ONE-STOREY TIMBER-FRAMED SHEAR WALLS WITH WINDOW OPENINGS AS PART OF THE LATERAL FORCE-RESISTING SYSTEM

Nadja Manser[1], René Steiger[2], Martin Geiser[3], Andrea Frangi[4]

ABSTRACT: For lateral force-resisting systems of multi-storey timber-framed buildings, the usual policy of current standards in Europe is to only consider wall segments continuous from the ground floor to the top edge of the building and to neglect wall elements with openings. Developing a design method that allows taking wall elements with window openings into account, would make the lateral force-resisting system more efficient and respective buildings more economic. This paper presents experimental investigations on horizontally loaded one-storey wall elements with large window openings. Different window opening sizes and force-transfer optimizations were investigated. The results show that one-storey timber-framed shear wall elements with window openings have sufficient stiffness and strength potential to act contributively to the lateral force-resisting system.

KEYWORDS: Timber-framed walls, shear walls, window openings, lateral stiffness, design

1 –BACKGROUND

Timber-framed shear walls are a structural system commonly applied when constructing low- to mid-rise buildings. Current design standards in Europe, such as the Swiss standard SIA 265:2021 [1], the German standard DIN 1052:2008 [2], and the European standards EN 1995-1-1:2008 [3], and FprEN 1995-1-1:2025 [4] typically adopt a segmentation approach that considers only those wall segments continuous from the ground floor to the top of the building as effective components of the lateral force-resisting system.

Modern architectural designs increasingly demand flexible interior layouts in plan, which often necessitate the use of exterior walls for stiffening the building. However, large openings, e.g. for placing windows, may lead to an insufficient number of continuous wall segments to sufficiently resist lateral forces due to wind or seismic action. One promising strategy to improve the efficiency of such structures is to incorporate wall segments with openings into the design. This approach not only enhances stiffness and load-carrying capacity but also reduces the required number of expensive anchorages.

Timber-framed shear walls with openings have been studied in North America [5-8], but comparisons of results of experiments reveal that North American calculation methods [9] cannot be directly applied to walls constructed according to European standards.

2 – TEST SERIES 1: INTRODUCTION

When a timber-framed shear wall elements with a window opening is subjected to horizontal loading, based on previous experimental investigations (Oberbach 2021 [10]), two critical points can be identified (Figure 1):

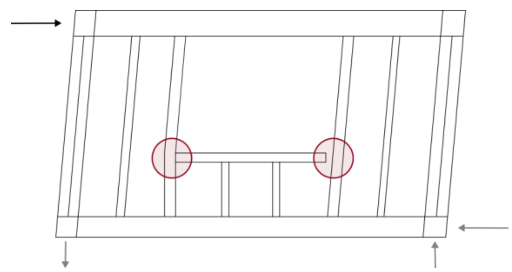

Figure 1: Schematic deformation of a horizontally loaded timber-framed shear wall element with a window opening. The two critical points at the window corners are marked with red circles.

- Corner at the side where the force is applied: The adjacent wall segment bends over the sill segment, provoking window stud failure due to bending.
- Corner opposite to the side where the force is applied: The wall segment next to the opening is insufficiently connected to the sill segment, leading to formation of a gap.

The experiments of Test Series 1 aimed at improving the structural behaviour of timber-framed shear wall elements with openings by optimizing the load transfer. The objective was to reduce the probability of bending failure in the window stud and to minimize the risk of formation of a gap in the corner of the opening, thereby increasing stiffness and load-carrying capacity.

Four types of wall elements were tested (Figure 2):

- Wall 1-1: Conventional design, no optimization of force-transfer.
- Wall 1-2: Additional framing members for distribution of compression force (sill blocking).
- Wall 1-3: Continuous sill rail spanning over the full length of the wall element.
- Wall 1-4: Window studs with bigger cross-sections.

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https://doi.org/10.52202/080513-0614

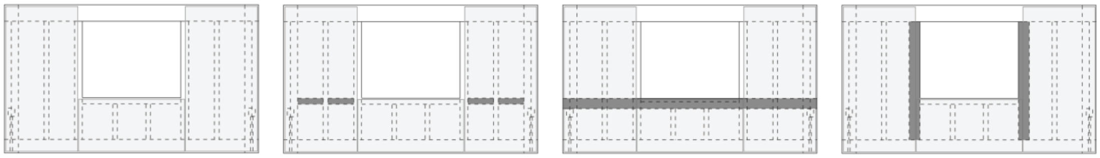

Figure 2: Schematics of the tested wall elements of Test Series 1, with force-transfer optimization methods marked in dark gray colour.

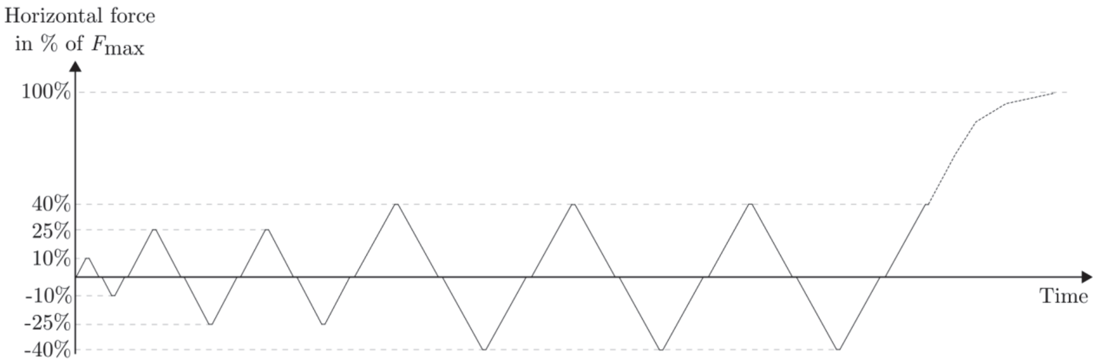

Figure 3: Loading protocol based on ISO 21581:2010, adapted for application in the experiments on the one-storey wall element with window openings. The protocol includes additional steps at 25% and 40% of the estimated maximum force $F_{h,max,est}$ to account for serviceability criteria and stiffness evaluation under monotonic loading, unloading, and reloading conditions.

3 – TEST SERIES 1: MATERIALS

3.1 FRAMING MEMBERS

Most framing members were composed of Norway spruce (*Picea abies*) glulam GL24h except for intermediate studs and sill rails, which were made of glued solid timber GL24h (EN 14080:2013 [11]).

3.2 SHEATHING

The wall elements were sheathed with 18 mm OSB/3 panels on one side, applied in three sections: left and right of the opening, and in the sill segment. There was a 20 mm gap between the sheathing panels, and a 20 mm offset to the wall element edges to prevent local crushing during testing.

3.3 SHEATHING-TO-FRAMING CONNECTION

The sheathing panels were attached to the timber frame using resin-coated staples (Haubold, KG 700, $\emptyset = 1.53$ mm, $L = 50$ mm and $f_u \geq 800$N/mm^2), as follows:

- two rows of staples every 40 mm along the panel edges and force-transfer elements;
- one row every 40 mm along the intermediate studs.

3.4 GEOMETRY OF WALL ELEMENTS

Each wall element measured 4.40 m (width) × 2.54 m (height), with a 1.70 m × 1.40 m window opening, classified as "large" in this research.

3.5 DESIGN OF THE WALL ELEMENTS

For Test Series 1, it was decided that neither the sheathing nor the tie down or the shear anchorage should fail. To ensure that failure was result-open regarding sheathing-to-framing connections and framing members, the sheathing, tie-downs, and shear anchorage were overdesigned applying a factor of 2.0.

3.6 CONSTRUCTION DETAILS

General framing members

- The top and bottom rails were mortise-and-tenon connected to the edge studs.
- The other framing members were notched 5 mm at connection points to account for tolerances.

Continuous sill rail

- The continuous sill rail and the studs were both notched 50% of the width of the continuous sill rail at the crossing points.

Sill blocking

- The window studs were notched 5 mm to accommodate the sill blocking.

4 – TEST SERIES 1: METHOD

4.1 LOADING PROTOCOL

The experiments were conducted according to ISO 21581:2010 [12] with modifications to the pre-cycle protocol (Figure 3). The force was applied displacement-controlled, evaluating the stiffness in both loading directions. Pre-cycles were run at levels of 10%, 25% and 40% of $F_{h,max,est}$ in compression and tension

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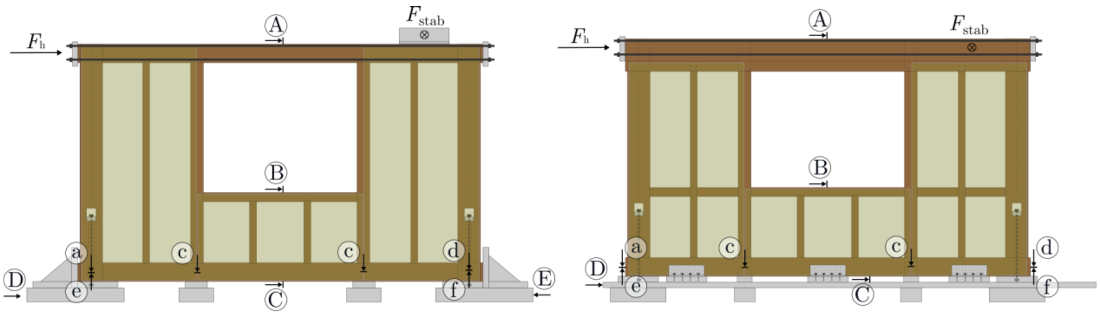

Figure 4: Schematics of the experimental setup of Test Series 1 on the left-hand side, and Test Series 2 on the right-hand side. The capital letters indicate the positions of the LVDT measurements in horizontal direction, the lower-case letters the ones in vertical direction. .

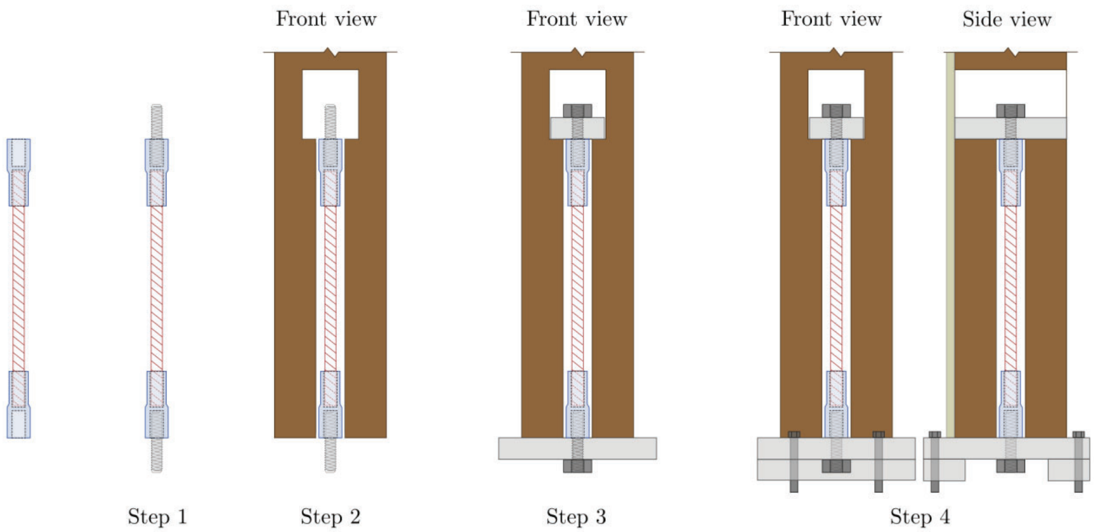

Figure 5: The SIMPLEX tie down system developed by Ancotech AG [13] transmits tensile forces to the test rig. It consists of a reinforcing bar with mechanical couplers and screwed-in threaded rods (Step 1). The assembly is inserted into the edge stud (Step 2), and steel plates are mounted at both ends (Step 3), with the bottom plate secured to the test rig (Step 4).

4.2 TEST SETUP

Figure 4 presents a schematic of the experimental setup. The specimens were fixed to a steel test rig at four points: beneath the edge studs and window studs. A 400 kN hydraulic jack with a precision class 1 load cell applied the horizontal force along the top rail axis. A movable roller support connected the hydraulic jack to the wall element and a fixed support connected the jack to the test rig.

To allow loading in both directions (tension and compression):

- Steel plates were mounted at both ends of the top rail.
- Threaded rods transferred tension forces from the jack to the opposite end of the specimen.
- The hydraulic jack was initially positioned at half of its maximum stroke.

The vertical tensile reaction forces were transmitted to the test rig using the SIMPLEX tie-down system ([13]). This system consists of a reinforcing bar with mechanical couplers at both ends. Installation of the tie-downs involved several steps (Figure 5):

1. Threaded rod sections were screwed into the mechanical couplers.
2. The assembled system was inserted from the bottom into a predrilled hole in the edge stud of the wall element.
3. Steel plates were mounted at both the top and bottom ends of the SIMPLEX tie-downs.
4. Finally, the bottom steel plate was securely attached to the test rig.

The vertical compressive reaction forces were transmitted directly to the test rig through contact.

The horizontal reaction forces were transferred using a steel angle bracket located at the side of the wall element opposite to the force application. Since the wall elements were subjected to both lateral tension and compression forces, angle brackets were installed at both ends.

Due to the asymmetry of the wall elements, with sheathing panels applied only on one side, out-of-plane displacements developed during horizontal loading. To prevent this, a steel support was attached to the top edge of the wall element. Additionally, a 50 kN hydraulic jack with a precision class 1 load cell was used to stabilize the wall element. The out-of-plane displacement was controlled by adjusting the hydraulic jack stroke to maintain a 0 mm displacement.

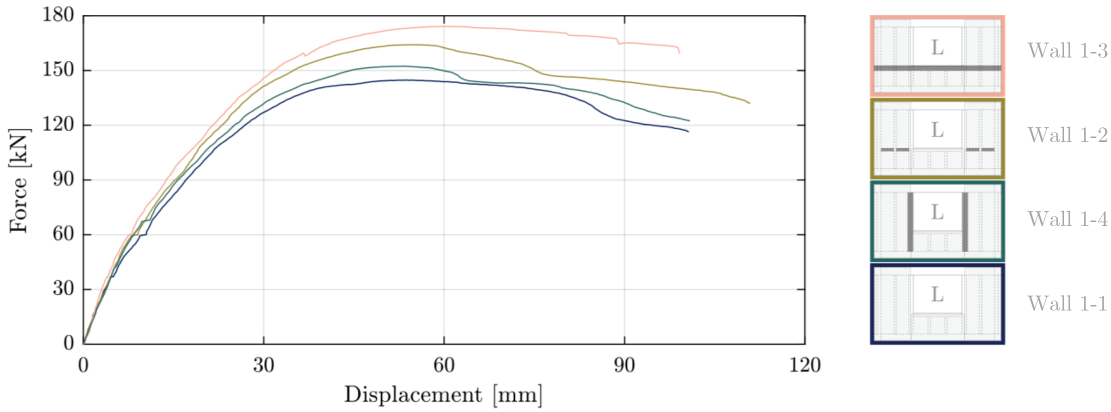

Figure 6: Load-Envelop Curves LEC from zero force up to failure and until reaching a reduction of the applied force to 0.8 $F_{h,max}$ for all four tested wall elements of Test Series 1. The maximum values of $F_{h,max}$ are summarized in Table 1.

4.3 MEASUREMENTS

Forces

Forces in the horizontal hydraulic jack and the stabilization jack were recorded with a frequency of 10 Hz.

Displacements

Measured displacements are shown in Figure 4. Following ISO 21581:2010, the horizontal displacement was recorded at the top and bottom edges of the wall element, while the vertical displacement was measured at both ends. The vertical displacement was measured on the bottom rail.

Additional measurements included:

- horizontal displacement at the midpoint of the sill rail;
- vertical displacement on the bottom rail at the location of the window studs;
- displacements in the test rig (both horizontal and vertical) for control purposes.

All displacements were recorded with a frequency of 10 Hz.

5 – TEST SERIES 1: RESULTS

Figure 7: Out-of-plane displacements of the sill segment of Wall 1-2. The behaviour of Wall 1-1 and 1-4 was similar.

5.1 OBSERVATIONS

All four wall elements exhibited ductile behaviour, characterized by failure in the sheathing-to-framing connection (staples). Brittle failures occurred only after the maximum force had been reached.

For all wall elements except Wall 1-3, optimized by placing a continuous sill rail, the right-hand side and the sill segment detached. The detaching caused an out-of-plane movement of the sill segments towards the sheathed side of the wall element (Figure 7).

5.2 STIFFNESS AND LOAD-CARRYING CAPACITY

The load envelope curve (LEC) curves for the four types of wall elements investigated are shown in Figure 6.

The stiffness was calculated as specified in ISO 21581:

$$K = (0.3\ F_{h,max}) / (u_{40\%F_{h,max}} - u_{10\%F_{h,max}}) \qquad (1)$$

Since the force-displacement behaviour of the tested wall element geometries was nonlinear from the very beginning of the experiment, stiffness was evaluated for a horizontal top wall element displacement of 5 mm (H/500) to complement the standard stiffness assessment between 10% and 40% of $F_{h,max}$. Specifically, stiffness was also evaluated between 10% and 25% of $F_{h,max}$ to better capture the initial response of the wall elements. All stiffness calculations were performed using the LEC curves, and the results are summarized in Table 1.

Table 1: Maximum force reached in the experiment ($F_{h,max}$), stiffnesses (K) determined between 10% & 25% and between 10% & 40% of $F_{h,max}$ on the LEC, and horizontal force needed to reach a top wall element displacement of 5 mm.

Specimen	$F_{h,max}$ [kN]	K_{10-25} [kN/m]	K_{10-40} [kN/m]	$F_{h,5mm}$ [kN]
Wall 1-1	145	7'420	5'670	37.5
Wall 1-2	165	7'470	6'090	40.9
Wall 1-3	174	8'500	6'950	44.0
Wall 1-4	153	8'090	6'880	40.2

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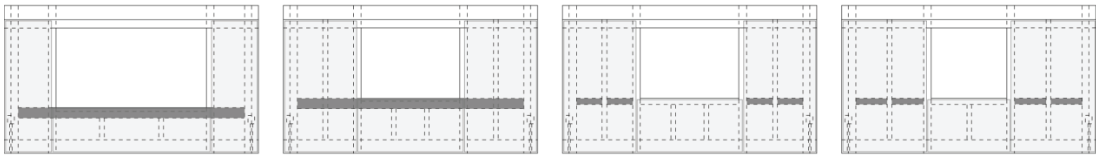

Figure 8: Schematics of the tested wall elements of Test Series 2, with force-transfer optimization methods marked in dark gray colour.

6 – TEST SERIES 1: DISCUSSION

In Table 2, the increase in stiffness and load-carrying capacity for all three options of optimizing the force-transfer compared to the conventional design (Wall 1-1) are summarized.

Table 2: Improvement of the three options of optimizing the force-transfer compared to the conventional design. The improvement compared to the conventional design (Wall 1-1) is given in percentage for the maximum force reached in the experiment ($F_{h,max}$), the stiffnesses (K) determined between 10% & 25% and between 10% & 40% of $F_{h,max}$ on the LEC, and the horizontal force needed for a horizontal displacement at the top edge of 5 mm.

Specimen	$F_{h,max}$	K_{10-25}	K_{10-40}	$F_{h,5mm}$
Wall 1-2	+9%	+1%	+7%	+23%
Wall 1-3	+17%	+15%	+23%	+19%
Wall 1-4	+5%	+9%	+2%	+7%

The results of Test Series 1 demonstrated that, compared to the conventional design (Wall 1-1), all three options of optimizing the force-transfer led to increased stiffness. The horizontal force needed to displace the wall element by 5 mm horizontally increased as well as the load-carrying capacity. Increasing the width of the window stud (Wall 1-4) did lead to a remarkably smaller increase in the force at 5 mm horizontal displacement and in the maximum force as well. Optimizing the force-transfer by means of sill blocking (Wall 1-2) and by placing a continuous sill rail (Wall 1-3) led to improvement of the wall behaviour regarding stiffness and load-carrying capacity the most.

7 – TEST SERIES 2: INTRODUCTION

Based on the results of Test Series 1, further investigations were conducted on the two options of optimizing the force-transfer, i.e.: sill blockings and the continuous sill rail. The primary goal of Test Series 2 was to experimentally evaluate the behaviour of wall elements with construction details more representative of real-world timber construction practice.

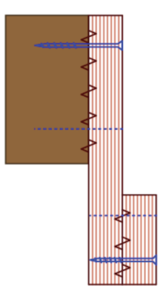

Figure 9: Schematic of the combined cross-section of the top rail of the wall elements of Test Series 2.

In this test series, four additional wall elements with different sizes of window opening were tested (Figure 8). Since the construction details in Test Series 2 differed significantly from those in Test Series 1, the "large" window opening size was tested again using both methods of optimizing the force-transfer for comparison. Additionally, sill blockings were tested on one wall element with a smaller window opening, while the continuous sill rail was tested on a wall element with a larger window opening.

8 – TEST SERIES 2: MATERIALS

8.1 MATERIALIZATION OF ELEMENTS

Materials used for the framing members, the sheathing and the sheathing-to-framing connection were identical to Test Series 1, see above.

8.2 GEOMETRY OF WALL ELEMENTS

Consistent with Test Series 1, the wall elements measured 4.40 m in width and 2.54 m in height. Three different window opening sizes were defined as:

- Medium: 1.04 m width, 1.24 m height;
- Large: 1.70 m width, 1.24 m height;
- Very large: 2.46 m width, 1.44 m height.

8.3 DESIGN OF THE WALL ELEMENTS

For the experiments in Test Series 2, the sheathing thickness and staple arrangement were identical to Test Series 1. The cross-sections of the framing members were also largely retained, with two key modifications:

- a slight reduction in edge stud width;
- an increase in the height of the continuous sill rail.

8.4 CONSTRUCTION DETAILS

General framing members

- As in Test Series 1, the top and bottom rails were connected to the edge stud by means of a mortise and tenon connection.
- The window stud connections to the top and bottom rails were changed to mortise and tenon joints.
- All other framing members were fitted in by notching the connected member by 5 mm to comply with tolerances.
- The top rail was a combined cross-section consisting of a GLT element and an L-shaped cross-section in Kerto Q LVL (EN 14374:2004 [14]), comprising two members (Figure 9). The Kerto Q element was positioned on the side with the sheathing panels, where it would serve as a slab support in practice.

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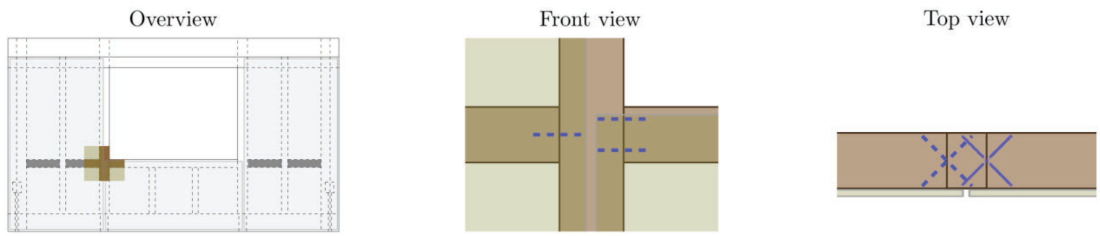

Figure 10: Schematics of the method to optimize force-transfer of using crossed screws (double-threaded screws) inserted between the window stud and the sill rail and between the sill blocking and the window studs, with the major aim to transfer compressive and tensile forces

- Adjusting the top rail design resulted in a reduction in height of the OSB/3 panels.

Continuous sill rail

- The continuous sill rail was notched 33% and the studs 66% of the sill rail's width at crossing points.

Crossed-screwed sill blocking

- The sill blocking was inserted between the window studs after creating a 5 mm notch in the studs.
- To enhance tensile force transfer, two pairs of crossed screws (double-threaded screws) were installed at the sill rail-to-window stud connections and one pair at the sill blocking-to-window stud connections (Figure 10).

9 – TEST SERIES 2: METHOD

9.1 LOADING PROTOCOL

The experiments in Test Series 2 followed the same loading protocol as in Test Series 1.

9.2 TEST SETUP

The test setup was largely like the one in Test Series 1 (Figure 4), with some modifications, as follows:

To better represent industrial construction practices, a single steel angle bracket at the ends of the wall elements was considered unsuitable. Instead, three steel angle brackets were installed on the sheathed side of the wall elements, directly on the bottom rail, requiring the OSB/3 panels to be cut accordingly.

Compared to Test Series 1, additional attachments were needed to fix the wall element to the test rig at intermediate points between the beam elements of the fixed test rig. This was achieved by:

- mounting a long steel plate underneath the wall elements;
- installing five smaller steel plates onto this long steel plate, allowing fixation at five points—beneath the edge studs and at approximately one-third positions.

The horizontal force was applied as in Test Series 1.

Since the sheathing was applied on one side only, out-of-plane displacement could develop during loading. To counteract this displacement, a 50 kN hydraulic jack with a precision class 1 load cell was used to stabilize the wall element. The out-of-plane displacement was controlled by regulating the hydraulic jack stroke to maintain a 0 mm displacement. The jack was placed on the top rail, between the two threaded rods used for tensile force application.

9.3 MEASUREMENTS

Forces

The horizontal force applied by the hydraulic jack and the force in the jack used for stabilizing the wall elements were measured with a frequency of 10 Hz.

Displacements

The measured displacements are shown in Figure 4. Following the specifications in ISO 21581:2010, the horizontal displacement was recorded at the top and bottom edges of the wall element, while the vertical displacement was measured at both ends. The vertical displacement was measured on the edge studs.

Additional measurements included:

- horizontal displacement at the midpoint of the sill rail;
- vertical displacement on the bottom rail at the location of the window studs;
- displacements in the test rig (both horizontal and vertical) for control purposes.

All displacements were recorded at 10 Hz.

10 – TEST SERIES 2: RESULTS

10.1 OBSERVATIONS

All four wall elements exhibited ductile behaviour, with failure occurring in the sheathing-to-framing connections (staples).

For the wall elements with crossed-screwed sill blocking, the maximum applied force was reached before brittle failure mechanisms emerged. The first brittle failure occurred as a shear failure of the window stud at its connection to the top rail, on the force application side (Figure 11). At very large deformations, the edge stud at the tie-down failed in shear at the location of the SIMPLEX tie-down.

For the wall elements with a continuous sill rail, the force plateaued, but it was unclear if further increases would have been possible without brittle failure. The first brittle failure in these specimens occurred in the OSB/3 panel at the height of the continuous sill rail. For the specimen with large window opening, failure occurred on the side opposite to the one where the force was applied, as shown in Figure 12, for the very large window opening, failure occurred on the side where the force was applied.

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Figure 11: Brittle failure of the window stud on the side opposite to the force application in Wall 2-2, after reaching the maximum force. Wall 2-1 exhibited a very similar failure pattern.

Figure 12: Brittle failure of the OSB/3 panel on the side opposite to the force application in Wall 2-3. Wall 2-4 exhibited a very similar failure pattern, but the OSB/3 panel failed on the side where the force was applied.

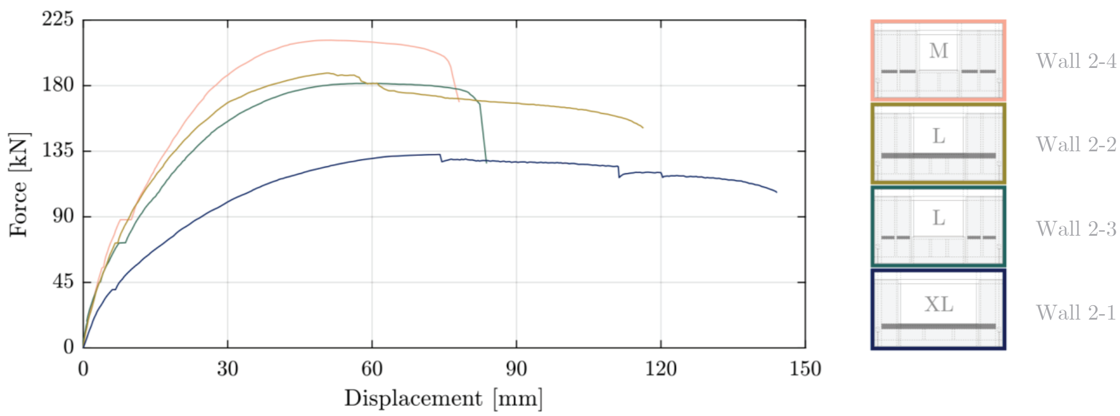

Figure 13: Load-Envelope Curves LEC from zero force up to failure and until reaching a reduction of the applied force to 0.8 $F_{h,max}$ for all four tested wall elements of Test Series 2. The maximum values of $F_{h,max}$ are summarized in Table 1

10.2 STIFFNESS AND LOAD_CARRYING CAPACITY

Figure 13 shows the LEC curves for the four wall elements investigated in Test Series 2.

As in Test Series 1, all tested wall elements exhibited a nonlinear force-displacement behaviour from the beginning. Therefore, the stiffness evaluation based on the LEC followed the same procedure as in Test Series 1.

Table 3 summarizes the maximum force ($F_{h,max}$), the stiffness values evaluated for forces between 10%–25% and 10%–40% of $F_{h,max}$, and the force required to displace the wall elements by 5 mm.

Table 3: Maximum force reached in the experiment ($F_{h,max}$), stiffnesses (K) determined on the LEC between 10% & 25% and between 10% & 40% of $F_{h,max}$, and horizontal force needed to reach a top wall element displacement of 5 mm.

Specimen	$F_{h,max}$ [kN]	$K_{10\text{-}25}$ [kN/m]	$K_{10\text{-}40}$ [kN/m]	$F_{h,5mm}$ [kN]
Wall 2-1	212	12'530	10'510	66.7
Wall 2-2	182	9'780	6'770	57.6
Wall 2-3	189	10'760	8'770	58.8
Wall 2-4	133	6'680	4'780	36.1

11 – TEST SERIES 2: DISCUSSION

The results indicate that adding pairs of crossed screws in sill blockings made their behaviour comparable to the one of a continuous sill rail.

For wall elements with identical window opening sizes (Walls 2-2 and 2-3):

- Maximum forces reached were similar.
- Forces required to lead to a horizontal top wall element displacement of 5 mm were comparable.
- Stiffness at levels of 10%–25% of $F_{h,max}$ was nearly identical.
- However, when considering stiffness at force levels 10%–40% of $F_{h,max}$, the continuous sill rail provided higher stiffness than the crossed-screwed sill blocking.

Additionally, wall elements with sill blocking exhibited an immediate force drop to 80% of $F_{h,max}$ after the first brittle failure occurred. In contrast, for wall element with a continuous sill rail, the load drop to 80% $F_{h,max}$ occurred at much larger displacements (Figure 13).

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12 – COMPARISON WITH ANALYTICAL CALCULATIONS

The maximum force applied in Test Series 2 experiments is now compared with the design values using the segmentation approach specified in the Final draft of Eurocode 5 (for Formal Vote), FprEN 1995-1-1:2025 [4], where only the side segments are considered in the calculation. For this comparison, it is assumed that the side segments are tied down at both ends. In cases, where the staples are governing the design, the design value of the wall elements depends on the shear resistance of a single staple, the distance between the staples within a row, the number of staple rows, and the width of the wall segments. According to FprEN 1995-1-1:2025 [4], the resistance of one single staple is 596 N (with k_{mod}=1.1 and μ_M=1.3). The two staple rows were spaced 40 mm apart around the sheathing panels of the side segments, and the widths of the side segments, depending on the window opening size, were 1.58 m, 1.25 m, and 0.87 m.

In the experiments, the wall elements exhibited ductile behaviour up to the maximum horizontal force, with the staples connecting the sheathing panels to the framing members being the only ductile element. Consequently, the behaviour of the wall elements is primarily depending on the connection between the sheathing panels and the framing members. According to the background document of DIN 1052 [15], the design value of the fastener is about 20% higher when applied in a timber-framed shear wall compared to experimental tests on fasteners (Oberbach 2021 [10]). The ratio between the design value of one staple (596 N, mode (f) of formula (11.14) in FprEN 1995-1-1:2025) and the experimentally determined load-carrying capacity (Oberbach 2021 [10]) - after this 20% increase to 1236 N - is approximately 50%. This "50% rule", derived from staple behaviour, was validated in experiments on wall elements in two other projects [10] and [16]. Therefore, 50% of the maximum forces determined in the Test Series 2 experiments were compared to the design values according to FprEN 1995-1-1:2025.

The resulting design shear forces of the wall elements, together with 50% of the maximum horizontal force from the experiment, are listed in Table 4.

The stiffnesses of the wall elements investigated in Test Series 2, evaluated on the LEC between force levels of 10% and 40% of the maximum horizontal force, were compared with the stiffness calculated for the wall element. Again, only the side segments contribute to the load-resisting system and are assumed to be tied down at both ends. According to FprEN 1995-1-1:2025, the overall horizontal displacement at the top of the wall element can be calculated by summing the following contributions:

- displacement from the deformation of the sheathing-to-framing connection;
- displacement from the axial deformation of the framing;
- displacement from the elongation in the tie-down connection (rigid body rotation);
- displacement from the rigid body translation, i.e. horizontal movement at the base;
- displacement from the deformation of the bottom rail perpendicular to grain;
- displacement from the sheathing panel shear deformation.

The fourth and fifth contributions were assumed to be zero. In the wall element experiments, the shear anchorage was over-dimensioned, resulting in negligible deformations even at maximum force and compression perpendicular to the grain in the bottom rail was avoided by the mortise and tenon connections to the studs. The stiffness summarized in Table 4 corresponds to the reciprocal of the displacement resulting from an imposed unit force, multiplied by that same unit force.

Table 4: Comparison of 50% of the maximum horizontal force ($F_{h,max}$) reached in the experiments of Test Series 2 and the design shear forces calculated according to FprEN 1995-1-1:2025. Comparison of the stiffness evaluated between force levels of 10% and 40% of $F_{h,max}$ and the stiffness of the wall element calculated according to FprEN 1995-1-1:2025 (K_{EC}).

Specimen	Walls with openings Experimental		Segments Calculated	
	0.5 $F_{h,max}$ [kN]	K_{10-40} [kN/m]	$F_{h,Rd}$ [kN]	K_{EC} [kN/m]
Wall 2-1	106	10'510	94.2	7'230
Wall 2-2	91.0	6'770	74.5	5'170
Wall 2-3	94.3	8'770	74.5	5'170
Wall 2-4	66.4	4'780	51.9	2'990

The measured stiffness was 30% to 70% higher than the values calculated according to FprEN 1995-1-1:2025. The shear resistance of the wall elements with window openings is only slightly higher than the shear resistance calculated using the segmentation approach. It should be noted that the calculations assumed tie downs on both ends of the side segments. Consequently, while the design values are in a similar range, only two of the four tie downs required in the calculation according to the segmentation approach, were present in the experiments in this study.

13 – CONCLUSIONS

The load-carrying capacity of a wall element with a window opening is slightly higher than that calculated according to FprEN 1995-1-1:2025 when wall segments with window openings are neglected. The stiffness of the tested wall elements was 30% to 70% higher than the values calculated according to FprEN 1995-1-1:2025, and the required number of tie downs can be reduced when taking all segments (i.e. also the ones with openings) into account when designing such wall elements or walls respectively.

The results of the experiments on single-storey wall elements with openings demonstrate that activating timber-framed shear walls with window openings and hence, making them part of the lateral force-resisting system offers significant potential for more economical design solutions in timber construction. By applying relatively simple reinforcement measures, the stiffness and load-carrying capacity of such wall elements can be markedly increased. The benefits of including walls with window openings in the design extend not only to enhanced stiffness and load-carrying capacity but also to

https://doi.org/10.52202/080513-0614

a reduction in the number of tie downs needed and hence, in a reduction of costs.

The findings of this study will serve as the basis for further investigations on one- and two-storey wall elements with window openings, with the overall project aim of developing a design method for timber-framed shear walls with window openings that contribute to the lateral force-resisting system of multi-storey timber buildings.

14 – OUTLOOK

Using the experimental results from the one-story wall element tests presented in this paper, a finite element (FE) model will be developed using the RFEM software by Dlubal. The FE model will be validated with data from three two-story wall tests and five long wall tests. Each of these experiments will involve two wall elements, in sizes identical to the ones of the one-story wall elements tested in this study.

ACKNOWLEDGEMENT

The experiments presented in this paper were supported by the *Swiss Federal Office for the Environment FOEN* within the framework of the *Aktionsplan Holz*.

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