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SEISMIC PERFORMANCE OF CONFINED SILL PLATE CONNECTIONS

By Joseph M. Bracci,[1] Rebecca F. Stromatt,[2] and David G. Pollock,[3] Members, ASCE

ABSTRACT: In the aftermath of the 1994 Northridge earthquake, extensive field investigations revealed damage in wood frame construction in the form of splitting of the 2 × 4 or 2 × 6 wood sill plates along the line of anchor bolts that typically connect shear walls to the masonry or concrete foundation. Due to the severity of such brittle failures, the city of Los Angeles has recently restricted the use of 2× dimension lumber in sill plates and requires the use of 3× dimension lumber. This paper presents an experimental investigation of the performance of 2× dimension lumber sill plate connections at the yield and ultimate limit states during incremental quasi-static reversed cyclic loading and suggests possible cost-effective retrofit strategies for their improved seismic performance without having to increase the sill plate thickness. Proposed retrofit strategies are based on providing confinement to the sill plate using metal reinforcing straps and reinforcing clamps to increase the deformation capability and energy dissipation capacity of the connection, while maintaining substantial levels of connection strengths.

INTRODUCTION

Over 90% of residential construction in the United States and a significant percentage of low-rise commercial construction are composed of wood frame wall and roof systems (Anderson and McKeever 1991). The performance of these structures during past earthquakes and hurricanes has been mostly successful due to the effectiveness of wood shear walls in resisting severe lateral loads (shear forces). However, in cases of significant structural damage, poor connection response performance was typically the incipient failure mechanism. Often, sill plate connections were the weak link in transferring shear forces from the wood frame walls to the concrete or masonry foundation.

Current building code requirements for anchor bolt connections in residential and some light-commercial wood structures typically requires 12.7 mm (0.5 in.) diameter (or larger) bolts spaced at 1.83 m (6 ft) centers or closer around the perimeter of the structure for attaching the wood frame walls to the concrete or masonry foundation (*Uniform* 1994). The sill plate is typically either a 2 × 4 or 2 × 6 piece of dimension lumber. The primary function of these connections is to resist the lateral shear force demands from wind and seismic loading and to prevent the sliding of the superstructure with respect to the foundation. These code requirements are based on past experience and tend to be prescriptive, rather than performance based. In addition, hold-down connectors with larger diameter bolts are required at the ends of shear wall segments to resist uplift from overturning moments.

In contrast, bolted connection design provisions in the *National design specification for wood construction* (NDS) (*National* 1991) follow a more performance-based design philosophy using equations for yield mode behavior based on connection strength limits from static tests. The input parameters for the equations are connection geometry (member thickness, fastener diameter, and fastener length), dowel bearing yield strength of member materials (for wood, this is correlated with the material specific gravity and angle of loading with respect to the grain), and fastener bending yield strength. Yield limits for these parameters are established at the intersection of the static load-deformation response curve with a line originating on the deformation axis at the 5% diameter (fastener) offset and parallel to the initial loading response (*National* 1991). Due to a scarcity of data on woods-to-concrete connections, the NDS incorporates some very conservative assumptions that can result in anchor bolt spacing that varies from 0.15 m (0.5 ft) to 1.22 m (4.0 ft) centers, depending upon the wind and seismic loading demands specified in model building codes.

Connection "yield modes" are representative of actual response behavior and can be described as a combination of wood failure by local crushing and/or the formation of one or more plastic hinges (yielding) in the metal fastener (see Fig. 1). Yield modes I and II are dominated by crushing of the wood fibers in bearing beneath the fastener, which with excessive deformation demands can ultimately lead to splitting along the grain of the wood. This type of behavior is typical in connections using large diameter fasteners to connect relatively thin wood members. Connections exhibiting yield modes I and II behavior are usually avoided in modern wood structures because of their tendency to develop brittle failure under extreme load conditions. However, hold-down connectors required at the ends of shear wall segments typically use large diameter bolts to primarily resist uplift from overturning moments in the wall, rather than the lateral shear forces. Unfortunately, during large deformation demands, brittle splitting in the wood member may initiate in these connections and propagate along the grain of the sill plate due to mode I yielding.

Yield modes III and IV are more common and desirable in modern wood structures due to their ductile behavior from fastener yielding. As illustrated in Fig. 1, the localized crushing of wood fibers and formation of plastic hinges in the fastener occur simultaneously. This connection behavior is typical when small diameter fasteners are used to connect relatively thick wood members.

It should be emphasized that the connection behavior modes describe the interaction between the fastener and the connected wood members at their yield limit state under static load conditions. However, connections designed to provide ductile response at the yield limit state (modes III and IV) may still ultimately fail by the crushing and splitting of the wood member from the prying action of the bolt during excessive deformation demands from extreme earthquake loadings. In addition, out-of-plane loading in sill plate connections creates tension stresses perpendicular to the grain of the wood (weak plane), which may create splitting along the grain.

After the 1994 Northridge earthquake in southern Califor-

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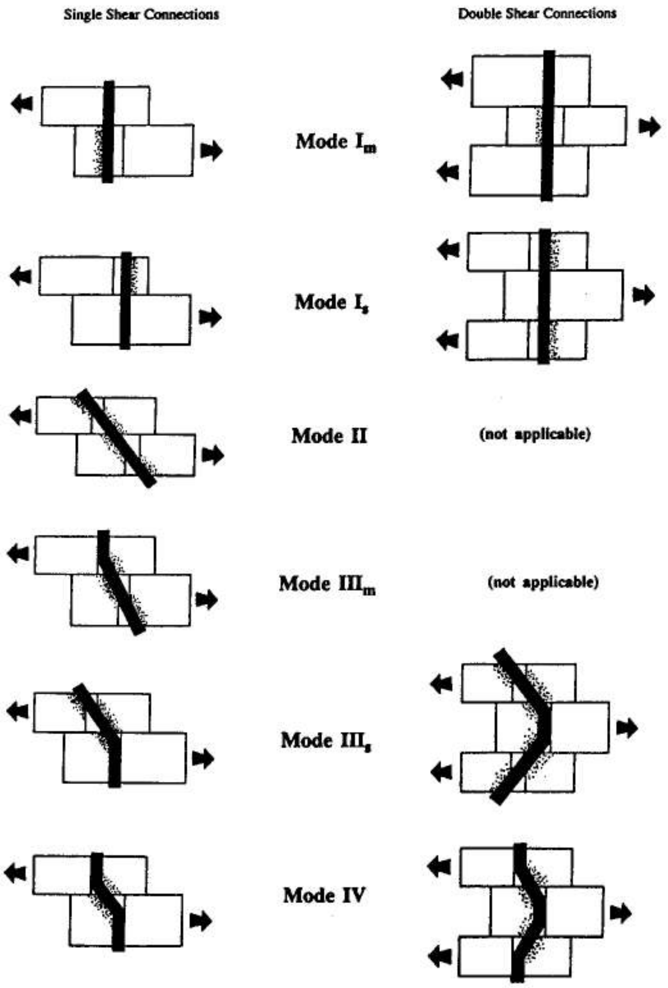

FIG. 1. Yield Connection Modes [Courtesy of American Forest & Paper Association (*National* 1991)]

nia, it was reported that a number of sill plates split along the line of anchor bolts connecting the wood frame walls to the concrete or masonry foundation (Hamburger 1994). This type of damage can ultimately cause the superstructure to slide off the supporting foundation during the earthquakes and can lead to excessive structural and nonstructural restoration costs. Due to the severity of damage in sill plate members, the city of Los Angeles (''Emergency'' 1994) currently restricts the use of 2× dimension lumber for sill plates and requires the use of 3× dimension lumber. By increasing the thickness of the wood member, the yield load capacity for a given connection will certainly increase and a more desirable performance may result at the yield limit state by forcing the connection to exhibit mode III or IV behavior. However, the ultimate failure mode under extreme loading conditions can still be brittle splitting of the sill plate when excessive deformation demands are placed on the connection. Thus, while noting that 3× dimension lumber may provide slight improvements in sill plate connection performance at the yield limit state, the overall loss of strength and energy dissipation capacity associated with splitting of the sill plate at large deformations may still exist.

RESEARCH OBJECTIVE

The objective of this research is to evaluate the response performance of wood sill plate-to-concrete foundation connections using 2× dimension lumber with and without member confinement at the yield and ultimate limit states such that more resilient wood frame structural systems can be designed to resist earthquakes and hurricanes. The supplemental confining devices, thin metal reinforcing straps and special reinforcing clamps (intellectual property owned by the Texas A&M University system), are relatively inexpensive and easy to install in both new and existing construction. A comparison of the developing yield and ultimate failure modes is made and corresponding critical strength and deformation capabilities are quantified. In addition, this research is aimed at improving the conservative assumptions made in the NDS (*National* 1991) for bolted wood-to-concrete connections.

PROPOSED RETROFIT ALTERNATIVES

Confinement of wood members has been studied to prevent brittle splitting failure during high loading demands. One such study used steel banding in heavy truss members to restore connection strength by confinement after splitting occurred in the wood members (Avent et al. 1980). However, cross-section shrinkage and swelling (dimensional changes) of the wood due to fluctuations in the moisture content from humidity changes caused the straps to loosen over time and to lose confining effectiveness of the members. In addition, stitch bolts have historically been used to prevent opening of checks and splits that may develop during loading (*Timber* 1956). However, the same problems related to shrinkage necessitate the periodic tightening of bolts.

The retrofit strategy used in this study for sill plate-to-concrete foundation lateral shear connections and vertical hold-down connections is to reinforce the critical wood member to deter brittle splitting failure and enhance the deformation capability and energy dissipation capacity of the connection. Two different retrofit alternatives are considered in this research based on providing confinement to the sill plate. (1) supplemental thin metal reinforcing straps wrapped completely around the wood member, and (2) supplemental reinforcing clamps that bound the three exposed faces of the wood member.

Reinforcing Straps

Detail of the retrofit sill plate connection using thin metal reinforcing straps is shown in Fig 2(a). In this study, adjustable metal hose clamps were used to completely encompass the wood member and were posttensioned to provide partial confinement to the sill plate near the anchor bolt. Since the straps are rather flexible, they do not significantly increase the splitting resistance of the sill plate. Rather, the straps are used to confine the wood member after splitting occurs so that lateral forces can still be transmitted through the connection from the bolt bearing on the sill plate. Problems associated with member shrinkage can still cause the straps to loosen. However, since sill plates typically have small cross sections, the relative shrinkage displacements are small and any slack in the straps can be taken up during the large deformations associated with splitting. The spacing and number of reinforcing straps are varied in the experimental program to compare the different response behaviors. It should be pointed out that the metal straps studied in this research program are very inexpensive. However, they may be difficult to install in existing wood frame structures, since nailed plywood shear walls would need to be disassembled and lifted to place the reinforcing strap around the sill plate.

Reinforcing Clamps

Detail of the retrofit sill plate connection using special reinforcing clamps (intellectual property owned by the Texas A&M University system) made of galvanized steel or a composite material is shown in Fig. 2(b). Reinforcing clamps of different sizes and orientation are placed over the anchor bolt and onto the sill plate. Helically threaded nails are inserted

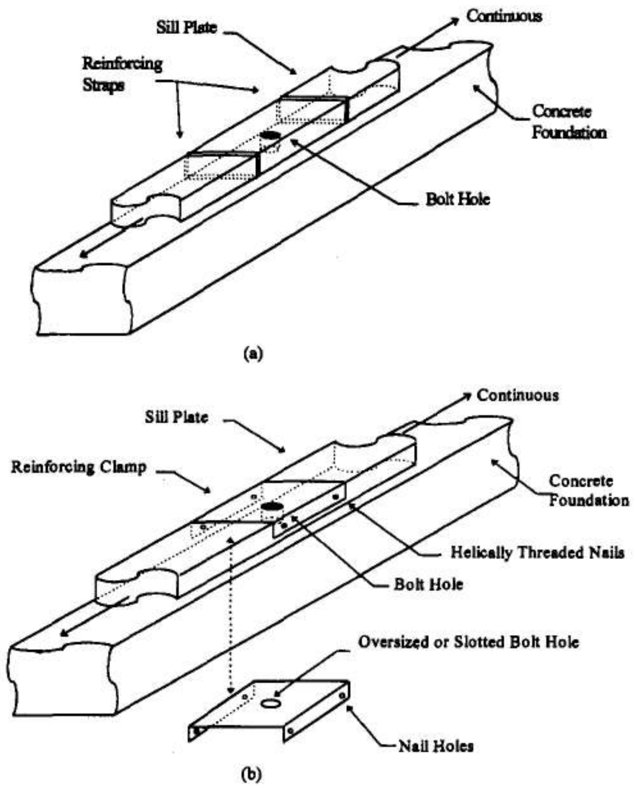

FIG. 2. Proposed Retrofit Alternatives: (a) Reinforcing Straps; (b) Reinforcing Clamp

into the sides of the sill plate so that the side walls of the clamp are restrained from slipping and deflecting outward if the sill plate splits. The nails are also inserted past the line of anchor bolts to enhance the splitting resistance of the sill plate. It should be noted that the clamps can be designed to increase both the strength and deformation capacity of the connection, if desired, by allowing the anchor bolt to bear on the clamp during lateral deformations. During large deformations, the clamp can buckle locally and dissipate energy. Additional strength can also be achieved by forcing an existing mode III behavior (single curvature) to perform in a mode IV fashion (double curvature) by providing flexural support at the top of the bolt using a heavy washer above the clamp. If additional strength in the connection is not necessary, the clamps can be designed to preclude the bolt bearing on the clamp during lateral deformations by using a slotted hole in the clamp. If the bolt deforms and crushes through the wood member, the reinforcing clamp will contain the member to avoid brittle splitting. Even if splitting develops, the reinforcing clamp will provide transverse resistance to the sill plate and ensure that sufficient lateral strength and energy dissipation capacity exists in the connection.

Two connection retrofit design scenarios exist. First, a connection is designed for strong bolt performance (mode I, as is the case for hold-down connections), then the clamps can help confine the wood member and deter brittle splitting. The deformation capability of the connection can be significantly enhanced to ensure that significant lateral resistance exists in the connection at large lateral deformation demands from the bolt bearing on the wood member. Crushing of the wood member occurs and dissipates energy from the input lateral forces. Second, if the connection is designed for strong sill plate performance (mode III/IV, as is the case for small diameter anchor bolts), the clamp helps confine the wood such that the sill plate does not split during large lateral deformations in the connection. The ultimate failure mode will be in the form of low cycle fatigue of the anchor bolts, provided proper anchorage of the bolt into the concrete foundation exists.

It should also be mentioned that the retrofit alternatives for sill plate connections provide additional resistance for tensile stresses perpendicular to the grain of the wood member (weak plane in wood members). Both the reinforcing straps and clamps can be designed to provide resistance to any out-of-plane loading in the connection and avoid brittle splitting along the grain of the sill plate.

EXPERIMENTAL TESTING PROGRAM

To carry out the previously mentioned research objectives, an experimental testing program was developed to identify the performance of existing wood-to-concrete sill plate connections and several enhanced connections during the yield and ultimate limit states (see Table 1). The enhanced connections include wrapping the sill plate with thin metal reinforcing straps and using special reinforcing clamps made of galvanized steel, as described in the previous section. Southern pine 2 × 6 dimension lumber was used in this study due to its widespread use in construction and its immediate availability. The metal fasteners were either 12.7 mm (0.5 in.) diameter low strength

TABLE 1. Experimental Testing Program

Specimen (1)	Bolt diameter (mm) (2)	Yield mode (NDS 1991) (3)	Description (4)
M34N-1	12.7	III	Unconfined sill plate
M34N-2	12.7	III	Unconfined sill plate
M34N-3	12.7	III	Unconfined sill plate
M34S2-1	12.7	III	Straps 50.8 mm from bolt centerline
M34S2-2	12.7	III	Straps 50.8 mm from bolt centerline
M34S4-1	12.7	III	Straps 101.6 mm from bolt centerline
M34S4-2	12.7	III	Straps 101.6 mm from bolt centerline
M34C1-1	12.7	IV	Clamp 101.6 mm length, oversized hole
M34C2-1	12.7	III/IV	Clamp 152.4 mm length, 50.8 mm slotted hole
M12N-1	22.2	I,II	Unconfined sill plate
M12N-2	22.2	I,II	Unconfined sill plate
M12N-3	22.2	I,II	Unconfined sill plate
M12S4-1	22.2	I,II	Straps 101.6 mm from bolt centerline
M12S4-2	22.2	I,II	Straps 101.6 mm from bolt centerline
M12S4-3	22.2	I,II	Straps 101.6 mm from bolt centerline
M12S4-4	22.2	I,II	Straps 101.6 mm from bolt centerline
M12C2-1	22.2	I,II	Clamp 152.4 mm length, 50.8 mm slotted hole
M12C2-2	22.2	I,II	Clamp 152.4 mm length, 50.8 mm slotted hole
M12C3-1	22.2	I,II	Clamp 203.2 mm length, 101.6 mm slotted hole
M12C3-2	22.2	I,II	Clamp 203.2 mm length, 101.6 mm slotted hole

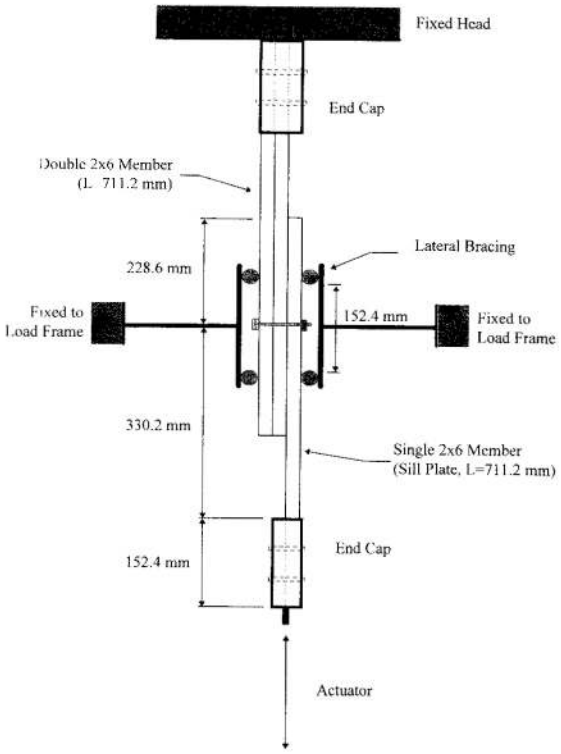

FIG. 3. Experimental Test Setup

ASTM A307 bolts or 22.2 mm (0.875 in.) diameter high strength Society of Automotive Engineers (SAE) grade 8 bolts, in which the weak link of the connection at the yield limit state (*National* 1991) was the metal fastener in flexure (mode III/IV) and the wood member in crushing (mode I/II), respectively. The bearing strength and stiffness of the concrete foundation are conservatively represented in the NDS (*National* 1991) by the bearing strength and stiffness of double (two) wood members. Therefore, double 2 × 6 southern pine members (specific gravity between 0.68 and 0.80) were used to simulate the concrete foundation and a single 2 × 6 member of less dense southern pine (specific gravity between 0.39 and 0.45) was used to represent the sill plate.

The experimental test setup is for full-scale component testing in single shear loading (shown in Fig. 3). End caps were fabricated to attach the 2 × 6 wood members to the load frame. Lateral support for the wood members to resist the moment created by the eccentricity of the loading was provided by rollers that attach into the load frame on each side of and above and below the connection. Incremental quasi-static reversed cyclic loading was used to identify the response behavior of the connections at the yield and ultimate limit states. Displacement control loading was applied in terms of actuator stroke in a series of two cycles with increasing displacement amplitudes of ±3.175 mm (0.125 in.), ±6.35 mm (0.25 in.), ±9.525 mm (0.375 in.), ±12.7 mm (0.5 in.), ±19.05 mm (0.75 in.), ±25.4 mm (1.0 in.), ±38.1 mm (1.5 in.), ±50.8 mm (2.0 in.), and ±63.5 mm (2.5 in.) at a rate of one cycle per minute. The load cell on the actuator was used to measure the applied shear force to the connection and a sonic displacement transducer was used to measure the relative displacement between the double 2 × 6 member representing the concrete and the 2 × 6 sill plate.

A total of 20 tests was performed with varying parameters that included design yield mode behaviors for anchor bolt hinging (mode III/IV) and for wood crushing (mode I/II), diameter and yield strength of metal fasteners, spacing of thin metal reinforcing straps from the anchor bolt, and various sizes and orientations of reinforcing clamps. Since this study was considered a preliminary evaluation for sill plate connections, a small sample size was used that precludes a complete statistical analysis of performance data. However, with the small number of tests, general trends and dramatic improvements in connection response at various response states are still expected.

EVALUATION OF RETROFIT CONNECTION BEHAVIOR

Model building codes (*Uniform* 1994) require 12.7 mm (0.5 in.) diameter anchor bolts at 1.83 m (6 ft) maximum spacing, which typically results in mode III behavior (bolt hinging) at the yield limit state according to the NDS (*National* 1991). Therefore, the yield and ultimate response behaviors of sill plate connections exhibiting yield mode III behavior are identified (see Table 2). The experimental response behavior for a typical connection using a 12.7 mm (0.5 in.) diameter ASTM A307 bolt with (1) unconfined sill plate (M34N-2); (2) confined sill plate using reinforcing straps at 101.6 mm (4 in.) centers from the anchor bolt (M34S4-2); and (3) confined sill plate using a special reinforcing clamp made of galvanized steel with a 16 gauge wall thickness, 101.6 mm (4 in.) length,

TABLE 2. Summary of Experimental Response

Specimen[a] (1)	$P_{y,\text{anal}}$ kN (2)	P_y kN (3)	δ_y mm (4)	$P_{\max}$ kN (5)	$\delta_{\max}$ mm (6)	δ_{split} mm (7)	δ_{ult} mm (8)	ΣE_{tot} kN·mm (9)	Observations (10)
M34N-1	9.4	8.4	4.6	13.3	33.8	45.5	56.4	3,308	Bolt yielded, plate split
M34N-2	9.4	9.3	3.9	14.8	22.9	24.3	24.3	1,450	Bolt yielded, plate split
M34N-3	9.4	9.8	4.3	13.8	22.9	33.8	33.8	2,065	Bolt yielded, plate split
M34S2-1	9.4	10.0	4.1	14.5	33.0	44.4	—[c]	3,770	Bolt yielded and necked, plate slit
M34S2-2	9.4	9.8	2.5	17.8	46.2	52.9	59.4	4,059	Bolt fractured, plate split
M34S4-1	9.4	8.9	2.0	17.8	33.8	41.3	59.2	3,870	Bolt and washer fractured, plate split
M34S4-2	9.4	11.1	4.6	16.9	33.8	35.9	—[c]	4,038	Bolt yielded and necked, plate split
M34C1-1	9.4	9.8	4.3	27.8	56.6	42.2	—[c]	4,807	Bolt yielded and necked, plate split
M34C2-1[b]	9.4	9.8	3.5	23.1	60.5	—[c]	60.5	5,004	Bolt fractured, plate did not split
M12N-1	24.4	18.2	5.6	25.6	10.4	10.6	10.6	577	Plate crushed and split
M12N-3	24.4	25.6	7.4	31.6	12.2	12.7	12.7	814	Plate crushed and split
M12S4-1	24.4	20.5	5.6	26.2	8.4	11.0	15.9/—[c]	2,664	Shear Wedge formed on one side
M12S4-2	24.4	18.7	3.0	30.3	9.4	13.3	—[c]	4,622	Plate crushed and split
M12S4-4	24.4	18.9	3.8	27.6	14.7	16.6	16.6/—[c]	2,728	Shear Wedge formed on one side
M12C3-2	24.4	22.2	3.6	34.2	11.7	14.5	—[c]	5,642	Plate crushed and split

Note: 4.448 kN = 1 kip; 25.4 mm = 1 in.

[a] Specimens M12N-2, M12S4-3, M12C2-1, M12C2-2, and M12C3-1 developed splitting in double 2x6.

[b] Developed bolt fracture during second cycle at 63.5 mm displacement and plate did not split.

[c] Response not achieved during testing history.

and 22.2 mm (0.875 in.) diameter hole (M34C1-1) is shown in Figs. 4(a), 4(b), and 4(c), respectively. The response behavior for the unconfined sill plate is primarily governed by flexural deformations in the anchor bolt. At a relative displacement demand of about 24.3 mm (0.96 in.), brittle splitting of the sill plate occurs from the prying of the bolt, resulting in a complete loss of connection strength. Although the connection behavior at the yield limit state is exhibiting a desirable mode III type response, the eventual failure mode is an undesirable brittle splitting of the wood member. Therefore, existing sill plate connections can ultimately fail by brittle splitting during large lateral deformations, which has been observed during past earthquakes.

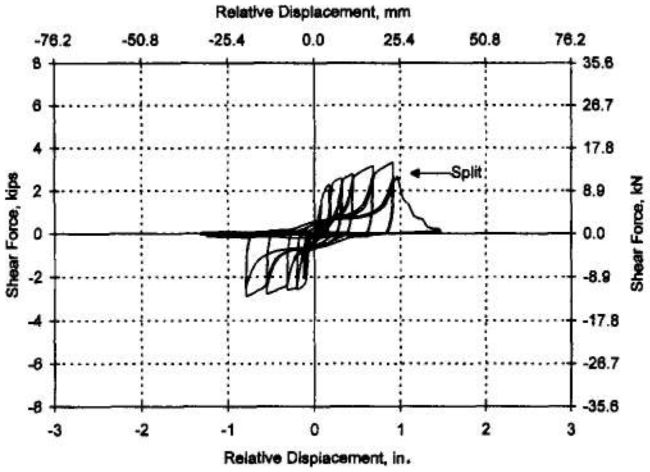

FIG. 4(a). Force-Deformation Response for Yield Mode III/IV Behavior [Unconfined Sill Plate (M34N-02)]

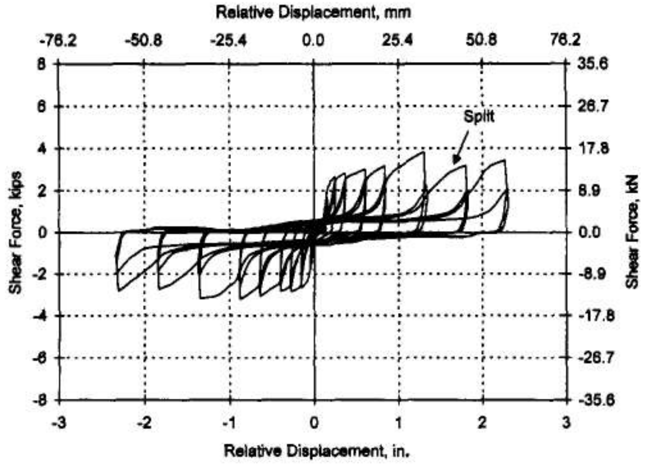

FIG. 4(b). Force-Deformation Response for Yield Mode III/IV Behavior [Confined Sill Plate Using Straps (M34S4-2)]

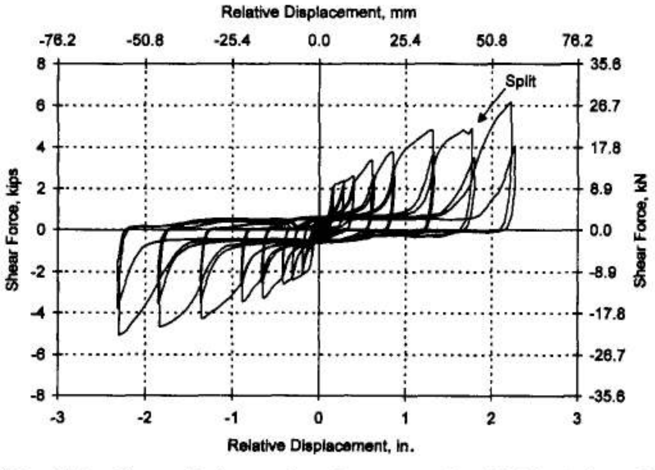

FIG. 4(c). Force-Deformation Response for Yield Mode III/IV Behavior [Confined Sill Plate Using Clamp (M34C1-1)]

For comparison, the confined sill plate performance using reinforcing straps shows that the displacements are again governed by bolt hinging and the sill plate eventually splits at a relative displacement of about 35.9 mm (1.41 in.). However, significant lateral strength exists in the enhanced connection after splitting, even at much larger displacement demands [exceeding 60 mm (2.36 in.)]. The maximum lateral strength is slightly increased (14%) as compared to the unconfined sill plate; however the ratios of maximum to yield strengths are similar (1.55). The ultimate failure mechanism did not completely develop during testing. However, necking of the anchor bolt was observed and the incipient failure mechanism was low cycle fatigue of the anchor bolt. For the connection using the reinforcing clamp, it can be observed that splitting in the sill plate occurs at relative displacements of about 42.2 mm (1.66 in.) and additional strength capacity (ratio of maximum to yield strength of 2.8) develops from the bolt bearing on the reinforcing clamp and the forced mode IV type response (double curvature). The ultimate failure mode for this connection did not completely develop during testing. However, a visual damage inspection revealed necking in the anchor bolt due to high flexural and tensile demands, indicating that low cycle fatigue of the anchor bolts was again the incipient failure mode.

The response behavior of sill plate connections exhibiting yield mode I/II behavior (wood crushing) using a 22.2 mm (0.875 in.) diameter high strength SAE grade 8 bolt with (1) unconfined sill plate (M12N-1); (2) confined sill plate using reinforcing straps at 101.6 mm (4 in.) centers from the anchor bolt (M12S4-2); and (3) confined sill plate using a special reinforcing clamp made of galvanized steel with a 16 ga. wall thickness, 203.2 mm (8 in.) length, and 22.2 mm (0.875 in.) diameter hole with a 101.6 mm (4 in.) slot (M12C3-2) is presented in Figs. 5(a), 5(b), and 5(c). The response behavior shows that brittle splitting of the sill plate without supplemental confining devices occurs at relative displacement demands of about 10.6 mm (0.42 in.). The deformation response is governed by elastic behavior in the anchor bolt and crushing of the sill plate until splitting occurs. It can be observed that when supplemental straps are used, splitting of the sill plate occurs at a relative displacement of 13.3 mm (0.52 in.). However, the connection still exhibits significant strength capacity (75% of maximum strength) at larger deformations due to confinement by the straps. The ultimate failure mechanism never completely develops but is in the form of the bolt crushing

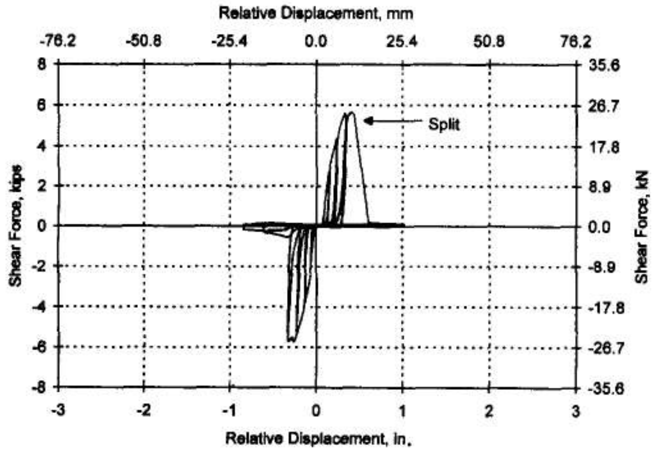

FIG. 5(a). Force-Deformation Response for Yield Mode I/II Behavior [Unconfined Sill Plate (M12N-1)]

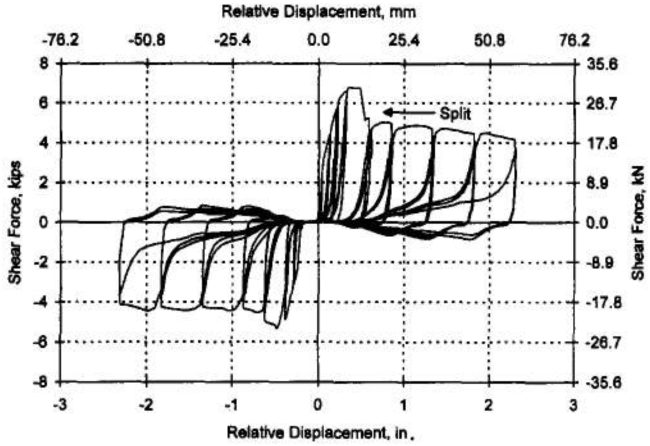

FIG. 5(b). Force-Deformation Response for Yield Mode I/II Behavior [Confined Sill Plate Using Straps (M12S4-2)]

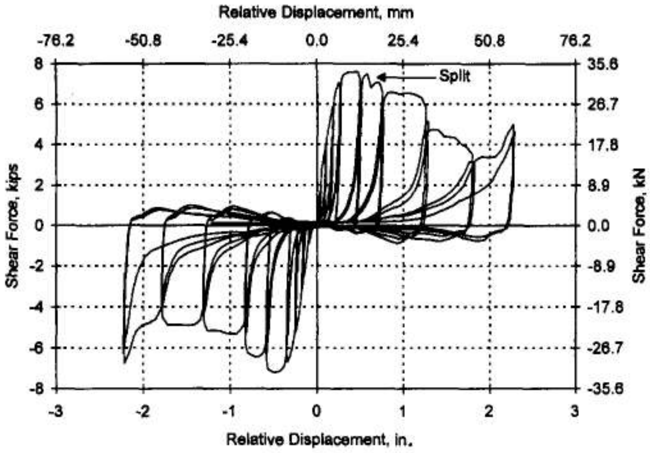

FIG. 5(c). Force-Deformation Response for Yield Mode I/II Behavior [Confined Sill Plate Using Clamp (M12C3-2)]

the wood member and forming a slot. When the special reinforcing clamp is applied, it can also be observed that significant improvements in deformation capability result and complete loss in strength does not occur. It is interesting to note that when relative displacement demands approach 50.8 mm (2 in.) the strength of the connection increases due to the bolt bearing on the reinforcing clamp [the clamp had a total slot length of 101.6 mm (4 in.)].

To evaluate the problems associated with end distances of anchor bolts, Fig. 6 shows the response of a sill plate connection using supplemental reinforcing straps at 101.6 mm (4 in.) centers (M12S4-4) having an initial yield mode I/II behavior and an end distance of 203.2 mm (8 in.). The NDS (*National* 1991) requires the minimum end distance for anchor bolts to be seven times the diameter of the bolt or 155.6 mm (6.1 in.) for a 22.2 mm (0.875 in.) bolt diameter, in order to ensure full design load capacity of the connection. It can be observed on the shorter end distance side that no strength capacity exists when displacements exceed 16.6 mm (0.65 in.) due to a shear wedge forming in the sill plate. However, on the longer side, significant strength exists to large deformations due to the confinement by the metal straps. Therefore, when end distances according to current codes are used, shear wedge failures can result during large deformation demands. However, complete loss in strength from wedge failures may not occur in the field due to bearing support from an adjacent sill plate. It should also be mentioned that wedge failures were not observed when the special reinforcing clamps were used due to added splitting resistance provided by the helically threaded nails.

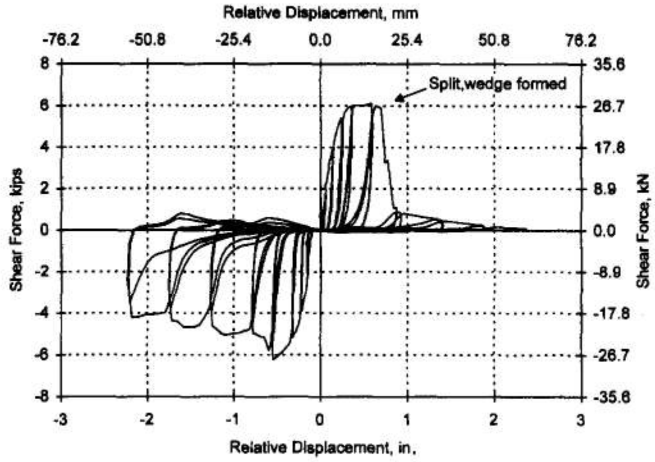

FIG. 6. Force-Deformation Response Governed by Shear Wedge Failure (M12S4-4)

A comparison of the energy dissipation histories (cumulative area under loading curve) from the previous component tests exhibiting mode III/IV and I/II behaviors is shown in Figs. 7 and 8, respectively. It can be observed that significant increases in energy dissipation capability occur when reinforcing straps are applied (180% for mode III/IV and 700% for mode I/II connection behaviors), and even better characteristics result when the reinforcing clamp is applied to the sill plate (230% for mode III/IV and 880% for mode I/II connection behaviors). The impact of using confinement of sill plates

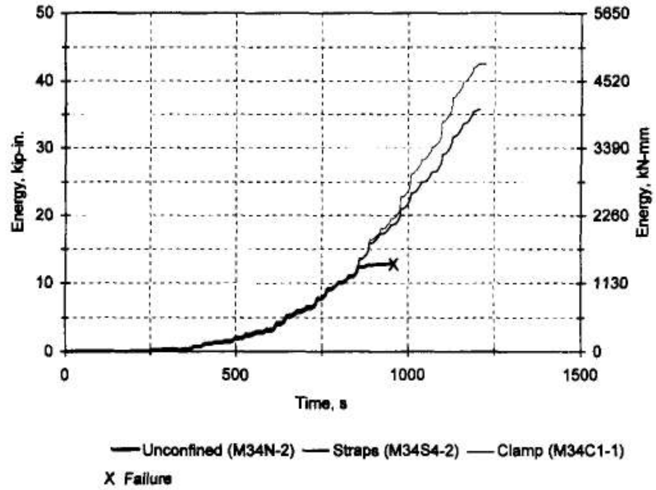

FIG. 7. Energy Dissipation History for Yield Mode III/IV Behavior

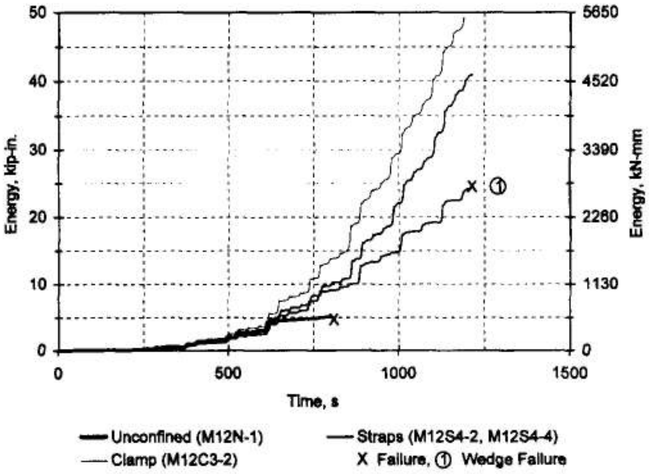

FIG. 8. Energy Dissipation History for Yield Mode I/II Behavior

for improved connection performance is clearly evident when the connection response is governed by strong bolt performance (mode I/II) when the brittle splitting of the sill plate occurs at relatively low deformation levels. It is again interesting to note that the strapped connection that developed a shear wedge near the end of the sill plate has improved energy dissipation capability compared to the unconfined sill plate (370%), but considerably less capability compared to the clamped connection (50%). However, it is obvious that the enhanced energy dissipation capability of all retrofit connections can be utilized to effectively resist input energy from severe lateral loading due to earthquakes and hurricanes.

Regarding the assumption that the bearing strength of concrete can be represented by double 2 × 6 members (*National* 1991), the experimental testing revealed some crushing in the double 2 × 6 members. In some tests (specimens M12N-2, M12S4-3, M12C2-1, M12C2-2, and M12C3-1), splitting failure occurs in these wood members and results in a void test (see Table 2). It has also been reported (Vintzeleou and Tassios 1986) that the dowel bearing strength of concrete may be as much as five times the compressive strength, which is significantly larger than that suggested by using the double 2 × 6 wood members. Therefore, further testing is required to better model connections with reinforced concrete and/or masonry foundations.

CONCLUSIONS

The experimental study described herein provides insight into the seismic response performance of 2× dimension lumber sill plate-to-concrete foundation connections detailed according to current model building codes. In addition, the response performance of retrofit sill plate connections, based on providing confinement to the wood member using supplemental reinforcing straps and clamps, is presented. It can be summarized that (1) in unreinforced sill plate connections, connection behavior at the yield limit state resembled that predicted by the NDS (*National* 1991) for specimens governed by both modes I/II and III/IV response. However, in both cases at the ultimate limit state, sill plate connections typically failed by brittle splitting along the grain of the wood member due to the prying action of the bolt during lateral deformations. This type of failure mechanism in sill plate connections has been observed during past earthquakes; and that (2) in retrofit sill plate connections, the supplemental confinement of the wood member provided by the reinforcing straps and clamps improved the deformation capability and energy dissipation capacity of the connection, while maintaining substantial levels of lateral strength. By deterring brittle splitting in the sill plate, the hysteretic response (postyield behavior) of the connection is significantly improved for both yield modes I/II (strong bolt) and III/IV (strong sill plate) type behavior to better resist seismic excitation loads. The retrofit alternative using reinforcing clamps seems to provide the most desirable response behavior in the connection with the greatest energy dissipation capacity. Retrofit of existing sill plate connections can easily be performed and can be economically justified based upon the significant improvement in connection response performance during earthquakes. The concept and application of confinement of wood sill plates using reinforcing clamps and straps can also be applied to new wood frame construction for better connection response performance.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

P_{max} = maximum lateral strength of connection;
P_y = yield lateral strength of connection;
δ_{max} = relative lateral displacement of connection at maximum lateral strength;
δ_{split} = relative lateral displacement of connection at splitting of wood member;
δ_{ult} = relative lateral displacement of connection at failure;
δ_y = relative lateral displacement of connection at yield lateral strength;
ΣE_{tot} = cumulative energy dissipation history; and
$P_{y,anal}$ = yield lateral strength based on published yield limit calculations (*National* 1991).