Tensile proof loading to assure quality of finger-jointed structural timber

Katzengruber, R.[1], Jeitler, G.[2], Brandner, R.[3], Schickhofer, G.[4]
Research Assistent[1,2,3], Professor[4]
Institute for Timber Engineering and Wood Technology, Graz University of Technology[1,4]
holz.bau forschungs gmbh[2,3]
Graz, Austria, Europe

Summary

The presented test method reflects how a quality assuring measure can be applied for finger jointed structural timber by integrating a tensile proof loading device in the production process. Thereby every produced rod or beam is clamped on both ends over profiled steel plates and subjected to a defined tensile loading in terms of duration and stress level. With this method, depending on the set proof level, greatly strength reducing timber features such as the global and local grain deviation, faulty finger joints, compression failures or reaction-wood are recognised by failure and can be rejected. The results of experimental research work on a high number of specimens (4,886 #) show clearly, that there is no appreciable damage to surviving timber due to tensile proof loading at low load levels. Within a double proof loading procedure 99,96 % of all specimens could sustain higher stresses than at the first time, indicating not being damaged. Tests and simulations based on the weakest link theory to determine the length effect regarding the tensile strength distribution of sawn timber resulted in $k_{\text{length}} = 0.17$, which is valuable for design purposes.

1. Introduction / Problem / Motivation

Timber as a natural growing raw material displays large variations in its mechanical characteristics like strength and stiffness in comparison to other materials such as e.g. steel. These variations can be considerable precisely with the beam-shaped product structural timber, characterised by lack of homogenisation over the cross-section through gluing of individual components. A statistical 'system effect' which can be considered for gluelam or bi- or trilam is not present for single sections. With the currently common grading processes strength reducing defects such as the global and local grain deviation, compression failures, reaction wood, pre-broken timber or damage of tree-top are only with difficulty and often not economically ascertainable. Rogues in the lowest quantile area of strength can not be excluded for sure. The grading process within the production of structural timber is therefore still a challenge.

Even so performance and minimum production requirements for finger joints are regulated in standards like e.g. EN 385 [1] a similar difficulty comes up with the joining. This is because for internal and external quality control only the bending strength and mode of failure of few randomly taken finger joint samples are determined in destructive tests. This also results in the fact that structural timber with features responsible for poor finger joint strength can reach the customers.

2. State of the Art

2.1 Grading of structural timber

In the German speaking area the most common grading method for structural timber is done by visual inspection according to DIN 4074 [2]. The structural timber is mostly graded to class S10 which is assigned strength grade C24 pursuant to EN 338 [3]. The grading criterions most commonly used are knottiness, cracks, deformations, annual ring width, wane and discolouration. For the product KVH® *(Konstruktionsvollholz)* additional more strict requirements like the moisture content ($u_m = 15 \pm 3\%$), sawing pattern (pith separated), the dimensional stability (± 1 mm for cross-sections ≤ 100 mm, ± 1.5 mm for cross-sections > 100 mm) and visual appearance (seasoning cracks, knottiness, discolorations, warping, surface quality, wane) are to be obtained. The requirements for KVH® differentiate between applications in visible and non-visible areas.
Stress grading of structural timber by means of bending machines, which determine average Modulus of Elasticity *(MOE)* over short lengths, are due to the limited operating range restricted to the grading of glulam laminations and scaffold boards with a maximum thickness of 75 mm. By use of X-ray radiation and vibration measurements (eigenfrequency) joists and beams up to 100 mm can be graded [4]. The preferred cross sections (width ≤ 140 mm, thickness ≤ 240 mm) used for KVH® production go beyond the capabilities of approved grading machines.

2.2 Proof loading

Proof loading is not a new development in the timber construction sector, it is rather already familiar for many years, primarily from North America and Australia and also embedded in manuals [5] and standards [6]. Whereas in Europe apart from those stress grading machines mentioned in 2.1 which in principal do a proof loading of the material in bending the authors know of no approved industrial proof loading application for structural timber. Test methods working with tensile loads are still uncommon obviously due to the difficulties of applying the loads.
Commonly spoken, *'proof loading'* as testing method is defined by specimens which are subjected to a defined and generally brief mechanical loading. All samples not reaching a set proof level due to premature material failure can be separated from those with greater strength. Proof loading is a recognized quality control technique to improve the characteristics of the lower tail of strength distribution. Numerous scientific research works on the topic and especially in respect of possibly damaging the material have been published since the late sixties of the last century. Proof of any possible damage is generally considered to be very difficult to impossible. Strickler et al. (1969) for example investigated in [7] proof loaded finger joints and concluded that a bending proof load up to 90 % of the expected ultimate strength did not significantly reduce the strength and by comparison, a tensile proof load was considered feasible, without qualification.
Woeste et al. (1987) conducted in [8] experiments on 1,200 pieces of lumber with single and reverse bending loads and detected no damage due to proof loading. Heatwole et al (1991), come in their literary research on damage [9] to the following statement: *'Based on published research it is valid to assume there is no appreciable damage to surviving lumber due to proof loading in tension or bending at these low load levels'*. Lam et al. (2003) pointed out in [10] that one of the difficulties is the need of rather large sample sizes for an experimental-based study to develop statistically solutions to quantify the effectiveness on the use of proof loading in relation to the proof level, the potential damage on the members and the improvement of performance in the context of reliability based design methods.

3. Tensile proof loading / Development of a testing device

The target definition of the research project 'qm_online' was the development of a quality control method to assure high product performance of finger jointed structural timber especially in respect to strength characteristics. In particular the following aspects should be fulfilled:

- Every produced piece and thereby the whole volume of the material should be tested.
- No dents are to be remain on the surface and damage is allowed.
- Testing has to be integrated in the production process and must not reduce production output.
- Information valuable for design purposes - like strength and stiffness - should be available.

The approach to comply with all defined aspects was tensile proof loading at a high production level. Because loading in bending is difficult to achieve with cross sections typical for structural timber and has disadvantages when stress reducing failures have to be detected in the compression zone, loading in tension was selected. Further this gives in contrast to bending a constant stress distribution over the entire timber volume within the free test length.

For development of an appropriate device for the 'Holzindustrie Leitinger GmbH' (Austria) research was carried out in respect of determination of the most significant mechanical parameters of the testing device (maximum tensile force, clamping plate geometry and surface structure, capacity of the machine and measuring technique) and to determine the time dependant strength of the adhesive used for the finger joints [11]. The 8 to 18 m long rods are individually loaded into the transverse conveyor of the proof loading device at least two hours after the finger jointing process. Tensile tests on jointed structural timber for determining finger joint time-strength relation showed that using the PU adhesive Purbond® HB 530 finger joint strengths already existed within the variance of the end strengths determined on fully cured joints after 90 minutes. A curing time of 120 minutes for the PU adhesive was determined as sufficient for the application of a proof level of 8 N/mm² up to 10 N/mm² without damage of the finger joint.

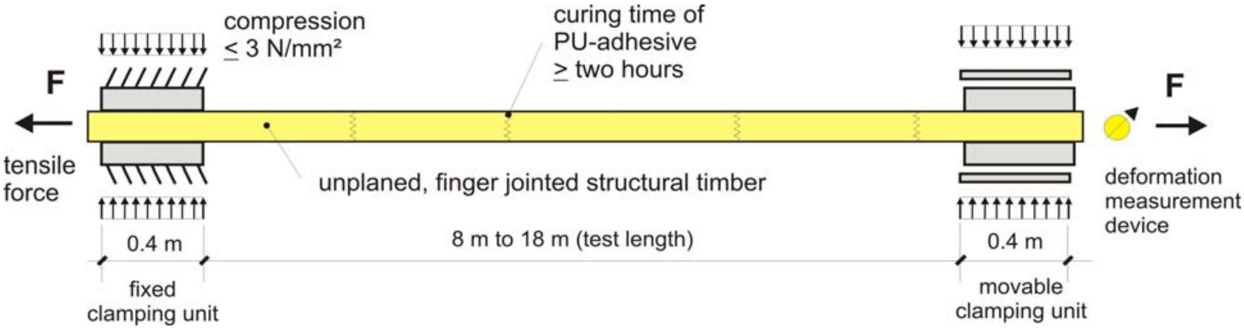
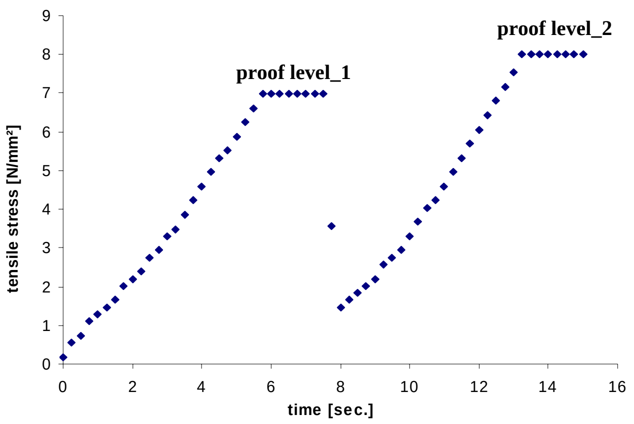


Fig. 1: System sketch of the tensile proof loading device for industrial application

Within the proof loading process a centering device puts each beam into a defined test position. The beam ends are then clamped with profiled steel plates over a length of 400 mm and the corresponding section width. The structural timber is so subjected to a defined stress in terms of duration and load factor. During the stress test the proof load and associated deformations are continuously recorded, whereby the mean MOE over the full length up to 18 m can be determined. Rejection parameters of the control program can be sudden drops of the tensile force, too great deflections or when the set proof level is not reached in a certain time. Only those rods running through the test without fraction or error in the control program are fed to the following profiling process. The device as shown in figure 1 demonstrates that up to 5 rods per minute can be tested within an industrial environment. Adjustment to the length of the structural timbers to be tested is provided by the lengthways continuously movable clamping unit.

4. Tensile proof loading / Experience

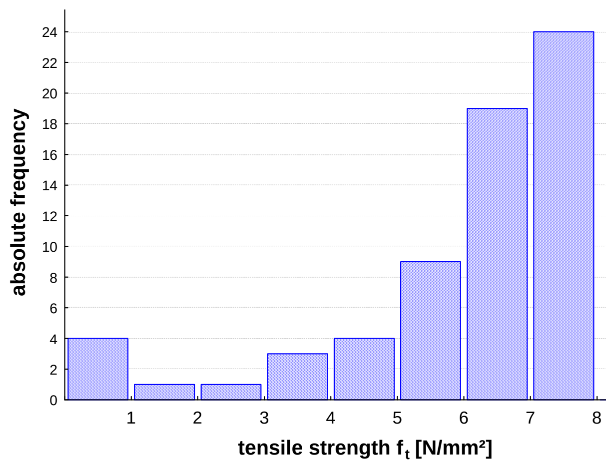
Within a special observation period 4,886 (!) rods with a mean free span of approximately 12.9 m were produced and all mechanically tested using the device as described in figure 1. The tested volume equals approximately to one thousand cubic meter of structural timber and around 30,000 finger joints were tensile proof loaded. Transposed onto the referred test piece length, acc. to EN 408 [12] of nine times the larger cross-sectional dimension, this would roughly equal to 39,000 tests with a free span of 1.6 m. The timber (spruce and pine) with various cross sections (65 mm < width < 125 mm, 105 mm < height < 285 mm) was graded acc. DIN 4074 [2] to class S10 by means of visual inspection and an X-ray scanner. The finger joints, fulfilling the requirements acc. to EN 385 [1], were characterized by a finger length of 20 mm and a distance between fingers of 5 mm. Especially to clarify the risk of eventually damaging the material within tensile proof loading a double stressing of the material was applied so that it comes to a repetition of the loading.



As illustrated in figure 2 first a proof level of 7 N/mm² and after a short relieve a proof level of 8 N/mm² was set. The speed of loading was, depending on the actual cross section, in the range of 10 to 60 kN/s and the proof levels were hold for at least 1.5 seconds. Within the total time of loading of about 15 seconds data (time, tensile force, extension of end grain) was recorded automatically at a rate of 4 Hz.

Fig 2: Tensile proof loading with two different proof levels to evaluate the risk of damaging the material

In total 65 rods (out of 4,886 #) failed within the double stress test due to fracture of the material or the joints. 37 rods failed before stress was relieved the first time (≤ 7 N/mm²) and 28 rods within the second proof loading step (≤ 8 N/mm²). Only 2 of those rods which failed within the second step failed on a level below proof level_1 thus indicating having been damaged. The extent of damage expressed as loss of strength was in the range of 9 to 12 %.



The frequency distribution of tensile strength of all broken specimens is shown in figure 3. Conspicuous is that near zero an accumulation is observed. This is because the specimens with nearly 'no strength' are related to faults of finger joints due to deficiencies in joint production. The rest of the lower tail of strength distribution shows the expected characteristic of rampant increase of failures with increased tensile strength.

Fig. 3: Frequency distribution of tensile strength of failed specimens within the double tensile proof loading procedure at 7 N/mm² and 8 N/mm²

The dominant cause of failure within the lower tail of strength distribution was as shown in figure 4 **failure of the wood** at 70.9 %. The failure analysis further shows that not the finger joints rather the local grain deviation often associated with the surrounding area of knots, knot clusters or a broken tree-top is thereby the main cause of failure. It has to be noticed that many of the failure causing features could have been only detectable with difficulty and apparently not with the employed grading procedure. This was confirmed by close examination of the broken pieces in respect to the grading criterions. Hence the associated grading represents the limiting factor for structural timber from this production.

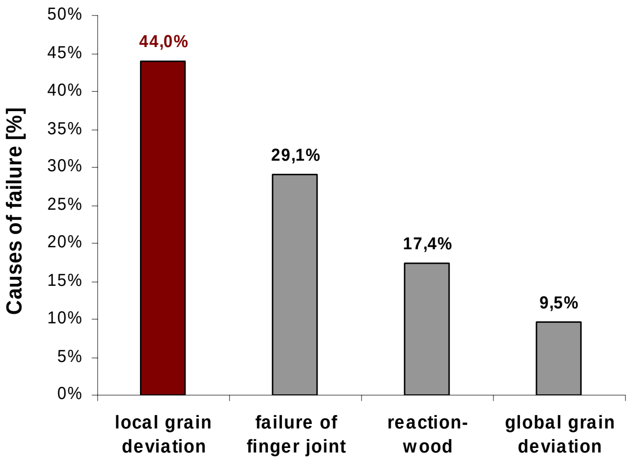


Fig. 4: Percentage distribution of causes of failure due to tensile proof loading

The following figures show some typical examples of severe timber defects which could be detected by means of tensile proof loading. Figure 5 shows an extreme local grain deviation caused by a broken tree top responsible for low tensile strength. It was also observed that not only one defect causes the failure, rather as illustrated in figure 6, it is a combination.

Fig. 5: Low tensile strength due to local grain deviation caused by a broken tree-top (Spec.Nr.827)

Fig. 6: Tensile strength = 5,77 N/mm² due to reaction-wood and global grain deviation (Spec.Nr.1333)

Compression damages are due to deformations of the wood fibres resulting from excessive compression shakes along the grain. They may develop in standing trees due to high loads from storm or snow. They also may result from stresses imposed by lumbering or inadequate handling. As shown in figure 7 they are very difficult to detect on planed surfaces. Because the distorted fibres lead to brittle fracture in processed timber already at relatively low stresses, compression damages can be detected with a tensile proof loading procedure.

Fig. 7: Tensile strength = 6,37 N/mm² due to compression damage of the timber (Spec.Nr.1349)

5. Considerations about testing length and determination of k_{length}

The length effect (k_{length}) in wood is characterised by reduced scatter and decreased strength characteristics with increasing length. General k_{length} in tension can be described by the 'weakest link theory' of Weibull, 1939 [13]. Based on a data set of 219 # beams for KVH® production, $l/b/h$ = 2500/200/60 mm, tested in tension parallel to grain, a simulation was carried out and the influence of testing length on the 5 % quantil of tensile strength was examined. First emphasis was taken on determining the best fitted statistical model for the given tensile strength values. Second, based on random numbers transformed according the gained model, k_{length} was simulated by a repetitive virtual arrangement of linked beams, respective tensile strength, and taken the minimum as probable test result. The generated data sets formed the basis in defining the k_{length} as power function acc. to Weibull. The first results are given in figure 8 and further results will be published.

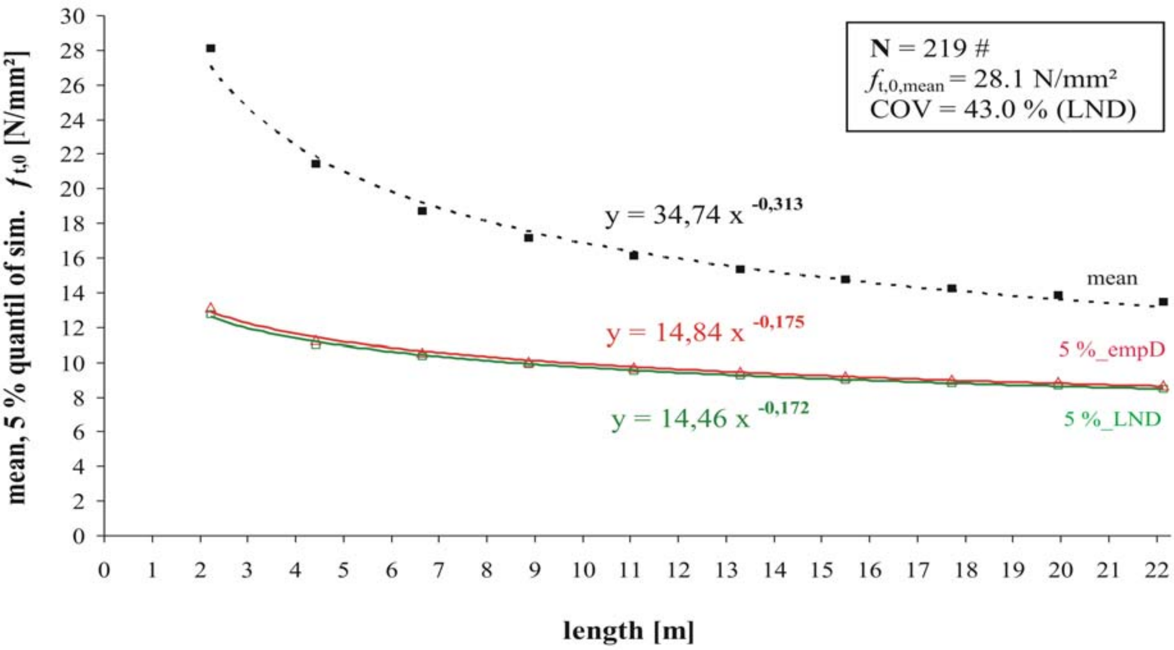


Fig. 8: Results of simulated length effect, based on test results of beams b/h = 60/200 mm

The functions represent the changed mean and 5 % quantils of *tensile strength*, determined by empirical way and based on assumption of logarithmic normal distributed values, which was found to represent best the given data set. A k_{length} = 0.17, based on a coefficient of variation *(COV)* of 43 % and spruce (*picea Abies*) in tension seems to be applicable at the level of 5 % of tensile strength.

But nevertheless the effects in length are important for design purposes, but have no influence on the effect of proof loading, based on the fact, that the failure strength level of certain weak sections always stay constant. Consequently the k_{length} results of increased probability of weak sections with increased length.

6. Discussion and Conclusions

The carried out double stress tests, as described in point 4, confirm that a low tensile stress not leading to failure, only minimally affects the strength of structural timber. The evidence that the material is not significantly damaged is herewith clearly adduced. The number of tested specimens (4,886 #) in relation to the number of faults with slightly reduced strength characteristics (2 #) after the first stressing seems to be sufficient to confirm that statement. The conclusion therefore clearly is that it is better to have tensile proof loaded timber than the risk of ‘rogues’ with poor strength characteristics. Further there should not be any doubt of stressing timber up to the level of design strength which is specified for grade C24 with $f_{t,0,d} = f_{t,0,k} / \gamma_m * k_{mod} = 14 / 1.3 * 1.1 = 11.8$ N/mm², assuming an instantaneous load duration.

In consideration of the fact that grading of timber still has inaccuracies and deficiencies in the joining processes can occur the use of a tensile proof loading device as described is today the best way to safely ensure that structural timber with features responsible for poor tensile strength do not reach the customers. In connection with the failure modes from the test operation and the associated ‘learning effect’, the proof loading method further represents a significant possibility of systematically improving grading within the production process, whether visual or mechanical.

Overall, a timber product with a more reliable minimum strength should be made available to the construction industry through the presented tensile proof loading method as every piece in the lower area of the strength distribution is rejected. The increased reliability for proof loaded finger jointed structural timber could also be reflected in a more favourable partial-coefficient. The corresponding quantification in dependency of the proof level and coefficient of variation of the base material is part of further investigations in cooperation with G.I. Schuëller (Institute of Engineering Mechanics, Leopold-Franzens University, Innsbruck, Austria).

A further area of application of the test method presented here and implanted on an industrial level exists for other sawn timber products in the branch. Gluelam production is particularly considered here. It is so conceivable to also implement the presented proof loading method in an adapted form for the online quality assurance of finger jointed single lamellas. Furthermore application of the method for testing finger jointed flange sections of I-profiles and nail plate binders is considered sound.

7. Acknowledgements

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