Influence of different standards on the determination of earthquake properties of timber shear wall systems

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1 Introduction

Shear wall tests on two modern timber construction systems were carried out by Karlsruhe Institute of Technology (KIT). Regarding test results such as stiffness, horizontal load-carrying capacity, hysteresis shape and hysteresis equivalent viscous damping ratio, all results are similar to or even better than the well-known timber frame system. This means that both systems should also be suitable for the use in seismic active areas.

Innovative systems usually do not fit into the design concepts according to Eurocode 8 (EC8, [1]), thus their behaviour factor cannot be found there. The only approach to classify systems into a ductility class specified in EC8 is the declaration of a static ductility. This is insufficient because important characteristics like the energy dissipation and the boundary conditions of the tests are not taken into account. Since no uniform standard for the determination of seismic properties of timber construction systems exists, several problems are identified.

Following from the insufficient static-ductility-approach, the ductility classes for the systems would be too conservative. Thus the evaluation of the behaviour factor q for the tested systems was carried out using a numerical simulation, taking into account the essential properties of the system considered. Difficulties when determining q are described in this paper since several standards influence the value of the behaviour factor. A possible solution of this problem is proposed.

2 Experimental study of shear wall systems

Most of today's timber residential houses are timber frame constructions. A great multitude of studies concerning almost any aspect of construction with timber frame systems exists. New ideas regarding building physics or simple assembling and finishing timber construction systems led to innovative constructions. In some cases (X-lam), manufacturing progress led to a general possibility of using innovative materials. The systems studied and several tests carried out with these are presented in the following.

2.1 X-Lam massive panel system

The X-lam massive panel system is made up of cross-laminated timber panels of 0.625 m x 2.5 m (length x height) with different thicknesses. Crosswise lamination of sawn timber members results in a closed load bearing layer on the outer panel side, an open grid on the inner side can be used for installation (Fig. 1 a)). To produce an entire wall, the panels are mounted between associated top and bottom rails. The outermost vertical boards of each panel are omitted to attach the so called shear (or connection) boards. These are attached to

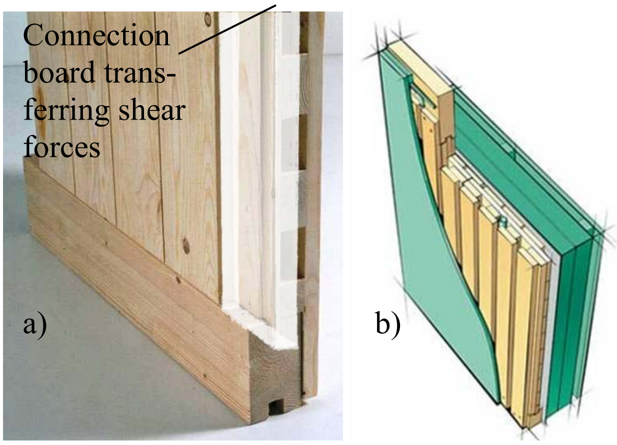


Fig. 1 a) Close-up view of the bottom of a single X-lam massive panel, b) Panel with inner finish plus installation and outer insulation

both panels with mechanical fasteners (such as staples, grooved coil-nails or screws) to transfer shear forces between the panels when the wall is loaded horizontally.

The vertical timber boards of the panels overlap on both, top and bottom side, where they are connected to the bottom and top rail with the same fasteners that are used for the shear boards. Openings for doors and windows are spared in the factory, so pre-assemblage is possible to a great extent. Wall sizes are primarily limited by transportation requirements; the erection of buildings thus is very fast. Ready made installation channels contribute to low costs and high flexibility for the completion of the interior (Fig. 1 b)).

2.1.1 Joints of X-Lam massive panel system

Looking at a timber framed wall, the dissipative zones are firstly the connections between the sheathing and the framing as well as the hold-downs. Hence, when investigating the earthquake behaviour of a timber framed wall, these connections should be considered as it is stated in EC8: “The properties of dissipative zones should be determined by tests either on single joints, on whole structures or on parts thereof in accordance with EN 12512 [2]” and it is also stated that “the dissipative zones shall be located in joints and connections, whereas the timber members themselves shall be regarded as behaving elastically.”

Looking at the X-Lam massive panel system, it is obvious that the dissipative zones are the fasteners at the connector boards as well as the connections to the top and bottom rails. To

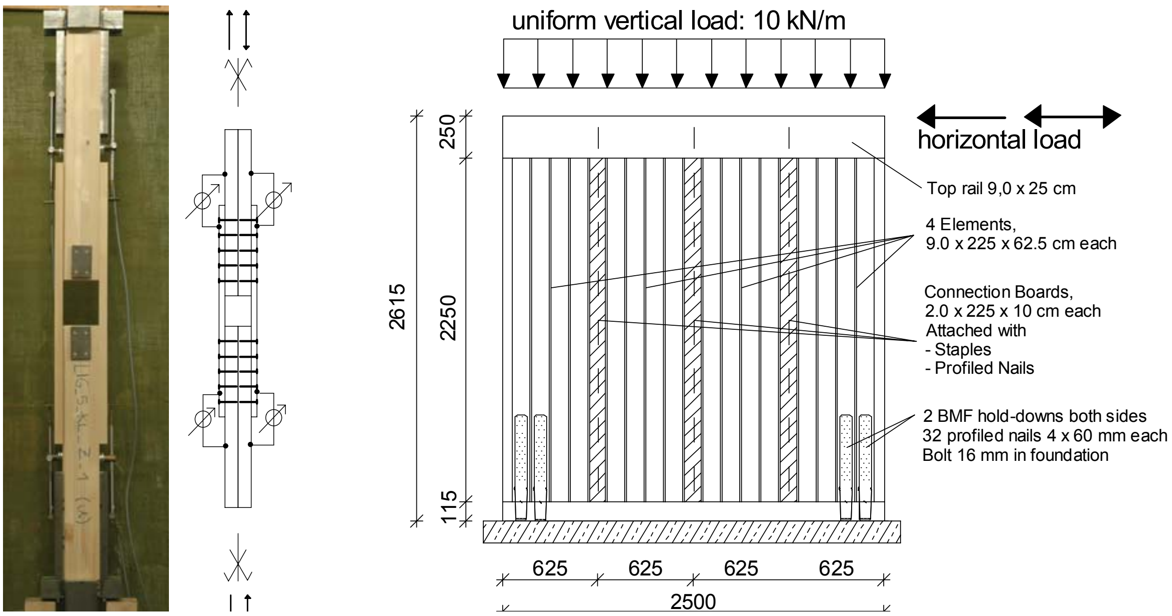


Fig. 2 Tension-Compression-Test for the X-Lam massive panel system using 5 connectors (left), Shear wall test specimen for X-Lam massive panel system (right)

gain information on the cyclic behaviour of the described joints, a test setup as shown in Fig. 2 (left) was chosen. This tension-compression test represents the geometry of the panel and the connector boards. Lateral supports to avoid bending and buckling of the specimen are not shown in Fig. 2 (left) but were used during the tests. A number of 2,5 and 10 connectors in a row were chosen for the tests to consider potential splitting effects as well as to gain calibration data for numerical models.

2.1.2 Shear wall tests on X-Lam massive panel system

A test specimen of a X-Lam massive panel shear wall can be seen in Fig. 2 (right). A total of 25 shear wall tests with the X-Lam massive panel system was carried out, however only cyclic tests with staples and grooved nails are shown in Table 1, since the application of screws is very time-consuming and hence not practicable. The numerous mechanical fasteners in combination with the stiffness of the X-lam panels promised favourable results when subjected to cyclic loading. During the tests the use of 1.83 x 64 mm staples showed to be most efficient for the quick erection of the panels, 2.8 x 65 mm grooved nails were used as an alternative.

The behaviour under cyclic loading is strongly affected by the fastener type. While staples showed pronounced ductile behaviour in all tests, nails tended to break apart at multiple repeated cycles. Softwood boards can be used when only minor horizontal loads, thus low shear forces have to be transferred by the connection boards. To avoid splitting caused by the alignment of fasteners, plywood panels were used. Due to the fact that realistic boundary conditions are postulated in the standard used for the testing (ISO/CD 21581 [3], based on [4]), commercially available hold-downs, which were connected to the panels by ringed-shank nails, were used. According to the high load-carrying capacity of the wall, two hold-downs on either side of the wall had to be employed in the cyclic tests.

Table 1 Shear wall test matrix for X-Lam massive panel system

No.	Description	Connector Boards	Connectors	Connector spacing	Hold-downs
1	ZYK_0_3	Softwood	Staples 1,53 x 55	a_1 = 40 mm	2 KR
2	ZYK_0_4	Softwood	Staples 1,53 x 55	a_1 = 50 mm	2 KR
3	ZYK_0_5	Softwood	Grooved Nails 2,8 x 65	a_1 = 60 mm	2 KR
4	ZYK_10_4	Softwood	Staples 1,53 x 55	a_1 = 50 mm	2 KR
5	ZYK_10_5	Softwood	Grooved Nails 2,8 x 65	a_1 = 60 mm	2 KR
6	ZYK_10_6	Plywood	Staples 1,83 x 63,5	a1 = 50 mm	2 x HTT 22
7	ZYK_10_8	Plywood	Staples 1,83 x 63,5	a1 = 50 mm	2 x HTT 22
8	ZYK_10_12	Plywood	Staples 1,83 x 63,5	a1 = 50 mm	2 x HTT 22
9	ZYK_10_9	Plywood	Grooved Nails 2,8 x 65	a1 = 50 mm	2 x HTT 22
10	ZYK_10_10	Plywood	Grooved Nails 2,8 x 65	a1 = 50 mm	2 x HTT 22
11	ZYK_10_11	Plywood	Grooved Nails 2,8 x 65	a1 = 50 mm	2 x HTT 22

2.1.3 Outcomes: Comparison between cyclic tests on joints and shear wall tests

Comparing the hysteresis shape for the joints tests and for the shear wall tests (Fig. 3), significant differences are observed. Pinching is more pronounced in the joint tests while the slope of the pinched part tends towards zero. The unloading part of the curve is nearly vertical in the joint tests, with the hysteresis equivalent damping being high in the first cycles and getting lower in the following cycles (Fig. 4 (top)). The contrary is observed in the shear wall tests: Exhibiting lower damping ratios in the first cycles, and increasing in the following (Fig. 4 (bottom). It is obvious that the hysteresis shape and also equivalent damping for a connection cannot be used to assess the hysteresis obtained in shear wall tests.

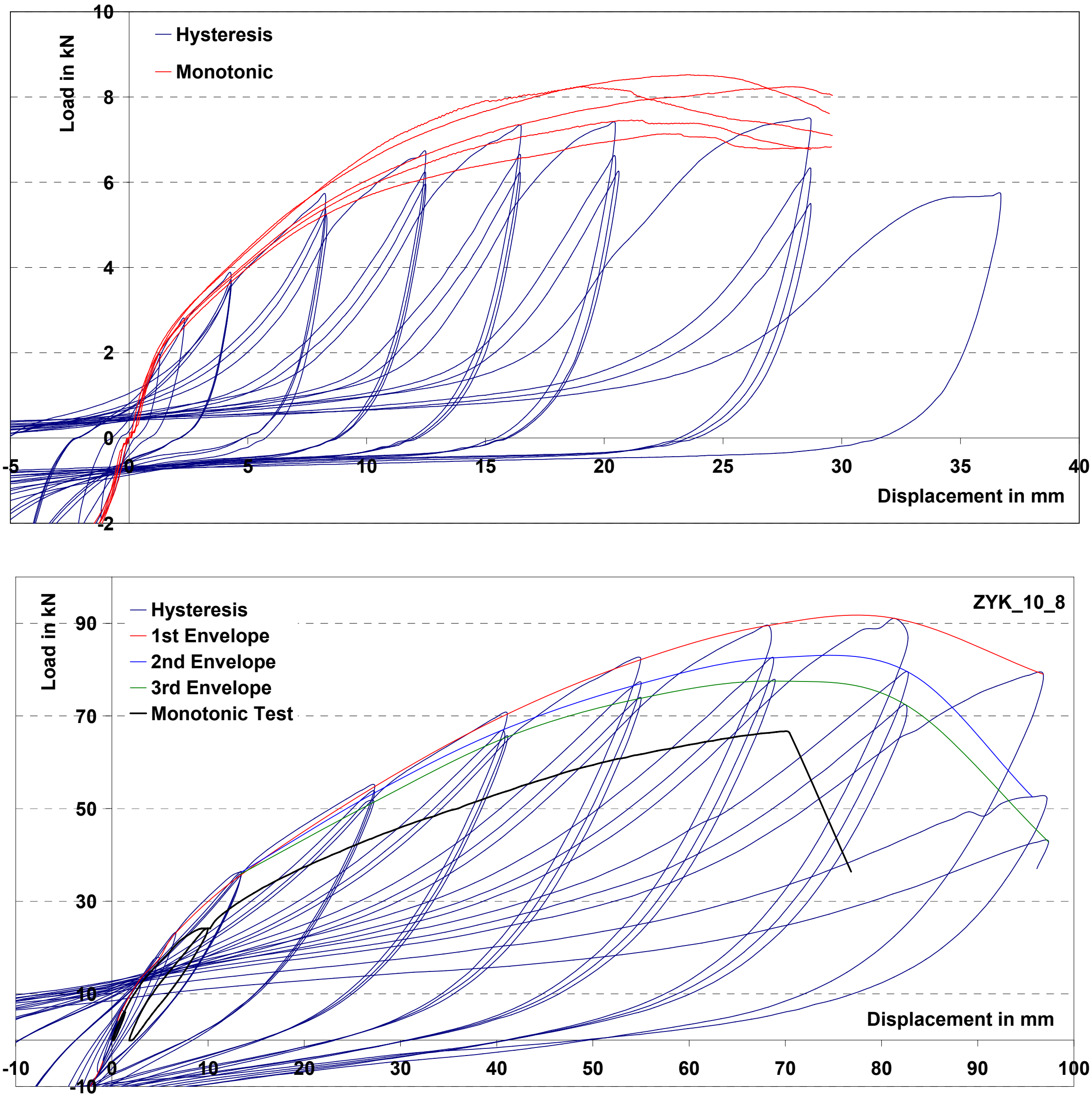


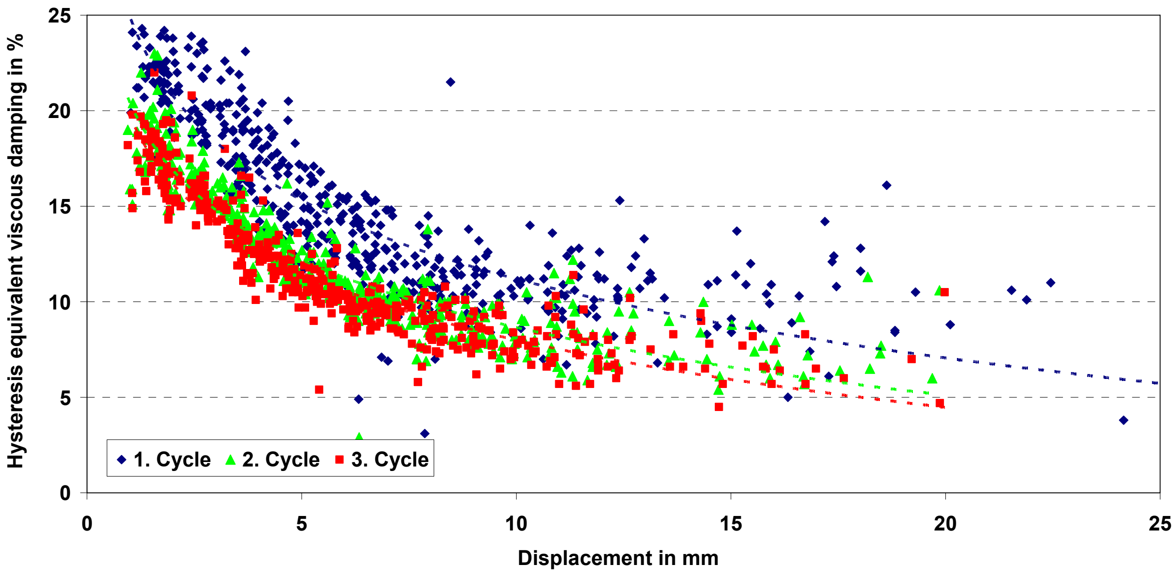
Fig. 3 Comparison of hysteresis of X-Lam massive panel system. Hysteresis of joint test with 5 staples (top), hysteresis of shear wall test with staples (bottom)

The described effect is getting even more pronounced when testing other connectors in e.g. brittle materials like gypsum wall boards.

2.2 Prefabricated timber wall elements (PFTE)

Prefabricated Timber Wall Elements (PFTE) represents a simple, easy to handle and sustainable construction system. The brick-like elements can be easily transported to the building site and are easy to handle due to their low weight. In its basic dimensions the “wooden brick” measures 1,0 m x 0,5 m (length x height) with different thicknesses. (Fig. 5). The wood columns are connected by dove tails to the (inner) chipboard layers. The overlapping of columns and sheathing provides initial stability. The hollow spaces between the columns are used for insulation or installation.

When erecting a wall with PFTE, the layers are simply laid by stacking the wooden “bricks”, where the offset of the outer layers and the offset of the studs of lower and upper elements slide into the next one (Fig. 5). When the planned wall height is reached, a continuous vertical stud is inserted from the top at least every 3 m of wall length. After finish-



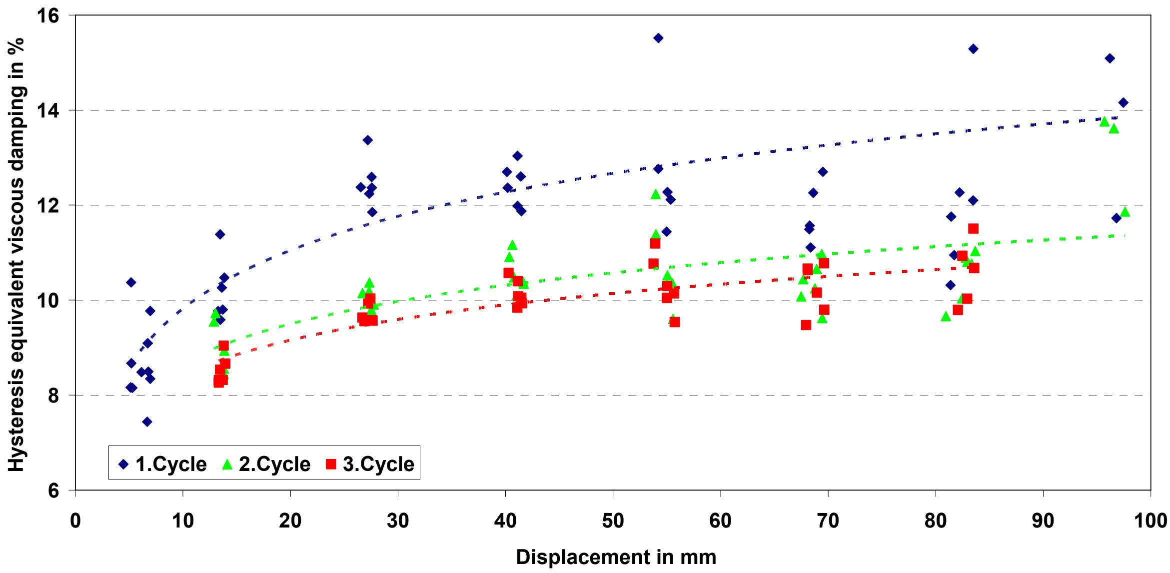


Fig. 4 Hysteresis equivalent viscous damping ratio for X-Lam joints tests (staples)(top), for X-Lam massive panel shear walls connected with staples (bottom)

ing erection, the overlapping parts of the sheathing are connected on the inner side of the building by staples to create a continuous shear wall. The system and several outcomes were already presented in [5].

2.3 Other novel systems and "conventional" timber framed walls

Several other novel systems were developed recently, probably best-known is the "pure" X-lam system, which in an excellent manner uses the advantages of timber construction: Cross-wise lamination nearly prevents swelling and shrinking, the amount of massive timber leads to excellent load-carrying capacities and good climate properties. When building in seismic active regions, dissipative zones can be designed by cutting the X-lam and to reconnect the elements using mechanical fasteners.

Several advantages are offered by conventional timber frame constructions. Flexibility in construction is also given as well as good building physics and sustainability. When sub-

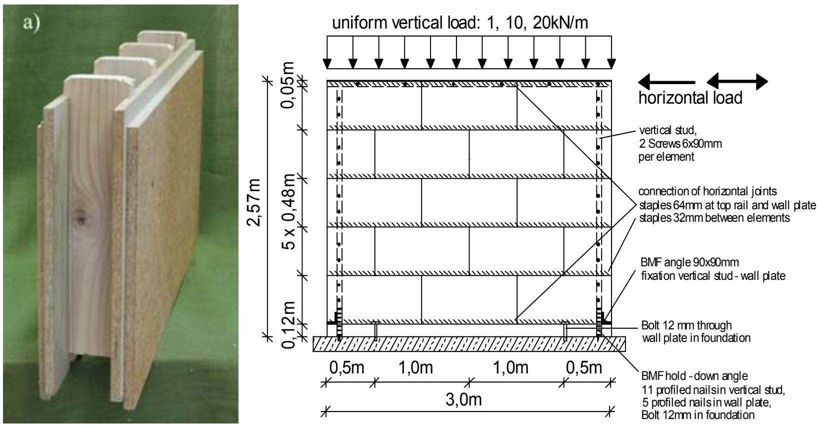


Fig. 5 PFTE (left), Shear wall specimen (right)

jected to seismic loads, the behaviour of timber frame construction is favourable. Three tests on timber framed shear walls were performed at Karlsruhe and were presented in [5].

3 Determination of earthquake properties of timber systems

3.1 EC8 approach

In terms of using the investigated systems in seismic active areas, EC8, the European code for the design of structures for earthquake resistance, provides some guidance. Apart from the general rules for the design of buildings for seismic active zones, specific rules for timber buildings are given.

EC8 includes 3 design concepts where "Depending on their ductile behaviour and energy dissipation (*) capacity, under seismic actions, timber buildings shall be assigned to one of the three ductility classes L, M or H as given in Table 2, where the corresponding upper limit values of the behaviour factors are also given".

It is obvious that Table 2 does (and maybe cannot and should not) cover all systems. The question when using an unlisted system is which ductility class applies to the construction system. Therefore EC 8 states that "In order to ensure that the given values of the behaviour factor may be used, the dissipative zones shall be able to deform plastically for at least three fully reversed cycles at a static ductility ratio of 4 for ductility class M structures and a static ductility ratio of 6 for ductility class H structures without more than a 20% reduction of their resistance." Notice that the specification of a static ductility does not take into account the energy dissipation of the system as it was requested before (*).

Table 2 Design concept, Structural types and upper limit values of the behaviour factors for the three ductility classes according to EC8

Design concept and ductility class	q	Examples of structures
Low capacity to dissipate energy - DCL	1,5	Cantilevers; Beams; Arches with two or three pinned joints; Trusses joined with connectors
Medium capacity to dissipate energy - DCM	2	Glued wall panels with glued diaphragms, connected with nails and bolts; […]; Mixed structures consisting of timber framing (resisting the horizontal forces) and non-load-bearing infill
	2,5	Hyperstatic portal frames with doweled and bolted joints
High capacity to dissipate energy - DCH	3	Nailed wall panels with glued diaphragms, connected with nails and bolts; Trusses with nailed joints
	4	Hyperstatic portal frames with doweled and bolted joints
	5	Nailed wall panels with nailed diaphragms, connected with nails and bolts

3.2 Cross-reference to EN 12512 – lack of shear wall test standard

As stated in 2.1.1, “Dissipative zones shall be located in joints and connections […]”, and should be tested according to EN 12512 [2]. The tests described in 2.1.1 are used to determine if the ductility ratio required in EC8 can be fulfilled and if DCH can be reached with the systems. In the EC8 definitions, the static ductility is defined as the “ratio between the ultimate deformation and the deformation at the end of elastic behaviour evaluated in quasi-static cyclic tests.”

Consequently, the definition of the ductility ratio is very important. Discussions on how to determine “the deformation at the end of the elastic behaviour” – the yield displacement – are ongoing. Four well-known procedures are 1) the 1/6 method according to EN 12512 (CEN Method), 2) the equivalent energy elastic-plastic method (EEEP), 3) the 0,5*F_{max}-Method and 4) the 10-40-90-Method. A detailed description of the methods can be found in [6].

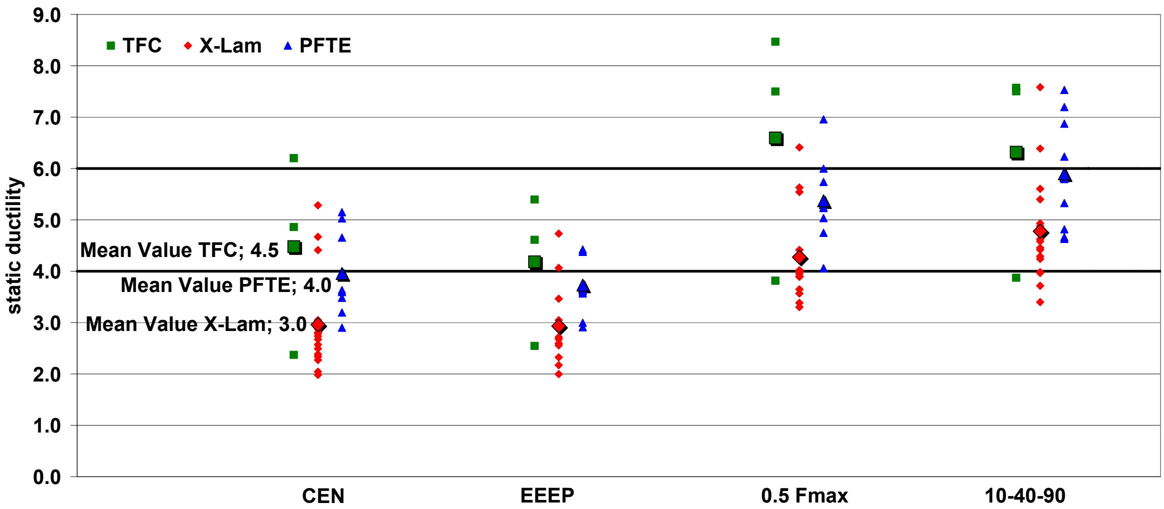


Fig. 6 Static ductility ratio of three different shear wall systems using four different methods of determination

This paper is not intended to contribute to any yield-displacement-discussion, however since the CEN method is specified in EC8 it is interesting to compare the static ductility using different methods. As can be seen in Fig. 6, the mean values for PFTE and X-Lam system using CEN method do not match a static ductility ratio of 4 what means that both systems have to be classified into DCL. Timber frame construction does “only” match DCM, certainly the test basis for the calculation (having three tests only) is weak. As it was proven in the past, nearly all kinds of timber buildings can resist strong earthquake actions, hence the investigated systems should also show better performance. Fig. 6 shows that the declaration of static ductility according to EC8 plus using the CEN method leads to (very) conservative results.

At this point it is important to state that the boundary conditions (BC) applied in all Karlsruhe tests correspond to “Shear cantilever mechanism” as described in [7] and [1]. Because of the lightweight structure of such buildings, rotation of the wall is possible. This BC is regarded as the conservative one, meaning that using other BC’s may lead to significantly higher values for the static ductility. Until today no uniform standard for the monotonic and cyclic testing of shear wall specimen exists. Since the importance of proper earthquake design is obvious especially in southern Europe, a uniform test standard is needed. The proposal of the authors again is to use ISO/CD 21581 [3], which combines in

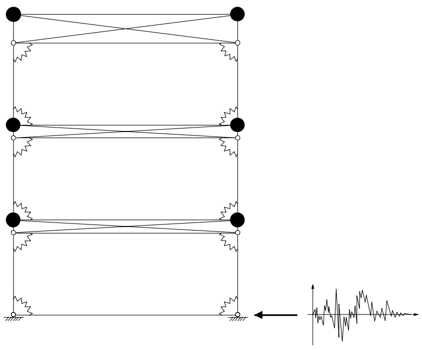


Fig. 7 Two-dimensional model

a great manner the freedom of engineering as well as it is regulative in the right way. One possible addition would be the definition of a standard vertical load. Common tests carried out at Karlsruhe use a “standard” upload of 10 kN/m, which is considered comparatively small.

3.3 Possible interpretation of test results

Due to the problematic interpretation of the hysteresis equivalent viscous damping (HED), as shown in (Fig. 4) it is suggested to determine HED for each cycle and add it to the hysteresis envelope data. According to ISO/CD 21581, the maximum displacement (u_{max}) gained in a monotonic test is used to calculate the amplitudes of the cyclic test protocol. As can be seen in Table 3, the HED at 100% of u_{max} gives useful information about the behaviour what is later verified when calculating the q-value.

Taking into account system properties e.g. in a standardized simulation, it has to be assured that the test data is sufficient and consistent as much as possible. This, again, can only be reached using a test method which is appropriate for shear wall testing such as [3].

4 Evaluating the q-value of investigated timber systems

The evaluation of the behaviour factor q for all systems is carried out with a model of a sample house reduced to a two-dimensional frame as shown in Fig. 7. The ratio of design ground acceleration to scaled ground acceleration at “near collapse” status equals the behaviour factor q. The essential properties of the system (ductility and energy dissipation) are taken into account in the simulation. The hysteretic behaviour of the shear walls was modelled with DRAIN-2DX [8] using the Florence pinching hysteresis model [9]. This procedure is described in [10], [11], [12]. The behaviour factors q for a XLAM building in [10] were calculated numerically with a model calibration solely based on the hysteresis shape gained from cyclic testing. Comparing the numerical data with the results of the shake table tests, the excellent quality of the model can be seen.

Table 3 HED of investigated systems. Values determined at 100% of u_{max}

	Hysteresis equivalent viscous damping 1st cycle	Hysteresis equivalent viscous damping 2nd and 3rd cycle
X-lam, staples	9.6% - 13.4%	8.4% - 10.9%
X-lam, nails	9.6% - 12.7%	9.3% - 11.9%
PFTE	13.9% - 15.7%	14.1% - 14.8%
Timber frame	10.9% - 12.9%	7.9% - 9.2%
Hysteresis equivalent damping $\nu_{ed} = \frac{E_d}{2\pi \cdot E_p}$		
where E_d = Dissipated Energy, E_p = Potential Energy		

To calculate the behaviour factor q, the model will be designed for a certain ground acceleration using force based design methods according to EC8 [1]. Thereafter the structure will be excited in each case by ten natural as well as ten artificial earthquakes and the response of the system will be calculated. The division of the ground acceleration reached in the simulation and the calculated one represents the behaviour factor q, where $PGA_{u,eff}$ is the maximal ground acceleration at “near-collapse“ status and $PGA_{u,code}$ is the maximal ground acceleration given in the correspondent code. The “near-collapse” status was taken to be 2,5% of storey height (≈ 65 mm), which was reached in all tests. No values were calculated for timber frame construction system since a data basis of 3 tests is insufficient.

When subjected to cyclic loads the systems showed favourable characteristics and a large amount of energy dissipation (see Table 3). The q-values for the PFTE- System only in three cases are lower than q = 4, while the 5 %-fractile is 3.7 (Table 4). In the chosen configuration the maximum interstorey drift is always reached in the first storey. Regarding the first floor of a three-storey building, the assumption of an upload of 10 kN/m is again conservative, since first floor walls usually have higher vertical loads. Because of the higher amount of energy dissipation when subjected to higher vertical loads a value of q = 4.0 was recommended for the PFTE-system. The q-value for the X-lam massive panel system never falls below a value of q = 3 while the 5%-fractile is 3.3. Therefore a value of q = 3.0 is recommended for the X-lam massive panel system. Choosing a multiplicity of 20 earthquakes, the statement of q with the 5%-Fractile is once more conservative. Stating q with the average value would also be possible, however then more importance should be attached to reliability analysis, which was not considered in this paper.

Comparing the q-values from Table 4 to the hysteresis equivalent damping in Table 3, one can see that the hysteresis equivalent viscous damping gives valuable information about the q-values derived with the numerical simulation.

5 Discussion

The research on two innovative timber construction systems is presented in this paper. Both systems as well as the established timber construction system have been tested under reversed-cyclic loading and showed a good performance. Since the behaviour of the systems can be classified similar to the well-known timber frame system, this means that they are well suitable for the use in seismic prone areas.

Table 4 Calculated q-values for the different systems

Earthquake	$PGA_{u,code}$	PFTE $PGA_{u,eff}$	X-lam $PGA_{u,eff}$	PFTE q-value	X-lam q-value
natural earthquakes	0.35	1.29 to 3,77	1.10 to 3.38	3.7 to 10.8	3.1 to 9.7
artificial earthquakes	0.35	1.16 to 1.58	1.15 to 1.55	3.3 to 4.5	3.3 to 4.8
$q = \frac{PGA_{u,eff}}{PGA_{u,code}}$		average value		5.1	4.7
		5% fractile		3.7	3.3
		=> suggested q-value		**4.0**	**3.0**

The classification of the earthquake properties of the systems using current European standards is not ideal at the moment since there is a major lack of information in EC8. The first step to correct this would be the establishment of a uniform standard for shear wall testing like ISO/CD 21581. Thereafter, rules for the interpretation of test results like the hysteresis equivalent viscous damping or static ductility should be more precise, and it should be stated that extended methods like a numerical simulation may be used to evaluate the behaviour factor q. The numerical simulation is more precise than the declaration of a static ductility as given in EC8 because the energy dissipation of the structure is taken into account. Comparison of different parameters suggests that the assumptions in EC8 are conservative.

Using a numerical simulation, the properties of the systems subjected to earthquake loading were reproduced and the behaviour factor q was calculated. Market opportunities for the systems can be seized quicker using these investigations. Based on few and common tests on shear walls an essential statement regarding the behaviour of the system can be given. Complex testing can be omitted. Looking at innovative timber systems, design fundamentals can be given in a short time.

The q-values are verified through the conservative testing on which the model is calibrated. The calculation is carried out using 20 accelerograms. Using this multiplicity of accelerograms, the calculated value has a broad basis. The chosen methodology may be widened to a 3d-Model [10] if needed. Torsion effects and other details can be taken into account. Further reliability analysis is not yet considered in this paper.

6 References

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