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In-plane cyclic behavior of structural insulated panel wood walls including slit steel connectors

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ABSTRACT

The objective of this paper was to experimentally investigate the behavior of structural insulated panel (SIP) walls under in-plane cyclic loading and to test several panel-to-panel connections in order to measure their effect on the behavior of the walls. Each wall was constructed using two SIP panels with one top plate, one sill plate, two end plates, and a panel-to-panel connection. Each SIP panel had a 5.5 in. (14 cm) thick expanded polystyrene core sandwiched between two 4′ × 8′ (1.22 m × 2.44 m) sheets of 7/16″ (1.11 cm) oriented strand board. The top sill plates were split up between each panel in an effort to increase the potential for racking behavior of the walls and, therefore, the relative vertical displacement between the panels. In addition, as a preliminary study, three different steel connector configurations utilizing 26 gauge steel shear panels were considered in an effort to introduce additional ductility compared to more traditional block spline connection. From experimental observation of the wall with the block spline connection and the wall with no connection, the panel-to-panel connection was shown to contribute significant strength and stiffness to the wall system. The walls that were constructed with the first two configurations of the shear panels did not show any significant increase in either stiffness or ductility over the wall with the block spline. These walls also showed a decline in peak strength, which occurred at lower lateral displacements than the peak strength of the typical wall. For both of these cases, the shear panels yielded early and ruptured at the lateral deformation which caused peak load in each wall. The SIP wall implementing the third style of shear panel also did not demonstrate a significant increase in ductility as compared to the standard SIP wall. Despite the initially outlined potential, the preliminary study of implementation of the slit steel shear panels considered in this study did not significantly alter the performance of the conventionally connected SIP walls. Further study with stiff connectors capable of significant ductility prior to fracture would need to be implemented to realize the benefits of increased wall ductility.

1. Introduction

1.1. Background and purpose

Structural insulated panels (SIPs) are most commonly used as an alternative to typical lumber framing in residential construction, though some variations are used in light commercial construction. In addition, SIPs made of concrete [1] and thin steel plate panels [2] have successfully been used. The advantages of building with SIPs, versus typical timber framing, include reduced construction time, reduced labor requirement, and most of all the increased thermal efficiency of the overall structure. The reduction in construction time and labor required are tied together and are a direct result of the prefabricated components and the integration of structure and insulation. In terms of thermal efficiency, an R-value rating is often used which indicates the capacity of a material to stop heat flow and is often used to characterize thermal resistance. A typical six-inch thick (15.24 cm) SIP wall has an R-value of 21.6 while a similarly sized conventional wood frame wall with fiberglass batts has a value of 13.7 [3]. The higher thermal resistance is credited both to the fact that the foam used in SIP manufacturing has a higher R-value than typical batts and that a SIP wall contains less thermal bridging than a wood frame wall. Furthermore, because SIPs tend to be optimally designed for a specific job, the waste accrued during construction can also be minimized [3].

The International Residential Code (IRC) imposes limits on SIP construction to sites with seismic design categories A, B, or C [4]. Construction with SIPs is allowed in design categories D, E, and F "when building code compliance is demonstrated through a

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Nomenclature

a	clear distance between slit openings
A_w	area of the web
b	wall width
C_d	deflection amplification factor
C_v	ratio of critical web stress to shear yield stress
d_a	hold down slip
E	Young's modulus
e_n	nail slip
F_v	reference and adjusted shear design value parallel to grain
F_y	yield strength
G_v	reference modulus of rigidity for wood structural panels
H	height of panel section
h	height of slit plate
h_t	total wall height
h/t	width to thickness ratio of slit panel
I	importance factor
K_r	form conversion factor
k_v	web plate shear buckling coefficient
m	number of nails
M	moment seen on panel section
n	number of slits
P	applied load on panel section
P_{v1}	load demand along nailing line
v	load per unit length
$V_{n,\ nail}$	nominal shear strength of nailing connection
$V_{n,conv\ wall\ panel}$	nominal shear strength of a SIP wall panel
V_{nail}	shear per nail
V_T	total shear on panel section
$V_{n,\ sill\ plate}$	nominal shear strength of sill plate
$V_{n,SIP\ wall\ panel}$	nominal shear strength of a SIP wall panel
W	total width of panel section
W_1	width of panel 1
W_2	width of panel 2
Z	bolt shear capacity
Δ_{total}	total deflection

manufacturer evaluation report" [4]. Because of this requirement, there were a number of proprietary tests conducted on the capacity of SIPs, but data on the capacities and modes of failure within the public domain were scarce. The purpose of this paper is to report on the behavior of SIP walls under in-plane, quasi- static cyclic loading typically used for evaluating the seismic capacity. The objective of the study was to observe the overall in-plane cyclic behavior and the demand imposed upon the panel-to-panel connection. An alternate panel-to-panel connection utilizing slit steel shear panels (slit panels) made from zinc-coated steel sheets was also experimentally investigated for its influence on the cyclic response.

1.2. Literature review

Jamison examined SIP wall behavior under monotonic and cyclic loading [5]. Two types of monotonic tests were conducted: a static ramp test at a constant rate of displacement and a static load test prescribed by ASTM E564 [6]. The cyclic test followed a modified version of the Sequential Phased Displacement (SPD) method employed by Jamison, now prescribed by ASTM E 2126 [7]. Jamison's study compared the performance of SIP walls under four different configurations and light frame timber walls under both loading conditions. Each SIP wall had the same fastener spacing and adhesive and was also connected to the test frame by four 5/8″ (1.59 cm) bolts placed 24 in. (60.96 cm) on center. The results showed that there were no significant differences between the strength, elastic stiffness, and behavior of the walls under monotonic loading versus SPD cyclic loading. The SIP walls were also observed to display racking behavior only when the hold-downs were used. The SIP walls with hold downs experienced failure at the top plate and panel-to-panel connections by shearing and pulling through of the screws. When the hold-downs were not implemented, the walls underwent rigid body rotation when loading was applied, and failure occurred along the base plate by shearing of the drywall screws on the OSB side and pulling through and shearing of the screws on the sheetrock side. The study showed that the SIP walls with hold downs had a similar strength capacity to the conventional wood frame walls, but had higher stiffness and lower ductility [5].

Gatto and Uang compared the performance of wood frame shear walls under monotonic loading and several cyclic loading protocols including the CUREE standard, the CUREE near-fault, the sequential phased displacement (SPD), and the International Standards Organization (ISO) protocols [8]. The primary focus of the tests conducted by Gatto and Uang was to compare the CUREE-Caltech protocols with the previously accepted cyclic and monotonic protocols. This research showed that the SPD protocol was not only conservative in determining strength and deformation capacity of wood frame walls, but also caused fatigue failure in fasteners that rarely occurred in the other protocols. This unique mode of failure was the result of the large number of cycles (relative to the other protocols) required by the SPD protocol and was not representative of what would occur in a seismic event. The study also showed that the ISO protocol was conservative in predicting shear strength capacity and ductility of a wood frame wall due to the high demands of the protocol. Ultimately, Gatto and Uang concluded that the standard CUREE protocol was best suited for cyclic testing of wood frame shear walls given the failure mode similarity to observations from earthquake performance [8].

Kermani and Hairstans observed the effect of gravity loads on the shear capacity of SIP walls. In addition to the typical wall specimens that consisted of two solid SIPs, wall specimens with different opening sizes and locations were also tested [9]. The results of the tests show that the average shear capacities of the walls increased 117 percent and 81 percent when constant gravity loads of 25 and 12.5 kN (5.62 and 2.81 kips) respectively were applied to the SIP walls. Terentiuk conducted both monotonic following ASTM E 564-06 and cyclic tests following the standard CUREE protocol as prescribed by ASTM E 2126-08 on conventional wood frame walls and SIP walls [6,7]. The purpose of the procedure was to observe and compare the behavior of the SIP walls with the behavior of the conventional walls and to determine an optimal SIP wall design considering variations in panel-to-panel connections, fasteners, placement of hold downs, and bearing of sheathing [10]. The SIP wall specimen with hold-downs placed at the interior end studs displayed higher ductility and shear stiffness (about 13% greater) than the specimens with hold-downs placed on the exterior of the end studs. This result was important because hold-downs are conventionally placed on the interior side of the studs in the field but on the exterior of the studs for testing. The specimens that used staples as the fasteners of the splines showed the least amount of strength, while the specimens that used screws as the fasteners for the splines showed the most brittle behavior. The specimens with nailed connections displayed an ultimate strength that was nearly 40% greater than the walls with staples, while the average displacements were 31% and 38% higher than the walls with stapled and screwed connections, respectively, at peak load [10]. Terentiuk et al. studied SIPs with different connector hardware including 8d nails, No. 6 plywood/particle board screws, and 16-gauge staples [11]. Their study confirmed the fastener hardware was the weakest factor of every specimen consistent with previous shear wall studies. Further similar study by Terentiuk et al. resulted in failure modes of either the fastener hardware or the OSB sheeting [12].