BENDING AND CREEP DEFORMATION OF A WOOD-BASED LIGHTWEIGHT PANEL: AN EXPERIMENTAL STUDY

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Abstract. When wood is exposed to long-term loading, creep deformation can occur because of its viscoelastic characteristic. The aim of this study was to increase the understanding and knowledge of creep deformation of a wood-based lightweight sandwich-type panel and to see if this type of panel has similar properties for creep as solid wood has. This was done by means of a study based on experiments. The panel studied consisted of two face sheets of beech wood and a core of pinewood struts cross-glued to the face sheets. A solid beech panel was used as a reference. In all, there were 27 samples for the test. The densities of the lightweight panel varied from 165 to 297 kg/m^3, compared with the density of the solid panel of 705 kg/m^3. The study consisted of two parts: a bending test and a creep test. The bending test was used to determine the maximum failure load for the panel. For the creep test, 30% of the original failure load was used. When the results from the bending tests were ranked for load capacity in relation to density, the results for the lightweight panel varied from 9.0 to 18.0 m^4/s^2, compared with the value of the reference panel at 27.3 m^4/s^2. This measured how effective the panel was in withstanding bending loads in relation to their density. However, this was not to say that the panel with the highest value also took the highest load in absolute terms. If the creep deformation is instead ranked in relation to density, the results for the lightweight panel varied from 10.4 to 33.7 kg/m, compared with the value of the reference panel at 45.5 kg/m. As with the bending test, these values rank how effective the panel was in resisting creep deformation in relation to density.

Keywords: Lightweight panel, bending, creep, deformation, rupture.

INTRODUCTION

In today's society, and probably even more in a future society, wood as a bio-based material will play an important role as raw material in many products (Araman et al 1982; Ratnasingam 2003; Puettmann and Wilson 2005; Goh et al 2013). Today wood is used in complex products and fulfils many requirements on, eg the functional, environment, and aesthetics level. Many wood products are exposed to a constant load for a long time. In the case of wood, this may result in a type of long-term mechanical degradation referred to as creep (Clouser 1959; Holzer et al 1989; Navi and Stanzl-Tschegg 2009; Du et al 2013). A common example is eg a book shelf. The main factors affecting the creep curve of a material (Fig 1) are the material itself, time, temperature, stress level, and moisture (Hanhijärvi 2000; Ranta-Maunus and Kortesmaa 2000; Navi and Sandberg 2012).

A material with both viscous and elastic properties is usually called a viscoelastic material. Wood can, thus, be called a viscoelastic material (Coleman and Noll 1961; Leichti and Tang 1989; Roylance 2001; Dinwoodie 2004). When wood is exposed to creep deformation, one part of the deformation will return to the unloaded state when the material is relieved (elastic deformation) while one part remains (viscous deformation).

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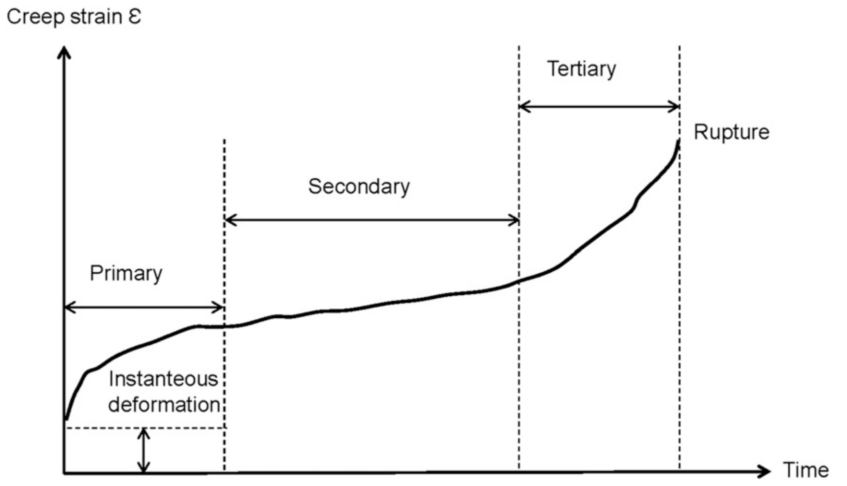


Figure 1. Schematic of a creep curve with the basic stages for creep (Yang et al 2018).

Moisture in wood also increases the creep deformation up to the fiber saturation point (FSP). A phenomenon that has a major impact on wood is the cyclic change of the moisture content (MC). This phenomenon is called mechano-sorption (MS) and impairs considerably the resistance of the wood material against creep deformation (Sandberg and Johansson 1995; Takahashi et al 2004, 2005, 2006; Huang 2016).

The modulus of rupture (MOR) for a material or product is a very important factor at the design and production stage of the product, especially as the development and/or the product changes. But for many products, those that have long been produced with the same type of material and design, the MOR is not a major problem. But creep deformation can be perceived as disturbing from a customer perspective, even if the MOR is sufficient.

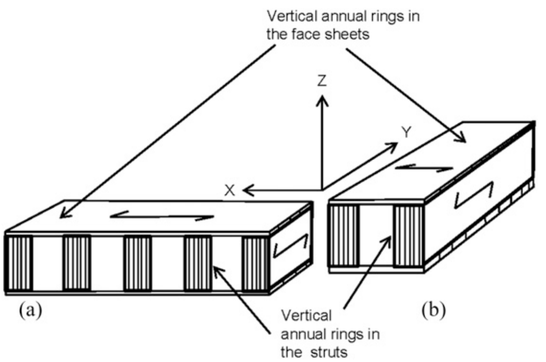


Figure 2. Samples from two directions, termed types (a) and (b).

In the modern wood industry, various types of panel materials are very common, eg in furniture, joinery, and constructional use (Haygreen et al 1975). Many of them are wood based and have material properties which to some extent liken to those of solid wood (Gnanaharan and Haygreen 1979). To save material and to fulfil different customer requirements such as low weight, lightweight panels are commonly used (Wood 1958). In these constructions, which can often be quite complex, there can be problems foreseeing creep behavior. This means that creep deformations that occur must be seen as both a material and a design phenomenon.

Table 1. Geometrical data of the samples.

Group/sample number	Thickness of the face sheets (10^{-3} m)	Center-to-center distance between struts (10^{-3} m)
1 & 6/1-3 & 16-18	6	160
2 & 5/4-6 & 13-15	3	160
3 & 7/7-9 & 19-21	3	96
4 & 8/10-12 & 22-24	6	96
9/25-27 (solid reference samples)	—	—

Table 2. Groups of samples, types of samples, and dimension of the samples.

Group/sample	Length X (10^{-3} m)	Length Y (10^{-3} m)	Dimension of the struts (W × H·10^{-3} m)	Samples for bending test	Samples for creep test
1/Type (b)	340	1300	20 × 28	3	—
1/Type (b)	180	1300	20 × 28	—	3
2/Type (b)	340	1300	20 × 34	3	—
2/Type (b)	180	1300	20 × 34	—	3
3/Type (b)	308	1300	20 × 34	3	—
3/Type (b)	116	1300	20 × 34	—	3
4/Type (b)	308	1300	20 × 28	3	—
4/Type (b)	116	1300	20 × 28	—	3
5/Type (a)	1300	300	20 × 34	3	—
5/Type (a)	1300	100	20 × 34	—	3
6/Type (a)	1300	300	20 × 28	3	—
6/Type (a)	1300	100	20 × 28	—	3
7/Type (a)	1300	300	20 × 34	3	—
7/Type (a)	1300	100	20 × 34	—	3
8/Type (a)	1300	300	20 × 28	3	—
8/Type (a)	1300	100	20 × 28	—	3
9/(Solid beech samples) 1300 × 40 × 150 (L × H × W)				3	—
9/(Solid beech samples) 1300 × 40 × 47 (L × H × W)				—	3

Therefore, this study has aimed to increase the understanding of longtime mechanical degradation (creep deformation) for one type of wood-based sandwich lightweight panel. The focus of the design was to reduce weight but still achieve acceptable stiffness and strength properties to the extent that would eg be tolerable for the manufacture of furniture. Mixing wood species could have technical, esthetical, and economic benefits. How the different settings of wood species affected the behavior of the panel was, however, not further evaluated in this study. But by experience, it is known that some wood species produce wood with lots of tension in them. Consequently, a wood species known to have lots of tension, such as beech, was chosen for certain parts of the panel. With the assumption that if it works with this wood species, it would also work with other wood species.

MATERIALS AND METHODS

Sandwich panels with an open strut structure served as the study object in this investigation. The study consisted of two parts; the first part was a bending test. To get an idea of the mechanical properties of the lightweight panel, it was sufficient to compare the results of the bending test with the requirements in standard DIN EN 312: 2010-12, which is a standard for particleboard when used under dry conditions for interior furnishing. At a later stage, the results from the bending test were also used to provide basic data for the creep test. Figure 2 in combination with Tables 1 and 2 gives the type and dimensions of

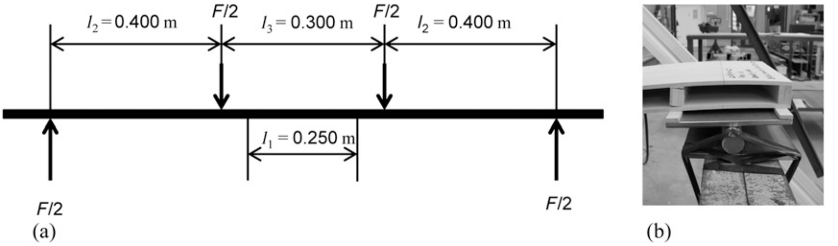


Figure 3. (a) Schematic test setup for the bending test. (b) Modified support point.

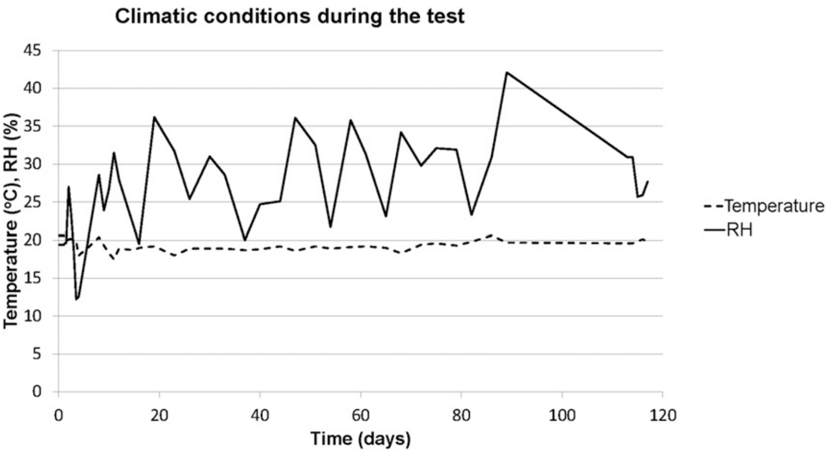


Figure 4. Temperature and RH conditions during the test.

the samples for each test. The test was based on a total of 27 samples divided into nine groups.

Description and Specification of the Samples

The face sheet material used was European beech (*Fagus sylvatica* L.), whereas the strut material was made of solid finger-jointed knot-free Scots pine (*Pinus sylvestris* L.). Both the face sheets and the struts were made of material with vertical annual rings. The panel product studied consisted of a number of struts and two thin outer face sheets that were tightly cross-glued onto the struts. The panels had a thickness of 40×10^{-3} m. The face sheets were of the same thickness on both sides, thus making the panel equilateral. The face sheets and the struts were glued in a cross-wise fiber direction. Further directions used in the panels are shown schematically in Fig 2. The three directions *X*, *Y*, and *Z* describe the global directions of the assembled panel. This means that test samples in both *X* and *Y* directions were studied. Figure 2 illustrates a sample in the *X* direction, the sample of type (a), and a sample in the *Y* direction, the sample of type (b).

Production of the Samples

The material was conditioned to an equilibrium moisture content (EMC) of approximately 12% before gluing and testing. Three replicates of solid edge-glued beech were used as reference panels. The annual rings in the reference panel were oriented as horizontal annual rings, compared with vertical annual rings in the struts and

Table 3. Differences between calculated and actual load for the creep test.

Group	Calculated load (N)	Actually used load (N)	Difference between calculated and used load (%)
1	398	403	1.3
2	397	402	1.3
3	428	428	0
4	506	511	1.0
5	107	112	4.7
6	195	198	1.5
7	167	168	0.6
8	260	261	0.4
9	1302	1304	0.2

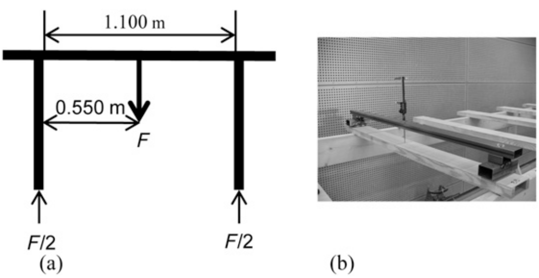


Figure 5. (a) Principles of the test setup for the creep test. (b) Jig in combination with a caliper for measuring of the creep deformation.

the face sheets of the lightweight panel. For the lightweight panel, the face sheet lamellae were glued together with polyvinyl acetate glue (according to SS-EN 204:2016 class D-3, classification of thermoplastic wood adhesives for nonstructural applications). The struts were bonded to the face sheets with a two-component adhesive consisting of a water-based disperser and an isocyanate hardener of metylendifenyldiisocyanat (MDI) type (according to SS-EN 204 class D4, Casco 1974/1993 adhesive system). The amount of adhesive used was 0.200 kg/m^2 at a pressure of 0.5 × 10^6 Pa (calculated with respect to the area of the struts), and they were pressed for 1800 s at a temperature of 20°C.

Bending Test

A four-point bending test was performed according to standard SS-EN 789:2004. The support points were slightly modified with two steel plates with dimensions of 0.350 × 0.180 × 0.008 m (L × W × T); this was to avoid the face sheets collapsing from the force of the supports. Figure 3(a) shows the schematic test setup, and Fig 3(b) shows the modified support points. The sample of type (b) was also adapted in width, depending on the differences in the distance between the struts.

Creep Test

The creep test was carried out in a temperate indoor environment in the south of Sweden over a period of 117 da, from January 2, 2017 to April 28, 2017. Figure 4 shows the relative humidity (RH) and temperature variations during the test. For most of the test, creep, temperature, and RH were measured twice a week. The measurements were made more often at the beginning and end of the test.

The load for the creep test was based on the bending test, and 30% of the maximum (F_{max}) load from the bending test was used for the creep test. The load, of metal scrap, was the average value for each group (see Table 3), although the weight of the scrap was not exactly 30% of the actual load. Table 3 presents the differences between the calculated and the actual load used.

Figure 5(a) illustrates the test setup for the creep test. The distance between the bearing points was 1.100 m, and the distance from the bearing point to the measured and load point was 0.550 m. Creep deformation was measured with a jig and a caliper (Fig 5(b)).

RESULTS

Bending Test

The results of the bending tests are summarized in Table 4.

Creep Test

Results of the creep test are shown in Fig 6. The deflections were given as individual graphs for each sample in the group. For samples 1, 10, 11,

Table 4. Material properties based on the bending test and densities of the panels. Average values and standard deviation shown for each group.

Group	F_{max} (N)/standard deviation	Deflection at F_{max} (10^{-3} m)/standard deviation	F_{max}/deflection at F_{max} (N)/10^{-3} m)/standard deviation	E-modulus (10^9 Pa)/standard deviation	Bending strength (10^6 Pa)/standard deviation	Density (kg/m^3)/standard deviation
1	2734/447	27/2	100/11	1.79/0.27	5.96/0.97	265/4
2	2729/214	33/11	88/25	2.05/0.37	5.94/0.44	180/7
3	3923/585	27/6	149/32	3.12/0.27	9.41/1.38	218/9
4	4638/135	38/6	124/16	2.36/0.30	11.06/0.27	297/6
5	1476/102	33/0	45/3	4.82/1.20	3.71/0.26	165/4
6	2675/126	16/2	173/14	4.12/0.12	6.70/0.34	256/6
7	2301/22	25/2	92/5	5.26/0.63	5.78/0.07	204/3
8	3569/420	15/1	237/18	6.29/0.34	8.85/1.11	283/4
9	19,273/644	71/8	272/22	20.59/14.95	93.17/3.37	705/49

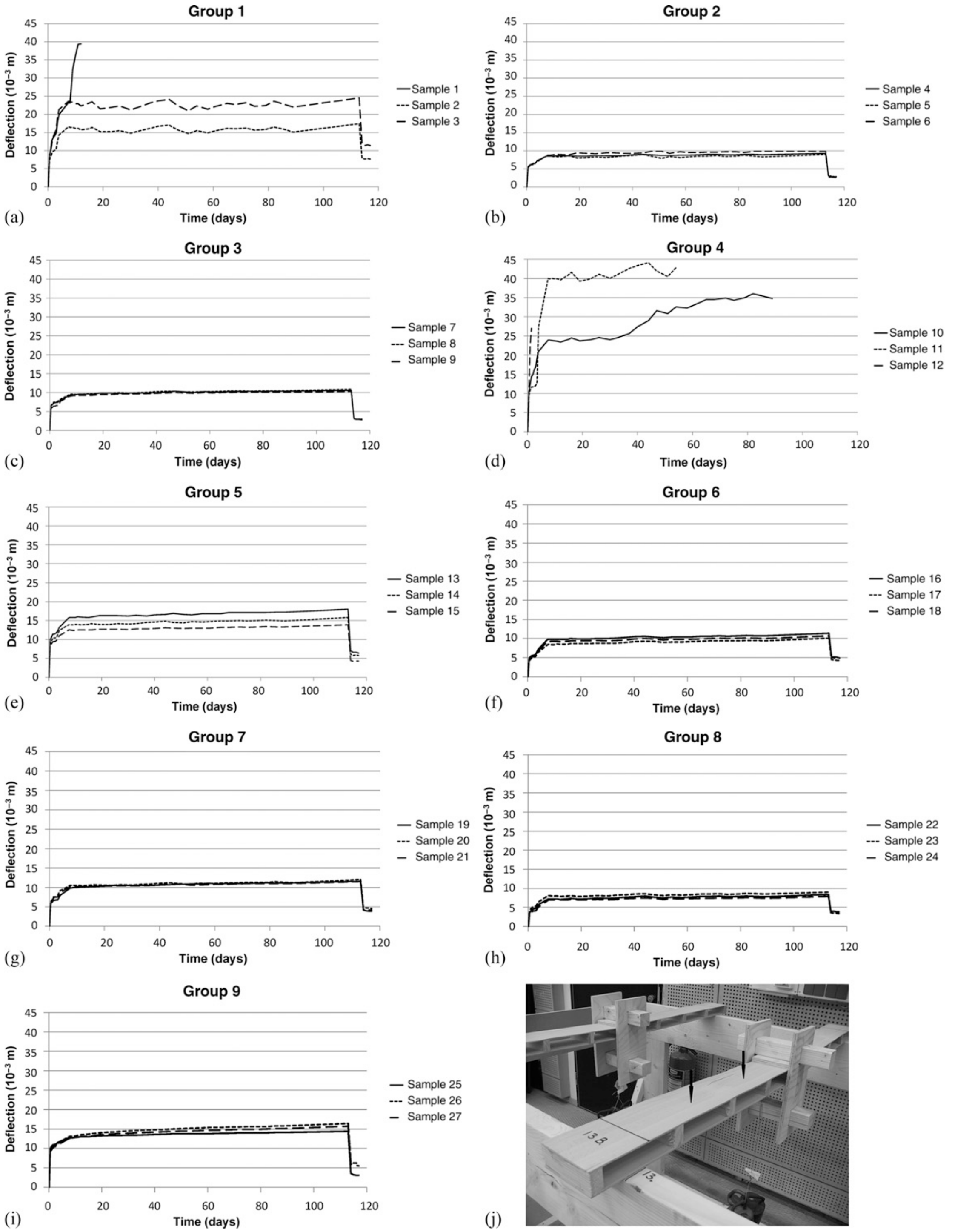


Figure 6. Overview of the creep deflection (a-i) and buckling of the surface sheet (j).

Table 5. Differences in the properties between samples of types (a) and (b). The comparison refers to samples with the same thickness of face sheets and distance between the struts. The values are presented in %.

Group	F_{max} (N)	Deflection at F_{max} (10^{-3} m)	F_{max}/deflection at F_{max} (N/10^{-3} m)	E-modulus (10^9 Pa)	Bending strength (10^6 Pa)
1	+2	+76	—	—	—
2	+85	+1	+84	—	+60
3	+71	+7	+59	+69	+63
4	+30	+153	—	—	+25
5	—	—	—	+135	—
6	—	—	+72	+130	+12
7	—	—	—	—	—
8	—	—	+95	+166	—

and 12, rupture occurred before the test was completed. For samples 13, 14, and 15, buckling between the struts occurred. The arrows in Fig 6(j) point to the buckled area.

DISCUSSION

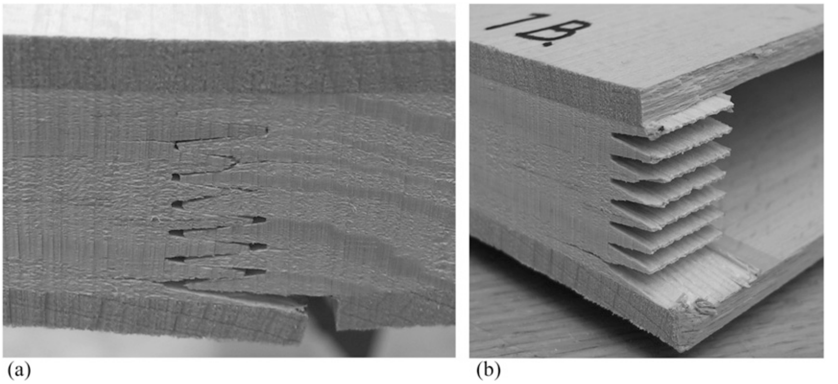
Bending Test

When the results of the bending tests (Table 4) are compared with the recommendations in the DIN EN 312:2010-12 standard for a 40×10^{-3} m thick particleboard, groups 1-8 of lightweight panels meet the requirements for E-modulus and groups 3, 4, and 8 for bending strength. This does not conclude whether the panels are good or bad; whether a panel is good or bad is determined by whether the panel fulfils the requirements for its intended use.

In Table 5, a comparison is made between the samples of types (a) and (b) with the same thickness of the face sheets and the same distance between the struts. The characteristics that were compared were F_{max}, deflection at F_{max}, E-modulus, and bending strength. The results are expressed as positive percentages. The results in Tables 4 and 5 show that the samples of type (b) both took more load and had larger deflections before rupture, compared with the samples of type (a) with the same thickness of face sheets and distance between the struts.

Creep Test

The reason for the early rupture of samples 1, 10, 11, and 12 was a lack of glue in the finger joints. Figure 7(a) shows the finger joints during the test for sample 1. Figure 7(b) shows the same finger joints after rupture. This type of failure cannot be seen with the naked eye before the sample is loaded. This shows the importance of all the



(a) (b)

Figure 7. Defects in gluing of the finger joint of a failed strut on sample 1. (a) Finger joint before rupture and (b) finger joint after rupture.

Table 6. Difference in creep between da 7 and da 113.

Group	Deformation at da 7 (10^{-3} m)/standard deviation	Deformation at da 113 (10^{-3} m)/standard deviation	Creep between da 7 and da 113 (10^{-3} m)/standard deviation
1	21.2/4.0	21.0/5.0 sample 1 failed	0.9/0.1 sample 1 failed
2	8.6/0.1	9.4/0.4	0.8/0.3
3	9.3/0.3	10.6/0.3	1.3/0.1
4	32.0/11.4	All failed	All failed
5	14.0/1.6	15.9/2.1	1.9/0.5
6	9.1/0.7	10.7/0.7	1.6/0.1
7	10.2/0.4	11.7/0.3	1.6/0.3
8	7.4/0.6	8.4/0.6	1.0/0.2
9	12.7/0.3	15.5/1.0	2.8/0.9

connections in a structure being made so that they meet the stipulated requirements.

If the primary creep is too large, this will often be noted at an early stage, and the load can be reduced. For practical application, the secondary stages of the creep are often the most interesting. In Table 6, the creep between da 7 and da 113 is compared between the groups.

The average of group 1 for da 113 is based only on two samples. This is why the deformation for this group is less for da 113 compared with that for da 7. The average value for samples of type (a) was 1.5×10^{-3} m; for samples of type (b), it was 1.0×10^{-3} m; and for group 9, it was 2.8×10^{-3} m.

What is perceived by the user is the total creep deformation (primary + secondary, and in some cases even the tertiary creep) at any time. Most ordinary private consumers do not know where they are on the creep curve when they identify creep deformation on, eg a book shelf. The total creep deformation (primary + secondary) for da 113 shows that the average value for samples of type (a) was 12.5×10^{-3} m; for samples of type (b), 13.6×10^{-3} m; and for group 9, 15.5×10^{-3} m. The remaining deformation after the load is removed can also be perceived as disturbing for the user. In Table 7, the remaining deformation for groups 1-9 is given; Table 7 shows that the remaining deformation amounts to some 30-45% of the total deformation. This, in turn, shows that the remaining deformation is large in relation to the elastic deformation.

Vierendeel girder is a name of a type of beam. The samples of type (a) are similar to these beams (Basha and Goel 1996; Zirakian and Showkati 2006; Alinia et al 2009). The buckling phenomenon in Fig 6(j) is typical for these beams when they are exposed to bending loads, as in this test. The buckling phenomenon decreased in this test as the thickness of the face sheet increased and the distance between the struts decreased. In this test, the buckling was only noticeable with the naked eye for samples in group 5.

The variations in RH during these tests, and the effect of the MS applied to the sample should be considered as small for the variation in MC on this type of panel (Nilsson et al 2017). The average RH during this test was 26.7%, the standard deviation 6.3, the average temperature 19.4°C, and the standard deviation 0.8. The indoor RH varies much more between summer and winter in this part of Sweden (Småland) than did the variation in RH during this test. So the creep deformation, which depends on the MS effect, would probably increase instead of decrease when considering the normal indoor use of furniture in the south of Sweden.

Table 7. Remaining deformation after unloading.

Group	Remaining deformation da 114 (10^{-3}m)/standard deviation	Remaining deformation (%) of the deformation from da 113 (10^{-3}m)/standard deviation
1	9.9/2.8	47/2.2
2	2.9/0.2	31/3.1
3	3.1/0.1	29.6/1.0
4	All failed	All failed
5	5.9/1.3	36.6/3.7
6	4.9/0.3	45.7/1.7
7	4.5/0.4	38.6/2.6
8	3.8/0.2	44.8/4.2
9	5.4/1.6	34.3/8.1

A very simplified fictitious specification requirement for a bookshelf could be length = 0.770 m, width = 0.300 m, maximum total deflection over a distance of 0.600 m = 1.1×10^{-3} m, and maximum load (widespread load) = 275 N. These values were measured on two identical bookshelves. A load of 275 N produced a creep deformation of 2.4×10^{-3} m over a distance of 0.600 m. This deformation was so large that it was perceived as disturbing. On the other bookshelf, the widespread load was 71.5 N and the deformation was 1.1×10^{-3} m over a length of 0.600 m. This deformation was not perceived, however, as disturbing. A load of 275 N is relevant for a bookshelf, but a load of 71.5 N is too little for a bookshelf of 0.600 m to be relevant. This example shows that the difference between acceptable and unacceptable deformation is in the range of about 1×10^{-3} m.

CONCLUSION

The results of the tests show that is possible to affect the physical properties such as density, E-modulus, bending strength, and resistance to creep deformation for this type of panel. This can be carried out by varying the thicknesses of the face sheets and/or varying the distances between the struts. The results show that many of the panels are the "best panel" in different respects. But the problem is that the panel that is best for one thing, eg resisting creep deformation, may not necessarily be the best for, say, load capacity. This means that it is the area of application that is crucial when finding the best panel for the purpose. The best panel is the panel that has the lowest density, the highest value for bending load, and the smallest creep deformation. A future work would be to build furniture where the various components are optimized to the specific application. If the optimization is properly done, it would mean a saving on materials, would lower weights, and reduce environmental impact.

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