SEISMIC PERFORMANCE OF WOODEN SHEAR WALLS ON DYNAMIC CONDITION

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SUMMARY

The highest probability where we will encounter to the big earthquake is in residences. As most residences are timber structures in Japan, seismic performance of timber structures is very important. In order to analyse real seismic performance of timber structures during earthquakes, shaking table test of nailed plywood shear walls was executed. Dynamic hysteresis loops were compared to static hysteresis loops obtained from static loading test. Dynamic yields were observed on dynamic hysteresis loops. So-called (static) yield points were not observed on dynamic hysteresis loops. For the purpose to analyse failure modes of shear walls, shear and pull loading tests for nailed fasteners were executed using static or dynamic loads. It was found pulling out of nails occurred just before the maximum shear-strength point. Pull-loading test of nailed fasteners shows friction on dynamic is half of static, after these nails start to move. These results indicate pulling out of nails start around dynamic yield points and dominate the maximum shear-strength of shear walls. Unsymmetrical hysteresis model after the maximum strength points is proposed. It is clarified pulling out of nails dominates this unsymmetrical hysteresis feature.

INTRODUCTION

Timber structures actually shared 38 % of the building construction market in 1996 of Japan. Most of timber structures are used for private residences in Japan. The share of timber structures in building construction market is more than that of steel structures, and twice of reinforced concrete structures. We must recognize timber structures are really major structures in Japan.

Kobe (Hyogoken Nanbu) earthquake impressed the difficulty of prediction of big earthquakes. We are unable to know when we will encounter to the big earthquake. However, where will we encounter to the big earthquake? We must consider the probability where we will encounter to the big earthquake. The people sleep about one third of the life. We may spend about half of the life in the residences. We stay in offices, schools and cars, etc. But we stay in the residences longer than we stay in the others. As the occurrence of the earthquake doesn't depend on the time, the probability that the people will encounter to the big earthquake in the residences is the highest. Thousands of people died in the residences during Kobe earthquake. This situation was the most probable situation. [Yamaguchi, 1998]

Structural performance of timber structures is affected by load duration. Creep deformation of timber is one of major effects by load duration. Seismic performance of structures during earthquakes is performance on dynamic. Effects of load duration, namely effects of dynamic loading should be considered. For the purpose to investigate real seismic performance of timber structures, seismic performance of nailed plywood shear walls on dynamic condition was evaluated. The ground motion of Kobe earthquake, real size specimens and shaking table were used. Failure modes of shear walls were analyzed by failure mechanism of nailed fasteners.

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TEST OF SHEAR WALLS AND FASTENERS

Test of Shear Walls

Specimens

Conventional Post and Beam structures and Wood Frame structures are used for most of timber residences in Japan. Post and Beam shear walls are called P&B shear walls and wood frame shear walls are called WF shear walls here. We use these shear walls for specimens. The specimen has two 910mm width nailed plywood walls and an 1820mm width opening between two nailed plywood walls. Top and bottom of columns are connected to beams and sills using hold-down connectors.

Static Loading Test and Allowable Strength

Monotonic loading test and reversed cyclic loading test were carried out.[Kawai, 1998] Vertical loads on shear walls change horizontal strength of shear walls. Preventing the effect of these vertical loads, all of static test was executed without vertical loads. When the tilting angle of shear walls is 1/120 radian, the strength is assigned to allowable shear-strengths of the walls. Another new method to assign allowable shear-strengths of walls is used for WF structures in Japan. Concept of this method indicates allowable shear-strength is based on strength at static yield point.[Japan Two-by-four Home Builders Association, 1998]

Dynamic Loading using Moving Frame & Shaking Table

We developed a new shaking table test method, which can apply horizontal loads to specimens like as static test. Figure 1 shows this new method. Weight with support is modified to "SDF using moving frame" of Figure 1. [Yamaguchi and Minowa, 1998] We used NS component of the ground motion record observed during 1995 Kobe Earthquake. This record is called JMA Kobe-NS motion here. The maximum acceleration, velocity, displacement of this motion is 817cm/s^2, 90.2cm/s, 20.2cm respectively. Peak period of the response spectra of this motion is 0.9 sec(1.11Hz).

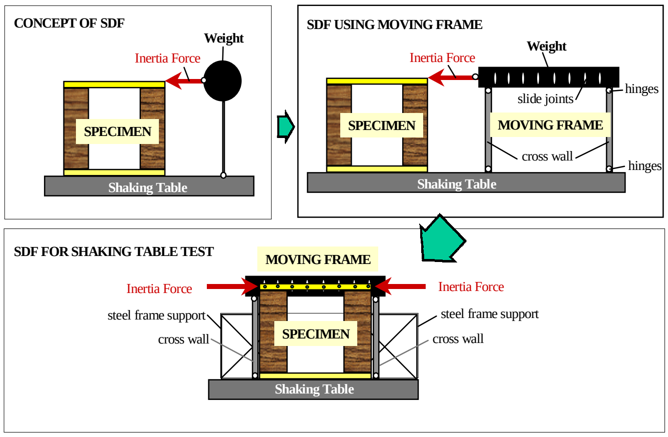


Fig.1: Specimens and Moving Frame

Seismic Shear Coefficients and Natural Periods

Seismic Shear coefficients for allowable strength design methods are calculated from equation (1). Shaking table tests use some sets of shear walls which have same specifications. Three shear coefficients of 0.3, 0.4 and 0.5 are used, in order to investigate effect of shear coefficients. These shear coefficients are controlled by the weight of masses on the moving frame. C_0 is shear coefficients based on allowable strength. P_{al} is allowable shear-strength of shear walls. W is sum of weights of masses, upper half of moving frame and upper half of specimens. Natural periods based on secant stiffness are calculated by equation(2). Equation(2) shows natural periods change according to shear coefficients. T_0 (sec) is natural periods based on secant stiffness on allowable strength points. α_0(rad) is radian of tilting angle on allowable strength point. H (cm) is story heights. G is 980 (cm/sec^2). Natural periods are depending on α_0 and C_0 when H is constant.

As C_0 are affected by methods to assign allowable strengths, another seismic shear coefficients are introduced. C_{pmax} is shear coefficients based on maximum strength and calculated from equation(3). P_{max} is maximum shear-strength of walls. T_{pmax} is natural periods based on secant stiffness on maximum strength point. T_{pmax} are calculated by equation (4). Equation (4) shows T_{pmax} is function of C_{pmax}. T_{pmax} (sec) is natural periods, α_{pmax} (rad) is radian of tilting angle of shear walls on maximum strength point. Shear coefficients based on allowable strength and maximum strength of P&B and WF shear walls are summarized on Table 1. Natural periods are also shown in Table 1. Table 1 indicates T_0 and C_{pmax} in case of C_0=0.4 of P&B shear walls is similar to those of C_0=0.3 of WF shear walls.

$$C_0 = \frac{P_{al}}{W} \quad (1)$$

$$T_0 = 2\pi\sqrt{\frac{\alpha_0 \times H}{C_0 \times G}} \quad (2)$$

$$C_{p\max} = \frac{P_{\max}}{W} \quad (3)$$

$$T_{p\max} = 2\pi\sqrt{\frac{\alpha_{p\max} \times H}{C_{p\max} \times G}} \quad (4)$$

Table 1: Weight and Natural Frequency

Strength	Post & Beam				Wood Frame
Allowable	C_0	0.3	0.4	0.5	0.3
	T_0(sec)	0.55	0.47	0.42	0.48
Max.	C_{pmax}	0.49	0.65	0.81	0.64
	T_{pmax}(sec)	1.02	0.89	0.79	0.79

Data processing

Absolute acceleration $(\ddot{x}+\ddot{y})$ and relative displacement (x) were observed. Relative velocity $(\dot{x})$ was calculated from relative displacement (x). Hysteresis loops are calculated by equation (6). Deformations are translated into tilting angles. We use 2% for damping factor h and secant stiffness on allowable strength points for k in equation (7). [Minowa and Yamaguchi, 1998]

$$m(\ddot{x}+\ddot{y}) + c\dot{x} + kx = 0 \quad (5)$$

$$kx = -\{m(\ddot{x}+\ddot{y}) + c\dot{x}\} \quad (6)$$

$$c = 2h\sqrt{km} \quad (7)$$

Test of Nailed Fasteners

For the purpose to analyze failure mechanism of nailed fasteners on static or dynamic condition, loading test of single shear nailed fasteners was executed. Lumber and nails for P&B shear walls are 105*105 mm section of Hemlock and N50. Lumber and nails for WF are 38*89mm section of S.P.F and CN50. Plywood is JAS 1G, excepting tests using high-density plywood. Several combinations about density of lumber and plywood are tested.

Figure 2-1 shows loading system of single shear nailed fasteners. In order to allow motion of plywood for out of plane, long (700*50mm) plywood specimens were used. In case of high-density plywood specimens, as length of the plywood (280*50mm) were not enough, plywood and load-transducer were connected by hinged-joints. Loads and slip displacements of fasteners were measured. In case to measure start-position of pulling out of nails, 9.5mm thick plywood and 38mm-width lumber were used. As length of nail (CN50) is a little longer than total length (47.5mm) of plywood and lumber, tip of nail is out of lumber. This tip of nail was tied to displacement transducer. Figure 2-2 shows loading system of pulling out of nails. Loads applied for nails and displacement of pulling out of nails were measured. Velocity of static loading was 0.025mm/sec. Velocities of dynamic loading were 250 and 50 mm/sec. Velocities of dynamic loading are 10,000 and 2,000 times of those of static test respectively. Direction of monotonic loading was pull.

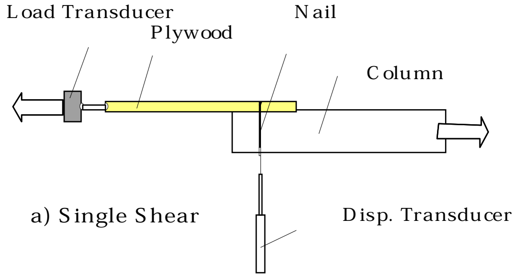


Figure 2-1: Single Shear Loading Test Method

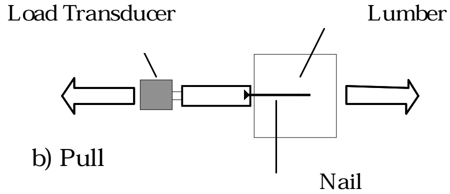


Figure 2-2: Pull Loading Test Method

STATIC AND DYNAMIC PERFORMANCE OF SHEAR WALLS

Required Seismic Shear Coefficients against JMA Kobe-NS Motion

Hysteresis loops of P&B shear walls are calculated from test results using equation (6). Figure 3-1, Figure 3-2 and Figure 3-3 show the calculated dynamic hysteresis loops in case of C_0=0.5, 0.4 and 0.3 respectively. In case that strength of dynamic response decreased strength less than half of the maximum strength, test result regards the specimen as collapsed. Figure 3-1 (in case of C_0=0.5) shows dynamic response did not exceed the maximum strength point, and specimen was not collapsed. Figure 3-2 (in case of C_0=0.4) shows dynamic response exceeded the maximum strength point, and strength decreased almost half of the maximum strength. Test result regards the specimen as almost collapsed. Figure 3-3 (in case of C_0=0.3) shows dynamic response exceeded the maximum strength point, and decreased strength less than half of the maximum strength. Test result regards the specimen as collapsed completely. P&B shear walls collapsed in case of C_0=0.3 and 0.4, and did not collapse in case of C_0=0.5. It is evident that required C_0 of P&B shear walls against JMA Kobe-NS motion is more than 0.4. Consequently, required C_{pmax} is more than 0.65 from Table 1.

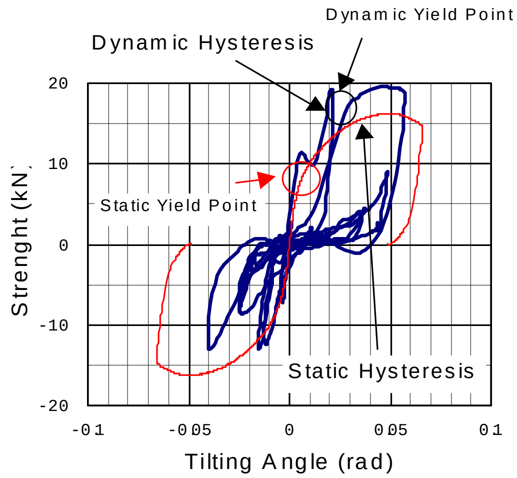


Figure 3-1: Hysteresis Loop (P&B, C_0=0.5)

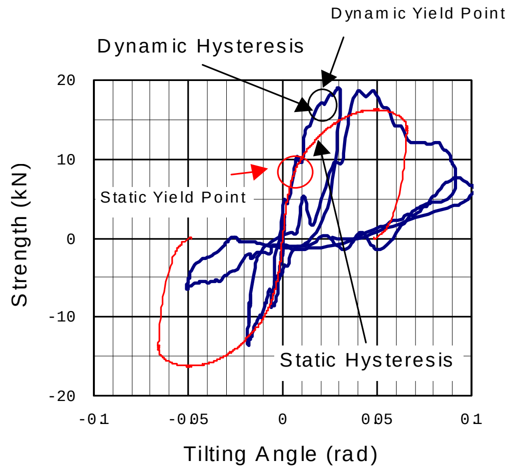


Figure 3-2: Hysteresis Loop (P&B, C_0=0.4)

Effect of Dynamic Loading for Shear Walls

Post & Beam Shear Walls

Fine lines on Figure 3-1, Figure 3-2 and Figure 3-3 show static hysteresis loops from static monotonic loading test. [Kawai, 1998] Although Figure 3-1, Figure 3-2 and Figure 3-3 suggest that envelope curves of dynamic hysteresis loops are similar to the shape of static hysteresis loops, dynamic strengths before the maximum strength points are greater than those of static strengths. Figure 3-3 (in case of C_0=0.3) shows the maximum strength on dynamic hysteresis loop is 14% more than that of static loop. Displacement at the maximum strength point on dynamic is about 50% of static. Dynamic hysteresis agrees with static hysteresis between zero to around 1/120 (0.0083) radian of tilting angles. After 1/120 radian, dynamic and static hysteresis loop are separated, and deformation of static hysteresis increase rapidly. So-called (static) yield points are not observed on dynamic hysteresis loops. Difference between dynamic and static hysteresis loops indicates that load duration of static loading tests add horizontal deformation and decrease strength of static hysteresis loops. These phenomena can be explained by properties of creep deformation and stress relaxation of timber respectively.

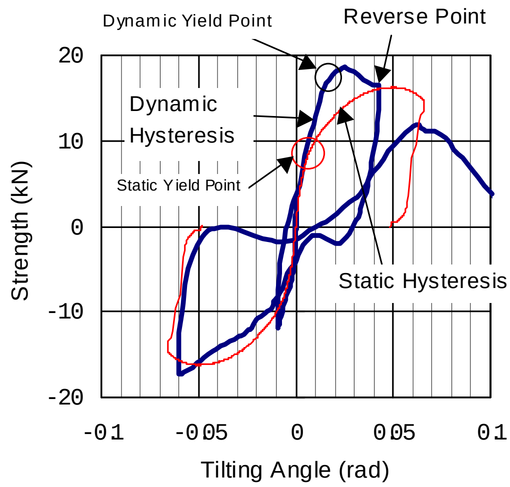


Figure 3-3: Hysteresis Loop (P&B, C_0=0.3)

Wood Frame Shear Walls

Figure 4 shows the dynamic hysteresis loop of WF shear walls, in case of C_0=0.3. Fine lines on Figure 4 shows static hysteresis loop by monotonic loading test. Comparing two cases of Figure 4 (C_0=0.3 and C_{pmax}=0.64) of WF shear walls and Figure 3-2 (C_0=0.4 and C_{pmax}=0.65) of P&B shear walls, these dynamic hysteresis loops were almost same. This result means seismic performances of these two tests are almost equivalent. When we evaluate seismic performance of these two walls using C_0, this result might suggest seismic performance (C_0=0.3) of WF shear walls is better than that (C_0=0.4) of P&B shear walls. But when we evaluate them using C_{pmax} , seismic performance (C_{pmax}=0.64) of WF shear walls and that (C_{pmax}=0.65) of P&B shear walls are almost same. It is evident that C_{pmax} is better seismic coefficient than C_0, in order to evaluate seismic performance of different walls which use different method to assign allowable strengths.

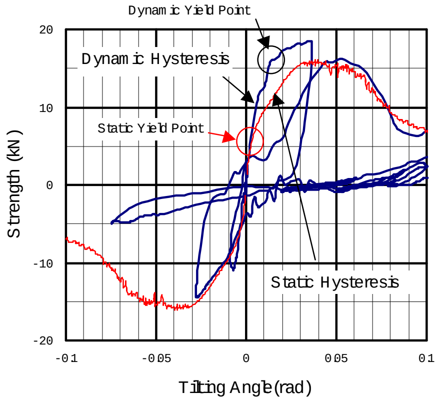


Figure 4 : Hysteresis Loop(WF, C_0=0.3)

Unsymmetrical Hysteresis Model after Maximum Strength Points

Dynamic hysteresis loops in Figure 3-1, Figure 3-2, Figure 3-3 and Figure 4 show following features. Hysteresis loops absorb energy passing along strength-decreasing area after the maximum strength point. Absorbed energy on positive deformation side is not absorbed on negative deformation side. It looks like area absorbed energy is memorized. Consequently area on another deformation side does not absorb energy. This unsymmetrical energy absorption feature is not apparent before the maximum strength point. This unsymmetrical hysteresis feature dominate response after the maximum strength point. Unsymmetrical hysteresis feature after the maximum point was translated into the unsymmetrical hysteresis model shown in Figure 5. “Rules of proposed unsymmetrical hysteresis model are as follows.

A; After the maximum strength point, deformation starts to decrease at 1st reverse point. B; Hysteresis loop goes to 1st reach point. 1st reverse point and 1st reach point are symmetry with regard to the origin. C; After 1st reach point, strength will be constant or start to decrease while deformation increases. D; Deformation starts to decrease at 2nd reverse point. E; Hysteresis loop goes to 2nd reach point. 2nd reverse point and 2nd reach point are symmetry with regard to the origin. F; Continue until the complete loss of strength of walls.

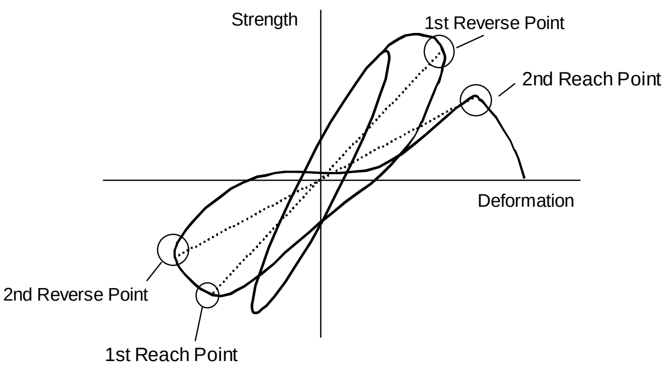
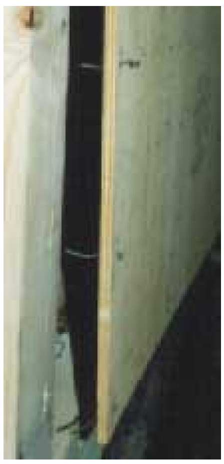


Figure 5: Unsymmetrical Hysteresis Model



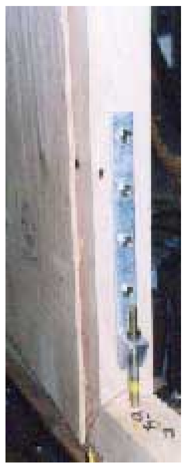


Photo :1, Pulling out of Nails

Photo 2: Punching out of Nails

Failure Modes of Shear Walls by Shaking Table Test

P&B shear walls collapsed by the JMA Kobe-NS motion in case of C_0=0.3 (Figure 3-3). Photo 1 and Photo 2 show damage of nailed plywood walls by this test. Photo 1 shows pulling out of nails after the shaking table test. Photo 2 shows punching out of nails into plywood. Figure 6 shows typical failure modes of nailed fasteners. Remain means no apparent damage of nailed fasteners. Side crack is damage of plywood between nail-holes and edge of plywood. Figure 7 shows ratio of failure modes of perimeter nails on plywood in tests of C_0=0.5, 0.4, 0.3 of P&B shear walls. These tests correspond to hysteresis loops of Figure 3-1, Figure 3-2 and Figure 3-3. Maximum responses by these tests are also shown in Figure 7. According as C_0 decreases, these maximum responses increase, and ratio of pulling out of nails decreases, and these ratios of punching out increase. Figure 3-1 (in case of C_0=0.5) shows maximum response reached almost the maximum strength point. 60% of nails of this specimen were pulled out by this test. These results suggest that pulling out of nails occur before responses have reached their maximum strength points. Further responses exceeding maximum strength points make pulled-nails punch out.

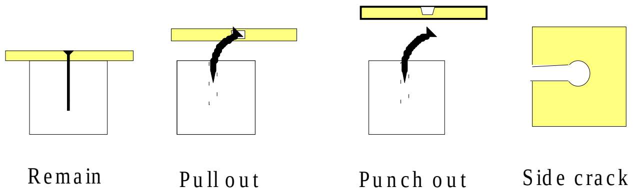


Figure 6: Failure Modes of Nails

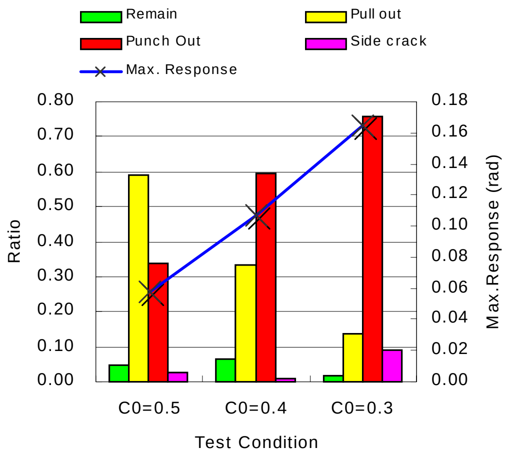


Figure 7: Ratio of Failure Modes of Nails

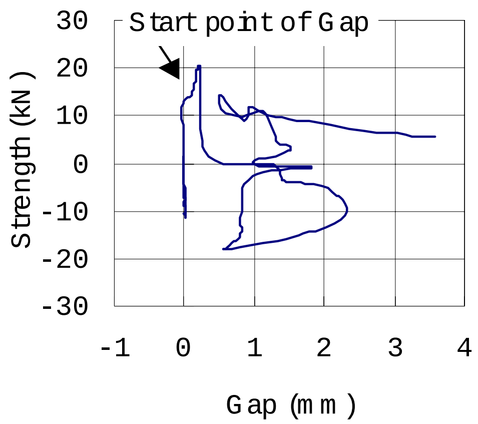


Figure 8: Gap Start point

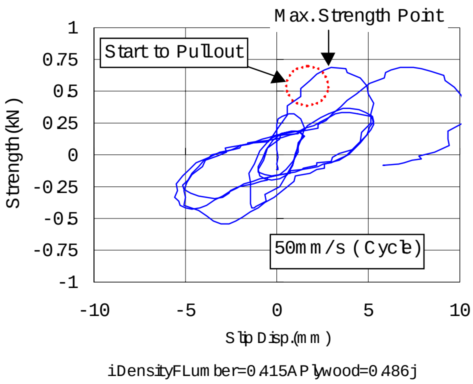
Dynamic Yield of Shear Walls

Static yield points are not observed on dynamic hysteresis loops of shear walls. We can observe dynamic yield points just before the maximum strength points on dynamic hysteresis loops (Figure 3-1, Figure 3-2, Figure 3-3 and Figure 4). We measured the gaps between plywood and columns. Figure 8 shows relationship between shear strength and gap in case of C_0=0.3 and P&B shear walls. The gap starts when the strength is around dynamic yield points. This gaps means some nails on plywood start to be pulled out around dynamic yield points.

STATIC AND DYNAMIC PERFORMANCE OF NAILED FASTENERS

Dynamic Yield Points of Shear-Strength of Nailed Fasteners

Figure 9-1 shows hysteresis loop of nailed fasteners for WF shear walls. Dynamic (50mm/s) reversed cyclic loads were applied for single shear nailed fasteners. Test method is shown in Figure 2-1. Figure 9-2 shows relationship between pulling out displacement and slip displacements of fasteners. When the nail started to pull out, the shear strength was just before the maximum strength point. These results indicate that dynamic yield-strengths and the maximum-strengths of shear walls are affected by this pulling out of nails. Pulling out of nails decreases nail-length in lumber. Decreasing of nail-length in lumber decreases shear-strength of nailed fasteners. It is evident that pulling out of nails causes shear walls to quit increasing shear-strengths at dynamic yield points. And pulling out of nails dominates maximum strengths of shear walls.



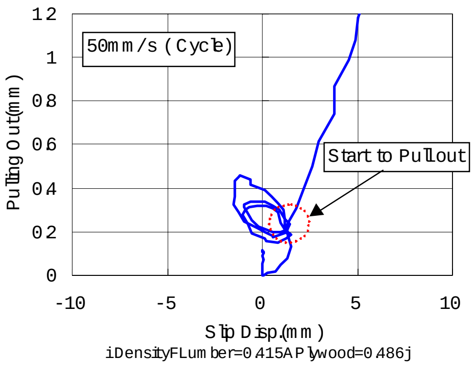
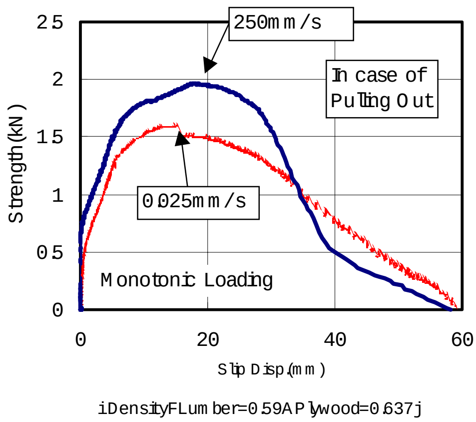


Figure 9-1: Shear Strength and Slip **Figure 9-2: Pulling out and Slip**

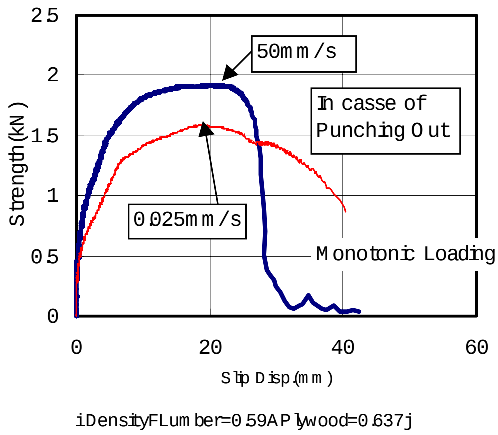
Dynamic effect of Shear-Loading for Nailed Fasteners

Figure 10-1 and Figure 10-2 show effects of loading velocities for single shear nailed fasteners by monotonic loading test. Lumber and nails of these tests were Hemlock and N50 for P&B shear walls. High-density lumber and plywood were used for these tests. Figure10-1 and Figure10-2 show shear-strength and slip displacement relationships of nailed fasteners in cases of pulling out and punching out. It is assumed 0.025mm/s is equivalent loading velocity to static loading. Dynamic loading generates greater maximum strength than static loading for both cases. But dynamic loading decreases strength rapidly than static loading after the maximum strength points. It is summarized that dynamic loading increases maximum strengths but decreases ductility.



(Pulling out)

Figure 10-1: Comparison of Shear Strength

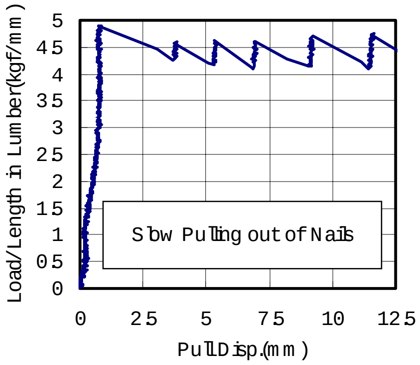


(Punching out)

Figure 10-2: Comparison of Shear Strength

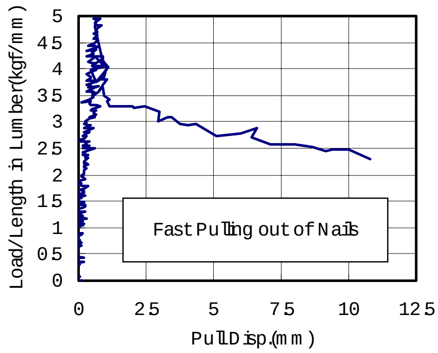
Dynamic effect of Pull-Loading for Nailed Fasteners

Figure 11-1 and Figure 11-2 show relationship between pull-loads for nailed fasteners and pull-displacement of nails. Lumber and nails for these tests were Hemlock and N50 for P&B shear walls. Vertical axis shows pull-loads divided by nail length in lumber. Nail length in lumber decreases according as pulling out of nails. Namely vertical axis shows friction between nails and lumber. Horizontal axis shows pull-displacement. Testing method is shown in Figure 2-2. Static (0.025mm/s) and dynamic(250mm/s) monotonic loads were applied for pulling direction of nailed fastener. Figure 11-1 and Figure 11-2 shows these relationships in case of static and dynamic loading respectively. Figure 11-1 shows friction is constant in case of static loading, but Figure 11-2 shows friction in case of dynamic loading decreases to half of the initial value. These results indicate if once the nails start to move, they will move with less friction than static. Dynamic pulling out of nails generates greater pulling out and rapid decreasing of shear-strength than static.



(0.025mm/s)

Figure 11-1: Pull Strength on Static



(250mm/s)

Figure 11-2: Pull Strength on Dynamic

CONCLUSIONS

Seismic performances of wooden shear walls were evaluated by static loads and dynamic loads. Effect of dynamic loads for shear walls is analyzed by failure mechanism of nailed fasteners.

- Dynamic hysteresis loops of nailed plywood shear walls is different from static hysteresis loops. Dynamic yield points were observed on dynamic hysteresis loops. Static yield points were not observed on them. The maximum strength on dynamic hysteresis loops is about 14% more than the maximum strength of static. Dynamic yield points are just before the maximum strength points of shear walls.
- Dynamic loads for single shear nailed fasteners increase maximum strengths than static, but decreases ductilities of them. And pulling out of nails occurred just before the maximum strength point. Dynamic pull loading for nailed fasteners decrease friction than static, after the nails start to move. Dynamic pulling out of nails with less friction generates greater pulling out of nails than static.
- Unsymmetrical hysteresis model of nailed plywood shear walls after the maximum strength point was proposed. If response of shear walls goes beyond dynamic yield points or maximum strength points, nails are pulled out. As the nails will not go back to their initial positions by themselves, pulling out of nails causes unsymmetrical hysteresis loops of shear walls.
- Start position of gap, start position of pulling out and friction on dynamic of nailed fasteners proved that pulling out of nails causes dynamic yields and dominates maximum strengths of shear walls.
- Evaluation of seismic performance on dynamic condition brought these new findings.

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