ESTIMATING DEFLECTIONS OF UNBLOCKED WOOD SHEAR WALLS

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ABSTRACT:

Wood is the most environmentally friendly building material. Shear walls play an important role in the wind and seismic resistance of low-rise wood-frame constructions. Current wood design codes provide design values for shear walls sheathed with wood-based panels oriented either vertically or horizontally with framing blocking. However, it is quite common to use shear walls without blockings for savings in construction time and material costs despite their lower lateral resistance compared with blocked shear walls. Design provisions for unblocked shear walls are limited and it is necessary to study their behaviors and get a better understanding of their responses to applied lateral loads. Estimation of deflections is an important part of building design when the object is to limit earthquake or wind damage. However, while some building codes (e.g. Uniform Building Code) provide methods for estimating blocked shear wall deflections, these methods are not adequate for unblocked shear walls. In this paper, a formula based on a relatively simple mechanical model is presented which can be used to estimate deflections for unblocked shear walls. And it gives values which compare well with test results till moderate load levels.

KEYWORDS, deflection, unblocked shear wall, wood structural panel, stud, nailed joint。

1. INTRODUCTION

Studies have shown wood to be the most environmentally friendly compared to other building materials. Wood is the only renewable building material, harvested and replanted in a continually regenerating cycle. Wood is energy conserving in manufacture and use. Wood can also be easily recycled or reused. Wood is by far the preferred building material for residential construction in North America and other areas. A host of building types including schools, warehousing and manufacturing facilities, offices, stores, recreational facilities and many others can efficiently be constructed of wood. Most of these buildings are platform wood-frame constructions.

In low-rise wood-framed buildings, shear walls typically consist of lumber framing and exterior and interior panel sheathing attached with fasteners. The shear walls are important in the wind and seismic resistance of the buildings, as they provide lateral stiffness and carry almost all of the lateral forces. They also provide some resistance to vertical loading and act as partitions.

Current wood design codes provide design values for shear walls sheathed with wood-based panels oriented either vertically or horizontally with framing blocking. In other words, perimeters of wood-based panels are always nailed to lumber framing. However, it is quite common to use shear walls sheathed horizontally with wood-based panels without blocking, since blocking poses some practical problems. Aside from the additional cost, builders prefer to leave a ventilation and expansion gap between panels, which would be closed off by the blocking.

Historically, the deflection of shear walls and diaphragms has not been a critical design consideration, as building codes have concentrated rather on life safety as a goal in earthquake design, and only to a lesser extent on limiting damage. However, several recent earthquakes have shown that while well-designed buildings perform well from a life-safety standpoint, the damage incurred can result in high repair costs, displacement of people from buildings, and costly business interruptions. The social and economic costs of some earthquakes have been very high and have strained community resources. Thus there is growing agreement that building code requirements should aim at mitigating damage as well as protecting life safety during earthquakes. One consequence of this is the need for a method to predict displacements. In order to limit damage in seismic events, the proposed design provisions of some codes are considerably more restrictive in the deflections that a building may undergo in an earthquake. Since the Northridge earthquake, many in the design community have begun classifying diaphragms as either flexible, where the diaphragm deflects at least twice as much as the shear walls, or rigid. Whether a diaphragm is flexible or rigid determines the distribution of seismic forces to various shear walls. Consequently, structural engineers are required to know the deflections of shear walls and diaphragms and to check whether the deflections are less than inter-storey drift limits.

In current wood design codes, shear wall deflection formulas are only provided for blocked shear walls and diaphragms. Strength design values are provided for unblocked shear walls in some codes but stiffness or deflection formulas for these shear walls are not provided in any codes.

The objective of this paper is to provide a method for estimating the deflections of unblocked shear walls. The method presented here is based on a relatively simple mechanical model. The method can be used to predict deflections at moderate load levels, and do not predict deflections all the way to ultimate strength.

2. BACKGROUND

Substantial experimental and analytical work has been done on the structural behavior of shear walls. A large number of full size shear walls have been tested under monotonic or reversed cyclic loads to study their behavior, including unblocked shear walls (Ni et al. 2000).

There have been some attempts to model the response of shear walls under different load regimes. For example, Foschi (1977), Falk and Itani (1989), and White and Dolan (1995) developed finite-element models to simulate the response of shear walls subjected to monotonic loads. While these finite element models accurately predict shear wall deflections, they are complex computer programs that require much geometric and material data. They are currently more suited to research than to design office use.

The four-term shear wall deflection formula in Uniform Building Code is derived from an approach first described in APA Report 55 for determining the deflection of wood structural panel diaphragms using a girder analogy which is considered the most appropriate for plywood or OSB sheathed shear walls or diaphragms with a regular configuration. In the method, the two end posts of the shear wall (the vertical framing members at the end of the walls) act as flanges, and the sheathing material acts as the web.

Shear wall deflection results from bending of the end posts, shear deformation of the sheathing, sheathing fastener slip, and displacement of hold-downs at the end posts. Equation 1 is adequate for blocked shear walls.

$$\Delta_s = \frac{2v_s H_s^3}{3EAL_w} + \frac{v_s H_s}{G_v t_v} + 0.0025 H_s e_n + \frac{H_s}{L_w} d_a \tag{2.1}$$

where Δ_s = calculated deflection, mm

v_s = maximum unit shear due to design loads at the top of the wall, N/mm

H_s = wall height, mm

E = modulus of elasticity of boundary elements (end posts), MPa

A = area of boundary elements (end posts), mm^2

L_w = wall length, mm

G_v =modulus of rigidity (shear) of wood structural panel sheathing, MPa

t_v =effective thickness in shear of wood structural panel sheathing, mm

e_n =fastener deformation, mm

d_a =deflection due to anchorage details (rotation and slip at hold-downs), mm

3. DEFLECTION FORMULA FOR UNBLOCKED SHEAR WALLS

Unblocked shear walls resist lateral forces in a different mode from those of either the girder or truss analogies. The racking behavior of the wall depends on the framing members which bridge the gap, and on the nails in the immediate vicinity of the seam. (Figure.1)

Figure 1 Deformation mechanisms of blocked and unblocked shear walls under lateral load

To develop a deflection formula for unblocked shear walls it is assumed that:

1. The wood-based panels are rigid for the purposes of deriving the deflection due to nail slip;
2. The framing members are hinged to each other;
3. The displacements are small relative to the width and height of panels;
4. The load-displacement relationships of the joints between the panel and the frame members are nonlinear.

For further simplicity it is also assumed that the lateral shear force is uniformly distributed to the studs and that the nail spacing in the end posts is the same as the nail spacing in the intermediate studs.

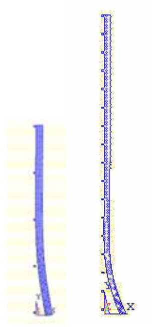


Figure 2 deformed shape of half studs with ANSYS

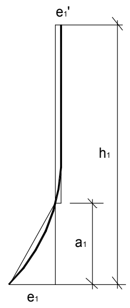


Figure 3 inter-deformation between panel and stud (part)

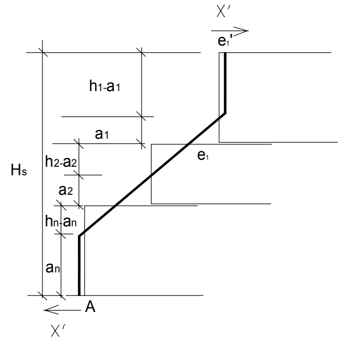


Figure 4 inter-deformation between analyzed tri-linear deformed stud and panels

Figure 2 shows the resulting shape of (half) studs analyzed with ANSYS Software. For simplification, the inter-displacement (nail slip) of panel and stud is represented as a series of rectangles and triangles, as shown in Figure 3. The final shape of the deformed stud is assumed to be tri-linear shown in Figure 4.

The properties of nailed joints are the controlling factors in the performance of shear walls. Nailed joint tests performed at Forintek Canada Corp. show that the nailed joint load-nail slip equations of CSA O86 and UBC do not capture the range of nailed joint behavior, especially above $n_u/3$. So we propose a load-nail slip equation $\Delta = 1.0dK_m(P/n_u)^{2.6}$ according to experimental curves of nailed joints with the same form as the equation in CSA-O86.

Because of symmetry, it is sufficient to consider only the panel attached to the top plate. This is treated as a free body element as shown in Figure 5. e_1 and e_1' are fastener slips at bottom and top of top panel, mm, respectively. S_{n1}, S_{n2} and S_{st} are perimeter nail spacing, intermediate nail spacing and stud spacing, mm. h_i is the height of panel i, mm. a_i is the space from non-inter-slip point to the bottom of the panel i.

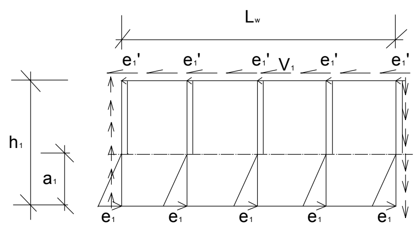


Figure5 free body of top

To satisfy equilibrium, $\sum X = 0$

$$\frac{L_w}{S_{n1}} n_u \left(\frac{e_1'}{dK_m}\right)^{\frac{1}{2.6}} + \left(\frac{L_w}{S_{st}}+1\right)\frac{h_1-a_1}{S_{n2}} n_u \left(\frac{e_1'}{dK_m}\right)^{\frac{1}{2.6}} = \left(\frac{L_w}{S_{st}}+1\right)\int_0^{a_1}\frac{n_u}{S_{n2}}\left(\frac{ye_1}{dK_m a_1}\right)^{\frac{1}{2.6}} dy$$

We can get the relationship between e_1 and e_1'.

$$[\frac{2.6}{3.6}(\frac{L_w}{S_{st}}+1)\frac{a_1}{S_{n2}}]e_1^{\frac{1}{2.6}}=[\frac{L_w}{S_{n1}}+(\frac{L_w}{S_{st}}+1)\frac{h_1-a_1}{S_{n2}}]e_1'^{\frac{1}{2.6}} \tag{3.1}$$

The top part of the wall from the seam up can be treated as a free-body element. (Figure 6)

$$\sum X=0$$

$$v_s L_w = X(\frac{L_w}{S_{st}}+1) \tag{3.2}$$

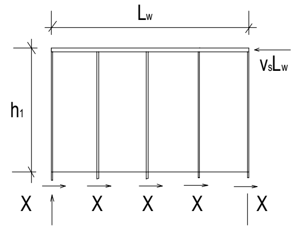


Fig.6 free body of top part of the wall

Consider one stud as a free-body element. (Figure 4)

$$X' = X-\frac{2.6}{3.6}\frac{n_u}{S_{n2}}(\frac{e_1}{dK_m})^{\frac{1}{2.6}}a_1+(h_1-a_1)\frac{n_u}{S_{n2}}(\frac{e_1'}{dK_m})^{\frac{1}{2.6}} \tag{3.3}$$

$$\sum M(A)=0$$

$$X'H_s-\frac{h_1-a_1}{S_{n2}}n_u(\frac{e_1'}{dK_m})^{\frac{1}{2.6}}(H_s-\frac{h_1-a_1}{2})+\int_0^{a_1}\frac{n_u}{S_{n2}}(\frac{ye_1}{dK_m a_1})^{\frac{1}{2.6}}(H_s-(h_1-a_1)-y)dy$$

$$-\int_0^{h_2-a_2}\frac{n_u}{S_{n2}}(\frac{ye_1}{dK_m a_1})^{\frac{1}{2.6}}[H_s-h_1-(h_2-a_2)+y]dy+\int_0^{a_2}\frac{n_u}{S_{n2}}(\frac{ye_1}{dK_m a_1})^{\frac{1}{2.6}}[H_s-h_1-(h_2-a_2)-y]dy+\cdots$$

$$-\int_0^{h_n-a_n}\frac{n_u}{S_{n2}}(\frac{ye_1}{dK_m a_1})^{\frac{1}{2.6}}[H_s-\sum_1^n h_i+a_n+y]dy+\frac{a_n}{S_{n2}}n_u(\frac{e_1'}{dK_m})^{\frac{1}{2.6}}\frac{a_n}{2}=0 \tag{3.4}$$

$H_s=\sum_{i=1}^n h_i$. Because of symmetry, it is reasonable to assume that $h_i-a_i=a_i=\frac{h_i}{2}$ $(i=2,3\cdots n-1)$ and for the top and bottom panels $h_1=h_n$, $a_1=h_n-a_n$. With Eqn. 3.2, 3.3 and 3.4 we can get

$$\frac{v_s L_w H_s}{\frac{L_w}{S_{st}}+1}=\frac{5.2}{6.2}\frac{n_u}{S_{n2}}(\frac{e_1}{dK_m a_1})^{\frac{1}{2.6}}[\sum_{i=2}^{n-1}(\frac{h_i}{2})^{\frac{6.2}{2.6}}+a_1^{\frac{6.2}{2.6}}]+\frac{5.2}{3.6}\frac{n_u(h_1-a_1)}{S_{n2}}(\frac{e_1}{dK_m a_1})^{\frac{1}{2.6}}a_1^{\frac{3.6}{2.6}}-\frac{n_u(h_1-a_1)^2}{S_{n2}}(\frac{e_1'}{dK_m})^{\frac{1}{2.6}} \tag{3.5}$$

Substituting e_1' in Eqn. 3.5 with Eqn.3.1 we can get

$$e_1 = 1.0dK_m a_1 \left\{ \frac{v_s L_w H_s S_{n2}}{(\frac{L_w}{S_{st}}+1)n_u} \frac{1}{0.84[\sum_{i=2}^{n-1}(\frac{h_i}{2})^{2.4} + a_1^{2.4}] + 0.72(h_1 - a_1)a_1^{1.4}[2 - \frac{h_1 - a_1}{\frac{L_w}{\frac{L_w}{S_{st}}+1}\frac{S_{n2}}{S_{n1}} + (h_1 - a_1)}]} \right\}^{2.6} \quad (3.6)$$

The value of a_1 depends on the magnitude of the load, as well as the configuration of the shear wall, such as nail spacing, stud spacing, behavior of nailed joints, and the properties of the studs. It is assumed that a_1 remains constant up to factored load. According to test results and the results of analysis by ANSYS software a_1 equals approximately 600 mm for 300 mm nail spacing or 400 mm for 150 mm nail spacing. The deflection of unblocked shear walls can be estimated as following

$$\Delta_s = \frac{2v_s H_s^3}{3EAL_w} + \frac{v_s H_s}{B_v} + [H_s - 2(h_1 - a_1)]\frac{e_1}{a_1} + \frac{H_s}{L_w} d_a \quad (3.7)$$

4. VERIFICATION OF THE FORMULA

4.1 Shear Wall Tests

Two groups of full-scale shear wall specimens, 2.44 m or 4.88 m in height and 4.88 m in length, were tested under monotonic and reversed cyclic tests at Forintek Canada Corp. All shear wall specimens were constructed using NLGA No.2 and better grades of Spruce-Pine-Fir 38 mm $\times$ 89 mm lumber for the wall studs, and 1650f-1.5E MSR 38 mm$\times$ 89 mm lumber for the top and bottom plates except that 38 mm$\times$ 140 mm lumber was used for the 4.88m tall wall. The top plate and end studs consisted of double members, while the bottom plate and interior studs consisted of single members. 1.2 m$\times$ 2.4 m structural wood-based panels were used for sheathing. The configurations of specimens including panel thickness, fastener type, size and spacing are shown in Table 1.

Table 1 Configurations of unblocked shear walls

No. of Tests	Panel Thickness (mm)	Nail Type/Size (mm)	Perimeter Nail/ Interior Nail/ Stud Spacing (mm)	Vertical Load (kN/m)	Factored Load (N/mm)	
29-01	9.5	STAN3*65	150/300/400	0	2.15	2440 mm tall, 1 gap.
51-05	9.5	STAN3*65	150/150/300	18.2	3.58	2440 mm tall, 1 gap.
51-21	9.5	STAN3*65	150/150/400	18.2	2.87	2440 mm tall, 2 gaps. The height of in-between panel is 1 foot.
66-06	12.7	P-COIL3.3*65	150/150/600	0	2.29	Type B, 4880 mm tall, vertical sheathed panel, 1 gap.
66-03	12.7	P-COIL3.3*65	150/150/600	0	2.29	Type A, 4880 mm tall, vertical sheathed panel, staggered joints.
66-08	12.7	P-COIL3.3*65	150/150/600	0	2.29	Type D, 4880 mm tall, horizontal sheathed panel, staggered joints.

Note: All hold-downs are SP/HD2A.

Lateral loads were applied along the top plate of the shear wall through a spreader bar which was bolted to the top plate of the shear wall and attached to a servo-controlled hydraulic actuator. The bottom plate was anchored by bolts to a steel beam fixed to the laboratory reinforced concrete floor. Supports were provided at the two ends of the load spreader to prevent out-of-plane movement. Conditioning and testing were performed at ambient laboratory conditions. Based on the oven-dry mass, the average moisture content of both lumber and wood-based panels was approximately 9%, and the relative density of the lumber was approximately 0.44.

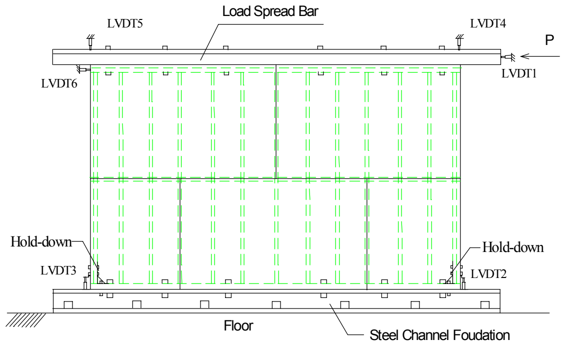


Figure 7 test set up

Displacement transducers were placed at four corners of the shear wall to measure the overall displacement, end stud uplift, and shear wall uplift, as shown in Figure.7. Details of the shear wall tests can be found in Karacabeyli and Ceccotti (1996b), and Ni and Karacabeyli (2002).

4.2 Comparisons of Predicted Deflections with Test Results

As lateral load-deflection curves of monotonic tests and reversed cyclic tests are similar up to the point of maximum load, only the monotonic tests results are compared with the values predicted by the formula. All loads obtained in testing are divided by 1.6 to account for load duration effects.

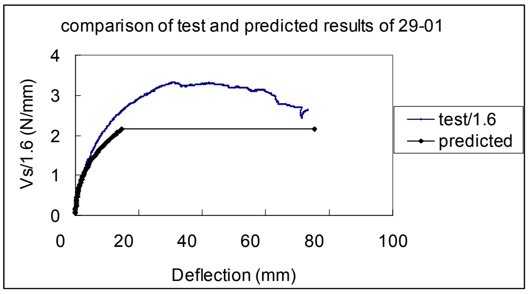


Figure 8 Comparison of wall 29-01

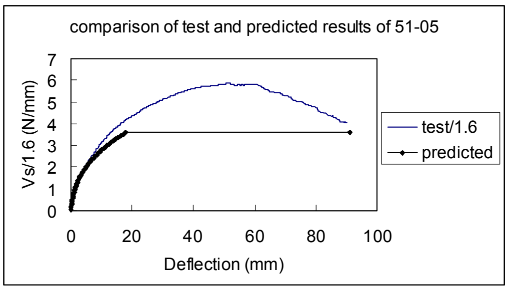


Figure 9 Comparison of wall 51-05

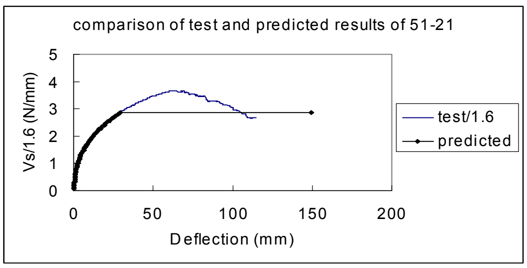
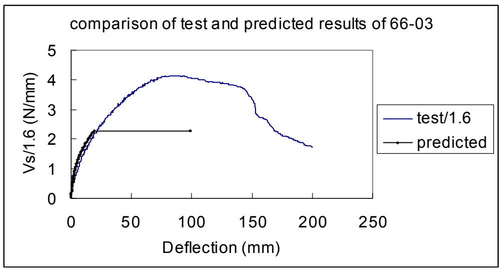
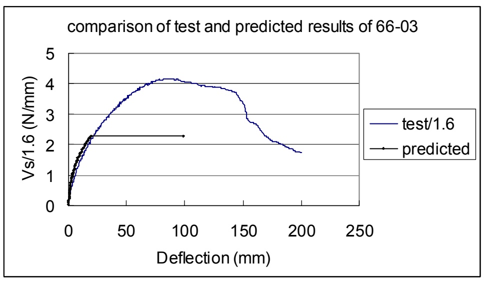


Figure 10 Comparison of wall 51-21





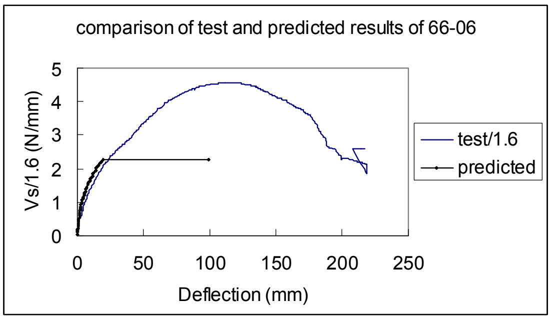


Figure 12 Comparison of wall 66-06

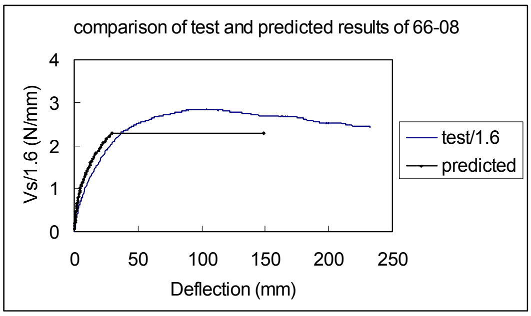


Figure 13 Comparison of wall 66-08

Figure 8 through Figure 13 are comparisons of experimental curves and predicted curves up to factored load. R_o and R_d are an overstrength-related force modification factor and a ductility-related force modification factor respectively.

The figures show that the equation presented for unblocked shear walls agrees well with test results.

5. CONCLUSIONS

A deflection formula is developed for unblocked shear walls. The formula appears to give reasonable displacements when compared with test results. Since the properties of nailed joints are the dominant factor in the behavior of shear walls, further research on behavior of nailed joints is needed, especially in view of the small number of test results used and the large variation in those test results. The formula looks a bit complicated and needs further simplification.

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