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PERFORMANCE OF WOOD PORTAL FRAME SYSTEMS AS ALTERNATIVE BRACING SYSTEMS IN LIGHT WOOD-FRAME BUILDINGS

Chun Ni[1], Mohammad Mohammad[2], Abdullah Al Mamun[3], Ghasan Doudak[4]

ABSTRACT: In this paper, results are presented from a testing program focused on evaluating the performance of portal frame systems. A total of nine full-scale portal frame assemblies with six different configurations were tested under monotonic and reversed cyclic loading. The portal frames were 3.66 m in length and 2.44 m in height, with 406 mm wall segment at each end of the portal frame. From the test results of full-scale portal frame, it was observed that the corner joint between the header and narrow braced wall segment dominates the lateral load carrying capacity and ultimate displacement of the portal frame. The installation of metal straps considerably increases the lateral load carrying capacity of the portal frame assemblies. Straps placed directly on the lumber framing showed increased resistance compared to those installed on the OSB. Portal frames with hold-downs have greater lateral load carrying capacity and ultimate displacement than those without hold-downs.

KEYWORDS: Portal frame, braced wall, lateral load resistance, monotonic loading, cyclic loading

1 INTRODUCTION

The lateral load resistance of light wood frame buildings is generally provided by braced walls sheathed with panels or diagonal lumber boards. To ensure that buildings have adequate lateral load carrying capacity to resist moderate-to-high wind and seismic loads, prescriptive requirements on the minimum length of braced walls, along with maximum spacing between braced walls, have been placed in Part 9 of the 2010 National Building Code of Canada (NBCC) [1]. Acceptable materials, fastening and framing details constituting a braced wall are also specified in the code.

Although most wood-frame buildings are able to meet the minimum braced wall requirements, there are situations where the required length of braced walls may not be met due to space limitations imposed by architectural requirements. For example, one common feature is the large opening required for multi-car garages. Alternative bracing systems which do not limit open space need to be developed to provide equivalent lateral load resistance to the minimum braced wall requirements in Part 9 of 2010 NBCC.

The wood portal frame system has been identified by engineers and builders as one of the alternative bracing systems that can meet the lateral load demand. This system was initially developed by APA - The Engineered Wood Association in the early 2000s. Full-scale portal frame specimens were tested by APA to show that portal frame has comparable performance to existing bracing requirements stipulated in the US International Residential Code (IRC). More than 25 full-scale cyclic tests in two phases confirmed that the 6:1 height-to-width ratio portal frame system performed approximately equal to or better than the 4:1 height-to-width ratio wall segment permitted in IRC [2,3]. The test results formed the basis for the acceptance of portal frame system in IRC since 2006.

There is a need to study and evaluate the performance of wood portal frame systems with different construction details and explore potential improvements to demonstrate that light wood frame structures with portal frames has the same level of performance as bracing walls with traditional designs. In this study, results are presented from a testing program focused on evaluating the performance of portal frame systems with different corner details and boundary conditions. Full-scale portal frame assemblies were tested under monotonic and reversed cyclic loading. The effect of variables such as metal strap type and location, sheathing placement and hold-downs on the performance of portal frame were evaluated.

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[1] Chun Ni, Principal Research Scientist, Wood Products Division, FPInnovations, Vancouver, BC, CANADA. Email: chun.ni@fpinnovations.ca

[2] Mohammad Mohammad, Group Leader, Wood Products Division, FPInnovations, Quebec City, Quebec, CANADA. Email: mohammad.mohammad@fpinnovations.ca

[2] Abdullah Al Mamun, Graduate Student, Department of Civil Engineering, University of Ottawa, Ottawa, Ontario, CANADA.

[4] Ghasan Doudak, Assistant Professor, Department of Civil Engineering, University of Ottawa, Ottawa, Ontario, CANADA. Email: gdoudak@uottawa.ca

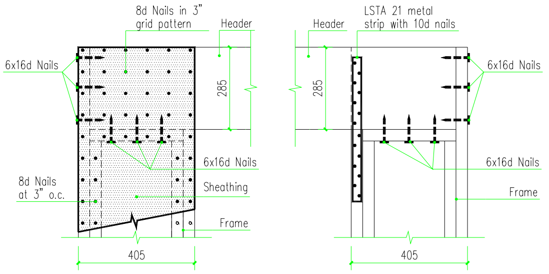
2 PORTAL FRAME TESTS

2.1 SPECIMEN DETAILS

The test matrix of the portal frames is given in Table 1. The corner details of the tested portal frame are shown in Figure 1. All the portal frames are 3.66 m in length and 2.44 m in height, with a 406 mm wall segment at each end of the portal frame. The wall framing was constructed with 38 mm x 89 mm NLGA No.2 and better Spruce-Pine-Fir lumber. The average moisture content of the lumber was 13% at the time of fabrication and testing and the average specific gravity of the lumber was 0.43. Except specimen No. 8 in which 38 mm x 286 mm (1.5” x 11.25”) No.2 and better Spruce-Pine-Fir lumber was used as header, the headers of the other walls were built up with 45 mm x 302 mm (1.75” x 11.875”) 1.5E laminated strand lumber (LSL). CSA 0325 oriented strand board (OSB), with a thickness of 12.7 mm (0.5”) and a span rating of 2R32, was used as sheathing panels.

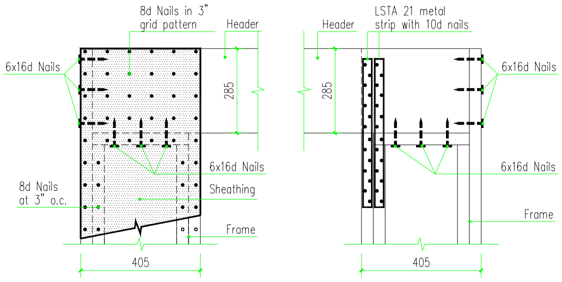
Table 1: *Test matrix of portal frames*

Specimen No.	Hold-down	Connection details at corner	Load protocol
1	No	Cl	Ramp & cyclic
2	HTT 16	C1	Ramp
3	HTT 16	C2	Ramp & cyclic
4	HTT 16	C2	Cyclic
5	HTT 16	C3	Cyclic
6	HTT 16	C4	Cyclic
7	No	C5	Cyclic
8	Steel rods	C5	Cyclic
9	HTT 16	C6	Cyclic



Side 1 Side 2

C1



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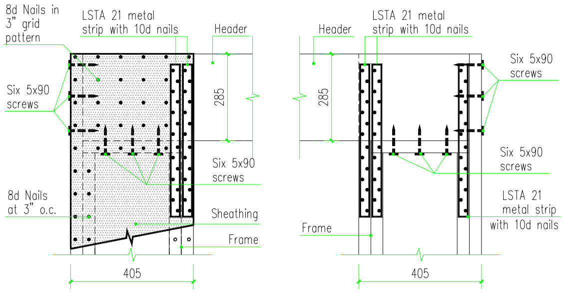
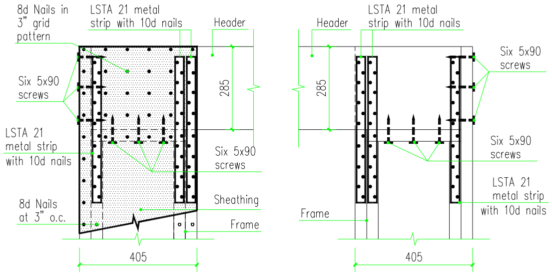
C2



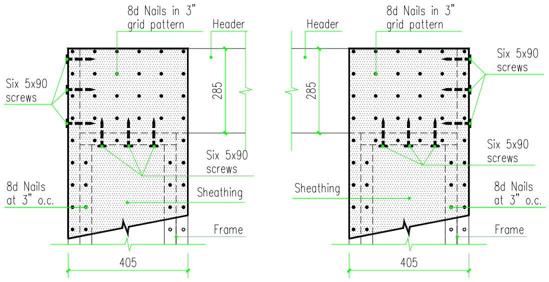
Side 1 Side 2

C3



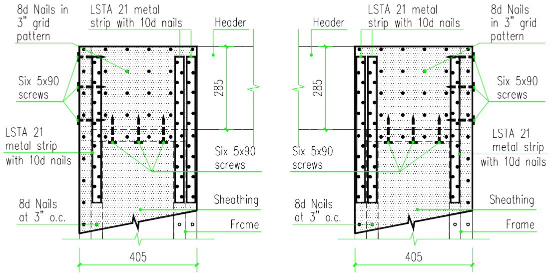
Side 1 Side 2

C4



Side 1 Side 2

C5



Side 1 Side 2

C6

Figure 1: *Corner details of portal frames*

The 8d common nails (3.3 mm in diameter and 63.5 mm in length) were used to attach sheathings to framing members. The following nailing schedule is used: a) one row of nails spaced at 75 mm on centre on top and bottom plates, b) two rows of nails spaced at 75 mm on centre on double end-studs, and c) grid pattern of nails spaced at 75 mm on centre on header.

For specimen No. 1 to No. 4, the top plate and the header were connected with two rows of 16d nails (4.2 mm in diameter and 89 mm in length) at 75 mm on centre. The end stud and the end of header were connected with two rows of the same type of nails at

75 mm on centre. For specimen No. 5 to No. 9, screws (5 mm in diameter and 90 mm in length) were used to connect the top plate and the header as well as the end stud and the end of header.

For specimen without hold-downs (No. 1 and No. 7), 12.7 mm diameter anchor bolts were used to fasten the bottom plate to the test frame. The anchor bolts were placed in the same locations as the bolts to connect the hold-down devices to the test frame. Where hold-downs were used, the bolts used to connect hold-down devices to the test frame were also used as anchor bolts to resist the shear force of the portal frame.

Two types of hold-down devices were used: a) Simpson Strong Tie HTT16 which is attached to end studs with 16-16d sinker nails, b) 12.7 mm diameter continuous steel rods. For specimen No. 2, No. 4, No. 5 and No. 9, Simpson Strong Tie HTT16's were installed at the ends of portal frame (no hold-downs at the opening). For specimen No. 3 and No. 6, Simpson Strong Tie HTT16's were installed at the ends of portal frame and around opening. For specimen No. 8, steel rods were installed at the ends of portal frame and around opening.

A Simpson Strong Tie LSTA 21 (1000 lb capacity) was used to connect the header and end studs to provide vertical continuity and moment resistance at the corner of portal frame. Where wall frame is sheathed with panels, metal straps are installed over wall sheathing. In areas where metal straps are installed over wall sheathing, wall sheathing is not fastened to the frame.

2.2 TEST SET-UP

A photo of the test setup is shown in Figure 2. The lateral load was applied through steel spreader bar attached to the top of the specimen. The spreader bar had lateral guides to ensure a steady and consistent unidirectional movement of the specimen.

Besides the load and actuator stroke, a string displacement transducer was placed at the top of the specimen to measure the lateral deflection of the assembly. Two displacement transducers were placed at the bottom of the header around the frame corners to measure the relative vertical movements between end studs and the header. Four transducers were used at the end-studs to measure the uplift of studs from the foundation.

Figure 2: *Test setup of the portal frame*

2.3 LOAD PROTOCOL

Monotonic and reversed cyclic displacement schedules were used in the test program. For monotonic tests, the displacement rate was 10.2 mm (0.4") per minute. The reversed cyclic displacement schedule followed the ISO 16670 Standard [4], in which the cyclic protocol consisted of the following reversed cycles: one cycle at each displacement level of 1.25%, 2.5%, 5%, 7.5% and 10% of the reference ultimate displacement, and three cycles at each displacement level of 20%, 40%, 60%, 80%, 100% and 120% of the reference ultimate displacement, as shown in Figure 3. Based on the monotonic tests of specimen No. 1, No. 2 and No. 3, the reference ultimate displacement was taken as 55.8 mm (2.198") for specimen without hold-downs and 88.9 mm (3.5") for specimen with hold-downs. A displacement rate of 20.3 mm (0.8") per second was used for reversed cyclic tests.

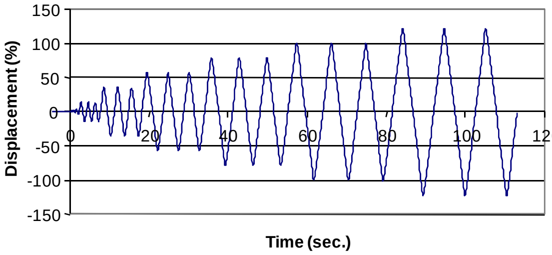


Figure 3: *Displacement schedule of cyclic tests*

3 RESULTS OF PORTAL FRAME TESTS

Analysis of test results was carried out in accordance with the Equivalent Energy Elastic-Plastic (EEEP) curve in ASTM Standard E2126 [5]. A summary of the test results under monotonic and cyclic loading is provided in Tables 2 and 3. For specimen under cyclic loading, the values are the average of positive and negative envelope curves. Figure 4 shows a typical load-displacement curve under cyclic loading. The envelop load-displacement curves of portal frames with panels sheathed on one and both sides are shown in Figures 5 and 6.

The notations in the tables are as follows: K_y is the initial (yield) stiffness; F_y is the yield load; Δ_y is the yield deflection; F_{max} is the maximum load; Δ_{Fmax} is the deflection at which the maximum load was reached; Δ_u is the ultimate deflection in post maximum load region where the load dropped to 80% of the maximum load.

Table 2: *Test results of portal frames under monotonic loading*

Specimen	K_y [kN/mm]	F_y [kN]	Δ_y [mm]	F_{max} [kN]	Δ_{Fmax} [mm]	Δ_u [mm]
1	0.45	9.01	20.0	10.93	55.4	55.8
2	0.38	12.88	33.8	14.77	67.5	80.2
3	0.62	14.91	24.0	16.37	158.7	163.5

Table 3: *Test results of portal frames under cyclic loading*

Specimen	K_y [kN/mm]	F_y [kN]	Δ_y [mm]	F_{max} [kN]	Δ_{Fmax} [mm]	Δ_u [mm]
1	0.42	9.00	21.5	10.27	52.4	71.8
4	0.56	14.00	24.9	15.74	87.6	124.7
3	0.54	14.31	26.5	16.54	64.2	90.2
5	0.63	18.67	29.6	21.37	80.2	140.0
6	0.68	18.78	27.7	21.21	63.1	121.2
7	0.61	15.76	25.9	18.04	65.0	82.9
8	0.51	20.46	39.8	23.24	136.0	153.4
9	0.99	23.07	23.4	25.84	61.2	71.8

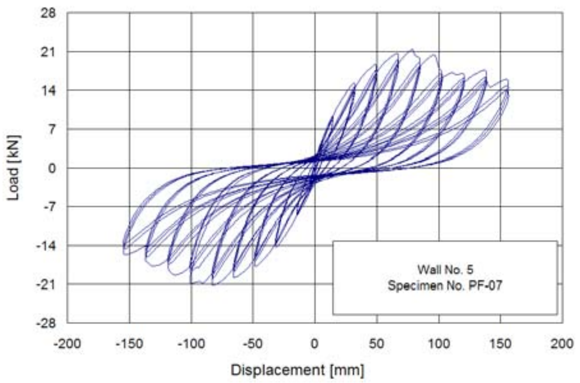


Figure 4: *Load-displacement of specimen No. 5*

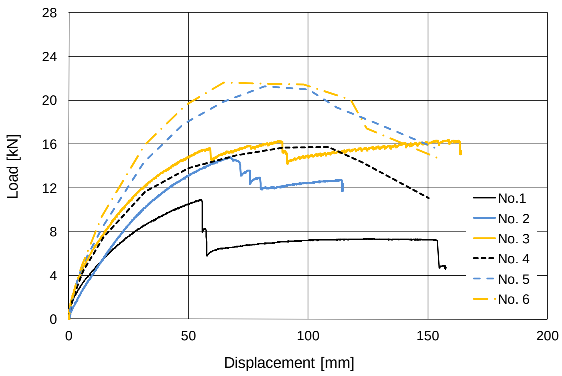


Figure 5: *Load-displacement of portal frames with panels sheathed on one side*

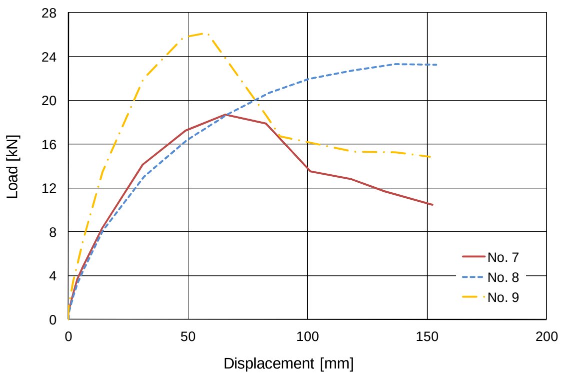


Figure 6: *Load-displacement of portal frames with panels sheathed on both sides*

3.1 FAILURE MODES

For all the portal frames, dominant failure modes were generally associated with failure in the OSB sheathing in tension at the corner of the portal frame. In all specimens where metal straps were used, failure of the metal strap due to load cycling (i.e., fatigue) was observed, following the failure of the OSB panels. For specimens without hold-downs (No. 1 and No. 7), separation of end studs from bottom plate was observed. In some cases (No. 1, No. 7 and No. 9), panel chip-out, nail withdrawal and bottom plate split were also observed. Photos of failure modes are shown in Figure 7.

a) Panel shearing and metal strap broken

b) Nail withdrawal and sill plate split

c) Panel chip out

d) Separation of stud from bottom plate

Figure 7: *Typical failure modes of portal frames*

4 DISCUSSION OF TEST RESULTS

4.1 PORTAL FRAME WITH PANELS SHEATHED ON ONE SIDE OF FRAMING

For portal frames with panels sheathed on one side of the framing, the maximum lateral load capacity is in the range of 11 to 21 kN, with portal frame without hold-downs (No. 1) has the lowest lateral load capacity and portal frames with corner configuration 3 and 4 (No. 5 and No. 6) having the highest lateral load capacities.

For portal frame without hold-down (No. 1), the lateral load carrying capacity is approximately 75% of the capacity of identical frames with hold-down (No. 2). For portal frames with hold-downs, the support contributes to the resistance of bending moment, and as a result the bending moment at the corner is smaller than that of portal frame without hold-downs under the same lateral load. As the lateral load capacity is governed by the bending moment at the corner, higher lateral load capacity is obtained for portal frame with hold-downs.

No significant differences were found between specimens No. 2, No. 3 and No. 4 in terms of lateral load resistances. This indicates that hold-downs around opening are not critical and can be omitted. Similarly, two metal straps installed side-by-side do not significantly increase the lateral load resistance of portal frame. However, significant increase is observed when metal straps are installed on both sides of the portal frame. The increase of lateral load capacity may also be due to the installation of metal straps on both ends of the studs (C3 and C4) for specimen No. 5 and No. 6, while for specimen No. 2, No. 3 and No. 4 metal straps were only installed at the inner corners of the specimens (C1 and C4). With metal straps installed on both ends of the studs, the metal straps in both wall segments provide resistance to the bending moment at corners. For metal straps installed only at the inner corners of the specimen, only the metal strap in tension provides resistance to the bending moment at corner.

4.2 PORTAL FRAME WITH PANELS SHEATHED ON BOTH SIDES OF FRAMING

For portal frames with panels sheathed on both sides of the framing, the maximum lateral load capacity is in the range of 18 to 26 kN. For portal frames without hold-downs, the portal frame with sheathing on both sides of the framing has approximately 75% higher lateral load capacity than the portal frame with sheathing on one side of the framing. For portal frame with hold-downs, the lateral load capacities of portal frame with sheathing on both sides of the framing are 20 to 40% higher than the portal frame with sheathing on one side of the framing.

Difference performance was noticed for portal frames with steel rod (No. 8) and HTT16 tie-down (No. 9). While the lateral load capacity is slightly lower for specimen No. 8, the displacement at ultimate lateral load is much larger. In fact, specimen No. 8 did not reach the ultimate displacement as the test was stopped due to reaching the actuator's displacement limit. Unlike portal frames with HTT16 tie-downs, the failure modes in specimen No. 8 were nail withdrawal or break. Panel failure in tension was not observed. Figure 8 shows the failure mode of specimen No. 8.

Figure 8: *Failure modes of specimen No. 8*

4.3 COMPARISON WITH BRACED WALLS

Results of braced walls are used to compare the lateral load resistance of portal frames. Table 4 summarises the test results of braced walls under different boundary conditions [6]. The wall framing was constructed with Spruce-Pine-Fir (SPF) 1650f-1.5E 38 × 89 mm machine stress rated lumber. Canadian softwood plywood (CSP) panels, 9.5 mm thick and 1.22 m × 2.44 m in size, were vertically sheathed to the framing. Power-driven spiral nails, 2.5 mm diameter and 63.5 mm long, were used to attach CSP to the framing. The nails were spaced at 150 mm along the perimeter of the panels and 300 mm elsewhere.

Comparison shows that for a portal frame without hold-downs, the lateral load capacity of a portal frame with panels sheathed on one side of the framing is equivalent to a 2.44 m braced wall without hold-downs. As can be seen in Tables 2 and 3 above, the lateral load capacity of a 3.66 m long portal frame with hold-downs can be as high as the lateral load capacity of a 4.88 m braced wall without hold-downs.

Table 4: *Test results of braced walls under monotonic loading*

Wall Length	Wall No.	Hold-down	F_{max} [kN]	Δ_u [mm]
2.44 m	C1-1	No	8.5	44.6
	C1-2	No	9.5	40.4
	C1-3	No	10.8	39.2
4.88 m	CR2	Yes	34.6	112.5
	C2-1	No	21.4	66.2
	C2-2	No	26.3	56.3
	C2-3	No	31.0	51.7

5 CONCLUSIONS AND RECOMMENDATIONS

There is a need to develop alternative bracing systems in light frame wood buildings that would allow for the increasing demand for more open space structures. This paper presents results of portal frame tests with different corner details and boundary conditions. Lateral load capacity, initial stiffness and ultimate displacement were determined from tests. From the test results of full-scale portal frame, it is evident that the corner joint between the header and braced wall segment dominates the lateral load carrying capacity and ultimate displacement of the portal frame. The installation of metal straps considerably increases the lateral load carrying capacity of the portal frame assemblies. Straps placed directly on the lumber framing showed increased resistance compared to those installed on the OSB. Portal frames with hold-downs have greater lateral load carrying capacity and ultimate displacement than those without hold-downs.

Comparison of lateral load capacity is made to a braced wall sheathed with 9.5 mm wood-based panel and with 8d nail spaced at 150 mm along the perimeter of the panels. Results show that for a portal frame without hold-downs, it has equal or greater lateral load capacity than a 2.44 m braced wall without hold-downs. The lateral load capacity of a portal frame with hold-downs can be as high as the lateral load capacity of a 4.88 m braced wall without hold-downs. More work is needed to develop design provisions for portal frames used in engineered building.

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