cost effective.

[47] Treated Wood Life Cycle Management Coalition. *Management of Used Treated Wood Products.*

V. CONCLUSION

Wood recycling is already happening. Strong niche markets exist for recycled wood products, driven by recent trends in "sustainable" and "green" building. Within a broad lumber market, however, recycled wood is a high-value but small-volume niche primarily consisting of large timbers and milled products. Breaking through the value added market to the widespread lumber market requires investigation into the long term strength evaluation of recycled timbers. Wood has proven to be a resilient material over time and maintains much of its original strength despite the effects of moisture, loading, temperature, and weathering. Long term exposure to chemicals and rot, however, can drastically reduce wood's mechanical properties and such members are not recommended for reuse. Timbers reclaimed from service present additional considerations when determining feasibility for reuse.

Current research shows promising possibilities for the reuse of lumber from every source discussed in this thesis. Dimensional lumber from deconstructed buildings offers the largest possibilities for reclaimed lumber use, due primarily to the vast number of homes demolished each year. Full size lumber reclaimed from deconstructed homes exhibited 25% lower bending strength and 10% lower stiffness than in-grade virgin lumber. Reclaimed timbers (without checking) from industrial buildings possessed 90% of the NDS design value for bending strength and had greater stiffness by 10%. Almost 40% of utility poles removed from service had the potential to be sawn into dimensional lumber and structural timbers with no significant reduction in strength compared to virgin timber.

However, fundamental barriers exist that currently inhibit reclaimed timbers from being regularly available on the lumber market. The primary obstacle is the lack of grading standards. Grading procedures must be established specifically for reclaimed lumber and the quality of grading must be assured. Creation of an accepted grade stamp will provide confidence in reclaimed wood products and enable distribution to market, permitting approval, and construction use. The value, volume, and types of reclaimed lumber will expand, driving down overall unit costs and enabling recycled wood to better compete with virgin timbers.

Further testing must continue with positive results. Without significant research on the engineering design properties, particularly bending and shear, overly conservative strength values are used, larger timbers are required, and costs increase. Additional sources of salvaged timbers, such as marine piles and underwater forestation, should also be carefully studied. Ultimately, widespread acceptance and use of reclaimed timbers will create economic opportunity and lessen the environmental impact of deforestation, demolition, and waste disposal.

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