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STRUCTURAL PERFORMANCE OF SHELF ANGLE FOR BRICK MASONRY VENEER USED IN WOOD-FRAMED BUILDING

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ABSTRACT

In Canada, clay brick veneers are often used to protect residential, commercial, and institutional buildings from external weather, thermal, and noise conditions, while allowing the building to maintain a pleasant architectural appearance. Wood-framed loadbearing structural systems are increasingly paired with this kind of brick veneer wall. However, these brick veneers often utilize a steel angle, known as shelf angle, attached to the rim boards of the wood framing floor system as a means to support the brick veneer. The through-bolts, commonly used for this type of connection, pose a problem in terms of thermal efficiency, as they must penetrate through the wood framing envelope. To overcome this problem, lag screws have been introduced to replace the through-bolts. However, there is very limited test data available for designing the shelf angle and spacing of lag screws for various wood framing systems. Hence, an experimental study has been completed to determine the structural interaction between a wood flooring system and the shelf angles that connect the rim boards to the brick veneer using lag screws and through-bolts as fasteners. The displacement of the connection subjected to vertical loads of brick veneer, stiffness, rotation of the rim board, and failure modes of the lag screw and through-bolt connection were investigated. This paper presents the test specimens, test procedures, and results obtained from this study.

KEYWORDS: *experimental testing, lag screw, shelf angle, through-bolt*

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INTRODUCTION

Clay brick veneers are an aesthetical pleasing and energy efficient system used in Canada for cladding many residential, commercial, and institutional buildings. The self-weight of the brick veneer in this type of cladding is supported by a steel shelf angle, which is anchored to the buildings structure at floor level when the height of the veneer exceeds 3-storeys. However, utilization of these shelf angles causes significant decrease in the overall thermal performance of the building envelopes, as the bottom leg of the shelf angle has to cut through the exterior insulation. This mere ½ in. (~12 mm) gap in the thermal insulation can result in the reduction of the thermal resistance of the insulation barrier in the order of 30% to 50% [1].

Traditionally, these shelf angles have been anchored to the rim boards of the wood-framed floor system using through-bolts. However, the through-bolts pose a problem in terms of thermal efficiency, as the bolts have to penetrate through the building envelope and are difficult to install. A potential solution to address this issue is to implement the use of lag screws. However, there is very limited test data available for anchoring the shelf angle using lag crews for various wood framing systems. Therefore, an initial experimental study was conducted to analyze the structural behavior of lag screw connection and compare that with through-bolt connection. As well, the results of this study were compared to an earlier study completed at the University of Alberta [2] where the lag screws in similar configuration were connected to a 3-ply, 2x12 in. (~ 50 mm x 305 mm) Laminated Veneer Lumber (LVL) rim board. In the current study, Spruce-Pine-Fir (SPF) rim board instead of LVL board was used.

SPECIMEN DETAILS

The feasibility of lag screws as an alternative to through-bolts was investigated using a specimen which was built in the same fashion as specimens tested at the University of Alberta [2]. The specimen replicates a typical wood-frame floor system commonly found in Canadian residential construction (Figure 1). The specimen spanned 56 in. (1,422 mm) in the direction of the shelf angle and spanned 56 in. (1,422 mm) in the direction of the joists. The total height of the specimen was 17 1/8 in (435 mm). TJI (Trus Joist I) 11 7/8 in. (~302 mm) was anchored to the SPF rim board using 3 1/4 in. (~83 mm) strip nails. Oriented Strand Board (OSB) sheathing tongue and grooved ¾ in. (19 mm) was attached on top of the TJIs and SPF rim board assembly using subfloor glue and nails. Furthermore, external 3/8 in. (10 mm) OSB was attached to the outer surface of SPF rim boards.

Steel angles 4 in. x 4in. x 1/4 in. (~102 mm x 102 mm x 6.4 mm) were anchored to each end of the specimen using two different types of fasteners: ½ in. (~12 mm) diameter and 6 in. (152.4 mm) long through-bolts and 5/8 in. (~16 mm) diameter and 4 in. (101.6 mm) long lag screws. This was done to draw a direct comparison between them without any variation in quality of craftsmanship and materials. Both the fasteners were spaced at 12 in. o.c. (on center). The connectors were installed at the center of the SPF rim boards and 1 ½ in. (~38mm) from the top edge of the shelf angle's vertical leg. Through-bolts were installed by drilling holes into the external OSB and SPF rim boards and lag screws were installed by drilling pilot holes of 5/16 in (~8 mm) using a rotary drill. Since the through bolts penetrated through the rim board system, the embedment length of through bolt was 4.5 in. (114.3 mm) and the embedment length of 4 in. (101 mm) lag screws was 3.12 in. (79.4 mm) (excluding the length of tip of the lag screw).

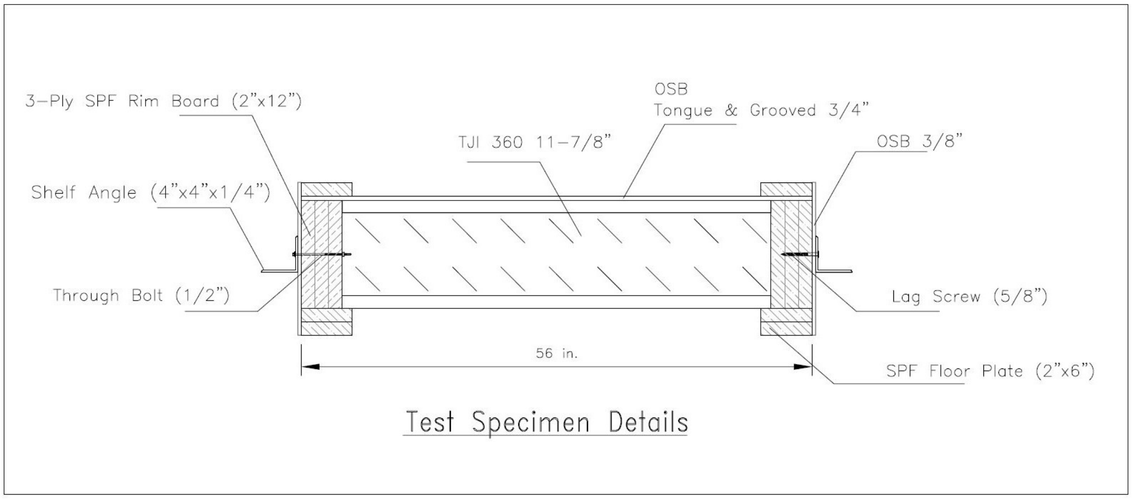

Figure 1: Test Specimen

The weight of the brick veneer was simulated by applying an axial load to the shelf angle attached to the floor specimen. The loading continued until a complete failure was achieved. A hydraulic loading actuator of 500 kN capacity was used to apply the axial load on the shelf angle. Gravity load on the rim board was also applied using distributed heavy steel blocks. The gravity load represented the floor load acting on the wood studs of the support wall on the edge of the floor system from a roof load only. This helped in preventing rotation of rim boards. The load on the shelf angle was applied using a steel loading truss made using 5 in. (~126 mm) x 3 in. x 1/4 in. (~127 mm x 76 mm x 6.4 m) HSS sections as shown in Figure 2 to simulate a uniformly distributed load on the shelf angle due to the self-weight of the brick cladding. The base of HSS section was welded to a 3 1/2 in. (~89 mm) wide plate to imitate the load applied by a 3 1/2 in. (~89 mm) wide brick veneer. To prevent the overturning of the specimen during testing, the specimen was strapped at the strong floor as shown in Figure 3.

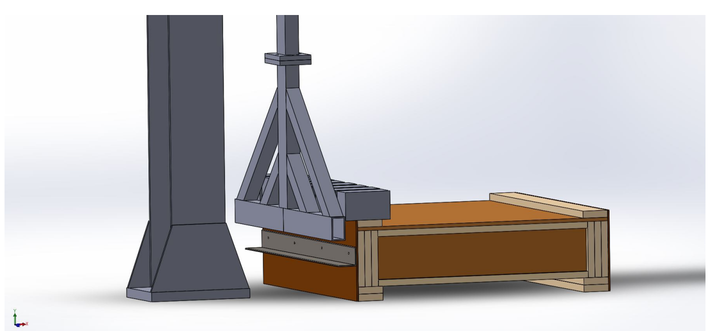

Figure 2: Experimental Set-up

INSTRUMENTATION

A loading actuator was used to apply uniformly distributed axial load on the shelf angle. Load cells attached to the loading actuator measured the load applied. A total of three linear variable differential transformer (LVDTs) were used to measure the vertical deflections at various locations at the underneath of the shelf angle. Two LVDTs were used to capture the vertical deflection of the shelf angle, one at the mid-span and one at the end. One LVDT was also attached perpendicular to the shelf angle at the distance of 3 ¼ in. (~83 mm) from the heel of the shelf angle to measure horizontal displacement of the vertical leg of the shelf angle. The values obtained from this LVDT was used to determine the rotation of the shelf angle. All the experimentation data was collected using a computerized data acquisition system connected to all the instruments. A camera was positioned at each end of the specimen to capture and understand the failure mechanism.

Figure 3: (a) Application of axial and gravity loads, (b) Straps used for anchoring the specimen

LOADING PROTOCOL

Entire loading was done in three different steps. In first step of loading, the specimen was subjected to a cyclic load which was applied onto the shelf angle. The maximum load applied in this cycle simulated the service load of 10 ft. (~3050 mm) high clay brick cladding that is 5 kN per meter length of the cladding or shelf angle. In the next step, another cyclic load with the maximum load of 8 kN per meter length of the brick cladding was applied and this load simulated factored or design load on the shelf angle. In the third and final loading step, the specimen was loaded to failure. The axial load was applied at 1 in. (~25 mm) away from the exterior sheathing, to account for requirements in the Alberta Building Code (2019) [3] specifying a minimum airspace of 1 in. for brick veneer over wood framing. The loading rate was maintained at approximately 1 kN per minute. A schematic sketch of the loading protocol is shown in Figure 4.

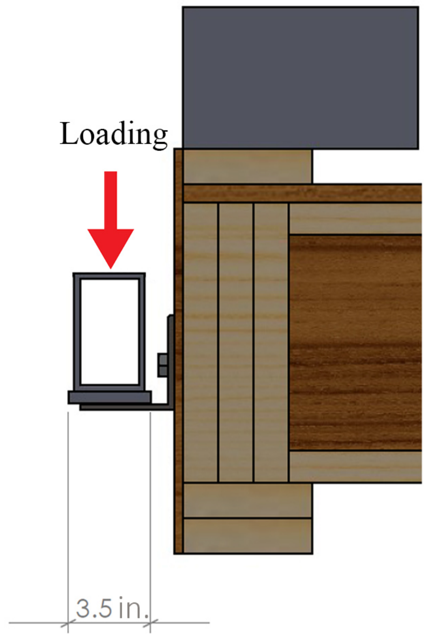

Figure 4: Loading Protocol

RESULTS AND DISCUSSION

The load-displacement and load-rotation behaviors obtained from two tests are shown in Figures 5 and 6, respectively. Figure 5(a) shows the entire history of the relationship for the mid-span deflection of the shelf angle and the load applied on the shelf angle. The cyclic responses in loading steps 1 and 2 are omitted for the clarity. Figure 5b shows only first two steps (cyclic loadings) histories.

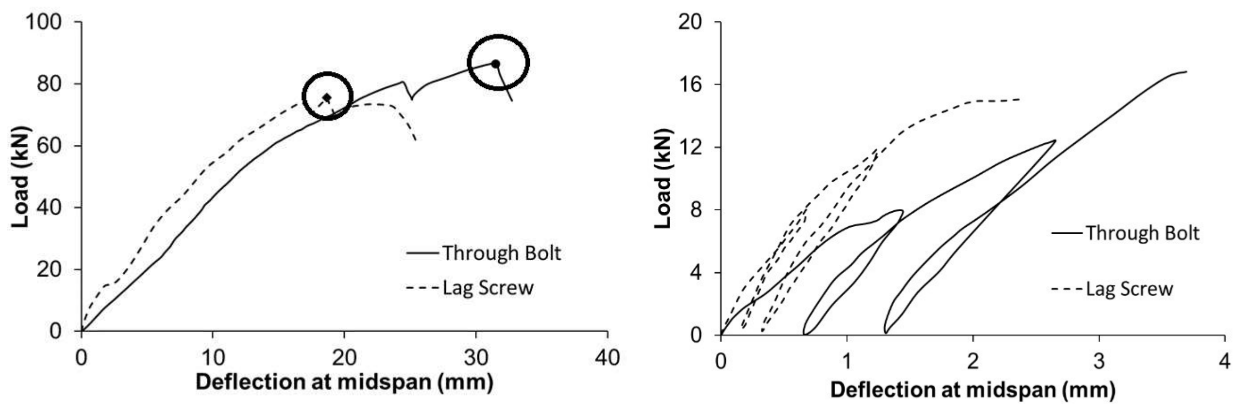

Figure 5: (a) Entire load-deflection relationships, (b) Cyclic load-deflection relationships

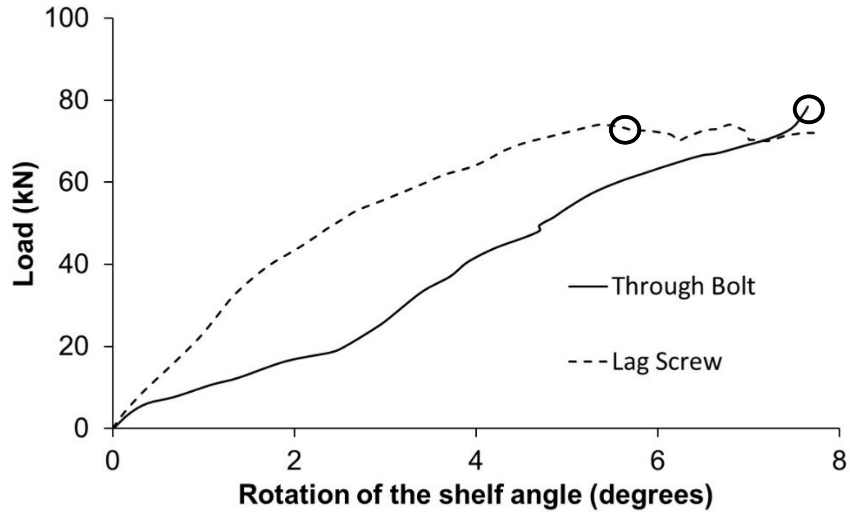

Figure 6: Load-rotation behaviors of the shelf angle

Specimen 1 with Lag Screws

The service and design loads for this specimen are 5 kN/m and 8 kN/m, respectively. However, the first sign of obvious failure was observed at about 63 kN (44.3 kN/m) which is more than five times of the design load (8 kN/m). The exterior most rim board began developing crack at this load and the crack propagated to the center ply of the rim board when the load reached about 69 kN (48.5 kN/m). It should be noted that the rim board had 3 plies (see Figures 1 and 2). Interestingly, the crack propagated only up to the embedment length of the lag screw (see Figure 7(a)). It is obvious that the gravity loads applied on the rim board helped preventing the rim boards from rotating, and the failure was due to the perpendicular-to-grain splitting of the rim board (SPF).

The lag screw connection exhibited the maximum load capacity of 75.5 kN or 53 kN per meter length and at that load, a mid-span deflection of 18.6 mm was recorded (shown by an open circle in Figure 5(a)). At this stage the rotation of the shelf angle was 5.6 degrees as shown by an open circle in Figure 6. The loading process continued until when the load dropped to about 60 kN when the mid-span deflection was 27 mm (see Figure 5a) and the rotation was 7.7 degrees (see Figure 6). The failure of the specimen made with lag screw (specimen 1) was due to the splitting of the rim board and this is shown in Figure 7(a). It is worth noting that according to the design recommendations of the Canadian wood design standard (CSA O86) [4], it was anticipated that the mode of failure for the specimen built with lag screws (specimen1) would be due to the withdrawal or shear of the lag screws at an axial load of 15-25 kN. Hence, this study shows that the recommendation of Canadian standard, CSAO86 are over-conservative and prediction of failure mode by this standard is incorrect.

Specimen 2 with Through-bolts

The test specimen with through-bolts (specimen 2) showed a slightly higher load capacity of 86 kN (60.5 kN/m) as shown by an open circle in Figure 5(a). However, the first sign of failure was observed at about 52 kN (36.5 kN/m) which is much higher than the design load of 8 kN/m. Thus, first obvious sign of failure in this specimen (specimen 2) was observed a bit earlier than the specimen 1. At this load (52 kN or 36.5 kN/m), the exterior rim board began to split. It was further observed that the center rim board (the middle ply) began to split at 62 kN (43.6 kN/m). Unlike specimen 1, the splitting in specimen 2 propagated to the interior ply of the rim board (thus all three plies of the rim board developed the crack) and it occurred at a load of about 83 kN (53.4 kN/m). The higher capacity obtained from specimen 2 (built with through bolts) can be attributed to the fact that the through-bolts were embedded into the all three plies of the SPF rim board assembly and hence, all three plies contributed in load sharing. Nonetheless, like specimen 1 (built with lag screws), the failure in specimen 2 (built with through-bolts) was also due to perpendicular-to-grain splitting of the rim board.

The shelf angle experienced a deflection of 32.5 mm when the specimen exhibited the maximum load carrying capacity (see Figure 5(a) and it is shown by an open circle). The reason for this larger deflection can be attributed to the fact that all three plies of the rim board system in specimen 2 were engaged, however, for specimen 1 (built with lag screws) only two plies of the rim board were probably engaged in load sharing. The maximum rotation for specimen 2 was found to be 7.6 degrees (shown by an open circle in Figure 6). The splitting of the rim board is shown in Figure 7(b).

Figure 7: Splitting failure of the specimens built using (a) lag screws and (b) through-bolts

COMPARISON WITH LVL RIM BOARD TESTING

Identical specimens built using LVL (Laminated Veneer Lumber) rim board were tested at the University of Alberta [2]. However, only lag screws were investigated, and the experiments when the lag screws were spaced at 12 in. (~305 mm) spacing o.c. are compared here. In the tests conducted by Pettit et al, identical shelf angles (4 in. x 4 in. x 1/4 in. or ~102 mm x 102 mm x 6.4 mm) were used. The ultimate failure loads observed from two tests completed at the University of Alberta were 83 kN (58.4 kN/m) and 94 kN (66.1 kN/m). The failure mode in that study (previous study) was the separation of the TJIs from the rim boards. This is a completely different failure mode than the one observed at the University of Windsor (current study). Further, the location of the OSB flooring seam also played a significant role in the failure of the specimen tested at the University of Alberta. This difference could be because of different wood materials used: LVL rim board system used in the University of Alberta's tests and SPF rim board system used in the University of Windsor's tests. Table 1 summarizes the key test data obtained from the tests conducted at the University of Alberta and the University of Windsor.

Table 1: Comparison of the structural performance of shelf angle anchored to SPF and LVL rim boards

Rim board	**3-ply SPF**		**3-ply LVL**	
Fastener Type	Lag screw	Through-bolt	Lag screw	Lag screw
Fastener Diameter (in.)	5/8	1/2	5/8	5/8
Fastener Spacing (in.)	12	12	12	12
Failure Load (kN)	75.5	86	83	94
Deflection at 8 kN (mm)	0.7	1.4	3.5	2
Deflection at 12 kN (mm)	1.24	2.5	5.1	3.7
Deflection at Failure (mm)	18.6	32.5	15.5	16

SAP 2000 MODEL OF THE SHELF ANGLE

A simplified shell element model was created to determine how accurately a typical structural analysis software package, SAP2000 [5] would predict the deflection of the shelf angle. Pinned connection at 1 1/2 in. (~38 mm) from the top edge of the angle was used to replicate the lag screw and through-bolt connection. The loading applied were a total of 12 kN, and the maximum failures of 75.5 kN and 86 kN respectively. Figure 8 shows the SAP model.

Table 2: Comparison of Experimental Results with SAP 2000 Model

	3-ply SPF		**SAP 2000**	
Fastener Type	Lag screw	Through Bolt	Pinned	Pinned
Failure Load (kN)	75.5	86	75.5	86
Deflection at 8 kN (mm)	0.7	1.4	0.18	0.18
Deflection at 12 kN (mm)	1.24	2.5	0.16	0.16
Deflection at Failure (mm)	18.6	32.5	1.46	1.71

There is a significant difference in the deflection values of the shelf angle predicted by the SAP2000 model, as can be seen in Table 2. This could be due to the fact that other material properties such as wood and lag screw and the interactions between them were not considered in the SAP 2000 model.

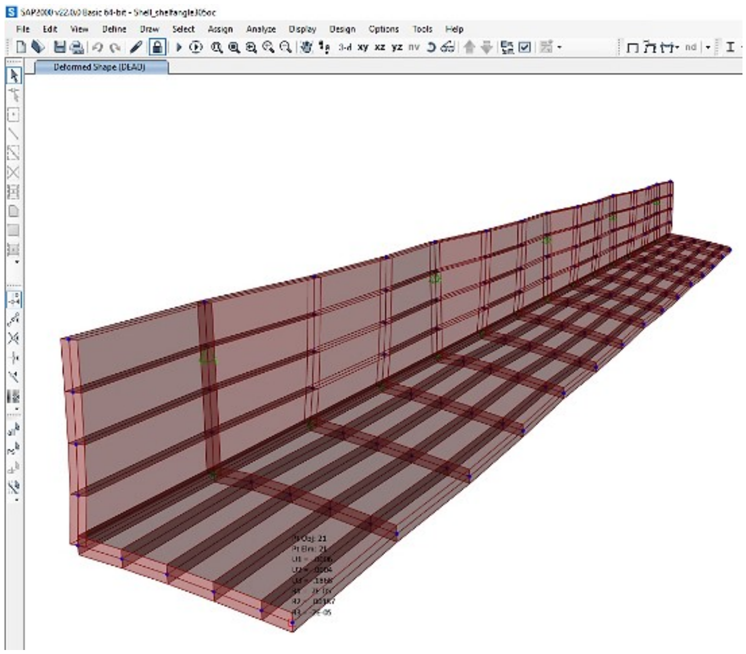

Figure 8: SAP 2000 model of the shelf angle

CONCLUSIONS

The primary objective of the current study conducted at the University of Windsor was to determine the structural performance of lag screws as an alternative to through-bolts for anchoring shelf angle to wood-frame structure in multi-storey residential buildings. To achieve this, a floor assembly was constructed, and the shelf angle was subjected to an axial load expected from the brick veneer. The test information such as failure load of the system, failure mode, and response of the shelf angle were obtained and analyzed. This information is presented in this paper. The study found the both lag screw and through-bolts are able to withstand the design load and the failure loads were 75.5 kN and 86 kN, respectively which are much higher than the service load of 8 kN (5 kN/m) and design (factored) load of 12 kN (8 kN/m). Final failure mode in both the specimens was the splitting of the rim boards (SPF). Propagation of splitting depended on the embedded length of the fastener used.

This study concludes that the lag screws can serve as a potential alternative to the through-bolts in anchoring shelf angles to wood-frame structures while using 3-ply SPF rim board system. Comparing the test results obtained by the University of Alberta and test results obtained in this study at the University of Windsor, it can be concluded that the failure mode of the specimen differs if LVL rim board systems are used. However, the capacity of the shelf angle built with lag screws with LVL rim board system (tested at the University of Alberta) was about 17% higher than that of the specimen that used SPF rim board system (tested at the University of Windsor).

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REFERENCES

[1] Finch, Graham, Michael Wilson, and James Higgins. 2013. "Thermal Bridging of Masonry Veneer Claddings and Energy Code Compliance." 12th Canadian Masonry Symposium.

[2] Pettit, Clayton, Jesus Salazar, Carlos Cruz-Noguez, and Mark Hagel. 2019. "Experimental Determination of the Behavior of Lag Screws in Masonry Veneer Shelf Angles." In 13th North American Masonry Conference, The Masonry Society, 1757–68.

[3] Alberta Building Code. 2019. National Building Code - 2019 Alberta Edition, National Research Council of Canada. Ottawa, Ontario, Canada.

[4] CSA O86-14 (R 2019), Engineering Design in Wood, Canadian Wood Council, Ottawa, Ontario, Canada

[5] CSI, SAP2000, Analysis Reference Manuals, Computers and Structures, Inc, Walnut Creek, California USHA 2020.