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Furniture design and product development principles considering end-of-life options and design for environment strategies

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FURNITURE DESIGN AND PRODUCT DEVELOPMENT PRINCIPLES CONSIDERING END-OF-LIFE OPTIONS AND DESIGN FOR ENVIRONMENT STRATEGIES

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ABSTRACT

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During last decades, environmental issues come into prominence and some governmental or organizational regulations are legislated to reduce environmental impacts of products within their life cycle. At the same time, costumers consider not only price, quality, branding, uniqueness, availability but also environmental impact, safety, and overall sustainability of products they select. Therefore, producers are addressing environmental impact of products they are producing and also making changes to their production process. This project is addressing End-of-Life (EoL) Options of wooden furniture.

Although wood is eco-friendly and natural material, its technological process, use and disposal might have ecological problem and challenge. Therefore, it should be considered individually from conception to end of its life to increase ecological quality. The main environmental problem for wooden furniture industry comes up during manufacturing process and disposal of furniture. Applying Design for Environment (DfE) strategies and End of Life (EoL) options can reduce product environmental impact.

This study will focus on implementation of DfE and EoL Options in the final stage of the selected product life cycle. Wooden stools constructed by different joinery methods were studies to demonstrate this case. A few solutions are presented: substitution of materials, joinery (such as replacement of metal fasteners with fully wooden joinery), and structure reinforcement techniques. These and other techniques will be investigated for production of reusable and recyclable furniture. The overall goal is to increase the awareness of furniture designers, producers and suppliers of new environmental regulations and to offer some product improvement solutions.

CHAPTER 1. INTRODUCTION

1.1 Statement of the Problem

Throughout history, furniture has improved the quality of life of humans. Even in primitive ages, humans used stones in their caves as furniture. At some point in time, human recognized that wood was easy to cut and shape, and it became the most important component of furniture. After the industrial revolution, furniture production greatly increased and became more available to all classes of the population — rather than only the elite — as production progressed from a craft-based to a machine based industry. Not surprisingly, these improvements in production and ease of acquisition brought increases in consumption not only to meet basic first-time needs, but also to replace old furniture with new "stylish" furniture in keeping family changes in wealth. Consumption of wood materials increased accordingly as did the amount of furniture waste in landfills, which has caused ever-increasing environmental problems.

To put these problems in perspective, in Europe, furniture lifetimes average 5 to 10 years, and although wood is a biodegradable and eco-friendly material, it takes around 13 years to degrade in landfills. The overall magnitude of the disposal problem becomes apparent when the amount of furniture discarded is considered. In the case of office furniture, 1.2 million tons of office furniture is discarded annually— half of which consists of wooden materials (Parikka, 2008). Similarly, according to U.S. EPA reports, furniture accounted for 4.1% (9.8 million tons) of household waste and it is one of the least recovered wastes in household furniture — the rate between 1960 and 2008 was 0.05% - 0.1% (EPA, 2010).

Recycling of products has many environmental benefits that range from conserving raw materials to decrease problems associated with disposal such as reducing gas emissions and water pollution (EU, 2011). Thus, recycling both conserves increasingly scarce resources and decreases the amount of energy required to produce end-use products (EU, 2011).

According to the Environmental Protection Agency (EPA), wood accounted for 6% of Municipal Solid Waste (MSW) in the U.S. in 2010 (EPA, 2010). The amounts of materials recovered from MSW are shown Table 1.

Table 1: Generation and Recovery of Materials in MSW, 2010 (EPA, 2010).

Material	Weight Generated	Weight Recovered	Recovery as Percent of Generation
Paper and paperboard	71.31	44.57	62.5%
Glass	11.53	3.13	27.1%
Metals	22.41	7.87	35.1%
Plastic	31.04	2.55	8.2%
Rubber and leather	7.78	1.17	15.0%
Textile	13.12	1.97	15.0%
Wood	15.88	2.3	14.5%
Other materials	4.79	1.41	29.4%

The materials contained in a product are the key factors in identifying the potential environmental impacts of the product throughout its life span. In the case of furniture, many types of materials are included in its construction such as wood, metal, glass, etc.

According to European Furniture Manufacturers Federation, material uses (by value) in furniture production are shown in Figure 1-1. Although many types of materials are used in furniture construction, wood and wood-based materials make up the largest part.

Therefore, the potential environmental impact of any given design of wooden furniture should be considered in terms of raw material consumption, manufacturing and production energy requirements, and product life to, retirement, disposal and possible part reuse (EC 2008).

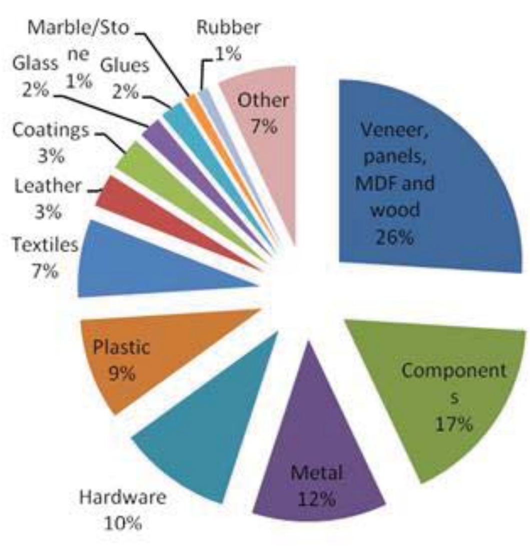

Figure 1: Share of materials used in furniture production by value (EC 2010).

In recent years, governments and environmentally conscious organizations have begun to consider environmental problems associated with furniture production. Increasingly, environmentally friendly consumers have also become interested in environmental issues of furniture production. Today, consumers consider not only price, quality, branding, uniqueness, and availability but also environmental impact, safety and overall sustainability in selecting furniture (Gonzalez et al., 2011) — their demands are growing and they are asking for reassurance. Gonzalez and at al., (2011) indicates these concerns:

- How are the products being made?
- What are the sources of the products? / Where are they being produced?
- What are the environmental consequences of their production and use?
- How are they disposed of when they are no longer useful?

New environmental regulations are dictating changes to reduce the environmental impact of furniture production around the world. Global producers must consider these regulations and rapidly adapt their production techniques, technology and products, in order to remain viable trade partners. In this respect, cradle-to-grave approaches come into prominence. Product life extension, durability, adaptability, ease of disassembly, timeless design, recyclability, and reusability must all be considered when designing new furniture — furniture that can be produced more economically and with a low environmental footprint.

Production of environmentally friendly furniture provides benefits beyond simply decreasing landfill and raw material requirements. Significant opportunities exist, for example, for manufacturing furniture from reusable furniture parts and partial constructions. Such furniture would likely not be acceptable in all markets, but would meet the needs of an enormous part of the world's populations (Gonzalez et al., 2011) — including the school furniture for children in disadvantaged areas of the world.

In summary, the most significant environmental impacts associated with furniture are generated during the production of the associated raw materials and the disposal of old furniture (Klopffer, 2012). The average life of typical wood based furniture is roughly 10-12 years. However, furniture might still have residual life even if it comes to the end of its conventional first life. Therefore, the following questions come into prominence for End-of-Life (EoL) strategies:

- Can replaced products be reused somewhere else?
- Can damaged products be repaired with replacement parts?
- Can parts from damaged products be re-used in repairing similar products?
- Can salvaged materials be incorporated into other products?

End of Life (EoL) and Design for Environment (DfE) concepts aim at avoiding or minimizing environmental impacts associated with the production and disposal of furniture through;

[1] Appropriate material selection,

[2] Use of energy efficient production processes that minimize waste,

[3] Increase useable product life through strength design,

[4] Remanufacturing of furniture from undamaged parts and constructions.

1.2 Aims and Objectives

The aim of this study is to increase the awareness of furniture designers, producers and suppliers of new environmental regulations and to offer some product improvement solutions. In doing so, environmental regulations will be presented with the intention of increasing product quality and the competitiveness of these products on the global market.

The goal is also to prolong product life span and to prove that products built by engineering design procedures are better for End-of-Life measures. The overall goal of the case study is to identify frame type furniture constructions (joinery) that are best-suited for initial long life of a product and subsequent reuse of parts and remanufacture product.

Project objectives:

- Identify current and potential product disposal options,
- Demonstrate how product durability can influence product life cycle,
- Determine how to increase product life through strength design principles, Design for Environment (DfE) strategies and End-of-Life (EoL) options,

- Determine the strength, durability, ease of disassembly, ease of repair, and reuse of parts of a simple frame design stools constructed with seven different joints.

1.3 Hypothesis

It is possible to that the joint constructions allowing for easy disassembly and reuse of parts (RTA joinery) do not provide the same length of service life as glued wooden joints that do not allow easy disassembly.

1.4 Significance of the Study

The ecological awareness of wood products manufacturers provides an important competitive advantage in foreign or home markets. As an example, the EU Timber Regulation, effective March 2013, requires manufacturers to demonstrate that their wood/wood products do not originate from illegal harvesting practices (EC, 2010). This opens the door for consumers and sellers to demand proof of compliance. The primary mechanisms for demonstrating this level of compliance are Environmental Product Declarations (EPDs). EPDs assess the total environmental impact of a product or material. They are being developed by a broad spectrum of industries under a framework of international standards (EPD, 2013). EDPs are emerging as potentially the best opportunity for the U.S. hardwood and solid furniture industry to compete in world industry as international markets become ever more environmentally sensitive (AHEC, 2013). Evaluating the environmental impact of a product could be a complicated task as there are numerous materials and energy flows involved in a product's life cycle and these flows interacts with the environment in different ways. To date, Life Cycle Assessment (LCA) is the most widely used tool for product environmental performance evaluation. One distinct advantage of LCA is that it systematically and objectively quantifies environmental impacts of a product or process and allows multiple products or processes to be compared (Spitzey et al., 2006). Analyzing and comparing LCA results can identify environmental hot spots and improvement opportunities, and thus guide the development of more environmentally responsible “eco-friendly” products.

This study is focused on Design for Environment (DfE) and End-of-Life (EoL) options. Increasing product recovery for second life must be addressed as a whole because the recovery rate in the first life can only be increased through initial design and development for further use and environmentally friendly disposal. DfE strategies are considered in order to build easy-assembly and disassembly, durable and, sustainable wooden furniture (wooden stools). EoL options are considered in order to provide more efficient recovery rates for second life considering mostly reuse, recycle and remanufacturing options.

CHAPTER 2. BACKGROUND

2.1 Sustainable Product Design and Product Design Strategies

2.1.1 Sustainable Design

The United Nations' World Commission on Environment and Development describes sustainable design as 'designs that meet the need of the present generation without comprising the ability of future generations to meet their own needs'. Thus sustainability has three dimensions – economic, social and environmental (WCED, 1987). The focus of this chapter is on the environmental sustainability of products.

Recently, companies and organization have been working on reducing the negative environmental impacts of their products throughout their life cycle. In doing so, several approaches have been identified. These approaches can be classified as shown in Figure 2-1. Sustainable design can be achieved by following the path from the lower left corner to the upper right corner. The life span of products, people and civilization can influence the gradation on the scale (Bras, 1997). Sustainability of a product dictates that its product life span must be considered to reduce the environmental impact of it efficiently throughout its entire life cycle. As indicated in Figure 2-1, Design of Environment and Life-Cycle Design concepts must be integrated for successful sustainable design. In addition, product use and disposal are necessary for sustainability so that End-of-Life Options can be integrated into sustainable design consideration. The environmental impact of a product is not only limited by product design and manufacturing processes but also by industrial ecology – energy and material use, use and transportation of product, and energy in biological ecosystems (Bras, 1997). Therefore, sustainable design approaches should go beyond simple product life cycles and consider second life opportunities and options.

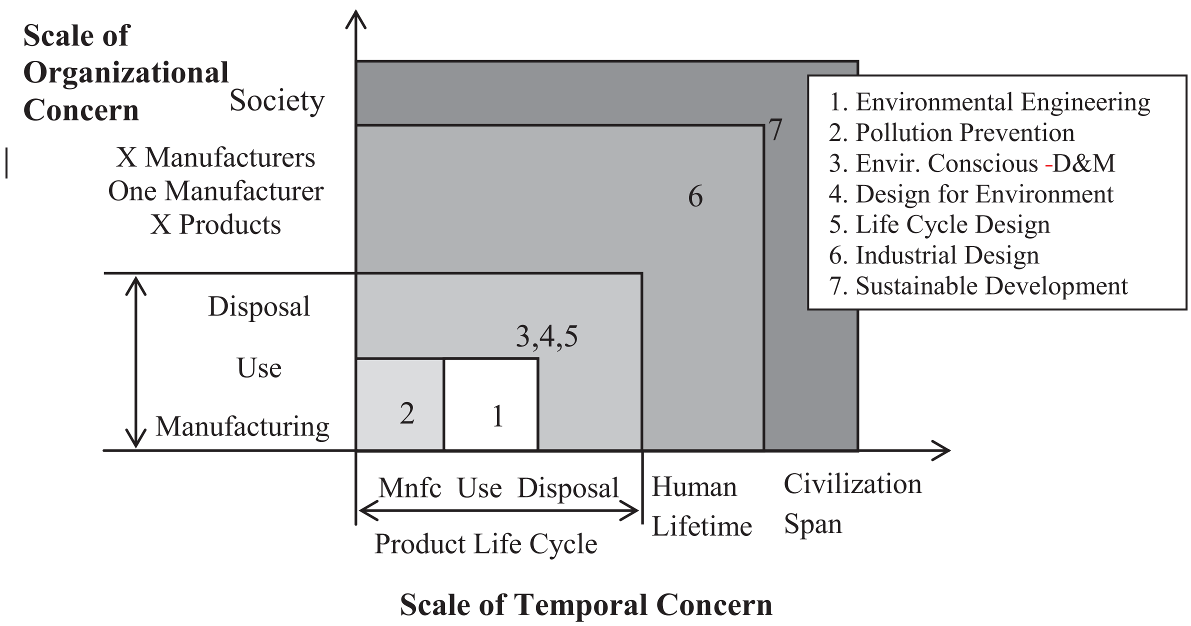

Figure 2-1: Environmental and temporal scale of environmental impact reduction approaches (Bras, 1997).

Design for Environment and Life Cycle Design tools have become available to compare product environmental impacts and evaluate recyclability and/or disassembly of products. Comparing environmental impacts in the design process are very important, but Bras (1997; page 9) indicated that furniture producers should consider following questions:

- "What new tools should be provided designers to aid them in dealing with increased emphasis on designing for the life cycle?"
- "How can these techniques be best integrated into existing and well-established design systems, tools and practices?"
- "How to minimized overlap and increase efficiency in gathering and managing information?"

The companies should have facilities and infrastructures to apply Design for Environment and Life Cycle Design tools. If not, applying them might have negative consequences. Thus, these tools should not only reduce the environmental impact of designs but should improve the manufacturing processes themselves (Bras, 1997). As a result, companies should consider the following seven guidelines for the processes they implement to meet the goals for sustainable design (Bras, 1997), namely,

- *Simple* – easy to use
- *Easy obtainable* – affordable and reasonable cost
- *Precisely definable* – obvious how to use
- *Objective* –same results should be obtained
- *Valid* – accurately measured, indicate and predicts what is intended
- *Robust* – insensitive to changes in the domain of application
- *Enhance understanding and prediction*

Design guidelines can be described by considering Life Cycle Analysis. A Life Cycle Design Strategies (LiDS) wheel is shown in Figure 2.2 (Brezet et al., 1994; Hemel & Keldmana, 1996).

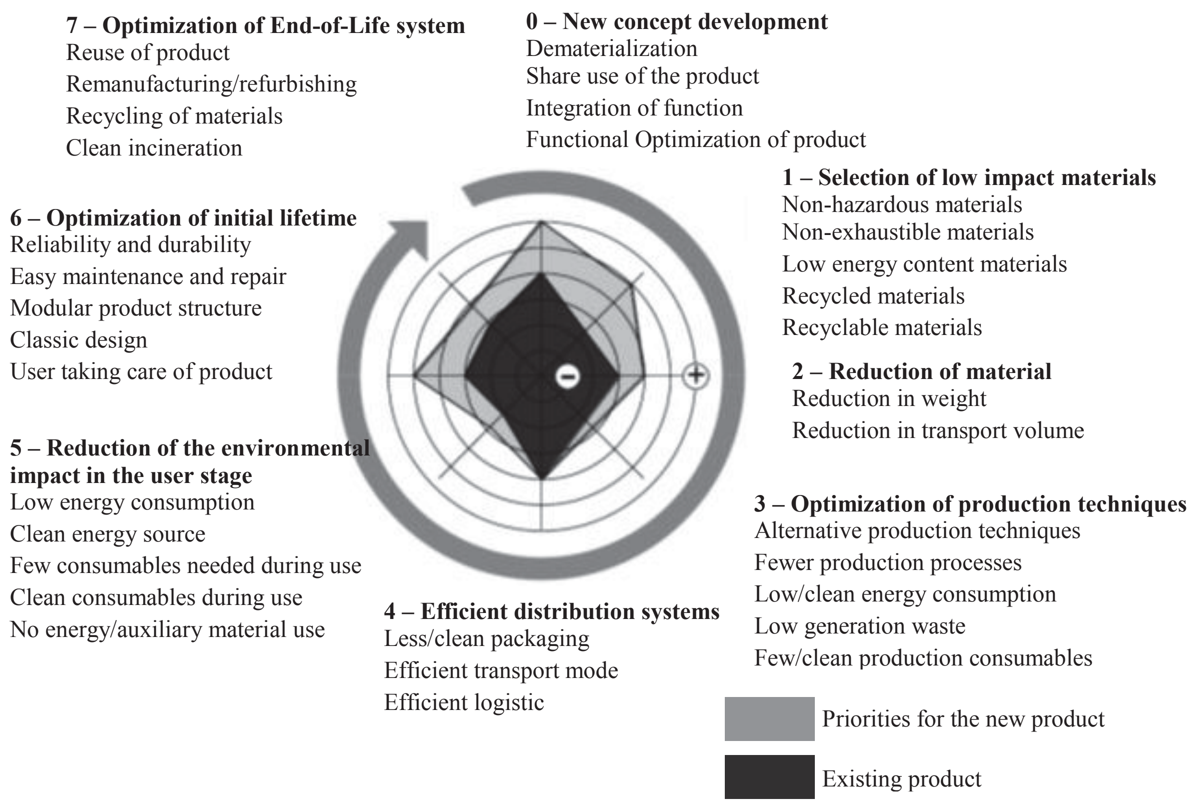

Figure 2-2: Life Cycle Design strategies (LiDS) Wheel (Brezet et al., 1994; Hemel & Keldmana, 1996).

2.1.2 Material Selection

During the last decades, both public demands and regulations concerning the environment have caused many changes in global market. These demands and regulations have caused manufacturers to change their processes and to act in a more environmentally responsible manner. Material selection is essential; therefore, that designers be fully informed of the potential environmental impacts of the materials of construction in the early stages of products design (Cinar, 2005).

2.1.3 Product Design Strategies

Product design strategies – Design for Environment, Design for Assembly and Design for Disassembly - aim to reduce the environmental impact of products and increase the recyclability level of products throughout the product life cycle. However, there is one drawback. If only one environmental issue is focused on, it can negatively influence other issues so that the environmental impacts of the product may be increased. Hence, all product life-cycle approaches should be considered together in choosing product design strategies (Bras, 1997).

2.1.3.1 Design for Environment

Design for Environment (DfE) includes any design process whose goal is to reduce the environmental impact of products during their life cycle. Many DfE methodologies have been developed since 1990, and many companies have established their own processes in applying these methodologies to their products. Generally, these methodologies have been focused on the life cycle of parts or products and their function during this cycle (Hauschild et al., 2004).Some methodologies have been aimed at applying DfE considerations in the early stages of design, whereas others have been aimed at applying them in the design process (Hauschild et al., 2004).

DfE consideration in product design and manufacturing process can be ordered as follows (Srinivasan et al., 1997):

- First understanding the relationship between product and environment
- Developing an initial product design
- Apply DfE strategies to the product

According to Bogue (1997, page 288), Design for Environment strategies are aimed at:

- "Reducing the material content and energy required in the manufacturing process"
- "Increasing the use of recycled parts"
- "Increasing the number of reused parts".

DfE studies are mainly associated with End-of-Life Stages because of waste handling problems. Some of Design for Environment strategies based on minimizing End of Life impacts are remanufacturing and reusing (Hauschild et al., 2004).Product should be also design in terms of cost effective remanufacturing and landfill waste reduction. Also, a set of Design for Environment rules are suggested below which summarized the guidelines in various Design for Environment methods and tools in literature (Lagerstedt, 2003)

- "Do not use toxic substances"
- "Minimize energy use and material consumption in manufacturing and transportation"

- “Minimize energy and resource consumption in product use”
- “Promote maintenance”
- “Provide long life”
- “Use structural features and high quality materials to minimize weight”
- “Use better materials, surface treatments or structural arrangements to protect products from dirt, corrosion and wear”
- “Arrange in advance for upgrading, repair and recycling, through good access, labeling, modules and breakpoints, and provide good manuals”
- “Promote upgrading, repair and recycle by using few, simple, recycled, unblended materials, and do not use alloys”
- “Use minimum joining elements possible, using screw, adhesives, welding, snap fits, geometric locking etc. according to Life Cycle Analysis”.

These suggestions may be summarized under the following three focus points:

Focus on the disposal of the products: Waste is an important problem in landfills so that disposal of products comes into prominence. The product should be disposed of according to the following waste disposal hierarchy – reuse, recycle, remanufacture and incinerate – to decrease landfill disposal (Hauschild et al., 2004).

Focus on the use of certain materials in the product life cycle: This point focuses on the use of renewable and biodegradable materials (Hauschild et al., 2004).Even with bio-degradable wooden furniture, there are environmental problems associated with their production and use. Composite materials have drawbacks because they can seldom be recycled into useful products (Hauschild et al., 2004).Also, the chemicals they contain increase their environmental impact. However, using wood composite materials in furniture give more opportunities to produce easy to assemble and disassemble furniture.

Focus on product life: Durability, remanufacturing and prolongation of product life is based on the material content of the products. The goal is to extend the product life provides using fewer materials for producing new products and reducing environmental impact of these products (Hauschild et al., 2004).

2.1.3.2 Design for Disassembly

The aim of Design for Disassembly (DfD) (derived from DfE) is to design products that readily can be disassembled at the end of their service lives in such a manner that the residual parts and materials can be reused, recycled, remanufactured into new products (Bogue, 2007).

In the design process, designers must anticipate and prepare for the potential uses of components of products salvaged from worn-out products at the ends of their normal service lives so that these components and parts are recycled and incorporated into new products rather than wastefully disposing of them in landfills (Bogue, 2007).

According to Bogue (2007, page 287), there are three critical factors that must be considered if a product is to satisfy the above criteria for successful DfD:

- “Selection and use of material”
- “Design of products”
- “Selection of joinery, connectors and fasteners”

Designing products for efficient disassembly improves ease of product repair along with material and part reuse and recyclability. However, designers and companies must first be aware of the options that are available to them that can be used in the production of such furniture (Srinivasan et al., 1997).

Table 2-1: Design for Disassembly factors (Bogue, 2007).

Factors affecting the disassembly process	Guides to improve disassembly
Product structure	Create a modular design Minimize the component count Optimize component standardization Minimize product variants
Materials	Minimize the use of different materials Use recyclable materials Eliminate toxic or hazardous materials
Fastener, joints and connection	Minimize the number of joints and connections Make joints visible and accessible, eliminate hidden joints Use joints that are easy to disassembly Mark non-obvious joints Use fasteners rather than adhesives
Characteristic of components for disassembly	Good accessibility Low weight Robust, minimize fragile parts Non hazardous Preferably unpainted
Disassembly conditions	Design for automated disassembly Eliminate the need for specialized disassembly procedure DfD with simple and standard tools

2.2 End-of-Life Options

2.2.1 End-of-Life Stage in Product Life Cycle

The wood furniture industry uses a biodegradable and eco-friendly material, namely, wood. However, solid wood and wooden-composite materials also have some negative impacts on the environment. Wood itself degrades in around 13 years, but chemical treatments and finishing applications increase degradation time. Therefore, End-of-Life (EoL) options must consider reducing environmental impacts at disposal as reducing amount of waste in landfills.

The most important concept to consider in designing for environment is that wooden furniture can be repaired or parts and materials reused after the end of its normal life span. EOL options that apply to its second service life include (Lee et al., 2001):

- *Reuse* – Out-of-style, but serviceable, furniture can be reused by selling to another user—second hand stores (second-hand furniture).
- *Repairing* – Unusable furniture can be repaired by changing parts and repairing joints.
- *Primary recycling* – Parts can be incorporated into other (often different) furniture.
- *Secondary recycling* – The wooden components in furniture can be chipped and incorporated into wood-composites.
- *Incineration* – Wooden materials can be used as fuel to heat homes, schools, etc.
- *Landfills* – This option is the worst case EoL option. At this point, the furniture has become a liability rather than an un-used asset.

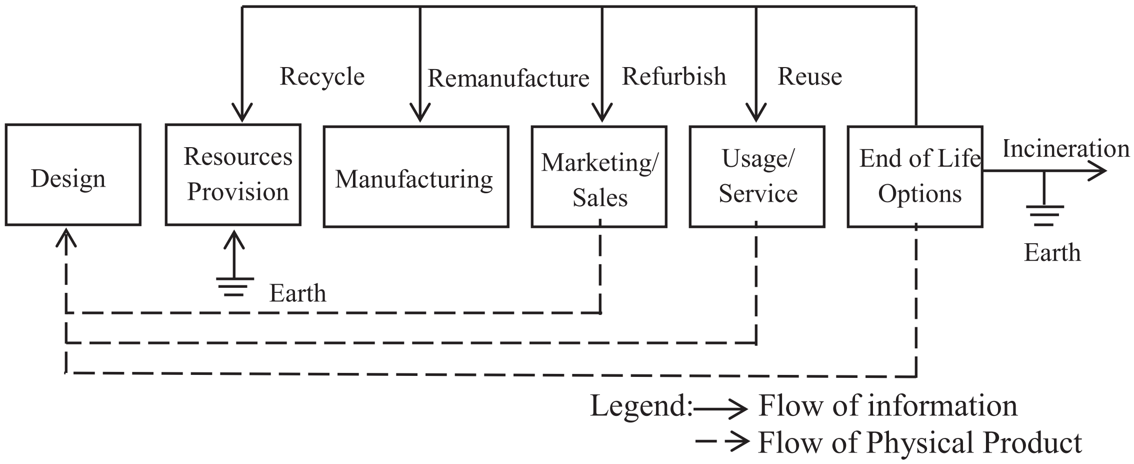

Figure 2-3: Product Life Cycle (Sundin et al., 2012)

Product recovery at End-of-Life is indicated include curative actions and preventative actions (Go et al., 2011). According to Go and et al., (2011, page; 2), curative actions “promote technical and economic development and improve recovery of products,” whereas preventative actions “improve product recovery through designing for recycling”

EoL options must be incorporated into the design process to increase the product recovery level; thus, curative actions and preventative actions must be considered together. Curative actions depend on the willingness and freedom of manufacturers to apply EoL options—and the willingness is greatly enhanced if manufacturing costs are reduced.

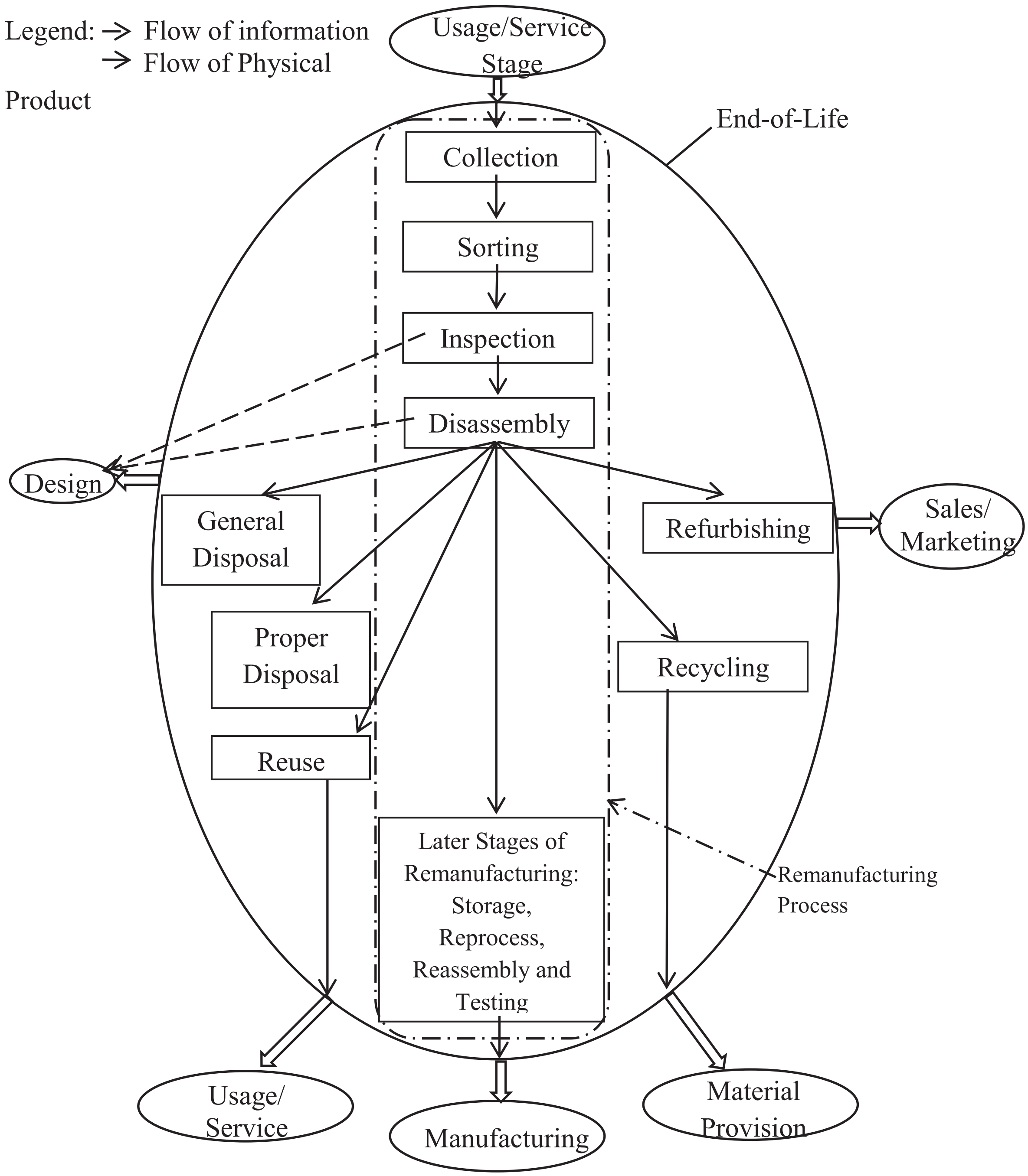

Figure 2-4: Decomposition of product EOL Stage (Lee et al., 2001).

The theoretical product recovery hierarchy is defined by repair/reuse efficiency at end-of-life (Figure 2-5). Reuse is the highest product recovery/end-of-life options in the hierarchy (Amelia et al., 2009). Often damaged components must be replaced with new components in order to reuse a product. This process is called remanufacturing and occupies second place in the product recovery hierarchy (Ostlin et al., 2009). The next step in the hierarchy is recycling which implies the construction of new furniture out of the old or changing the furniture in such a way that gives it a useful second life (Lambert & Gupta, 2005). The next potential step in the hierarchy of operations is energy recovery (incineration), i.e., use of the waste to produce energy for beneficial purposes. The last, and least desirable, option is burial in a landfill (Saman & Blount, 2006).

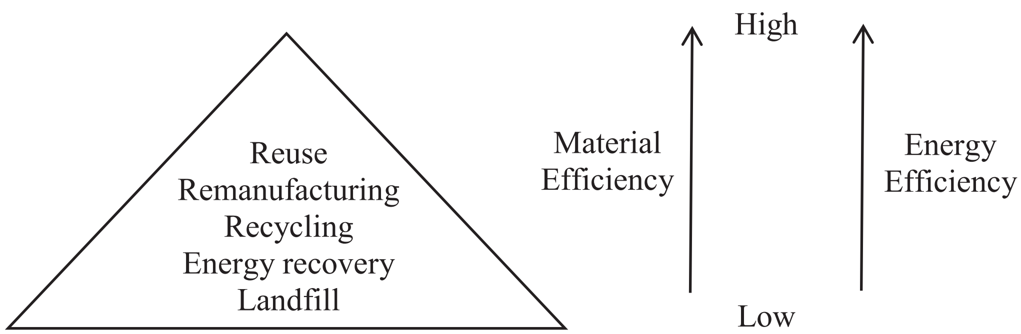

Figure 2-5: The theoretical product recovery hierarchy (Ostlin et al., 2009)

2.2.2 End-of-Life Impacts on Environment

The Eco-Indicator, proposed by Product Ecology Consultants, may be used to compute the environmental impact of products during their use and manufacturing process (Lee et al., 2001; PEC, 1999). This eco-impact tool expresses environmental impact in terms of Eco-Indicator points (Pt) or mili-indicator (mPt) which is one-thousandth of a Pt (Lee et al., 2001).

The End-of-Life impact (EOLI) of product is determined as shown below (PEC, 1999):

$$EoLI = \sum_{i=1}^{N_T} (IE_i \times W_i)$$

where,

N_T = Total number of materials in the product

IE_i = End-of-Life impact of material i

W_i = Weight of material i

n = number of materials in component i

2.2.3 End-of-Life Options and Disassembly of the Product

Disassembly is a sub-stage of EoL options – includes reusing, remanufacturing and recycling (Lee et al., 2001). Product recovery rate must be maximized into End-of-Life stages, and so product design is the key process that ensures sustainable design, and, determines the economic and environmental benefits of remanufacturing (Wahab, 2010; Kerr & Ryan, 2001). Product recovery rate can be increased via designing for easy assembly and disassembly and by developing disassembly tools and technologies (Lee et al., 2001). Therefore, Design for X, which refers Reuse, Remanufacture and Recycle, – aims to indicate design and assembly guidelines – provides higher product recovery (Wahab, 2010; Kerr & Ryan 2001).

Disassembly can be a major problem at the end of product life so that disassembly processes must result in high recovery rates for End-of-Life Option on products. According to Lee and et al., (2001; page 150), successful disassembly produces the following results:

- “All recyclable and valuable component are retrieved”
- “Economic gains are maximized and deficits minimized”
- “Environmental impacts are within expectations”
- “The time for disassembly is within predefined limits”.

Successful End-of-Life disassembly occurs when highest product recovery is obtained which reduces the environmental impacts of product and results in a second or even third life of the product. Lee et al., (2001, page 151) proposed the following sequence of operations for EoL disassembly of products:

- “Remove toxic and hazardous components from the product and separate them individually”
- “If cost effective, extract reusable components from the product and separate them”
- “If cost effective, extract remanufacturable components from the product and separate them”

- “Group compatible recyclable components together, and, if cost effective, extract the remaining incompatible but recyclable components”
- “Group components for incineration together”
- “Transport remaining components to landfill for disposal”.

End-of-Life disassembly considers not only product recovery rate but also cost in diminishing the environmental impact of products (Lee et al., 2001). Thus, it is important early on to determine how a product would be disassembled after use. Sometimes, high product recovery occurs when only a few, but important or hazardous components, are recovered from a product (Harjula et al., 1996).

2.3 Environmental Issues and Impacts of Wooden Furniture

Furniture is an essential contributor to the quality of life of humans. Thus people buy new furniture as soon as they perceive that their old furniture doesn't meet their needs. This replacement causes millions of tons of old furniture to be disposed of in landfills. Because of the huge amount of wooden furniture replaced each year, governments/ organizations should consider enacting environmental regulations designed to reduce the environmental impact of wooden furniture disposal.

The most important environmental impacts associated with the use of wood in furniture arise in the transformation of lumber into finished furniture components and the EoL disposal of those components in landfills (Parikka, 2008). The extraction of raw materials includes machining, drying, assembly and finishing. The major environmental problems in the process mentioned above are (Parikka, 2008):

- Machining – Energy consumption, discarded wooden materials and sawn dust
- Drying – Carbon monoxide (CO) emission
- Assembly – Urea formaldehyde and solvents emission
- Finishing – Volatile Organic Components (VOCs) emission and bleaching agents.

Wooden furniture disposal in landfills also causes major problems simply in the growth of the landfill. Degradation of wood materials takes about 13 years. In addition, finishing and other treatments can also affect the degradation time of wooden furniture. Also, VOCs emissions and pollution of the soil both in the landfill and in the surrounding areas are major concerns.

Although, recycling of wood materials can reduced the environmental impact of wooden furniture but it is not an optimal solution, yet. According to European Federation of Furniture Manufacturers (UEA) statics, 10% of furniture waste is recycled whereas 80 – 90 % of furniture is incinerated (CREM, 2004). Although incineration is one of the End-of-Life options which aims to reduce environmental impact of products, the other options (reusing, remanufacturing and recycling) should be considered substantially to profit by wood material so that its life span can be increased with high recyclable level (EC, 2008).

Although there is no strict pressure on companies to apply environmental regulation, many companies are willingness to manufacturing process in respect of environmental sound furniture and extinct in global market (Parikka, 2008). Product design and development process is essential to increase recyclability and life span, and reduce environmental impacts so following criteria should be taken into the consideration (Parikka, 2008; EC, 2008):

- Use of certificated materials
- Type of materials
- Environmental impact of these materials
- Manufacturing process
- Reduction of use of hazardous substance and formaldehyde emission
- Design product for easy assemble and disassembly
- Use recycling and recyclable materials
- Costumer's criteria about green product

2.3.1 Environmental Regulations and Legislation

Increasingly, governments and other organization have been taking actions to reduce destruction of natural resources and reduce the amount of waste entering landfills. In some cases, these regulations have been influenced by Design for Environment (DfE) strategies and End-of-Life (EoL) options (Parikka, 2008).

The Dutch Government, for example, has developed an assertive national environmental policy called the Green Plan. By following these policies, Dutch companies enjoy an advantage in the competitive global market whereby global environmental concerns among users are increasing (Srinivasan et al., 1997)

Similarly, the Japanese Ministry of International Trade and Industry enacted regulations which promote both the use of recyclable materials in products and the recyclability of these products (Srinivasan et al., 1997)

Likewise, in Italy in 2001, a 'Life Environmental Eco-friendly Furniture Projects' was initiated to make prototypes of environmentally sustainable furniture that consider all stage of the life cycle of furniture (Parikka, 2008).

Finally, in 2004, the following criteria were defined for environmentally sound furniture by the Finnish Furniture Panel (Parikka, 2008):

- Products should have a long lifetime and should include consideration of durability, adaptability, compatibility, timeless design, easy assembly and disassembly, reusability and remanufacturing.
- The ecological profile of materials should be evaluated and consideration given to the use of those materials with lower chemical content which use non-toxic substances.
- Environmental impact of the packaging should be considered (i.e. reusable packages, packaging service system).

- The ease of disassembly of the product for repair or reuse of parts should be considered.
- Environmentally sound production processes should be considered (i.e. low energy consumption, low production emission and amount of chemicals).

In Europe, several European Environmental policies and legislation directives have been released (EC, 2008):

- Forest Law Enforcement Governance and Trade (FLEGT) – concerns wood and wood-based materials.
- Directive 79/117/EEC and amendments – concerns wood treatment
- Directive 67/548/EEC and Directive 1999/45/EC – concerns marketing and labeling of chemical product for furniture; for dangerous substance and for dangerous preparations, respectively
- The new REACH regulation – concerns registration, evaluation, authorization and restriction of chemicals
- Directive 1999/13/EC, amended by Directive 2004/42/EC – Concerns volatile organic components (VOC)
- Directive 199/44/EC – concerns the sale of consumer goods and associated guarantees
- Directive 94/62/EC – concerns packaging and waste packaging.

According to the European Commission of Green Public Procurement, the following actions (Table 2-2) are needed to reduce environmental impact of furniture (EC, 2008).

Table 2-2: Key environmental impacts for furniture (EC, 2008)

Impact		GPP Approach
• Loss of biodiversity, soil erosion and degradation as a result of unsustainable forest management and illegal logging • Landscape impact from mining activities • High energy consumption in the production of several materials • Use of hazardous substances that can be released during production, use or disposal • Use of organic solvents and generation of VOC emissions • High amount of packaging • Early replacement of furniture due to a lack of reparability options, low durability, ergonomics or furniture not fit for purpose		• Procure legal timber and timber from sustainably managed forests • Use materials made partly or totally from recycled materials and/or renewable materials (such as wood) • Limit the organic solvent content and VOC emissions in products, adhesives and surface treatment substances • Avoid certain hazardous substances in materials production and surface treatment • Ensure recyclability and reparability of packaging materials and furniture parts • Procure durable, fit for use, ergonomic, easy to disassemble, repairable and recyclable furniture

In the United States, the concerns of agencies that impact the furniture industry are given below (NIST, 2013);

- Customs and Border Protection (CBP) – Regulations that govern the importation of products

- Consumer Product Safety Commission (CPSC) – Flammability of upholstered furniture; lead containing surface coatings; children's furniture
- Environmental Protection Agency (EPA) – Formaldehyde in wood
- Federal Trade Commission (FTC) – Labeling
- United States Department of Agriculture (USDA) – Organic fibers

Environmental Protection Agency - EPA – Releases laws and regulations that specify export and import requirement of materials, considering human health and environment (NIST, 2013).

Individual countries have different concerns that have been expressed in the legislation discussed above, but if all the criteria were collected under a single umbrella term such as 'green furniture', all of the individual effort would have only one coordinated aim – reducing the environmental impact of furniture throughout all stages of its life.

2.3.2 Environmental Certifications for Furniture

The Forest Stewardship Council (FSC) and International Organization for Standardization (ISO) are the recognized certifiers for the Forest Product Industry.

Forest Steward Council (FSC) is an international non-profit organization that was founded 1993. It aims to provide international labels for forest products in term of environmentally, socially beneficial, and economically viable management of world's forest (Morris and Dunne, 2004). The council is an interdisciplinary group that assesses forest products in terms of sustainability and environmentally friendly actions; it includes environmental and social groups, timber and trade professions, community forest groups and forest product certification organizations from all over the world (Morris and Dunne, 2004).

Upon certification, FSC provides a trademark logo (in Figure 2-6) for furniture producers, stakeholder and costumers about (Morris and Dunne, 2004) that indicate:

- "Where the wood material comes from"
- "The sustainability of the supply and the credibility of reports concerning its sustainability"
- "And that it meets certified social, economic and environmental standards"

Figure 2-6: Forest Stewardship Council (FSC) trademark logo

Standards issued by the International Organization of Standardization (ISO), namely, ISO 14040 (new) and ISO 14044, are related to environmental regulations and the carbon footprints related to Life Cycle Analysis (LCA) (Finkbeiner et al., 2006). These are important international standards for environmental analysis of a products' life cycle with respect to cradle-to-grave or holistic method concepts (Klopffer et al., 2012). Calculation of carbon footprint as an indicator of Global Warming of a given product is displayed on an Eco-Label that communicates the total amount of greenhouse gas (GHG) emission linked to a product (Gonzalez et al., 2011).

2.3.3 Eco-Labels for Furniture Manufacturing

Eco-Labels identify the environmental criteria for public procurement of furniture; the demands in these Eco-Labels are based on life cycle perspectives (Parikka, 2008). The concerns of environmental groups has been growing, and they have been pushing governments to establish Eco-labels that aim (EU, 2001, page 2) “to promote the design, production, marketing and use of products that have a reduced environmental impact during their life cycle and to provide consumers with better information on the environmental impact of products”. Some Eco-labels from European countries are shown below (EU, 2011):

a b c

d e

Figure 2-7: European Eco-Labels**:** a. Blue Angel – Germany, b. Green Home – Italy, c. NF Mark – France, d. Nordic Swan – Scandinavia, e. Oko – Austria.

Recyclability level of a product depends on the materials of construction and the product design. According to CREM, there are several EU Eco-Labels that potentially apply to the recyclability of product (CREM, 2004).

- Nordic Swan and NF Environment - Non-specified reference to international and national legislation
- Okocontrol, Nordic Swan, EU Eco-label hard floor coverings, NF Environment, Osterreichisches Umweltzeichen - Measure based standards
- Stichting Milieukeur, EU Eco-label Mattresses - Consumer information.

Table 2.2 shows what the European Eco-Labels consider for furniture manufacturing. In 2009, the European Union (EU) released their decisions about ecological criteria for the award of the Community Eco-Label for wooden furniture.

Their directives provide a guide for reducing the environmental impact of wooden furniture both on the environment and human health throughout its life cycle (EC, 2009). These guidelines include (EC, 2009):

- Use of materials produced in more sustainable way
- Reduction of the use of hazardous substance and emissions of polluting substance
- Product testing for durability

Table 2-3: Main environmental criteria covered by several European Eco-Labels (CREM, 2004).

	Stichting Milieukeur	NF Environment	Okocontrol	RAL-RG 430	Nordic Swan	RAL-UZ* 38	UZ 06 ** UZ 34**
Wood							
Forestry	X		X	X	X	X	X
Use of hazardous substances	X	X		X	X		X
Heavy metals in coatings	X		X	X	X	X	X
Coating	X	X	X		X	X	X
VOC emissions by coating	X	X		X	X	X	X
Formaldehyde emission	X		X	X	X	X	X
Glues and adhesives							
VOC emissions	X				X		X
Energy use							
Max. energy defined		X			X		
Functional aspects							
Quality				X	X		X
Health and safety			X		X		X
Reparability, durability	X		X	X	X		X
Packaging materials	X						
Tack-back guarantee					X		
Waste at production sites					X	X	X
Maintenance	X						X

CHAPTER 3. CASE STUDY – END-OF-LIFE OF WOODEN STOOL – FRAME TYPE CONSTRUCTION

3.1 Introduction

The judicious use of timber resources, especially in disadvantaged countries of the world dictates that furniture should be durable and easy to repair, and, in so far as possible, the parts should be reusable.

At present, however, chairs, tables, and other furniture are regularly discarded, sometimes owing to fractured legs and rails, but most often owing to loose or failed joints. In affluent areas of the world, replacement of such furniture may be nothing more than an inconvenience — in disadvantaged areas, however, replacement may not be possible. Difficulties in replacement of school furniture are of particular concern — many schools are furniture deficient and replacement of existing furniture is unlikely or slow to occur. In addition, given the ever-growing demand on world timber resources, it is important to investigate whether the structurally sound parts of broken or discarded furniture (that cannot be simply repaired) such as legs, rails, stretchers can be recycled, i.e., incorporated into "new" furniture.Aesthetics must, of course, also be considered. And it must be accepted that recycled furniture would not be acceptable in all design situations; however, in a recycle-or- nothing situation, recycled furniture likely would provide an acceptable and welcome solution.

If recycling is to be done efficiently, however, pre-planning for reuse needs to be incorporated into the original design of the furniture.

In today's terminology, environmentally and eco-friendly furniture designs—that is designs that are strong and durable with long service life, that are easy to repair, and allow for reuse of parts that over time reduces the amount of new timber needed for replacement furniture — are termed "sustainable" designs.

Thus sustainable furniture should be durable and have long service life, and should have joints that retain partial structural integrity even after partial failure—thus increasing service life and decreasing the need for immediate replacement. Sustainable furniture construction should also be designed for easy disassembly so that joints can easily be repaired, damaged parts replaced, or undamaged parts recovered for use in other constructions — finally, the joints in sustainable furniture should fail in a manner that causes minimum peripheral damage to the members they join together.

Only minimal machining of members should be needed to accommodate dowels, tenons, and mechanical fasteners since the amount material that must be removed from the members to construct a joint may play a decisive role in whether or not a part may be re-used. Holes and mortises can be filled for esthetic reasons, but this action does not restore structural integrity to the member.

Simplicity of construction also must be weighed against the amount of material wasted to form a joint—which may cause design conflicts. The amount of material that must be machined from the ends of rails to form tenons, for example, weighs against their use in sustainable designs, but on the other hand, the furniture can be constructed from local material alone—which makes it ideally suited for use in underdeveloped areas of the world.

Finally,—when esthetics allows— sustainable furniture construction should allow for the use of low-quality fast-growing materials not suitable for other types of construction. And in disadvantaged areas of the world, such designs should allow for the use of sawmill offal that would otherwise be wasted.

3.1.1 Why Select a Stool Frame for the Case Study

A stool frame was selected as the base structure for studying EoL Options, (specifically product life extension) because it is the foundation structure for both chairs and tables—two of the most important furniture structures relating to quality of life, especially in disadvantaged areas of the world. Furthermore, chairs and tables are essential classroom components that are entirely lacking in schools in some parts of the world (Malawi, for example) and are difficult to replace in others.

Extensive research has been conducted on the design of chairs and tables at the Wood Research Laboratory at Purdue University and product development outcomes of this research serve as a knowledge base for EoL studies (Eckelman and Haviarova 2006).

Further, *LCA analysis of wooden chairs* were conducted at the WRL, which demonstrated that the wooden furniture is already a highly sustainable product and its sustainability could be improved even farther by applying “End of Life “strategies (Haviarova et al., 2013).

Finally, *frame type of construction is globally applicable and sustainability* can be optimized by selecting appropriate joinery systems which help to improve durability and reparability and thus extend product life (Eckelman et al., 2003).

In summary, a stool frame was selected as an ideal subject to study EoL Options, specifically product life extension through different construction options and to study product recovery for the next life.

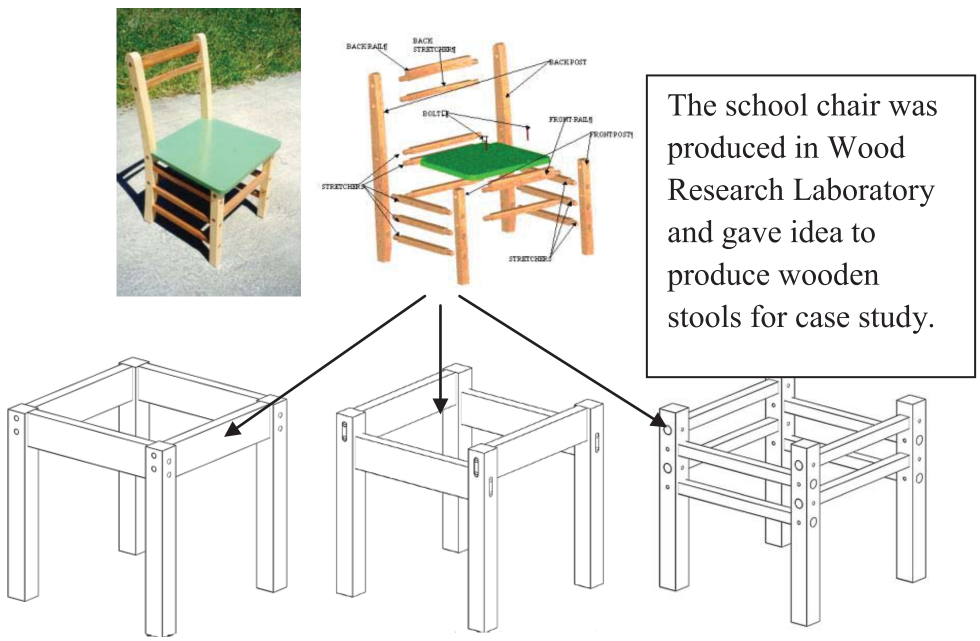

Figure 3-1: Simple wooden school chair and baseline model (Haviarova at al., 2013).

3.1.2 Selection of Construction Systems for the Case Study

Applicable joinery systems were selected and evaluated in the case study. Stools assembled with different joints were rated in terms of product durability, ease of assembly and disassembly, possibility of product repair and associated cost.

Two types of joinery were implemented into this system and tested:

1. *Ready-To-Assembly (RTA) Joinery* -- Screws, Barrel Nuts, Pinned Round Mortise & Tenon, Pinned Rectangular Mortise & Tenon

2. *Permanent (Glued) Joinery* – Dowel, Glued Round Mortise & Tenon, Glued Rectangular Mortise & Tenon

3.1.3 Objectives

The primary objective of the study was to investigate which joints are best-suited for "sustainable" furniture construction. Specific objectives included:

a. Determine the cyclic front-to-back load capacity of chairs constructed with eight types joints;

b. Determine which joints allow for the simplest repairs following failure.

c. Determine which joints allow for simplest disassembly following failure.

d. Determine which fasteners and connectors are best suited for repair of the stools or reassembly of parts.

e. Determine static load capacities of the seven types of joints used in construction of the stools.

f. Benchmark glued permanent joinery with ready to assembly (RTA) joinery.

3.2 Materials and Methods

3.2.1 Materials

3.2.1.1 Wood materials

All of the structural members used in this study were constructed of Yellow Poplar (*Liriodendron tulipifera*) lumber which had been conditioned to 7% moisture content. The physical and mechanical properties of Yellow Poplar are as follows (The Encyclopedia of Wood):

- The sapwood is white while heartwood is brownish, green and sometimes purple, blue and red.

Figure 3-2: Yellow Poplar (Liriodendron tulipifera) lumber.

- The grain is straight and uniform in texture
- When slow-grown, the wood is light in weight, moderately low in bending strength and low in shock resistance
- The wood has high shrinkage characteristics in the tangential direction.

  Specific mechanical properties of yellow poplar are given in Table 5.1.

In this study, plain white oak (*Quercus alba*) dowels were used to construct the dowel joints. In the case of joints constructed with dowel nuts, a single dowel embedded in the end of a rail and in a mating hole in a corresponding post was used to prevent the rail from rotating about its longitudinal axis. Dowels used in the two-pin moment resisting joints measured 3/8 inches in diameter by 2 inches in length, whereas those used as “locaters” measure 1/4 inches in diameter by 1-1/2 inches in length.

Figure 3-3: Oak Dowel

(a) (b)

Figure 3-4: a. Wood screw, b. Dowel-nut and bed bolt.

Table 3-1: Mechanical properties of Yellow Poplar (The Encyclopedia of Wood)

	Moisture content	Specific gravity	Static Bending			Impact bending (in)	Compression parallel to grain (lbf/in)	Compression perpendicular to grain (lbf/in)	Shear parallel to grain (lbf/in)	Tension perpendicular to grain (lbf/in)	Side hardness (lbf)
			Modulus of Rupture (lbf/in^2)	Modulus of Elasticity (x10	Work to maximum load (in-lbf/in^2)						
Yellow Poplar	Green	0.4	6,000	1.22	7.5	26	2,660	270	790	510	440
	12%	0.42	10,100	1.25	8.8	24	5,540	500	1190	540	540

3.3 Specimen Construction

3.3.1 Construction of Specimens for Cyclic Front-to-Back Load Test

Frames consisting of the front and back legs, and the front, back, and side rails of a typical stool frame were constructed with each of the following joint fastening systems,

(1) Two wood screws, Figure 3.3; 3.5

(2) Dowel nut with bed bolt, Figure 3.3; 3.6

(3) Pinned round mortise and tenon (two-stretcher side frame construction) Figure 3.7

(4) Pinned rectangular mortise and tenon, Figure 3.9

(5) Glued two-pin dowel, Figure 3.11

(6) Glued round mortise and tenon (two-stretcher side frame construction) Figure 3.8.

(7) Glued rectangular mortise and tenon, Figure 3.10

(8) Glued round mortise and tenon, Figure 3.12.

Reasons for inclusion of frames constructed with these joint types were as follows:

(1) Frames constructed with screw joints were included because of ease of assembly and disassembly of the frame.

(2) Likewise, frames constructed with dowel nuts and bed bolts with locator dowel were included because they have inherent high load capacity, permit easy disassembly of frames, and provide a simple means of repairing damaged joints.

(3) Two-stretcher side frames with pinned round mortise and tenon joints, were included because they can be produced from materials such as small rapidly grown timbers and sawmill offal, and because of their simplicity and ease of construction. In addition, a substantial body of information exists concerning testing of similar frame constructions

(4) Frames with pinned rectangular mortise and tenon joints were included because they can be manufactured from local materials alone—and thus are well-suited for use in under-developed countries.

(5) Frames with adhesive-based two-pin moment resisting dowel joints were included in the study because they are perhaps the most widely used production joint.

(6) Two-stretcher side frames with glued round mortise and tenon joints were included because they can be produced from materials such as small rapidly grown timbers and sawmill offal, and because of their simplicity and ease of construction. In addition, their long history of successful use (Shaker furniture) of this type of construction and a substantial body of information exists concerning the performance of similar frame constructions.

(7) Frames with glued rectangular mortise and tenon joints because of because they are still widely commercially used, can be manufactured from local materials alone in under-developed countries—provided adhesives are available, and when properly constructed, can have high joint strength.

(8) Frames constructed with side rails and glued round and mortise and tenon joints were included because of the simplicity of construction and relatively high moment capacity reported for glued round mortise and tenon joints with "wide"shoulders.

3.3.1.1 Screw Joint Frame Construction

Frames with screw joints (1) were constructed with two 3-inch long # 14 wood screws, Figure 3-4a, and 3-5. Relief holes in the posts measured 0.375 inches in diameter; pilot holes in the ends of the rails measure 0.25 inches. Screws were tightened until the head of the screw was embedded flush with the surface of the post.

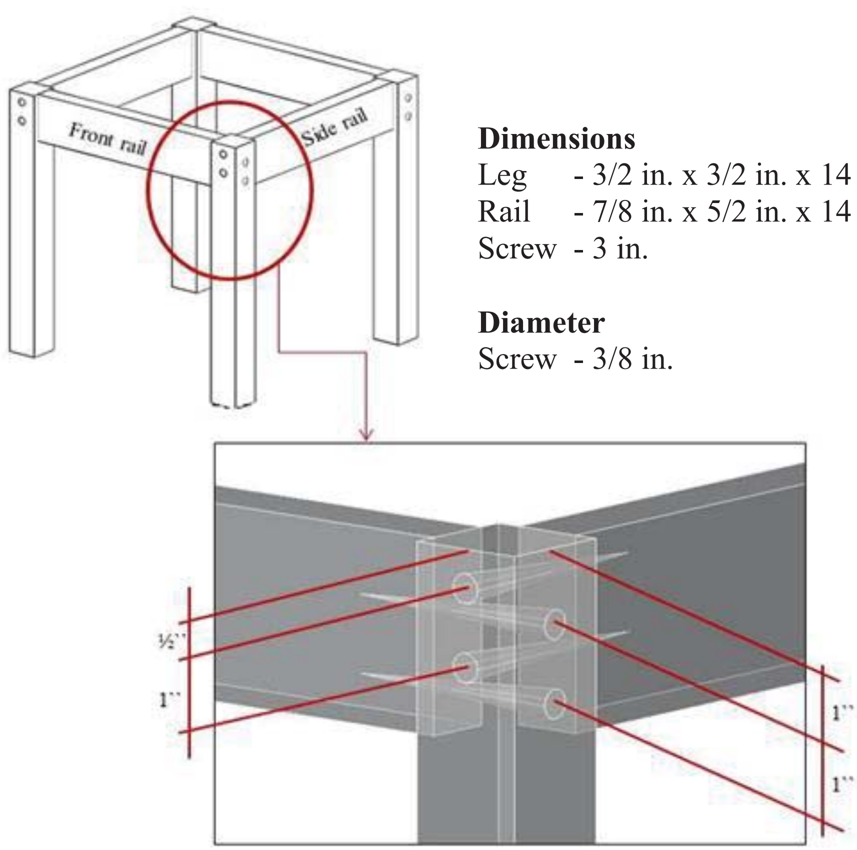

Figure 3-5: Screw joint frame construction configuration.

3.3.1.2 Bed Bolt (Dowel Nut) Joints Frame Construction

Frames with dowel nut and bed bolt joints (2) were constructed with 3-inch long by 0.25-inch diameter and 0.375 inch diameter dowel nuts, Figure 3-4b, 3-6,. Relief holes, 0.25 inches in diameter, were drilled for the bed bolts; 0.375 inch holes were drilled to accommodate the dowel nuts.

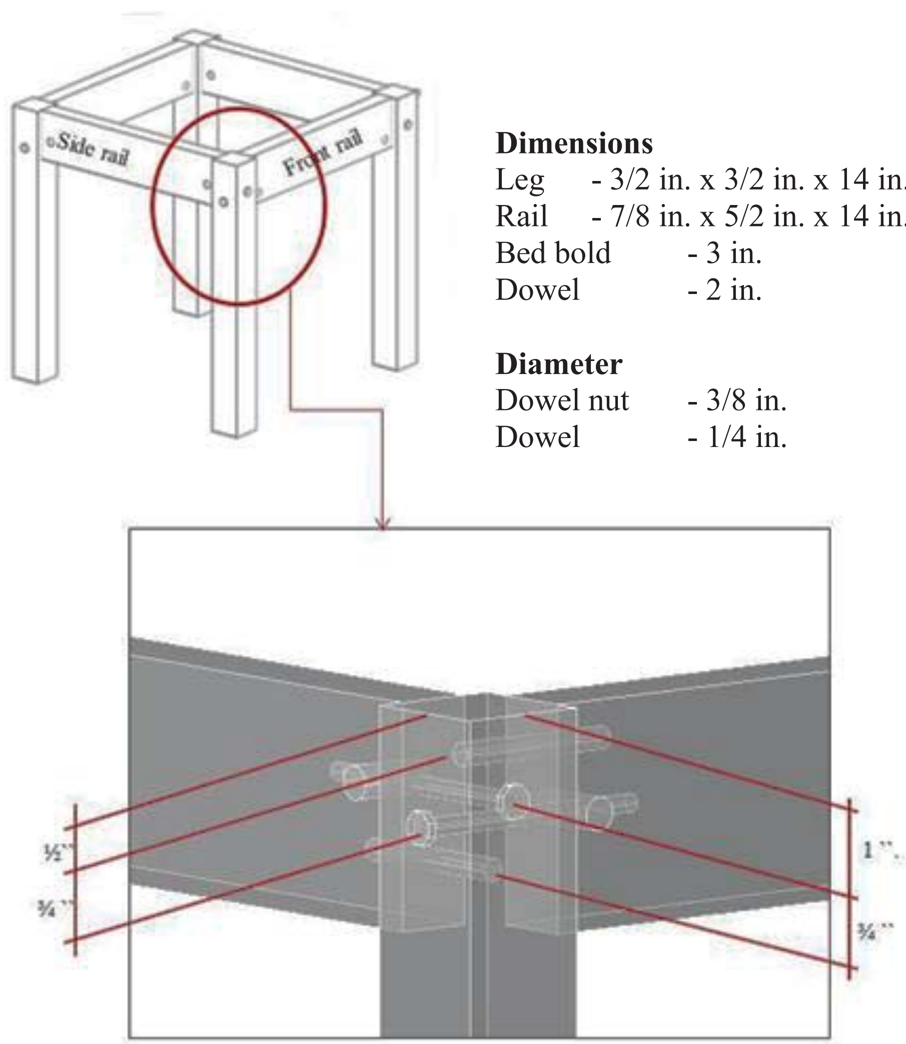

Figure 3-6: Bed bolt (Dowel nuts) joint frame construction configuration.

3.3.1.3 Round Mortise and Tenon Joint, Two Stretcher Frame Construction

Frames with two side stretchers were constructed with tenons (and matching mortises) that measured 0.72-inches in diameter by 1.5 inches long. Tenons were machined with a 23/32 inch hole saw; corresponding mortises were machined with a 23/32 drill bit; mortise/tenon clearance was such that tenons could be inserted with little force three-fourths of the way into the mortise. Joints (3) were pinned with 0.25-inch white oak pins, Figure 3-7.

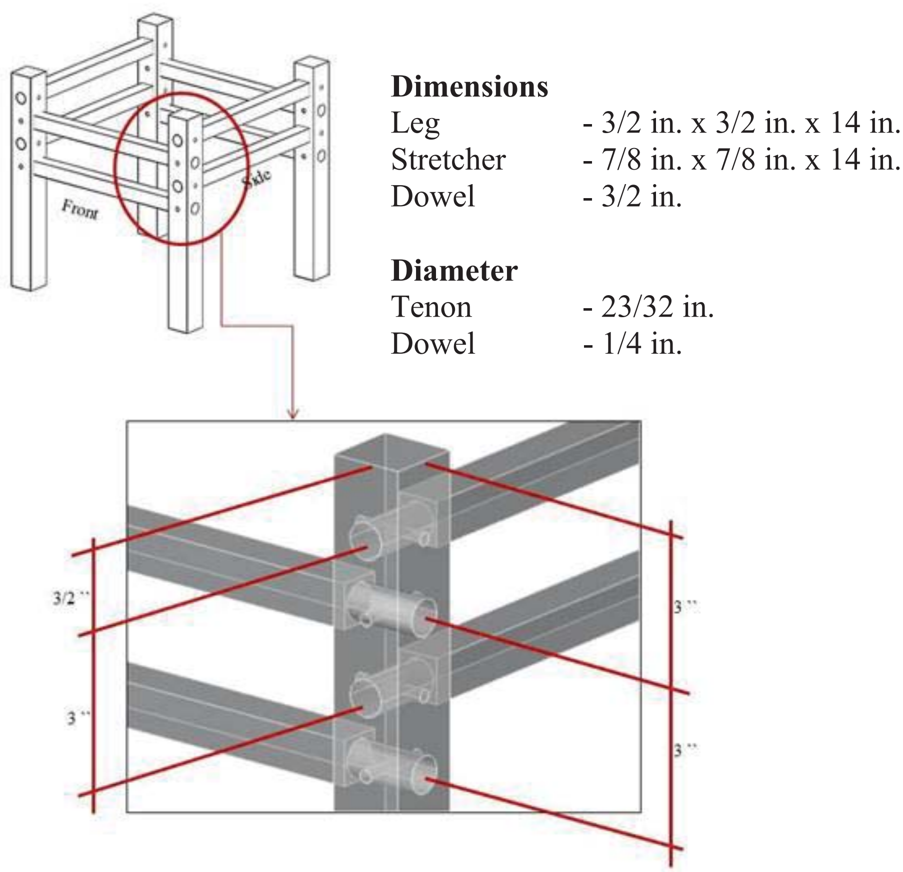

Figure 3-7: Pinned round mortise and tenon joint, two stretcher frame construction.

Frames with two side stretchers were constructed with tenons (and matching mortises) that measured 0.72-inches in diameter by 1.5 inches long. Tenons were machined with a 23/32 inch hole saw; corresponding mortises were machined with a 23/32 drill bit; mortise/tenon clearance was such that tenons could be inserted with little force three-fourths of the way into the mortise. The joints (6), Figure 3-8, were assembled with a 40% PVA adhesive.

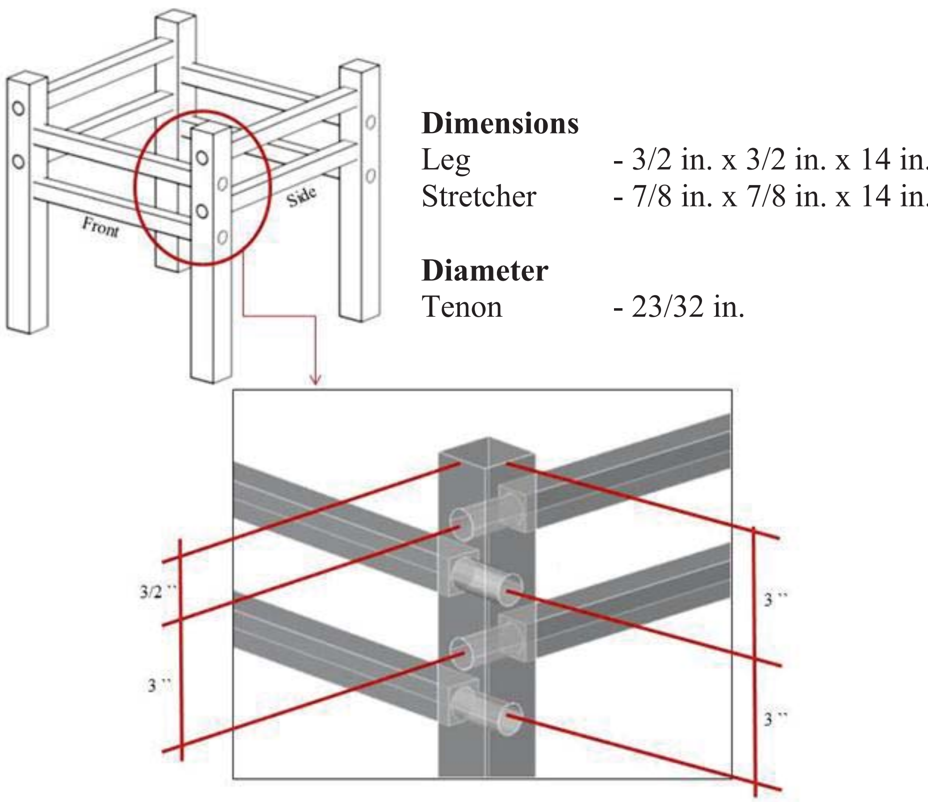

Figure 3-8: Two stretchers glued round mortise and tenon joint frame construction configuration.

3.3.1.4 Rectangular Mortise and Tenon Joint Frame Construction

Frames with pinned rectangular mortise and tenon joints were constructed with tenons (and matching mortises) that measured 0.375 inches thick by 1.5 inches wide by 1.5 inches long.. Tenons were machined with table saw and sander, whereas mortises were machined using multiple chisel. Clearance between tenon and mortise was 0.05 inches. Pinned round-shouldered mortise and tenon joints (4) were constructed with 0.25-inch diameter plain white oak pins, Figure 3-9.

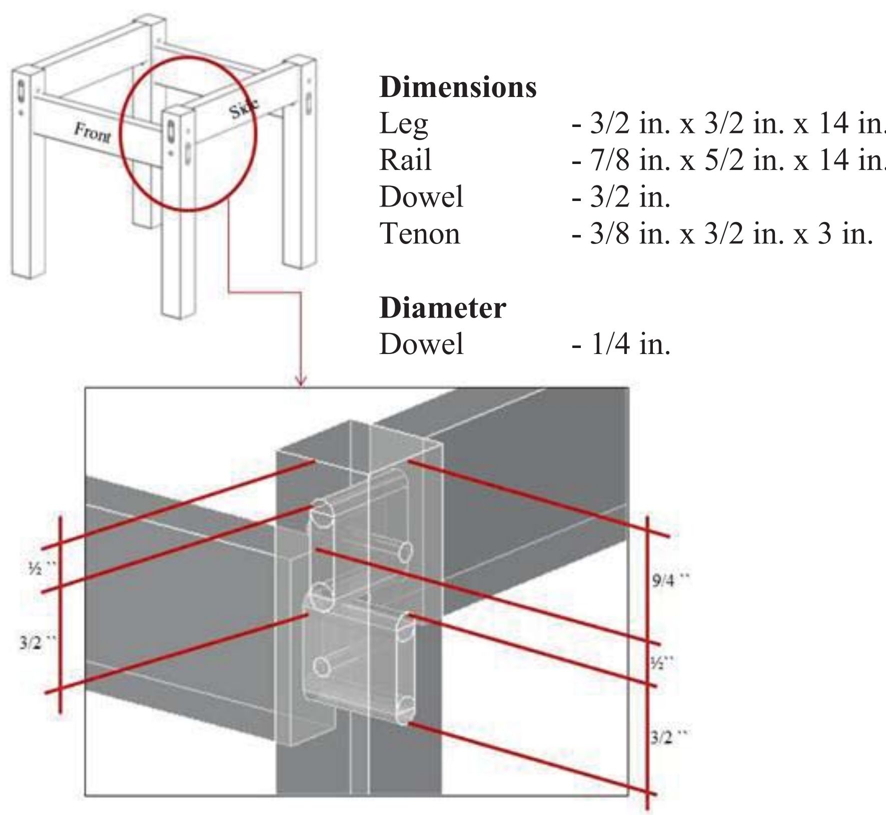

Figure 3-9: Pinned round-shouldered rectangular mortise and tenon joint frame construction configuration**.**

Frames with glued rectangular mortise and tenon joints were constructed with tenons (and matching mortises) that measured 0.375 inches thick by 1.5 inches wide by 1.5 inches long.. Tenons were machined with table saw and sander, whereas mortises were machined using multiple chisel. Clearance between tenon and mortise was 0.05 inches. Joints (7) were assembled with a Polyvinyl Acetate adhesive (40% solid content), Figure 3-10, and were allowed to cure at least 1 day before testing (8 hours as recommended for adhesive).

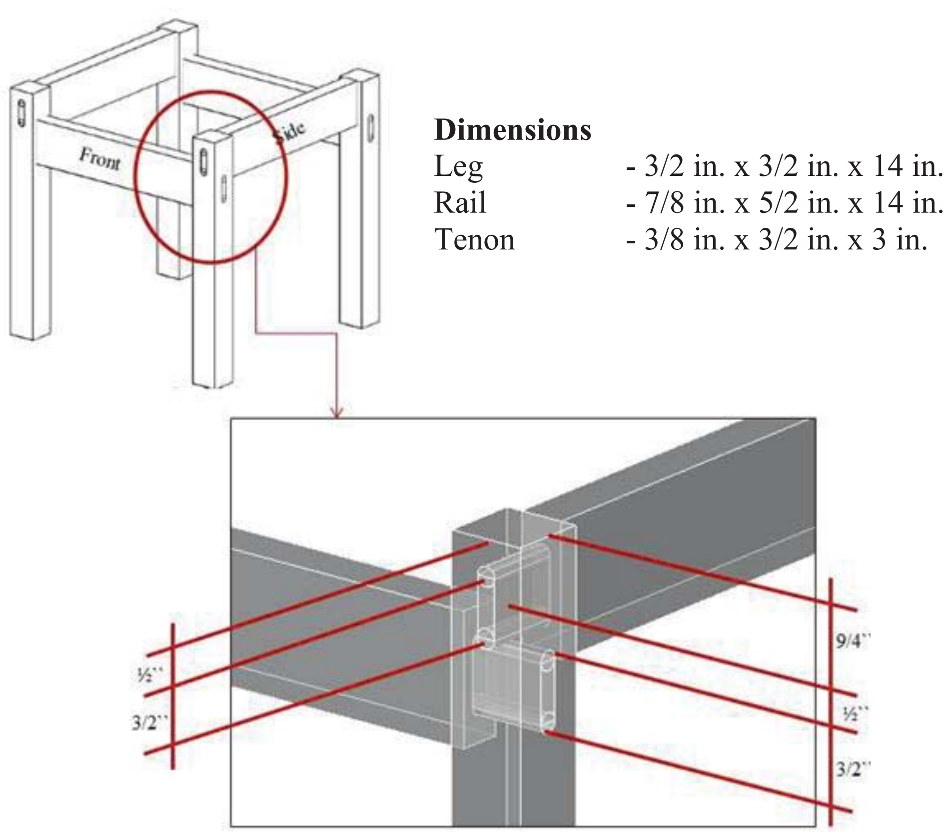

Figure 3-10: Glued round-shouldered rectangular mortise and tenon joint frame construction configuration.

3.3.1.5 Dowel Joint Frame Construction

Frames with dowel joints were constructed with 0.375 –inch diameter by 2-inch long white oak dowels. Holes for the dowels (5) were machined with a 0.375-inch diameter drill bit. Dowels were embedded 1-inch in the ends of the rails and 1-inch in the walls of the posts, Figure 3-11. Walls of the holes were throughly coated with a Polyvinyl Acetate (40% solid content). Completed assemblies were allowed to cure at least 1 day before testing.

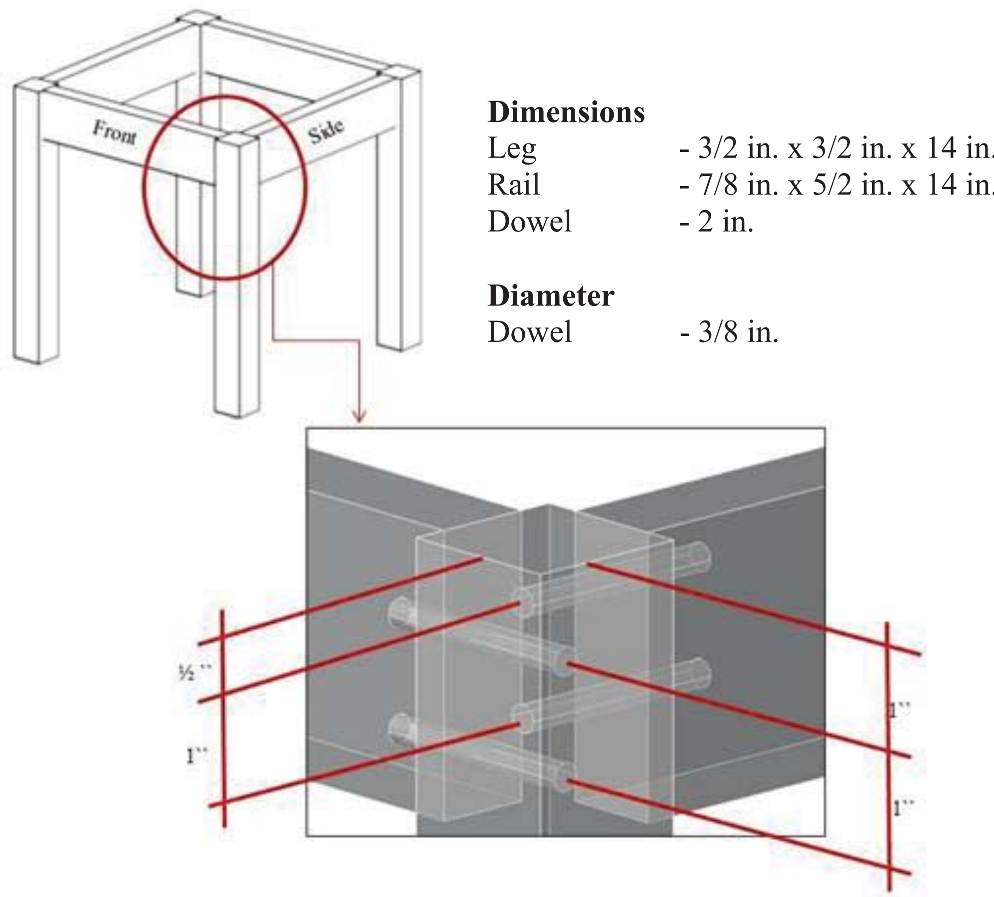

Figure 3-11: Dowel joint frame construction configuration

3.3.1.6 Glued Round Mortise and Tenon Joint, Single Rail Frame Construction

Frames with a (single) side rail and round mortise and tenon joints were constructed with tenons (and matching mortises) that measured 0.72 inches in diameter by 1.5 inches long. Tenons were machined with a 23/32 inch hole saw; corresponding mortises were machined with a 23/32 drill bit; overall, tenons could be inserted with little force three-fourths of the way into the mortise.

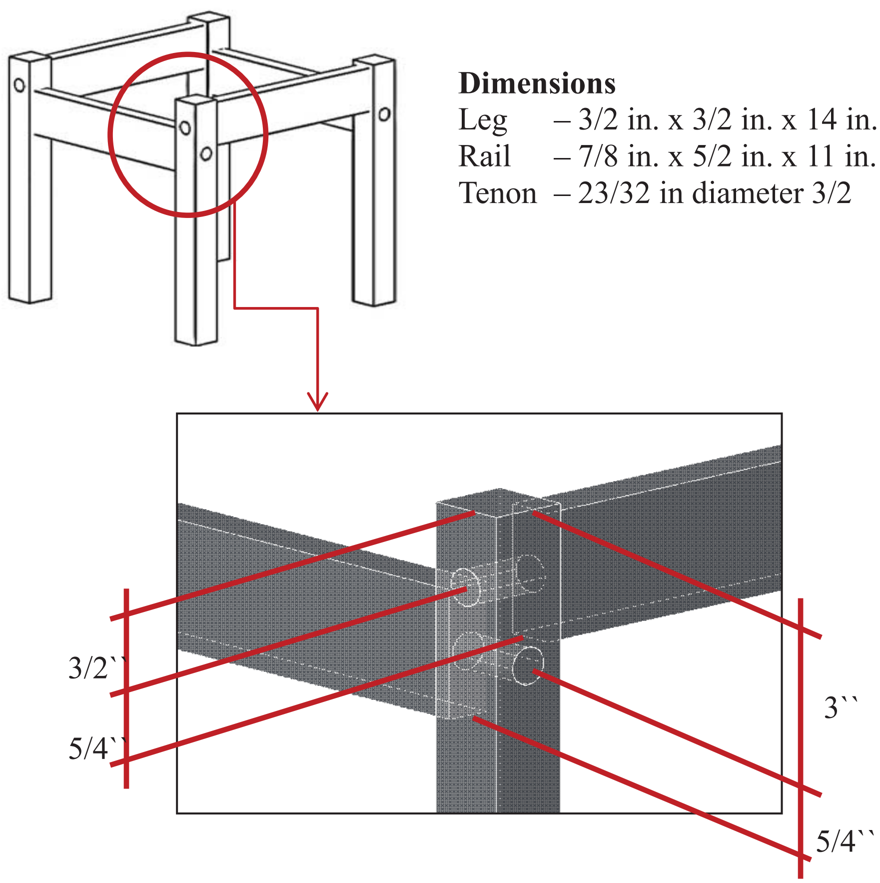

Figure 3-12: Glued round mortise and tenon joint, single rail frame construction

3.3.2 Construction of Specimens for Static Test

Construction of the static test specimens is shown in Figures 3-11 through 3-17. The joints were constructed in a manner identical to that used in construction of the stools except that the screw-, dowel nut-, rou

nd mortise and tenon, and dowel-joints were constructed as T-shaped specimens in order to facilitate their attachment to the testing apparatus. All of the round-shouldered mortise and tenon joints were constructed as L-shaped joints, however, because of the possibility of failure of the top of the post with this type of joint. Leg length of all specimens was 10 inches, whereas rails and stretchers lengths were 12 in.

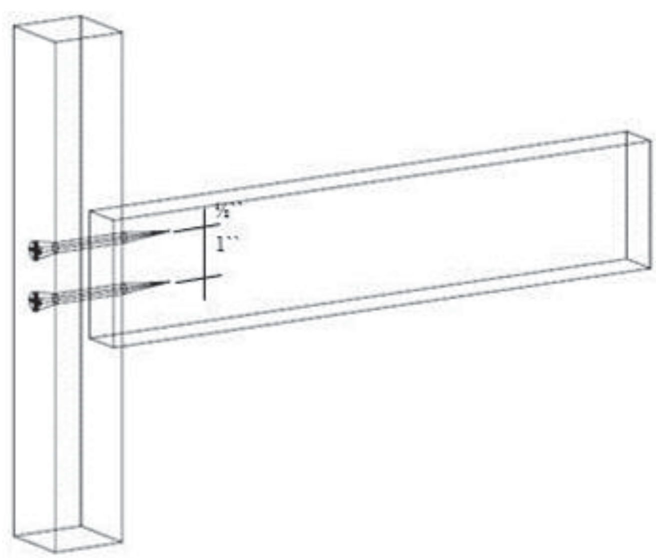

Figure 3-13: Screw T-joint configuration.

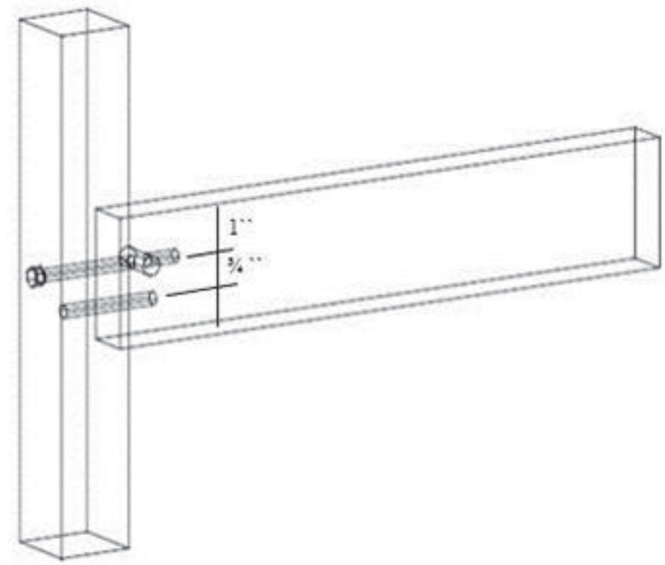

Figure 3-14: Bed bolts (Dowel nuts) T-joint configuration.

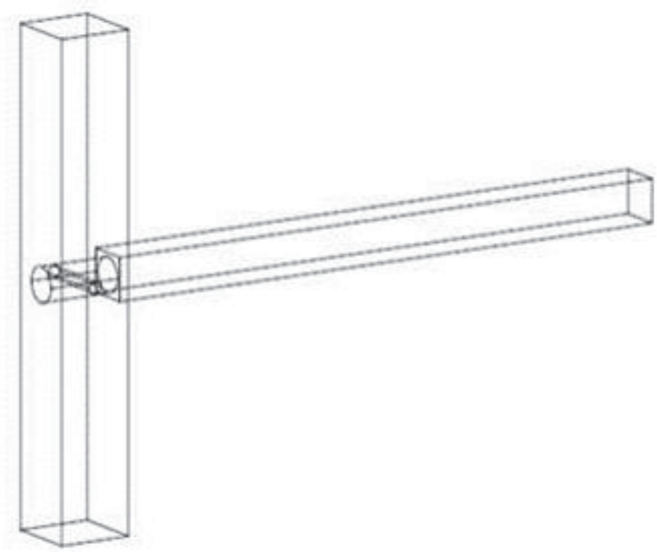

Figure 3-15: Pinned round mortise and tenon T-joint configuration.

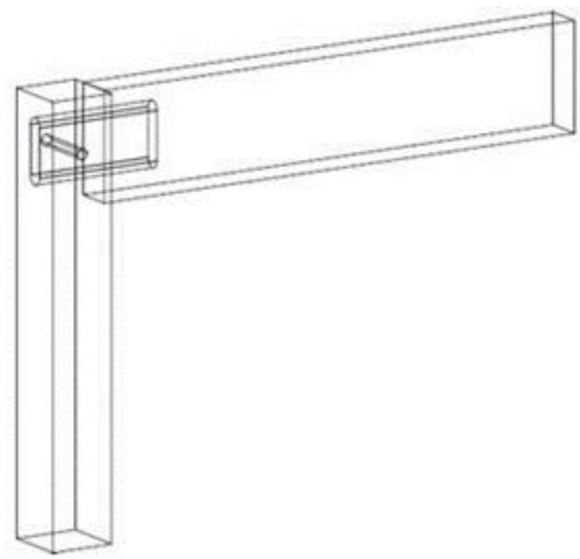

Figure 3-16: Pinned rectangle mortise and tenon L-joint configuration.

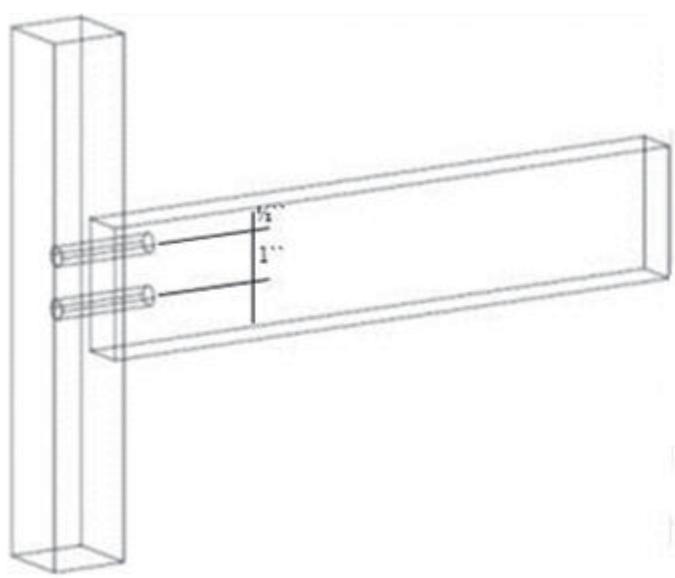

Figure 3-17: Dowel T-joint configuration.

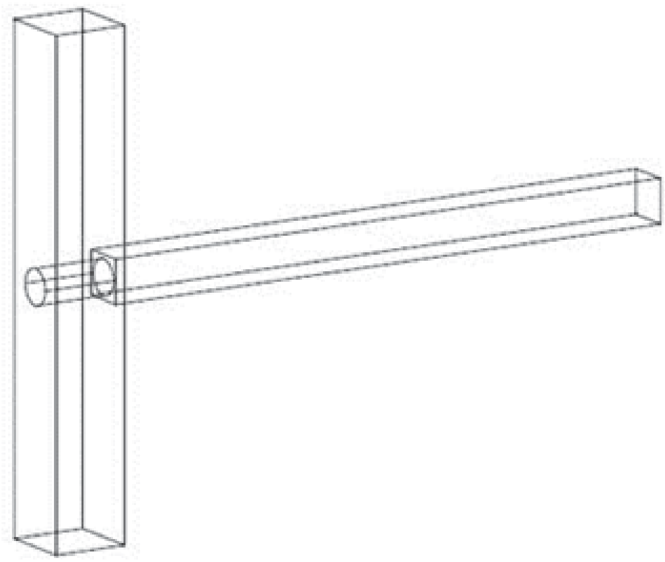

Figure 3-18: Glued round mortise and tenon T-joint configuration.

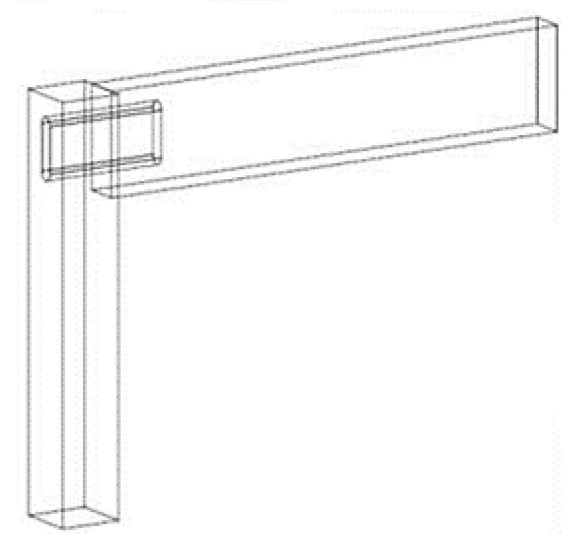

Figure 3-19: Glued rectangle mortise and tenon L-joint configuration.

3.3.3 Construction of MOR and MOE Specimens

All of the specimens were machined from yellow poplar lumber that had been conditioned to, and maintained at 7% moisture content. All of the specimens measured 2.5 inches square by 35 inches long.

3.4 Testing Methods

3.4.1 Modulus of Rupture and Modulus of Elasticity Test

Tests were carried out in accordance with British standard (BS 373:1957). The test set up is shown in Figure 3-20. All tests were conducted on Riehle 30 kip Universal Test Machine with a sensitivity of 0.25.

Modulus of Rupture (MOR) may be determined from maximum load (for the test set up shown) by means of the expression (Wood Handbook, 2010)

$$\mathrm{MOE} = 1.5 \times \frac{P \times L}{b \times h^2} \quad lbf/in^2 \qquad (1)$$

where,

MOR: Modulus of Rupture (lbf/in^2)
P: Maximum load (lb)
L: Span Length (in)
b: Width (in)
h: Depth (in)

Likewise, for the set up shown, Modulus of Elasticity may be determined from the deflection versus load curve by means of the following expression (Wood handbook, 2010).

$$\text{MOE} = \frac{(P_1 - P_2) \times L^3}{4 \times (Y_1 - Y_2) \times b \times h^3} \quad lbf/in^2 \qquad (2)$$

where,

MOE: Modulus of Elasticity (lbf/in^2)

P: Maximum load (lb)

L: Span Length (in)

b: Width (in)

h: Depth (in)

Y: Deformation (in)

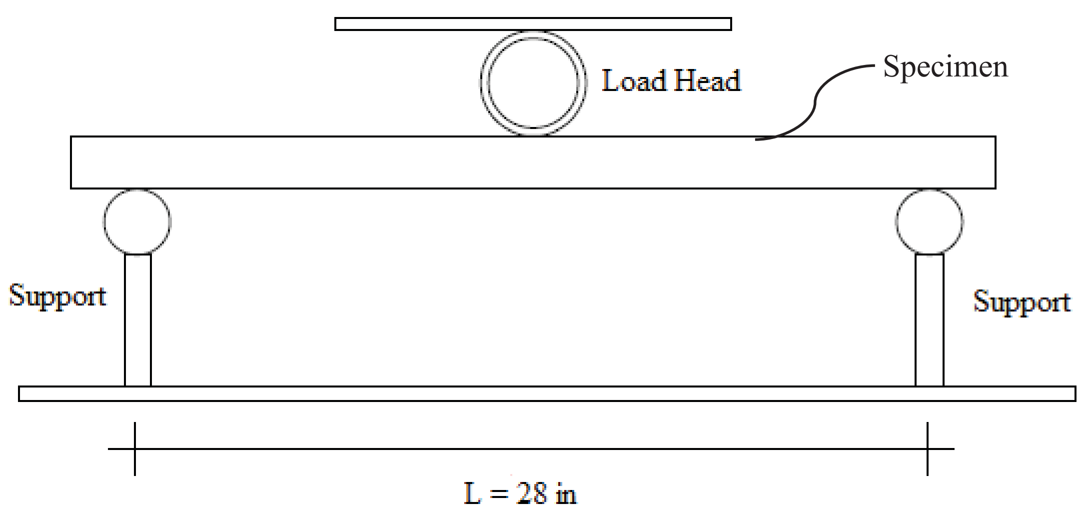

Figure 3-20: Test set up for determination of MOR and MOE.

3.4.2 Static Load Joint Test

Five specimens were prepared for each joint group as described in construction of the specimens. Static load test were conducted as shown in Figure 3-21. All tests were conducted on a Riehle 30 kip Universal test machine at a cross head load rate of 0.25 inches/min (Erdil et al. 2005). The test conducted until a non-recoverable drop off in load occurred. T-shaped joints were attached to the test jig as shown. L-shaped joints were clamped to the L-shaped post of the testing with C-clamps. Bending moment capacity was based on the highest load obtained.

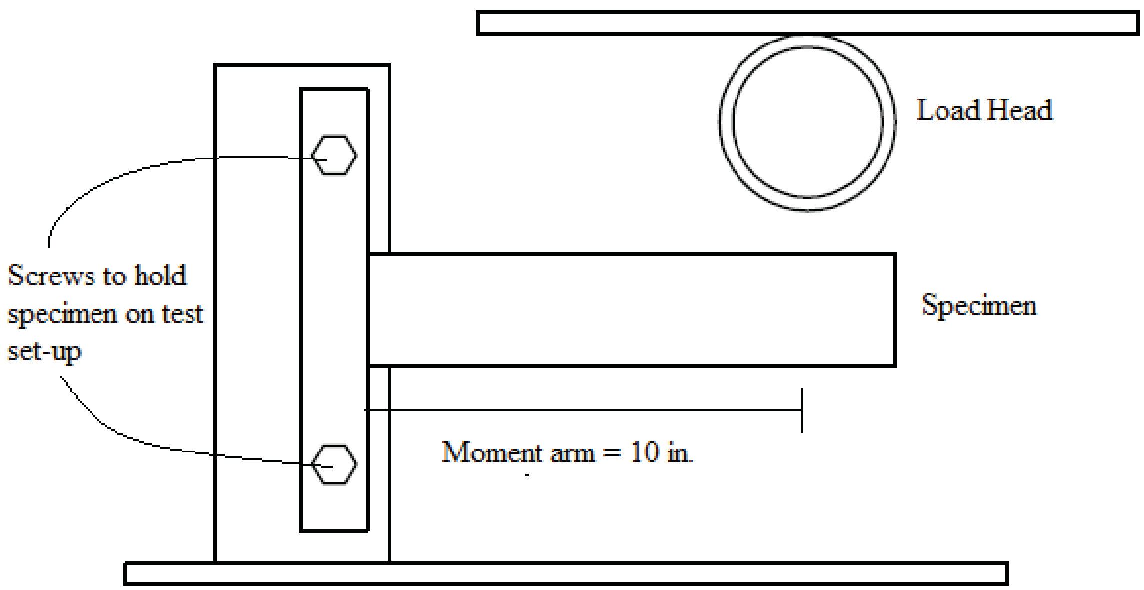

Figure 3-21: Static load test set up.

3.4.3 Cyclic Front-to-Back Load Frame Test

3.4.3.1 Background

Studies by the American Library Association (Eckelman, 1995) indicate that the most common damage to chair frames arises from cyclic front to back loading of the seats—as typified by a user sitting down in a chair and pushing backward or by tilting backwards—which causes bending moments to be imposed on the rail and stretcher to front and back post joints. Hence, the front-to-back load test reported by the American Library Association was used to evaluate the chair frames included in this study. Use of this test permitted determination of ultimate load capacity and durability; resulting damage to the frame and parts at failure; ease of frame repair; and ease of frame disassembly after failure.

Following initial testing, reconstruction and retesting of frames assembled from damaged and undamaged parts demonstrates whether or not reconstruction is feasible and reconstructed frames are structurally sound.

3.4.3.2 Test Procedure

As stated above, the aim of the cyclic front-to-back load test is to determine the resistance of the side frame of the stools to front to back loading in a manner that simulates someone sitting down and tilting backward on the stool (Eckelman, 1999).

In this test, a horizontal load is applied from front to back on stools at a rate 20 cycles per minute (Eckelman, 1995; 1999). Tests are started at the 50 lb. load level and are increased 50 lb. after 25,000 cycles are completed. This procedure is repeated until some type of failure occurs.

The stools were mounted for testing as shown in Figure 3-22. The horizontal portion of the strap provides the front to back load on the stools, whereas the vertical portion of the strap provides the restraining force needed to keep the stool from overturning. The strap should be anchored directly below from edge of the front rail (Eckelman, 1995).

Tests were conducted in three phases in order to compare durability in each life. Following completion of the first life tests, the damaged parts were removed and the stools were constructed—new parts were used where needed. All of the re-built stools were tested as described above.

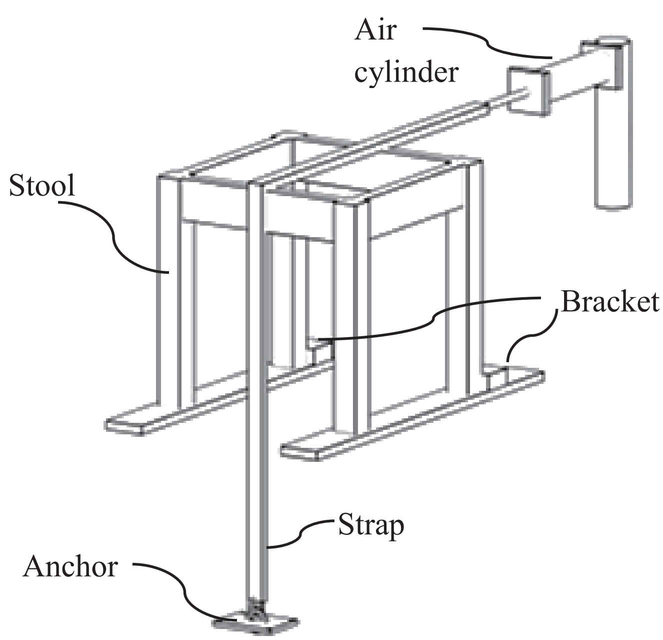

Figure 3-22: Cyclic front-to-back load test configuration.

3.5 Test Results

3.5.1 Modulus of Rupture and Modulus of Elasticity Tests

Results of the tests are given in Table 3-2. The mean value for MOR was 11,172.58 lb/in^2 with a standard deviation of 867 lb/in^2. The mean value for MOE was 1.7 x 10^6 lb/in^2 with a standard deviation of 0.15 x 10^6 lb/in^2.

Table 3-2: Modulus of Rupture and Modulus of Elasticity of Yellow Poplar

Spec. No.	MOR lb/in^2	MOE lb/in^2	MC %	MOR Adjusted to 12%	MOE Adjusted to 12%	Table Value	
						MOR	MOE
1	13,890.85	1,649,294	6.7	10,740.82	1.49 x 10^6		
2	14,526.09	2,010,347	6.9	11,158.95	1.72 x 10^6		
3	14,545.41	2,001,427	6.7	11,089.41	1.71 x 10^6		
4	12,982.69	1,889,640	6.8	10,280.66	1.64 x 10^6		
5	18,585.34	2,469,323	5.7	12,593.06	1.92 x 10^6		
Mean				11,172.58	1.69 x 10^6	10,100	1.58x106
Std. Dev.				867.007	1.38 x 10^5		

3.5.2 Static Load Joint Tests

Results of the static load joint tests are given in Table 3-3. In the case of the static-load joint tests, the highest average moment capacity was obtained with rectangular mortise and tenon joints, 2,656 in-lb with a standard deviation of 151.26 in-lb, whereas the moment capacity and standard deviation for comparable pinned joints amounted to 1,558 in-lb and 110.77 in-lb, respectively. The least capacity was obtained with pinned round mortise and tenon joints, 414 in-lb with a standard deviation of 60.25 in-lb; however, the glued round mortise and tenon joints had a mean capacity of 710.0 in-lb with a standard deviation of only 73.49 in-lb. The average moment capacity of the dowel nuts joints was 2,336 in-lb with a standard deviation of 347.6 in-lb. Likewise, the average moment capacity of the screw joints was 1,570 in-lb with a standard deviation of 594.9 in-lb. Similarly, the barrel nuts specimens had a mean capacity of 896 in-lb with a standard deviation of 151.92 in-lb.

Table 3-3: Static load test results (in-lb).

Spec. No.	Ready-To-Assembly (RTA) Joinery				Permanent (Glued) Joinery		
	Screws	Barrel Nuts	Round M&T - Pinned	Regt. M&T - Pinned	Dowel	Round M&T - Glued	Regt. M&T - Glued
1	1,040	720	470	1,580	2,640	810	2,710
2	2,040	1,060	480	1,540	1,940	740	2,490
3	2,280	880	360	1,510	2,710	620	2,770
4	930	1,040	350	1,730	2,360	720	2,500
5	1,560	780	410	1,430	2,030	660	2,810
Mean	1,570	896	414	1,558	2,336	710	2,656
Std. Dev.	594.9	151.92	60.25	110.77	347.6	73.49	151.26

3.5.3 Cyclic Front-to-Back Load Test

Results for the cyclic front-to-back load tests are given in Table 3-4, 3-5 and 3-6 for the first life, the second life and the third life of stools, respectively.

Table 3-4: Results of the first life front to back cyclic load tests of stools (lb).

Spec. No.	Ready-To-Assembly (RTA) Joinery				Permanent (Glued) Joinery		
	Screws	Barrel Nuts	Round M&T - Pinned	Regt. M&T - Pinned	Dowel	Round M&T - Glued	Regt. M&T - Glued
1	200.65	101.03	202.32	156.67	197.21	245.50	200.00
2	116.86	100.29	155.76	156.44	150.03	248.37	200.00
3	104.20	134.72	151.88	150.06	100.88	250.86	200.14
4	100.03	100.03	166.89	150.02	85.30	200.04	150.21
5	100.07	101.99	201.05	112.90	150.28	200.04	207.68
Mean	124.36	107.61	175.58	145.22	136.74	228.96	191.61
Std. Dev.	43.20	15.17	24.46	18.36	44.58	26.47	23.38

Table 3-5: Results for the second life cyclic front to back load test of stools (lb).

Spec. No.	Ready-To-Assembly (RTA) Joinery				Permanent (Glued) Joinery		
	Screws	Barrel Nuts	Round M&T - Pinned	Regt. M&T - Pinned	Dowel	Round M&T - Glued	Regt. M&T - Glued
1	215.44	100.07	150.08	151.57	100.21	200.05	150.10
2	200.29	86.95	150.06	151.21	110.68	289.57	200.07
3	200.07	100.06	178.03	53.65	101.06	200.56	153.04
4	150.75	100.02	165.00	102.27	150.94	264.36	127.33
5	150.04	100.02	150.00	102.27	158.04	207.83	122.66
Mean	183.32	97.42	158.64	112.20	124.19	232.47	150.64
Std. Dev.	30.69	5.86	12.63	40.92	28.08	41.69	30.72

Table 3-6: Results for the third life cyclic front to back load test of stools (lb).

Spec. No.	Ready-To-Assembly (RTA) Joinery				Permanent (Glued) Joinery		
	Screws	Barrel Nuts	Round M&T - Pinned	Regt. M&T - Pinned	Dowel	Round M&T - Glued	Regt. M&T - Glued
1	150.15	51.37	151.33	105.97	161.58	151.28	126.01
2	100.01	50.21	150.02	151.69	103.54	188.94	126.01
3	150.06	50.21	150.02	100.46	163.59	272.68	150.45
4	151.15	50.14	152.64	103.67	151.86	220.44	197.44
5	100.04	50.14	100.03	80.17	151.82	250.79	111.82
Mean	130.28	50.42	140.81	108.39	146.48	216.82	142.34
Std. Dev.	27.62	0.53	22.82	26.28	24.61	48.38	33.79

Table 3-7: Comparison for two-stretcher glued round mortise tenon and glued single round mortise and tenon with rail (lb).

Specimen No.	Round M&T - Glued with Stretcher	Round M&T - Glued with Rail
1	245.50	200.22
2	248.37	200.02
3	250.86	150.64
4	200.04	221.86
5	200.04	200.86
Mean	228.96	194.72
Std. Dev.	26.47	26.34

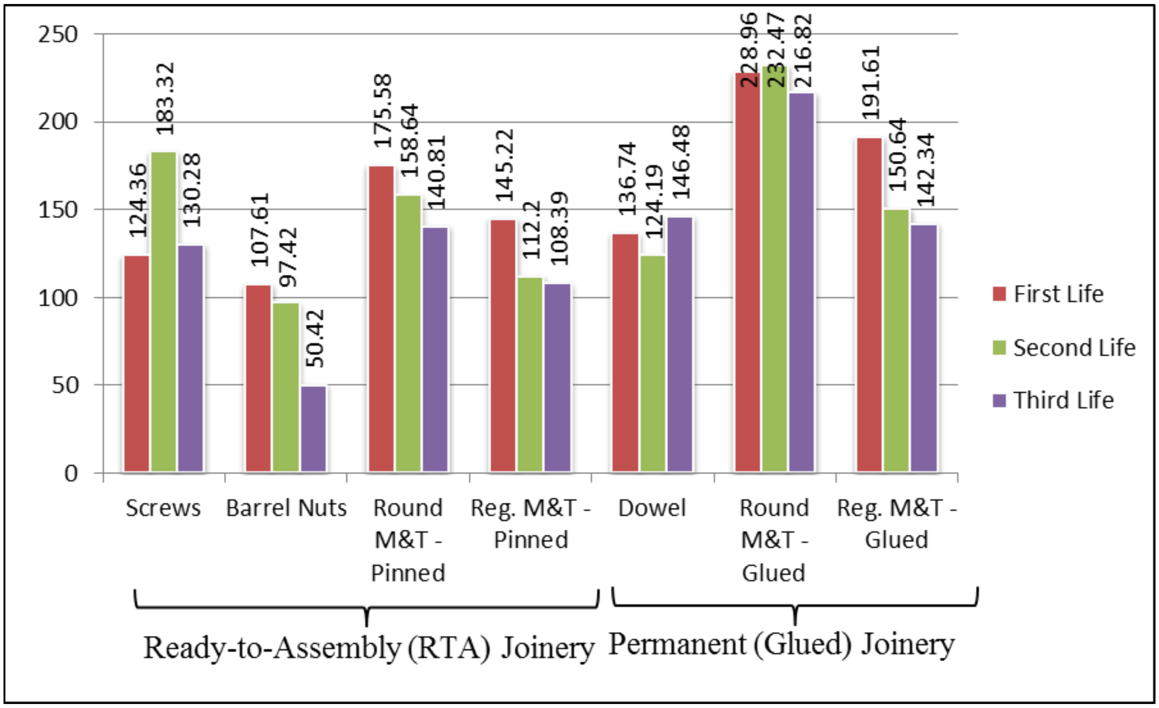

Figure 3-23: Average load caring capacity of the stools
with different joinery systems in each life.

3.5.3.1 Screw Joints

In the first life cycle front-to-back load tests, stool #1 failed at the 250 lbs. load level after 323 cycles were completed, and others failed at 150 lbs. load level; 8432, 2100, 17 and 34 cycles, respectively. The failures were obtained withdrawal of screws from rails for all stools and stool #1 and #4 had also crack on side rails.

In the second life cycle front-to-back load tests, stool #1, #2 and #3 failed at 250 lbs. load level; 7722, 143 and 36 cycles, respectively when stool #4 and #5 failed at 200 lbs. load level; 377 and 19 cycles, respectively.

In the third life cycle front-to-back load tests, stool #1, #3 and #4 failed at 200 lbs. load level after 75, 30 and 573 cycles were completed, respectively. Stool #2 and #5 failed at 150 lbs. load level; 4 and 20 cycles, respectively.

3.5.3.2 Bed Bolt (Dowel Nut) Joints

In the first life cycle front-to-back load tests, all stools failed at 150 lbs. load level with 516, 146, 17358, 16 and 994 cycles, respectively. The failures were obtained on side rails as splitting throughout the fiber direction from nuts connected with back lacks to front legs because of tension and compression rails.

In the second life cycle front-to-back load tests, stool #1, #3, #4 and #5 failed at 150 lbs. load level; 33, 28, 12 and 12 cycles, respectively when stool #2 failed at 100 lbs. load level after 18475 cycles were completed.

In the third life cycle front-to-back load tests, all stools failed at 100 lbs. load level; 684, 107, 107, 72 and 72 cycles, respectively.

3.5.3.3 Pinned Round Mortise and Tenon Joints – Two Stretchers Stool

In the first life cycle front-to-back load tests, stool #1 and #5 failed at 250 lbs. load level after 1162 and 523 cycles were completed, respectively. Stool #2, #3 and #4 failed at 200 lbs. load level after 2882, 938 and 8445 cycles were completed, respectively. The failure for stool #1 were obtained as splitting all tenons from legs while stool #2, #3, #4 and #5 failed all tenons on the one side of the stools.

In the second life cycle front-to-back load tests, stool #1, #2, #3 and #4 failed at 200 lbs. load level after 41, 32, 14016 and 7499 cycles were completed, respectively. Stool #5 failed at 150 lbs. load level before 25000 cycles were completed.

In the third life cycle front-to-back load tests, stool #1, #2, #3 and #4 failed at 200 lbs. load level; 663, 10, 8 and 1319 cycles, respectively. Stool #5 failed at 150 lbs. load level after 16 cycles were completed.

3.5.3.4 Pinned Round-Shouldered Rectangle Mortise and Tenon Joints

In the first life cycle front-to-back load tests, stool #1, #2, #3 and #4 failed at 200 lbs. load level after 3334, 3219, 32 and 10 cycles were completed, respectively. Stool #5 failed at 150 lbs. load level after 6449 cycles were completed. The failure for pinned rectangle mortise and tenon joints were obtained as all tenons were damaged at pin and withdrew from the back legs. Furthermore, the top of back leg of stool #5 cracked.

In the second life cycle front-to-back load tests, stool #1 and #2 failed at 200 lbs. load level after 787 and 607 cycles were completed, respectively when stool #3 failed 100 lbs. load level after 1826 cycles were completed. Stool #4 and #5 failed at 150 lb. load level after 1134 cycles were completed for both of them.

In the third life cycle front-to-back load tests, stool #1, #3 and #4 failed at 150 lbs. load level; 2984, 230 and 1836 cycles, respectively. Stool #2 failed at 200 lbs. load level after 844 cycles were completed whereas stool #5 failed at 100 lb. load level after 15084 cycles were completed.

3.5.3.5 Dowel Joints

In the first life cycle front-to-back load tests, stool #1. #2 and #5 failed at 200 lbs. load level after 23603, 13 and 139 cycles were completed, respectively. Stool #3 failed at 150 lbs. load level after 440 cycles were completed when stool #4 failed at 100 lbs. load level after 17648 cycles were completed. The failures were obtained dowels on the side rails glued to back legs as splitting. In addition, the back rail of the stool #5 was damaged because of torsion.

In the second life cycle front-to-back load tests, stool #1, #2 and #3 failed at 150 lbs. load level after 106, 5340 and 529 cycles were completed, respectively. Stool # 4 and #5 failed at 200 lbs. load level after 472 and 4019 cycles were completed, respectively.

In the third life cycle front-to-back load tests, stool #1, #3, #4 and #5 failed at 200 lbs. load level; 5790, 6796, 932 and 912 cycles, respectively. Stool # 2 failed at 150 lbs. load level after 1768 cycles were completed.

3.5.3.6 Glued Round Mortise and Tenon Joints – Two Stretchers Stools

In the first life cycle front-to-back load tests, stool #1, #2, #4 and #5 failed at 250 lbs. load level after 22750, 24187, 22 and 22 cycles were completed, respectively. Stool #3 failed at 300 lbs. load level after 429 cycles were completed. The failures on stools were obtained at end of the tenons. However, the stretchers on the side of the stool #1, #3, #4 and #5 were damaged while the top stretches of the stool #2 failed at end of the tenons but the failures were obtained at middle of the bottom stretchers.

In the second life cycle front-to-back load tests, stool #1, #3 and #5 failed at 250 lbs. load level after 27, 279 and 3914 cycles were completed, respectively. Stool #2 and #4 failed at 300 lbs. load level after 19784 and 7179 cycles were completed, respectively.

In the third life cycle front-to-back load tests, stool #1 and #2 failed at 200 lbs. load level; 638 and 19468 cycles, respectively. Stool #3 and #5 failed at 300 lbs. load level; 11339 and 395 cycles, respectively. Stool #4 failed at 250 lbs. load level after 10221 cycles were completed.

3.5.3.7 Glued Round-Shouldered Rectangle Mortise and Tenon Joints

In the first life cycle front-to-back load tests, stool #1 and #2 failed at 200 lbs. load level before 25000 cycles were completed for each stools. Stool #3 and #5 failed at 250 lbs. load level after 68 and 3841 cycles were completed, respectively when stool #4 failed at 200 lbs. load level after 105 cycles were completed. The failures were obtained tenons on the back legs as splitting from legs. Furthermore, back rail of the stool #3 damaged because of torsion.

In the second life cycle front-to-back load tests, stool #1 and #3 failed at 200 lbs. load level after 49 and 1519 cycles were completed, respectively. Stool #2 failed at 250 lbs. load level after 33 cycles were completed when stool #4 and #5 failed at 150 lbs. load level after 13667 and 11331 cycles were completed, respectively.

In the third life cycle front-to-back load tests, stool #1, #2 and #5 failed at 150 lbs. load level; 13003, 13003 and 5912 cycles, respectively. Stool #3 and #4 failed at 200 lbs. load level; 226 and 23718 cycles, respectively.

3.6 Product Recovery

Parts for the 2nd life and 3rd life tests were salvaged--in so far as possible--from the first life specimens. This part recovery was done in order to evaluate the potential for product repair and part recyclability.

In Table 3-7, the parts recovered parts from the 1st life samples are shown. As can be seen, all of the legs were recovered but not all of the rails and stretchers because of the failures that occurred during the first round of testing most notably, 100% of the parts from the pinned rectangular mortise and tenon joints could be reused. In specimens with glued rectangular mortise and tenon joints, only the tenons were damaged so that stools could be reconstructed with inserted tenons. Thus, there was no loss of parts. On the other hand, the lowest recovery of parts was for stools constructed with dowel nuts. In these specimens, the side rails split so that only the legs could be recovered and reused.

In the case of the stools constructed with round mortise and tenon joints, those stools with pinned joints could readily be disassembled and reconstructed, whereas those frames with glued joints had to be forcibly disassembled and the leg mortises re-drilled. In the case of the stools constructed with dowel joints, both the legs and the rails could be reused, but the damaged stools first had to be forcibly disassembled and the holes in the ends of the rail and the legs re-drilled.

Stools constructed with screws could be easily disassembled for repair, but occasional splitting of rails occurred, which decreased part reusability.

Recovery of parts after the second life testing of stools is given in Table 3-8. The highest part recovery obtained was for inserted tenon, glued rectangle mortise and tenon joints. Recovery of parts was also high for inserted tenon, pinned rectangular mortise and tenon joints. The screw joints have 65% recovery rate when barrel nuts joinery has 60%. Pinned round mortise and tenon joinery has 70% recovery rate – whereas recovery rate of glued mortise tenon joinery is 62.5%. The recovery rate of the dowel joinery is 80%.

In remanufacturing process for the third life of stools, 2 ½ in. diameter dowels were used to increase contribution. Similarly, in screw joints, 3 ½ -inch long # 14 wood screws were used to increase contribution. Other joinery systems were remanufactured in the same way with remanufacturing of stool in second life.

The recovery of parts after the third life testing of stools is given Table 3-9. The highest recovery rate obtained was for inserted tenon – pinned rectangle mortise and tenon and glued rectangle motise and tenon – with 100% and 95%, respectively. The screw joints have 65% recovery rate while barrel nuts joinery has 55%. Recovery level of the dowel nuts is 90%. The two stretchers pinned round mortise and tenon joints have 70% recovery rates, correspondingly the two stretchers glued round mortise and tenon joints have 47.5%.

Table 3-8: Numbers of recovered parts from cyclic front-to-back load test in first life of stools.

Joinery Type	Number of Recovered Legs	Number of Recovered Rails	Number of Recovered Stretchers	Number of Recovered Hardware
Screws	20/20	20/19	---	80/78
Barrel Nuts	20/20	20/12	---	40/35
R-M&T pinned	20/20	---	40/28	---
Rec. M&T pinned	20/20	20/20	---	---
Dowels	20/20	20/18	---	---
R-M&T glued	20/20	---	40/27	---
Rec. M&T glued	20/20	20/17	---	---

Table 3-9: Numbers of recovered parts from cyclic front-to-back load test in second life of stools.

Joinery Type	Number of Recovered Legs	Number of Recovered Rails	Number of Recovered Stretchers	Number of Recovered Hardware
Screws	20/20	20/13	---	80/59
Barrel Nuts	20/20	20/12	---	40/35
R-M&T pinned	20/20	---	40/28	---
Rec. M&T pinned	20/19	20/18	---	---
Dowels	20/20	20/16	---	---
R-M&T glued	20/20	---	40/25	---
Rec. M&T glued	20/20	20/19	---	---

Table 3-10: Numbers of recovered parts from cyclic front-to-back load test in third life of stools.

Joinery Type	Number of Recovered Legs	Number of Recovered Rails	Number of Recovered Stretchers	Number of Recovered Hardware
Screws	20/20	20/13	---	80/72
Barrel Nuts	20/20	20/11	---	40/36
R-M&T pinned	20/20	---	40/28	---
Rec. M&T pinned	20/20	20/20	---	---
Dowels	20/20	20/18	---	---
R-M&T glued	20/20	---	40/19	---
Rec. M&T glued	20/20	20/19	---	---

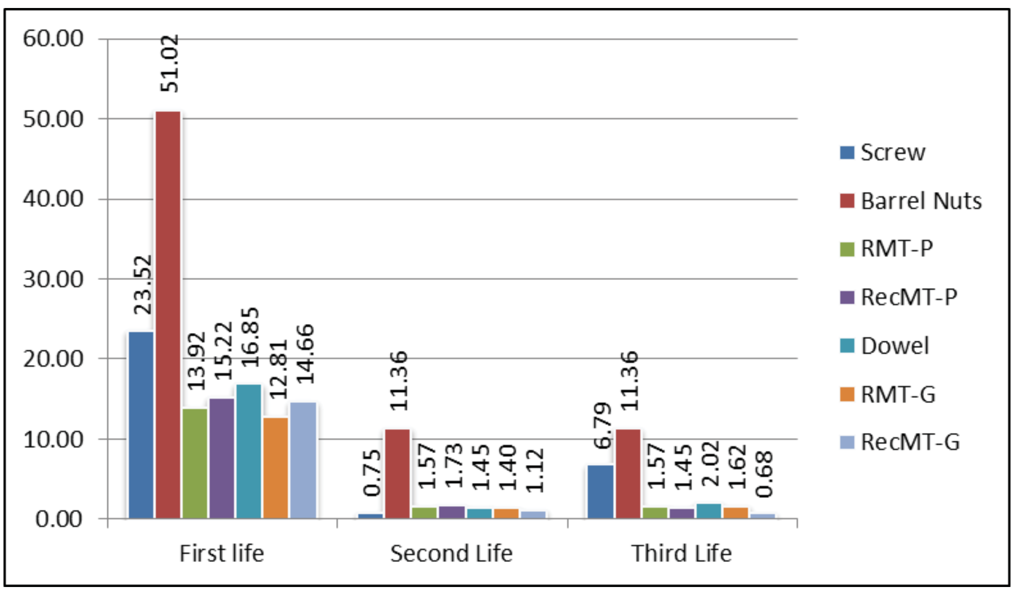

Figure 3-24: Material cost of stools in each life (In the second life and the third life, only new material cost – U.S. Dollars ($))

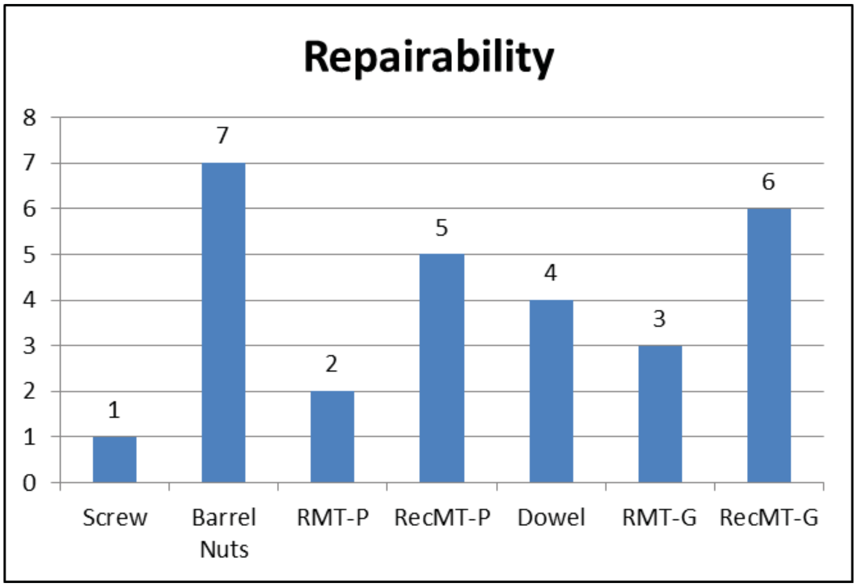

Figure 3-25: Reparability level of stool (easiest – 1 to hardest – 7)

3.7 Statistical Report

Test of hypothesis were conducted using Tukey's Studentized Range (HSD) adjusted alpha level of 0.05. Results indicated that the average number of errors was significantly different in strength of the stools $F(7,32) = 9.77$, $p < 0.0001$.

Table 3.11: ANOVA table

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	59501.4299	8500.20427	9.77	<.0001
Error	32	27838.9696	869.9678		
Corrected Total	39	87340.3995			

Table 3.12: Tukey's Studentized Range test

Tukey Grouping			Mean	N	trt
	A		228.96	5	Glued RM&T
	A				
B	A		194.72	5	Glued SRRM&T
B	A				
B	A		191.61	5	Glued RecM&T
B	A				
B	A	C	175.59	5	Pinned RM&T
B		C			
B	D	C	145.22	5	Pinned RecM&T
B	D	C			
B	D	C	136.74	5	Dowel
	D	C			
	D	C	124.36	5	Screw
	D				
	D		107.61	5	Bed bolts

3.8 Test Conclusions

3.8.1 Joint Characteristic

3.8.1.1 Screw Joints

Screws can be used in joints in two ways, a) two screws can be used as a replacement for dowels—or for two bed bolts, or, b) as a replacement for a single bed bolt. Pilot hole diameters should be equal to the root diameter of the screw. The stools with screw joint are easy to repair as changing screw size and the material recovery rate is 95%, 65% and 65%; in the first life, second life and third life, respectively.

3.8.1.2 Bed Bolt and Dowel Nut Joints

Joints constructed with bed bolts (with square nuts or dowel nuts) ordinarily fail owing to an initial split emanating from the slot or hole for the nut that extends along the longitudinal axis of the rail. Hence, nuts should be located an appropriate distance from the end of the rail—1.5 to 2 inches. Hence, nuts should be located as far as design allows from the end of the rail. It is also advisable to countersink the head of the bolt in the back post in order to lessen the perpendicular to grain distance between the underside of the bolt head and the face of the rail—provided this does not weaken the back post unduly. This joint type is not easy to repair because of too much machinery work in reprocess materials. Also, it is not only less load capacity level but it also has less recovery rate among all joinery groups.

3.8.1.3 Glued/Pinned Round Mortise and Tenon Joints – Two Stretchers Stools

Glued round mortise and tenon joints fail owing to fracture of the tenon at its point of entry into the back post. In some cases a shear failure may first develop near the neutral axis of the tenon followed by fracture of the tenon at its point of entry into the back post. These joint may be easily repaired because it is required less machinery work. However, it has one of the less recovery rates with 67.5%, 62.5% and 47.5%; in the first life, second life and third life, respectively.

Joints with cross-pinned tenons fail owing to shear of that portion of the tenon between the cross pin hole and the end of the tenon Cross-pinned joints have only about one-half the cyclic load durability of glued joints.

3.8.1.4 Round-Shouldered Rectangular Mortise and Tenon

Glued rectangular mortise and tenon joints (with the geometry of those used in the study) may be expected to fail owing to fracture of the tenon at its point of entry into the post. These joints may be expected to have the highest load capacity of the joints tested. However, many failure was because of glue failure on the mortise and tenon walls.

Cross pinned joints may be expected to fail owing to shear failure of the material between the wall of the cross pin and the end of the tenon. The moment capacity of pinned joints averages is less than %30 of glued joints.

These joint types are easy to repair because after failure on stools, damaged tenons cut off and they repaired with inserted tenon strategy. In this way, material recovery rate was increased

3.8.1.5 Dowels Joints

Dowel joints (in the constructions tested) fail owing to withdrawal of the top dowel from the corresponding post. Cyclic load durability of these joints is less than %20 of glued rectangular mortise and tenon joints.

CHAPTER 4. SUMMARY AND RECOMMENDATIONS

4.1 Summary

In this study, stools with two different joinery systems, *Ready-to-Assembly (RTA) joints*, namely, screws, bed bolts with barrel nuts, two stretcher pinned round mortise and tenon, and pinned round-shouldered rectangular mortise and tenon; and *Glued Wooden joints*, namely, dowel, two-stretcher glued round mortise and tenon, and glued round-shouldered rectangular mortise and tenon were compared to determine which joinery systems:

- Provide the best disposal options
- Provide longer life span, design for Environment (DfE), and End-of-Life (EoL) Options
- Provide the best assembly and disassembly options

Static load tests and cyclic front-to-back load tests were made to determine the load capacities of the stools for each joint type. Based on the test outcomes (indicated in Chapter 3) the best joint system or systems were determined taking into consideration strength, reparability and cost.

4.2 Recommendations

4.2.1 Design for Environment Strategies

Wood and wood-based materials: Wood material should carry an Eco-label certification proved by FSC (program for the Endorsement of Forest Certification) or any equivalent certification proof. In addition, the wood materials should be recyclable, and when possible, recycled materials (EC 2009) should be used.

Transportation: Shipping options should be evaluated in order to minimize transportation distances since shipping is the most significant energy consumer in product LCA.

Product Development - Design consideration: The potential second life of a product should be considered during the first life design of the product. Factors of concern include ease of assembly and disassembly along with ease of incorporation into new products.

Durability / reparability / fitness for use and ergonomic: The long term usability of furniture should be considered--ability to satisfy safety requirements, ergonomic criteria, strength and durability criteria should be assessed in the product development stage (EC 2009).

Manufacturing: Consider sustainable practices and low energy consumption should be considered in the manufacturing stages.

Surface coating of wood, plastic and/or metal parts: Products should be designed to eliminate hazardous substances such as carcinogens that are harmful to reproductive systems and to the environment in the first stage of the design process (VOC mustn't exceed 5% of total weight of product--EC 2009).

Adhesives and glues and finishes: Products should be designed to minimize the VOC content of adhesives, glues and finishes used in the assembled furniture—the content of these materials mustn't exceed 10% of weight (EC 2009).

4.2.2 End-of-Life Options

End-of-Life options, including reuse, remanufacturing, recycle, landfill and incineration, are the last step in the history of the product. In this study, the principle focus was on reusing and remanufacturing of stools. As indicated in Figure 2-3, a theoretical product recovery hierarchy should be considered when applying EoL options for products. The hierarchy given in Figure 2-3 provide a better understanding of how to use less energy in product recovery processes, reduce material usage, and lower labor costs.

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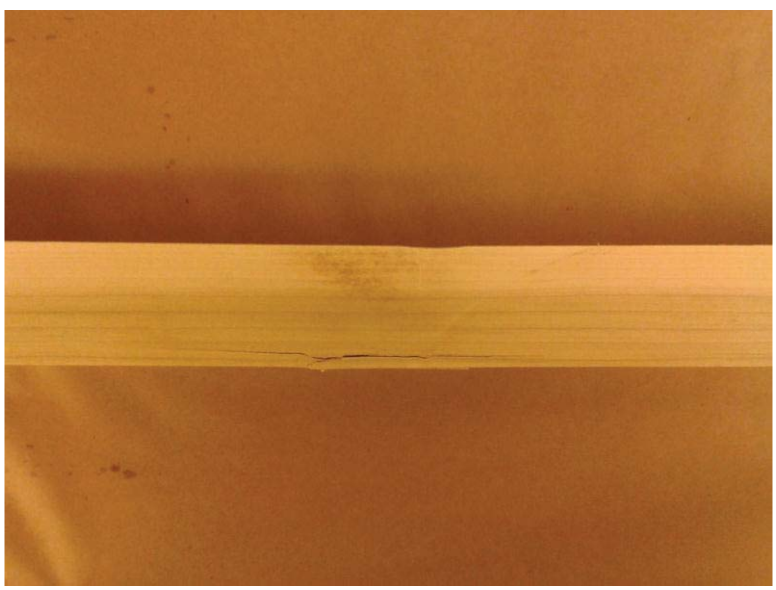
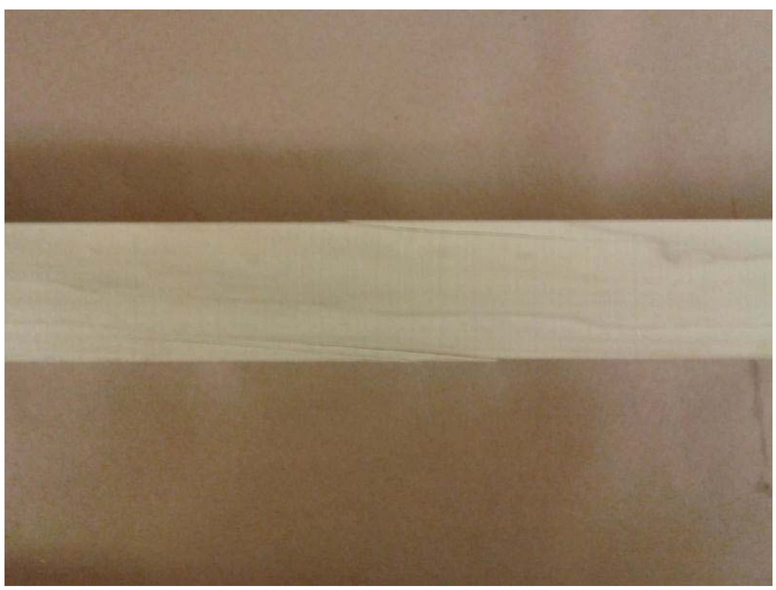
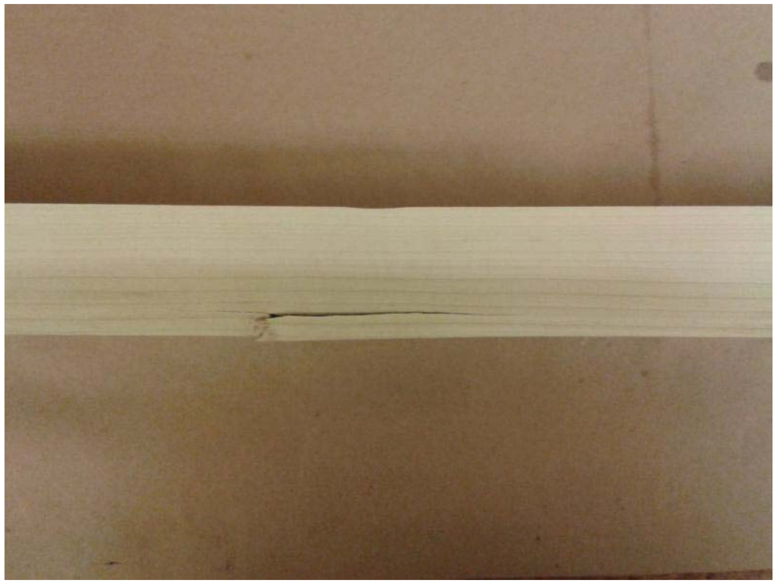
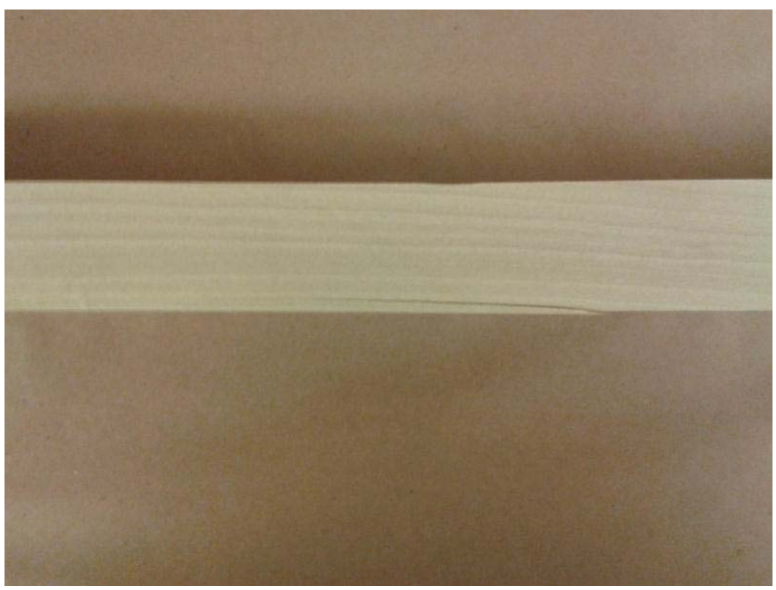
APPENDICES

Appendix A: Particular Failure of Specimens for Modulus of Rupture and Modulus of Elasticity





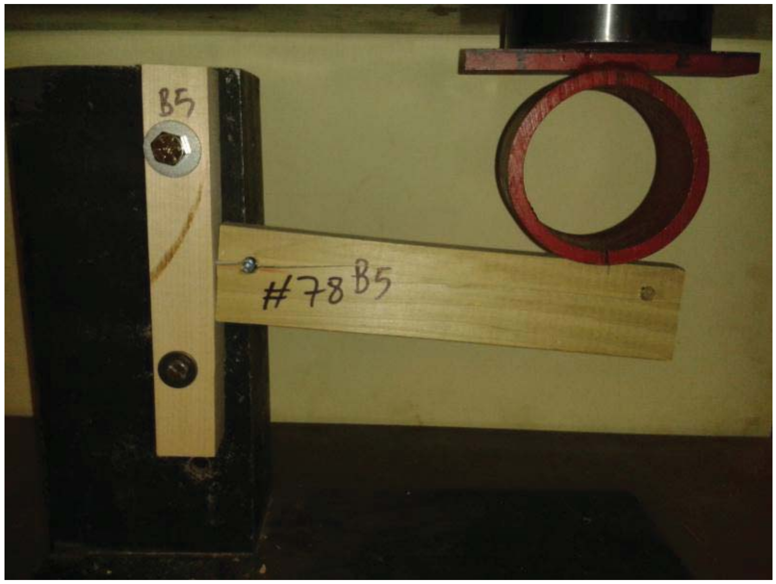




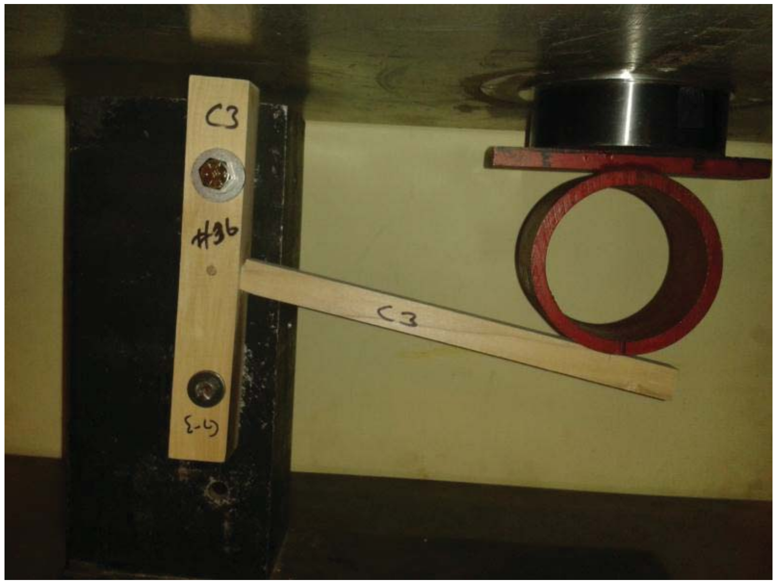
Appendix B: Particular Failure of Joint Specimens for Static Load Test

Failure on the T-shaped screw joints

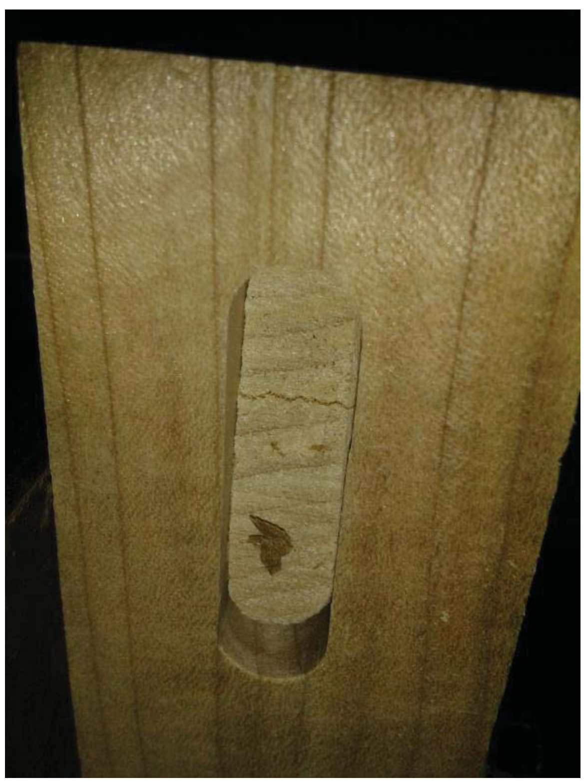
Failure on the T-shaped bed bolts (with dowel nuts) joints



Failure on the T-shaped pinned round mortise and tenon joints

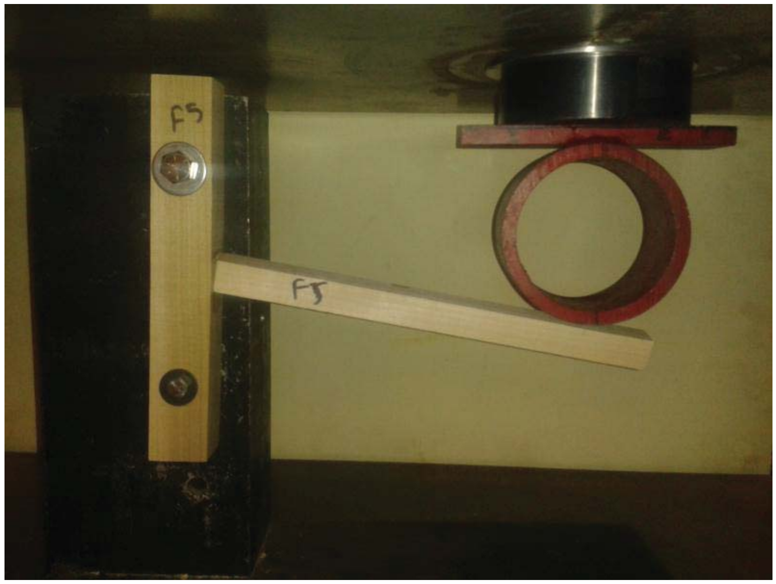


Failure on the L-shaped pinned rectangular mortise and tenon joints

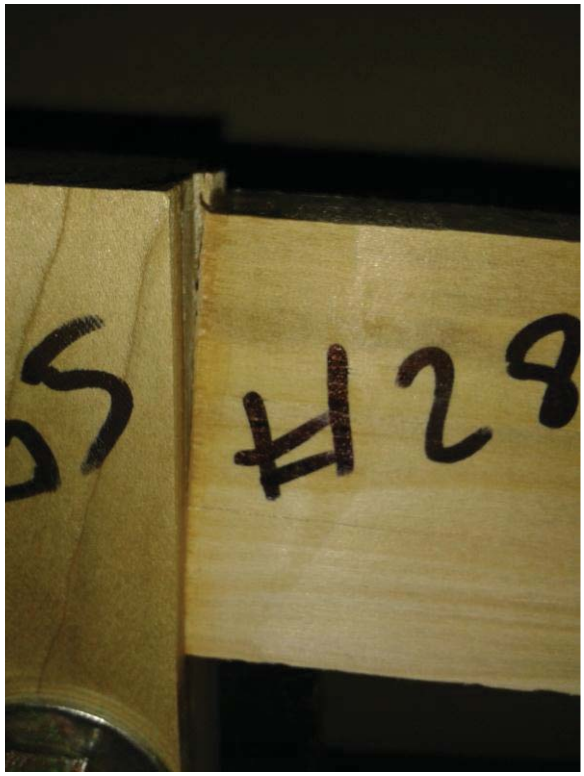


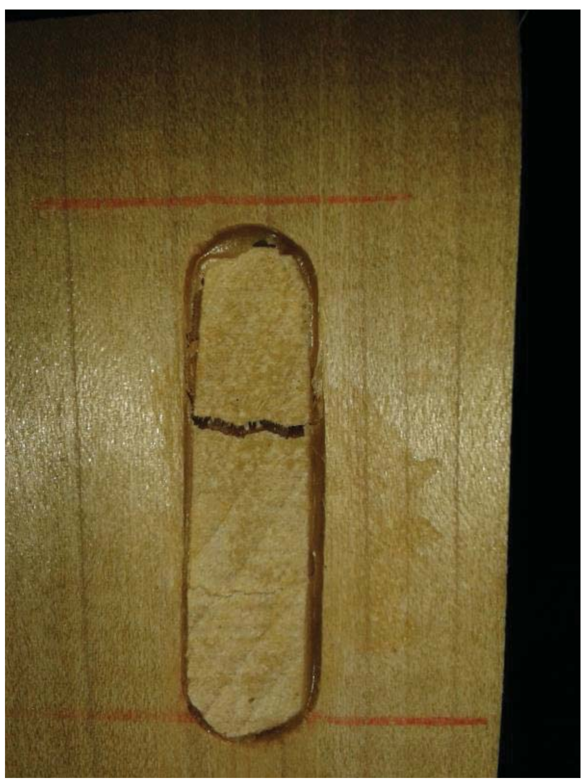
Failure on the T-shaped dowel joints

Failure on the T-shaped glued round mortise and tenon joints



Failure on the L-shaped glued rectangular mortise and tenon joints





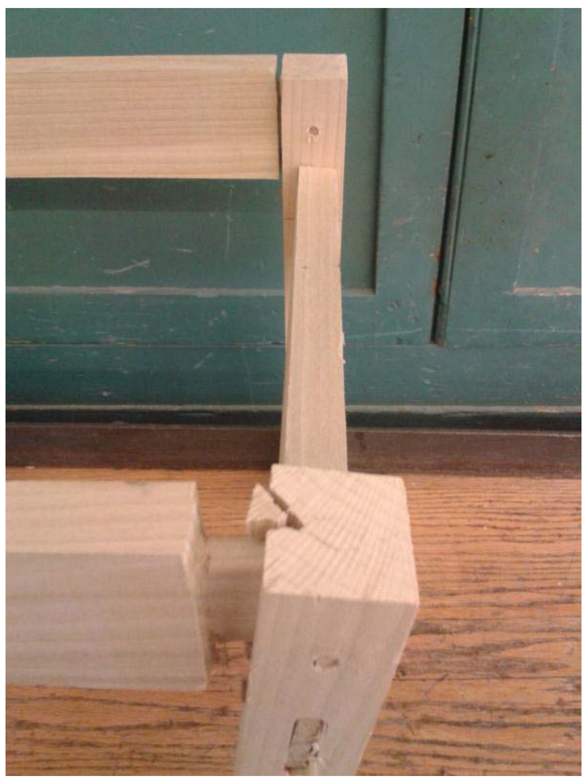
Appendix C: Particular Failure of Stool Specimens for Cylic Load Test

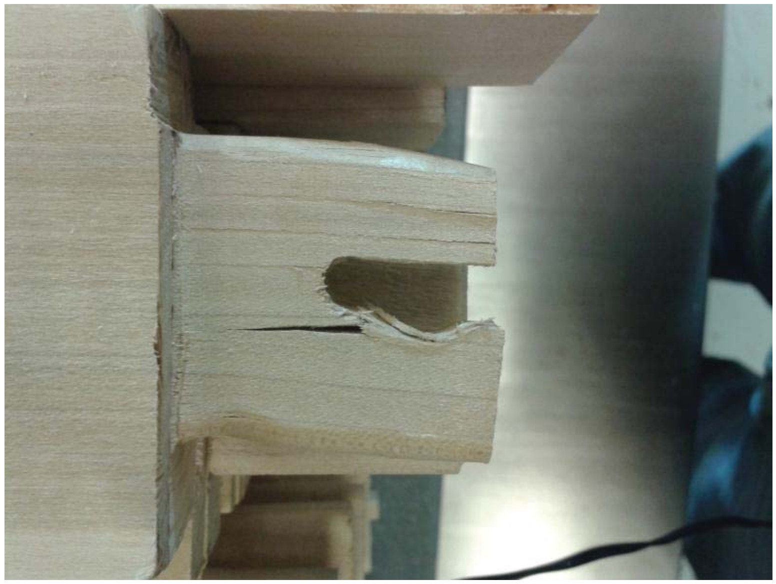
Failure on the stools with screw joints.

Failure on the stools with bed bolts (with dowel nuts) joints.

Failure on the stools with pinned round mortise and tenon joints.

Failure on the stools with pinned rectanglar mortise and tenon joints.

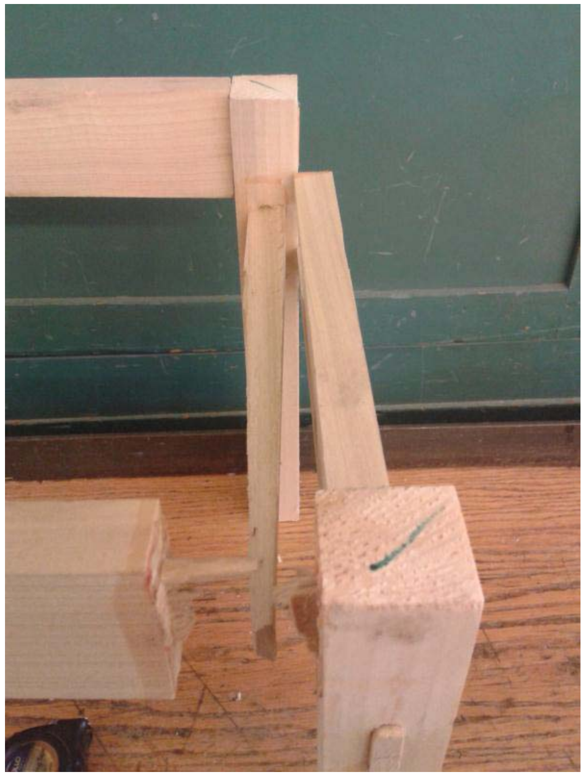


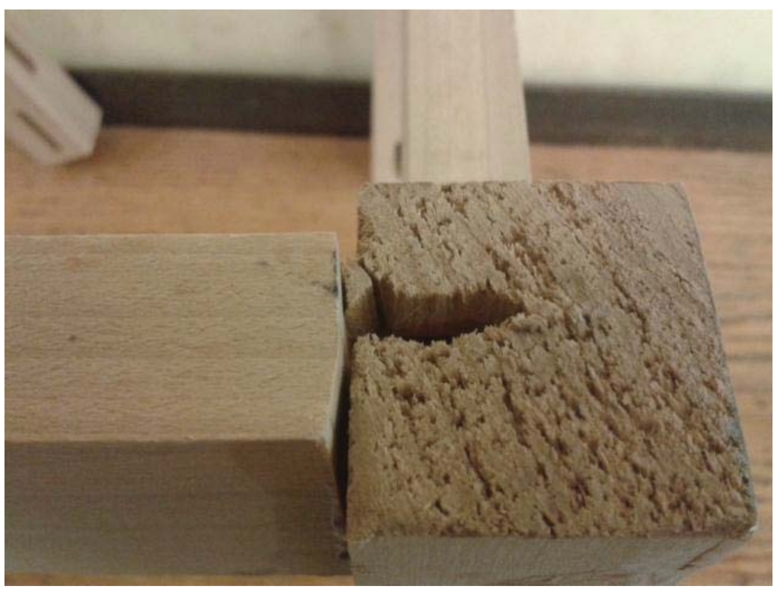


Failure on the stools with dowel joints.

Failure on the stools with glued round mortise and tenon joints.

Failure on the stools with glued rectangular mortise and tenon joints.





VITA

VITA

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In 2010, Mesut started to study Master of Science in Wood Mechanics and Technology in Suleyman Demirel University in Isparta, Turkey, researching mechanical properties of wood and wood composite. In 2011, he won scholarship supported by Ministry of National Education in Republic of Turkey to pursue Master of Science and Doctor of Philosophy in Forest Products behalf of Bursa Technical University in Bursa, Turkey. In 2012, he was accepted to study Master of Science at Purdue University in field of Wood Products and Wood Products Manufacturing with this scholarship, researching furniture strength design.

His main field of expertise is in furniture strength, design and, wood mechanics and technology.