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PROTOCOLS AND RESULTS ANALYSIS METHODS FOR CYCLIC TESTS OF TIMBER JOINTS. A DISCUSSION

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ABSTRACT: Current testing procedures for cyclic loading are quite flexible and the influence of fundamental testing parameters on the obtained load-deformation behaviour is often questioned (number and amplitude of the loading cycles, loading rate, number of specimens, etc.). On the other hand, different methods for data assessment have been used for the definition of stiffness, ductility, strength and stiffness degradation, as well as parameters for analytical and numerical models. However, reliable and well-established assessment methods are required, to support the safe and economic design of timber joints. Fundamental parameters for seismic design, such as ductility or strength degradation, cannot depend on the testing protocol and method for assessment of the data results. In this context, it is important to compare the most representative loading protocols, and assessment methods of the test results, through detailed analysis and discussion. Different types of timber connections, made of distinct materials and tested in different laboratories, must be evaluated. This work will be developed within the RILEM TC TPT, and this paper represents a first contribution to a needed discussion about the testing protocols to evaluate timber connections. In the end, it is expected to present proposals on how to characterize better the properties and behaviour of timber connections under cyclic loading and how to fully utilize their potential in design.

KEYWORDS: Testing protocols, Cyclic loading, Data assessment, Timber connections, RILEM TC TPT

1 INTRODUCTION

The behaviour of timber joints is one of the most important topics in the field of timber structures, and one of the most studied, given their critical role and importance in the local and overall behaviour of timber structures. Due to the brittle nature of wood material, timber elements must be considered elastic, while the nonlinear responses must be concentrated on the joints. The yielding of the metallic dowel-type fasteners can ensure the dissipation of seismic energy together with deformation capacity [1]. As a result, mechanical connections have to be properly designed in order to show adequate low-cyclic fatigue strength, developing plastic deformations with medium-to-high amplitude when subjected to cyclic loads [2]. Given the complexity of their behaviour (anisotropic behaviour of wood, stress concentration around fasteners, variability of mechanical properties, moisture-dependency, size effects), in particular under cyclic loading, research is often based on the experimental evaluation of joints.

Current testing procedures for cyclic loading are quite flexible and the influence of fundamental testing parameters on the obtained load-deformation behaviour is often questioned (number and amplitude of the loading cycles, loading rate, number of specimens, etc.). On the other hand, different methods for data assessment have been used for the definition of stiffness, ductility, strength and stiffness degradation, as well as parameters for analytical and numerical models [3]. Several studies have highlighted the importance of achieving a general consensus within the research community to define a unique cyclic-test procedure and the appropriate definition of yield and ultimate slips to avoid inconsistencies due to high variability in the definition of ductility [3, 4]. Following the initiatives of research and professional community, a technical report ISO/TR 21141 entitled “Timber structures – Timber connections and assemblies – Determination of yield and ultimate characteristics and ductility from test data” was published in 2022 [5] as a result of work and discussions of the ISO/TC 165 technical committee for timber structures. In the document, different methods for determining the yield and ultimate characteristics and ductility of joints and assemblies from test data used in existing standards in Europe, North America and Far East Asia are described and the basic data for unifying the evaluation methods of

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parameters by clarifying their similarities and differences is provided.

Meanwhile, a guideline to determine ultimate slip and consequently ductility of timber joints from cyclic tests by considering also strength degradation and impairment is included within an annex to the new Eurocode 8 proposal, namely prEN 1998-1-2:2022, Annex N [6]. However, the relationship between strength degradation and ductility has not been discussed in detail.

2 CYCLIC TEST LOADING PROTOCOLS AND RESULTS ANALYSIS METHODS

The most representative load protocols for cyclic tests are the EN 12512 [7] and ISO 16670 [8]. Equally important, the method used to analyse the test data can differ. Widely used are the analysis methods according to EN 12512, Yasumura and Kawai [9], Kobayashi and Yasumura [10] and the ASTM E2126 [11].

2.1 Cyclic loading protocols

For both EN 12512 and ISO 16670, the loading protocols are defined in dependence on the non-linear response of the connection obtained under monotonic loading, conducted according to EN 26891 [12] and ISO 6891 [13], respectively.

However, according to EN 12512 (and the prEN1998 as well), the imposed cyclic loading in terms of the cyclic displacement schedule (Figure 1) is set based on yield displacement, obtained in monotonic test ($\nu_{y,M}$), while in ISO 16670, the loading time history is defined based on ultimate displacement ($\nu_{u,M}$).

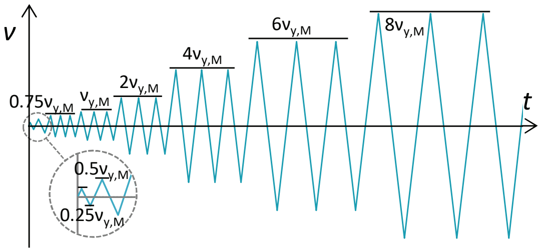

Figure 1: *Loading protocol defined in dependence of yield displacement according to EN 12512 [7].*

The loading protocol in EN 12512 is definite; the first two loading steps applied in one loading cycles (amplitudes 25% and 50% of ν_y), are followed by subsequently increased amplitude displacements each with three loading cycles (75%, 100%, 200%, 400%, 600%,… of ν_y).

On the other hand, initial loading amplitudes in ISO 16670 up to 10%ν_u. (1.25%, 2.5%, 5% and 10% of ν_u), are conducted with one loading cycle, but may be omitted or repeated depending on the joint stiffness and testing/measuring equipment. All the subsequent amplitude displacements are loaded in three loading cycles (20%, 40%, 60%,… of ν_u).

The ASTM E2126 is more flexible with loading protocols allowing the displacement-controlled loading to be conducted according to: a) Sequential Phased Displacement (SPD) Loading Protocol, which involves displacement cycles grouped in phases at incrementally increasing displacement levels (either sinusoidal or triangular); b) ISO 16670 loading protocol or c) CUREE Basic Loading Protocol, with displacement cycles grouped in phases at incrementally increasing displacement levels and the loading history starting with a series of (six) initiation cycles at small amplitudes (of equal amplitude). Further, each phase of the loading history consists of a primary cycle with amplitude expressed as a fraction (percent) of the reference cycle deformation and subsequent trailing cycles with an amplitude of 75 % of the primary one.

The loading rates also differ according to the standards; the slip rate should according to EN 12512 be constant and may range between 0.02 and 0.2 mm/s, while according to ISO 16670 alternative cyclic displacement schedules – either velocity or frequency based - are allowed with the slip rates between 0.1 and 10 mm/s. Similar is according to ASTM E2126, where the displacement loading rate should be between 1.0 and 63.5 mm/s (standard intended for both lateral resisting systems and shear and hold-down connections) and the cyclic frequency range from 0.2 to 0.5 Hz.

Regarding the loading protocols, Casagrande *et al.* [2] concluded that an increase in the number of cycles leads to greater precision of the results and propose an amendment to the cyclic test protocol given by EN 12512.

2.2 Analysis of the test results

From the lateral force-deformation hysteresis curves various characteristics can be evaluated; besides the performance of the connection in terms of strength and deformation, hysteresis with repeated cycles enables the analysis of strength and stiffness degradation and energy dissipation.

To compare different responses, hysteresis envelope curves are often used. Important parameters, such as elastic and plastic stiffness, yield and ultimate displacement (slip), and ductility are evaluated from hysteresis envelopes by considering agreed criteria for idealisation.

Ductility is defined as the ultimate to yield slip ratio and it therefore highly depends on both yield and ultimate slip definitions.

Ultimate slip ν_u is commonly defined as the smallest of failure slip, slip at 20% of strength drop considering 1st Load-Slip Envelope Curve (1st LEC) or absolute slip limit (30 mm in EN 12512).

Yield slip ν_y can according to EN 12512 be calculated considering two different procedures. When the 1st LEC presents two well-defined linear parts, the yield slip ν_y is determined by the intersection between the two lines

(Method A). When two well-defined linear parts are not observed, ν_y is determined by the intersection of two additional lines (Method B): the first line (denoted as the elastic line), with slope K_α (stiffness), is determined as that drawn through the point on the curve corresponding to 10% of the maximum load F_{max} and the point on the curve corresponding to 40% of F_{max}. This stiffness is in the paper labelled $K_{10\text{-}40}$, in the prEN 1998-1-2 proposal $K_{SLS,v,c}$, but it is also commonly referred to as elastic stiffness and labelled K_e. The second line (denoted as plastic line) is the tangent to the backbone curve having an inclination K_β equal 1/6 inclination of the first line (K_α).

ASTM E2126 [11] and Kobayashi and Yasumura [10] apply the Equivalent Energy Elastic-Plastic (EEEP) method to determine the yield slip ν_y and the ductility (D), through the definition of equivalent bi-linear ideally elastic, ideally plastic curve. In general, to determine such a curve considering the EEEP criterion, two more criteria besides EEEP are needed. While there are not many differences in the definition of ultimate displacement (one criterion), the other criterion may either be assumed/defined effective stiffness and less commonly assumed/defined idealised strength capacity. The first is adopted by Kobayashi and Yasumura, who determine yield slip ν_y through EEEP by assuming K_{ef} and calculating idealised force. The K_{ef} is in their case defined according to Yasumura and Kawai [9] as the point in the curve at the same force, at which the secant line through 10 and 40% F_{max} intersects a tangent line to the curve with an inclination of a secant line through 40 and 90% F_{max}. Similar is proposed in ASTM E2126, where the assumed effective stiffness K_{ef} is defined as stiffness at 40% F_{max}. Some authors use in a similar way the EEEP criterion to define the bi-linear curve considering the effective stiffness determined from EN 12512 (stiffness corresponding to ν_y) and to evaluate ductility more conservatively in comparison to EN 12512 by defining the yield slip as the elastic displacement of the idealised bi-linear curve. The use and comparison of such idealisation are presented in the paper for the second case study.

Within the revision process of Eurocode 8, Casagrande *et al.* [1] proposed a novel methodology, which defines an interaction between the strength degradation and the ductility capacity, offering two major contributions to the field: i) it defines a relationship between the slip amplitude and the impairment of strength from the 1st to 3rd cycle and provides an additional condition for determination of ultimate slip in dependence of strength impairment limit; and, ii) it considers the strength degradation as an additional condition for the determination of ultimate slip of dissipative connections subjected to low-cyclic load testing.

The strength impairment factor φ_{imp} is determined as the ratio of reduction of resistance between the 1st (F_1) and the 3rd (F_3) loading cycle to the resistance obtained at the 1st loading cycle (F_1) for the evaluated amplitude displacement ν_i (Equation (1)).

$$\varphi_{imp}(\nu_i) = \frac{F_1(\nu_i) - F_3(\nu_i)}{F_1(\nu_i)} \tag{1}$$

According to the prEN 1998-1-2, Annex N, the φ_{imp} should be lower than 0.3 and if reached or exceeded, the corresponding deformation should be considered as ultimate deformation.

The strength degradation factor k_{deg} is calculated as the ratio of the resistance obtained in 1st loading cycles (in cyclic tests) to the mean resistance obtained in monotonic tests $F_{max,M}$ (Equation (2)).

$$k_{deg} = \frac{F_1}{F_{max,M}} \tag{2}$$

According to the proposal, the value of k_{deg} should not be smaller than 0.8; if this value is not reached at all, the joint should be considered as non-dissipative, whereas otherwise the deformation at which the defined k_{deg} limit is reached is set as ultimate displacement.
At this point, it can be mentioned that to the authors' knowledge, the reductions of ultimate lateral displacements, apart from those specified also in the current EN 12512 (failure slip, 1st LEC post-peak strength reduction or/and absolute displacement limit) are very rare in the literature for both connections and structural elements. One example is the limitation of ultimate displacement to the intersection of the 1st LEC and the idealised bi-linear curve, obtained with EEEP, in the idealisation of non-linear response of structural masonry walls [14], which is however not used in current practice.

Energy dissipation is another important parameter of non-linear behaviour that is according to EN 12512 evaluated from the tests results in terms of equivalent viscous damping coefficient, ν_{eq}. As opposed to the original definition for its calculation by Jacobsen [15], (Equation (3)), which considers dissipated and input/potential energy (E_D and E_P, respectively) of the whole loading cycle as defined in Figure 2a, EN 12512 considers only half loading cycle (Equation (4)) with E_D and E_P as defined in Figure 2b.

$$\nu_{eq} = \frac{E_D}{4\pi E_P} \tag{3}$$

$$\nu_{eq} = \frac{E_D}{2\pi E_P} \tag{4}$$

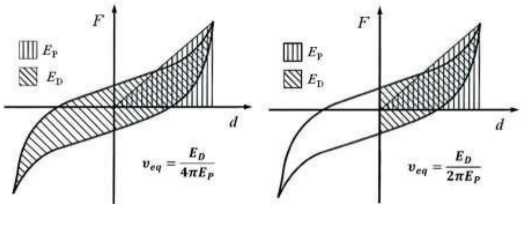

Figure 2: *Equivalent viscous damping according to a. Jacobsen [15], and b. EN 12512 [7].*

3 COMPARISON BETWEEN THE EN 12512 AND ITS PROPOSAL UPDATED FOR ANALYSIS OF RESULTS IN 2019

A first comparison of different methods for the analysis of cyclic test results is presented. In an experimental campaign conducted at the University of Minho (UMinho), a series of angle brackets (AE116) and hold-down (HTT22) connections have been tested under monotonic and cyclic loading. Tension and shear loads were considered while varying the support element (steel and CLT). The loading protocol adopted for the cyclic tests was the one proposed by Casagrande *et al.* [2]. However, two different approaches have been used to analyse the results of the tests. The current version of EN 12512 [7] and a new proposal for this standard presented within the CEN/TC250/SC8/WG3 in 2019 [16], have been used. It is worth mentioning that the definition of the cyclic test protocol was based on yielding displacement quantified based on the method suggested in [16], which is in accordance with ASTM E2126 [11], see Figure 3.

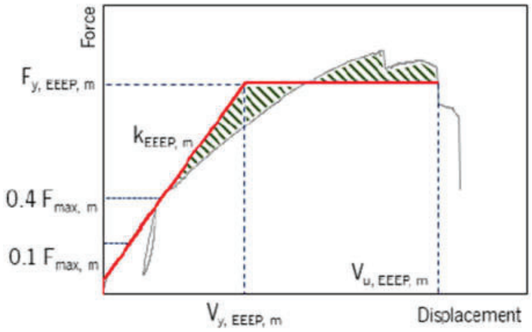

Figure 3: *Analysis of the data from a monotonic test made following EN 26891, as defined by [6] and [14].*

Regarding the degradation factor, which represents a load reduction factor between the 1st Load-Slip Envelope Curve (1st LEC) and 3rd Load-Slip Envelope Curve (3rd LEC), the new proposal [16] does not recommend values less than 0.6, while the current version [7] says nothing about it. The quantification of the different parameters and definition of the bilinear curve is analogous to the monotonic tests, it is being quantified through the 1st Load-Slip Envelope Curve (1st LEC), as can be seen in Figure 4. To define the ultimate displacement, besides those reported for monotonic tests, it can be given by the minimum value of degradation factor (0.6). However, it is important to note that the 3rd Load-Slip Envelope Curve (3rd LEC) can be crucial for the quantification of the ultimate displacement. On the other hand, the strength degradation and the 1st LEC can only be quantified if the total number of cycles is applied to the step.

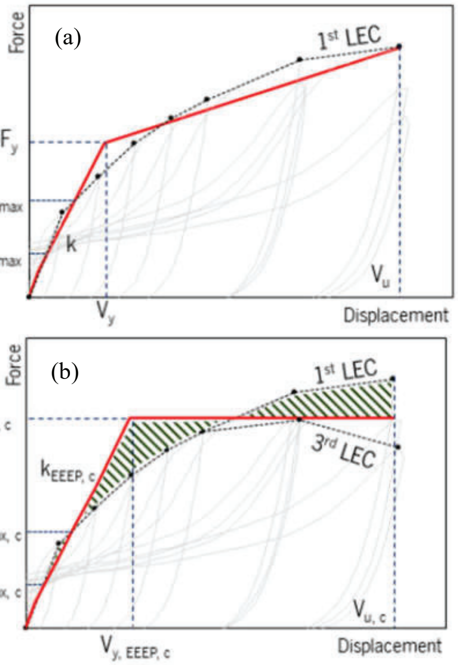

Figure 4: *Brief comparison of the analysis of cyclic tests data between current EN 12515 [7] (a) and the new proposal [14] (b).*

Table 1 summarizes the main results as the average of the three cyclic tests performed for each case studied considering both directions of loading as suggested by [16].

Table 1: *Results of the cyclic tests applying the EN 12512 [7] and the new proposal [16].*

Sample	Method	$K_{10\text{-}40}$ (N/mm)	ν_y (mm)	ν_{eq} (%)	D
AE116	[7]	6141	3.3	15,6	5,4
Shear	[16]	5392	5.7	3.9	3.3
Steel base	Δ (%)	12.2	70,9	74,8	39,4
AE116	[7]	2749	4.4	20.6	4,9
Shear	[16]	2282	7.7	5.0	2.6
CLT base	Δ (%)	17.0	75.5	75.8	48.2
AE116	[7]	7263	2.6	17.2	8.4
Tension	[16]	5626	6.5	8.7	3,6
Steel base	Δ (%)	22.5	152	49.5	56.7
AE116	[7]	12337	0.6	47.8	7.8
Tension	[16]	6535	2.0	22.5	3.2
CLT base	Δ (%)	47	235	52.8	58.4
HTT22	[7]	8624	2.9	36.5	6.5
Tension	[16]	6456	6.6	19.8	2.9
	Δ (%)	25.1	125	45.8	55.2

The comparison between the methods of analysis come out a difference for all mechanical parameters, where the smallest differences are relative to the elastic stiffness ($K_{10\text{-}40}$). It is possible to see higher values of yielding displacement (ν_y), and, on the other hand, lower values of equivalent viscous damping (ν_{eq}), and ductility (D), applying the new proposal discussed within CEN/TC250/SC8/WG3 [16] in comparison to the current EN 12512 [7].

4 COMPARISON BETWEEN THE EN 12512 AND THE prEN 1998-1-2, ANNEX N PROPOSAL

In the second case study, the impact of the analysis method is evaluated for experimental tests conducted according to EN 12512 [7]. The results are analysed according to the referred standard and according to the new proposed prEN 1998-1-2, Annex N[6]. For the comparison, the results of an extensive testing campaign studying the shear behaviour of cement-particle board-to-timber connections by metal staples, conducted at the Slovenian National Building and Civil Engineering Institute (ZAG), have been re-evaluated according to the proposed guideline. The chosen experimental tests are interesting for comparison, because in cyclic tests, large strength degradation was obtained for the connections already before achieving maximum load-bearing capacity (evident from typical backbone envelope hysteresis curves presented in Figure 5, lower). Furthermore, the performance of the studied sheathing-to-timber connections were tested also on the level of structural elements. The connections were used in the construction of light-frame timber shear wall panels (LFTP) whose behaviour under in-plane monotonic and cyclic loading has been experimentally tested as well.

Monotonic and cyclic shear tests were conducted for two variations of boards-to-timber connections with different staple geometry and cement-particle board thickness. They were labelled in dependence of the boards' thickness; B12 for 12-mm and B16 for 16-mm board, respectively, with corresponding staple geometry 1.53 × 11.25 × 45 mm and 2.0 × 11.76 × 50 mm. More specific details on the materials, test specimens and on the test setup of the experimental monotonic and cyclic shear tests of two variations of connections can be found in [17] where the experimental results of cyclic shear tests on LFTP constructed using the tested connections are presented as well.

The test results of connections analysed according to current EN 12512 [7] proved that the connections exhibit large ductility both under monotonic (Figure 5, upper) as well as under cyclic loading (Figure 5, lower). Calculated average ductilities, D, the corresponding yield slip, v_y, the load-bearing capacity, F_{max}, and elastic stiffness, $K_{10\text{-}40}$, are for the conducted tests of connections with monotonic (M) and cyclic (C) loading protocols summarised in Table 2. Furthermore, the table presents ductility calculated by considering EN 12512 and additional EEEP criterion (definition of yield point is equal to elastic displacement v_e of the bilinearly idealised hysteresis curve defined considering equal input energy, see Figure 6), and by considering Kobayashi and Yasumura idealisation criteria [10]. For both tested connections at least three tests were conducted and are considered in statistics for both loading protocols (monotonic and cyclic).

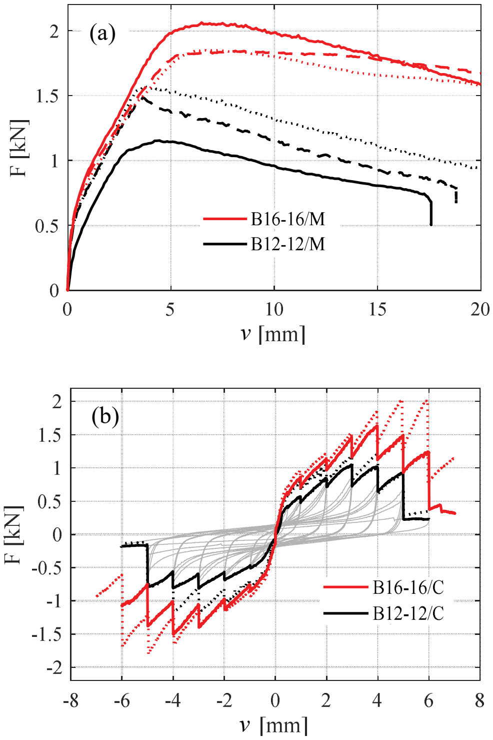

Figure 5: *Lateral load-lateral displacement curves obtained for the two studied sheathing-to-timber connections with staples in monotonic (a) and cyclic ((b), hysteresis backbone envelopes and one full hysteresis curve presented) shear tests.*

Results show that significant differences in ductility are obtained if different yield point definitions are assumed for its calculation. More conservative ductility compared to EN 12512 was obtained considering EN 12512 and additional EEEP criterion. The obtained ductilities in cyclic tests are then lower by 28 and 27% for B12 and B16 connections, respectively. Idealisation by Kobayashi and Yasumura produced even more conservative ductility results, i.e. ductility is in average for 42% and 39% lower than according to EN 12512 for B12 and B16 connections, respectively. Both criteria which consider EEEP are more conservative, since the yielding point for ductility calculation is considered as the yielding point of the idealised bi-linear curve, which is larger than then the yielding point according to EN 12512.

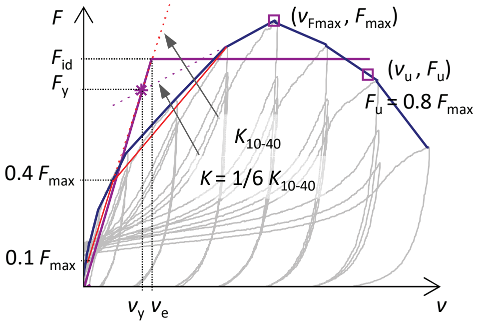

Figure 6: *Idealisation according to EN 12512 and idealisation to bi-linear curve with additional EEEP criterion.*

Furthermore, large differences in average lateral strength were obtained between monotonic and cyclic tests. As evident from the table, the average lateral strengths obtained in the first loading direction of cyclic tests are 14.2 and 17.0% lower than those obtained in monotonic tests for the B12 and B16 connections, respectively. Moreover, the difference in the lateral strength capacities obtained in the two testing directions was not negligible. The strength results are for both connections in the second loading directions lower on average by 12%. The average values of both loading directions are for all the characteristic results too presented in Table 2 (in brackets next to the first loading direction results). For the B16 connection, the average lateral cyclic strength capacity in both directions ($C^{+,-}$) is on average 20% lower than monotonic (M) lateral strength.

While the lateral strength capacity was in the second loading direction evidently smaller, there was however no significant change in ultimate displacements achieved in the two loading directions (that is in case only EN 12512 limit for ultimate displacements, i.e. 20% post-peak maximum lateral strength drop in hysteresis envelope, is considered).

Table 2: *Average results of the monotonic (M) and cyclic tests in first (C) and both loading directions ($C^{+,-}$, in brackets) with evaluated idealised parameters according to EN 12512 [7], EN 12512 with additional EEEP criterion and Kobayashi and Yasumura criteria [10].*

Connection	Loading protocol	No. of tests	$F_{max/staple}$ [kN]	$K_{10\text{-}40}$ [kN/mm]	v_y [mm]	v_e [mm]	D	D	D
				EN 12512 [7]	EN 12512 [7]	EN 12512 +EEEP	EN 12512 [7]	EN 12512 +EEEP	Kobayashi and Yasumura [10]
B12	M	3	1.41	1.00	1.09	1.29	9.9	8.2	7.7
	C ($C^{+,-}$)	10	1.21 (1.14)	1.15 (1.10)	0.71 (0.69)	0.94 (0.92)	7.8 (7.8)	5.6 (5.6)	4.54 (4.55)
	Δ (%)		14.2 (19.1)	-15.0 (-10.0)	34.9 (36.7)	27.1 (28.7)	21.2 (21.2)	31.7 (31.7)	69.5 (69.1)
B16	M	3	2.00	0.96	1.25	1.68	18.3	13.2	11.6
	C ($C^{+,-}$)	8	1.66 (1.56)	1.21 (1.20)	0.93 (0.83)	1.21 (1.07)	8.5 (9.7)	6.2 (6.5)	5.20 (5.45)
	Δ (%)		17.0 (20.0)	-26.0 (-25.0)	25.6 (33.6)	28.0 (36.3)	44.1 (36.2)	45.1 (42.5)	123 (113)

The minimum, maximum and average values of ultimate cyclic displacements obtained considering strength impairment limitation equal 0.3, $v_{u,\varphi30}$, relative to ultimate cyclic displacements, $v_{u,c}$, are presented in Table 3. Similarly, relative comparison of obtained ultimate displacements calculated considering the strength degradation limit equal 20% (k_{deg} = 0.8), $v_{u,kdeg0.8}$, compared to ultimate displacement is presented in Table 4. Since the yield slip v_y is according to prEN 1998-1-2, Annex N the same as according to EN 12512, the presented reductions of ultimate displacements apply for the ductility as well. Nevertheless, the obtained values of ductility corresponding to these reductions are for clarity stated in the tables; ductility calculated according to prEN 1998-1-2 considering both strength impairment and degradation criteria is presented in Table 4 ($^*D$).

With strength impairment limitation equal to 0.3, a significant reduction in ultimate displacements is obtained; $v_{u,\varphi30}$ range from 0.558 to 0.745 $v_{u,c}$ for B12 and from 0.712 to 0.962 $v_{u,c}$ for B16 connections with average 0.679 and 0.822 $v_{u,c}$, respectively. It should be noted that for B12 connections the strength impairment equal to or higher than 0.3 was achieved prior to maximum strength in 60% of tests, while for B16 connections in 25% of tests. The minimum, maximum and mean strength impairment values obtained at maximum strength displacements in the first loading cycle direction $\varphi_{imp}(v_{Fmax})$, are presented in Table 3.

Table 3: *Minimum, maximum and mean values of strength impairment for maximum strength displacements φ_{imp} (v_{Fmax}), relative values of reduced ultimate displacements $v_{u,\varphi30}$ and ductility D obtained considering strength impairment.*

Connection		φ_{imp} (d_{Fmax})	$v_{u,\varphi30}$ / $v_{u,c}$	D = $v_{u,\varphi30}$ / v_y
B12	Min	0.251	0.558	2.96
	Max	0.419	0.745	8.10
	Mean (CV)	0.330 (7.9%)	0.679 (7.9%)	5.27 (26.3%)
B16	Min	0.339	0.712	4.00
	Max	0.233	0.962	16.69
	Mean (CV)	0.268 (12.9%)	0.822 (8.8%)	7.17 (55.2%)

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The average strength degradations obtained at maximum strength in the first loading directions of cyclic tests were 0.853 and 0.828 for the B12 and B16 connections, respectively, with minimum values 0.680 and 0.653 for the two connections, respectively.

For the particular tests, in 40% of B12 and in 38% of B16 cyclic tests the strength achieved in the first loading direction did not reach 80% of the average connection strength achieved in monotonic tests, $F_{\mathrm{max,M,mean}}$, and the connections should according to prEN 1998-1-2 be classified as non-dissipative ("N.D." in Table 4). If the second (negative) loading direction is considered, 60% and 75% of the tested B12 and B16 connections, respectively, do not meet this criterion. It can also be noted that strength degradation at maximum resistance was in most cases higher in the second (negative) loading direction. The average k_{deg} at maximum resistance in negative loading direction were 0.766 and 0.721 for the B12 and B16 connections, respectively, with minimum values as low as 0.577 and 0.634.

The strength degradation criterion is, however, for the tested connections in all cases except for one B16 test, not critical in comparison to the strength impairment criterion in case the strength in cyclic tests indeed reached 80% $F_{\mathrm{max,M,mean}}$. For these tests the mean reduced ultimate deformations due to set strength degradation limit, $v_{\mathrm{u,kdeg0.8}}$, are 0.965 and 0.920 $v_{\mathrm{u,c}}$ for B12 and B16, respectively.

Table 4: *Minimum, maximum and mean relative reductions of ultimate displacements $d_{u,kdeg0.8}$ and resulting ductility D due to strength degradation and final ductility $^{*}D$ according to prEN 1998-1-2, Annex N, obtained from cyclic tests.*

Conn-ection		$v_{\mathrm{u,kdeg0.8}}$ / $v_{\mathrm{u,c}}$	D = $v_{\mathrm{u,kdeg0.8}}/v_{\mathrm{y}}$	$^{*}D$ acc. to prEN8-1-2, Annex N
B12	Min	**0.887	**4.23	**2.96 (N.D.)
	Max	1.00	10.7	6.60
	Mean	**0.965	**7.39	**5.17 (N.D.)
	(CV)	(4.5%)	(27%)	(23.7%)
B16	Min	$^{\underline{**}}$0.738	$^{\underline{**}}$4.66	$^{\underline{**}}$3.99 (N.D.)
	Max	1.00	6.48	5.45
	Mean	$^{\underline{**}}$0.935	$^{\underline{**}}$5.75	$^{\underline{**}}$4.72 (N.D.)
	(CV)	(10.6%)	(11.4%)	(10.2%)

Note: * both $v_{\mathrm{u,\varphi30}}$ and $v_{\mathrm{u,kdeg0.8}}$ considered

** 6/10 specimens considered (4/10 specimens did not achieve 0.80 $F_{\mathrm{max,M,mean}}$)

$^{\underline{**}}$ 5/8 specimens considered (3/8 specimens did not achieve 0.80 $F_{\mathrm{max,M,mean}}$)

Connections should be declared as non-dissipative (N.D.) according to prEN 1998-1-2

Whether it is reasonable to declare the tested connections as non-dissipative, could somewhat be opposed with the results of cyclic tests of LFTPs constructed with the tested connections. For all the tested panels with symmetric board and fastening disposition, ductility higher than 4 was obtained, if more conservative EN 12512 idealisation with additional EEEP criterion was considered (4.82 for panels with B16 connections and 4.14 for panels with B12 connections) and higher than 5 if no EEEP was considered (6.93 and 5.76 for B16 and B12 panels, respectively).

5 SHORT SUMMARY OF MAIN RESULTS AND POINTS FOR DISSCUSSION

The following can be concluded from the conducted and re-evaluated test results:

- The proposed new idealisation considering strength impairment and strength degradation may in some cases significantly reduce the ultimate deformation capacity, and consequently also the ductility.
- For the presented re-evaluated test results of stapled connections, the ultimate slip limitation by strength impairment is more critical than by strength degradation, in case 80% of monotonic strength capacity was at all obtained in cyclic tests; approximately 40% of cyclic tests did for not achieve strength degradation factor equal 0.8.
- The strength degradation limit defined in prEN 1998-1-2 may result in declaring as non-dissipative connections, which exhibit ductile behaviour and enable ductile failure of structural elements.

While the new proposal upgrades the analysis of test results by considering strength impairment and strength degradation criteria, its positive and negative effects should be discussed together with other open questions/issues regarding analysis, some of them being:

- Is considering the results of the second loading direction in case of cyclic shear tests of symmetrical connections relevant; is neglecting them safe? As evident also from the second presented case study, most commonly the strength in the second loading direction is lower than in the first loading direction.
- Should lateral strength obtained in monotonic tests be considered as nominal strength and the characteristic value for design be evaluated from it? It can be seen from the test results that the differences between monotonic and cyclic tests may be quite high. If so, this should be considered in defining the safety factors in the design guidelines.
- What are the results of cyclic (and monotonic) tests intended to be used for? Besides determining resistance, stiffness, and ductility for the design perhaps also for comparisons, modelling, and other applications? If so, should the behaviour be idealised and how and which results should be reported? According to ISO 16670, the testing report should among other present also the tabulated envelope curves

for both loading directions, enabling further test analysis to other parties if needed. In comparison to EN 12512 it is according to ISO 16670 not necessary to report the strength impairment and damping ratios for each loading steps (time consuming and expensive analysis if not automated). On the other hand, it is according to EN 12512 not necessary to report stiffness, e.g. $K_{10\text{-}40}$, though it is necessary to calculate it to obtain the yield slip modulus.

- How should the initial slip, often evident in the curves as part with significantly smaller stiffness, be considered in determining the yield and ultimate slip? Specially in test results, where the loading protocol is not controlled through the deformation measured directly in the joint, but for instance through the actuator, this slip may be quite big. While not eliminating it results in conservative estimations of ductility, it increases absolute values of yield and ultimate displacements potentially limiting also ultimate displacements (if higher than absolute limits, such as 30 mm in the current code).
- Does considering the strength impairment and degradation for determining ultimate displacements indeed produce “better” or more safe results? What are their advantages in comparison to considering other criteria which yield lower ductility, such as the EEEP criterion in Kobayashi and Yasumura or EN 12512, but do not reduce ultimate displacements? Are the over-conservative assumptions on ultimate deformation capacity (and ductility) beneficial for performance-based assessment of structures, which is displacement-based?
- Should the new prEN 1998-1-2, Annex N proposal specify also the minimum number/percent of the tested specimens in group, which can exhibit non-dissipative behaviour in terms of strength degradation, that the connection would/could in general still be considered as ductile (as in the presented second case study)?
- Are the definitions of input and potential energy in dependence of “half cycles” for calculation of equivalent viscous damping optimal? They are in comparison to original definition (set in dependence of the “entire loading cycle”) beneficial for shear testing of non-symmetrical connections or testing of the connections in tension and compression. It may however be less convenient for non-symmetrical connections or connections loaded in tension and compression that the “halves” are determined in dependence of deformation (positive and negative slip) and not loading (positive, negative); the ratio of input to dissipated energy can vary significantly in dependence of loading direction and corresponding damage/failure mechanism.

The differences in the loading protocols between different standards, which may influence the behaviour, need to be discussed as well but with considering also other criteria related to tests executions and objectives. Some of these considerations are:

- Regarding the loading rates; the allowed ranges provided in the codes are not the same but are quite large, which is beneficial due to enabling tests execution with various testing and measuring equipment and in acceptable time, but negative in terms of results comparison. The use of EEEP criterion in idealisation of results may be beneficial to reduce the effect of the loading rate, since the influence of loading rate is smaller on the input energy than on the resistance and deformation behaviour (commonly with higher loading rate higher resistances and lower deformation capacities are obtained).
- Regarding the changes of the loading rate within the tests; the possible changes allowed in ISO 16670 enable faster test execution, because for loading cycles with higher displacement amplitudes, higher loading rates can be assigned.
- Regarding the execution of initial slip loading cycles; ISO 16670 is again more flexible by allowing the initial cycles to be omitted and this way enabling the use of wider range of equipment, since inducing loading through very small controlled initial slips according to EN 12512 results in demand for high accuracy controlling and measuring equipment.
- Regarding the definition of amplitude displacements and number of cycle repetitions; issue on how to obtain the proper failure modes of connections under cyclic loading, related to the objectives of the tests, should be addressed; which loading protocol should be used for instance in case of studying the low-cycle fatigue behaviour of the connection or which in case of studying the behaviour under seismic loading.

6 CONCLUSIONS AND OUTLOOK

In the paper, a more detailed state-of-the-art regarding cyclic testing of timber connections is given and the different aspects with need for further test development are discussed. A first comparison of different testing protocols and methods for data assessment is applied for a variety of timber joints. In the case of the experimental campaign performed at UMinho, it was possible to verify large differences between the obtained values by applying two methods for data analysis, namely the current EN 12512 [3] and a proposal discussed within CEN/TC250/SC8/WG3 [14] that has been used as base for Casagrande *et al.* [1]. In this comparison, the smallest difference is relative to the elastic stiffness. Large differences in final results were found also for the second presented case study conducted at ZAG that compares the results of experimental tests analysed according to EN 12512 and the prEN 1998-1-2, Annex N [6]. While already the strength impairment limitation significantly reduces the ultimate displacements (and consequently ductility), the strength degradation limit set in prEN 1998-1-2 is for the presented experimental campaign in most tests not reached. The connections are therefore according to the new proposal classified as non-dissipative, even though they exhibit significant ductility in cyclic tests of connections as well as in the cyclic test of structural elements.

The need for a unified testing standard for cyclic testing of timber connections and analysis of results is often emphasised within the research community and would be beneficial for the industry as well to enable easier sales and use of products in various markets. Nevertheless, aspiration toward such standards should be accompanied by awareness of all the different purposes such tests are carried out for, the implications of the proposed specific guidelines, as well as of the limitations that laboratories/institutes might have in their implementation.

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REFERENCES

[1] A. Jorissen and M. Fragiacomo, ‘General notes on ductility in timber structures’, *Engineering Structures*, vol. 33, no. 11, pp. 2987–2997, 2011, doi: https://doi.org/10.1016/j.engstruct.2011.07.024.

[2] D. Casagrande *et al.*, ‘A methodology to determine the seismic low-cycle fatigue strength of timber connections’, *Construction and Building Materials*, vol. 231, p. 117026, 2020, doi: https://doi.org/10.1016/j.conbuildmat.2019.117026.

[3] W. Muñoz, M. Mohammad, A. Salenikovich, and P. Quenneville, ‘Need for a harmonized approach for calculations of ductility of timber assemblies’, in *Proceedings of the Meeting*, 2008, vol. 41.

[4] M. Piazza, A. Polastri, and R. Tomasi, ‘Ductility of timber joints under static and cyclic loads’, *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, vol. 164, no. 2, pp. 79–90, 2011, doi: 10.1680/stbu.10.00017.

[5] ISO, ‘ISO/TR 21141 Timber structures – Timber connections and assemblies – Determination of yield and ultimate characteristics and ductility from test data’. ISO, 2022.

[6] CEN/TC 250/SC 8/WG3 N156, ‘prEN 1998-1-2:2022 (E), Annex N - v.2022.05.12 (informative) Determination of mechanical properties of dissipative components in timber buildings from experimental cyclic test data’, May 2022.

[7] EN 12512:2005, ‘Timber structures - Test methods - Cyclic testing of joints made with mechanical fasteners’.

[8] ‘ISO16670:2003 Timber structures - Joints made with mechanical fasteners - Quasi-static reversed-cyclic test method’.

[9] M. Yasumura and N. Kawai, ‘Estimating seismic performance of wood-framed structures’, in *Proceedings of 5th WCTE*, 1998, vol. 2, pp. 564–571.

[10] K. Kobayashi and M. Yasumura, ‘Evaluation of plywood sheathed shear walls with screwed joints tested according to ISO 21581’, in *Proceedings of CIB-W18 meeting. KIT, Alghero, Italy*, 2011, vol. 10.

[11] ASTM, ‘ASTM E2126-11 - Standard Test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Vertical Elements of the Lateral Force Resisting Systems for Buildings’. ASTM, 2018.

[12] CEN, ‘EN 26891:1991 Timber structures - Joints made with mechanical fasteners - General principles for the determination of strength and deformation characteristics (ISO 6891:1983)’, 1991.

[13] ISO, ‘ISO 6891:1983 Timber structures — Joints made with mechanical fasteners — General principles for the determination of strength and deformation characteristics’, May 1983.

[14] M. Tomaževič, *Zidane zgradbe na potresnih območjih*. Fakulteta za arhitekturo, gradbeništvo in geodezijo, VTOZD Gradbeništvo in …, 1987.

[15] L. S. Jacobsen, ‘Steady forced vibration as influenced by damping’, *Transactions of ASME*, vol. 52, p. 13, 1930.

[16] CEN/TC 250/SC8/WG3A, ‘A proposal for the revision of the European Standard EN 12512, Timber structures - Test methods - Cycling testing of timber connections and assemblages for seismic design, Version n. 20190312’. 2019.

[17] M. Kržan, T. Pazlar, and B. Ber, ‘Improved seismic response of light-frame-timber panels with cement-particle-board sheathing of various thicknesses and different configurations of fasteners’, *Engineering Structures*, vol. 253, p. 113757, 2022, doi: https://doi.org/10.1016/j.engstruct.2021.113757.

https://doi.org/10.52202/069179-0479