Development of a Seismic Connection System for Post and Beam Construction

By

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Abstract

In recent years, the Japanese housing industry has been focusing on improving the seismic response of light wood-framed residential buildings. The purpose of this project was to design a connection system for light wood-frame walls that improved upon the seismic response of the current Japanese post and beam shear wall. The results demonstrated that the system outperformed the traditional Japanese connection system as it provided additional strength and superior energy dissipation properties. This connection system is comprised of a steel connector that connects the diagonal brace to the column and sill/header and provides an enclosed support for the end of the brace. Moreover, the column is connected to sill/header using a steel L-bracket and two double-threaded lag screws. The two latter components proved to be the more effective part of the system in tensile loadin
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1.0 Introduction

Among of the 193 countries in the world, Japan typically receives more that 10% of the earthquakes or seismic events annually. Currently, Japan is experiencing a growth in its suburbs with a corresponding increase in the construction of two and three storey wood framed, single-family dwellings. These facts, coupled with a generally high population density, have created a need for improvements in the current construction methods with respect to the seismic response of the post and beam wood frame structures.

The purpose of this project was to design a connection system that improved upon the seismic response of the current Japanese post and beam shear wall, which could potentially reduce or delay failure of new homes minimizing loss of life and damage to the structure. Central to this goal was the design, construction, and testing of a connection system that had enough strength and stiffness to resist the ground motions also in addition to adequate ductility to dissipate the energy introduced by seismic thrust. This objective was accomplished by integrating traditional and newly designed timber connections to arrive at a solution that met the stated requirements as well as improving upon the construction practices and manufacturing costs. This report takes an in depth look into the design, construction, and testing phases of the connection system in addition to providing a detailed analysis of the test results.
2.0 Construction Techniques

The North American construction industry primarily uses planar, platform construction for residential housing (Wood Design, 2002). Small, closely placed members allow flexibility in design, ease of installation, and strength from load sharing and the integration of the primary framing structure and the secondary sheathing material. Load bearing walls are created by increasing the conventional, interior wall framing member dimensions from 38 x 89mm to 38 x 140mm.

Post and Beam construction, a technique that has existed for hundreds of years, is not as common in the North American market as it is reserved for larger buildings or were the wood members are left exposed for aesthetic purposes. Known for its enlarged members that are arranged farther apart than those used in planar construction, post and beam construction does not integrate primary and secondary members. Sheathing is applied to the primary structure to provide a barrier of the interior and exterior environments only but serves no purpose in adding strength to the structure. Where members are connected together using nails, bolts, and a variety of intermediate connectors in planar construction, they have traditionally been connected using mortise and tenon joints in post and beam (Whittaker et. al., 1997). Intricate in its implementation, mortise and tenon joints require a great deal of labour and precision fitting (Hunt, 2003). This has and continues to be the construction technique of choice in the Japanese market and is illustrated in Figure 1. (Whittaker et. al., 1997).
Figure 1. Current Japanese post and beam construction layout.

Large 2460 x 105 x 105mm Hemlock-Fir (Hem-Fir) columns are spaced 910mm apart on center, span between the 105 x 105mm header and sill, and constitute the primary structure of a post and beam building. Spaced mid-span between the columns, 150 x 30mm vertical members made of Hem-Fir called Mabashira provide additional mounting for sheathing. Spanning from the end of one column to the opposite end of the next column in a typical, reversing arrangement similar to roofing trusses, 90 x 45mm diagonal bracing members are also employed: something not required in planar construction due to the close spacing of structural members (Jossen, 2003). The ends of the braces are cut to match the profile of the column and sill/header.
3.0 Current Seismic System

Mortise and tenon detailing is commonly used to connect the column and sill/header in post and beam construction. Various steel gusset plates are installed at these connection joints to ensure the stability of the structure during loading. Depending on the presence of the brace at the joint, different plates are installed. Where a brace is present a “BP” plate connects the brace to the column and the sill/header. In addition, a “VP” plate is installed at the joint of the column and sill/header. At joints without a brace present, only a single t-shaped “CP-T” plate is installed connecting the column to the sill/header. These plates, shown in Figure 2, come predrilled for nail placement and include guide marks for proper alignment at the joint.

Figure 2. Placement of the BP, VP, and CP-T gusset plates currently used in Japanese construction.
An additional hold-down device is required to connect the frame to the foundation. Mounting to the inside of the column, a large, expensive steel connector is connected to a threaded steel rod that is fixed to the foundation.

Previous experiments of this connection system had been conducted using full wall-frames. These frames were analysed to observe the state of the frame after it had been subjected to seismic loading and identify the modes of failure. Where BP and VP plates had been installed, significant wood cracking had occurred along the horizontal plane of the sill and header, specifically along the bottom row of nails that were used to install these connectors. These plates along with the CP-T plate were bent out of the plane of the wall resulting in nail withdrawal. From the disfigurement of the connectors it was apparent that the column uplift had occurred during loading; an event that leads to the destruction of building services such as electrical, plumbing, and gas pipelines. The resulting wall frame would not be suitable for future use due to the reduced capacity to transfer loads and therefore requires replacement in the structure. Being a timely and costly construction technique, more research should be conducted in this area.
4.0 Investigating the Alternatives

Several alternatives have been proposed to prevent or reduce the affect of failures associated with the current connection system used in Japanese post and beam construction. As British Columbia is a major exporter of wood, The University of British Columbia (UBC) has been involved with several experiments in this field. One particular study by Georg Finklestein looked at the implementation of steel L-brackets connecting the column to the sill/header. Using a sub-section of the wall-frame, several tests were conducted with a proposed L-bracket design. In his report “Earthquake Resistant Connections for Post and Beam Timber Construction” he showed that by installing the L-bracket at the non-critical joints (joints without the presence of the brace) the resistance of the structure would improve over the use of the CP-T connector used in the Japanese connection system. Both monotonic (pure tension) and cyclic (load reversing) tests confirmed this result (Finklestein, 1999). Finklestein observed that the L-bracket had to be installed on both sides of the column to be effective, an arrangement that is not possible on the end column of a wall.

An experimental connection design was developed by a graduate student at UBC by the name of Didier Jossen. Jossen’s proposed connector mated the column, sill/header, and brace with a single piece of steel. Observing the resulting full wall-frames from the various tests that were performed made it easy to identify several problems in the design. His connector can be envisioned as the combination of an L-bracket that mounts to the column and sill/header, extends up the column, and ends in a shoe or cup that allows the brace to “slip in” as it is forced against a back plate and surrounded on two sides. The fact that the brace was not surrounded on all four sides would be detrimental to the performance of the connector. The wall-frames showed severe cracking of the brace where the connector was attached. By not surrounding the brace
completely, the connector couldn’t provide resistance against the moment applied to the brace during loading. Therefore the brace was able to rotate, caused stress perpendicular to the grain, and resulted in cracking and reduced performance. To allow the brace to “slip in” the length of the diagonal brace member had to be shortened thereby creating a gap between the brace and the column-to-sill/header joint. This gap meant that upon compression of the brace, the brace had to move the distance of the gap before the column and sill/header provided resistance against the brace. Moving this distance required the shoe part of the connector to rotate resulting in rotation of the brace and the application of stress in the brace perpendicular to the grain. Also of notable mention, was the fact that the connector was deformed at the column-to-sill/header joint indicating that column uplift had occurred.

Jossen conducted both monotonic and cyclic testing according to industry standards on full wall-frames and determined that the force applied to the column was 0.76 times the force applied to the brace. The results from his tested showed his connection system to have the same capacity, four times as much energy dissipation, but twice the displacement over the Japanese system (Jossen, 2003). This made it apparent that Jossen’s design provided improved resistance against seismic loading over the traditional Japanese system and therefore served as the basis for this project.
5.0 Design Analysis and Progression

Guidelines for the project were decided according to performance, practical, economic, and manufacturing factors in a priority sequence. At the forefront of these design considerations, the resulting connection system had to perform better than the current Japanese connection system in delaying failure of the structure to be effective and worth producing. Focusing on the development of a primary connector that would work together with other less critical components of the connection system, proper sizing and efficient use of material for the connector were key considerations as current connectors that are large and heavy even though effective are not used for these reasons. To reduce the resistance of the Japanese construction industry towards the use of the connector, it was decided that the connector be made of common 1018 16-gauge steel. Steel is a material that is abundant, malleable, inexpensive, easy to manufacture, strong, and currently in use by the construction industry. In addition, the time constraints of the project prevented a thorough material selection process to be undertaken.

Considering the placement of the connector in the wall-frame at the design stage of the project, the connector was to require minimal time, labour, and equipment to install. With the current Japanese connection system, the gussets are attached to the sides of the column and sill/header. The sheathing that is applied to the structure must be modified to account for the presence of the gussets. Concealing the connector within the 105mm width of the framing was therefore a design parameter. Other advantageous goals were to simplify the manufacture of the connector as much as possible to reduce the costs associated with manufacturing. Creating a retrofitable design that can be implemented in currently built structures was also considered.

5.1 From Conceptual to Physical
Researching construction techniques, building codes, and existing or proposed connection systems provided the backbone of the project. From several brainstorming sessions with team members and professionals familiar with the Japanese construction industry, several preliminary designs for the connector were created. Applying the conceptual design parameters reduced the list of possible designs and scale models served as a means to visually analyse the designs and apply modifications. A two-piece design resulted with a base section that connected to the column and sill/header and provided an open channel with one closed end to contain the brace, and a cap plate that connected to the base and provided the important forth side of the connector that would fully contain the brace (that which was missing from Jossen’s design). The base section was to be formed from a single piece of steel that underwent a series of bends and drilling operations whereas the cap plate was only a flat piece of steel with the necessary attachment holes drilled. Figure 3 provides an example.

**Figure 3.** A version of the base (right) and cap plate (left) arrangement surrounding the diagonal brace (center).
To achieve adequate performance of the structural wall system when the diagonal is being loaded in compression, it was stressed that the diagonal brace should have a solid connection to the sill. In current Japanese post and beam construction the brace would bear on the column horizontally and the sill vertically. Although this arrangement provides good energy transfer, removing the necessity for a detailed end of the brace and employing a straight crosscut would reduce the amount of work required to install the brace and connection system. Therefore a strong, flat surface would have to provide a bearing surface for the end of the brace. With installation complexity in mind, the dimensions of the sections of the brace that connect to the column and sill/header and the type of attachment (bolt or lag screw) were estimated to allow construction equipment, such as high-speed drills, to be used.

5.2 Sectional Analysis

Each attachment point for the connector was analysed for wood and steel failure and redesigned if necessary to provide adequate resistance. Analysis was based on seismic forces recorded during the Kobe earthquake, an event that is considered a baseline for seismic analysis (Finklestein, 1999). Therefore analysis was performed estimating a 25kN force in the brace and 19kN in the column (25kN x 0.76 = 19kN as per Jossen). It was determined that 3/8” lag screws would be suitable to connect the connector to the column and sill/header and that the steel base would not fail at these locations. The width of the base was hereby determined to be 45mm to prevent steel failure.
Analysis of the vertical loading on the connector revealed that the design was unable to resist column uplift. From the accounts of Finklestein’s experiments, an L-bracket was designed and included as part of the connection system: the attachment locations of the lag screws into the sill were too far from the column. An L-bracket was formed from a 120mm long piece of 14-gauge steel that was bend mid-span and attached at the joint of the column and sill/header. Using the same 3/8” lag screws to reduce installation complexity, the locations of these attachments were much closer to the column and thereby reduced the moment arm. Calculations showed that the factor of safety of the connection system doubled from 0.69 to 1.2 with the inclusion of the L-bracket. The width of the L-bracket was determined to be the width of the wall (105mm) minus the width required for the connector: 60mm.

For the section of the base adjacent to the sill the factor of safety was determined to be 0.9 without the L-bracket installed. Using the L-bracket, the factor of safety increased to a more suitable 1.6. The factor of safety for the section of the base adjacent to the column was found to be 2.1 without the presence of the L-Bracket therefore modification were unnecessary. These results indicated that the steel would not fail under bending when the maximum design load was applied. Analysis was conducted to determine the maximum force at which the steel would fail under bearing stress. The factor of safety for the attachment to sill was calculated to be 1.3 however the calculations showed that the factor of safety for the attachment to the column was 0.38 even after taking into account the effect of the L-bracket. This result indicated that the steel would most likely fail under bearing stress. Increasing the factor of safety could be accomplished by using thick washers in between the bolt head and the metal. Buckling analysis concluded that the member would not fail due to bucking under the maximum design load.
The attachment method for the cap plate had to be able to transfer load from the brace to the connector during tensile loading. Through the consideration of various attachment methods and arrangements, such as the number of bolts per row and the number of rows, an attachment method with adequate resistance was determined using bolt and lag screw selection tables along with standardized calculations defined by the Canadian Wood Council (2002). This attachment arrangement however was very stiff and deemed very conservative through conversation with a civil engineering professional. The attachment method was reduced to 2-3/8” bolts with spacing between them, from the edge of the brace, and from the end of the brace that exceed requirements: 37.2mm, 28mm, and 96.2mm respectively (Canadian Wood Council, 2002). This spacing was partially determined through analysis of the 1.6mm thick steel that was to be used for the cap plate and base section. The minimum length of the portion of the connector that surrounded the brace was thereby determined: 133.35mm (5.25-inches). With the realization that steel deformation is preferable to wood splitting, this attachment method was implemented for the final design.

A secondary attachment method was then developed to increase the number of connections of the cap plate to the base to prevent bending and tearing of the base. Instead of the edges of the base resting flush against the side of the cap plate, a key-and-socket approach was developed where small teeth were cut along the edges of the base and installed through socket cutouts in the cap plate (see Figure 4).
Figure 4. An illustration of the key-and-socket approach.

Such an attachment method is also used in the fabrication of electrical service boxes. Steel failure analysis led to the dimensioning of the keys and sockets. The keys were 1.6mm wide (steel thickness) and 10mm long with 7mm between them while the sockets were 2.5mm wide and 11mm long with 5mm between them.
5.3 The MMA Connector Final Design Overview

With the wood and steel analysis complete, the overall dimensions and attachment methods of the connector were therefore finalized. The final design of the connector is provided in Figure 5.

**Figure 5.** The final design of the MMA connector (Mk 1).

This design requires no welding, a single size of lag screw for the connections to the column and sill/header, a single size of bolt and nut for the attachment of the cap plate to the base, and incorporates a unique key-and-socket approach for the lateral resistance of the cap plate. In addition, the diagonal brace does not have to be cut to match the column-sill corner geometry.

A revision to this design was made during testing. The location of the lag screws that attached the connector to the sill, specifically their distance from the column, resulted in significant steel bending and eventually tearing to occur (large moment arm). It was decided to install a new lag screw closer to the column, which was checked to be accessible by construction tools. Along with the introduction of washers to the lag screw connections, this altered design was deemed the Mk 1A.
6.0 Construction and Testing

Four different connection systems were built and tested. The first of these test samples used the current Japanese connection system with a mortise and tenon joint where the column meets the sill/header. This system served as the baseline from which all other systems would be judged. The next samples involved the Mk 1 MMAS connector with the same mortise and tenon joint followed by a series of samples that used the improved Mk 1A connector. Finally, two double-pitched lag screws were installed to connect the column to the sill instead of the mortise and tenon in addition to the Mk 1A connector. This connection system was named the Mk 2. Two of each test sample variation were constructed and tested. The tests associated with these various samples are respectively referred to as traditional Japanese, Mk 1, Mk 1A, and Mk 2.

6.1 Methods of Construction – Connector and L-Bracket

Normally in a mass production system the connector and L-bracket would be made on a 10-ton hydraulic press with a custom punch and die that feeds into a bender, then a paint sprayer or dipper that produces one finished part every 1 to 3 seconds. The connectors were manufactured by hand involving the following six steps:

- Cutting the connector base and cap plate out of a steel sheet
- Drilling holes for bolt and screw attachment
- Drilling small holes at the corners of future bends
- Punching the keys and sockets
- Bending the connector to its final shape
- Finishing the edges of the connector
From producing a prototype of the design, it was observed that the design did not allow adequate clearance for the cup section of the base to be bent to the correct position. The amount of “bounce back” of the steel during the bending operation was an unforeseen problem. The design was therefore modified by removing more material along with bottom edges of the cup section of the base to account for bounce back.

The holes required for the attachment of bolts or lag screws were drilled 1/16” larger than the required diameter to ease installation. In addition, small 3/16” holes were drilled at specific locations to ease the alignment procedure during bending.

A 2-ton manual press was originally used installed in a custom frame to punch the keys and sockets. Custom ordered punches and dies in addition to a custom made punch adapter were used. After producing several connectors, this system providing marginally acceptable results and suffering repeated failures due to damage of the punches. The use of a 4-ton hydraulic press increased the pace of construction, reduced the occurrences of failures, and was less labour intensive.

The bending procedure required four steps. First, one side of the cup section of the base and the portion of the base that rests against the column were bent 90 degrees. The portion of the base that rests against the column was then bent back 16.4 degrees. Next, the other side of the cup and the portion of the base that rests against the sill/header were bent 90 degrees into the same plane as the previous 90 degree bend. The portion of the base that rests against the sill/header was then bent back 73.6 degrees. The final bend brought the entire cup section of the base up 90 degrees to bring the cup into a vertical orientation. It was impossible to devise a bending
arrangement that didn’t require two or more sections to be bent twice. For each bend, metal plates were tightly secured to the sections to produce a clean, bend with minimal distortion of the connector. The formation of the L-bracket required only a single 90 degree bend mid-span.

Finally, the edges of the connector were filed to remove burs and inconsistencies. The time required to produce the connectors was drastically reduced from the original 3 hours when the process was perfected and the 4-ton press became available. There was also setup and cleanup times of approximately one hour for each stage of the processing. It should also be noted that a few units were produced that did not meet specifications and were discarded.

6.2 Methods of Construction – T-section

The critical connection of the full wall-frame, the joint where the column, sill/header, and brace attach, was selected to test the various connection systems and was constructed with proper wood dimensioning and grade as per Japanese construction. These sections involved a 914.5 x 105 x 105mm sill, a 609.6 x 105 x 105mm column, and a 609.6 x 90 x 45mm diagonal all made of hemlock-fir, a common construction material in Japan. The wood was kept in an environmentally controlled, conditioning room near the testing lab to maintain the required 12% humidity specified in the industry testing standards. The arrangement of this “T-section” design was to provide the worst-case scenario, which would occur at the end of a wall where a connector can only be installed on one side of the column. With the column mounted slightly off mid-span of the sill, adequate spacing was provided between the attachment points of the connector to the sill and the sill to the make-shift foundation.

Every piece was cut on site from material supplied by the UBC Department of Wood Science for this project. Two $\frac{3}{8}$” (9.5mm) diameter bolts were used to hold the sill to the foundation. The
The foundation was specifically designed for this project as no similar experiment has ever been undertaken at UBC. The foundation was a combination of 3 - 2” (50.8mm) metal slabs designed and fabricated to hold the T-section to the lab floor where testing was to occur. Connecting the sill of the T-section to this hold-down assembly were two bolts with large square washers located 4” (101.6 mm) and 20” (508 mm) from the same end and along the centerline of the sill.

Mounting locations on the column and brace were required to serve as the points of application of the tensile load during testing. A single, 1” (25.4 mm) diameter tension bolt hole was drilled through the column whereas 3 - 3/8” (9.5 mm) diameter tension bolt holes were drilled through the brace. The sizing and arrangement of these attachment points were determined from past experiments and are shown in Figure 6.

**Figure 6.** Sample T-section with mounting locations, MMAS connector, and transducer arrangements.
The mortise and tenon joints required for the various test samples were all hand made. After laying out the location and size of the mortise, an auger bit was used to remove most of the material. This was followed by hand chiseling the finished shape and depth of the mortise.

Cutting the tenon on a band saw was a crude yet effective method. Tighter, more accurate connections could be made with more expensive, automated equipment. For the test samples using the double-threaded lag screws, pilot holes were drilled the length of the screws using a hand drill and custom alignment techniques that ensured the intermediate zone between the two different pitches of the screw was located at the joint of the column and sill. The installation of the lag screws could be simplified using a custom designed installation tool that can be purchased from the screw manufacturer.
7.0 Testing Arrangements

Applying the tensile load to the column and brace would be two large actuators mounted overhead. To achieve the correct angle (16.4°) between the column and the brace, two steel C-channel header beams were set 95 5/8” (2428.9 mm) above the floor and bolted to two steel I-beam support columns. The height of the actuators was governed by their stroke cycle and the height of the column and brace. Installing the T-section on the hold-down assembly lifted it 4” (101.6 mm) above the floor. The actuators were connected to the bottom flanges of the header beams by 2” thick Actuator Connection Plates that were custom made for this project. The two actuators are mounted 24” (609.6mm) apart, a distance required by the allowable mounting locations on the header. The arrangement of equipment necessary for testing is illustrated in Figure 7.

Figure 7. Layout of test sample, hold down, and actuators.
The design of the hold-down assembly allowed proper location and orientation of the T-section. The actuator connecting to the column is directly above the column providing a perfectly vertical line-of-action. The installation of the Mabashira in Japanese post and beam construction requires that the diagonal brace be installed to one side of the centerline of the sill. Placing it in the center of the sill would require too deep a cut in the Mabashira. With the brace off the centerline of the sill and the actuator connecting to the brace aligned with the centerline of the sill, the T-section had to be rotated 2.8° to make the line-of-action of the actuator coincide with the skewed line-of-action of the brace.

Connecting the actuators to the T-sections required the design and/or modification of two tension plate assemblies. These assemblies consist of three parts: two side plates that provide a mounting surface for the bolt that is installed through the column or brace, and a top plate that is attached to the two side plates in addition to the actuator by a threaded connector. The top tension plate used to connect to the column had a 1” (25.4 mm) 12 UNC thread whereas the top plate for the brace-to-actuator connection used a ½” (12.7 mm) 12 UNC thread. Every piece was made from mild steel.

**7.1 Programs and Equipment**

Both actuators employed a load cell to measure force and a magnetostrictive transducer to measure displacement, the details of which are listed below.

Diagonal (Brace) Actuator:

MTS Actuator Assembly 243.25T

Load cell – MTS 661.22c-01/55
Transducer – MTS Temposonic II Magnostrictive APM, RH, 20.3” (515.6 mm)

Vertical (Column) Actuator:
MTS Actuator Assembly 243.30T

Load cell – MTS 661.20E-03/22

Transducer – MTS Temposonic II Magnostrictive APM, RH, 20.3” (515.6 mm)

The system was controlled by a MTS Structural Flextest GT 4 Channel Controller and Flextest software operated by a Compaq Pentium III microcomputer and a four-station MTS Hydraulic manifold system. This system setup with two actuators had never been attempted before and as such was thoroughly tested, which included the testing of a complete T-section.

7.2 Data Acquisition

Four, 6-inch travel transducers were installed on each T-section prior to testing. One was installed on either side of the column, with one end attached to the column and the other, retractable end forced against an aluminum L-bracket mounted to the sill, to measure the displacement of the column (uplift). With the MMAS connector mounted off the centerline of the sill, it was foreseeable that the column might rotate out of the vertical plane. Have a transducer on either side would make this event apparent. A transducer was installed to measure the displacement of the brace from the connector along the diagonal direction with one end on the brace and the other against another aluminum L-bracket mounted on the connector. The final transducer was mounted between the column and the sill. Since a transducer could not be installed to directly measure the displacement of the connector from the sill, the same result could be achieved by subtracting the displacement of the brace-to-connector from the displacement of the brace-to-sill. Figure 6 shows this arrangement. Prior to each test, the
operation of the transducers was verified. The data collection from the transducers was via MTS Flextest software using MTS Model 793 System Software and MTS Model 793.10 Multipurpose Test Software.

7.3 Testing Methods

The tests were conducted under controlled, laboratory conditions with the samples being kept in the climate-controlled room until 2 hours before the tests. The actuators operated at a rate of 0.13mm/s for the column and 0.17mm/s for the brace (a 0.76:1 ratio). Performing under monotonic loading, the T-sections were subjected to only tensile forces since most failures in a structure occur under tensile loading, a determination made through interviews with field professionals and literature research. Video photography recorded the length of the test and included commentary of the observers as the tests progressed. Extensive still photography was taken of each T-section before and after each test. Along with personal observations, analysis of the various T-sections was now performed.
8.0 Experimental Results

Each connection system was tested twice in order to confirm the observations from the first test.

The data collected for each connection system were averaged and the corresponding load-displacement curves for the vertical and the diagonal members were created (Figure 8 and 9).

Figure 8. Vertical force-displacement curves for the various connection systems.
Figure 9. Diagonal force-displacement curves for the various connection systems.

Table 1. Connection System Performance

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<th>Diagonal</th>
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<td>( D_{\text{Pmax}} ) (mm)</td>
<td>( S ) (kNmm)</td>
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<td>50.1</td>
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8.1 Overall Response

From the force-displacement graphs, the performance of each connection system was observed and recorded in the above table (Table 1). The three MMAS connection systems exhibited more resistance to load in the vertical direction than the diagonal direction. This could be because that the L-bracket is made of thicker material than the MMAS connector. The capacity of the system is described as the highest load, \( P_{\text{max}} \) resisted by the structure. The Mk 1A system demonstrates
significant improvement in terms of capacity over the Mk1 system (163% for the uplift load and 73% for the diagonal load) because the moment arm is reduced with a lag screw located closer to the point of application of the load. Although both these systems are inferior to the traditional Japanese system in terms of capacity they are highly ductile, which is confirmed by the large displacement, \( D_{p_{\text{max}}} \) at the peak load. Overall, the Mk 2 connection system withstood the highest uplift load (an 80% increase over the standard Japanese system). This significant increase is due to the use of the double-pitched lag screws connecting the column to the sill.

The dissipated energy, \( S \) represents the ability of the system to absorb energy via the deformation of the connection system. It was determined for each system by calculating the area under the associated load-displacement curve (between zero and 80% of the maximum load on the downward slope). Because the load did not drop to 0.8 \( P_{\text{max}} \) after reaching the peak load in some of the tests, the dissipated energy was calculated between zero and the observed \( P_{\text{max}} \).

It is shown that MMAS connection systems have poor energy dissipation properties in the diagonal direction when compared with the standard Japanese system, which indicates that the system needs to be strengthened in the diagonal direction. However, they all dissipate similar if not higher amounts of energy dissipation in the vertical direction. Mk 1A systems absorbed the highest amount of energy in the vertical direction due to their shallow load–displacement curves. Although the Mk 2 systems absorbed only 11% more energy than the standard Japanese system at peak load, it is apparent that they could absorb much higher amounts of energy as the load drops off. It should be noted that both the Mk 1A and Mk 2 system loads levelled off at approximately 9kN after reaching their peak. This observation indicates that these systems continue to resist uplift load and dissipate energy even after the system has theoretically failed.
8.2 Failure Modes

During the tests of the traditional Japanese connection systems nail withdrawal and excessive cracking was observed along the length of the sill. This failure was partially caused by the fact that the bottom series of nails used in installing the VP and BP connectors were on the same horizontal plane creating large loads perpendicular to the grain and therefore cracking.

Considerable post uplift was also observed during these tests.

No significant wood failure was observed during the Mk 1 connection system tests because most of the load was absorbed by the connector and the L-bracket. The system didn’t seem to be able to resist the applied load very effectively, made apparent by the metal yielding very early on in the test. Plastic hinges appeared where lag screws were installed to attach the connector and L-bracket to the sill. In addition, significant post uplift was observed during this test.

The Mk 1A system showed significant improvement over the Mk 1 system. As previously mentioned, this improvement can be attributed to the improved attachment method of the MMAS connector and L-bracket: the lag bolts connecting the connector and the L-bracket to the sill were moved closer to the base of the column that effectively reduced the moment arm.

Similar to the previous set of tests for the Mk 1, plastic hinges appeared where lag screws were installed to attach the connector to the sill. As the test progressed these lag screws were gradually withdrawn from the sill and significant metal tear was observed at the base of the connector.
Mk 2 connection systems demonstrated the most effective overall response. Initially no post uplift was observed. As the test progressed, the double-threaded lag screws began to withdraw in which case similar failure modes to that of the Mk 1A tests were observed.
9.0 Conclusion and Recommendations

The results from the experiments involving the various MMAS systems displayed very little wood damage therefore indicating good energy dissipation properties of these systems. However, the trade-off is a large displacement of each system: a non-desirable effect. All MMAS connection systems exhibited great overall uplift resistance. If incorporated into the wood frame-wall system, this characteristic will prevent the structure from deforming easily into a parallelogram: a result that significantly increases the diagonal forces. Furthermore, the enclosed configuration of the connector resisted cracking of the diagonal member. With previous connector designs, cracking occurred due to the moment created by the rotation of the diagonal member that in turn created tension perpendicular to the grain hence wood cracking: a result prevented by the MMA connector. The enclosed design of the MMA connector allowed the metal to absorb the energy that was previously absorbed by the wood. The MMAS system also eliminated the need for detailing the diagonal member to match the column-sill joint geometry, a necessity with the traditional Japanese system. Large hold-down connectors that provide a connection to the foundation are currently used in conjunction with the traditional Japanese system to prevent uplift. The MMAS system eliminated the need for using these hold-downs with the implementation of an L-bracket and double-threaded lag screws. If additional uplift resistance is required, L-brackets could be installed at the frame joints where MMAS connectors are not installed (non-critical joints). It should be noted that the tests carried out incorporating the worst-case scenario as the connector and the L-bracket were used on one side of the column only. This situation would only occur at the ends of a wall, which is normally comprised of several frames. The following recommendations are made to improve the overall response of the MMAS connection system:
• Thicker sheet metal could be used to fabricate the MMAS connectors. This alteration would cause the capacity and the energy dissipation properties of the system to increase in the diagonal direction. Unfortunately, metal thickness was a limiting factor during the fabrication process of this project: bending thicker sections of steel was not feasible given equipment limitations.

• Replacing the lag screw connections that mount the connector to the sill with bolts would eliminate lag screw withdrawal and therefore increase the capacity of the system. Of note is the fact that bolts are difficult to install with the construction methods currently employed in Japan due to access limitations to both sides of the bolt: using bolts would therefore affect the constructability of the frame.

• Full frame-wall tests should be conducted to determine full frame reactions. This would include cyclic and monotonic tests that require large amounts of resources and a significant amount of capital.
References


