Low cycle ductility of self-tapping screws

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1 Introduction

In principle, timber structures show an excellent behaviour in the event of earthquakes. The positive ratio of strength and mass leads to lower seismic loads. Traditionally, many slender metallic fasteners are used in timber structures, e.g., in timber frame construction. Joints using such dowel-type fasteners generally behave ductile and thus dissipate energy.

With the advent of massive timber construction using materials such as CLT, the individual elements have larger formats and are stiffer than in traditional timber frame construction. Additionally, whereas timber frame construction makes use of many, small-diameter joints distributed over the whole structure, fewer and more discrete joints are needed in massive timber construction. Consequentially, earthquake loads increase, leading also to higher forces in the joints. Self-tapping timber screws are suitable for the transmission of large forces. However, they are usually made of hardened carbon steel, which fails brittle. By means of special hardening processes, the screws are treated in such a way that they remain ductile to a certain extent. For earthquake design, however, a secure ductile behaviour is required, which means that screws must be able to form plastic hinges.

prEN 14592 Annex E (2017) introduces a new test method that divides fasteners into so-called "low cycle ductility classes" to describe the ductile behaviour of fasteners. This new test method shall guarantee that the fasteners are able to form plastic hinges under reversed loading without failure resp. to classify the screws in dependence of their plastic deformation capacity. The aim of this work is to investigate if the proposed classification depends on the test setup parameters and if it is possible to divide screws directly into low cycle ductility classes by more simple tests according to EN 409 (2009), with which the yield moment of fasteners is determined. Both test methods, prEN 14592 and EN 409, however, encompass tests using only the fasteners. Therefore, this work moreover investigates if tests with only fasteners deliver significant results also for joints, where a system of fastener and timber must behave ductile. For this scope, quasi-static reversed cyclic tests on timber-to-timber joints with screws according to EN 12512 (2005) are carried out, using screws assigned to different low cycle ductility classes. The focus here is on self-tapping timber screws from different manufacturers and different diameters. The new test method from prEN 14592 Annex E, EN 409 and EN 12512 for the determination of the ductility and the cyclic behaviour of joints are considered.

2 State of the art

Self-tapping timber screws can be arranged differently in timber joints. If they are axially loaded, they can activate their high stiffness and load-carrying capacity. However, these joints fail in a rather brittle manner. If the screws in the joint are laterally loaded, they exhibit a more ductile behaviour and can also dissipate energy under cyclic loads (Hossain et. al, 2018).

Ductile behaviour in timber construction is hence mainly created in joints with laterally loaded dowel-type fasteners by the formation of plastic hinges in the metallic fasteners and the embedding strength of the timber components. The timber components themselves fail brittle, especially under tensile and bending loads (Jorissen and Fragiacomo, 2011; Ottenhaus et. al., 2021). The steel properties of the fasteners influence the ductility of a joint. Hardened fasteners fail brittle compared to unhardened ones. In most cases, several fasteners are arranged in a row and are thus exposed to different loads. Ductile fasteners are advantageous here because they can redistribute stresses (Geiser et. al, 2021). The ductility of an entire joint depends not only on the fastener itself, but also on the geometry of the joint, such as fastener spacing. To determine the ductility of entire joints, test standards are available, such as EN 12512 and ASTM E2126 (Casagrande et. al, 2020).

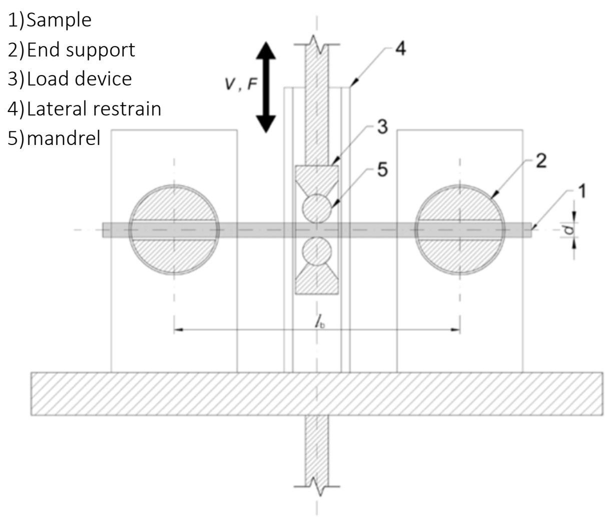
Concerning joints with laterally loaded screws, the screws must be able to withstand reversed cyclic bending to dissipate energy under cyclic loads. Concerning a screw's bending capacity, the current certification of screws in accordance with EN 14592 (2017) and EAD 130118-01-0603 (2019) so far is only based on monotonic tests with screws (EN 409). As a robustness criterion, a certain bending angle depending on the screw diameter must be achieved during the test. To be able to make a statement about the cyclic properties of fasteners, prEN 14592 contains a test method that divides the dowel-type fasteners into different "low cycle ductility" classes with respect to their low cycle behaviour. Initial studies have shown that the test method allows the classification into classes for commercially available timber screws (Izzi and Polastri, 2019; Cervio and Muciaccia, 2020).

3 Test in accordance with prEN 14592:2017 Annex E

3.1 Normative requirements and their implementation

To classify a screw in a low cycle ductility class, three tests under cyclic load and three tests under monotonic load are necessary, where only the screw itself and not a whole joint is tested. The cyclic test encompasses three fully reversed cycles up to a bending angle α_c and a final monotonic loading to determine the residual bending moment capacity. Two criteria must be met for the screw to be classified in a low cycle ductility class. For ***criterion 1*** (see (Figure 3), screws with diameters up to 8 mm must reach a minimum bending angle during monotonic loading of at least 45° respectively 30° for screws with larger diameters, where the standard is unclear if this applies to both the monotonic tests and the final monotonic loading during the cyclic tests. At KIT, both curves must reach the minimum bending angles. If the residual bending moment capacity after three fully reversed cycles reaches at least 80 % of the moment capacity under monotonic load, the screw passes the test, ***criterion 2*** (see Figure 3). Three different low cycle ductility classes are defined where for the higher classes providing more energy dissipation capacity, larger bending angles α_c must be reached during the cyclic test. This means that the bending angle α_c must be defined beforehand in order to apply the correct deformations during the cycles and if the test failed, a new test with a lower bending angle α_c is necessary. The bending angles α_c for the classification into the three low cycle ductility classes are defined for the low cycle ductility class S1 as $\alpha_c = \alpha$, S2 as $\alpha_c = 1.5\alpha$ and S3 as $\alpha_c = 2\alpha$. For this, α can be calculated by the formula $\alpha = 45°/d^{0.7}$, with d being the nominal diameter of the screw.

Annex E of prEN 14592 furthermore describes a test setup for the determination of the low cycle ductility classes. Figure 1 shows the principal test setup from prEN 14592. Figure 2 shows the implementation in the laboratory of the KIT Research Centre for Steel, Timber, and Masonry. Using this test setup, the monotonic and the cyclic tests (including a final monotonic loading) are carried out.



"The length of the support, l_b shall be less than 16d. The diameter of the mandrel which the sample is bent over shall be 2d ± 0.5d. The end supports shall allow for axial displacements and free rotations of the sample. The sample shall be laterally restrained in order to prevent out of plane rotations." Annex E to prEN 14592

Figure 1: Test setup and requirements given in prEN 14592 Annex E, there Figure E.1

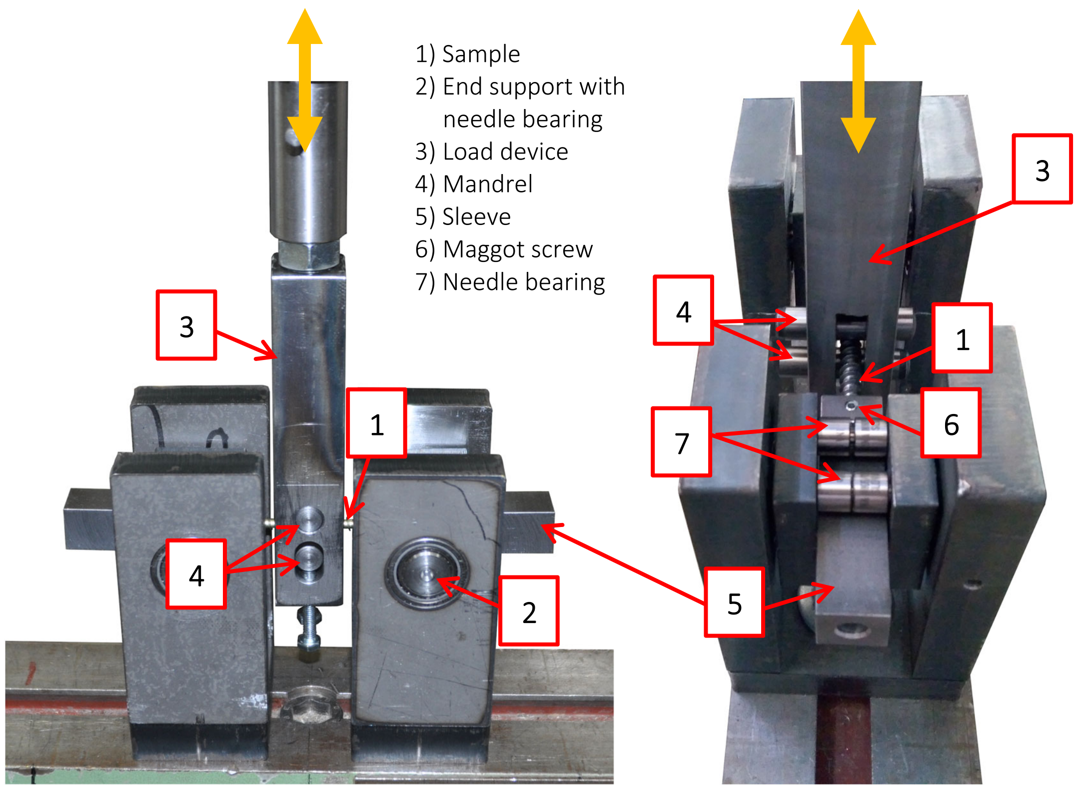


Figure 2: Implemented experimental setup at KIT

The dowel-type fastener is inserted in two sleeves (5) and fixed with two maggot screws (6) per sleeve. The fixation prevents lateral movement of the fastener under alternating load. Eight needle bearings (7) in turn hold one sleeve per support side to ensure free movement in the axial direction of the fastener, which prevents normal forces in the fastener. The needle bearings are connected to steel plates, which are held vertically via further needle bearings (2), allowing for rotation. The fastener is attached to the load device (3) via two mandrels (4). With a vertical shift of the load device, the fastener is loaded with a moment and a shear force. The test device is installed in a universal testing machine, a vertical displacement is applied via the load device and the associated force and displacement are measured.

From the measured forces and displacements, the moment and the bending angle are calculated. In Figure 3, such a moment-bending angle diagram is shown. The black curve shows the monotonous test of a screw up to the bending angle α_{max} = 45°. The blue curve shows the three cycles of a test up to the bending angle α_c and then the red curve shows the final monotonic loading up to the bending angle α_{max}. Due to the change of load direction, a force-free displacement in the zero crossing is created due to the backlash between mandrel and fastener.

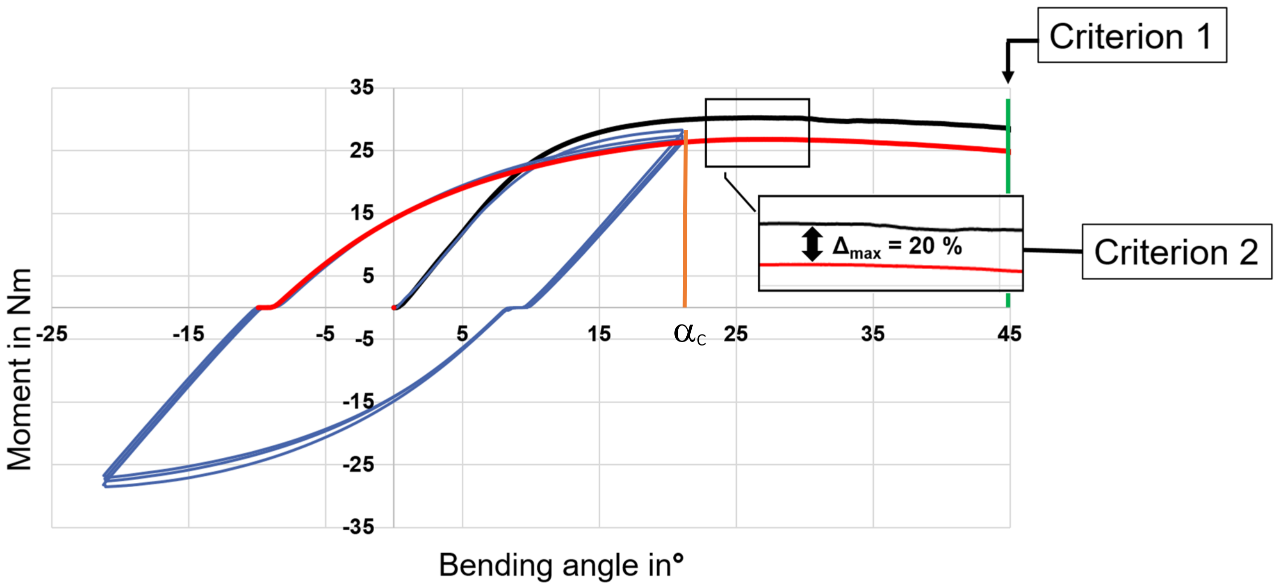


Figure 3: Moment-bending-angle-diagram of cyclic test in accordance with prEN 14592 and the criteria 1 and 2

3.2 Variation of test parameters and their effect on the test result

The test procedure in prEN 14592 is new and there is little knowledge about the influence of test parameters, which can in parts be chosen freely. For this reason, extensive tests with variations of these three parameters were carried out:

- Testing time
- Mandrel diameter *D*
- Support distance l_b

The prescribed testing time seems with t = 300 s ± 60 s very long compared to a real cyclic load due to earthquakes. Therefore, the normative testing time was compared with a significantly shorter testing time. Kuck and Sandhaas (2022) have shown that tests according to EN 409 lead to different results when varying the free bending length. They have shown that a variation of the free bending length has an influence on the stiffness and the maximum yield moment. The smaller the free length is chosen, the more critical the test is in terms of ductility, i.e., the more likely an early failure is to be expected, as bending radii decrease. This behaviour was also expected in the tests for the classification of the screws into the low cycle ductility classes according to prEN 14592. It was expected that the same influence can be shown by variation of the mandrel diameter which influences the radius of the plastic hinge, and by varying the support distance.

Seven different screws with diameters from 5 mm to 12 mm were tested. All screws were fully threaded with exception of one screw, which was partially threaded. It is expected that the influence of the three parameters is greater in the higher low cycle ductility classes since the deformations are then at their maximum. For this reason, the screws were tested in the highest low cycle ductility class S3.

3.2.1 Influence of testing time

prEN 14592 specifies a possible test duration of t = 300 s ± 60 s. The specified average test duration of t = 300 s was selected as reference. In order to show the greatest possible influence, the standard specification was largely reduced and a test duration of one tenth, i.e. t = 30 s, was chosen. Five different types of screws with diameters from 5 to 12 mm was examined. 10 test series with 3 cyclic and monotonic tests per series were carried out.

Screws that already show a significant drop in moment load-carrying capacity during the final monotonic loading after the cyclic loads with a test duration of t = 300 s also show this with a test duration of t = 30 s, only that the drop in moment load-carrying capacity is greater and occurs at smaller bending angles (red rectangles in Figure 4). In the case of screws that showed no drop in moment load capacity, no influence of the different loading rates could be determined. Figure 4 shows an example of a comparison of the two load rates for screws where a drop in the moment carrying capacity could be observed.

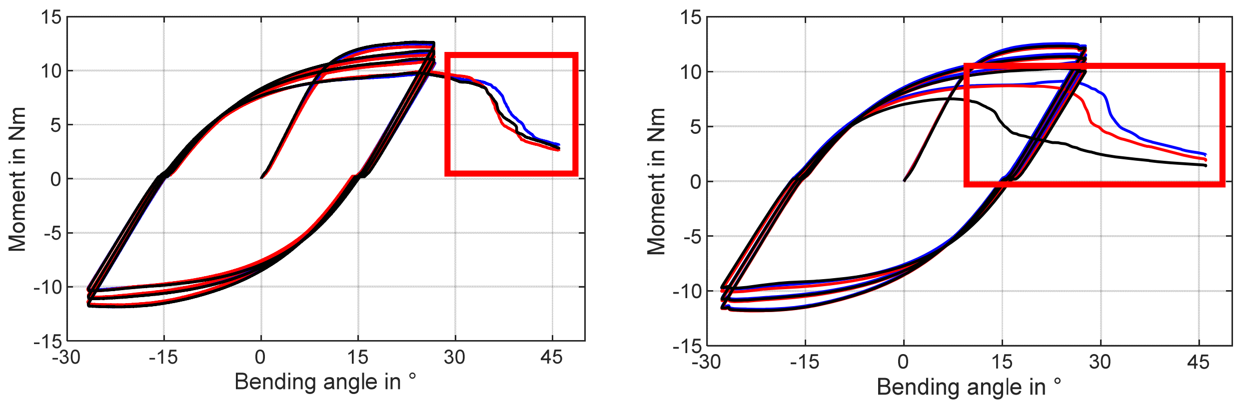


Figure 4: Influence of time - left side t = 300 s and right side t = 30 s, screw with d = 6 mm

3.2.2 *Influence of mandrel diameter*

prEN 14592 specifies a possible margin for the diameter of the mandrel from $2d \pm 0.5\ d$, over which the fasteners must be bent. Two mandrels with a diameter D of 12 mm and 18 mm were available for the investigations. Screws with diameters of 6 mm, 6.5 mm and 7.5 mm were tested. The ratio of mandrel diameter and screw diameter was between 1.6 d and 3.0 d with a mean difference of about 1.0 d. A total of six series with 3 cyclic tests each were carried out.

An increase in the mandrel diameter led to a slight improvement of the test result, i.e. the achievement of a greater bending angle during the final monotonic loading without failure. However, as in the tests with different loading rates, this also only occurred with screws that proved to be critical in the final monotonic loading. Figure 5 exemplifies the influence on the variation of the mandrel diameter, which shows a small increase in the bending angle up to rupture.

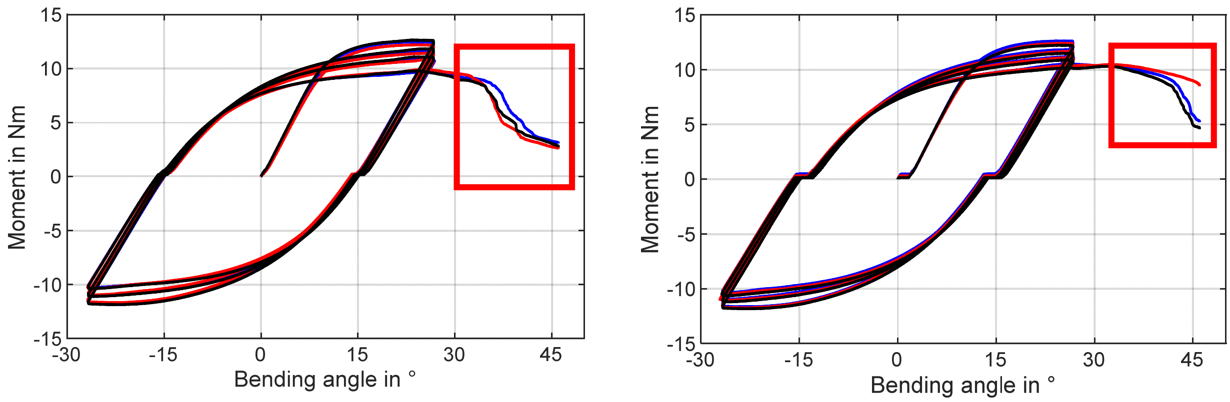


Figure 5: Influence of mandrel diameter – left side D = 12 mm and right side D = 18 mm, screw with d= 6 mm

3.2.3 *Influence of the support distance l_b*

prEN 14592 specifies a support distance of $l_b \leq 16\ d$, but no lower limit. Since the support distance has an influence on the elastic part of the bending angle, tests were carried out on screws with diameters of 6 to 12 mm. The support distance was chosen between a maximum distance of $l_b = 16\ d - 1$ mm and a distance of $l_b = 10\ d$. Due to the test device, this could not be reduced further than 10 d. In addition, the plastic bending angle β of each tested fastener was determined and documented after carrying out the test. All screws have been tested in their highest possible low cycle ductility class. An overview of the test results can be found in Table 1. It shows that for both the monotonic and the cyclic tests, the plastic bending angle β increased with decreasing the support distance l_b. This led to larger plastic deformations in the screw. A steady increase in moment capacity under monotonic loading (M_m) was also observed, confirming the increase in plastic bending angles β. On the other hand, the residual capacity of the bending moment after the cyclic tests (M_c) showed only slightly increased or even reduced values. This can be explained by increased alternating stress/fatigue. In the case of the criteria for classification into the low cycle ductility class, there is no influence of the support distance for criterion 2. For criterion 1, in which a bending angle of 45° or 30° must be achieved, it can be seen that this is not achieved with small support distances. This shows that small support distances and large plastic bending angles are the critical parameters for the classification into the low cycle ductility classes. From this, it could be assumed that a monotonic test with a small contact distance and a large plastic bending angle can potentially replace the cyclic tests.

Table 1: Test results of support distance l_b

d in mm	support distance l_b in mm	Low cycle ductility class	Monotonic Tests		Cyclic Tests		Criterion 1 min. bend. angle	Criterion 2 Δ M_m to M_c ≤ 20 %
			M_m in Nm	β_m in °	M_c in Nm	β_c in °		
6	16 *d* - 1	S2	12.2	34.8	11.5	34.3	pass	pass
	13 *d*	S2	13.0	36.5	10.9	38.2	fail	pass
6.5	16 *d* - 1	S2	-	-	24.8	34.5	fail	-
	16 *d* - 1	S1	26.7	34.5	26.3	34.3	pass	pass
	13 *d*	S1	27.2	39.3	26.6	39.3	fail	pass
7.5	16 *d* - 1	S2	21.5	33.7	21.3	34.2	pass	pass
	13 *d*	S2	22.7	36.7	22.1	38.7	pass	pass
	11 *d*	S2	23.3	38.3	20.8	41.5	fail	pass
9	16 *d* - 1	S3	37.4	20.5	35.8	20.3	pass	pass
	13 *d*	S3	38.7	22.0	36.8	21.8	pass	pass
	10 *d*	S3	41.2	24.5	38.7	24.7	fail	pass
12	16 *d* - 1	S3	89.6	17.5	81.3	19.0	pass	pass
	13 *d*	S3	86.2	19.5	90.0	19.5	pass	pass
	10 d	S3	92.2	21.8	85.0	21.3	pass	pass
12	16 *d* - 1	S3	77.0	18.3	75.1	19.0	pass	pass
	13 *d*	S3	80.3	21.5	73.1	21.5	pass	pass
	10 *d*	S3	81.4	24.3	71.3	26.3	fail	pass

M_m: Mean bending moment under monotonic load / M_c: mean bending moment after cyclic load
β: Mean measured plastic bending angle of screw after testing under monotonic or cyclic load

4 Comparative tests between EN 409 and prEN 14592

4.1 Test setup

EN 409 describes a test method for determining the yield moment M_y of dowel-type fasteners. Here, a pure moment is applied to the fastener by carrying out a four-point bending test. During the test, the moment and the bending angle are measured. The bending angle, at which the yield moment is determined, corresponds to $45/d^{0.7}$ according to EN 14592 (2012). However, during the test, the fastener is usually bent far above 45°and the moment is recorded. The free bending length in the test is limited to a maximum of 3 *d*, resulting in a small support distance and a large plastic bending angle. Therefore, based on the results from section 3.2.3, it should now be checked if a classification into the low cycle ductility classes can be made using this (critical) test setup.

Comparative tests according to EN 409 and cyclic tests according to prEN 14592 were hence carried out on 27 different screws made of carbon steel and eight different screws made of stainless steel. The different screws were fully threaded as well as partially threaded with nominal diameters ranging from 5 mm to 12 mm. Per series, three tests were carried out.

In the test setup according to prEN 14592, a support distance of $l_b = 16\,d - 1$ mm was selected, and a mandrel diameter $D = 12$ mm was used for screws with diameters $d \leq 8$ mm and $D = 18$ mm for screws with diameters $d > 8$ mm.

In the tests according to EN 409, the screws were bent up to a bending angle of 60° if they did not fail beforehand and the moment and the angle were measured.

4.2 Results and discussion

Figure 6 shows three normalised moment-bending angle curves of tests according to EN 409. It can be seen that the three curves show different moment-bending angle behaviour, which leads to a possible classification of the screws in classes F1 to F3. Curve F1 shows an almost ideally plastic behaviour of the screw, whereas the moment bending angle curves of class F2 screws decrease after having reached a maximum. The screw of curve F3, finally, fails before reaching a bending angle of 60°. Based on these three typified curves, the tested screws were divided into the corresponding classes F1 to F3 based on their moment-bending angle curves.

Class F1 screws can be accepted as ductile and class F3 screws as quite brittle. The curves of class F2 screws indicate that the cross-section was damaged, reducing the moment capacity.

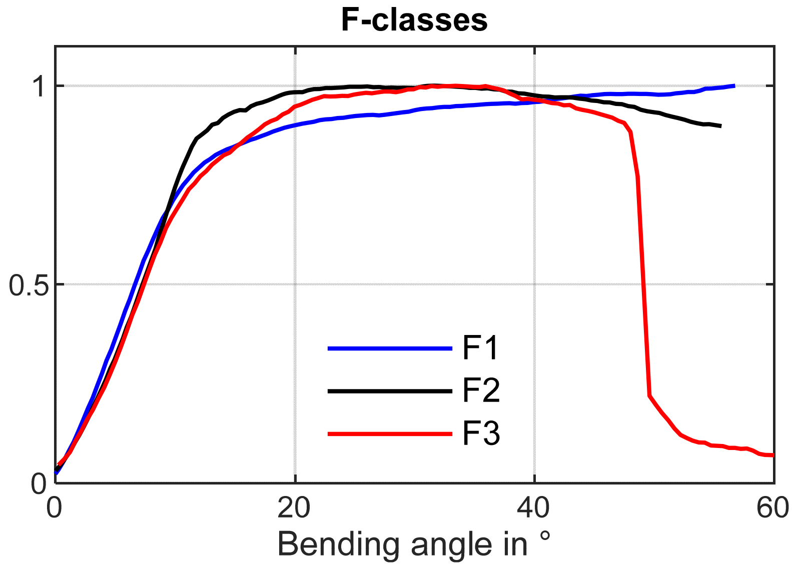


Figure 6: Exemplary curves of the different classes F1, F2, F3.

The cyclic tests according to prEN 14592 were carried out as described in section 3.1 and the screws were classified into the corresponding low cycle ductility classes.

Figure 7 shows the assignment of the determined values of the low cycle ductility classes according to prEN 14592 to the classes F1 to F3. With 24 out of 35 screws, most of them could be classified in class F1. As expected, most of them, 21 screws, can be classified in low cycle ductility class S3. But one screw was classified in low cycle ductility class S1 and two in class S2. Classes F2 and F3 do not show a clear trend that this classification corresponds to the classification of the low cycle ductility classes. One screw each from classes F2 and F3 could not even be classified in the lowest low cycle ductility class S1 because it did not meet the criteria. However, it can be clearly seen that most of the screws were classified in the low cycle ductility class S3 and the number of screws in the other classes was small. However, this shows that commercially available screws can usually reach class S3.

The results show that screws that are classified into F3 tend not to be able to be classified into low cycle ductility class S3 and screws that are classified into F1 are more likely to reach class S3. But it cannot be safely assumed that screws that have been classified into F1 can be safely classified into the low cycle ductility class S3. In other words, tests according to EN 409 cannot replace tests according to prEN 14592.

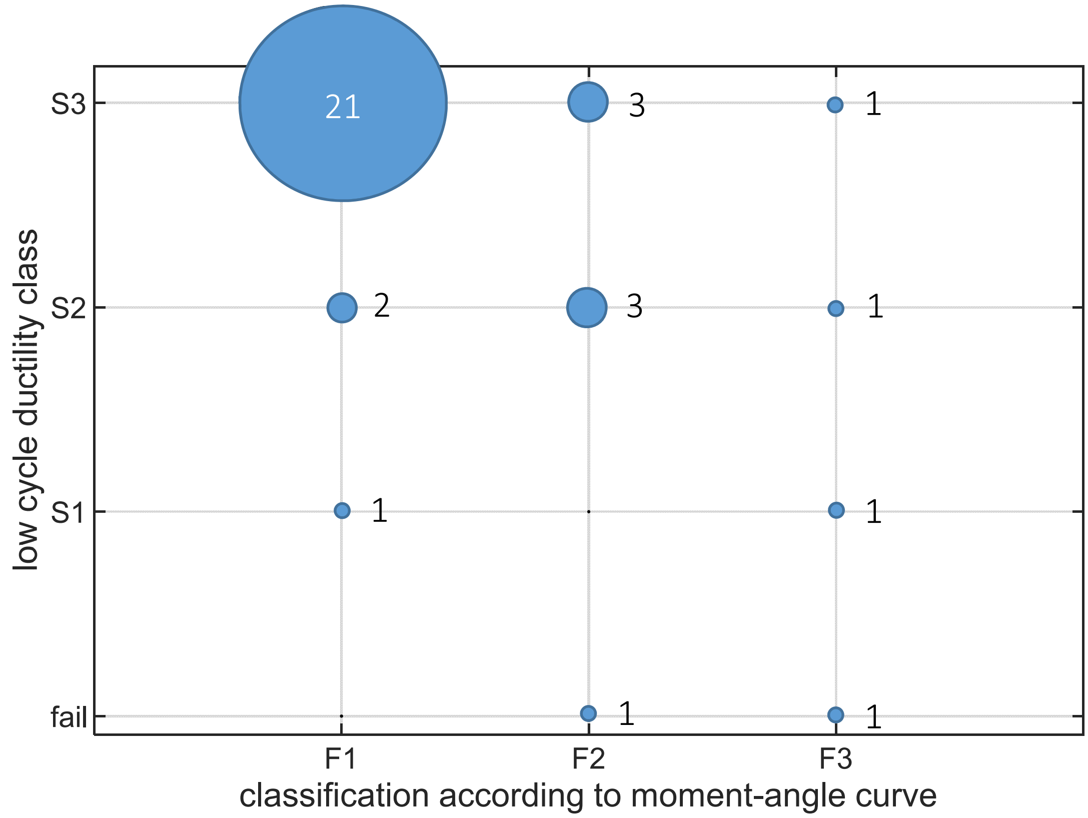
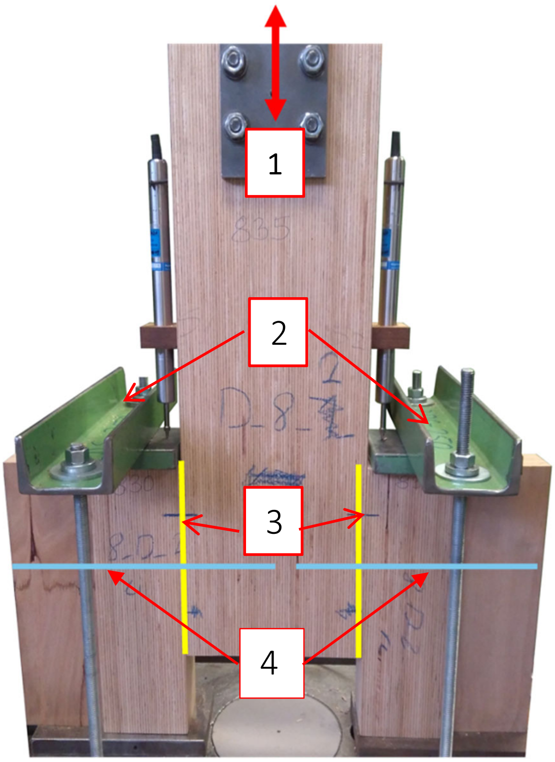


Figure 7: Assignment of the low cycle ductility classes to the classes F1 to F3 (The numbers indicate the number of associated screws)

5 Tests in accordance with EN 12512

Based on prEN 14592, screws can be divided into three different low cycle ductility classes. Investigations that verify this classification with actual cyclic tests on timber joints are not yet available. To gain initial insights into this, screws tested according to prEN 14592 were selected, which achieved both the highest classification S3 as well as the lowest S1. These screws were then used for cyclic tests according to EN 12512 on timber-to-timber joints. The aim of the investigation was to evaluate if joints with screws with different classifications in the low cycle ductility classes show different behaviour under cyclic loading of the joints.

To carry out the tests in accordance with EN 12512, the focus was placed on ductile joint behaviour, testing a joint with only one screw. For this reason, the timber cross-sections as well as the end and edge distances were chosen to be very large in order to prevent early timber failure. Two different timber materials were used, spruce (Picea abies) and laminated veneer lumber made of beech (beech LVL). In Figure 8, the test setup and the test procedure can be seen. Tests with two different fully threaded screws were carried out, where the specimen layout was symmetric, testing two joints with one screw per shear plane. The screws classified in low cycle ductility class S1 had a diameter of 6.5 mm and for the screws classified in class S3, the diameter was 8 mm. A total of nine tests were carried out.



1) Load device
2) Holding device
3) Shear plane
4) Inserted screws

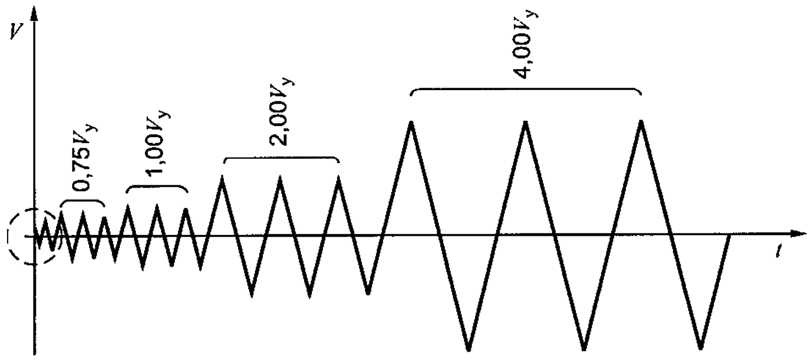


Figure 8: Left: Test setup. Right: Test procedure according to EN 12512

Figure 9 and Figure 10 show the load-displacement curves of joints with beech LVL and softwood. On the left side, the joint with S1-classified screws is shown (d = 6.5 mm), and on the right side, the joint with S3-classified screws (d = 8 mm). The joints with the S1-classified screws failed at a number of cycles that the S3-classified screws could go through without failure. The reason for failure was the breaking off of the S1-classified screws.

It is striking that the shape of both curves for each wood type is almost identical although both diameters differ by 1.5 mm. This suggests a stronger hardening, which could explain the lower classification in S1. Summarising, the joint with S3-classified screws shows a more ductile behaviour compared to the joint with S1-classified screws, which confirms the differentiation in classification of the screws according to prEN 14592.

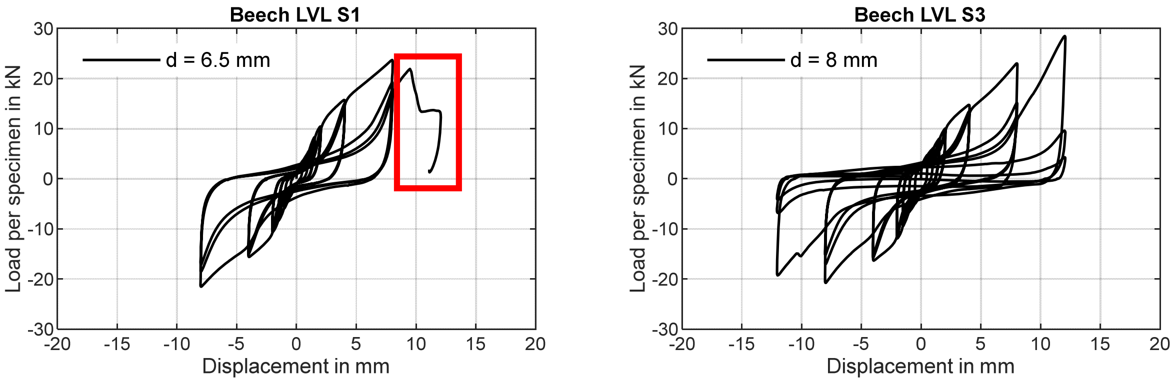


Figure 9: Load-displacement curves for tests according to EN 12512 in beech LVL; left side: S1-classified screw, right side: S3-classified screw

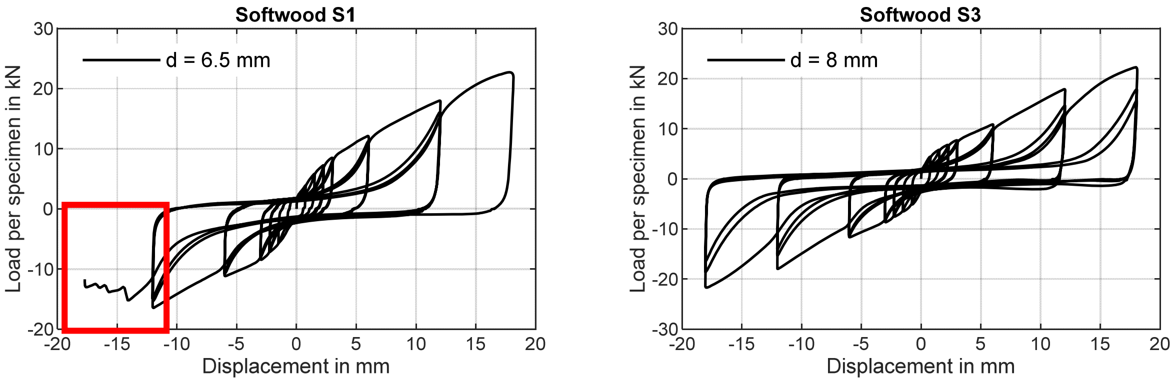


Figure 10: Load-displacement curves for tests according to EN 12512 in softwood; left side: S1-classified screw, right side: S3-classified screw

6 Conclusion and outlook

Tests were carried out on screws according to the test procedure in prEN 14592 for classification into low cycle ductility classes. The parameters testing time, diameter of the mandrel and support distance were examined and discussed for their influence on the results of tests according to prEN 14592. It was found that the support distance l_b has the greatest influence on the test results. In the standard, this parameter only has an upper limit. However, a more precise definition of the support distance is required, in particular to be able to compare test results between different test laboratories.

Furthermore, the relationship between monotonic bending tests according to EN 409 and cyclic tests according to prEN 14592 was examined. It could be shown that although there is a tendency that fasteners with ductile behaviour according to EN 409 can be classified in a high low cycle ductility class according to prEN 14592, this cannot be determined with certainty. Therefore, the tests according to prEN 14592 cannot be replaced by purely monotonic tests according to EN 409.

Finally, tests were carried out on timber-to-timber joints according to EN 12512 with screws classified in low cycle ductility classes S1 and S3, to evaluate the influence of screw classification on cyclic behaviour of joints. The tests were carried out on beech joints and softwood joints, each with one screw per shear plane. In these tests, a tendency can be seen that S3 screws lead to improved cyclic behaviour than S1 screws, especially in beech joints. However, a joint with only one screw with a very large edge and end distance was selected for the tests. Real joints, however, consist of several screws, with smaller distances. Further tests are therefore necessary to investigate the influence of the low cycle ductility classification of the screws on the cyclic behaviour of more realistic joints, including tests on steel-to-timber joints.

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