LOAD-DEFLECTION BEHAVIOR OF RATTAN CHAIR SEATS

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Abstract. Static and fatigue performances of seat foundations of natural rattan chairs subjected to vertical loads were investigated. Static performance evaluation results indicated that rattan strip weaving patterns had significant effects on the vertical load-carrying capacity and stiffness performance of chair seat foundations. Herringbone- and grid-pattern woven seat foundations had significantly greater vertical load-carrying capacity than those made with a square-corner pattern. Square-corner-pattern seat foundations yielded a softer sitting surface than herringbone and grid patterns. Herringbone- and grid-pattern seat foundations provided firmer sitting feel and better deep down support for heavier sitters. The Burger model could be used to describe the force–deflection–time behavior of a rattan woven seat foundation subjected to vertical cyclic loading.

Keywords: Rattan chairs, seat foundation, rattan weaving pattern, Burger model, deflection, static load, cyclic load, fatigue.

INTRODUCTION

Rattan weaving is a traditional handicraft technique that has been used in furniture manufacturing for centuries because of its decorative effect. Rattan furniture has a unique aesthetic appeal and natural style. The rattan woven surface mainly for the seat foundation and back support of seating furniture has the unique characteristics of flexibility and breathability, which provide comfortable support. Figure 1a shows the rattan woven seat surface called soft drawer, which can be removed with its frame like a drawer. This sample is in the Ming and Qing Su style chair collection in the Metropolitan Museum, New York. A typical soft drawer style seat surface consists of two layers, top and bottom. The top layer is woven using 1-mm-wide or less rattan bast material with an intricately twilled weaving pattern. The bottom layer is woven with palm ropes providing support for the top layer. In the history of Chinese traditional furniture, the rattan woven surface was widely used in stools, chairs, couches, dressers, tables, and other traditional hardwood furniture, especially for the seats and backs of chairs. Since the middle of the 17th century, rattan woven furniture has also been widely used in western countries. Figure 1b shows a rattan rocking chair made by Heywood

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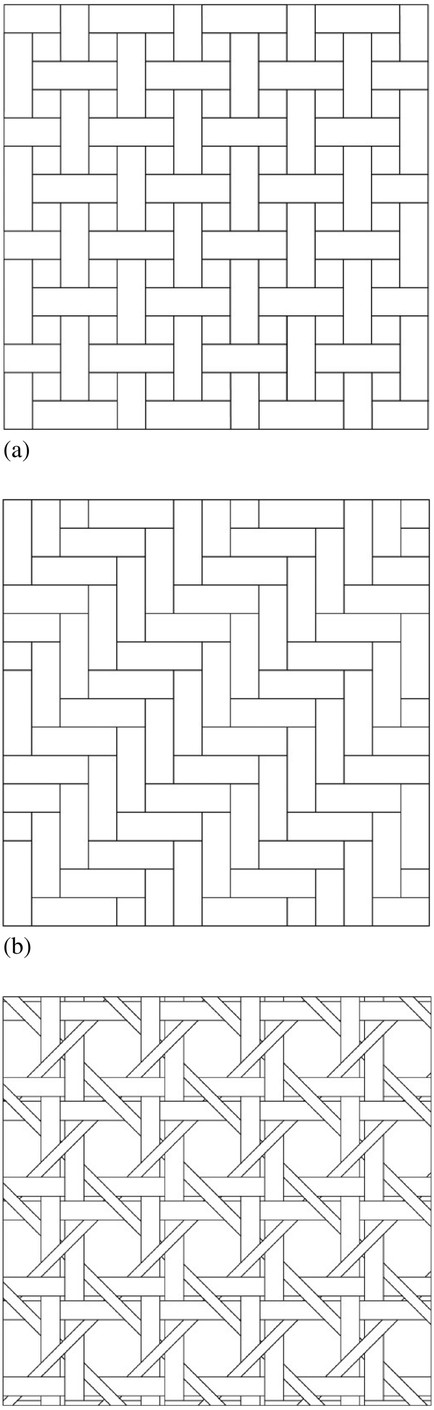
(a) (b)

Figure 1. Rattan chairs: (a) a soft drawer exhibition of Ming style chair from the Metropolitan Museum collection and (b) rocking chair made by Heywood Wakefield Rattan Company in late 19th century.

Wakefield Rattan Company in the late 19th century, its seat, back, and arms form an enclosed rattan woven surface (Pina 2008).

Rattan woven surfaces consist of warps and wefts interweaved into a geometrical pattern, ie wefts travel over and under warps according to certain weaving pattern rules (CNFS 2013). Warps are the strands arranged lengthways, whereas wefts are the strands arranged sideways and crossed by the warp yarns. Various weaving patterns have been designed by craftsmen for 1000s of years. Many of these weaving patterns done by human hands have been inherited from generation to generation, but some disappeared because of industrialization. Figure 2 illustrates three basic types of weaving patterns commonly seen in natural rattan furniture: grid, herringbone, and octagonal patterns (Miller and Widess 1991; Widess 2006; Gu 2008). The grid pattern (Fig 2a) is the most basic and popular one with its warps and wefts interweaved through a weft (warp) crossing over and under the warp (weft). The herringbone pattern (Fig 2b), also called V-shape, is a twilled three-under and three-over weaving pattern. The octagonal pattern (Fig 2c) is woven through using vertical and twilled weaving methods and its surface holes and gaps produce a visual effect of a transparent surface. Therefore, the octagonal pattern is mostly used in decorative parts in furniture such as chair back surfaces and screens. On the basis of the octagonal pattern weaving method, the square-corner pattern and the triangle pattern can be derived through alternating twilled angles.

The warps and wefts can be woven with and without gaps among them. A weaving pattern with gaps can be referred to as an openly woven surface, whereas a pattern without gaps is a tightly woven surface (CNFS 2013). Examples of openly woven surfaces are octagonal, triangular, and square-corner patterns, which are usually for decorative purposes. Tightly woven surfaces are grid, herringbone, and basket patterns, which are good for load-bearing surfaces. Grid patterns can be either openly or tightly woven. The openly woven ones can also be called box woven (Fig 2a). Five levels (superfine, fine-fine, fine, medium, and normal) are used for evaluating how tightly or openly a rattan surface is woven. The evaluation levels are based on the gap between two warps (or wefts) or the distance between two centers of repeating geometrical patterns. Superfine for a tightly woven surface means the distance between two warps (or wefts) should be less than 1 mm. A 9 mm distance between two centers of the holes in an


(a)

(b)

(c)

Figure 2. Three basic types of weaving patterns commonly seen in natural rattan furniture: (a) grid, (b) herringbone, and (c) octagonal.

octagonal pattern surface will be rated as a superfine openly woven surface (Miller and Widess 1991).

Weaving materials in rattan furniture vary from natural rattan materials to many other kinds, for instance, rush, paper string, leather, rawhide, strips of parchment, and varieties of high-density polyethylene-based synthetic rattan or wood–synthetic composite materials (Cody 1983; Phukringsri and Hongsriphan 2011). However, natural rattan material always has its unique features of lightness, flexibility, durability, and exotic tropical looks.

Natural rattan strips for furniture weaving applications generally are 1-2 mm thick and are mainly obtained from the bast or core portions of rattan palms through manual separation or by splitting machines. The rattan strips made from the bast portion without surface epidermis material removed can maintain natural beauty and also be waterproof because the epidermis contains siliceous material. Rattan strips from core materials can have various shapes such as flat, round, half-round, and triangular (Gu 2008; Gu et al 2015).

Li cane (*Calamus simplicfoilius* Wei., commonly known as Calamus) is the most popular raw material for the production of rattan strips for surface weaving and warping components in rattan furniture (Cai 1989, 1992, 1994; Gu 2008). It naturally grows in the virgin forest at an altitude of 300-1100 m above sea level and also in plantations of the eastern and southern Hainan Island and the south of Guangdong, Guangxi, and Fujian provinces in China (Jiang 2002; Gu 2008).

Cane species commonly used for rattan furniture frame stocks are Rattan manau (*Calamus manan* Miq.) and Baden cane (*Calamus zollingeri* Becc.). Both belong to the Calamus family and mostly grow in the tropical forests of Southeast Asia. Manau from Indonesia's Sumatra Island, Peninsular Malaysia, southern Thailand, and Kalimantan is the most popular commercial rattan in furniture applications because of its high quality and beautiful appearance. Baden cane, from southern Sulawesi, Indonesia Moluccas

Islands, and West Java, is comparable with manau in performance and is the most cost-effective cane material for furniture making (Jiang 2002; Li et al 2003; Gu et al 2013).

Like joints in a rattan chair (Wan Tarmeze 2001; Gu et al 2013), which need to resist service loads without failure, a chair seat surface made of fine rattan strips with beautiful weaving patterns requires not only that it has sufficient strength and durability to resist external service loads applied but also that it provides a comfortable sitting experience. There was no literature found on performance evaluation of a rattan sitting surface in terms of its static strength and durability in resisting vertical loads. Specifically, there was no study found on the stiffness performance of rattan furniture seat surfaces as seat cushioning systems that provide sitting support. Human sitting experiences such as sitting down, getting up, and shifting in terms of sitting comfort indexes are affected by material stiffness.

The main objective of this study was to evaluate strength and stiffness performances of seat foundations of rattan chairs. Specific objectives were to 1) evaluate the effect of three commonly used weaving patterns on strength and stiffness of rattan chair seat foundations subjected to static vertical loads; 2) compare stiffness of evaluated rattan woven seat foundations to foam materials commonly used for chair seat cushions in terms of cushion material performance indexes considering human sitting comfort experience; 3) investigate the fatigue performance of rattan chair seat foundations through subjecting them to vertical cyclic loading; and 4) propose a mathematical model for describing the time-dependent behavior of rattan chair seat surfaces as they were subjected to vertical cycle loadings.

MATERIALS AND METHODS

Specimens and Materials

Figure 3 shows three selected weaving patterns of seat foundation specimens, grid, herringbone, and square-corner, used in this study. The grid


(a)

(b)

(c)

Figure 3. Three weaving patterns of natural rattan seat foundation specimens used in static tests: (a) grid, (b) herringbone, and (c) square-corner.

pattern was a close type woven with superfine warp and medium weft rattan strips perpendicular to each other. The herringbone pattern was a fine twilled and close type weaving. The square-corner pattern, a derivative of the octagonal pattern (Fig 3c), was an open type woven with fine warp and fine weft rattan strips perpendicularly first, then twilled with fine strips to form 10-mm square holes. All specimens measured 410 mm wide and 410 mm deep. Five replicates were evaluated for each of the three weaving patterns, ie #g-1, #g-2, #g-3, #g-4, and #g-5 for grid pattern; #h-1, #h-2, #h-3, #h-4, and #h-5 for herringbone pattern; and #sc-1, #sc-2, #sc-3, #sc-4, and #sc-5 for square-corner pattern, respectively.

Figure 4 shows a rattan chair used for evaluating the load-deformation behavior of the seat foundation surface of rattan chairs subjected to cyclic vertical sitting loads. The seat foundation surface was woven with rattan strips using the three-warps and three-wefts grid pattern, ie every three fine-warps crossly meets each three fine-wefts. The seat foundation surface measured 410 mm wide, 410 mm deep, and 440 mm above the ground. Three replicates labeled as #1, #2, and #3 were evaluated.

Figure 4. A rattan chair used for evaluation of load-deflection behavior of its seat foundation surface subjected to cyclic vertical loads.

All frames in the specimens tested in static and cyclic loadings were constructed with Baden canes in 30 mm diameter. Rattan strips used to weave the seat foundation surfaces were made from Li cane bast materials and measured 6 mm wide by 1 mm thick. All rattan materials were provided by Boxuan Rattan Furniture Co., Ltd. (Nanjing, China).

Specimen Preparation and Test

Both static and cyclic loading specimens were handmade by a craftsman with 8 yr of rattan furniture making experience. Static testing specimens were prepared with prewoven inner sections attached to premade outer frames with nails. The next steps were covering the four edges with small-diameter rattan strips and then wrapping the four corners with 3-mm-diameter cross section strips made with a core material of Li cane. Before testing, all specimens were stored in a conditioning room at 20°C and 65% RH for 2 wk.

All static vertical loading tests were performed on a CMT6104 universal testing machine at a loading rate of 10 mm/min (CNS 2009), provided by laboratory for material mechanics of Nanjing Forestry University in China. Figure 5 shows the setup for evaluating load-deflection behavior of seat foundation surfaces of rattan chairs subjected to a static vertical load. The loading span between two end supports was 380 mm (Fig 5). The vertical load applied to the center of seat foundation samples was through a flat circular head with a diameter of 150 mm. Load middle-point deflection curves, ultimate vertical loads, and failure modes were recorded.

One-sided cyclic loading tests on seat foundations of rattan chairs were performed using a YZBS-2 chair testing machine (Fig 6), provided by laboratory for furniture quality testing of

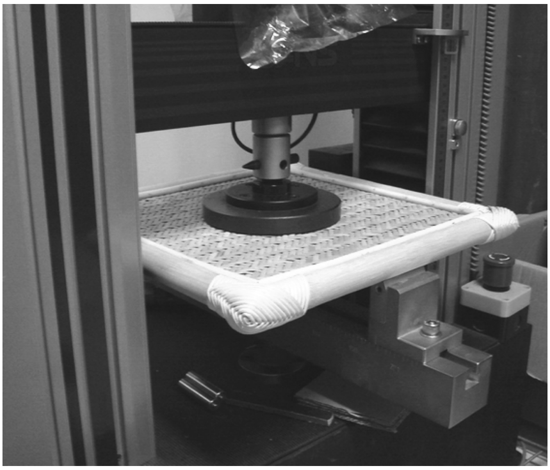


Figure 5. Test setup for evaluating load-deflection behavior of rattan chair seat foundation surface subjected to static vertical loads.

Nanjing Forestry University in China. The test followed the procedure described in CNS (1989), ie Level 3 loading condition (950 N) was selected. The flat circular loading head measured 200 mm in diameter. It was made of a 150-mm-diameter metal plate wrapped in soft leather material. All tests started with a 950 N downward force applied vertically on the center of a seat foundation at a loading rate of 30 cycles per minute until damage occurred to the seat foundation that would affect normal sitting performance of the chair or until 50,000 cycles were reached. The deflection at the center point of a seat foundation was measured at an interval of every 1000 cycles for the first 10,000 cycles and then every 2000 cycles until 20,000 cycles were completed. After that, the middle-point deflection was measured every 5000 cycles. Failure modes were also recorded. For all static and cyclic loading tests, specimens were tested in the laboratory with its condition maintained at 23 ± 2°C and 50 ± 2% RH.

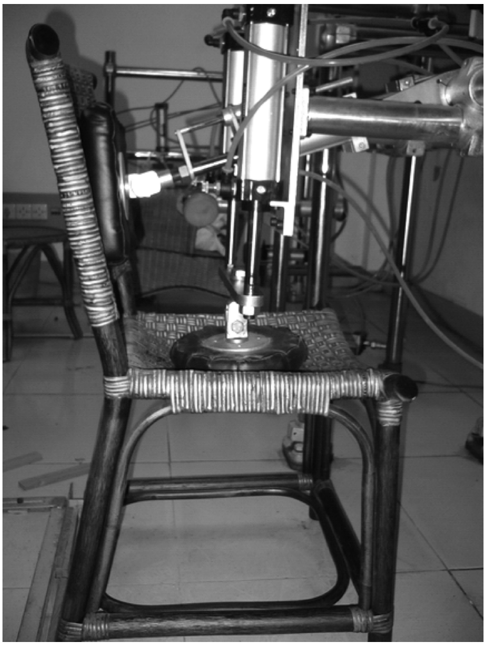


Figure 6. Test setup for evaluating load-deflection behavior of rattan chair seat foundation surface subjected to cyclic vertical loads.

RESULTS AND DISCUSSION

Static Load Test

Two types of failure modes occurred in static tests: nonrecoverable concaved deformation (Fig 7a-c) and broken strips along frame edges (Fig 7d-f) and at different spots along deformed edges (Fig 7g). Table 1 summarizes failure modes observed for each of 15 tested specimens.

Figure 8 shows typical load-deflection curves of three weaving patterns of tested seat foundation specimens. Table 2 summarizes mean values of ultimate vertical loads of three weaving patterns of seat foundation specimens tested. Each value represented a mean of five replicates tested. The protested least significant difference (LSD) multiple comparison procedure was performed at the 5% significance level to determine mean differences of ultimate vertical loads among three weaving patterns based on a single LSD value of 220 N. The results indicated that there was no significant difference in ultimate vertical loads between herringbone- and grid-pattern specimens. Square-corner pattern specimens had a significantly lower ultimate vertical load than the other two patterns.

The load-deflection curves of rattan seat foundation specimens were evaluated in accordance

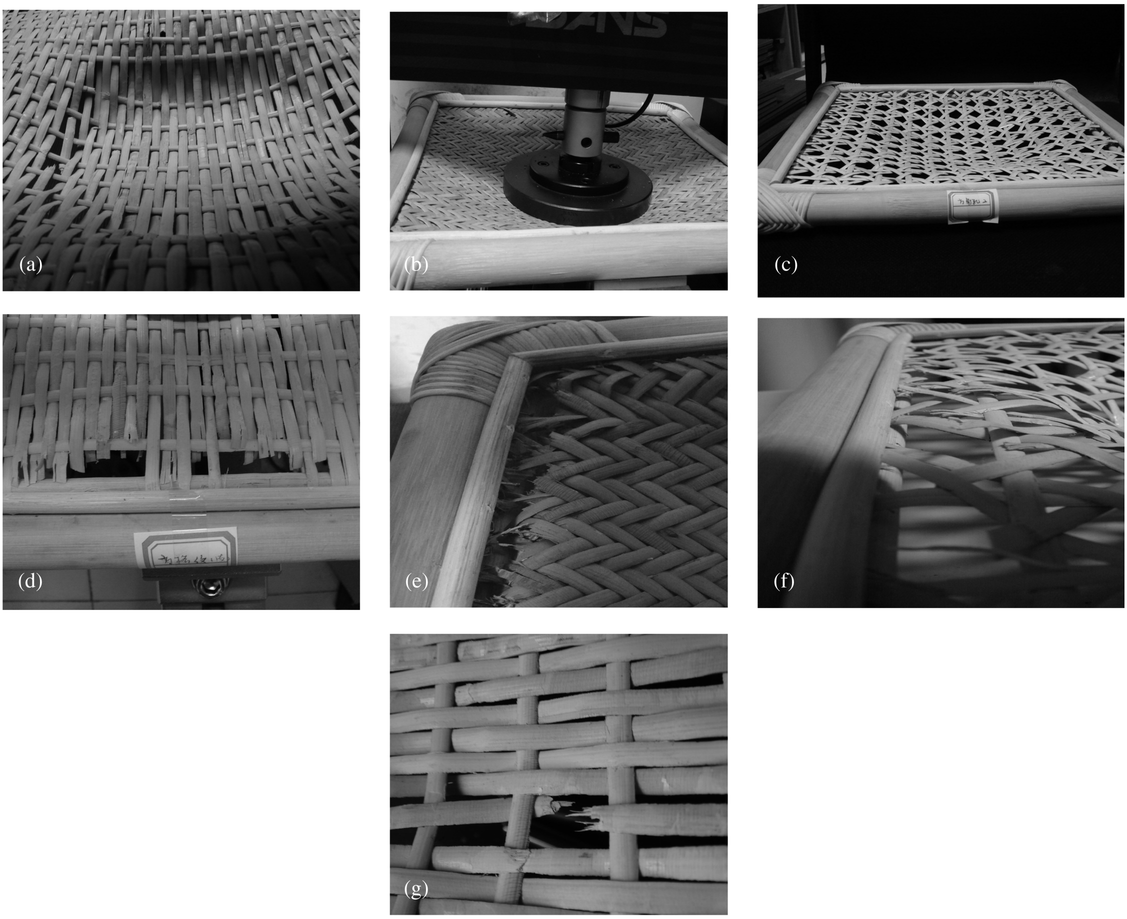


Figure 7. Two typical failure modes occurred in static tests of rattan seat foundation specimens: (a), (b), and (c) nonrecoverable concaved deformation, (d), (e), (f) broken strips along frame edges, and (g) at different spots along deformed edges.

with the procedures outlined in ASTM (2012) because these samples were treated as seat cushioning materials such as foams. The evaluated properties for rattan seat foundation specimens were 25% indentation force deflection (IFD), 65% IFD, and support factor (SF). An IFD of 25% means the force necessary to generate 25% deflection of the seat surface, also 25% IFD is the measure of a cushion's firmness. The more force that is required to indent a cushion to 25% of its original thickness, the firmer the cushion is. Cushion materials with 25% IFD values from 132 N to 159 N obtain a firmer rating for seat cushions and mattresses (JIPFC 1994). Cushions with 25% IFD values from 106 N to 132 N have a firm rating for average seat cushions, upholstery padding, tight seats, certain mattress types, and quilting. Cushions with 25% IFD values from 80 to 106 have a soft rating for thin back pillows, tufting matrix, very thick seat cushions, and wraps. Cushion materials with 25% IFD values from 53 to 80 have a softer rating for back pillow, upholstery padding, and wraps. These IFD values were obtained based on ASTM (2012) using a 203-mm-diameter loading plate. Sixty-five percent IFD is a measurement used to determine the ability of a cushion to provide deep down support. SF, which is a ratio of 65-25% IFD, is a measure of the ability of the cushion to provide support. In general, a cushion

Table 1. Typical failure modes of seat foundation specimens subjected to static vertical loads.

		Typical failure mode		
		I	II	
Weaving pattern	Specimen no.	Nonrecoverable deformation	Broken strips along frame edges	Broken strips along deformed edges
Grid	#g-1	√	√	
	#g-2	√	√	√
	#g-3	√	√	
	#g-4	√	√	√
	#g-5	√	√	
Herringbone	#h-1	√	√	
	#h-2	√	√	
	#h-3	√		
	#h-4	√	√	
	#h-5	√		
Square-corner	#sc-1	√	√	
	#sc-2	√	√	
	#sc-3	√	√	√
	#sc-4	√	√	
	#sc-5	√	√	

is required to have a minimum value of 2 for its SF for a sitter to experience comfortable sitting (Mehta and Tewari 2000).

In this study, the deflection corresponding to the first peak load on the load-deflection curve of a tested rattan seat foundation specimen was considered the maximum deflection of that specimen. This deflection was assumed to be the equivalent thickness of that specimen if it were used as a foam cushion material. Therefore, mean values of 25 and 65% IFD and SF for each of three patterns were calculated and summarized in Table 2. For comparison purposes, their corresponding load values in terms of the 203-mm-diameter testing plate (ASTM 2012) were calculated and summarized in Table 2 with the assumption of the same compression pressure applied to the seat foundation. The greater than 2 value of SF indicated that all three weaving patterns of rattan seat foundations can provide comfortable sitting experience. A value of 99 N for the 25% IFD of square-corner-pattern specimens indicated that a seat surface made from the square-corner weaving pattern yielded a soft rating seat, which was much softer than the other two patterns. Both grid and herringbone patterns yielded much firmer cushioning systems but provided better deep down support for heavier sitters, whereas the square-corner did not. In other words, the square-corner-pattern rattan woven seat foundation was better for lighter sitters, whereas the other two patterns fit heavier users better for deep down support.

These results indicated that the weaving pattern can significantly affect strength and stiffness or firmness performance of rattan seat foundations. The firmness performance of rattan seat foundations as a seat cushioning system especially can be altered through different weaving patterns to obtain different levels of soft, firm, and firmer ratings and also to achieve reasonable comfort

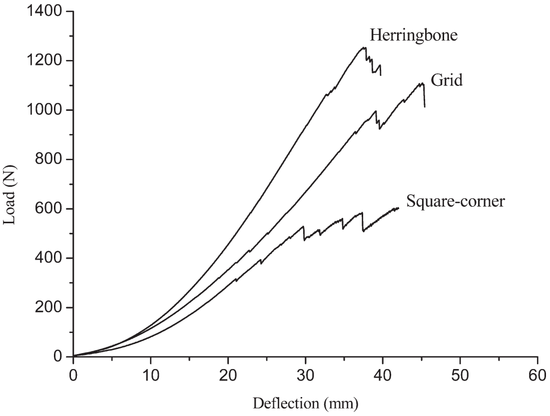


Figure 8. Typical load-deflection curves of three weaving patterns of rattan seat foundation specimens subjected to static vertical loads.

Table 2. Mean values of ultimate vertical loads, 25 and 65% indentation force deflections, and support factor of five tested seat foundations within each of three weaving patterns.

		Indentation force deflection				
		25%		65%		
	Ultimate load	150 mm plate	203 mm plate	150 mm plate	203 mm plate	
Weaving pattern		N				Support factor
Grid	1048 (10) A[a]	126 (19) A	231	643 (17) A	1178	5.13 (8) A
Herringbone	1127 (19) A	129 (30) A	236	674 (25) A	1234	5.28 (6) A
Square-corner	552 (25) B	54 (20) B	99	270 (20) B	495	4.96 (5) A

[a] Values in parentheses are coefficients of variation.

Means within the same column not followed by a common letter are significantly different from one another at the 5% significance level.

support levels. Furthermore, if this rattan-made seat support system can be combined with foam materials as a composite material, then a new seat cushioning material system with unique properties could be obtained.

Cyclic Load Test

Two types of failure modes occurred in cyclic vertical load tests: nonrecoverable concaved deformation of the seat foundation surface (Fig 9a) and broken and loosened strips along frame edges (Fig 9b). Table 3 summarizes failure modes observed for each of three tested chairs.

Figure 9. Two typical failure modes in seat foundation surfaces of rattan chairs subjected to vertical cyclic loads: (a) nonrecoverable concaved deformation and (b) loosen and broken strips along frame edges.

Figure 10a shows the center-point deflection–time curves of the seat foundation surfaces of all three evaluated rattan chairs. Figure 10b shows the typical deflection change rate–time curve of chair specimen #1 with its corresponding deflection–time curve. Three stages of deflection can be identified from the curve: primary, secondary, and tertiary (Bodig and Jayne 1982). The deflection change rate decreased in the primary region, approximately kept about constant in the secondary region, and sharply increased in the tertiary region.

The force–deflection–time expression of the Burger model (Bodig and Jayne 1982) was proposed to fit primary and secondary regions with the intention of using the model to describe the time-dependent behavior of the seat foundation surface of rattan chairs subjected to vertical cyclic loadings:

$$\mu = P\left[\frac{1}{k_e} + \frac{1}{k_{de}}\left(1 - e^{-\left(\frac{k_{de}}{r_{de}}\right)t}\right) + \frac{t}{r_\nu}\right] \qquad (1)$$

where μ is the deflection (mm); P is magnitude of vertical cyclic loading (N); t is cycle

Table 3. Typical failure modes of grid-pattern woven seat foundations of three rattan chairs subjected to vertical cyclic loads.

	Failure modes		
	I	II	
Specimen no.	Nonrecoverable deformation	Loosen strips	Broken strips
#1	√	√	—
#2	√	√	—
#3	√	—	√

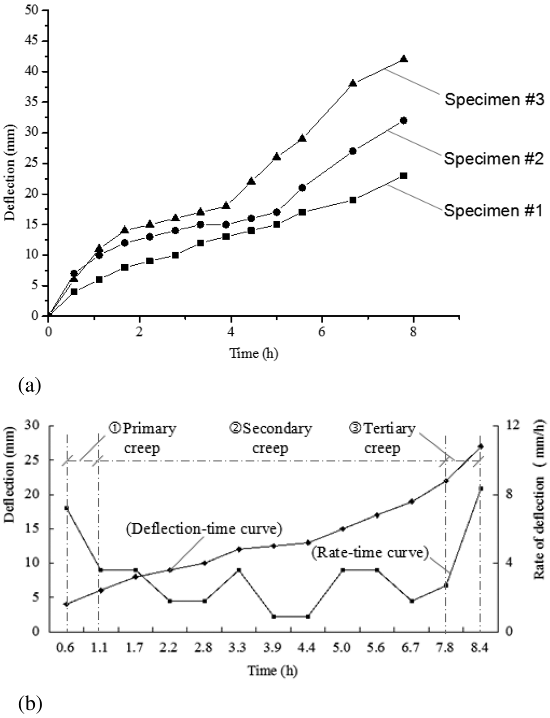


Figure 10. (a) Center-point deflection–time curves of seat foundations of three rattan chairs subjected to vertical cyclic loads and (b) a typical rate–time curve of chair specimen #1 with its corresponding deflection–time curve.

time (h); k_e and r_v are account for the elastic and viscous behaviors of a tested material, respectively, ie k_e is the elastic constant related to the instantaneous elastic deformation (N/mm) and r_v is the damping constant related to viscous deformation, which is permanent and nonrecoverable (N-h/mm); k_{de} and r_{de} are account for the delayed elastic behavior of a tested material, ie k_{de} is the delayed elastic constant related to the delayed elastic deformation (N/mm) and r_{de} is the damping constant related to recoverable deformation (N-h/mm).

The following equation was used to fit individual data points in primary and secondary regions for each of three curves recorded for three tested chairs using the least squares regression method:

$$Y(t) = \mathrm{A} + \mathrm{B}[1 - \exp(-\mathrm{C}t) + \mathrm{D}t] \qquad (2)$$

where Y is the deflection (mm); t is cycle time (h); and A, B, C, and D are regression fitting constants.

Table 4 summarizes mean values of fitting constants A, B, C, and D obtained from regression equations with their coefficient of deformation r^2 and viscoelastic constants derived based on their relationships to fitting constants, ie $k_e = P/\mathrm{A}$; $k_{de} = P/\mathrm{B}$; $r_{de} = P/\mathrm{BC}$; and $r_v = \mathrm{P/D}$. The high r^2 value indicated that the Burger model fit the experimental data well. This suggested that the Burger model could be used to describe the time-dependent behavior of the seat foundation surface of rattan chairs subjected to vertical cycle seat loads. The lower value of the damping constant, r_v, related to viscous deformation compared with polyurethane foam materials indicated that the evaluated grid-pattern seat foundation yielded larger nonrecoverable deformation (Xu et al 2015). The lower value of the damping constant, r_{de}, related to recoverable deflection indicated that the evaluated grid-pattern seat foundation recovered delayed elastic deformation more quickly than foam material. The higher elastic and delayed elastic constants of tested rattan seat foundations indicated that the seat made from it felt feel harder than the foam materials, which was consistent with the result from the 25% IFD analysis of seat foundation surfaces subjected to static vertical loads.

Table 4. Mean values of derived fitting constants for regression equations with their coefficient of determination, r^2, and derived viscoelastic constants of Burger model equations for describing time-dependent behavior of rattan chair seat surfaces subjected to cycle vertical loadings.

					k_e	k_{de}	r_{de}	r_v
A	B	C	D	r^2	N/mm		N-h/mm	
0.044 (36)[a]	8.097 (32)	1.461 (22)	1.577 (30)	0.994	24,027 (44)	125 (28)	90 (46)	643 (31)

[a] Values in parentheses are coefficients of variation.

CONCLUSIONS

The static and fatigue performances of seat foundations of natural rattan chairs subjected to vertical loads were investigated. Static performance evaluation results indicated that the three weaving patterns evaluated in this study had significant effects on the vertical load-carrying capacity and stiffness performance of the seat foundations of rattan chairs. Herringbone- and grid-pattern seat foundations had significantly greater vertical load-carrying capacity than did square-corner. Herringbone-pattern seat foundations showed greater vertical load-carrying capacity than did grid patterns, but this difference was not significant. Square-corner-pattern seat foundations yielded a softer sitting surface than herringbone and grid patterns and provided good deep down support as a chair cushioning support for lighter sitters but might not be suited for heavier sitters. Herringbone- and grid-pattern seat foundations used as a seat cushioning system yielded a firmer feel but provided better deep down support for heavier sitters.

Three distinct stages, primary, secondary, and tertiary, occurred in deflection–time curves of rattan grid-pattern woven seat foundations subjected to vertical cyclic loads. Regression analyses results indicated that the Burger model could be used to describe the force–deflection–time behavior of a rattan woven seat foundation subjected to cyclic loading. The viscoelastic constants of derived mathematical equations indicated that the rattan seat foundations tested in this experiment, compared with polyurethane foam materials, yielded larger nonrecoverable deflection, recovered delayed elastic deformation more quickly, and felt firmer.

Results of this study suggest that basic mechanical properties related to static and fatigue loading capacities of rattan strips when used as seat foundation building materials, such as tensile strength and stiffness, need to be investigated. Deflection behavior of seat foundation surfaces when used as a seat cushioning support system needs to be studied under both static and cyclic loadings. Therefore, knowledge bases can be built for engineering design of seat foundations with rattan materials to meet comfort, strength, and durability requirements.

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