BENDING BEHAVIOR OF GLULAM BEAMS REINFORCED WITH FLAX FIBER SHEETS

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ABSTRACT: The structural performance of timber beams in bending could be considerably improved if the behavior of the flexural tension face were enhanced. This paper reports on an experimental and analytical study on the structural behavior of full-scale beams made of glued laminated timber, reinforced with natural fiber sheets. Two 5m-span beams were strengthened with flax fiber sheets and tested to rupture, along with a non-reinforced reference specimen. Comparisons between analytical predictions and experimental results proved very satisfactory, although the latter were rather disappointing. The paper further discusses improvement options for the applied reinforcement concept, as well as other reinforcement applications for flax fiber sheets.

1. Introduction

Structural behavior of timber differs greatly whether it is submitted to tensile or compressive stresses. Under tension, timber generally shows a linear-elastic behavior up to a brittle fracture. On the other hand, timber usually exhibits a high plastic deformation capacity in compression. This phenomenon is intuitively understood by thinking of timber as relatively short, aligned fibers; when timber is in tension, the fibers tend to separate from each other, resulting in a brittle fracture. If the same fibers are compressed, they rather displace relatively towards each other, allowing substantial displacements and hence a more ductile behavior. This explains why the maximum load of timber beams under bending is usually attained by rupture at the tension face. Moreover, timber being a natural material containing flaws, such as knots, and fiber misalignments, its mechanical properties vary significantly. The tensile strength is especially affected by these flaws. For those reasons, strengthening the tension face of timber beams would allow a better exploitation of their loadbearing capacity.

Among other possible materials, flax fiber sheets are considered both interesting and appropriate as reinforcement. They have been commercially available recently and exhibit impressive mechanical properties. Furthermore, their softness allows reinforced beams to be sawn and planed without damaging the cutting tools. Finally, flax being a renewable resource, its use is considered more sustainable than that of other reinforcement materials, such as carbon fiber and steel. However, the structural behavior of timber beams reinforced with flax fiber sheets is a priori unknown. This was investigated in a preliminary analytical and experimental study on full-scale specimens.

2. Full-scale tests

Three 5.40m-long GL24 (glued laminated timber with a characteristic bending strength $f_{m,k}$ = 24 MPa) beams were submitted to a six-point bending test: one unreinforced beam (“ref”), one reinforced with two layers of flax fiber sheets (“+2”) and one reinforced with four layers of flax fiber sheets (“+4”). The reinforcement was inserted during the beams’ fabrication; flax fiber sheets of average thickness t = 0.2 mm per layer were laid on top of the bottom lamella before the glued boards were pressed according to usual standards of fabrication. Fig. 1 shows the reinforcement of the +4 beam. It was decided to place the reinforcement sheets above the bottom board (and not under it) for fire protection and aesthetics. The static system in the tests was a single-span beam submitted to four point loads applied at the fifths of the span. This six-point bending test produces a moment diagram approaching that

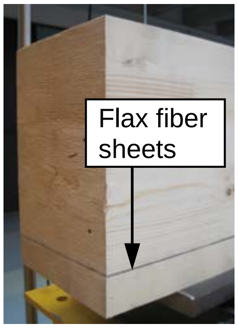

Fig. 1 – +4 beam

of a uniformly distributed load and a constant moment between the two inner point loads. The applied load was measured with the central jack, corresponding to the sum of the four point-loads. Deflections were measured by LVDTs (Linear Variation Differential Transformers) at mid-span and at the supports, on both side faces, for deriving net mid-span deflections. Furthermore, cross-sectional strains were measured at mid-span on both side faces. Fig. 2 illustrates the test set-up.

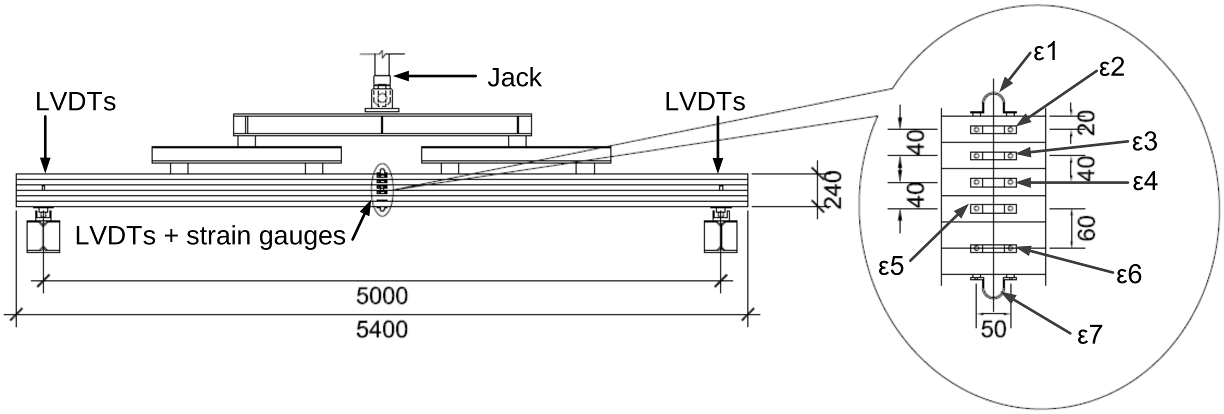

Fig. 2 Test set-up and measurements [mm].

Fig. 3 shows the global behavior of all specimens.

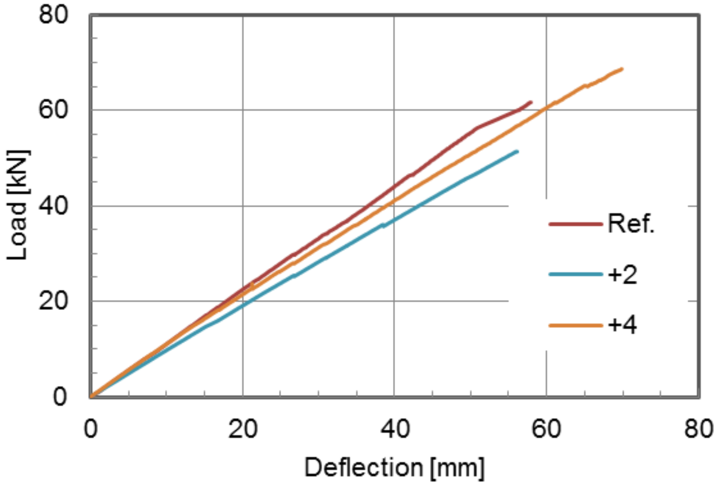

Fig. 3 - Global behavior of all specimens.

The results were overall disappointing. All specimens exhibited a linear-elastic behavior up to rupture. Both reinforced beams proved less rigid than the reference specimen. The +4 beam showed a slightly higher rupture load than the reference beam. The +2 specimen was of a particularly poor quality; its results were inferior to those of the reference specimen, both in terms of bending stiffness and bending strength. All three beams reached rupture by failure at the tension face.

Selected results for the serviceability limit state (SLS) and the ultimate limit state (ULS) are shown in Tables 1 and 2, respectively.

Table 1 - Test results at SLS

	***F* [kN]**			**Relative increase [-]**		
	corresponding to a deflection at mid-span of					
Specimen	***L*/500**	***L*/350**	***L*/300**	***L*/500**	***L*/350**	***L*/300**
Ref	11.1	16.0	18.7	-	-	-
+2	9.7	13.9	14.7	-12.0%	-13.2%	-21.6%
+4	11.1	15.5	18.1	0.2%	-2.8%	-3.5%

The necessary loads to attain the standard values of deflections at SLS were between 12% and 22% lower for the +2 beam than for the ref. specimen. The +4 beam showed approx. the same performance as the ref. specimen at SLS.

Table 2 – Test results at rupture (ULS)

Specimen	F_u [kN]	Relative increase [-]	w_u [mm]	Relative increase [-]
Ref	61.7	-	57.9	-
+2	51.4	-16.7%	56.1	-3.1%
+4	68.7	11.3%	69.9	20.7%

The rupture load of the +4 beam was approx. 11% higher than that of the ref. specimen. The poor quality of the +2 beam was also visible at ULS, with a rupture load approx. 17% lower than for the ref. specimen.

3. Comparison to analytical results

Test results were compared to analytical findings. The constitutive law used in this context corresponds to a model proposed by Buchanan (1990), Fig. 4. According to this model, timber exhibits a linear-elastic behavior in tension. A brittle rupture occurs at tensile strength f_t. In compression, timber shows a bilinear behavior; once the maximum compressive stress f_c is reached, linear strain-softening, i.e. linear decreasing stress with increasing strain, is assumed. The estimated value of the maximum compressive stress considered in this study is f_c = -35.0 MPa, corresponding to a strain of about 3‰ (Brunner 2000). The softening branch has a slope *mE*, *m* being a ratio of the Young's modulus (Buchanan 1990). As suggested in Buchanan (1990), m = 0.02 was used in this study.

Young's modulus *E* and flexural tensile strength f_{tm} were recalibrated for each specimen considering the test results. Material stiffness *E* was derived from the bending stiffness *EI* that is necessary to attain the measured deflection at a load level of 0.4 F_u. Values of E = 12.7/10.9/12.0 GPa were obtained for the specimens ref/+2/+4, respectively. Equalling the bending resistance calculated according to Thunell and calculated elastically allows the determination of f_{tm}, as described in Brunner (2000). Values of f_{tm} = 31.6/27.1/34.6 MPa were obtained for the specimens ref/+2/+4, respectively.

Results of tension tests on flax fiber composites allowed the establishment of a bilinear constitutive law, considering equivalent deformation energy of test results and the analytical stress-strain curve (Fig. 5).

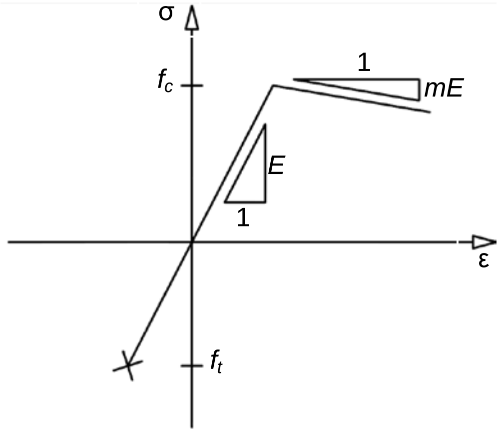

Fig. 4 - Constitutive law for timber

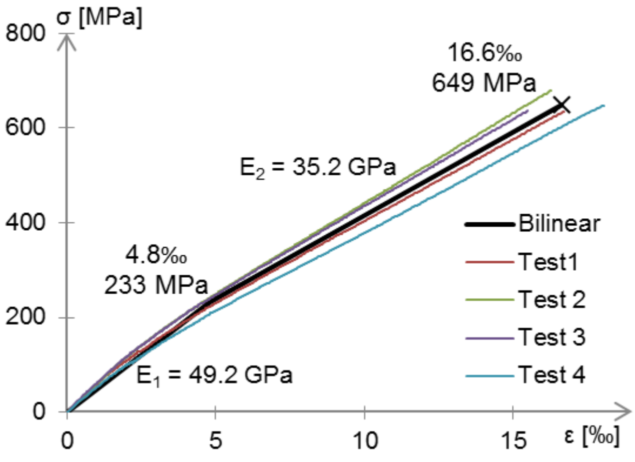

Fig. 5 - Constitutive law for flax fibers

Cross-section analysis was conducted with the help of spreadsheets considering the constitutive laws shown above, the recalibrated values of *E* and f_{tm}, Bernoulli's hypothesis of plane sections remaining plane, and assuming rigid bond between timber lamellas and flax fiber sheets. Moment-curvature relationships were established for each test specimen, and were further used to calculate the global deformation behavior (load-deflection curves) using Mohr's analogy. For reinforced beams, it was assumed that a reduced cross-section would withstand further displacement increase, after the rupture of the outermost lamella. Successive ruptures of the remaining bottom lamellas would finally lead to the reinforcement reaching its tensile strength and the global failure of the system. These behavior predictions were established considering a displacement-controlled bending test.

Experimental and analytical moment-curvature and load-deflection curves for the reference beam are shown in Figs. 6 and 7. Figs. 8 to 11 show the same results for the strengthened specimens.

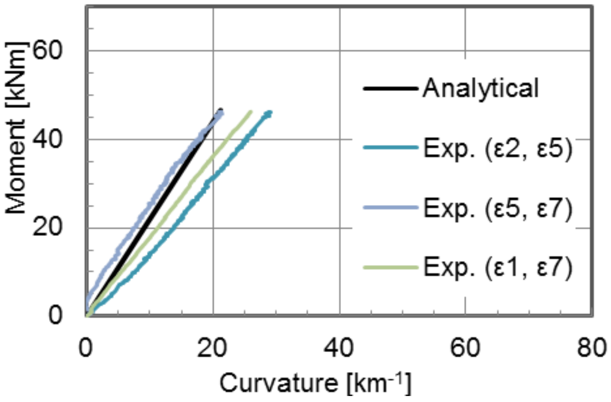

Fig. 6 Moment-curvature, reference beam.

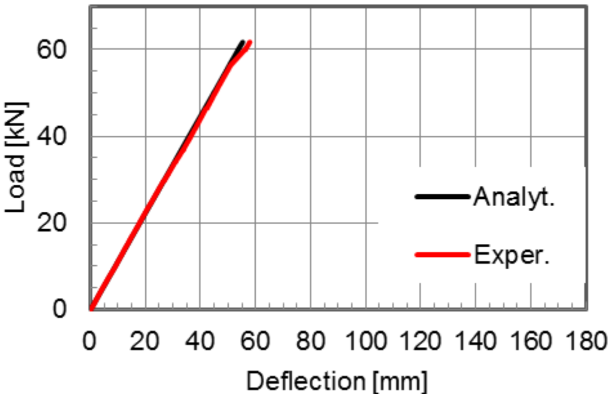

Fig. 7 Load-deflection, reference beam.

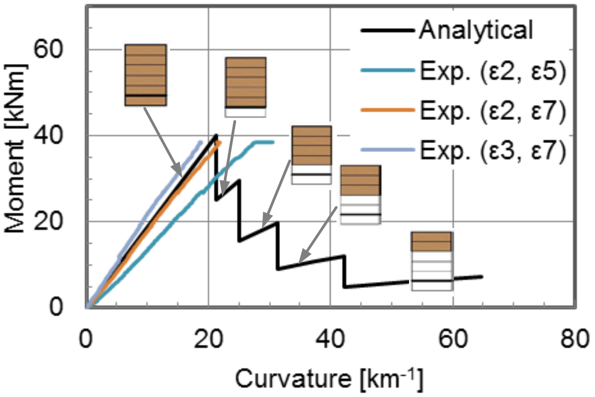

Fig.8 – Moment-curvature, +2 beam

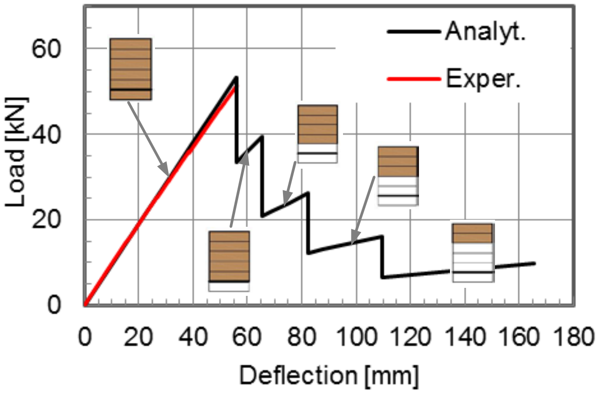

Fig.9 – Load-deflection, +2 beam

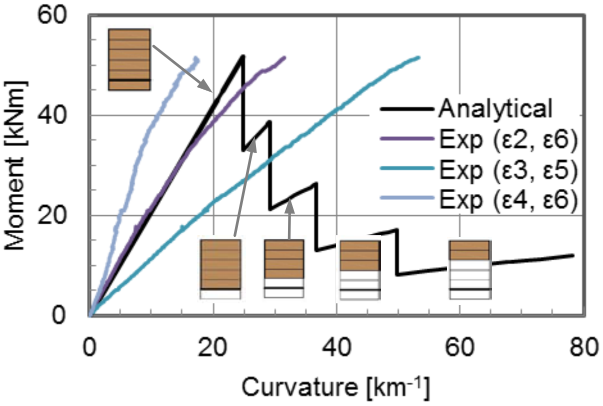

Fig.10 – Moment-curvature, +4 beam

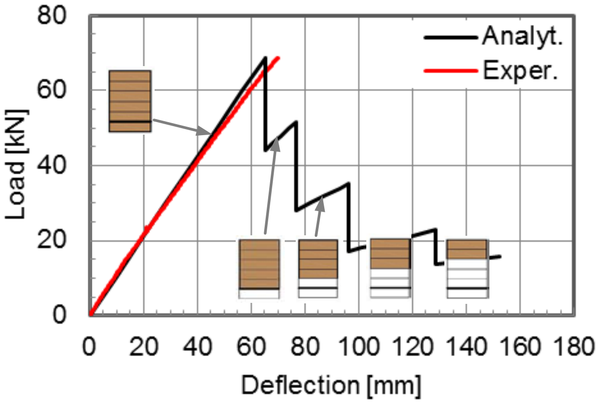

Fig.11 – Load-deflection, +4 beam

For all specimens, the sectional behavior can be reproduced satisfactorily only. However, global behavior is excellently reproduced. The elastic energy liberated at rupture of the outermost timber lamella cut the flax fiber sheets, preventing the tests to go on with a reduced cross-section, as established analytically. The experimental load-deflection curve of specimen +4 tends to flatten at approximately 85% of the maximum load. Calculations show that the compressive stress in the upper fiber at mid-span at failure was approx. -35.0 MPa; thus, plastic deformations were starting to take place when the beam failed at the tension side. Again, weakness of timber at the flexural tension face prevents exploitation of its compressive deformation capacity.

4. Improvement options

With regard to the rather disappointing experimental results, analytical evaluations were carried out to quantify the reinforcement needed to obtain substantial improvements of the reinforced systems, in terms of thickness t and Young's modulus E of the reinforcement.

4.1. Performance of a higher nominal strength class

One of the evaluations consisted in reaching the performance of a higher nominal timber strength class (GL28) with a GL24 reinforced beam, considering timber behavior of Fig. 4 and using the values listed in Table 3. Values of f_{tm} in Table 3 were estimated from the relation f_{tm} = 1.63 $f_{m,k}$. Values of f_c were estimated at -35.0 MPa for both strength classes.

Table 3 – Properties for GL24 and GL28 strength classes.

	E [GPa] acc. to SIA 265 (2012)	f_{tm} [MPa]	f_c [MPa]
GL24	11.0	39.0	-35.0
GL28	12.0	45.6	-35.0

The analysis was conducted considering two different reinforcement materials – a flax fiber composite material and carbon fiber reinforced polymers (CFRP). Although CFRP was not deemed an appropriate reinforcement material in this study due to machinability and sustainability reasons, its use was nevertheless analysed to allow comparisons between flax fibers and an approved strengthening material. CFRP, being a composite material itself, has to be compared to flax as a composite material (and not as fibers only). The flax-based composite material consists of the fibers described in Fig. 5 in an epoxy matrix. The composite exhibits a Young's modulus of 32 GPa.

Table 4 - Reinforcement thickness to obtain the performance of a higher nominal timber class.

Reinforcement	E [GPa]	$t_{nec.}$ [mm]
Flax fiber composite	32.0	**6.2**
CFRP	165	**1.4**

Table 4 shows the necessary thickness $t_{nec.}$ to obtain the performance of an unreinforced GL28 cross-section of the same dimensions as that of the tested beams, both in terms of bending strength and stiffness. Due to its relative softness, a substantial thickness of flax fiber composite is needed. CFRP is much more efficient, strictly structurally speaking, thanks to its considerably higher stiffness.

4.2. Minimum reinforcement

Necessary minimum reinforcement was also analysed: how thick should the flax fiber sheets be to prevent rupture when the inferior timber lamella breaks? The thickness of the reinforcement was varied until the reduced cross-section (i.e. after rupture of the bottom lamella) was able to resist a bending moment equal to the one that led to rupture of the outermost timber lamella. This analysis was carried out for a timber strength class GL24, Table 3. The reinforcement consists of flax fiber sheets, Fig. 5. Fig. 12 illustrates the result of the cross-sectional analysis.

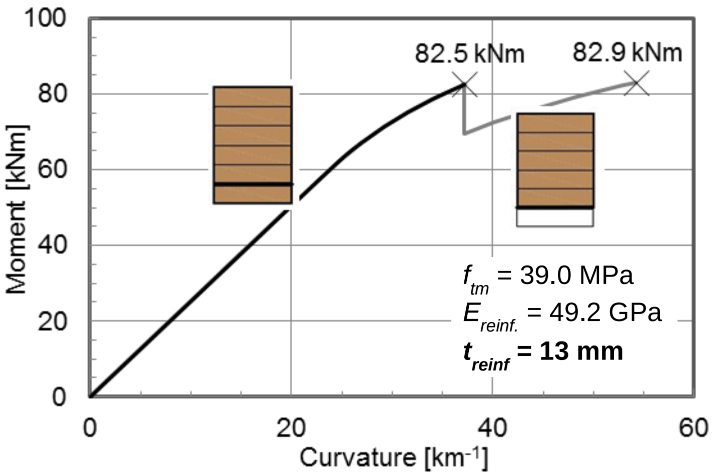

Fig. 12 – Moment-curvature diagram illustrating the minimum reinforcement.

The full section (160/240 mm) withstands a bending moment of 82.5 kNm when the inferior timber lamella breaks. A flax fiber sheet with a thickness of approx. 13 mm is needed so that the reduced cross-section (160/200 mm) can resist the same bending moment. This corresponds to a geometrical reinforcement ratio of 5.4% (ρ=13 mm/240 mm). This has to be considered a strictly minimum value, as the second lowest lamella in turn reaches f_{tm} when M = 82.9 kNm.

5. Conclusions and outlook

The very small thicknesses of flax fiber sheets available for this study (e.g. 4x0.2 mm = 0.8 mm for the +4 beam) result in an almost negligible contribution to the beams' bending strength. This is also due to the fact that flax is not rigid enough in relation to its tensile strength to be considerably exploited: at rupture, the tensile stress in the reinforcement is less than 20% of its tensile strength. Flax's ultimate strain being approx. five times higher than that of timber, it is not the ideal material to be associated with timber. Other materials may be analysed in further studies; nettle, for example, has a Young's modulus of 87 GPa and a tensile strength of 1'500 MPa, Baley and Bodros (2008). Commercially available nettle fiber sheets yet have to be developed. Pre-tensioning the flax fiber sheets is another improvement possibility, as the reinforcement would be activated at an earlier stage of loading history. Other applications of flax fiber sheets may nevertheless be interesting: their use in combination with materials subject to high strain localization (e.g. masonry, reinforced concrete) would allow a better exploitation of their properties, the reinforcement being activated as the cracks develop.

6. Acknowledgements

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