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Experimental Study to Determine the Development of Axial Stiffness of Wood Screws with Increasing Load Cycles

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Abstract: 123 withdrawal tests were conducted to investigate the change in axial stiffness of fully threaded screws under axial loading and up to four loading cycles. The screws were initially loaded in two cycles within the elastic range, followed by two cycles up to 90% of the characteristic load-carrying capacity. Several parameters relevant to construction practice were varied. The angle between the screw axis and the grain ranged from 30° to 90°, the timber material was varied between glued laminated timber (glulam) and laminated veneer lumber (LVL) made of beech, and the screw diameter ranged from 8 mm to 12 mm. The test results indicate that axial stiffness increases upon reloading compared to the initial loading. On average, axial stiffness increases by 11% between the first and second loading and remains at this level during unloading and further load cycles. However, if the load exceeds the linear–elastic range, the axial stiffness is reduced due to plastic deformation. A comparison with tests on the composite axial stiffness of fully threaded screws in glulam shows that even with a different test setup and testing objective, there is a slight increase in axial stiffness from the first to the second load cycle in the range of 4 to 8%.

Keywords: timber engineering; self-tapping screws; axial stiffness; withdrawal tests; cyclic loading

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1. Introduction and State of Knowledge

As shown by Ringhofer [1], self-tapping axially loaded screws can provide high load-carrying capacity and stiff connections. However, the load-bearing behaviour of such connections differs fundamentally from connections with laterally loaded, dowel-type fasteners [2], which generally behave more ductile. In connections with inclined screws, the axial stiffness of the screws is crucial to achieving a competitive and material-compatible design of the connection. It is therefore key to know the mechanical behaviour of these connections under changing load conditions. The stiffness of screwed connections has, to the knowledge of the authors, only been considered under initial load or with a maximum of one load cycle. This hardly allows statements about the long-term development of the stiffness of screwed connections. The objective of this study is to investigate the effect of alternating loads on the stiffness of axially loaded screws. Relevant influencing factors are included in the form of a parameter study.

In past investigations, the axial stiffness of fully and partially threaded self-tapping screws was tested using various experimental setups. Bejkta and Blaß [3] conducted initial investigations, followed by comparative tests in withdrawal, compression shear, and diagonal shear by Blaß and Steige [4]. Tomasi et al. [5] also used a shear load test setup in investigations on load-carrying capacity and stiffness of axially loaded screws. Brandner and Ringhofer also carried out a large number of withdrawal tests in various hardwoods [6] and CLT [7]. Later studies revealed that deformations and stiffnesses are greatly affected by the test setup. Azinovic and Frese [8] conducted numerical analysis on diagonal shear tests with crosswise screw arrangement. It was shown that friction between the components has a significant impact. De Santis and Fragiacomo [9] and also

Girhammar et al. [10] provide a summary of test results from different investigations on axial stiffness. Ringhofer et al. also added combinations of axial and lateral loading [11]. The latest overview comes from Hu et al. [12], who compared experimental tests and FE-models of withdrawal tests. As Blaß and Steige [4] showed, it is evident that the test results vary significantly in some cases, making it challenging to calculate the corresponding axial stiffnesses. This variation is partly due to the different test setups such as tension tests, compression tests, shear tests under tension or compression, and varying number of screws. The determined deformations are generally very small. Therefore, it is crucial to determine the relative deformations at the correct location on the test specimen. Local compression stresses perpendicular to the grain and resulting indentations can significantly increase the measured deformations, which reduces the calculated axial stiffness. Additionally, contact and friction between components can reduce the load transmitted by screws, which leads to an increase in the calculated axial stiffness.

2. Research Objectives

The effect of pre-loading and cyclic loading on the axial stiffness of fasteners have so far not been studied in-depth. Such an effect is particularly relevant in roof structures subjected to seasonal snow loads or in roofs and exterior walls under wind load. While cyclic investigations are widely published for radially loaded, dowel-type fasteners in connection with ductility investigations or energy dissipation in the event of an earthquake, as presented by Piazza et al. [13], there has been little consideration of the previously mentioned aspect. Consequently, there are very few studies on the development of axial stiffness of screws under multiple loading and unloading cycles. Regarding the reinforcement of glulam with fully threaded screws, Dietsch [14] conducted some exploratory investigations. The objectives of the experiments presented in the following section were to investigate cyclic load–deformation behaviour of axially loaded screws. In roof structures, in particular, inclined screws subjected to tensile loads are increasingly used. Often, the deflection (SLS) is decisive for the design of these components. Roof structures, in particular, are subject to various short-term (e.g., wind) and long-term (seasonal) load cycles. Reduced stiffness in the connections could lead to larger deflections than predicted in design. In addition to the general component behaviour, various parameters relevant in building practice should be examined with respect to their influence on the research question. These parameters include wood material, screw diameter, pre-drilling, and the load level.

3. Experimental Investigation

The investigation focused on the axial stiffness of the threaded part of a screw rather than the entire system. To achieve this, a simple test setup was chosen, consisting of withdrawal tests with two LVDTs placed in the exposed threaded part between the screw head and the timber.

3.1. Material

The evaluation included 119 out of 123 withdrawal tests conducted in 11 series. The study investigated the abovementioned effects under the variation of timber product (GLT from spruce (*Picea albies*) and beech-LVL (*Fagus sylvatica*), as shown in Figure 1. GLT from spruce was used because it is the most common timber product in Europe. Beech-LVL was used because of its high homogeneity. The intention was to reduce the influence of the scattering of wood properties within a single series. Furthermore, the angle between screw axis and grain direction (and as a result, load-to-grain-angle (see Figure 1)), screw diameter, and pre-drilling were also analysed as variation parameters. Table 1 shows the details and varied parameters of each series. For the experimental study, fully threaded screws complying with ETA 011/0190 [15] were used. The load F_{est} corresponds to the characteristic withdrawal capacity of the screws, according to the assessment document [15]. The diameters of the screws were varied within diameters relevant to timber engineering. In addition, pre-drilling was examined as an influencing parameter, since most screws can be inserted with or without pre-drilling. The number of tests per series was generally set to 10 per series. This corresponds to the number of tests required to determine the mechanical properties, according to EN 14592:2012 [16]. Additionally, some samples were prepared as a reserve in order to allow for the removal of any unsuitable results (e.g., internal knots in spruce glulam, shear failure at low load-to-grain-angles, etc.) from the sample size. In order to expand the database, all samples were used. In series 1, only nine of the tests carried out were suitable for evaluation.

Figure 1. Timber products tested: beech-LVL (**left**) and GLT from spruce (*Picea albies*) (**right**) with different load-to grain angles (45° (**left**) and 30° (**right**)).

Table 1. Test series and variation parameters.

Series	Number of Tests	Timber Product	Mean Density	COV	Screw Diameter	Load-to-Grain Angle	Pre-Drilling	F_{est}
			[kg/m^3]	[%]	[mm]	[°]		[kN]
1	9	GLT spruce	449	0.0	8	90	no	7.5
2	12	GLT spruce	457	2.7	8	45	no	7.5
3	13	GLT spruce	389	1.0	8	90	yes	7.5
4	12	GLT spruce	487	0.0	8	60	yes	7.5
5	11	GLT spruce	451	0.0	8	45	yes	7.5
6	10	GLT spruce	462	4.8	8	30	yes	5.8
7	12	Beech-LVL	813	0.0	8	90	yes	22.4
8	10	Beech-LVL	795	0.0	8	45	yes	17.9
9	10	GLT spruce	456	3.6	12	90	yes	10.3
10	10	GLT spruce	419	1.1	12	45	yes	10.3
11	10	Beech-LVL	805	1.1	12	90	yes	33.6

Pre-drilling was performed using the diameters specified in ETA 011/0190 [15]. Any unwanted deviations were eliminated through guided pre-drilling on a box column drill and guided screwing (see Figure 2). This ensured that there was no falsification of the determined stiffness as a result of excessive misalignment of the screws. The screws were screwed in until the screw tip protruded from the opposite side of the timber specimen by twice the nominal diameter. This was done so that the screw tip would not affect the test results.

All specimens were conditioned in a standardized climate at 20 °C/65% rel. hum. until equilibrium moisture content was reached. Whenever possible, timber of the same density was used within the same series. The density variation coefficient ranged from 0% (when all tensile tests were conducted on the same timber specimen) to 5%. For the GLT from spruce, knots in the screw area were minimized. In some cases, knots could have been present in the area of the screw channel when screws were inserted into glued laminated timber with multiple layers. In the tests with beech-LVL, the screws were inserted into the wide face at different angles.

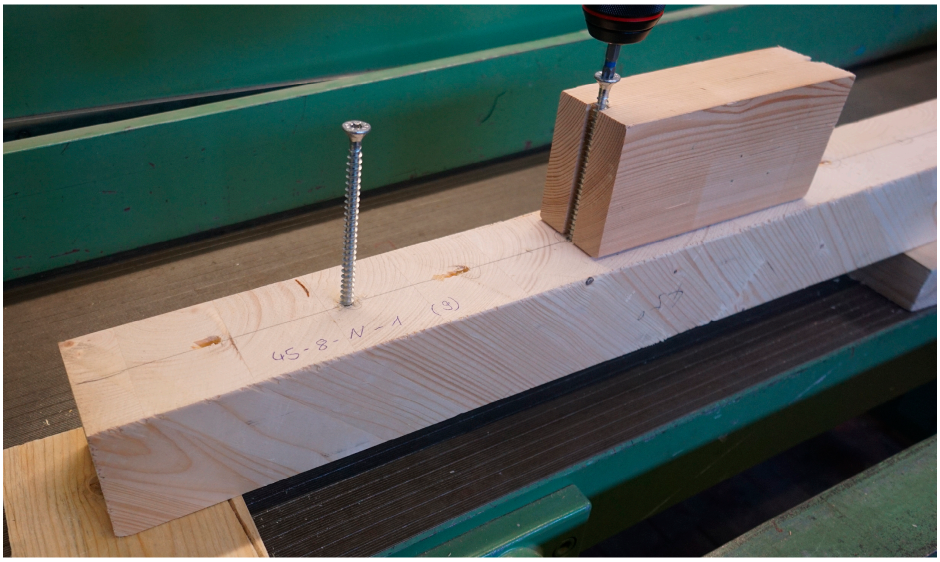

Figure 2. Insertion of screws using a drill guide.

3.2. Test Setup

Figure 3 shows the test setup, which was based on the widely used withdrawal tests also conducted in [3,4,6,7]. The screws were inserted into timber specimens with a thickness of 80 mm, equivalent to 10 times the nominal diameter of 8 mm screws.

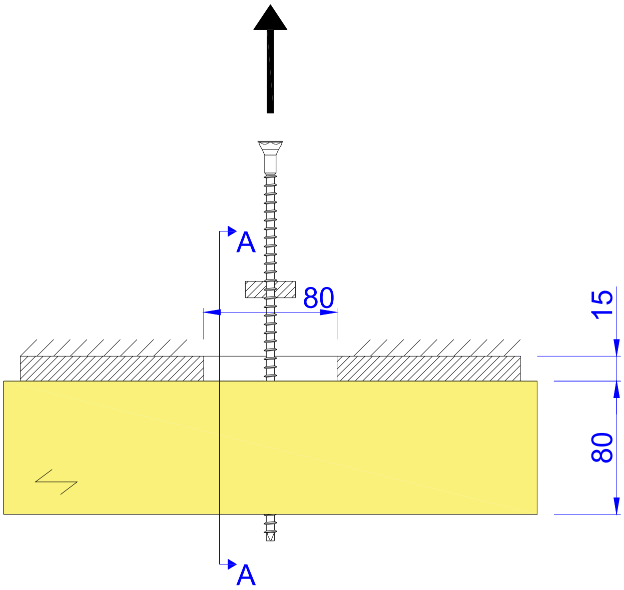

Figure 3. Longitudinal cross-section of the test setup (identical for 8 mm and 12 mm screws).

The cross-sections A-A of the test setup for screws with nominal diameters of 8 mm and 12 mm are presented in Figure 4. The applied edge distance $a_{3,c}$ was $5 \times d$. Two high-precision LVDTs with a 2 mm sensor measurement range (class 1 from 0.1 to 2 mm) were used to measure deformation, mounted at a distance of 50 mm from the screw axis. The deformation in the area of the screw axis was determined by averaging the measured values of the two LVDTs. This ensures that there are no measurement errors due to misalignment. In all series with screws with a nominal diameter of 8 mm, the elongation was measured on a steel plate with a rectangular opening of 80 × 80 mm due to the smaller cross-section of the timber specimen. The structure of the test setup and the installation of the LVDTs are also shown in Figure 5. For screws with a nominal diameter of 12 mm, measurements were taken directly on the timber specimen. The compressive strain perpendicular to the grain may have influenced the measured connection deformation. This is especially important for 8 mm screws, as they were not directly measured against the timber cross-section but against a steel plate above it due to geometric reasons. However, this was only of secondary importance for the tests conducted here, as the focus was on comparing several load cycles. But, due to this situation, the absolute axial stiffness values may differ from those of other studies.

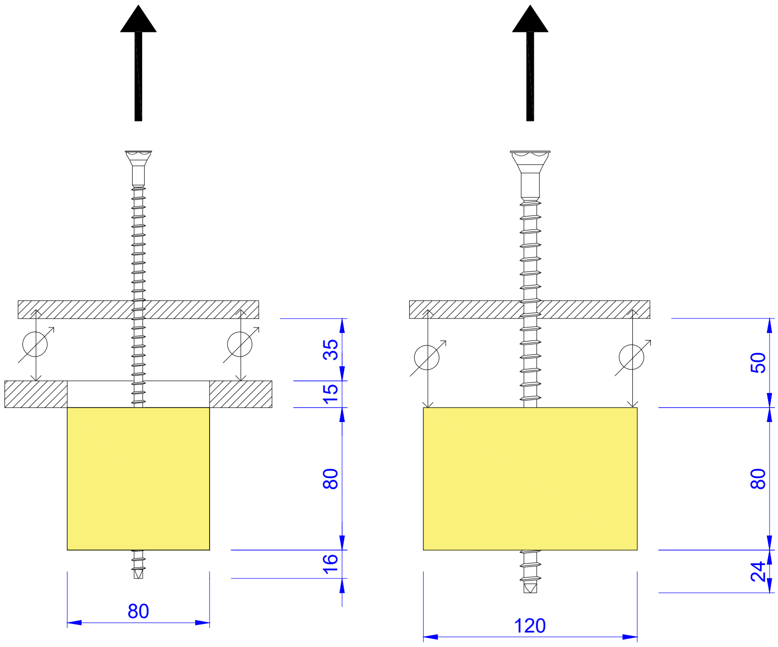

Figure 4. Cross section A-A of the test setup with screws of 8 mm (**left**) and 12 mm nominal diameter (**right**).

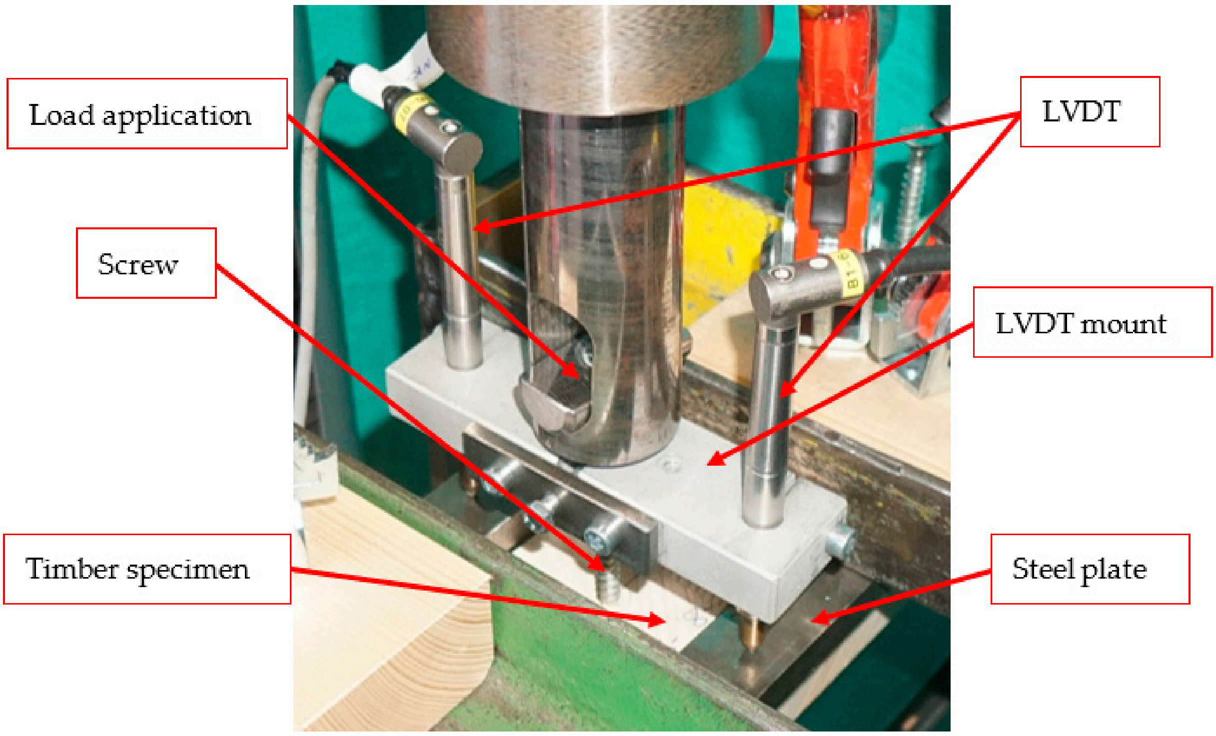

Figure 5. Attachment of the screw in the test setup and mounting of the LVDTs.

3.3. Test Procedure

The test sequence was based on EN 26891:1991 [17]. It is compared with the cyclic, load-controlled test of the abovementioned standard in Figure 6. However, instead of one loop between 10% and 40% of the maximum load, two corresponding loops between 10% and 40% of the estimated load were run, followed by two loops between 10% and 90%. The estimated load F_{est} is defined as the characteristic axial withdrawal capacity of the screw. To accelerate the test procedure, the test speed was doubled from 0.2 F_{est}/min to 0.4 F_{est}/min, and the holding time was reduced from 30 s to 5 s. All tests were load-controlled. The duration of a single test was only slightly longer than that of a test according to EN 26891:1991. Unlike the procedure according to EN 26891:1991 [17], the final load was not displacement-controlled up to the maximum load but rather load-controlled unloading. This was done in order to prevent the screws from being torn off. Following this testing procedure, it is possible to determine the initial axial stiffness up to 40%, four axial stiffnesses between 10% and 40%, and two between 10% and 90%, as well as the corresponding number of axial stiffnesses at load removal. The test load for the screws was determined according to Formula (1) from the technical assessment document ETA 011/0190 [15], with n_{ef} as the factor to account for the effective number of screws, k_{ax} as the factor to account for the angle between the screw axis and the grain direction, k_β as the factor to account for the angle between the screw axis and the LVL's wide face, $f_{ax,k}$ as the characteristic withdrawal parameter, d as the outer thread diameter of the screw, l_{ef} as the penetration length, ρ_k as the characteristic density, and ρ_a as the associated density for $f_{ax,k}$. The withdrawal capacity of the screw thread from the timber was, in all configurations, the decisive factor.

$$F_{ax,\alpha,Rk} = \frac{n_{ef} \times k_{ax} \times f_{ax,k} \times d \times l_{ef}}{k_\beta} \times \left(\frac{\rho_k}{\rho_a}\right)^{0.8} \quad [\text{kN}] \tag{1}$$

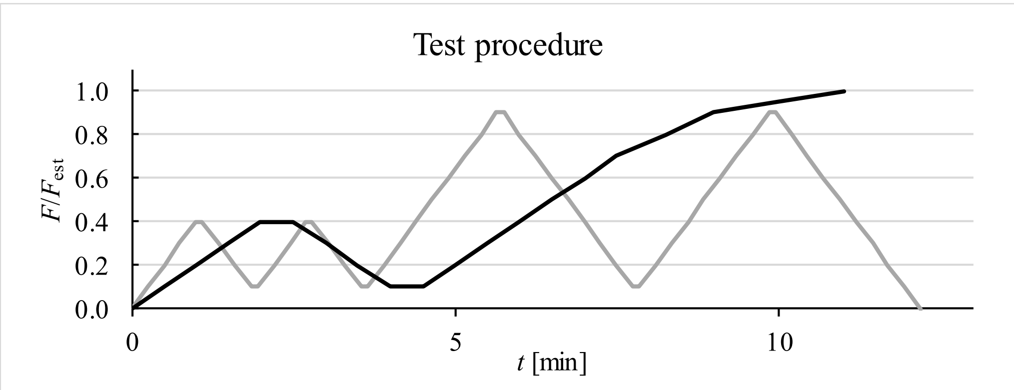

Figure 6. Applied test procedure (grey) in comparison to EN 26891:1991 (black) [17].

3.4. Test Observations

The tests can be conducted without causing any significant damage to the test specimens. The load–displacement curves depicted in Figure 7 are exemplary. All load–displacement curves feature a similar shape, with a maximum displacement ranging from 0.2 mm to 1.0 mm. The permanent deformation after unloading is up to 0.2 mm. There is a noticeable difference between screws with a diameter of 8 mm and those with a diameter of 12 mm, which can be seen in the load–displacement curve at the beginning of loading. The screws with a diameter of 8 mm exhibit a gradual increase in the curve, while the screws with a diameter of 12 mm show an immediate linear increase. Additionally, the screws with a diameter of 8 mm display an almost linear–elastic behaviour after a small initial deformation. The load–displacement curve for all screws is largely linear during both loading and unloading. Plastic deformation begins to occur when loaded up to 90% of the calculated load-bearing capacity.

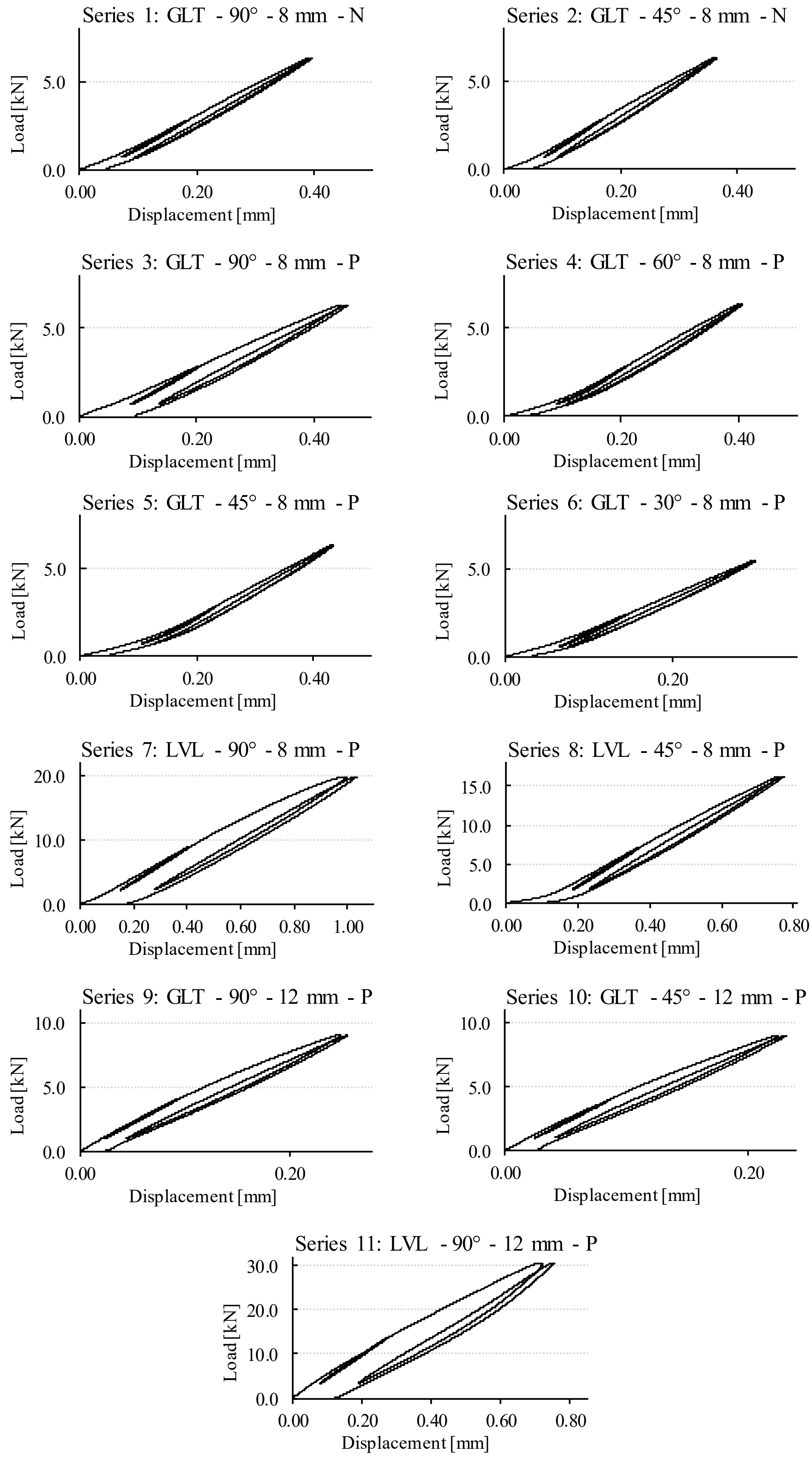

Figure 7. Exemplary load–displacement curves over four loading circles.

3.5. Results and Analysis

The axial stiffnesses were determined based on EN 26891:1991 [17]. For load cycles up to 40% F_{est}, the stiffness was determined according to Formula (2), with $F_{x,4}$ and $F_{x,1}$ representing 40% and 10% of the estimated load, respectively, and $\nu_{x,4}$ and $\nu_{x,4}$ as the corresponding mean displacement of the LVDTs. For this purpose, the tensile force in the screw was plotted against the corresponding deformation at this load level. The calculation for load cycles up to 90% F_{est} was carried out in the same manner.

$$k_{i,x} = \frac{F_{x,4} - F_{x,1}}{\nu_{x,4} - \nu_{x,1}} \quad \left[\frac{\text{kN}}{\text{mm}}\right] \tag{2}$$

As previous studies [4] have shown, the stiffness determined also depends on the test setup selected. A direct comparison with calculated stiffnesses (K_{ser}) should therefore not be made at this point. The main focus is on comparing the test results with each other. The axial stiffness values show a higher level of variation than the load-carrying capacities. The coefficients of variation within a series range from 2% to 35%. It is important to note that the density of the timber specimens, which has a significant impact on axial stiffness, can vary within a test specimen and between test specimens within a series. Table 2 compares the initial axial stiffness up to 40% loading with the modified initial axial stiffnesses. For the reloading cycles, the increase or decrease in stiffness compared to the initial load is also provided as a proportion to simplify the comparison of the values. Note that the third and fourth loading cycles are applied up to 90% of F_{est}, resulting in a significantly higher load level after the third load.

Table 2. Mean axial stiffness of screws [kN/mm] over all load cycles up to 40%.

Series	1. Loading 0–40%		1. Loading 10–40%		2. Loading 10–40%			3. Loading 10–40%			4. Loading 10–40%		
	[kN/mm]	COV [%]	[kN/mm]	COV [%]	[kN/mm]	COV [%]	Change [%]	[kN/mm]	COV [%]	Change [%]	[kN/mm]	COV [%]	Change [%]
1	10.9	19.2	13.8	10.5	15.9	7.2	+15.7	16.1	7.0	+17.2	16.1	6.5	+17.1
2	11.4	35.3	14.3	30.1	17.7	24.6	+23.5	18.0	24.2	+25.6	18.0	23.5	+25.9
3	13.2	10.2	15.0	7.6	16.9	6.9	+12.5	17.1	6.8	+14.2	16.6	7.5	+10.9
4	14.4	21.9	17.2	13.0	20.2	11.5	+17.6	20.7	11.7	+20.0	20.3	10.1	+18.1
5	13.5	17.3	15.2	16.4	18.2	13.7	+19.3	18.4	13.6	+21.1	18.3	13.7	+20.3
6	14.8	18.3	18.4	10.7	21.8	9.8	+18.7	22.3	9.9	+21.4	22.1	9.9	+20.1
7	21.6	4.1	24.2	2.9	26.1	1.8	+8.0	26.5	1.9	+9.4	25.6	2.1	+6.0
8	19.9	16.2	26.5	3.5	29.5	2.3	+11.1	29.8	2.2	+12.3	29.3	2.3	+10.3
9	40.9	7.7	40.1	9.0	43.4	6.6	+8.2	43.8	6.4	+9.2	42.0	7.2	+4.6
10	39.6	11.7	38.9	10.2	42.3	10.6	+8.7	42.9	10.4	+10.3	40.3	12.1	+3.6
11	56.0	7.2	55.7	8.7	60.1	8.3	+7.7	60.7	8.0	+8.9	58.6	8.9	+5.2
Mean	--	**15.4**	--	**11.2**	--	**9.4**	**+13.7**	--	**9.3**	**+15.4**	--	**9.4**	**+12.9**

The axial stiffnesses up to the higher load levels in the third and fourth loading procedures are shown in Table 3. For all values stated in the table, mean values and coefficients of variation are provided to represent an indication of the scatter of the values. In addition, the change in axial stiffness from the modified initial axial stiffness of the first loading is shown. The difference between the initial axial stiffness of 0% to 40% and the modified initial axial stiffness of 10% to 40% is striking. For screws with a diameter of 8 mm, the modified initial axial stiffness is approximately 20% higher. On the other hand, screws with a diameter of 12 mm show no significant increase or even a minimal decrease in average axial stiffness. This is probably due to the test setup or, more specifically, the measurement of deformation. The deformation of screws with a diameter of 12 mm are measured directly against the cross-section of the timber. However, the deformations of the 8 mm diameter screws are measured against a steel plate placed against the timber section. Despite ensuring the applied load, this can result in minimal gaps, which are compressed during the initial load but result in lower axial stiffness.

Table 3. Mean axial stiffness of screws [kN/mm] over all load cycles 10–90%.

Series	3. Loading 10–90%			4. Loading 10–90%		
	[kN/mm]	COV [%]	Change [%]	[kN/mm]	COV [%]	Change [%]
1	15.8	4.2	+14.8	16.8	4.2	+22.0
2	17.8	16.6	+23.9	19.0	15.9	+32.3
3	15.5	8.8	+3.6	16.6	7.0	+10.6
4	19.8	7.1	+14.8	20.8	6.5	+20.7
5	18.4	11.2	+20.8	19.5	10.4	+28.2
6	21.6	9.3	+17.6	22.7	9.4	+23.4
7	22.5	3.1	−7.0	24.4	1.9	+0.7
8	26.2	3.3	−1.3	27.5	2.5	+3.8
9	37.0	10.6	−7.7	39.6	8.4	−1.3
10	34.2	12.0	−12.1	38.2	14.0	−1.8
11	50.0	6.8	−10.3	56.4	6.7	+1.1
Mean	**--**	**8.5**	**+5.2**	**--**	**7.9**	**+12.7**

An evaluation of all 11 series shows that the axial stiffness of the connection increases compared to the initial loading. The increase between the first and second loading is between 8% (series 11) and 23% (series 2). The average increase over all series is around 14%. During the following cycles, the axial stiffness does not change significantly compared to the second loading. Even at a higher load level, there is an increase in average axial stiffness with a simultaneous decrease in scatter. The axial stiffnesses are slightly lower up to the higher load level. This is due to the load up to 90% and the plastic deformation that begins to occur at correspondingly high loads. As an example, the scatter of the axial stiffness of all series are shown in Figure 8. The diagrams show the four load cycles between 10% and 40% and the two load cycles between 10% and 90%.

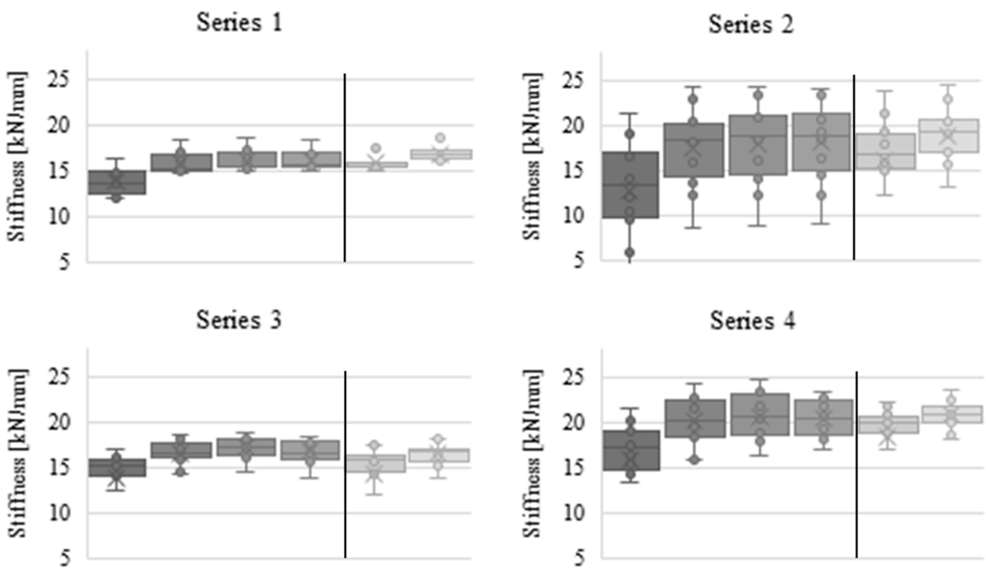

Figure 8. *Cont.*

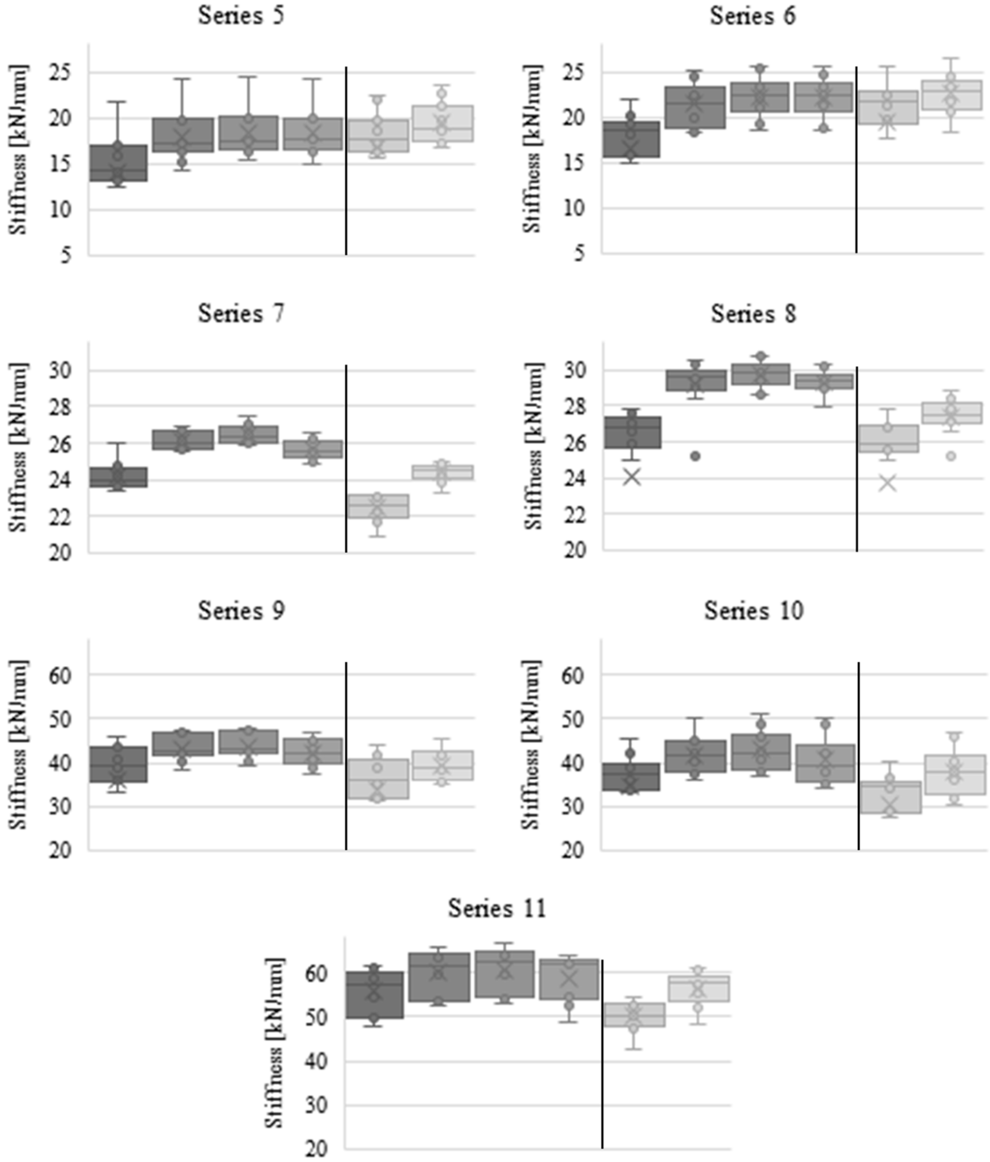

Figure 8. Axial stiffnesses of series 1 to 11 between 10% and 40% (**left**) and 90% (**right**).

3.6. Discussion of Test Results

In the following section, the varied parameters in each series are analysed individually.

3.6.1. Influence of Pre-Drilling

The influence of pre-drilling in spruce GLT can be analysed using series 1 and 3 and series 2 and 5. On average, the axial stiffness of the screws with pre-drilling is slightly higher (about 4.6%), although the used timber specimens had a lower gross density. On the other hand, pre-drilling has no noticeable effect on the behaviour during unloading and reloading.

3.6.2. Influence of Timber Product

When comparing the timber products, it is immediately apparent that the screws in beech-LVL feature a significantly higher axial stiffness. However, this was expected as the density of beech-LVL is approximately 80% higher compared to spruce GLT. The variation in the axial stiffnesses between specimens is also slightly lower. However, this was expected for a homogenized material such as beech-LVL. On the other hand, the timber product into which the screws are screwed seems to have no effect on the change in axial stiffness during initial loading, unloading, and reloading.

3.6.3. Influence of Insertion Angle

Series 3 to 6 allow for a comparison of the insertion angle to the grain direction from 30° to 90°. There is no significant effect of the insertion angle. There is also no significant effect on the behaviour during unloading and reloading.

3.6.4. Influence of Screw Diameter

A direct comparison of the absolute values between the screw diameters is not possible due to the slightly different test setup. It is possible that the axial stiffness of the 8 mm screws is underestimated compared to the 12 mm screws, as no steel plate was applied during the related tests. However, the comparison between the initial load and the reloading cycles clearly shows that the screw diameter has no significant effect here either.

3.6.5. Influence of Load Level

The first two cycles feature loads up to approximately 40% of the ultimate withdrawal strength. The following two cycles feature loads up to 90% of the ultimate withdrawal strength. Elastic behaviour can be assumed for the first two cycles. With a load of up to 90%, plastic effects can be expected, which can significantly reduce the axial stiffness. This parameter is of particular interest for investigating the effects of a single overload on a structure, as may occur as a result of an exceptional load case.

The expected effect occurred in the beech-LVL series and the series with 12 mm diameter screws. A comparison of the curves in Figure 7 (series 1 to 6 compared to series 7 to 11) clearly shows a flattening of the load–deformation curve. This is accompanied by a reduction in axial stiffness. When comparing the initial load from 10% to 40% and the initial load from 10% to 90%, the average reduction in axial stiffness is approximately 8%. In contrast, no significant flattening of the curve can be observed for the 8 mm diameter screws in spruce GLT. In fact, the axial stiffness of these series increases by an average of 16%. This indicates that there are no plastic effects. The higher values can be explained by the fact that the influence of plastic effects at the initial load (cf. axial stiffness 0–40% and axial stiffness 10–40%) are far greater at correspondingly low load levels (F_{est} = 7.5 kN).

4. Comparison with Existing Experimental Results

Cyclic loading tests on axially loaded partially and fully threaded screws have only been carried out to a limited extent [14]. Challenges of these types of testing procedures are the sometimes very long test duration and the choice of test setups. In particular, the latter has a major influence on the determined axial stiffnesses and possibly also on the corresponding effects under cyclic loading. The reasons for this are the small deformations, which are often superimposed by other effects, such as compressive strains perpendicular to the grain. In a fundamentally different test setup, Dietsch [14] carried out cyclic tests on GLT from spruce reinforced with fully threaded screws. The aim of this investigation was to determine a possible change in the composite behaviour of timber and screw for shear reinforcement. For this purpose, a fundamentally different test setup was used, which differs from the typical test setups derived from a screwed connection. Instead, a screw was inserted into a 200 mm-high GLT cross-section ($A = 120 \times 120$ or 200 mm^2). The test setup shown in Figure 9 illustrates the difference to the tests carried out within the test campaign presented in the previous section. In the next step, a compressive load is applied to the timber cross-section. In the meantime, the change in length of the screw is measured. The aim was to investigate whether cyclic loading weakens the bond between screw thread and wood matrix, for example, by destroying the structure of the wood matrix in the area of the threads. For this purpose, seven test specimens were produced in which fully threaded screws were inserted with 45° and 90° grain directions. Following this, the compressive load was applied to the GLT specimen. The direction of loading was parallel to the screw axis. The test was displacement-controlled up to a compressive strain of the timber of ε = 1.0%. This ensured that the deformations remained within the elastic range. The load was then held for 60 s, then reduced to a load of 10 N. This process was repeated four times. Again, the total test duration was approximately 15 min. One specimen from each series was tested in 12 cycles. The deformation of the screw was measured with high-precision Multisens sensors on the free parts of the screw protruding from the timber specimen, as shown in Figure 9 (right).

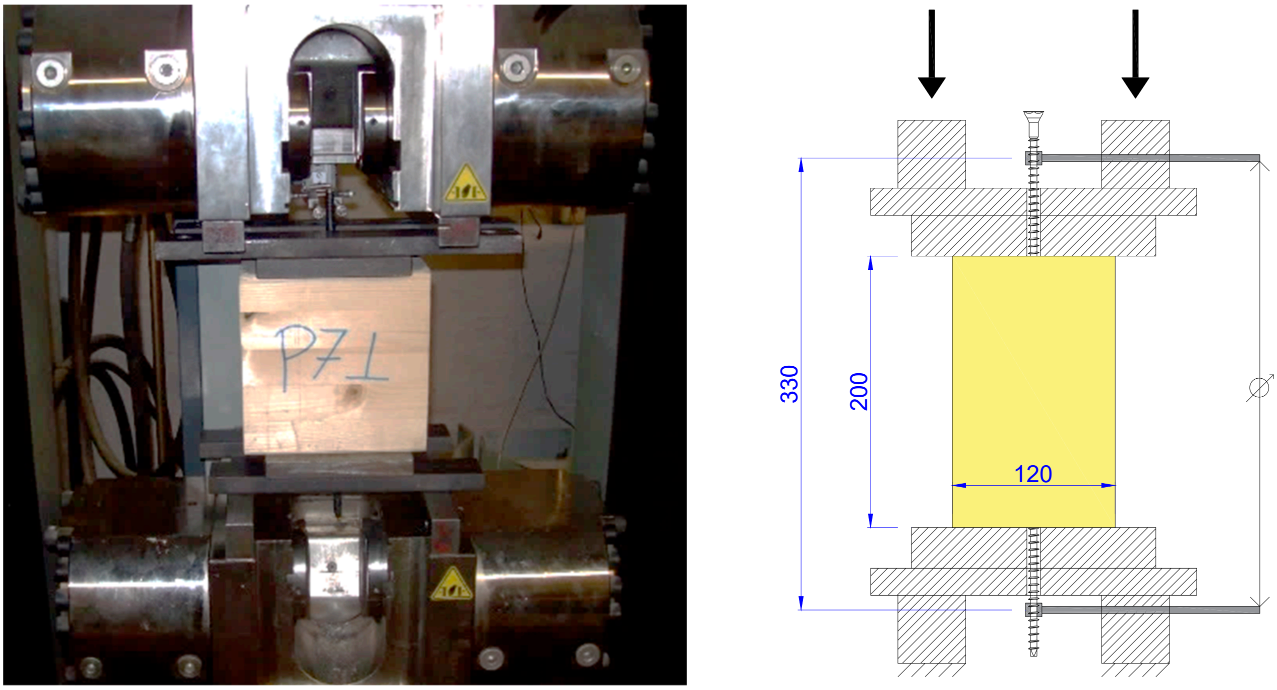

Figure 9. Setup (**left**) and test specimen in test setup (**right**) according to Dietsch [14].

The results of this test series show, on average, a slight decrease in deformation and therefore an increase in axial stiffness from the first to the second load cycle. This is shown in Figure 10 for an example of screws at 45° and four load cycles. The axial stiffness level of the subsequent load cycles corresponds to the second cycle. The scatter of the test results in this investigation does not change significantly as the number of load cycles increases.

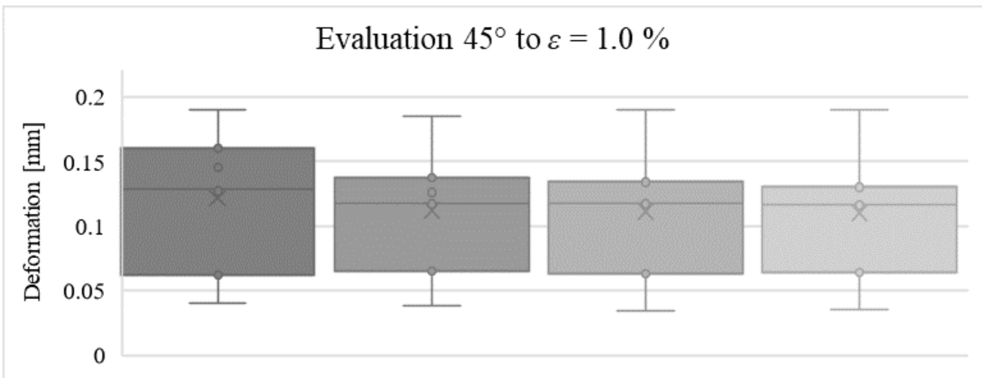

Figure 10. Test series with ε = 1.0% under load-to-grain-angle 45°.

At low compressive strains in the timber (ε = 0.3%), no increase in axial stiffness was determined. This could be due to relaxation of the screws that were under tensional stress from the prior insertion. Only at higher strains (ε = 1.0%) does an increase in axial stiffness occur. The average increase from first load to first reload in the tests done by Dietsch [14] is around 2.7%. This is significantly lower than the 11% found here, but nonetheless, the direction of the trend is similar.

5. Conclusions

- The tests carried out show that repeated loading will increase the axial stiffness of an axially loaded screw in timber products as long as the load is within the elastic range of the connection. The average increase is around 11% from first to second loading.
- Possible influencing factors such as screw geometry, axis-to-grain angle, pre-drilling, or type of timber product have no significant influence on the development of axial stiffness under cyclic loading.
- Only the load level has a significant influence. If plastic deformation occurs during high loading, the axial stiffness will be reduced by up to −12%.
- It can therefore be assumed that the axial stiffness generally increases when reloading in the elastic range. This is also consistent with the tests previously carried out by Dietsch [14]. As the same effect was observed despite fundamentally different test setups, it is evident that an increase in axial stiffness is a basic phenomenon that is independent of the applied test setup.
- This specific behaviour of connections has positive implications for practical design situations. Cyclic loading does not lead to significantly higher deformations in connections with axially loaded screws. Therefore, it can be assumed that the development of axial stiffness does not have a negative influence on long-term deformations.
- Loads leading to plastic deformation would cause a significant reduction in axial stiffness. However, with the exception of accidental design situations, it is unlikely that such high loads will occur in structures in practice. Even after loading close to the characteristic load capacity, the reduction in axial stiffness is only slightly below the level at initial loading.
- It should be pointed out that increased connection stiffness could lead to a possible increase in undesired secondary stresses. However, this effect is mitigated by the specific material behaviour of timber product such as the relaxation behaviour.

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References

1. Ringhofer, A. Axially Loaded Self-Tapping Screws in Solid Timber and Laminated Timber Products. Ph.D. Thesis, Graz University of Technology, Graz, Austria, 2017.
2. Jockwer, R.; Steiger, R.; Frangi, A. Design model for inclined screws under varying load to grain angles. In Proceedings of the International Network on Timber Engineering Research INTER, Meeting 47, Bath, UK, 1–4 September 2014.
3. Blaß, H.J.; Bejtka, I.; Uibel, T. *Tragfähigkeit von Verbindungen mit Selbstbohrenden Holzschrauben mit Vollgewinde*; Universitätsverlag Karlsruhe: Karlsruhe, Germany, 2006.
4. Blaß, H.J.; Steige, Y. *Steifigkeit Axial Beanspruchter Vollgewindeschrauben*; KIT Scientific Publishing: Karlsruhe, Germany, 2016.
5. Tomasi, R.; Crosatti, A.; Piazza, M. Theoretical and experimental analysis of timber-to-timber joints connected with inclined screws. *Constr. Build. Mater.* **2010**, *24*, 1560–1571. [CrossRef]
6. Brandner, R.; Ringhofer, A.; Reichinger, T. Performance of axially-loaded self-tapping screws in hardwood: Properties and design. *Eng. Struct.* **2019**, *188*, 677–699. [CrossRef]
7. Ringhofer, A.; Brandner, R.; Schickhofer, G. A Universal Approach for Withdrawal Properties of Self-Tapping Screws in Solid Timber and Laminated Timber Products. In Proceedings of the International Network on Timber Engineering Research INTER, Meeting 48, Šibenik, Croatia, 24–27 August 2015.

8. Azinovic, B.; Frese, M. FE modelling of timber connections with inclined and cross-wise arranged screws—Few findings on testing the shear stiffness. In Proceedings of the International Network on Timber Engineering Research INTER, Meeting 53, Online, 17–19 August 2020.
9. De Santis, Y.; Fragiacomo, M. Slip modulus formulas for timber-to-timber inclined screw connections. Comparison with other simplified models. In Proceedings of the International Network on Timber Engineering Research INTER, Meeting 54, Online, 16–19 August 2021.
10. Girhammar, U.A.; Jacquier, N.; Källsner, B. Stiffness model for inclined screws in shear-tension mode in timber-to-timber joints. *Eng. Struct.* **2017**, *136*, 580–595. [CrossRef]
11. Ringhofer, A.; Burtschner, M.; Sieder, R.; Gstettner, M. Self-tapping Timber Screws Subjected to Combined Axial and Lateral Loading. In Proceedings of the International Network on Timber Engineering Research INTER, Meeting 54, Online, 16–19 August 2021.
12. Hu, W.; Liu, Y.; Konukcu, A.C. Study on Withdrawal Load Resistance of Screw in Wood-Based Materials: Experimental and Numerical. *Wood Mater. Sci. Eng.* **2023**, *18*, 334–343. [CrossRef]
13. Piazza, M.; Polastri, A.; Tomasi, R. Ductility of timber joints under static and cyclic loads. *Proc. Inst. Civ. Eng. Struct. Build.* **2011**, *164*, 79–90. [CrossRef]
14. Dietsch, P. Einsatz und Berechnung von Schubverstärkungen für Brettschichtholz. Ph.D. Thesis, Technische Universität München, Munich, Germany, 2012.
15. *ETA-11/0190*; Würth Self-Tapping Screws for Use in Timber Constructions. Adolf Würth GmbH & Co. KG: Künzelsau, Germany; DIBt: Berlin, Germany, 2018.
16. *DIN EN 14592:2012-07*; Holzbauwerke—Stiftförmige Verbindungsmittel—Anforderungen. Beuth Verlag: Berlin, Germany, 2012.
17. *DIN EN 26891:1991-07*; Holzbauwerke—Verbindungen mit Mechanischen Verbindungsmitteln—Allgemeine Grundsätze für die Ermittlung der Tragfähigkeit und des Verformungsverhaltens. Beuth Verlag: Berlin, Germany, 1991.