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TESTS ON THE SPLITTING FAILURE CAPACITY OF THE BOTTOM RAIL DUE TO UPLIFT IN PARTIALLY ANCHORED SHEAR WALLS

Giuseppe Caprolu[1], Ulf Arne Girhammar[2], Bo Källsner[3], Helena Johnsson[4]

ABSTRACT: Källsner and Girhammar have developed a new plastic design method for wood-frame shear walls at ultimate limit state. The method is capable of calculating the load-carrying capacity of partially anchored shear walls, where the leading stud is not necessarily anchored against uplift. In fully anchored shear walls, the leading stud needs to be anchored using some kind of hold-downs to resist uplift and the bottom rail needs to be fixed by anchor bolts to resist horizontal shear forces. In partially anchored shear walls, where hold-downs are not provided, the uplifting force is resisted by the sheathing-to-framing joints along the bottom rail. Hence, it is important that the bottom rail is anchored to the floor structure or foundation by anchor bolts and, therefore, able to transmit the forces to the structure below. Because of the eccentric load transfer, transverse bending is developed in the bottom rail and splitting of the bottom rail can occur. In order to use the plastic design method, a ductile behaviour of the sheathing-to-framing joints must be ensured. In this paper, results of tests on the splitting capacity of the bottom rail due to uplift in partially anchored shear walls are presented. Specimens with single-sided sheathing were tested, varying the size of washer, pith orientation of the bottom rails and anchor bolt position along the width of the bottom rail. The aim of the tests was to evaluate the influence of these parameters in order to avoid splitting failure of the bottom rail. Two types of brittle failure modes occurred during testing: (1) a crack opening from the bottom surface of the bottom rail and (2) a crack opening from the edge surface of the bottom rail along the line of sheathing-to-framing joints. These failure modes were mainly dependent on the washer size and the location of the anchor bolt. The results show that the distance between the edge of the washer and the loaded edge of the bottom rail has a decisive influence on the maximum load and the failure modes of the bottom rail.

KEYWORDS: Timber shear walls, Partially anchored, Sheathing-to-framing joint, Bottom rail, Cross-wise bending, Splitting of bottom surface, Splitting of edge surface

1 INTRODUCTION

1.1 BACKGROUND

In EC5, the European timber design code, two analytical methods are given to design shear walls: method A which only can be applied to shear walls with a tie-down at their ends, and method B where the stud at the end of the wall is free to move vertically and the bottom rail is anchored to the substrate.

In the test standard EN 594 [1], a test method to be used in determining the racking resistance is given.

The anchorage system of shear walls is provided from anchor bolts and hold downs. Prion and Lam [2] pointed out the importance to understand the difference between hold-downs and anchor bolts. Anchor bolts provide horizontal shear continuity between the bottom rail and the foundation. Hold-downs serve as vertical anchorage devices between the vertical end studs and the foundation. When hold-downs are not provided, the corresponding forces can be replaced by vertical loads from upper storeys, the roof or corner framing. In this case the bottom row of nails transmits the vertical forces in the sheathing to the bottom rail (instead of the vertical stud) where the anchor bolts will further transmit the forces into the foundation. Because of the eccentric load transfer, transverse bending is created in the bottom rail and splitting may occur.

[1] Giuseppe Caprolu, PhD Candidate, Division of Structural and Construction Engineering – Timber Structures, Luleå University of Technology, SE-971 87 Luleå, Sweden. Email: giuseppe.caprolu@ltu.se
[2] Ulf Arne Girhammar, Professor, Division of Structural and Construction Engineering – Timber Structures, Luleå University of Technology. Email: ulf.arne.girhammar@ltu.se
[3] Bo Källsner, Professor, School of Engineering, Linnaeus University Växjö, and SP – Technical Research Institute of Sweden, Stockholm. Email: bo.kallsner@sp.se
[4] Helena Johnsson, Ass. Professor, Division of Structural and Construction Engineering – Timber Structures, Luleå University of Technology. Email: helena.johnsson@ltu.se

Mohammad, Karacabeyli and Quenneville [3] carried out tests to determine the lateral resistance of bolted timber-to-concrete connections loaded parallel and perpendicular to grain. Specimens were made of hemlock-fir and spruce-pine-fir and bolted to concrete blocks using anchor bolts. Three different sizes of anchor bolts were used, with diameters of 12.7 mm, 15.8 mm and 19.1 mm. The dominant modes of failures observed in the connections loaded perpendicular to grain were splitting and bearing (crushing) of the wood, associated with the bending deformation of the anchor bolts.

Ni and Karacabeyli [4] developed two methods, one empirical and one mechanics-based to account for effects of uplift restraint on performance of shear walls without hold-downs. In order to quantify effects of overturning restraints on performance of wood-frame shear walls, full-scale shear wall specimens were tested under lateral load. The bottom rails of the walls were attached to the foundation through 12.7 mm diameter anchor bolts spaced at 406 mm on centre. The distance between the anchor bolt and the outer edge of the walls was 203 mm. The bottom rails did not present any failure during the tests, meaning that their design of the anchorage of the bottom rail was sufficient.

Yeh and Williamson [5] tested the resistance of wood structural panel shear walls against combined shear and wind uplift. In a previous study it was shown that the cross-grain bending of the bottom rail could be avoided by using 5.8×76×76 mm washer with 15.9 mm diameter anchor bolts spaced at 406 mm on centre. These tests were conducted in lateral shear and tension separately, and the combined effect was evaluated based on an engineering analysis. Seven full-scale walls were tested at Clemson University designed to address the concern of cross-grain bending of the bottom rail. The test setup was capable of increasing the shear and uplift forces simultaneously until failure was reached by using a pulley system controlling the bi-axial forces in both lateral and vertical directions. Also, tests were conducted with another device capable of bi-axial loading in both lateral and vertical directions with independent but synchronized loading mechanism. For all tests 38×88 mm studs at 400 mm on centre, 11/12 mm OSB sheathing and 3.3/3.8×64/76 mm common nails at 100/150 mm (300 mm on intermediate studs) on centre were used. 16 mm anchor bolts and 75×75×3 mm or 75×75×6 mm washer at 400 mm on centre were used. Among all tests only one failed due to cross-bending of the bottom rail, occurring when 3 mm thin washer was used.

Bracci, Stromatt and Pollock [6] made extensive investigations in the field in relation to damage in wood frame construction in the form of splitting of the bottom rail along the line of anchor bolts that typically connect shear walls to the masonry or concrete foundation. The objective of their research was to evaluate the response performance of wood bottom rail-to-concrete foundation connections using 50.8 mm dimension timber with and without member being clamped to the substrate at the yield and ultimate limit states. They used for their tests two supplemental reinforcement devices for the bottom rail: thin metal reinforcing straps and special reinforcing clamps. Southern pine 50.8×152.4 mm dimension timber was used in this study and either 12.7 mm or 22.2 mm diameter bolts. The experimental test set-up was for full-scale component testing in single shear loading. The bottom rail was fixed to a double 50.8×152.4 mm southern pine member that simulated the concrete foundation. The bottom rail was subjected to a quasi-static reversed cyclic loading. In unreinforced bottom rail the results show a typical failure by brittle splitting along the grain of the bottom rail. In reinforced bottom rail by reinforcing straps and clamps the results show an improved deformation capability and energy dissipation capacity of the connection. Since the straps were rather flexible, they did not significantly increase the splitting resistance of the bottom rail. Reinforcing clamp instead can improve the splitting resistance.

Källsner and Girhammar [7] have presented a new plastic design method of wood-framed shear walls at ultimate limit state. This method allows the designer to calculate the load-carrying capacity of partially anchored shear walls where the leading stud is not fully anchored against the uplift. The tests described in this paper are part of this research.

In order to be able to use the plastic design method proposed by Källsner and Girhammar [7], ductile behaviour of the bottom rail and the joints must be ensured. Brittle failure modes in the bottom rail can be avoided using large washers (square or rectangular) at the anchor bolts. The size of the washer influences of course the eccentricity moment in the bottom rail.

Girhammar and Källsner [8, 9] have conducted tests where they found that the distance between the edge of the washer and the loaded edge of the bottom rail has a decisive influence on the capacity and the failure modes of the bottom rail.

1.2 AIM AND SCOPE

The aim of this investigation is to extend the experimental work previously conducted by Girhammar and Källsner where the splitting capacity of the bottom rail was studied. The main focus of the present paper is on evaluating the influence of the anchor bolt position (in the cross-wise direction of the bottom rail), the size of the washer and the position of the pith on the splitting capacity and the failure modes of the bottom rail.

The study in this paper is limited to single-sided sheathing.

2 MATERIALS AND METHODS

2.1 TEST SPECIMEN

The specimens were built by hand using rails of length 900 mm with a cross section of 45×120 mm, joined to a hardboard sheet of 900×500 mm by nails 50×2.1mm.

2.2 TEST PROGRAM

A total of 142 specimens were tested. The specimens were divided into three different series, where each series was divided into different sets. The series were subdivided with regard to the orientation of the pith of the bottom rail, the washer size and the position of the anchor bolt with respect to the width of the bottom rail. The test program is specified in Table 1.

Table 1: *Test program (notation as in Fig. 1)*

Series	Anchor bolt position	Set	Size of washer [mm]	Number of Tests[1]	Distance s [mm]
1	$b/2$ 60 mm from sheathing	1	40×40×15	16	40
		2	60×60×15	16	30
		3	80×70×15	16	20
		4	100×70×15	16	10
2	$3b/8$ 45 mm from sheathing	1	40×40×15	14	25
		2	60×60×15	16	15
		3	80×70×15	16	5
3	$b/4$ 30 mm from sheathing	1	40×40×15	16	10
		2	60×60×15	16	0

[1)] Half of the specimens with pith downwards and half of the specimens with pith upwards.

2.3 MATERIAL PROPERTIES

The details of the test specimens were as follow:

- Bottom rail: Spruce (Picea Abies), C24 according to EN 338, 45×120 mm.
- Sheathing: Hardboard, 8 mm (wet process fibre board, HB.HLA2, EN 622-2, Masonite AB).
- Sheathing-to-timber joints: Annular ringed shank nails, 50×2.1 mm (Duofast, Nordisk Kartro AB). The joints were nailed manually and the holes were pre-drilled, only in the sheet, 1.7 mm. Nail spacing was 25 mm or 50 mm. Edge distance was 22.5 mm along the bottom rails.
- Anchor bolt: Ø 12 (M12). The holes in the bottom rails were pre-drilled, 14 mm.

2.4 TEST SET-UP

The testing arrangements are shown in Figure 1.
The bottom rail was fastened to a supporting welded steel structure by two anchor bolts. The distance between the bolts was 600 mm and the distance between bolt and the end of the bottom rail was 150 mm. To tighten the bolts a torque moment of 50 Nm was used. A rigid square or rectangular washer was inserted between the bottom rail and the bolt head throughout all tests. A hydraulic piston (static load capacity 100 kN) was attached to the upper panel using a C-shaped steel profile and four bolts Ø16, inducing a tensile force with a constant displacement rate of 10 mm/min (by mistake it was 10 mm/min instead 2 mm/min; the testing rate should ideally be such that the failure occurs after 5 minutes).
During loading, the rails were free to rotate around the hinge, Figure 1.

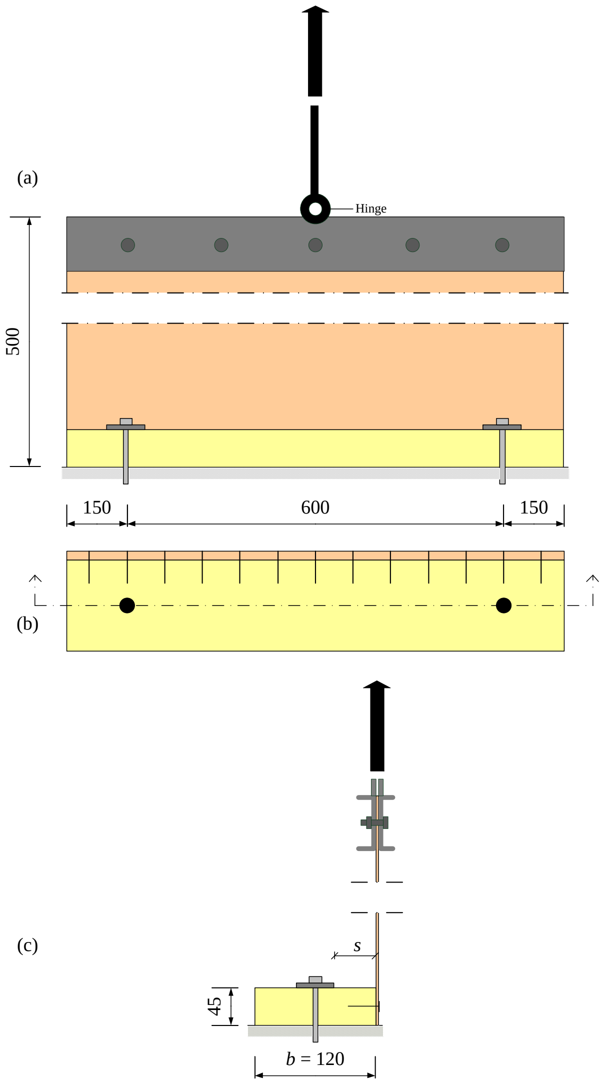

Figure 1: *Test set-up and boundary conditions of sheathed bottom rails subjected to single-sided vertical uplift*

For each specimen the moisture content and density of the bottom rail was measured after the test, according to ISO 3130:1975 and ISO 3131:1975, respectively.

3 RESULTS

3.1 FAILURE MODES OF THE BOTTOM RAIL

Three primary failure modes were found during the tests. They were dependent on the washer size and the location of the anchor bolt. The different failure modes were:

(1) Splitting along the bottom side of the rail according to Figure 2a.
(2) Splitting along the edge side of the rail according to Figure 2b.
(3) Yielding and withdrawal of the sheathing-to-framing joints according to Figure 2c.

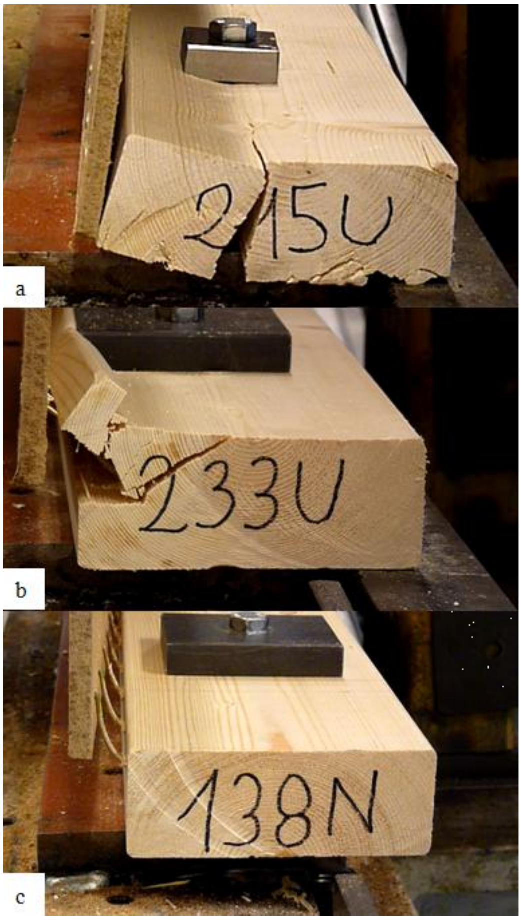

Figure 2: *(a) Splitting failure along the bottom side of the rail; (b) Splitting along the edge side of the rail; (c) Yielding and withdrawal of the sheathing-to-framing joints*

In Figure 3 the percentage of the three different failure modes is graphically shown for the series tested. It is noted that the failure modes are strongly dependant on the distance *s* from the washer edge to the loaded edge of the bottom rail. For $s \geq 25$ mm only failure mode 1 occurs. The reason for this failure mode is that the bottom rail is subjected to crosswise bending giving rise to tensile stresses along the bottom side of the rail. For small values of the distance *s* failure mode 2 (splitting along the edge side of the rail) and mode 3 (yielding and withdrawal of the sheathing-to-framing joints) dominate.

3.2 FAILURE LOAD OF THE BOTTOM RAIL

The failure load is defined as the load at which there is a first distinct decrease in the load carrying capacity due to a propagating crack in the bottom rail or due to withdrawal of the nails. The results of the different test series are summarised in Table 2. There is no distinction between different pith orientations in the table.

Table 2: *Results from testing of sheathed bottom rails subjected to single-sided vertical uplift. There is no distinction between different pith orientations. The distance s is defined in Figure 1*

Series	Washer size [mm]	Distance *s* [mm]	Failure load [kN]	Dry density [kg/m^3]	Moisture content [%]
1	40	40	9.87 ± 2.20	395 ± 30	12.1 ± 0.67
	60	30	12.0 ± 2.50	386 ± 25	10.9 ± 0.32
	80	20	17.6 ± 2.33	417 ± 57	10.8 ± 0.35
	100	10	20.9 ± 1.83	414 ± 42	11.0 ± 0.49
2	40	25	13.1 ± 2.70	401 ± 36	9.31 ± 2.96
	60	15	17.4 ± 3.56	378 ± 34	12.6 ± 0.69
	80	5	23.1 ± 3.57	416 ± 26	11.6 ± 0.61
3	40	10	18.4 ± 2.21	371 ± 21	11.5 ± 0.54
	60	0	22.5 ± 2.80	408 ± 35	12.0 ± 0.53

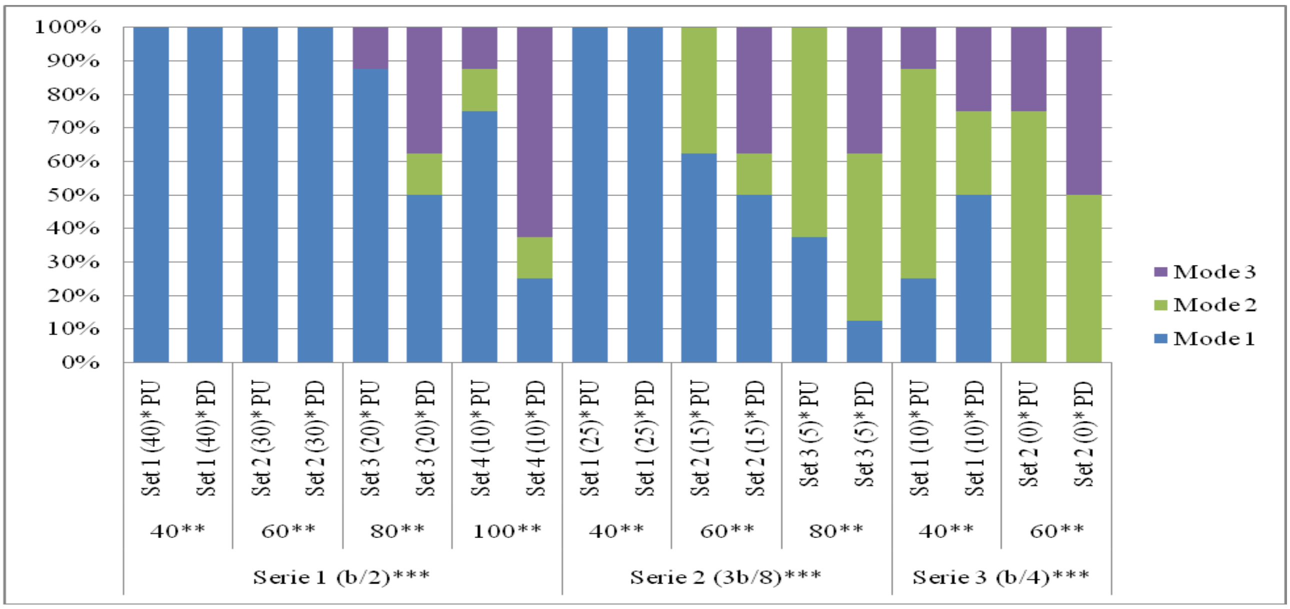

Figure 3: *Recorded failure modes for the different test series and sets (PU = Pith upwards, PD = Pith downwards). *Distance from washer edge to loaded edge of the bottom rail [mm], **Size of washer [mm], ***Bolt position*

In Figure 4 the relationship between mean failure load and size of washer is shown. The results are not separated with respect to pith orientation. Figure 4 illustrates that for a given position of the anchor bolt, the failure load of the bottom rail increases when the washer size is increased. This is of course consequence of the smaller *s*-distance for increased washer size.

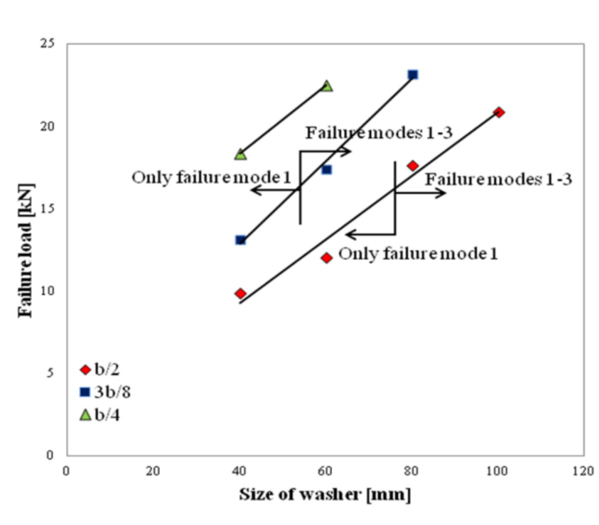

Figure 4: *Mean failure load versus size of washer. The vertical lines show borders between different failure modes*

In Table 3 and Figure 5 the results of test series 1 are separated with respect to pith orientation.

Table 3: *Results from testing of sheathed bottom rails subjected to single-sided vertical uplift. In series PU the pith is oriented upwards and in series PD the pith is oriented downwards*

Series	Washer size [mm]	Distance *s* [mm]	Failure load [kN]	Dry density [kg/m^3]	Moisture content [%]
PU	40	40	9.49 ± 2.59	397 ± 28	11.9 ± 0.77
	60	30	10.6 ± 2.04	390 ± 27	10.9 ± 0.38
	80	20	17.1 ± 2.77	409 ± 43	10.7 ± 0.24
	100	10	20.0 ± 1.62	422 ± 55	11.1 ± 0.56
PD	40	40	10.3 ± 1.84	392 ± 37	12.3 ± 0.64
	60	30	13.5 ± 2.06	383 ± 24	10.9 ± 0.27
	80	20	18.2 ± 1.47	426 ± 71	10.9 ± 0.41
	100	10	21.8 ± 1.65	406 ± 24	10.9 ± 0.43

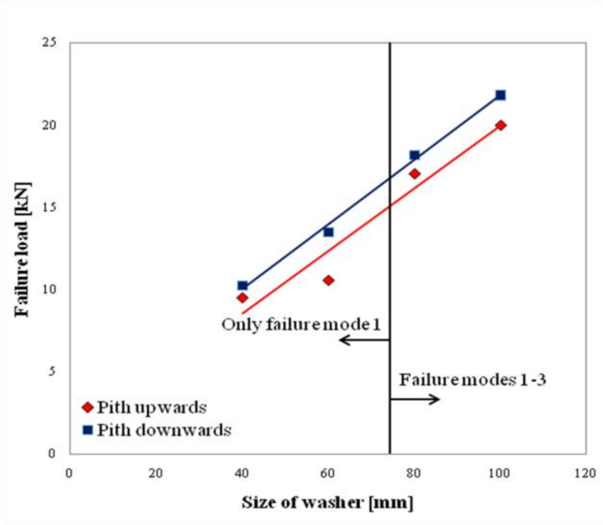

Figure 5: *Mean failure load versus size of washer when the pith is oriented upwards and downwards. The vertical line shows a border between different failure modes*

From Figure 5 it seems that the orientation of the pith in the bottom rail seems to have a certain influence on the failure load. The failure load is about 10% higher when the test specimens are oriented with the pith downwards. This tendency can also be seen by studying Figure 3 in which less mode 1 failures occur when the pith is oriented downwards, thus, leading to higher failure loads.

In Figure 6 the relationship between mean failure load and distance *s* from washer edge to the loaded edge of bottom rail is given. It is evident that the failure load of the bottom rail increases when the distance *s* is decreased.

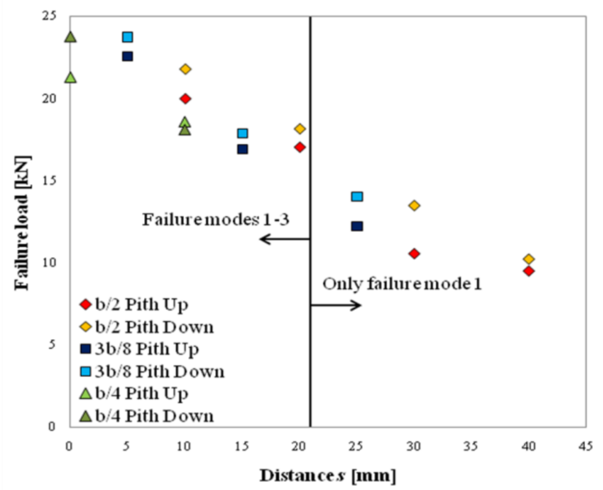

Figure 6: *Mean failure load versus distances from washer edge to loaded edge of bottom rail. The vertical line shows a border between different failure modes*

In Figure 7 the same relationship is given but all individual test results are presented.

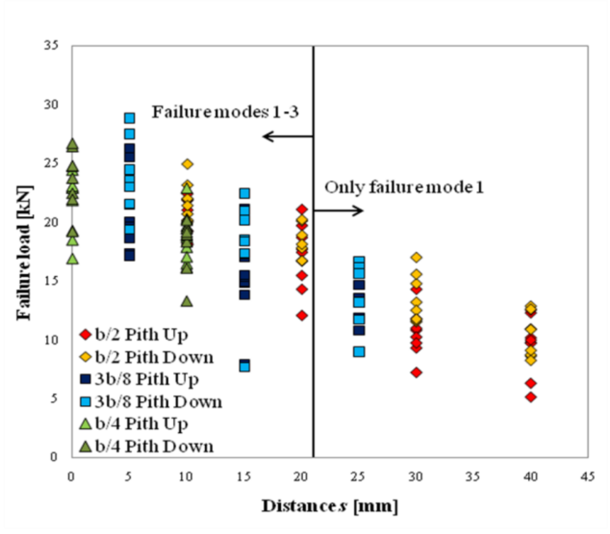

Figure 7: *Failure load versus distances from washer edge to loaded edge of bottom rail for each individual test. The vertical line shows a border between different failure modes*

The test results reported in this paper seem to be in good agreement with previous test results presented by Girhammar and Källsner [8, 9].

4 CONCLUSION

Tests on the splitting failure capacity of the bottom rail in partially anchored shear walls have been conducted. The rail was sheathed on one side and it was subjected to uplift force applied on the sheathing.

The test results show that the size of the washer and the position of the anchor bolt have a significant influence on the failure modes and the failure load.

Three failure modes were found during the tests:

- Splitting of the bottom side of the rail. This brittle failure occurs when the distance from the washer side to the loaded edge of the bottom rail is large;
- Splitting of the edge side of the bottom rail. This brittle failure occurs when the distance between the washer edge and the loaded edge of the bottom rail is small;
- Yielding and withdrawal of the sheathing-to-framing joints. This failure mode was not planned (the test series were planned so that splitting would occur), but happens when the distance between the washer edge and the loaded edge of the bottom rail is small.

Decreasing the distance from the washer edge to the loaded edge of the bottom rail increases the maximum load.

The results show that the resistance of the bottom rails with the pith oriented downwards is about 10% higher than those with the pith oriented upwards.

It was also observed that failure due to splitting of the bottom side of the rail usually starts from one of the ends and very seldom simultaneously from both ends of the bottom rail.

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REFERENCES

[1] European Committee for Standardisation (2006) prEN 594: Timber Structures – Test Methods Racking strength and stiffness of timber frame wall panels.

[2] Prion H. G. L. and Lam F. Shear walls and Diaphragms. In S. Thelandersson and H.J. Larsen, John Wiley & Sons Ltd, editors, *Timber Engineering*, pages 383-408. Chichester, England 2003.

[3] Mohammad M., Karacabeyli E. and Quenneville J. H. P.: Lateral resistance of bolted wood-to-concrete connections loaded parallel or perpendicular to grain. Canadian Journal of Civil Engineering, 30(1):226-239, 2003.

[4] Ni C. and Karacabeyli E.: Capacity of shear wall segments without hold-downs. Wood Design Focus, 12(2):10-17, 2002.

[5] Yeh B. and Williamson T. G. Combined shear and wind uplift resistance of wood structural panel shearwalls. In: proceedings CIB-W18, St. Andrews, Canada, Paper 41-15-6, 2008.

[6] Bracci J. M., Stromatt R. F. and Pollock D. G.: Seismic performance of confined sill plate connections. Journal of Structural Engineering, 122(11):1357-1363, 1996.

[7] Källsner B., and Girhammar U. A. Plastic design of partially anchored wood-framed wall diaphragms with and without openings. In: Proceedings CIB-W18 Timber Structures Meeting, Karlsruhe, Germany, Paper 38-15-7, 2005.

[8] Girhammar U. A. and Källsner B. Design aspects on anchoring the bottom rail in partially anchored wood-framed shear walls. In: Proceedings CIB-W18 Timber Structures Meeting, Dübendorf, Switzerland, Paper 42-15-1, 2009.

[9] Girhammar U. A., Källsner B. and Daerga P.A. Recommendations for design of anchoring devices for bottom rails in partially anchored timber frame shear walls. In: Proceedings of WCTE 2010, Riva del Garda, Italy, 2010