Materials and Design 87 (2015) xxx–xxx

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/jmad

A comparison of the cyclic durability, ease of disassembly, repair, and reuse of parts of wooden chair frames

Mesut Uysal, Eva Haviarova *, Carl Albert Eckelman

Purdue University, Department of Natural Resources and Forestry, West Lafayette, IN 47906, USA

A R T I C L E I N F O

Article history:
Received 19 February 2015
Received in revised form 28 July 2015
Accepted 2 August 2015
Available online 4 August 2015

Keywords:
Wooden Joints
Reusing
Remanufacturing
Recycling and cyclic load tests

A B S T R A C T

Simple, statically-determinate wooden chair frames constructed with seven types of joints were subjected to cyclic front to back load tests to determine joint durability, chair reparability, and parts' reuse. Knockdown joints, namely, screw, bed bolts (with dowel nuts), pinned round mortise and tenon, and pinned rectangular mortise and tenon joints; and glued joints, namely, dowel, round mortise and tenon, and rectangular mortise and tenon joints were included in the study. Glued round and rectangular mortise and tenon joints had the highest levels of cyclic load durability whereas bed bolts had the least. Chairs constructed with knockdown joints were easiest to repair, whereas chairs constructed with glued joints were the most difficult to repair. Parts' recovery with rectangular mortise and tenon joints was high when tenons were replaced with inserted tenons. Likewise, recovery was high with dowel joints since the failed dowels were replaced with larger dowels. Parts' recovery with metal knockdown fasteners was low because of side rail splitting; however, parts' recovery with pinned round and rectangular mortise and tenon joints was high.

1. Introduction

When chairs and tables fail in service, owing to fractured legs and rails, but more often owing to loose or failed joints, they are regularly discarded [5,6]. In affluent areas of the world, replacement of such furniture may be nothing more than an inconvenience but in disadvantaged areas replacement may not be possible [15]. Difficulties in replacement of school furniture in the latter areas are of particular concern since many schools already lack sufficient furniture and replacement of the existing furniture is difficult and slow to occur [14]. Product and part reuse is not a new concept, it has been considered increasingly in remanufacturing of industrial activities since Second World War. Nowadays, benefits of reused parts – reducing energy required and environmental impacts of products in manufacturing [2] – and changing demands in society has caused to increase interest in remanufacturing [8].

It is important, therefore, to determine how furniture should be designed [5] a) to have the longest possible service life, b) to be easily repaired, and c) to have reusable parts so that broken or discarded furniture (that cannot be simply repaired) such as legs, rails, and stretchers can be recycled, i.e., incorporated into a new generation of furniture. Aesthetics, of course, must also be considered and it must be accepted that furniture constructed from recycled parts would not be acceptable in all design situations; however, in a reuse-or-nothing situation, such as school furniture in developing world, new furniture constructed from reused furniture parts seemingly would provide an acceptable if not welcome solution [14,15]. If recycling is to be done efficiently, however, pre-planning for reuse needs to be incorporated into the original design of the furniture.

Overall, the initial life of a chair is usually related to joint failure [5,6]. Hence the cyclic load durability of the joints used in construction of a chair is critical to the initial length of life [5,6]. Ease of repair is largely a function of how easily the chair can be disassembled. In this respect, knockdown joints would be expected to have an inherent advantage over glued joints.

Reuse and recycling of parts are both a function of the damage done to the parts in service and also a function of the amount of material that has been removed from the part to accommodate fasteners such as dowels, tenons, and knockdown fasteners. Materials initially removed for fastening can be filled to satisfy esthetic considerations, but this action does not restore structural integrity to the member. Hence the amount of material that has been removed from a part in construction of a joint plays a decisive role in whether or not a part may be re-used [5,7,16].

Ordinarily, length of service life is one of the most important considerations in the design of furniture, and in most cases, it is a function of joint construction [5,6]. Two questions follow, a) what is the relationship of joint design (type of joint) to load capacity (particularly cyclic load capacity), and b) what is the relationship of joint design to furniture reparability and parts re-usability? To provide insights and useful answers to these questions, the study described below was conducted a) to determine the cyclic load capacity of knockdown and glued joints (in a typical statically determinate frame construction) and b) to determine the nature of the damage associated with the failure of each type of joint and its relationship to frame repair and part reusability.

* Corresponding author.
E-mail address: ehaviar@purdue.edu (E. Haviarova).

http://dx.doi.org/10.1016/j.matdes.2015.08.009
0264-1275/© 2015 Published by Elsevier Ltd.

Numerous studies of static load capacity of joints, such as square and round mortise and tenon, dowel, CAM and other joints, have been conducted [3,10–12,16]. Published information concerning the cyclic performance characteristics of most commonly used wooded furniture joints as well as full frames made with these joints is largely lacking [10]. The purpose of this study was to provide such information. The study objectives are listed below.

1.1. Objectives

a. Determine the cyclic front-to-back load capacity of frames constructed with seven types of joints—and thereby joint capacity.
b. Determine which joints allow for the simplest repair of chairs following failure.
c. Determine which fasteners and connectors are best suited for reconstruction of chairs.

2. Materials and methods

2.1. Design of experiment

The study was carried out in three stages. In the first stage, five frames [9] (Fig. 1a) were constructed with each of seven types of joint

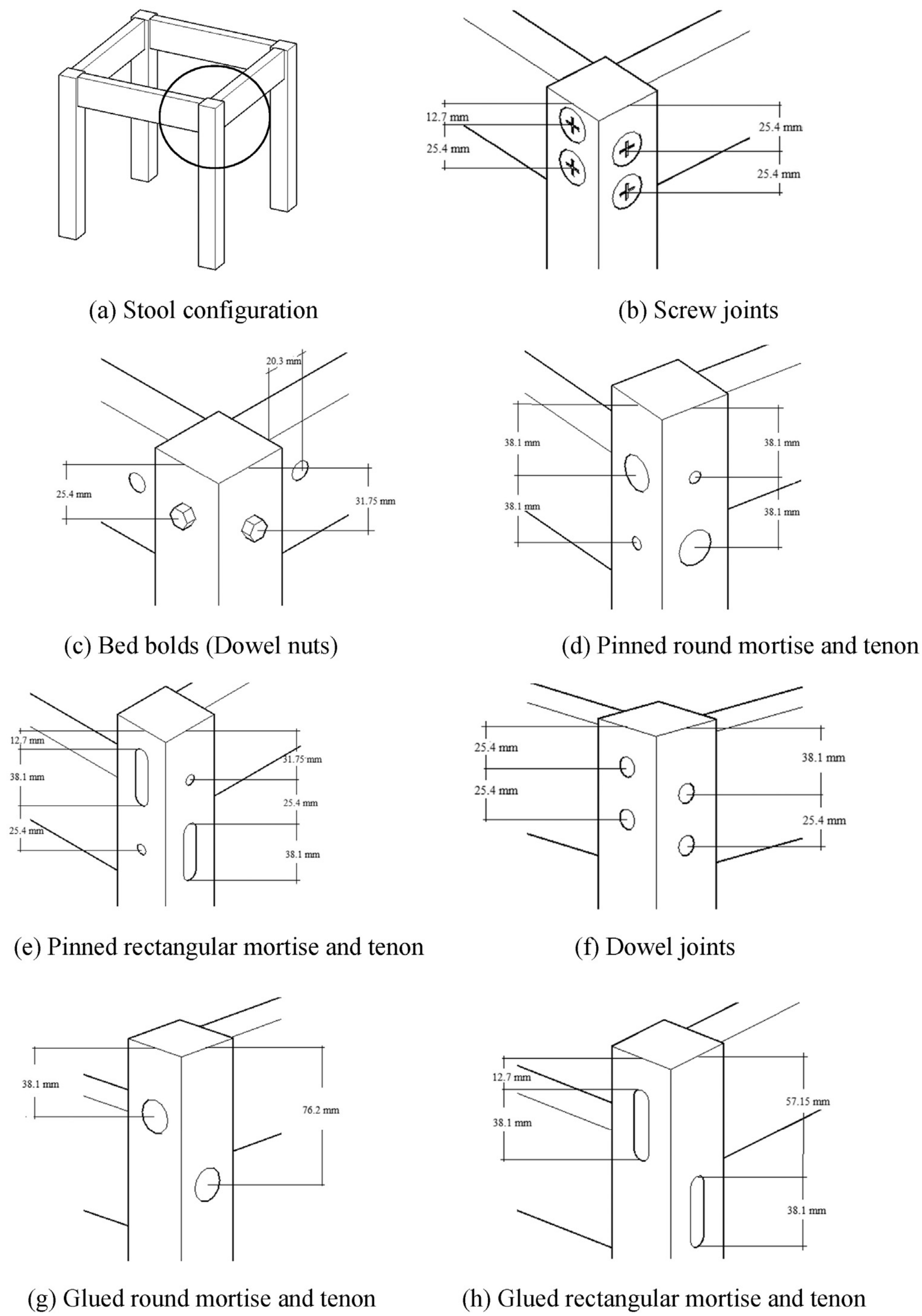

Fig. 1. Stool and joint configuration. (a) Stool configuration. (b) Screw joints. (c) Bed bolds (Dowel nuts). (d) Pinned round mortise and tenon. (e) Pinned rectangular mortise and tenon. (f) Dowel joints. (g) Glued round mortise and tenon. (h) Glued rectangular mortise and tenon.

connections, namely, wood screws, bed bolt with dowel nut, pinned rectangular mortise and tenon, pinned round mortise and tenon; glued dowel, glued round mortise and tenon, and glued rectangular tenon joints, for a total of 35 specimens.

Following the 1st stage of testing, frames were repaired for use in the 2nd stage of testing; i.e., broken rails were replaced or joints repaired as needed. In the reconstruction of the rectangular mortise and tenon joints, inserted tenons were substituted for machined tenons (to allow reuse of the side rails). A total of 35 specimens were reconstructed.

Following the 2nd stage of testing, the frames were repaired again for use in the 3rd stage of testing. Again, broken rails were replaced or joints repaired as needed. A total of 35 specimens were constructed.

2.2. Specimen design and construction material

Design of each frame and its corresponding joint construction are shown in Fig. 1. 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.

Each frame consisted of four posts which measured 38.1 mm square by 355.6 mm long, and four rails (two side rails plus a front and back rail) that measured 22.2 by 63.5 mm in cross section by 279.4 mm long. Statically determinate frames were used in order to obtain direct comparisons of joint performance, i.e., to eliminate the need to take joint rigidity into consideration.

In the specimens constructed for the first stage of testing, frame members were joined together with either knockdown connectors (screw, dowel nut with bed bolt, pinned rectangular mortise and tenon, pinned round mortise and tenon connectors) or glued connectors (dowel, rectangular mortise and tenon, and round mortise and tenon connectors).

Likewise, in the case of specimens reconstructed for the second stage of testing, frame members were joined together either with knockdown fasteners or with glued fasteners—but both the pinned and glued rectangular mortise and tenon fasteners were replaced with inserted tenons. Specimens constructed for the third stage of testing were constructed in a manner identical to that for the second stage.

2.2.1. Screw joints

In the 1st stage, frames were constructed with 63.5 mm long by 6.1 mm diameter screws. In the 2nd stage, frames were repaired with 76.2 mm long by 6.1 mm diameter screws. Lastly, in the 3rd stage, frames were repaired with 76.2 mm long by 7.9 mm diameter lag screws. Relief holes in the posts measured 5.6, 5.6, and 6.3 mm in diameter. Pilot holes in the rails measured 4, 4, and 4.4 mm in diameter. Screws were tightened until the head of the screw was embedded flush with the surface of the post (Fig. 1b).

2.2.2. Bed bolt and dowel nut joints

Frames with dowel nut and bed bolt joints were constructed in all life stages with 76.2 mm long by 6.4 mm diameter bed bolts and 9.5 mm diameter dowel nuts. Relief holes, 6.4 mm in diameter, were drilled for the bed bolts; likewise, holes 9.5 mm in diameter were drilled to accommodate the dowel nuts. Locator dowels (not glued) measured 6.4 mm in diameter by 38.1 mm long (Fig. 1c).

2.2.3. Glued dowel joints

Frames for the 1st and 2nd stages of testing were constructed with 9.5 mm diameter by 50.8 mm long white oak dowels. Frames for the 3rd stage of testing were constructed with 9.5 mm diameter by 63.5 mm long dowels. Holes for the dowels were machined with a 9.5 mm diameter drill bit. Dowels were embedded 25.4 mm in the ends of the rails and 25.4 mm in the walls of the posts (Fig. 1f). Walls of the holes were thoroughly coated with a Polyvinyl Acetate (40% solid content). Completed assemblies were allowed to cure at least 1 day before testing.

2.2.4. Glued and pinned round mortise and tenon

Frames with round mortise and tenon joints were constructed in all life stages with tenons (and matching mortises) that measured 18.3 mm in diameter by 38.1 mm long (Fig. 1g). Tenons were machined with a 18.23 mm hole saw; corresponding mortises were machined with a 18.3 mm drill bit. Fit between tenon and mortise was such that tenons could be inserted with little force three-fourths of the way into the mortise. Pinned mortise and tenon joints were constructed with 6.4 mm diameter plain white oak pins (Fig. 1d).

2.2.5. Glued and pinned rectangular mortise and tenon

Frames with glued rectangular mortise and tenon joints were constructed for the 1st stage with tenons (and matching mortises) that measured 9.5 mm thick by 38.1 mm wide by 38.1 mm long (Fig. 1h). Tenons were machined with table saw and the corners rounded to 4.8 mm radius, whereas mortises were machined with a 9.5 mm router bit on a multiple chisel. Similarly, in the 2nd and 3rd stages, inserted tenons were used. Clearance between tenon and mortise averaged 1.3 mm. Joints were assembled with a Polyvinyl Acetate adhesive (40% solid content) and were allowed to cure at least 1 day before testing (8 h as recommended for adhesive). Pinned mortise and tenon joints were constructed with 6.4 mm diameter plain white oak pins (Fig. 1e).

2.3. Performance tests—cyclic front-to-back load tests

Studies by the American Library Association [1] indicate that the most common damage to chair frames arises from cyclic front to back loading of the seats—such as occurs when a user sits down in a chair and pushes backward or tilts backward—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.

In conducting this test, chairs are mounted for testing as shown in Fig. 2 [4,13]. Reaction brackets are placed behind the back legs to prevent the chair from sliding backwards. A strap is then passed over the seat from front to back and attached to a small clevis connected to the rod end of an air cylinder that applies loads to the chair. The other end of the belt is dropped over the front edge of the seat, allowed to hang vertically, and attached to an anchor ring on the floor. As the seat is pulled to the rear, the chair tends to tip over backward. As it begins to

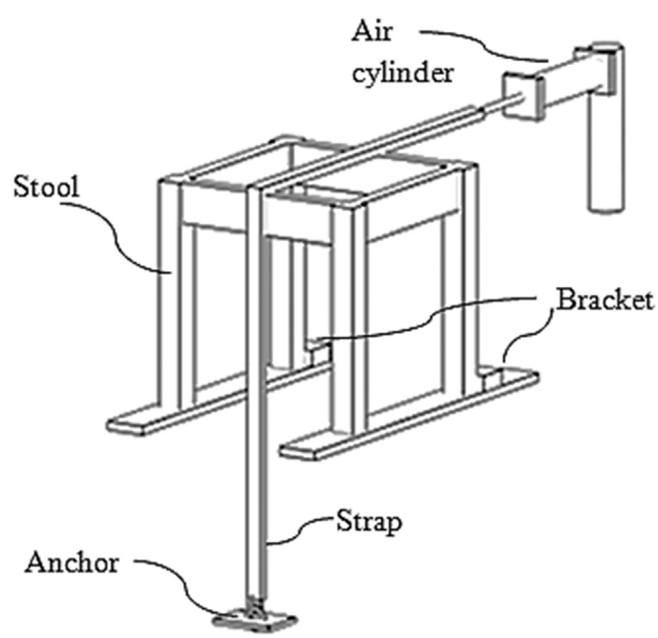

Fig. 2. Cyclic front to back load test configuration.

tilt, however, its motion is resisted by that portion of the strap that hangs vertically from the front edge of the seat and is anchored below (in effect, the vertical portion of the strap always provides the exact force needed to keep the chair from overturning).

In this study, loads were applied to the chair seat in a front to back direction at a rate of 20 cycles per minute [4,13]. Unless otherwise noted, tests were started at the 222.5 N load levels. Loads were increased by 222.5 N after 25,000 cycles had been completed at each preceding load level. Tests were discontinued after one or both side-rail-to-back-post joints fractured or front to back deflection of the frame exceeded 50.8 mm. In some cases, only one joint failed (and the test was terminated), whereas in other cases, failure of one joint leads to the almost simultaneous failure of the 2nd joint.

Following testing, a load durability factor was computed for each frame/joint configuration where the load durability factor is defined as load level at failure multiplied by the number of cycles at failure divided by 25,000, i.e.,

$$P = P_{(\mathrm{Failure})} \times (N/25000) \quad (1)$$

$$M = P \times L \quad (2)$$

where;

P	load durability factor (kN)
$P_{(\mathrm{Failure})}$	load level at failure (kN)
N	number of cycles at failure
M	average moment capacity (kN·m)
L	moment arm (m)

3. Results and discussion

All failures arose owing to fracture of either the left or right (or both) side rail to back post joints. Tests were discontinued after one or more joint fractures caused front to back deflection of the frame to exceed 2 in. In some cases, only one joint failed (and the test was terminated), whereas in other cases, failure of one joint leads to the almost simultaneous failure of the 2nd joint. In recording the results, failure of five joints indicates that only one joint failed on each frame, whereas failure of more than five joints indicates that both the right and left hand joints failed in one or more frames. Only failed joints (or rails) were repaired or replaced—non-fractured joints and rails were reused in their existing condition.

Average moment capacities are graphically illustrated in Fig. 3; coefficients of variation are illustrated in Fig. 4. Moment capacity results could be divided into three categories:

(1) *High moment capacity joints* – above 0.275 kN·m – which includes joints constructed with screws, glued round mortise and tenon, and glued rectangular mortise and tenon;
(2) *Moderate moment capacity joints* – between 0.160–0.275 kN·m – which includes pinned rectangular mortise and tenon and dowel joints and
(3) *Low moment capacity joints* – less than 0.160 kN·m – which includes bed bolds and pinned round mortise and tenon joints.

Likewise, coefficients of variation could be divided into similar categories: namely,

(1) *Low coefficient of variation*: Joints with low coefficients < 15%—which included screws, 9.6%; dowel nuts, 0.5 to 14.1%; pinned rectangular mortise and tenon, 12.6%;
(2) *Moderate coefficient of variation*: Joints with moderate coefficients < 30%—which includes pinned round mortise and tenon, 18.9–29.8%; glued round mortise and tenon, 12.2 to 22.3%; inserted glued rectangular mortise and tenon, 5.8 to 17.9%;
(3) *High coefficient of variation*: Joints with maximum coefficients > 30%—which includes inserted pinned rectangular mortise and tenon, 24.2–36.5%; and dowel, 16.8 to 32.6%.

During remanufacturing, frames constructed with different joint types required different machining, assembly and disassembly processes. In Fig. 5, remanufacturing levels of stools are illustrated in term of effort and time needed for remanufacturing process, including machinery, assembly and disassembly. According to this chart, screw joints required less remanufacturing (easiest) and frame contracted with glued rectangular mortise and tenon scored the highest (hardest) remanufacturing level.

3.1. Screw joints

Moment capacity of the joints constructed with 6.1 mm × 63.5 mm was 0.175 kN·m compared to 0.275 kN·m for 6.1 × 76.2 mm screws and 0.332 kN·m for 7.9 × 76.2 mm lag screws. Thus, in terms of the categories established above, the moment capacity of the 6.1 mm screws may be classified as moderate, whereas the capacity of the lag bolt may be

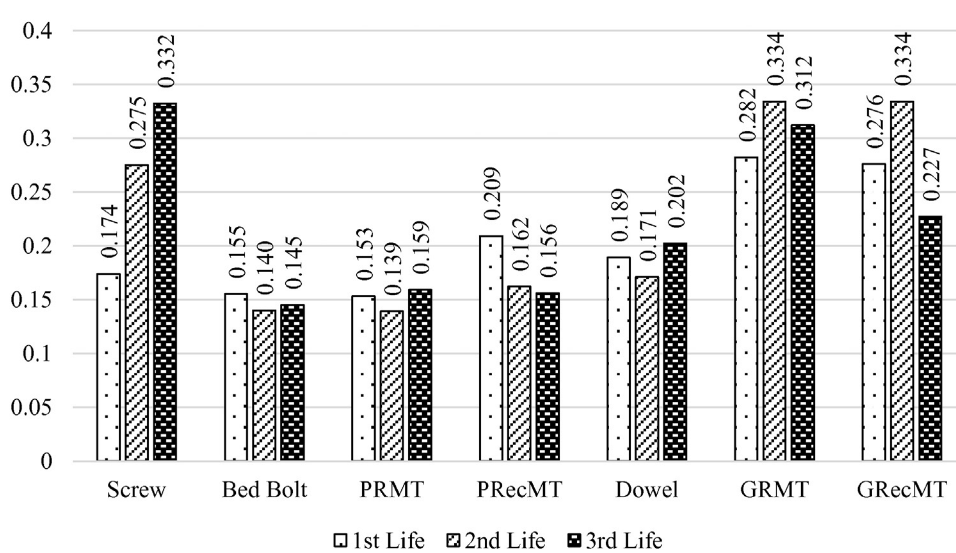

Fig. 3. Average moment capacity of stools in each life cycle for cyclic load test (2nd life and 3rd life of PRecMT and GRecMT are inserted tenon)—(kN·m).

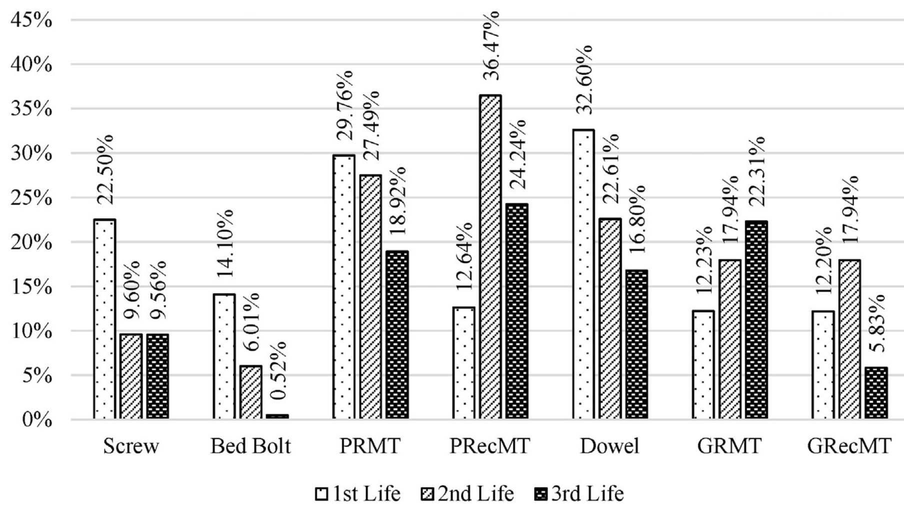

Fig. 4. Coefficient of variation of joints in each life cycle (2nd life and 3rd life of PRecMT and GRecMT are inserted tenon).

classified as high. The coefficient of variation of the joints constructed with 6.1 × 63.5 mm long screws was 22.5%, whereas the coefficients of variation for the 6.1 × 76.2 mm and 7.9 × 76.2 mm lag screws were 9.6%. Thus, the joints with 6.1 × 63.5 mm long screw may be classified as having a moderate coefficient of variation, whereas the joints with 6.1 × 76.2 mm long screws and 7.9 × 76.2 mm long lag screws may be classified as having low coefficient of variation.

Failures arose owing to withdrawal of the screws from the end of the rail. One side rail also split along the axis of the screw. Five joints failed in the 1st set of tests, 7 in the 2nd set, and 8 in the 3rd set. Frames were disassembled by removing the screws. Only failed joints (or rails) were repaired or replaced—non-fractured joints and rails were reused as is. Frames from the first set of tests were reassembled with 5 existing and 5 new rails and longer screws (6.1 mm × 76.2 mm); frames from the second set of tests were reassembled with 3 existing and 7 new rails and larger (7.9 × 76.2) lag screws. In the 2nd set of frames, 5 out of 10 rails were recovered from the 1st set (50%); in the 3rd set of frames, 3 out of 10 rails were recovered from the 2nd set of frames (30%). After the 3rd set of tests, the 2 rails were unsuitable for further use (Table 1).

3.2. Bed bolt with dowel nut joints

Moment capacity of the joints ranged from 0.140 to 0.155 kN·m; thus, the moment capacity of the joints may be classified as low. The coefficient of variation of the joints ranged from 0.5 to 14%; thus, the joints may be classified as having a low coefficient of variation.

Failures arose owing either to splitting of the rails along the longitudinal axis of the rail, coincident with the geometric center of the dowel nut, or to relish failure of the material adjacent to the dowel nut. Six joints failed in the 1st set of tests, 5 in the 2nd set, and 8 in the 3rd set. Frames were disassembled by removing the dowel nuts and were repaired by replacing the rails and reconnecting them to the posts with bed bolts and dowel nuts. The failed rails could not be reused. In the second set of frames, 4 out of 10 rails were recovered from the 1st set (40%); in the 3rd set of frames, 3 out of 10 rails were recovered from the 2nd set of frames (30%). Two rails from the 3rd set of tests were suitable for reuse (20%) (Table 1).

3.3. Pinned round mortise and tenon joints

The moment capacity of the joints ranged from 0.138 to 0.159 kN·m; thus, the joints may be classified as having low moment capacity. Coefficients of variation ranged from 18.9 to 29.8%; thus the joints may be classified as having a moderate coefficient of variation.

Failures arose owing either to bending-related fractures of the tenon or relish failures. Eight joints failed in the 1st set of the tests, 8 in the 2nd, and 6 in the 3rd set. Frames were disassembled by removing the cross pins from the side rail to back post joints and were repaired by replacing

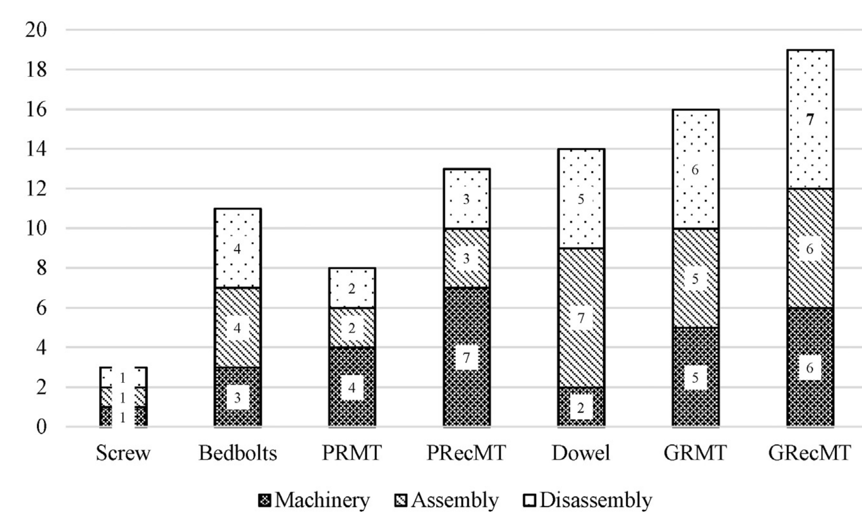

Fig. 5. Remanufacturing levels of stools (easiest 1 to hardest—7).

the side rails as needed and re-pinning the side rails to the posts. Failed rails cannot be reused for the 1st life chair repair but can be reused in screw, bed bolt, dowel, and inserted tenon constructions. In the second set of frames, 3 out of 10 were recovered from the 1st set of frames; in the 3rd set of frames, 2 out of 10 rails were recovered from the 2nd set of frames; 4 out of 10 from the 3rd set of tests were suitable for reuse (40%) (Table 1).

3.4. Pinned rectangular and pinned inserted rectangular mortise and tenon joints

Average moment capacity of the pinned rectangular mortise and tenon joints was 0.209 kN·m; thus, the moment capacity of the joints fell into the moderate moment capacity category. Average coefficient of variation of the joints was 12.6%; thus the coefficient of variation of the joints fell in the low coefficient of variation category. Average moment capacities of the pinned inserted rectangular mortise and tenon joints ranged from 0.156 to 0.161 kN·m; thus, the pinned rectangular mortise and tenon joints also fell into the low capacity category. The average coefficient of variation of the pinned inserted tenon joints ranged from 24.2 to 36.2%; thus, the pinned inserted tenon joints fell into the highest coefficient of variation category.

Failures arose owing either to fracture of the tenon itself or relish failure. Tenons of failed rails can be sawn off flush with the ends of the rails and the faces of the posts and reused with inserted tenons. Six joints failed in the 1st set of tests; 7 in the 2nd set of tests; and 7 in the 3rd set of tests. Frames were disassembled by removing the cross pins from the side rail to back post joints and were repaired by sawing off the tenons flush with the ends of the rails and replacing them with inserted tenons. In the 2nd set of frames, 10 out of 10 rails from the 1st set of frames were reused (4 unbroken + 6 inserted tenon); in the 3rd set of frames, 8 out of 10 rails (80%) from the 2nd set of tests were reused with inserted tenons (2 rails split and were not reusable); 10 out of 10 rails from 3rd set of tests (100%) were suitable for reuse (with inserted tenons) (Table 1).

3.5. Dowel joints

Average moment capacities of the dowel joints ranged from 0.171 to 0.202; thus, the moment capacities of the joints fell into the moderate moment capacity category. Average coefficients of variation of the joints ranged from 16.8 to 32.6%; thus the coefficient of variation of the joints fell into the high coefficient of variation category.

Failures arose owing to dowel withdrawal from the post or to fracture of the dowel itself. Six joints failed in the 1st set of tests; 6 in the 2nd set of tests; and 6 in the 3rd set of tests. A saw was used to sever the dowels and release the rails. Dowels were sawn off flush with the ends of the rails, and holes for replacement dowels were drilled coincident with the axes of previous dowels in the ends of the rails and the faces of the posts and new dowels inserted. Provided the joints have not been unduly damaged, failed dowel joints may be repaired by simply sawing off and drilling out the failed dowels and replacing them with longer dowels—which would increase the moment capacity of the joint. In the 2nd set of frames, 10 out of 10 rails from the 1st set of tests (100%) were reused; in the 3rd set of frames, 10 out of 10 rails (100%) from the 2nd set of tests were reused; rails from the 3rd set of tests were not reusable for dowel joints but could be used for barrel nuts joints (Table 1).

3.6. Glued round mortise and tenon joints

Average moment capacities of the glued round mortise and tenon joints ranged from 0.282 to 0.334 kN·m; thus, the moment capacity of the joints fell into the high moment capacity category. Average coefficients of variation of the joints ranged from 11.2 to 22.3%; thus the coefficient of variation of the joints fell into the moderate coefficient of variation category.

Failures arose owing to bending fracture of the tenon. Nine joints failed in the 1st set of tests; 8 in the 2nd set of tests, and 8 in the 3rd set of tests. A saw was used to sever the tenons flush with the ends of the rails and the faces of the posts. Mortises were re-drilled in the faces of the posts; all of the side rails were replaced with new rails. Rails cannot be reused for 1st life chair repair, but the tenons can be sawn off flush with the ends of the rails and the rails reused in screw, bed bolt, dowel, and inserted tenon constructions (Table 1).

3.7. Glued rectangular and glued inserted tenon rectangular mortise and tenon joints

Average moment capacity of the glued rectangular mortise and tenon joints averaged 0.276 kN·m; thus, the moment capacity of the joints fell into the high moment capacity category. Average coefficient of variation of the joints was 12.2%; thus the coefficient of variation of the joints fell into the low coefficient of variation category. Average moment capacities of the glued inserted rectangular mortise and tenon joints ranged from 0.227 to 0.334 kN·m; thus, the moment capacities of the joints fell into the moderate to high moment capacity categories. Average coefficient of variation of the joints ranged from 5.83 to 17.9%; thus the coefficient of variation of the joints fell into the low to moderate categories.

Failures arose owing to fracture of the tenons or to withdrawal of the tenons from the mortise with partial fracture of the tenon. Six joints failed in the 1st set of tests; 6 in the 2nd set of tests, and 6 in the 3rd set of tests. Frames could be disassembled and repaired by sawing off the tenons flush with the ends of the rails and replacing them with inserted tenons. In the 2nd set of frames, 10 out of 10 rails from the 1st set of tests (100%) were reused; in the 3rd set of frames, 10 out of 10 rails from the 2nd set of tests were reused; finally 10 out of 10 from the 3rd set of tests were suitable for reuse (Table 1).

Table 1
Number of side rail failure, reusable side rail and reused side rails.

Joint type	1st Cycle no. of side rail failures	No. of side rail suitable for reuse	2nd Cycle side rail reused from 1st Cycle	2nd Cycle no. of side rail failures	No. of side rail suitable for reuse	3rd Cycle side rail reused from 2nd Cycle	3rd Cycle no. of side rail failures	No. of side rail suitable for reuse
Screws	5	5	5	7	3	3	7	2
Dowel Nuts	6	4	4	5	3	3	8	2
PRMT	8	10	3	8	10	2	6	10
PRecMT	6	10	***	***	***	***	***	***
Ins PRecMT	***	***	10	7	8	8	7	10
Dowel	6	10	10	6	10	10	6	10
GRMT	9	10	2	8	10	2	8	9
GRecMT	6	10	***	***	***	***	***	***
Ins GRecMT	***	***	10	6	10	10	6	10

Table 2
ANOVA test results.

Source	DF	Sum of squares	Mean square	F value	Pr > F
Model	8	0.40017474	0.05002184	19.47	<.0001
Error	96	0.24659269	0.00256867		
Total	104	0.64676743			

R^2	Coeff var	Root MSE	Moment capacity mean
0.61873	23.49501	0.050682	0.215714

Source	DF	Anova SS	Mean square	F value	Pr > F
Joint Type	6	0.39461183	0.06576864	25.6	<.0001
Life Cycle	2	0.00556291	0.00278146	1.08	0.3427

3.8. Statistical analysis

In this study, two way-ANOVA test was conducted to establish that the means of moment capacity for each joint type are significantly different ($F = 19.47$ and p-value < 0.0001) (Table 2). 62% of variation in the model is explained by changing joint type and life cycle. In addition, there is enough evidence that joint type is significant in the test (p-value < 0.0001) whereas life cycle is not significant (p-value $=$ 0.3427). Also, Tukey grouping was used to determine which joint types are not significantly different (Means with same letter are not significantly different.) (Table 3).

4. Conclusions

This study provides useful information concerning cyclic performance test of chair frames constructed with seven types of joints. Presented information is of a particular value to producers, product developers, designers and craftsman who are striving to build strong and durable wooden furniture. It is also of special interest to humanitarian groups involved in the production of school furniture and the repair of broken furniture especially in the developing world.

Two main groups of joints were included in the study: *first knockdown joints*, namely, *screw, bed bolts and pinned mortise and tenon*, and *second more permanent glued joints*, namely, *dowel and glued mortise and tenons*. All joints were compared in terms of a) joint strength b) ease of assembly and disassembly, and c) ease of repair in different life stages.

Knockdown joints included in the study yield lower moment capacity than glued joints (Fig. 3); i.e., the average moment capacity of knockdown joints (0.183 kN·m) was 71% of the average moment capacity of glued joints (0.259 kN·m). However, joints constructed with large screws (0.332 kN·m) produced about the same moment capacity as glued round and rectangular mortise and tenon joints (Fig. 3) and could also provide long product service life.

Glued joint construction has greater cyclic load durability and glued round and rectangular mortise and tenon joints provided high levels of strength which potentially would increase product service life. Glued joints are more labor intensive, in general, requires more machining (Fig. 3) and more challenging to repair than knockdown joints (Fig. 5).

Table 3
Tukey grouping.

Tukey Grouping	Mean	N	Joint Type
A	0.310	15	GRMT
A	0.279	15	GRecMT
A	0.261	15	Screw
B	0.188	15	Dowel
B	0.176	15	PRecMT
B	0.150	15	PRMT
B	0.147	15	Bed Bolts

Overall, frames constructed with knockdown joints were found to be the easiest to assembly, disassembly, repair, and resulted in the largest reuse of parts (Fig. 5). However, knockdown joints are often more costly. They should be considered when planning for furniture solutions intended for on-site assembly and disassembly and for flat shipment. Moreover, high strength of screw joints is important and they also constitute a simple solution for furniture repair, as well as on site repair of broken furniture.

Use of results from this study could affect the amount of furniture that is repaired, remanufactured, or discarded to landfill. The most feasible application could be for wooden school furniture manufacturing where collection and repair of used furniture, especially in underdeveloped areas of the world, is more organized and could become a new sustainable practice.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.matdes.2015.08.009.

References

[1] American Library Association (ALA), The use of performance test and quality assurance programs in the selection of library chairs, Libr. Technol. Rep. 18 (5) (1982) 483–571.
[2] R.D. Bergman, S.A. Bowe, Life-cycle inventory of manufacturing hardwood lumber in southeastern US, Wood Fiber Sci. 44 (1) (2012) 71–84.
[3] M. Derikvand, G. Ebrahimi, C.A. Eckelman, Bending moment capacity of mortise and loose-tenon joints, Wood Fiber Sci. 46 (2) (2014) 159–166.
[4] C.A. Eckelman, Performance testing of side chairs, Holz Roh Werkst. 57 (1999) 227–234.
[5] C.A. Eckelman, Textbook of Product and Strength Design of Furniture, Purdue University, West Lafayette, 2003.
[6] C.A. Eckelman, E. Haviarova, Performance tests of school chairs constructed with round mortise and tenon joints, For. Prod. J. 56 (3) (2006) 51–57.
[7] C.A. Eckelman, E. Haviarova, Rectangular mortise and tenon semi rigid joint connection factors, For. Prod. J. 58 (12) (2008) 49–58.
[8] G.D. Hatcher, W.L. Ijomah, J.F.C. Windmil, Design for remanufacture: a literature review and future research needs, J. Clean. Prod. 2011 (2004–2014) 19.
[9] E. Haviarova, J. Bois, H.P. Quesada, Development of optimal forest products supported by LCA, in: Proceedings of ISCHO 2013–4th International Scientific Conference on Hardwood Processing. Florence, Italy, 2015, 327–334.
[10] A. Kasal, Y.Z. Erdil, S. Demirci, C.A. Eckelman, Shear force capacity of various doweled frame type furniture joints, Kastamanou Univ. J. Forest Fac. 13 (1) (2013) 60–71.
[11] A. Kasal, E. Haviarova, H. Efe, C.A. Eckelman, Y.Z. Erdil, Effect of adhesive type and tenon size on bending moment capacity and rigidity of T-shaped furniture joints constructed of Turkish beech and Scotch pine, Wood Fiber Sci. 45 (3) (2013) 287–293.
[12] E. Likos, E. Haviarova, C.A. Eckelman, Y.Z. Erdil, A. Ozcifci, Effect of tenon geometry, grain orientation, and shoulders on bending moment capacity and moment rotation characteristics of mortise and tenon joints, Wood Fiber Sci. 44 (2012) 462–469.
[13] E. Likos, E. Haviarova, C.A. Eckelman, Y.Z. Erdil, A. Ozciftci, Static versus cyclic load capacity of side chairs constructed with mortise and tenon joints, Wood Fiber Sci. 45 (2) (2013) 223–227.
[14] R.C. Aldo, R.S. Montero, C.A. Eckelman, E. Haviarova, Estructuras livianas a partir de piezas menores de madera de plantación, Tecnol. Marcha 20 (3) (2007) 55–68.
[15] R.C. Aldo, R.S. Montero, C. Madriz-Quirós, E. Haviarova, C.A. Eckelman, School furniture for developing countries: a field performance evaluation, For. Prod. J. 59 (7/8) (2009) 1–5.
[16] Milan Simek, E. Haviarova, C. Eckelman, The effect of end distance and number of ready to assemble furniture fasteners on bending moment resistance of corner joints, Wood Fiber Sci. 42 (1) (2010) 11–15.