Behaviour of Prefabricated Timber Wall Elements Under Static and Cyclic Loading

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1 Introduction

Prefabricated Timber Wall Elements (PFTE) represent a simple, easy to handle and sustainable construction system. In a current research project at Universität Karlsruhe the PFTE building system is tested under both vertical and horizontal loading to determine its shear wall capacities. For this purpose a new testing assembly for vertical and horizontal loads able to produce various boundary conditions was installed at Universität Karlsruhe. The shear walls were tested following ISO/CD 21581 [3] while assuming boundary conditions reflecting the intended construction details. In this paper the test results are presented and are compared with test results of conventional timber frame walls.

2 Idea of the PFTE building system

Fig. 1 Building made of Prefabricated Timber Wall Elements

The main feature of PFTE is prefabricating wooden "brick" elements primarily out of the residues of a sawmill. The brick-like elements can be easily transported to the building site and are easy to handle even for beginners under the guidance of a site foreman. The mass of a single element is less than 25 kg, it can be moved by hand and walls can be built without a crane. Thus the system can be cost-saving. In Germany a technical approval for up to three - storey buildings was issued in Sept. 2007.

The basic element (as shown in Fig. 2 and Fig. 3) consists of four solid wood columns and two OSB–like chipboards as an inner sheathing layer on both sides. The wood columns are connected by dove tails to the chipboard layers. On the one hand this means a simple and close connection between the inner sheathing layer and the columns, on the other hand it allows the columns of the lower element to slide into the sheathing of the element on top. Quite similar to the Lego brick system the single elements are stuck together by these overlapping/shortened columns with dove tail geometry at the top/bottom of the element. The overlapping/shortening of the columns gives the wall initial stability. On both sides a second sheathing layer is fixed to the inner sheathing layer. The second (outer) layer consists of chipboard on the subsequent inner side of the building and of timber boards on the subsequent outer side of the building. The second sheathing layer is fixed with an offset of 30 mm horizontally and vertically. When setting up the wall the offset of the outer layers of lower and upper elements slide into the next one, so that the outer layer overlaps from one element to another. After finishing erection the overlapping parts of the sheathing are connected on the inner side of the building by staples to create a continuous shear wall.

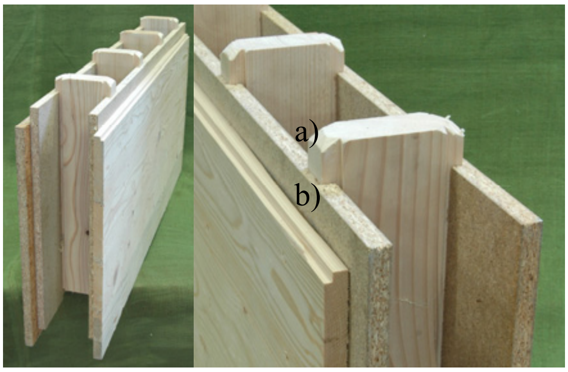

Fig. 2 Prefabricated Timber Wall Element (left); Offset of columns (a) offset of layers (b) (right)

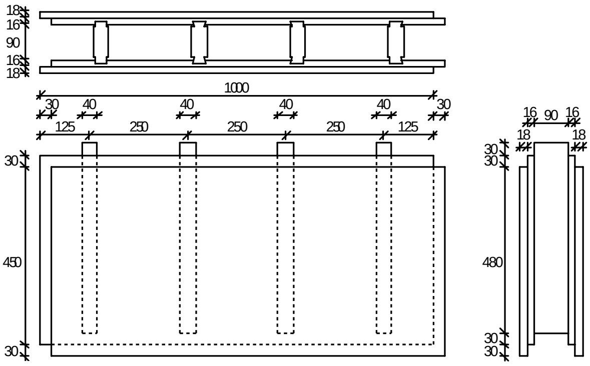

Fig. 3 Scheme of Prefabricated Timber Wall Element, dimensions in mm

The basic element with a length of ℓ = 1,0 m and a depth of h = 0,5 m is available in wall thicknesses of b = 160 mm, b = 240 mm or b = 300 mm. The columns are spaced 250 mm, the hollow space between the colums can be used for insulation and installation. For the acceptance of the technical approval in 2007, tests with loads perpendicular to the surface were successfully carried out. Also some tests with in-plane shear forces were performed. The manufacturer and Universität Karlsruhe decided to study more extensively the shear wall behaviour of the system particularly with regard to exporting the system to regions with seismic activity and high wind loads. Because the wall sheathing is not continous but is composed of several smaller areas, the main attention was focussed on the connection between the single elements. When erecting a wall with PFTE, first a wall plate is fixed to the foundation. The first row of the elements is installed by fixing each element to the wall plate via one BMF 90 x 90 mm angle connector. When the wall height is reached, a continuous vertical stud is inserted from the top at least every 3 m of wall length. The vertical studs transfer the in-plane up-lift forces to the foundation, and

Top rail on top element, fixed with:
-vertical screw 6 x 140 mm every 2nd column
-Horizontal screw 5 x 60 mm – spaced 250 mm solely on chipboard side
-Horizontal staples 64 mm – dist. 50 mm solely on chipboard side

Basic elements, overlap connected with staples 32 mm – spaced 50 mm solely on chipboard side

-Douglas fir wall plate with spruce element, connected via screws 6 x 160 mm spaced 250 mm
-First line connected to spruce element via 1 BMF-Angle per wall element
-First-Line elements connected with staples 64 mm – spaced 50 mm solely on chipboard side

Fig. 4 Details of Prefabricated Timber Wall Element System they provide bending stiffness for loads perpendicular to the wall plane, e.g. wind loads. At the top of the wall the top rail is put into position and the vertical studs as well as the top rail are connected to the elements via self-drilling screws. Normally the spaces between the vertical columns are filled with insulation. The tests, however, were performed without insulation. All the connections described in Fig. 4 are of prime importance for the behaviour of the wall under the different loading conditions.

3 Test Setup at Universität Karlsruhe

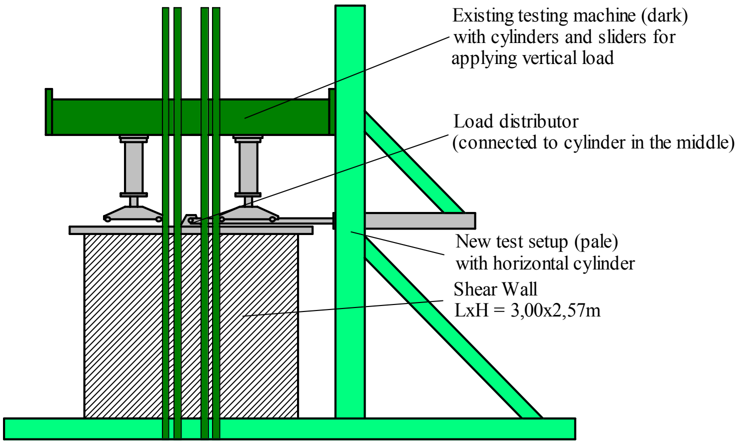

Fig. 5 Scheme of new test equipment at Universität Karlsruhe

A new test equipment for shear wall tests was part of the research project. In the past years it was discussed [1], [2] how to apply realistic boundary conditions in shear wall tests. An existing testing machine for applying vertical loads was incorporated into the new wall testing facility. The new test setup should enable different boundary conditions for the test specimens. The two hydraulic jacks for the vertical loads are either force or displacement controlled, so that the three different boundary conditions “Shear Wall Mechanism”, “Restricted Rocking Mechanism” and “Rocking Mechanism” (see Fig. 6) can be applied.

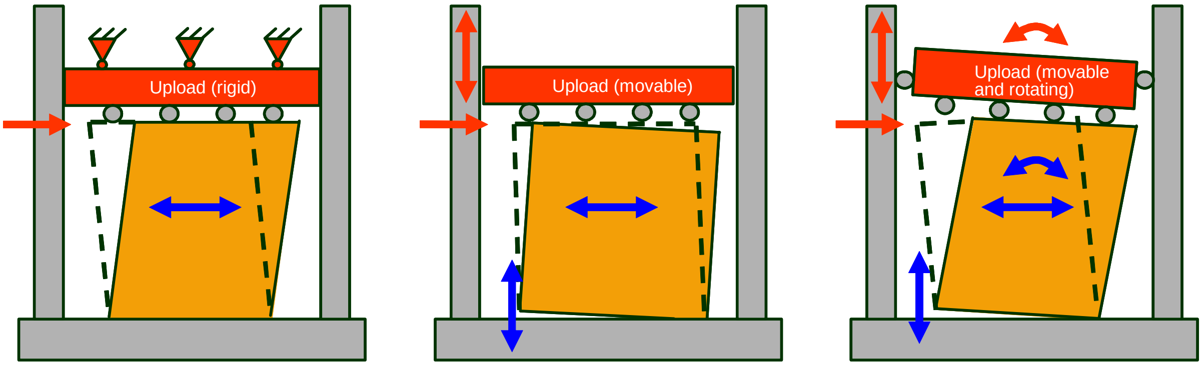

Fig. 6 Boundary conditions as described in [1], a) Shear Wall Mechanism, b) Restricted Rocking Mechanism, c) Rocking Mechnism

The centre of the load distributor is connected to the horizontal hydraulic jack. A powerful 400 kN hydraulic jack with a displacement range of +/- 300 mm was chosen to enable tests with cross-laminated timber wall elements with very high lateral resistance. By attaching the centre of the load distributor to the horizontal hydraulic jack it is assured that all three boundary conditions are possible while always keeping the hydraulic jack nearly horizontal. The vertical load is applied to the test setup via two slides on the load distributor.

4 Shear Wall Tests

4.1 Shear Wall Tests with PFTE

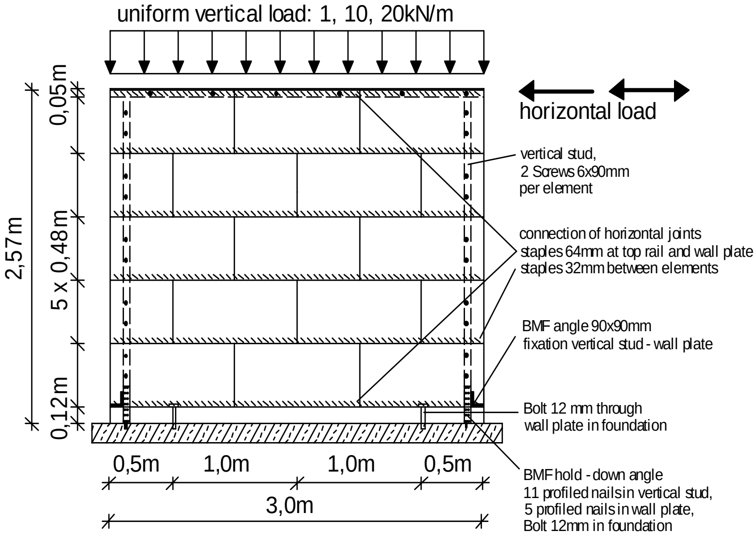

Fig. 7 PFTE Test Wall Specimen

The test setup for the PFTE shear wall tests is shown in Fig. 7. Similar to the approach in practice, first of all the wall plate is fixed to the foundation of the test setup via two 12 mm bolts (one bolt in each outer element). The first layer of elements is put on the wall plate and fixed via one BMF 90 x 90 mm angle per element. The next four layers are simply layed by putting the wooden "bricks" together. Afterwards the vertical studs and the top rail are put into position and the load distributor is attached to the top rail by multiple inclined screws. The inclined screws perform very well as they exhibit a very stiff behaviour even at high loads. After the weight of the load distributor is applied on the wall, the fasteners between the wall elements are driven in. All tests were performed using a PFTE wall thickness of 160 mm.

4.1.1 Monotonic Tests with PFTE

The monotonic tests with PFTE were performed using the ISO/CD 21581 [3] load protocol which corresponds to the load protocol given in EN 594 [5]. A total of 11 monotonic tests was performed with PFTE.

Three tests were carried out without additional vertical load on top (only the weight of load distributor itself being 1,33 kN/m, in the following denoted as 1 kN/m). The tests with a vertical load of 1 kN/m were carried out using a test setup according to Fig. 7. On the outer wall side a steel nailing plate was additionally fixed as a connection between wall plate and the first line of elements. The nails were driven through the plate into the vertical studs to relieve the hold-down on the chipboard side. The first two tests with a load of 1 kN/m achieved maximum horizontal loads of about 48 kN, however with different failure mechanisms. In the first test, the stapled connection loaded in shear between top rail and the upper wall elements failed in a ductile manner, while the wall itself showed minimal displacements. In the second test the hold-down of the vertical tensile stud failed. At a certain displacement, additionally the first horizontal joint began to open because the staples were pulled out. The third test was performed with additional staples in the vertical joints to increase maximum load as well as stiffness. This test showed a very sudden failure because the hold-down failed and simultaneously the nails in the horizontal part of the inner BMF angle were suddenly pulled out.

Five tests with an additional vertical load of 10 kN/m were conducted: three with additional screws in the overlap of the vertical columns and two without those screws.

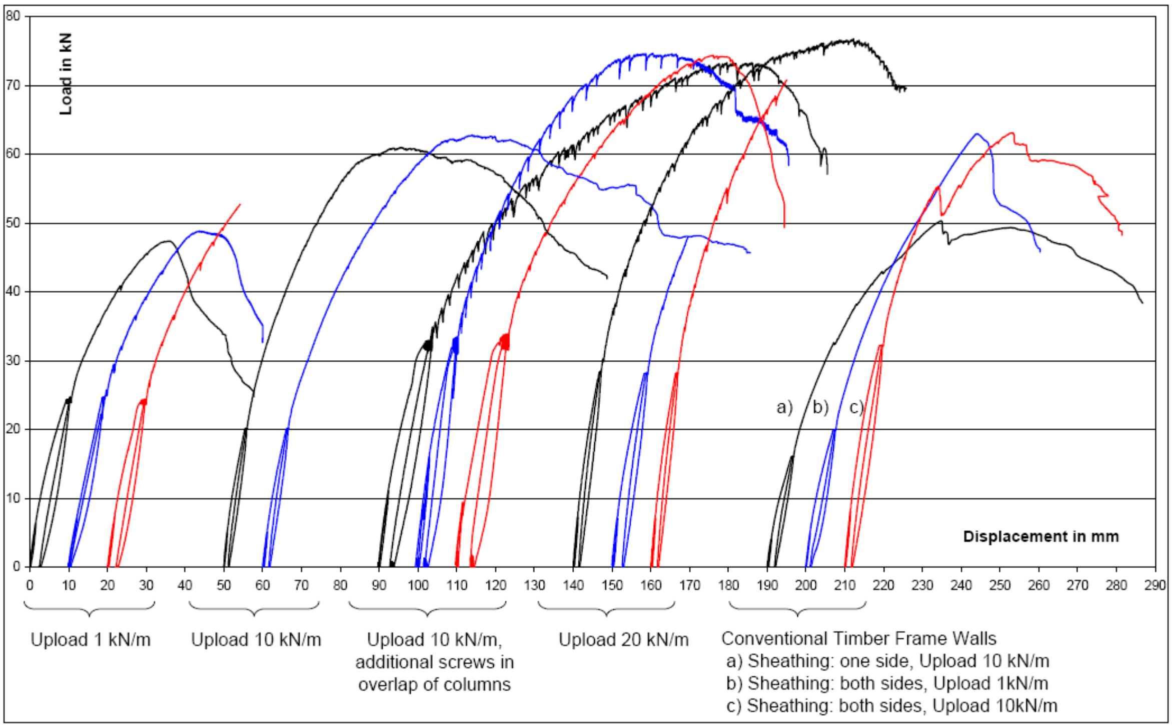

Fig. 8 Load-displacement curves of monotonic (Push-Over) Tests

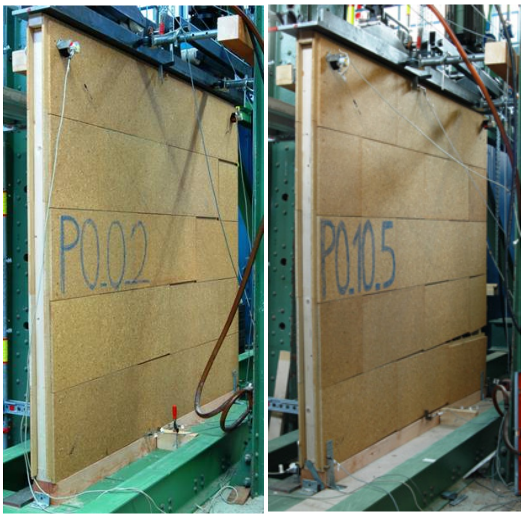

Fig. 9 Test Wall Specimen after test

The test results with vertical load 10 kN/m using no additional screws (PO_10_4 and PO_10_5) are shown at position 50 and 60 mm in Fig. 8. The test configuration was nearly the same as in the tests with no vertical load, only the steel plate as an additional connection between the lower elements and the wall plate was left out. Compared to the tests with no additional vertical load, the horizontal load capacity increased to about 62 kN while the stiffness only slightly increased. Ductility of the wall raised, as can be seen from the displacements at 80% of F_{max}: while being about 44 mm in the case with no additional vertical load, it rose to about 93 mm with a vertical load of 10 kN/m. This is a result of changed boundary conditions between the two cases. While the wall without additional vertical load shows restricted rocking behaviour [1], the shear deformations of the wall turn out to be rocking behaviour [1] until failure of the test specimen was reached by the staples in the horizontal joints being pulled (see Fig. 9 on the right).

The screws provide additional shear resistance, however, placing the screws means a lot of extra work: for the test wall with 2,5 x 3,0 m about 50 screws have to be placed. The load bearing capacity increased due to the additional screws to about 74 kN compared to the 62 kN in the tests without screws.

Finally, three tests with an additional vertical load of 20 kN/m were carried out. In the first test a horizontal load of nearly 77 kN was reached with a ductile failure mode. Failure of this specimen was quite similar to the failure with lower vertical loads. Beginning from the vertical stud on the tensile side, the horizontal joints started to open because the staples were pulled out. In the second test, similarly to PO_0_3 the top rail connection failed in shear due to a very low timber density. The third test with a vertical load of 20 kN/m showed a brittle failure at a maximum load of about 71 kN. Suddenly the first horizontal joint and the connection between the vertical stud and the wall plate failed simultaneously.

Table 1: Overview and Results of monotonic (Push – Over) Tests

	F_{max} in kN	u_{max} in mm	$u_{80\%Fmax}$ in mm	F at disp. u = 5mm	Stiffness K $^{1)}$	Comment
PO_0_1	47,4	35,2	42,7	16,0	2693,1	top rail connection failed (ductile)
PO_0_2	48,9	32,8	45,1	14,4	2757,2	
PO_0_3	52,7	35,5	-	16,2	2875,8	Staples in vertical joints too, brittle failure of specimen
Mean Value	49,7	34,5	43,9	15,5	2775,4	
PO_10_1	73,4	87,7	110	18,9	2715,4	Additonal screws in overlap of vertical columns
PO_10_2	74,6	65,8	101,1	22,9	3127,4	
PO_10_3	74,4	51,8	64,9	20,0	3500,5	
Mean Value	74,1	68,4	58,7	20,6	3114,4	
PO_10_4	61,0	47,8	86,1	18,8	2892,0	
PO_10_5	62,8	52,3	100,2	17,6	2773,7	
Mean Value	61,9	50,0	93,2	18,2	2832,9	
PO_20_1	76,8	70,9	106,6	23,3	3390,0	
PO_20_2	47,4	19,4	-	19,8	3625,1	top rail connection failed (brittle)
PO_20_3	70,8	34,6	-	23,5	3603,8	Failure of vertical stud and first horizontal joint, brittle behaviour of specimen
Mean Value	65,0	41,6	-	22,2	2832,9	
TF_one_10 $^{2)}$	50,3	50,6	107,7	13,2	1915,7	
TF_two_1	63,1	45,8	54,3	16,3	2400,2	
TF_two_10	63	49,1	78,6	21,6	3651,0	

[1] Stiffness $K = \frac{0{,}3 \cdot F_{max}}{\upsilon_{40\%\,Fmax} - \upsilon_{10\%\,Fmax}}$ where e.g. $\upsilon_{40\%\,Fmax}$ is the displacement at 40% of F_{max}

[2] Timber Frame_Sheathing one/two sides_Vertical load 1/10 kN/m

4.1.2 Cyclic Tests with PFTE

The cyclic tests were performed using the same test setup as for the monotonic tests (see Fig. 7). All cyclic tests were carried out using the cyclic displacement schedule given in ISO/CD 21581 [3] which corresponds to the displacement schedule given in ISO 16670 [6]. Before cyclic testing, the ultimate displacement v_u was determined from the monotonic tests. The ultimate displacement is defined a) as the displacement at failure or b) the displacement at 80% of F_{max} in the descending portion of the load-displacement curve or c) the displacement reaching H/15 (PFTE: 2570/15 = 171 mm) whichever occurs first. Having three tests each, v_u was taken to be the average of the three tests.

The multiple element connections with a large number of mechanical fasteners and the friction between the elements should lead to a favourable behaviour under cyclic loading. The staples used for the connections are very slender fasteners which bend easily. The subsequent plasticity of the staples as well as the timber under embedding lead to a ductile behaviour and a large energy dissipation during the repeated cycles. The friction between the elements cause additional energy dissipation. In ISO/CD 21581 [3] there is no approach to determine the energy dissipation of the wall, but it is noted that in future there may be a need to determine such additional properties. To gain some information about the energy dissipation of the tested walls, the equivalent hysteretic damping v_{ed} according to EN 12512 [4] is used. In Table 2 and Table 4, selected tests and the energy dissipation are tabulated.

Fig. 10 Typical failure in cyclic tests.
Vertical load 1 kN/m (left)
20 kN/m (right)

All tests were carried out using boundary condition "Rocking mechanism" [1]. This boundary condition was chosen because it is the boundary condition assumed to appear in most PFTE buildings. Because of the light-weight structures of such buildings, rotation of the wall is possible. Again, while conducting the tests with a vertical load of 1 kN/m, a steel plate was affixed as a connection between wall plate and the first line of the elements on the timber board side. The tests without additional vertical load showed a higher ductility than expected from the monotonic tests (See Fig. 11 a) compared to Fig. 8). This is caused by the various connections between the elements and the connection between the vertical studs and the elements. Having no additional vertical load in combination with cyclic loading the connections very soon become loose. However the maximum load is similar to the one in the monotonic tests.

The tests with vertical load 10 kN/m and 20 kN/m showed higher maximum loads and higher energy dissipation values v_{ed} due to the friction activated by the vertical load. As can be seen in Fig. 11 b) and c) the hysteretic curves become more voluminous. Also the uneven course of the curve shows friction effects between the columns as well as between sheathing panels of the single elements.

Two tests with gravel infill were carried out. Filling the wall with gravel improves the acoustic and the temperature storage capacity of the wall. The higher dead load of the wall itself especially in low-rise buildings also leads to a better performance in the case of high wind loads. The friction between the pebbles causes an additional energy dissipation in cyclic loading. Finally in case of tornados the additional mass of the wall increases the safety for residents in a building by preventing parts flying around to penetrate the wall. As can be seen in Fig. 11 d), its equivalent hysteretic damping compared to the wall without gravel infill is exellent. However it must be said that the maximum loads and also the ductility of the wall is reduced by pepples locking the joints between the elements once the gap is open.

Table 2 Tabulated Values of Cyclic Test with PFTE, Vertical load 10 kN/m

ZYK_10_1, Cyclic, Upload 10 kN/m, No. 1																		
ultimate displacement obtained in static test				νu = 70mm			*) length of wall = 3,0m				equivalent hysteretic damping v_{ed} = Ed/(2*pi*Epot)							
displacement rate for cyclic test				dr = 40mm/min														
total duration of test				1h 40min														
	First envelope curve						Second envelope curve						Third envelope curve					
	Positive			Negative			Positive			Negative			Positive			Negative		
% of vu	mm	kN *)	ved in %	mm	kN *)	ved in %	mm	kN *)	ved in %	mm	kN *)	ved in %	mm	kN *)	ved in %	mm	kN *)	ved in %
1,25	0,83	3,75		-0,82	-5,74													
2,50	1,61	5,40		-1,54	-9,13													
5,00	2,99	10,49		-3,49	-15,45													
7,50	4,97	15,48		-5,22	-19,64													
10,00	6,59	18,15		-6,96	-24,13													
20,00	13,93	30,41	13,1	-13,64	-35,80	13,8	13,92	30,28	13,1	-13,60	-34,97	11,7	13,90	29,74	12,3	-13,59	-34,69	11,0
40,00	27,92	45,18	14,6	-27,65	-50,70	13,8	27,96	43,20	12,7	-27,71	-48,65	11,3	27,99	41,70	12,4	-27,79	-47,79	10,9
60,00	41,50	51,58	14,4	-41,24	-56,20	13,2	41,58	48,86	12,3	-41,93	-53,24	10,8	41,63	47,26	12,4	-41,99	-51,29	10,6
80,00	55,08	54,22	13,6	-55,52	-56,66	12,7	55,88	50,04	12,9	-55,61	-53,01	11,2	55,91	47,90	12,2	-55,59	-51,52	10,6
100,00	69,26	52,84	13,9	-69,57	-48,98	15,7	69,89	44,80	14,5	-69,59	-44,49	14,4	69,90	41,83	14,8	-69,53	-42,23	14,1
120,00	83,84	46,49	15,0	-82,86	-45,54	15,3	83,85	42,52	14,7	-83,50	-42,53	14,2	83,86	40,75	14,8	-84,03	-40,73	14,1
140,00	97,17	44,29	15,3	-96,86	-43,54	14,8												

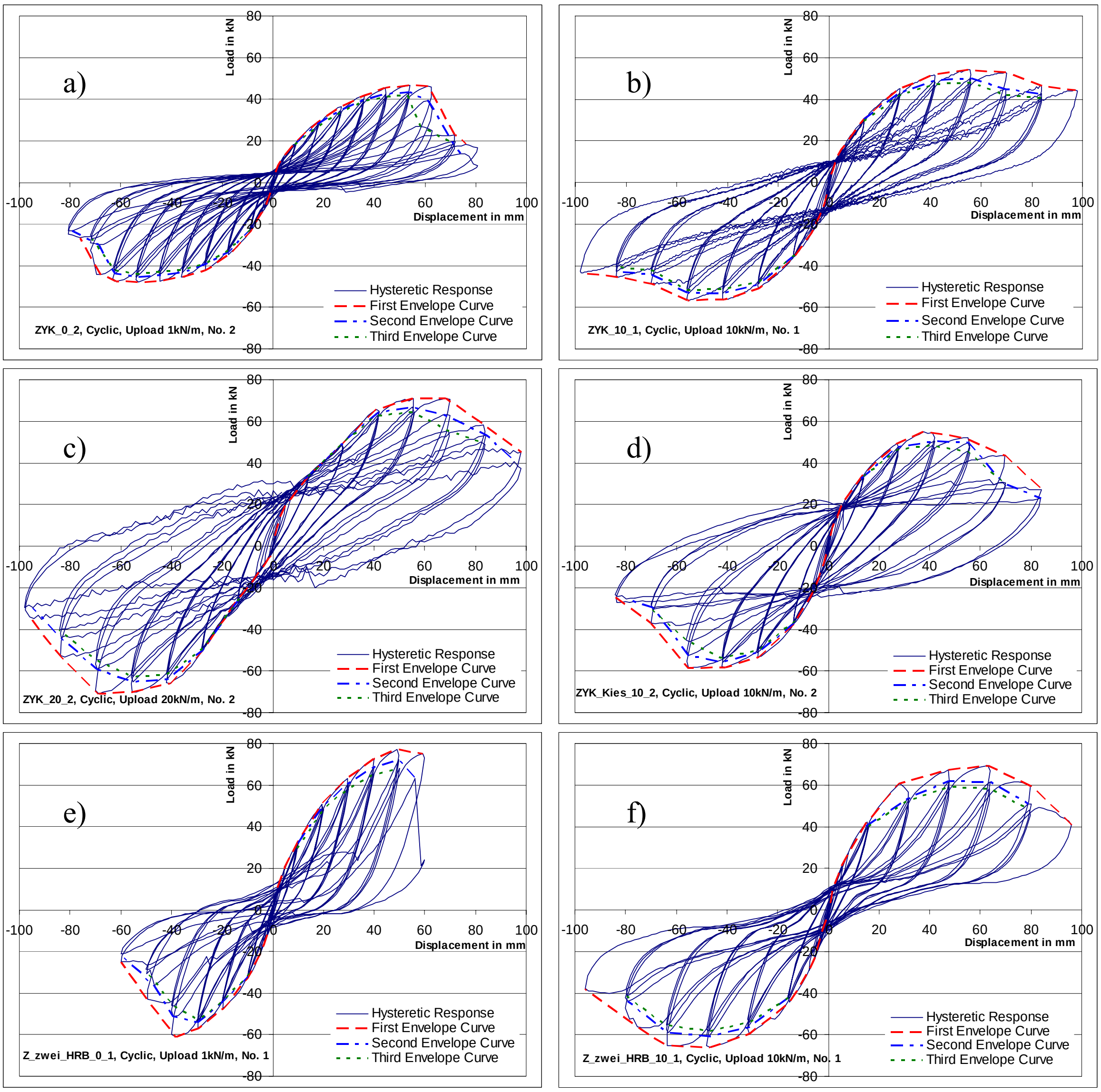

Fig. 11 Hysteretic responses of tested walls

4.2 Shear Wall Tests with conventional Timber Framed Walls

To compare the test results of PFTE with other timber construction methods, six tests with conventional timber framed shear walls were carried out. Fig. 12 shows the test setup for these walls. The walls have the same height as PFTE walls, due to the standard dimension of the sheathing (2,5 x 1,25m), length was shorter. Therefore two panels of sheathing could be used with only one joint in the middle of the wall.

Since PFTE wall elements are connected by staples on the chipboard side only, a continuous sheathing only exists on one side of the wall. The first tests similarly were carried out with timber framed walls sheathed on one side. The results of the monotonic test can be seen in Fig. 8 and Table 1. The load bearing capacity increased due to the additional screws to about 74 kN compared to the 62 kN in the tests withot screws. While the maximum horizontal load for a PFTE wall is about 62 kN, the timber frame wall achieves a maximum load of about 50 kN at a displacement of approx. 50 mm.

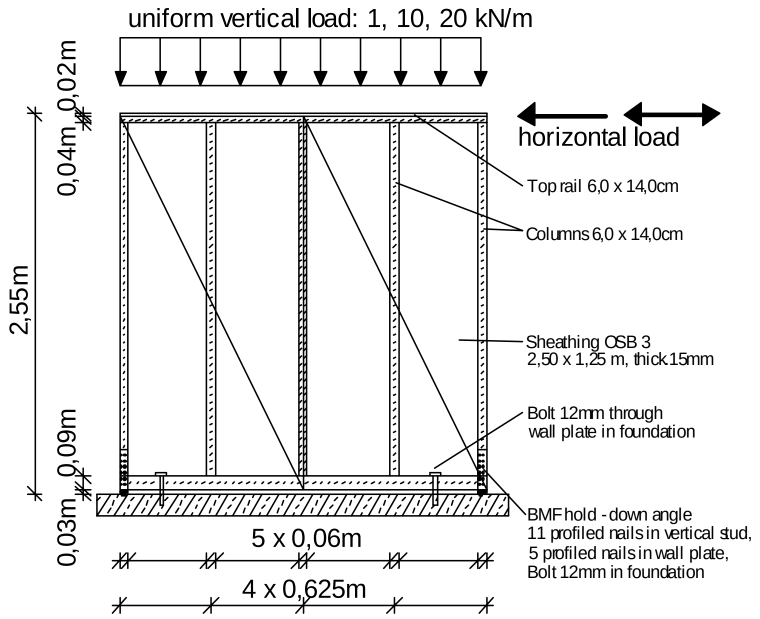

Fig. 12 Test Specimen of Timber Framed Wall

Failure of the test specimen was reached by tensile failure of the OSB sheathing just above the hold-down. The first envelope curve of the cyclic test with the timber frame wall showed nearly the same behaviour as the monotonic one, achieving about the same loads and displacements. The equivalent hysteretic damping v_{ed} for the first cycles is similar to the values achieved by PFTE, v_{ed} for the second and third cycle is significantly lower than the corresponding values of PFTE system.

The next four tests were conducted with the same test setup as shown in Fig. 12, but with the wall being sheathed on both sides. Two tests were carried out with a vertical load of 1 kN/m, two tests with a vertical load of 10 kN/m, each with monotonic and cyclic loading. Beginning with the monotonic test and a vertical load of 10 kN/m, a maximum horizontal load of 63 kN at a displacement of 49 mm was reached, compared to the 3 m long PFTE wall without screws in the overlap of the columns with values of 62 kN at a displacement of 50 mm. Again failure was caused by the OSB sheathing's tensile failure just above the hold-down angle connector.

For the first envelope curve a maximum horizontal load of 69 kN at a displacement 63 mm was reached. While energy dissipation for the first cycles achieved values between 10,6% and 15,4%, the dissipation for the second and third cycles ranged from 7,5% – 9,2%. The corresponding values with PFTE walls are 12,7% to 15,3% in the first cycles and 10,6% to 14,8% in the second and third cycles. PFTE hence shows very good performance even when damaged in previous load cycles.

Table 3 Test Matrix for Timber Framed Walls

	Sheathing	upload	Load
TF_Mon_One_10_1	One side	10 kN/m	Monotonic
TF_Cyc_One_10_1	One side	10 kN/m	Cyclic
TF_Mon_Two_1_1	Two sides	1 kN/m	Monotonic
TF_Cyc_Two_1_1	Two sides	1 kN/m	Cyclic
TF_Mon_Two_10_1	Two sides	10 kN/m	Monotonic
TF_Cyc_Two_10_1	Two sides	10 kN/m	Cyclic

Due to the tensile failure of the OSB sheathing right above the hold-down the angle was elongated for the final tests without vertical load. The total number of nails driven in the vertical stud was doubled by this measure. As can be seen in the results for both the monotonic and cyclic test, performance of the wall was consequently improved. The monotonic test without additional vertical load achieved the same results as the test with vertical load 10 kN/m. The cyclic test with the elongated angle achieved a maximum horizontal load of 77 kN at a displacement of 49 mm. Again the energy dissipation in the first cycles was quite high (from 8,6% to 17,9%) while the energy dissipation for the second and third cycle showed lower values (from 7,7% to 15,0%).

Table 4 Values of Cyclic Test with timber-framed shear wall, Vertical load 10 kN/m

HRB_zwei_ZYK_10_1, Cyclic, Upload 10 kN/m, No. 1																		
ultimate displacement obtained in static test					vu = 80mm		*) length of wall = 2,5 m					equivalent hysteretic damping v_{ed} = Ed/(2*pi*Epot)						
displacement rate for cyclic test					dr = 100mm/min													
total duration of test					34min													
	First envelope curve						Second envelope curve						Third envelope curve					
	Positive			Negative			Positive			Negative			Positive			Negative		
% of vu	mm	kN *)	ved in %	mm	kN *)	ved in %	mm	kN *)	ved in %	mm	kN *)	ved in %	mm	kN *)	ved in %	mm	kN *)	ved in %
1,25	0,80	3,41		-0,88	-4,45													
2,50	1,66	8,66		-1,76	-7,85													
5,00	3,94	16,33		-3,88	-16,55													
7,50	5,31	20,98		-5,27	-22,77													
10,00	7,98	27,47		-7,70	-29,27													
20,00	15,28	42,46	10,0	-15,22	-44,48	10,9	15,11	40,02	8,4	-15,88	-42,22	8,7	15,94	40,05	8,0	-15,98	-42,45	8,2
40,00	28,21	60,79	15,4	-31,17	-59,41	14,5	32,00	53,62	8,9	-31,91	-56,80	8,9	31,64	52,31	7,5	-31,22	-54,34	8,7
60,00	47,49	67,26	11,5	-46,75	-66,24	12,9	47,68	62,03	8,5	-46,95	-60,87	8,2	47,80	59,20	7,7	-47,08	-58,24	8,2
80,00	63,00	69,18	10,6	-63,63	-65,35	12,2	63,98	61,68	8,2	-63,09	-59,01	8,8	63,71	58,36	7,6	-64,01	-55,48	8,2
100,00	79,91	59,37	10,9	-75,23	-56,40	12,9	78,79	50,95	8,1	-79,08	-43,91	9,2	79,30	48,08	7,5	-79,53	-41,63	8,5
120,00	96,05	40,74	11,0	-96,06	-37,59	12,1												

5 Discussion and future prospects

All tests were carried out using ISO/CD 21581 [3]. Boundary conditions were assumed to reflect the actual building conditions. At high vertical loads the shear capacities were achieved. The practicability of ISO/CD 21581 [3] is determined, the applicability also for exeptional timber construction systems is proven.

The system with PFTE showed good performance in monotonic and cyclic testing as well. In monotonic tests the results for maximum horizontal load and for stiffness values are quite similar to conventional timber frame systems.

PFTE showed excellent results for the energy dissipation in cyclic loading, enlarging its potential range of application to seismic and windstorm prone areas. Further work is being done to improve the hold-down of the vertical tensile studs. The PFTE system can cover the same application range as conventional timber frame buildings, yet it is easy to handle and therefore cost effective.

Future research work will be developing a finite – element model to simulate the system properties and to give basics to be implemented in codes.

6 References

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