Connections for Stackable Heavy Timber Modules in Midrise to Tall Wood Buildings

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EXECUTIVE SUMMARY

In Phase I (2018-19) of this project on *Prefabricated Heavy Timber Modular Construction*, three major types of connections used in a stackable modular building were studied: intra-module connection, inter-module vertical connection, and inter-module horizontal connection. The load requirement and major design criteria were identified. The connections were designed and tested to quantify their performance.

Conventional methods to build timber modules based on platform construction may not be most suitable for midrise to tall stackable buildings, due to the weak compression perpendicular to grain property of wood. Balloon construction is proposed here to manufacture individual modules so that non-disruptive vertical load transfer path is maintained along the structural height. Three screwed connections were tested to evaluate the load transfer between the elements, with steel angle brackets and Laminated Veneer Lumber (LVL) blocks. Screws at 90° were found to be inadequate for this application due to the low stiffness and high variation. When screws were installed at 45°, both the steel plates and LVL blocks had high stiffness, high strength, and good ductility.

The inter-module vertical connection joins the walls of an upper module with a lower module. The connector is able to resist both the uplifting force and horizontal sliding. It was tested under horizontal loading here. The achieved load was about 80 kN at a displacement of 6 mm for a connection. Under reverse cyclic loading, the reverse cycles had a lower load than the corresponding positive cycles. There was a low stiffness region near zero displacement due to manufacturing and test setup issues. Several options to increase the connection stiffness were proposed.

The inter-module horizontal connection is designed to dissipate energy in an earthquake, as individual modules are very rigid. A damping device was manufactured and tested using low yield steel (LYS). For one damper with a size of 50 mm by 50 mm by 6 mm, the peak load was in the range of 53-57 kN. The deformation at failure was in the range of 15-20 mm, which was 30-40% of the damper length. The results showed a very high deformation and energy dissipating capacity. There was no cyclic degradation before failure. The repeated cycle had equivalent or even higher amount of energy dissipated. The failure occurred at or near the welding due to stress concentration.

The connection is intended to limit the damage to the damper so that only the damper needs to be replaced after severe damage. The connecting plates and CLT blocks were reused multiple times in the test, and the results showed that there was no significant reduction in terms of energy dissipating capacity or stiffness, although the negative cycles had been affected more than the positive cycles.

Further research will include the optimization of the connections and the investigation of their performance when incorporated into a building.

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1 INTRODUCTION

Prefabricated modular construction is a good solution to the increasing housing demand and shortage of skilled labor in the construction industry. It offers great benefits in terms of construction speed, material/labor cost, construction safety, and quality control. Modular units are traditionally built with light wood framing or light steel framing. Compared to them, heavy timber products have inherent advantages fit for modular construction, such as fire safety, structural integrity, durability, and flexibility.

Engineering and cost challenges exist that restrain the application of heavy timber modular construction. For example, the way the module is built now (platform construction method) exposes the CLT floor/roof to compression perpendicular to grain. The weak perpendicular to grain strength of CLT limits the stackable height of modules. Additional supporting structures have to be introduced in order to prevent failure under compression perpendicular to grain. Another urgent issue is the seismic performance of the whole structure. For a low rise building, this would not be a major issue. But for taller wood buildings, since a rigid individual module does not have energy dissipation mechanism within itself, the seismic energy input has to be absorbed by the connections between modules. The design and performance of these connections will be critical, and there has not been a satisfying solution yet.

This project identified and studied major connections used in stackable heavy timber modular construction. The scope of research included the design and testing of floor to wall connections within a module, the horizontal connection between modules, and the vertical connection between modules.

2 MATERIAL AND METHODS

The material used in the manufacturing and testing of the specimens is shown in Table 1. The CLT was E1M5 175E 5 layer, manufactured by Structurlam Products Ltd. (Penticton, BC). The lumber in the major direction layers was MSR 2100 1.8E Spruce-Pine-Fir (SPF), and the lumber in the minor direction layers was SPF #2 & Better. The Laminated Veneer Lumber (LVL) was LP SolidStart® 2950Fb-2.0 E (13.8 GPa). The screws and washers were made by SWG Schraubenwerk Gaisbach GmbH (Waldenburg, Germany).

Three types of connections were investigated in Phase I (2018-19) of this project, as shown in Figure 1: the intra-module connection to connect the floor/roof elements to the walls in a module; the inter-module horizontal connection to connect the modules side by side; and the inter-module vertical connection to connect the upper module with the lower module. They work together to provide structural integrity for individual modules as well as the whole structure under regular and seismic loading. For a midrise to tall modular building, the connections are vital to its lateral and vertical stability.

Table 1 Material list

Item	Material
CLT	Structurlam E1M5 175 E 5 layer, 175 mm thick
LVL	LP SolidStart® 2950Fb-2.0 E
Screws	SWG ASSY Plus VG screws 8×120, 8×160, CSK head
Washers	45° washers for 8 mm countersunk screw head
Low yield steel	Yielding strength 160 MPa, 6 mm thick
Steel plate	A36, 6.4 mm thick

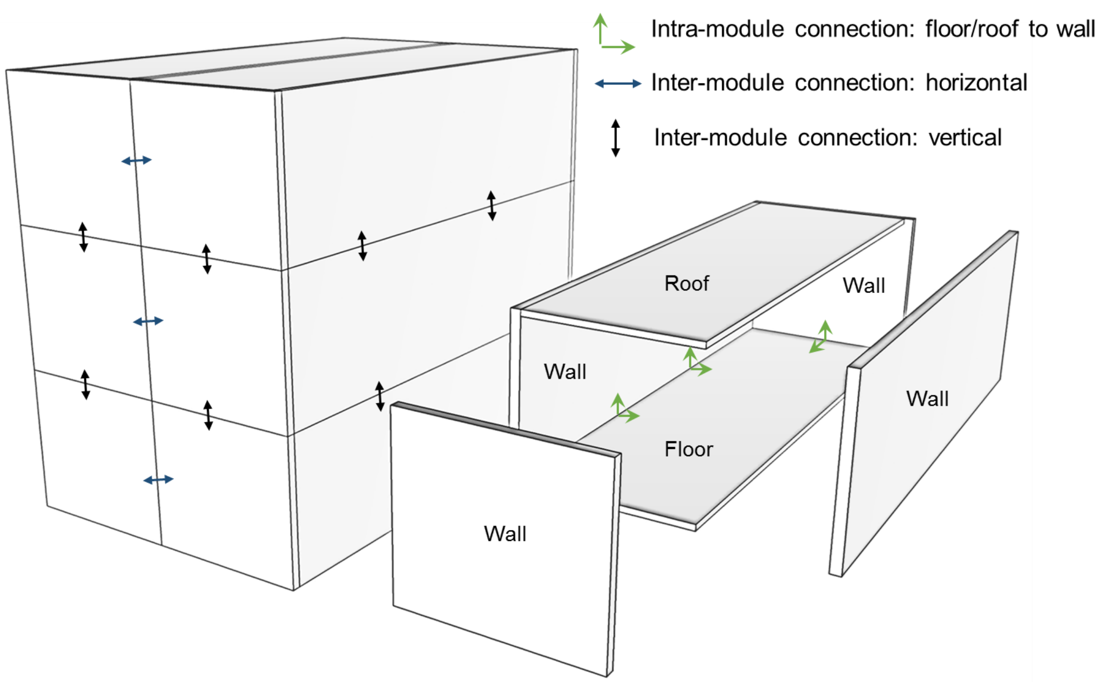

Figure 1 Connections studied in this project

Currently most CLT buildings, including CLT modules, are built using the platform construction method, in which the walls are placed in between the floor and roof, as shown in Figure 2(a). In a midrise to tall wood building, the horizontal elements at lower levels are under high compressive stress perpendicular to grain. This leads to excessive height shrinkage and compression creep over time. Special connections and reinforcements, including connections with the façade, have to be introduced in order to mitigate this problem. In this project balloon construction was proposed to build a single module, by placing the horizontal elements between the walls thus keeping a non-disruptive vertical load transfer path in a stackable structure, as shown in Figure 2(b). Each floor only bears the load at its own story, which was transferred to the surrounding walls and finally to the foundation. The floor element was offset from the bottom of the walls to create a space for sound/heat insulation as well as piping/wires.

Two issues are critical to this design: the connection between the floor/roof and the walls, and the vertical connection between modules to ensure the precise alignment of walls along the building height. They are addressed in Sections 2.1 and 2.2, respectively.

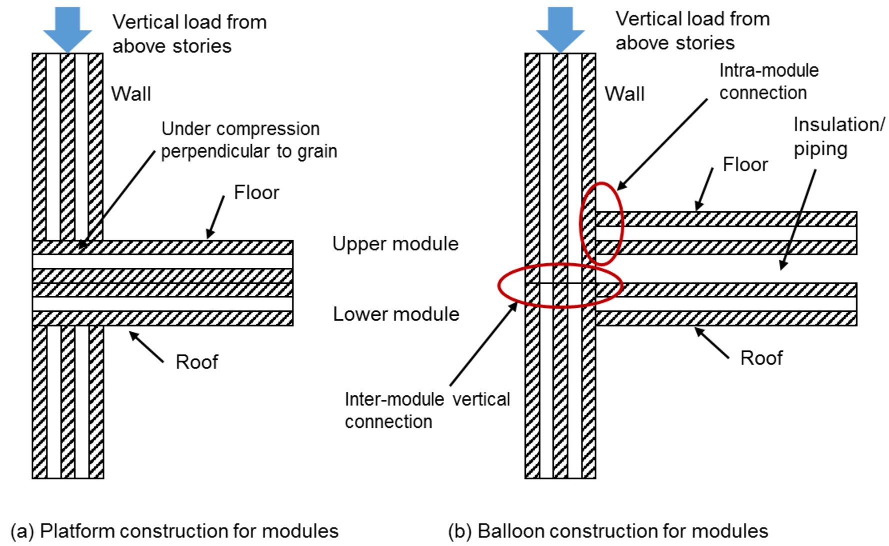

Figure 2 Construction methods to build modules

The modules are connected in both the horizontal and vertical directions, as shown in Figure 3. The vertical connections position the upper module on the lower module, and provide resistance to potential vertical uplifting and horizontal sliding between them. The connectors at the top of walls are also used as lifting devices during assembly. The horizontal connections join the modules on the same story. Due to the high rigidity of CLT modules, the structure lacks energy dissipating capacity for seismic reactions. A connection with replaceable seismic dampers was designed and tested.

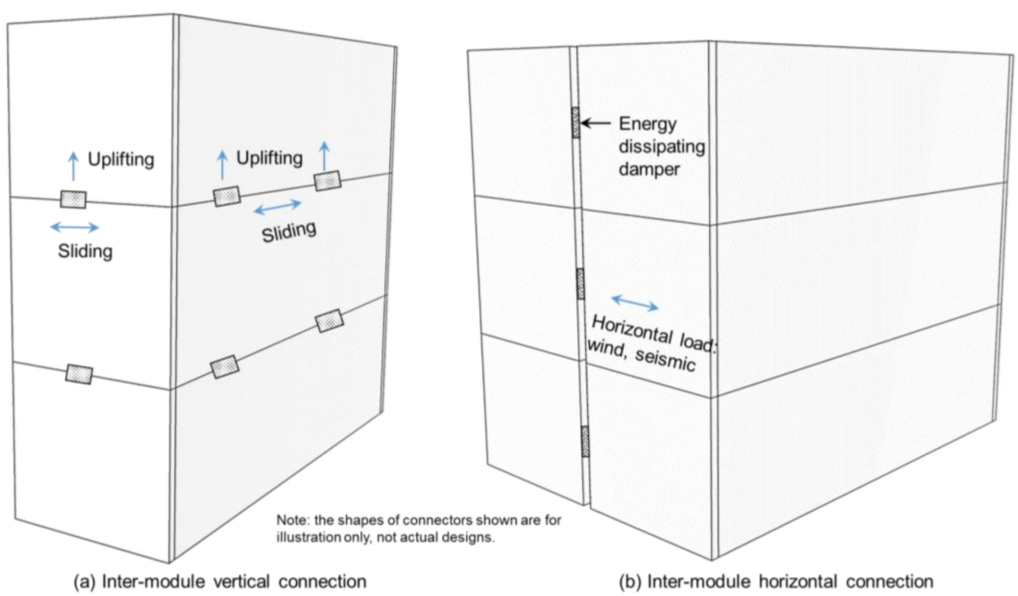

Figure 3 Principle loads applied on the connections

2.1 Intra-module connection

The horizontal elements (floor/roof) could be connected to the vertical elements (walls) in a module using the options shown in Figure 4, as suggested by the *CLT Handbook*. The floor load is transferred to a steel angle bracket or an engineered wood block, which is then connected to the wall by self-tapping wood screws. The angle between the screws and the wall surface may be 90° or 45°. Since the floor span/depth ratio is small in a module, the deflection of the floor is mainly controlled by the stiffness of the connection. Under balloon construction, the performance of this connection directly affect the structural safety. But the current design guides for this kind of connection lack information on stiffness.

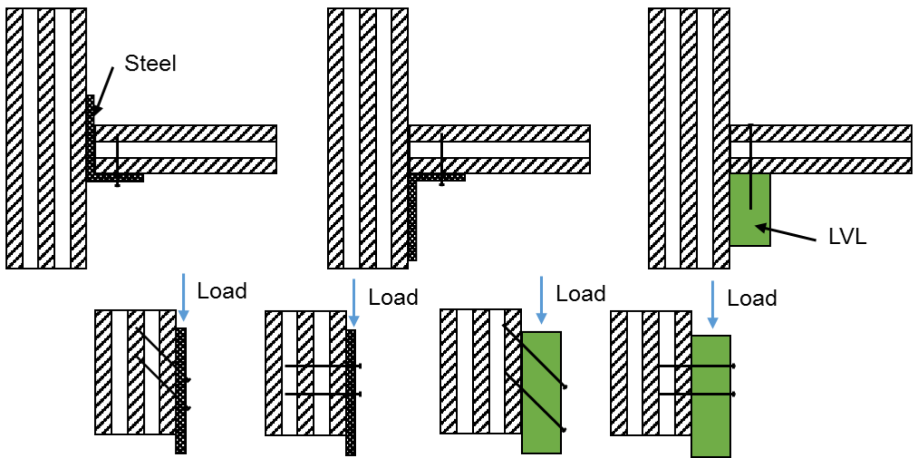

Figure 4 Intra-module connections

The performance of this connection was quantified using an H-block test, as shown in Figure 5, in which shear force was created between CLT and the steel plate (or wood block) by loading the center member. Three configurations were tested as shown in Table 2. The LVL connection with screws at 90° was not included in the test matrix because S90 group already had a very low stiffness. Two Ø 8 mm screws were installed on each side plate. The loading rate was 0.8 mm/min. Two transducers were mounted to measure the relative displacement between CLT and side members.

Table 2 Configurations of Intra-module connection test

Group	S90	S45	L45
Side plate	Steel	Steel	LVL
Thickness (mm)	6.4	6.4	40
Screw angle	90°	45°	45°
Screw length (mm)	120	120	160
Washers used	Yes	Yes	No
Replicates	10	12	11

Figure 5 Setup for the intra-module connection test

2.2 Inter-module vertical connection

The design of the inter-module vertical connection is shown in Figures 6-7. The connector had a Part A attached to the wall of the upper module, and a Part B attached to the wall of the lower module. The opening shape of Part A was designed to fit with Part B at a prescribed tolerance. The sloped shape was intended to facilitate the positioning of modules during assembly, and also to prevent horizontal sliding in use. In order to balance the two demands, the angle between the side plate and the horizontal plate was chosen to be 120° for Part A (60° for Part B). A bolt (or threaded rod) was welded to the center of Part A and secured to Part B with a nut. The detailed drawings of the connection are shown in Appendix A.

This connection ensures the precise positioning of modules and the vertical alignment of wall elements. The bolted connection at the center provides resistance to the uplifting force. The fitted components restrain the relative movement of modules in the horizontal direction, besides the friction between the walls. Part B would work as a lifting hook for the module during assembly.

The performance of the connection under uplifting force could be estimated by calculating the strength of the bolted connection and the withdrawal capacity of screws, both of which have existing design guidelines. Therefore, this test focused on the behavior of the connection under horizontal sliding. In order to investigate the connection, friction between the two walls was eliminated in the test by leaving a gap between two CLT blocks.

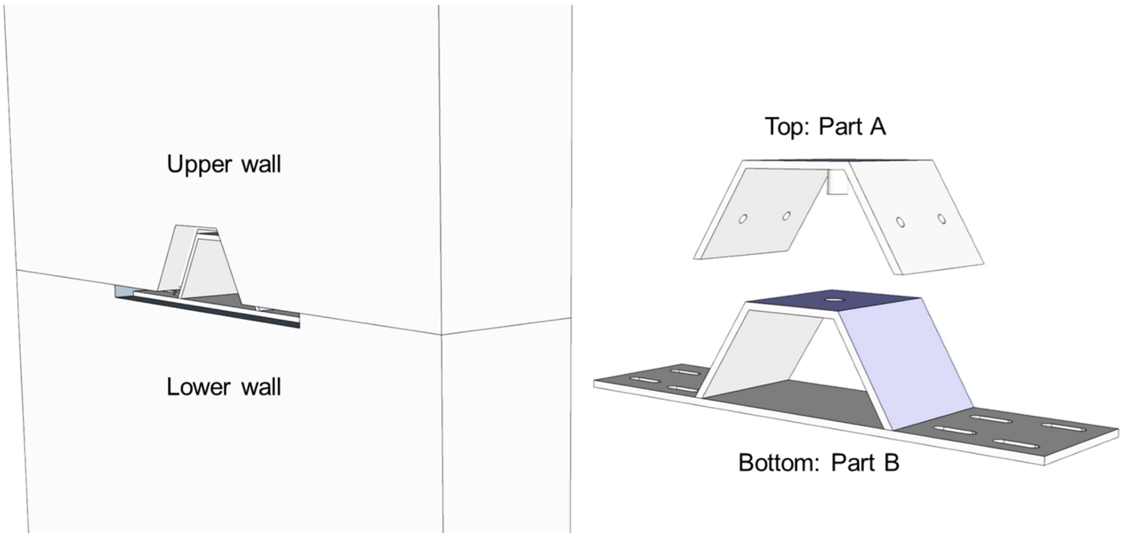

Figure 6 Inter-module vertical connection design I

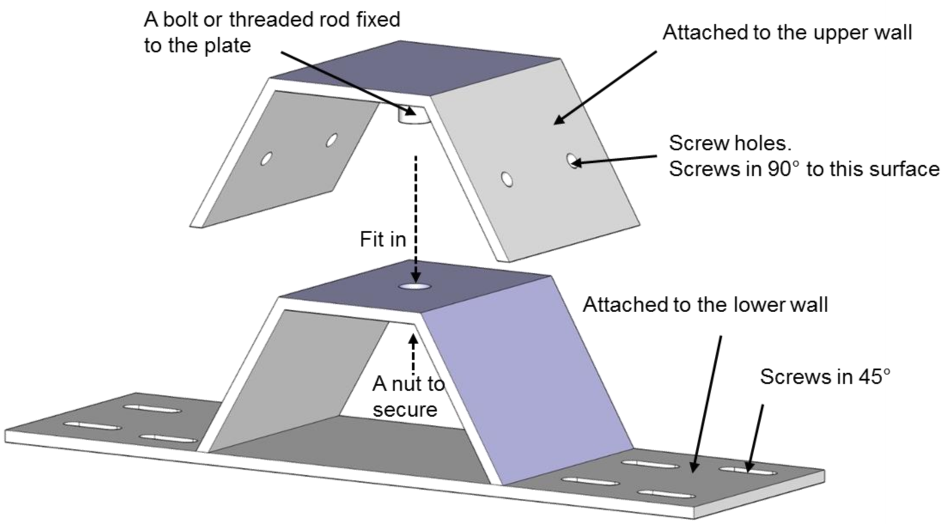

Figure 7 Inter-module vertical connection design II

The connectors were manufactured by Select Steel Ltd. (Delta, BC). Part A was attached to the upper CLT block with four Ø 8 mm by 160 mm screws. Part B was attached to the lower CLT block with eight Ø 8 mm by 160 mm screws. The number of screws was designed for the purpose of this test alone. The assembled parts are shown in Figure 8. The two parts of the connector were not fully countersunk into CLT so that there was enough gap between them during the whole testing period.

The specimen was positioned vertically in order to fit the test frame. One part was clamped to the test fixture, while the other part was under a reverse-cyclic loading. The loading history is shown in Appendix B, as a modified CUREE basic loading protocol. The loading rate was 0.5 mm/min and five replicates were tested. The test setup is shown in Figure 9.

One transducer was mounted on the loaded member to measure the relative displacement between the two parts.

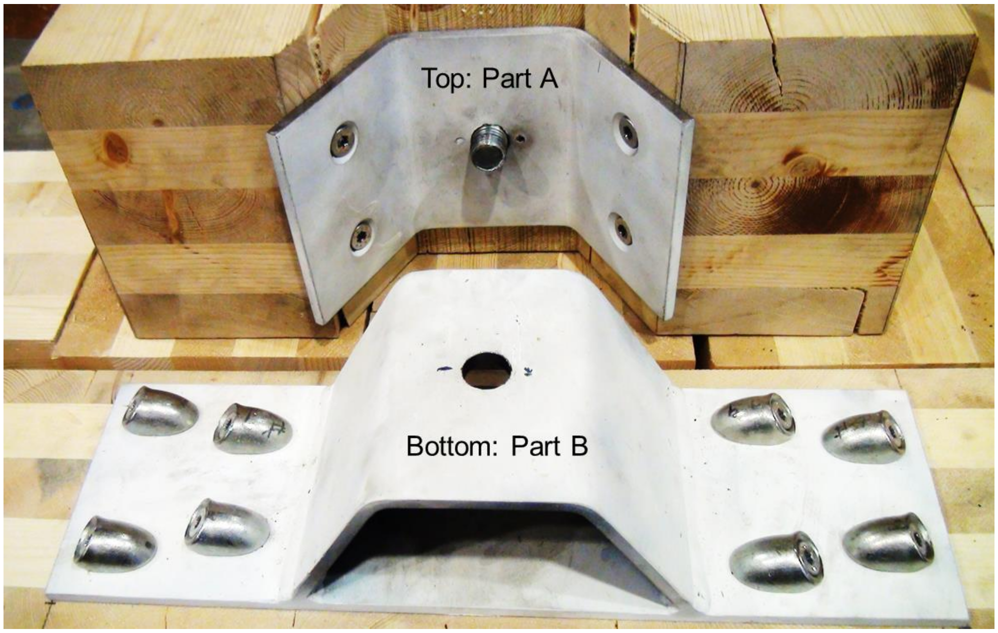

Figure 8 Assembled parts for the inter-module vertical connection

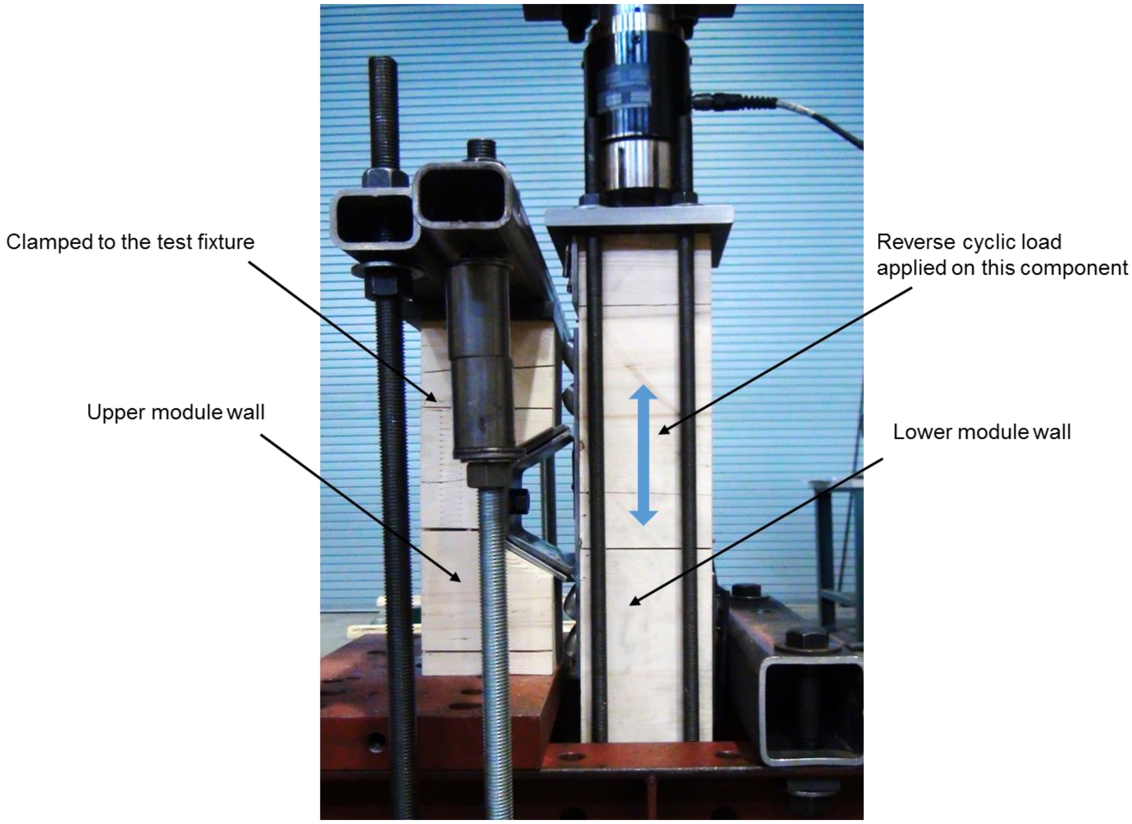

Figure 9 Setup for the inter-module vertical connection test

2.3 Inter-module horizontal connection

The inter-module horizontal connection has two major design criteria: it shall have good energy dissipating capacity for the structure under minor to moderate seismic loading, and it can be easily replaced after severe damage. Common energy dissipating devices used in steel and concrete structures do not work with timber buildings because of the lower stiffness and strength of wood compared to steel/concrete. The damage would occur in the timber components as a result. Therefore the connection should limit the deformation to the damping material and ensure the integrity of wood during its action.

Based on previous studies, Low Yield Steel (LYS) was found to be a suitable material for energy dissipation in timber structures. LYS has a much lower yielding point (160 MPa in this test) with larger deformation capacity compared to regular steel. The energy is dissipated by the shear deformation of the steel. The LYS damper was connected to a rigid steel plate with bolts, so that it could be easily installed and replaced whenever necessary. The connection between the steel plate and the wall was designed to be much stiffer than the damper itself, as to make sure no significant deformation or permanent damage would occur in this part. The LYS had a dimension of 50 mm by 50 mm by 6 mm. The arched shape was designed to reduce stress concentration at the corners. Eight screws (Ø 8 mm × 160 mm) were installed at 45° on each steel plate. Slots were cut on CLT surface in order to fit the bolts. The connection design is shown in Figure 10 and the detailed drawings are shown in Appendix C. It is to be noted that the size and details of the connection used here were for the purpose of this test only.

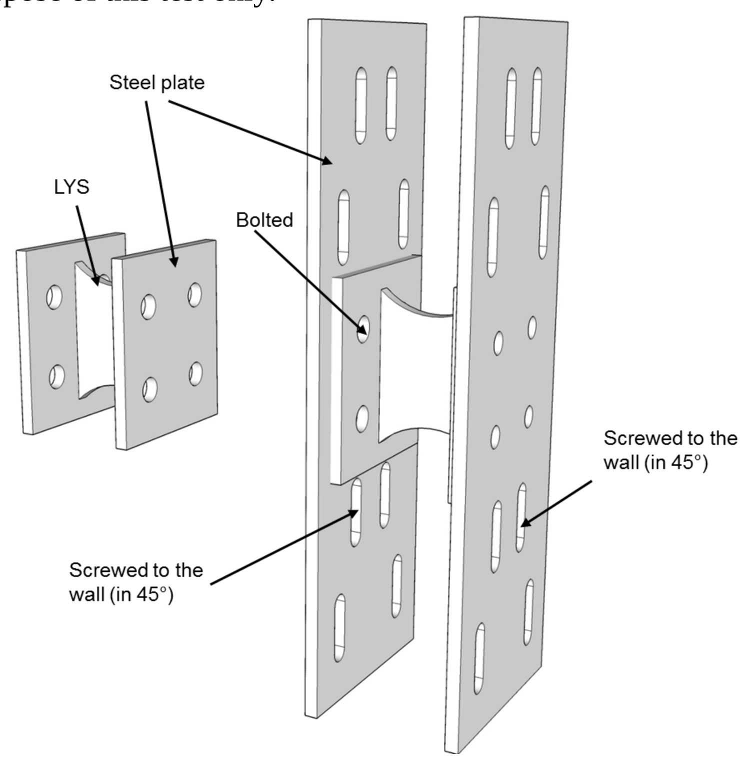

Figure 10 Inter-module horizontal connection

In the test, three wood members and two connections formed an H-shaped specimen, with the center member under reverse cyclic loading, as shown in Figure 11. The symmetric setup was to minimize the possible rotation of the center member. The loading protocol can be found in Appendix D. The same amplitude was repeated in two cycles in order to monitor the degree of cyclic degradation. The loading rate was 0.5 mm/min. Two transducers were installed to measure the displacement between the two walls connected by one damper. The side member was clamped to test fixtures and its horizontal movement restrained by steel bars.

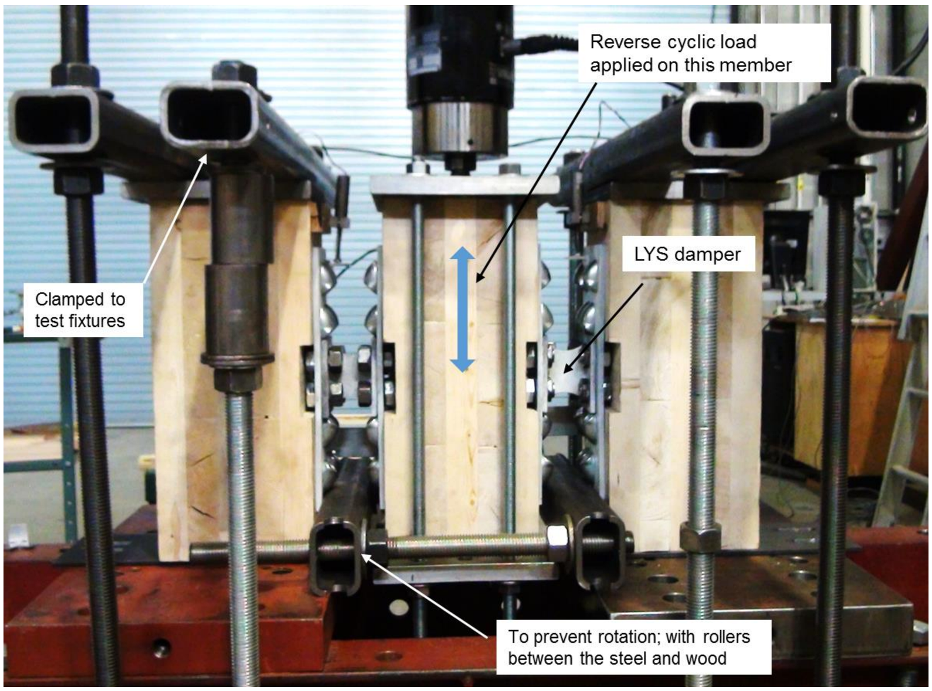

Figure 11 Setup for the inter-module horizontal connection test

3 RESULTS AND DISCUSSIONS

3.1 Intra-module connection

The summary statistics of the test results are shown in Table 3. The peak load of the three groups was in the same range, with L45 at the lowest on average and S45 at the highest. The coefficient of variation was 5-10% in a group. The specimens with screws at 90° had a much lower stiffness (5.1 kN/mm on average) and a higher variation. When the screws were installed at 45°, the withdrawal of screws was mobilized to resist the shear force, therefore the stiffness increased considerably to 44.1 kN/mm in S45 and 42.0 kN/mm in L45. The steel side plate had a slightly higher stiffness than the LVL side plate, but the difference was not significant.

The load-displacement relationship of four representative specimens is shown in Figure 12. S90 specimens behaved differently from the other two. They had a high stiffness period in the beginning, but could end as early as 3 kN and as late as 10 kN. The variation meant this portion cannot be considered in the design. Both S45 and L45 specimens had a linear load-displacement portion until the load reached 80% of the peak. After the peak the load did not drop abruptly but maintained at a high level for a prolonged period of time. The failure in S90 was due to the bending of screws at the steel plate, while the failure in S45 and S45 was mainly due to screw withdrawal.

For the intra-module connection, screws at 90° shall not be used alone due to their low stiffness and high variation. The steel connection and LVL connection do not have much difference in terms of their performance. Other factors shall be considered in selecting an appropriate design. The LVL connection has lower manufacturing cost but requires longer screws. The steel angle bracket is more susceptible to fire since at least part of the steel would be exposed.

Table 3 Intra-module connection test results

Specimens	Stiffness (kN/mm)			Peak load (kN/mm)		
	S90	S45	L45	S90	S45	L45
Max	8.1	52.3	54.6	60.3	65.6	55.2
Min	2.9	30.5	32.3	46.4	47.2	46.0
Average	5.1	42.3	40.7	52.5	58.7	51.5
Stdev	1.8	6.0	6.8	5.0	4.4	2.6
CoV	36%	14%	17%	10%	7%	5%

Note: S90 – steel with screws in 90°; S45 – steel with screws in 45°;
L45 – LVL with screws in 45°;

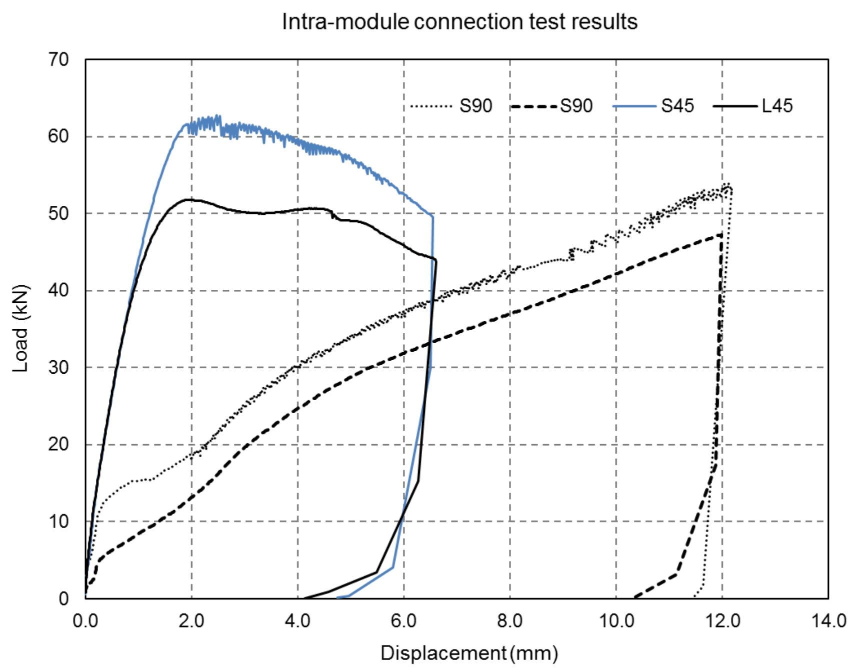

Figure 12 Load-displacement relationship of intra-module connection test

3.2 Inter-module vertical connection

This test investigated the performance of the inter-module connection under a horizontal reverse cyclic load, simulating seismic action. Two of the specimens are shown in Figure 13. As expected, the positive cycles had higher load and higher stiffness than the reverse cycles. The specimens performed in a similar manner at large displacement cycles and the stiffness was at the same level. What reduced the overall stiffness was the low stiffness region near zero displacement. The length of this portion varied from specimen to specimen. There were two factors leading to this result, as shown in Figure 14. The first was an initial gap between the wood and Part A due to cutting inaccuracy (not cut by CNC machine). In order for the wood to react against the side plates on Part A, these gaps had to be closed first. The second was that the sloped surfaces of the two pars did not have full contact as designed. Since there was no lateral restraint the loaded member rotated, so the load was disproportionally applied on the end of the side plates in Part A. The wood reacted much more near the opening while deformed much less at the top. The small area of wood was easily compressed which led to permanent deformation of Part A.

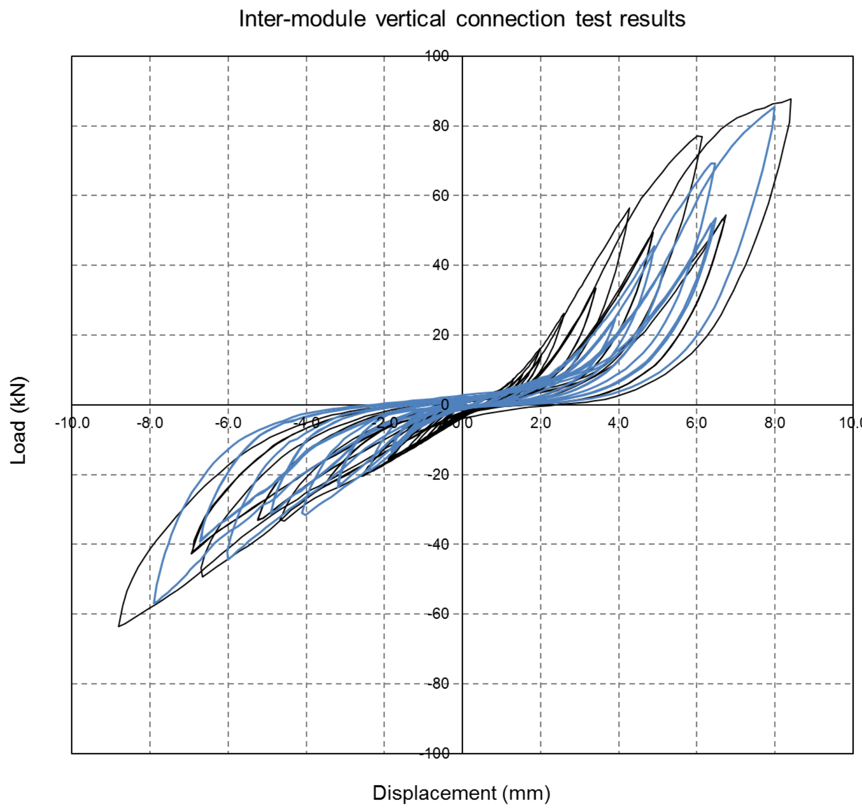

Figure 13 Inter-module vertical connection test results

The gap between the connector and wood could be minimized by using a CNC machine to precisely control the angle and depth of the cut. The fastening screws on the side plates then ensure the gap is closed. The degree of rotation will be much less in the building than what was found in the test due to the restraint of other structural members. Therefore the actual stiffness would be higher than the measured value here.

A stiffer connection could be achieved by connecting the sloped plates of Part A and Part B together using fasteners (i.e. bolted to pre-threaded holes). In the configuration tested here, the only restraint to the further opening up of Part A was wood behind the side plates. If the sloped plates are connected, the deformation of the connector itself gets involved in resisting the horizontal loading. The trapezoid shape was intended to provide some room of deformation thus certain degree of ductility. If necessary, stiffeners may be welded inside to control its deformation ability.

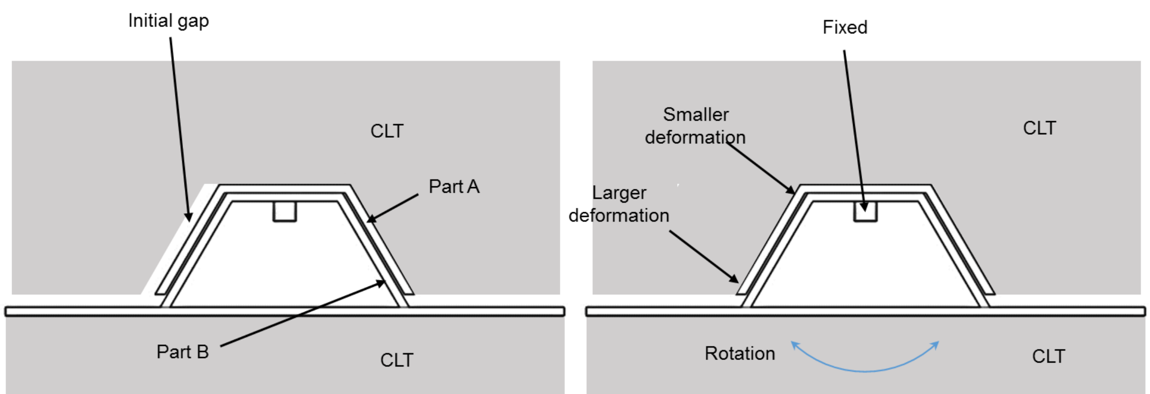

Figure 14 Factors leading to initial low stiffness

3.3 Inter-module horizontal connection

The load discussed in this section was the measured value divided by two since two dampers were tested in every H-block specimen. The peak load was in the range of 53-57 kN per damper and the load difference between the positive cycles and reverse cycles was not significant. The load and shear stress of one specimen are shown in Figures 15-16. The damper had a very high deformation and energy dissipating capacity. There was little cyclic degradation before failure, as shown by the almost identical curves of two repeated cycles at large displacement levels. Significant yielding started to show up at around its yielding point (160 MPa, about 45 kN). The deformation at failure was in the range of 15-20 mm, which was 30-40% of the LYS length. The actual displacement was not exactly symmetric because of the side member rotation.

The small displacement cycles and large displacement cycles are separated in Figure 18. Below 5 mm (10% of the LYS length), the load developed in an approximately linear relationship with the displacement indicating the LYS was in the elastic range. With increasing displacement, the curve gradually turned into a semi-rectangular shape because of the LYS yielding. There were relative movements between the damper side plate and the steel plate connected to the CLT block, which led to the offset of the positive load and negative load near 0 kN.

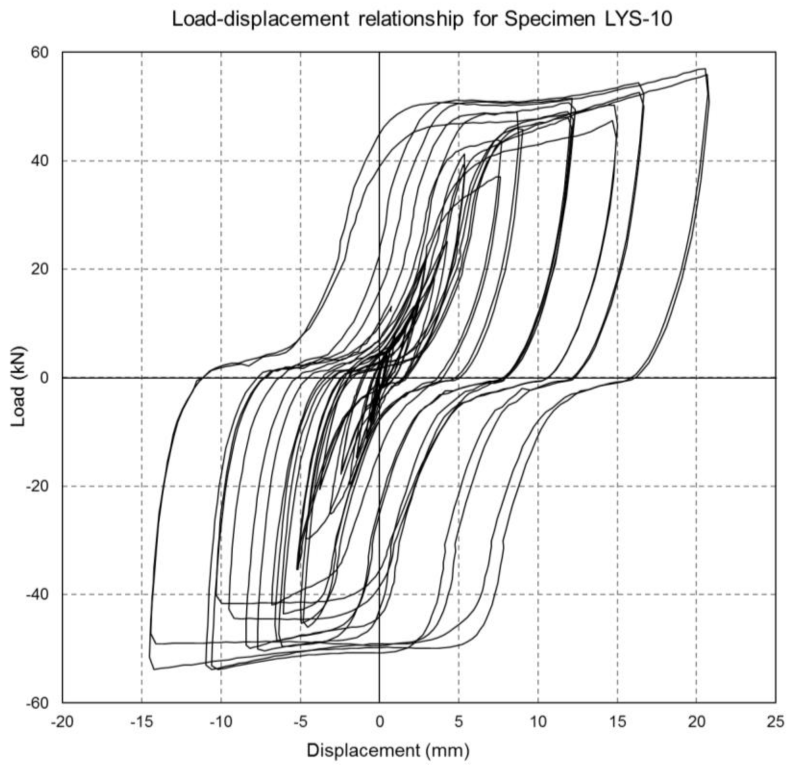

Figure 15 Load - displacement curve of LYS damper

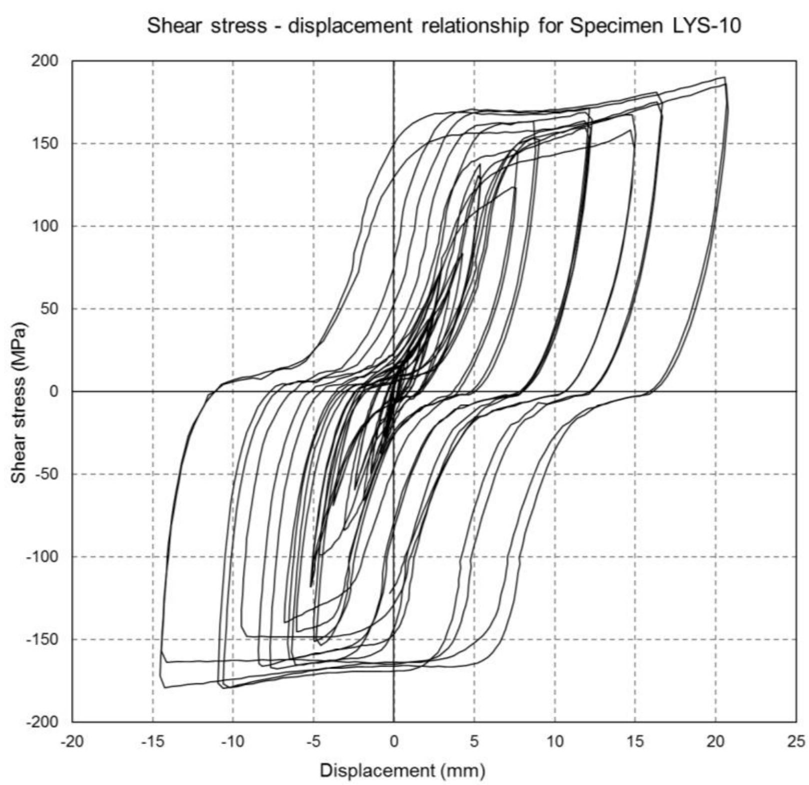

Figure 16 Shear stress - displacement curve of LYS damper

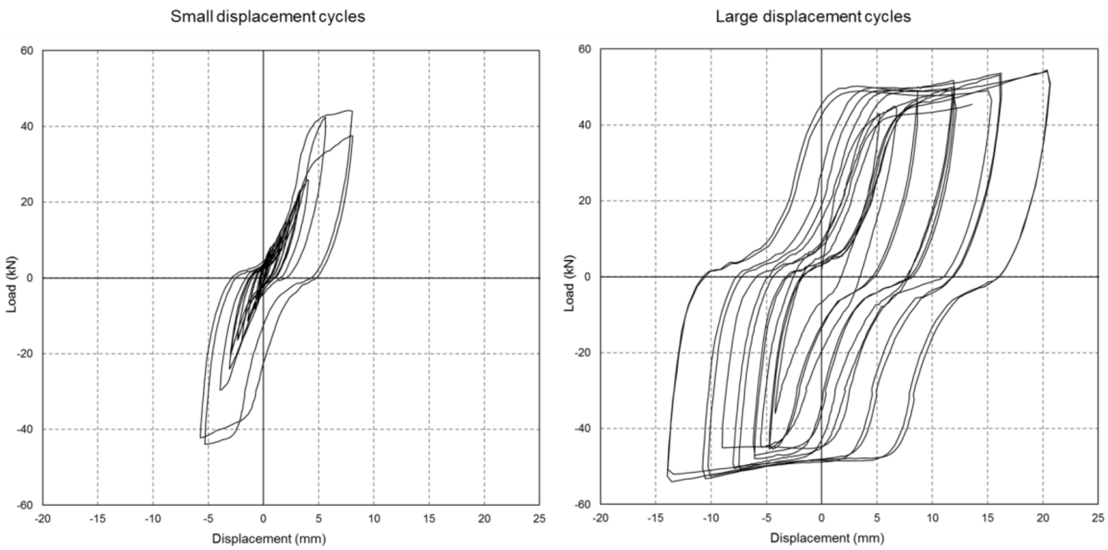

Figure 17 Comparison of different displacement levels

The specimens behaved consistently, as shown in Figure 18. The energy dissipated per cycle was in the same range amongst different specimens. The relationship between the energy E_d (in kN mm) and the cycle amplitude A (in mm) could be expressed as:

$$E_d = \alpha \times A^{\beta} \quad (1)$$

where α and β are constants depending on the damper geometry. For this case, α was in the range of 7.4-8.1, and β was in the range of 1.78-1.82. The R^2 of the fitting was above 99%.

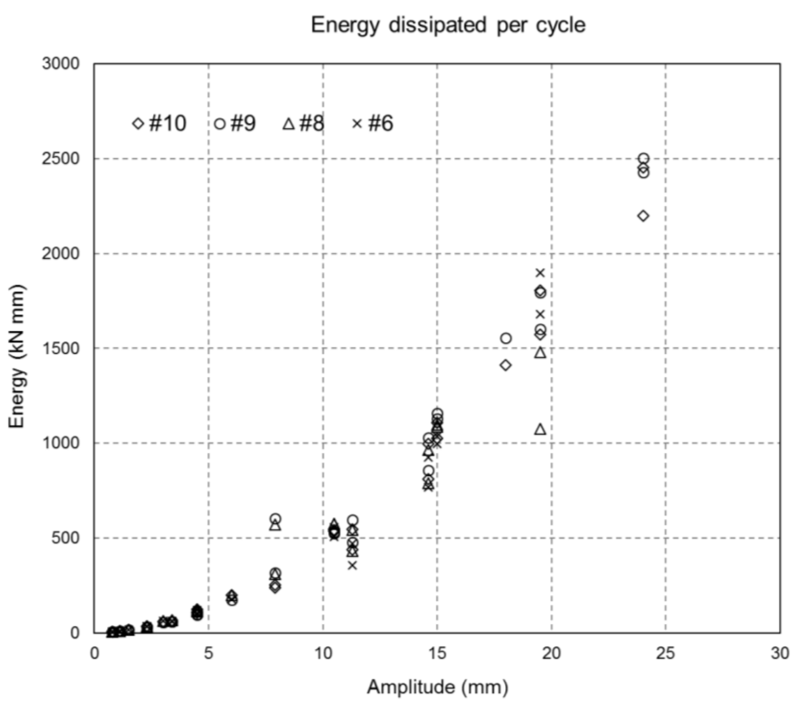

Figure 18 Energy dissipated per cycle

The energy dissipated in the first cycle and following repeated cycle(s) are compared in Figure 19. In most cases, the repeated cycle had an equivalent or higher energy dissipated. As long as the device did not fail, the damping capacity maintained at a high level throughout, which is an outstanding property under seismic load.

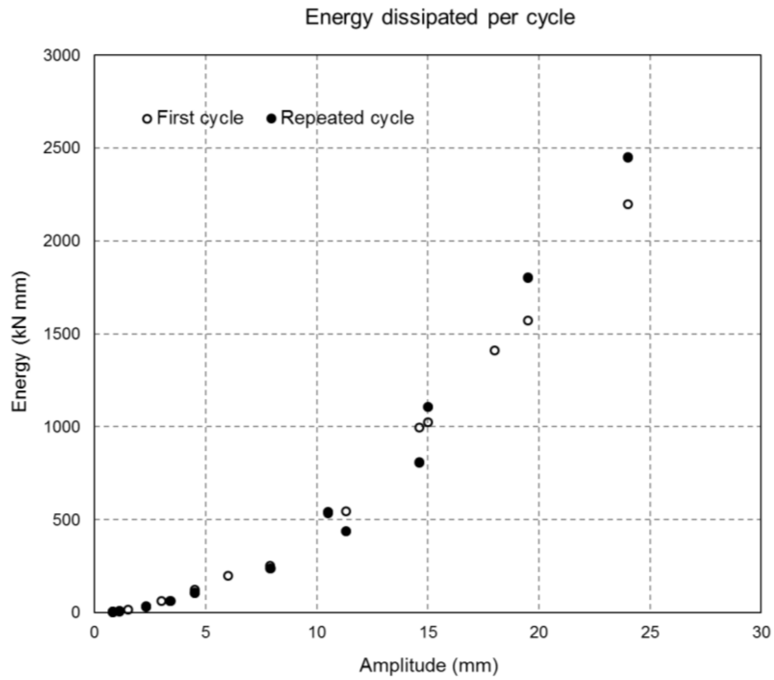

Figure 19 Comparison of first cycle and repeated cycle

The damper deformation is shown in Figures 20 and 21. Stress concentration occurred at the corners of the LYS, especially the two diagonal corners under shear-tension. When the stress approached its yielding point, a visible "neck" formed at these places and finally led to facture. Therefore, the failure always occurred at or near the welding. The welding quality thus becomes critical. Since the LYS used here was small in size, no buckling was observed.

The connection was designed to limit the damage to the LYS damper, so that only the damper requires replacement after failure. Due to the relative high rigidity of steel plates, this would depend on the connection between steel plates and CLT. The displacement between them was in the range of 1-2 mm at the peak. Figure 18 shows the results of three specimens using the same steel plates and CLT blocks in the test. The connection performance was affected more in the reverse cycles than in the positive cycles. But there was no significant reduction in terms of energy dissipating capacity or stiffness (compare #8, #9, and #10 in Figure 18).

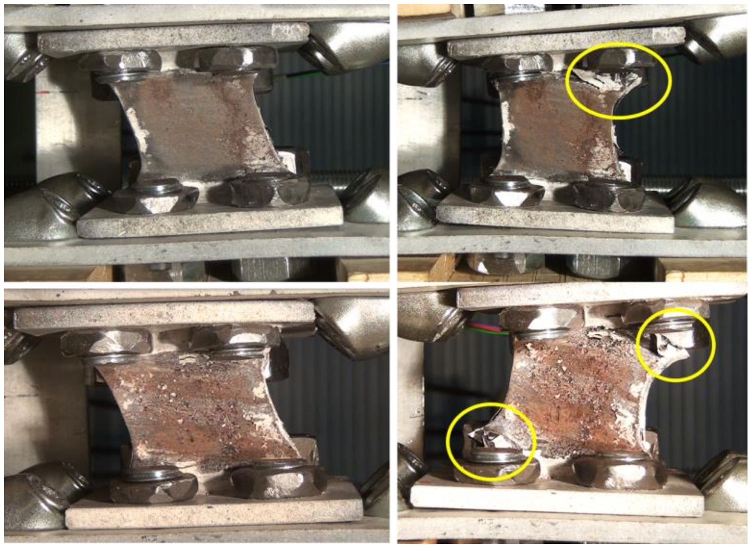

Figure 20 Deformation and failure of the dampers

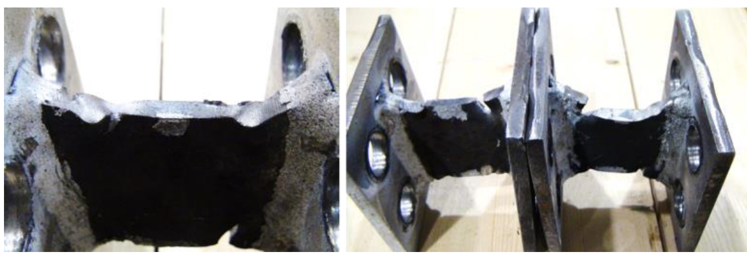

Figure 21 Yielding and failure of LYS

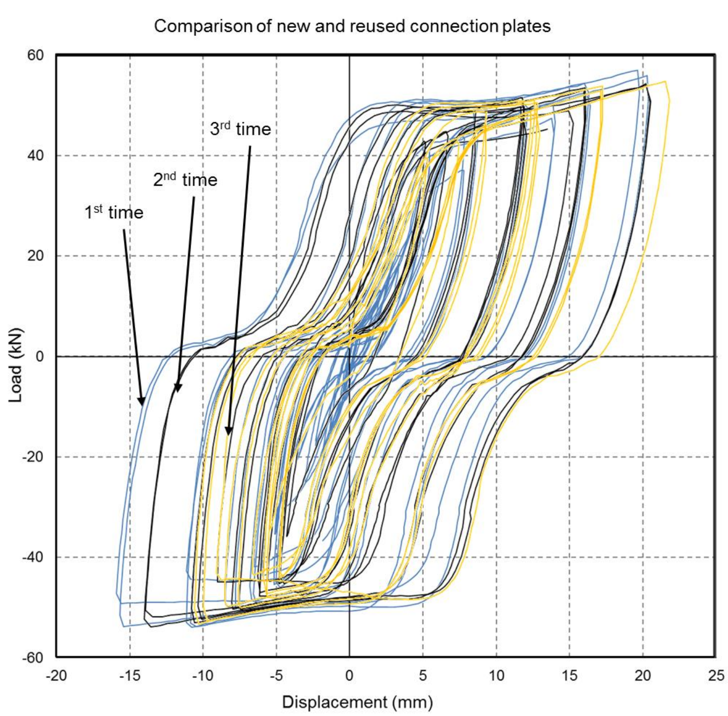

Figure 22 Comparison of new and reused connection plates (only LSY dampers changed)

4 CONCLUSIONS AND RECOMMENDATIONS

In Phase I (2018-19) of this study three major types of connections used in stackable heavy timber modular construction were designed and tested: the intra-module connection, the inter-module vertical connection, and the inter-module horizontal connection. The load and major design criteria for these connections were identified. The connections were manufactured and tested in order to quantify their performance and find out potential issues for future research in Phase II. The following is the summary of the results and recommended design/construction practice.

4.1 The construction of individual modules

The traditional method used in building modules is platform construction by placing the walls on top of floors. This has been found to be easy to design and to work with, but the floor/roof elements are under compression perpendicular to grain. This compressive stress increases as the building goes higher. For midrise to tall timber buildings, there will be considerable height shrinkage and compression creep leading to complicated problems in design, construction, and use. In order to build taller buildings, balloon construction is recommended so that a non-disruptive vertical load transfer path is maintained along the structural height. In this way the height of the building would be determined by the high compressive strength/stiffness in the longitudinal direction, rather than the low strength/stiffness in the perpendicular to grain direction. If necessary, the lower level module could use post laminated LVL or post laminated Glulam as wall elements, so that the stackable building could reach even taller.

The floor is now offset from the bottom of the wall, leaving a gap between the floor and the roof below. This space is intended for sound/heat insulation as well as piping/wires. It also reduces the airborne noise transmitted between two adjacent stories.

The connection between the floor/roof and walls was tested in three configurations: steel angle brackets with screws in 90°, steel angle brackets with screws, and LVL blocks with screws in 45°. The 90° application was found to be inadequate for this application due to its low stiffness and high variation. Its average stiffness was 5.1 kN/mm, compared to 42-44 kN/mm of the other two groups. When screws were installed at 45°, using steel angle brackets or LVL blocks did not affect the shear stiffness or peak load significantly. Both showed a good ductility after reaching peak load. Four 8 mm screws achieved a minimum stiffness of 30 kN/mm and a minimum peak load of 46 kN. For comparison, a floor area of 3 m by 10 m with a live load of 4 kPa, which is equivalent to 120 kN in total. The LVL connection has lower manufacturing cost and better fire protection, although requires longer screws than the steel angle brackets.

4.2 Assembly of modules

The modules are connected in both the vertical and horizontal directions. Comparatively, the connection resisting the vertical load is designed to be stiffer while the connection resisting the horizontal load less stiff. Two types of connections were designed and tested: one connecting the end surfaces of two walls along the vertical direction, and the other connecting the faces of two walls along the horizontal direction.

The vertical connector has two fitting parts: Part A is attached to the bottom of the upper module, and Part B to the top of the lower module. Part B works as a lifting hook, while the sloped shape is designed to position the upper module during assembly. Once positioned, the two parts are fastened to prevent uplifting between two modules. The performance of this connection under horizontal sliding was singled out for testing as there has been design guidelines to estimate the uplifting resistance. The reverse cyclic protocol simulated the possible load applied during an earthquake. The five specimens behaved in a similar manner. The load was about 80 kN at a displacement of 6 mm in the positive cycle. The reverse cycle had a lower load as expected, since the damage to the wood was permanent. A low stiffness region was found near zero displacement, as a result of the test setting and the specimen manufacturing. The two parts did not have full contact as designed due to the rotation of loaded members. The stiffness of the connection could be further increased by adding connections between the sloped plates or welding stiffeners in the trapezoid shape. Besides the connection, the friction between walls also contributes to the prevention of horizontal sliding, especially at lower levels.

One major challenge in building taller CLT modular structures is seismic action. An individual module has little energy dissipating capacity due to its high rigidity. It is also not desirable to have the module deformed in an earthquake. Therefore, the connections shall be designed to dissipate energy under lateral load. Another objective is to isolate the damage to the damping material alone while keeping the integrity of wood during the whole process. The damper can be easily replaced after failure. Based on these requirements, an inter-module horizontal connection was designed and tested using LYS as damping material. LYS has a much lower yielding point than regular steel. The difference between LYS and wood in terms of their stiffness/strength is much smaller. The damper was connected to the wall by steel plates.

For one damper with a size of 50 mm by 50 mm by 6 mm, the peak load was in the range of 53-57 kN. The deformation at failure was in the range of 15-20 mm, which was 30-40% of the damper length. The results showed a very high deformation and energy dissipating capacity. The damper behaved elastically in the low displacement cycles. The yielding started when the shear stress reached to 150-160 MPa. There was little difference between the specimens for their overall performance. The energy dissipated per cycle had a power relationship with the cycle amplitude. There was no cyclic degradation before failure. The repeated cycle had equivalent or even higher amount of energy dissipated.

The largest deformation on the damper occurred at its diagonal corners. The failure occurred at or near the welding due to stress concentration. The welding quality is important to the proper function of the damper. No out-of-plane buckling was found in the test. Large LYS sheet tends to have out-of-plane shear buckling, which compromises the energy dissipating capacity. There are several methods to deal with that: design the damper within its out-of-plane buckling load; add stiffeners or ribs on the damper, which may alter its energy dissipating capacity; and use multiple smaller dampers rather than one large damper. Since timber buildings are often lighter than concrete/steel structures, the corresponding seismic load is small. Therefore, the number of dampers and the size of damper are not comparable to what have been used in other buildings.

The displacement between the connecting steel plates and CLT blocks was monitored during the test. The relative movement was in the range of 1.5-2.0 mm at the peak. Therefore, the steel plates and CLT blocks were reused multiple times to test the design concept that only the damper needs to be replaced after failure. By comparing their results, it was found that there was no significant reduction in terms of energy dissipating capacity or stiffness, although the negative cycles had been affected more than the positive cycles.

Some of the design configurations need to be adjusted based on the test results. In this project the three connections were considered separately. Their performance when incorporated into a building requires further study.

5 REFERENCES

Gagnon S, Pirvu C (eds., 2011) *CLT Handbook*: cross-laminated timber. Canadian Edition. ISBN:978-0-86488-547-0

Appendix A Drawings for the inter-module vertical connection

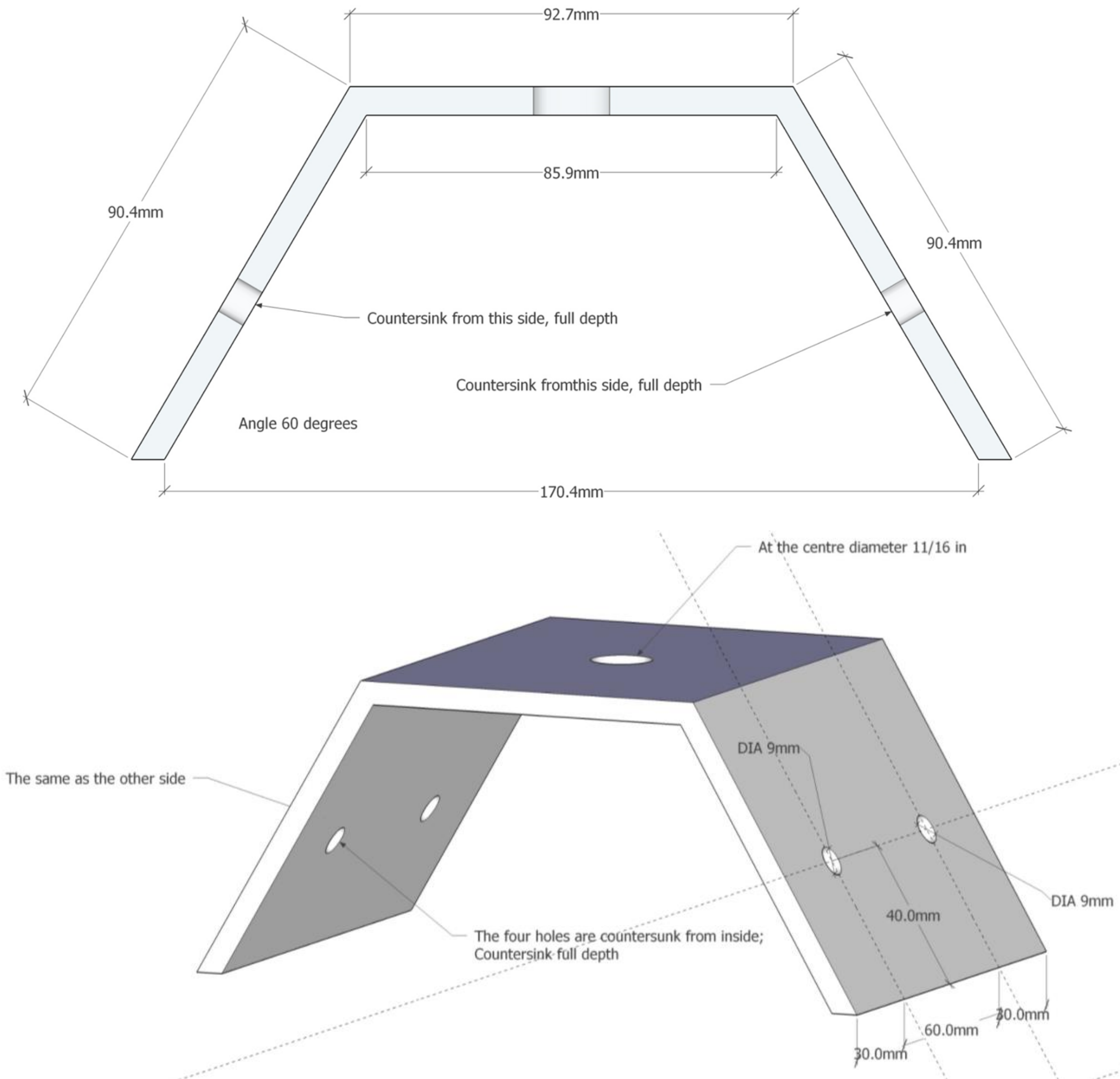

Figure A- 1 Dimensions for Part A of the inter-module vertical connection

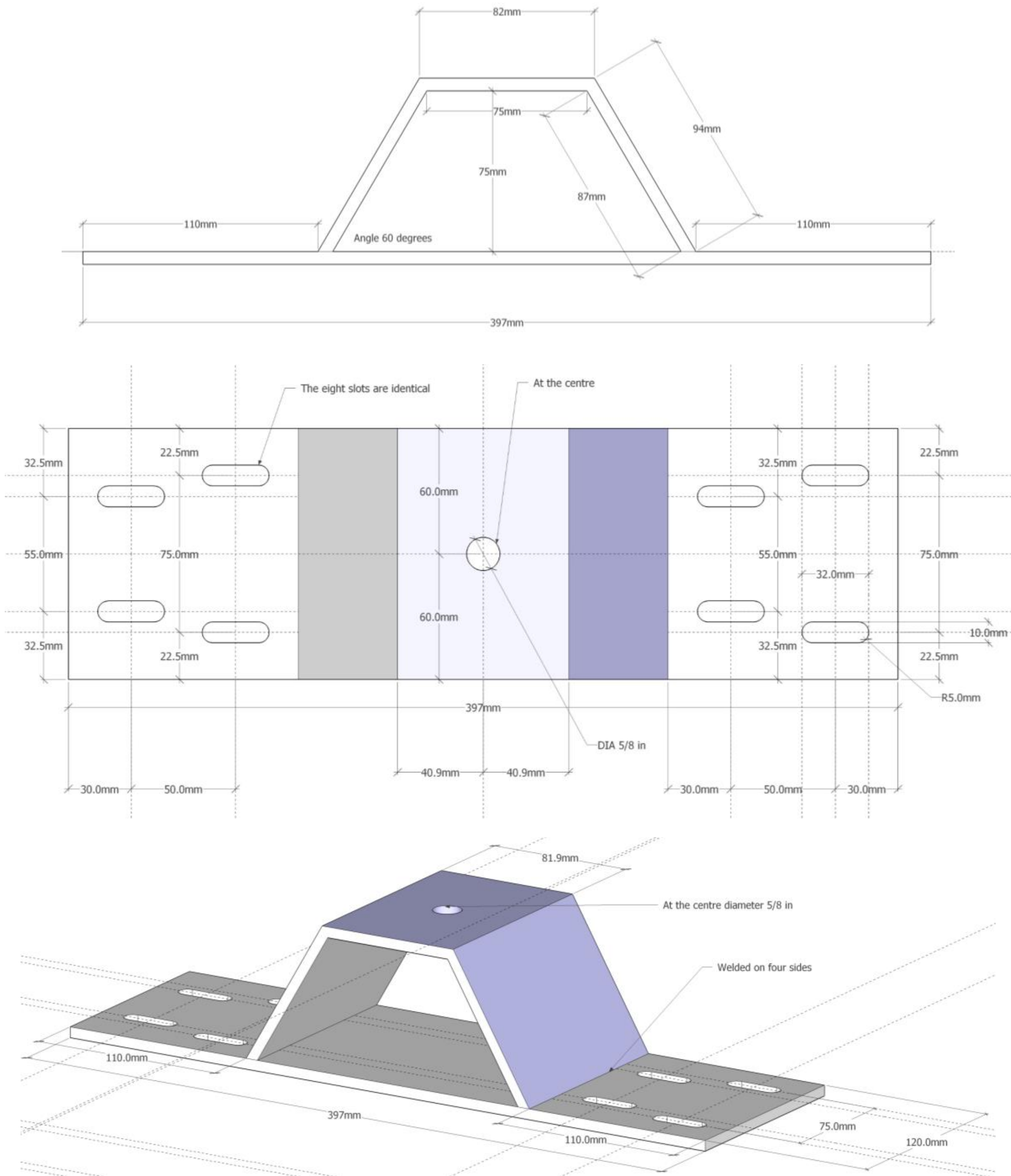

Figure A- 2 Dimensions for Part B of the inter-module vertical connection

Appendix B Loading protocol for inter-module vertical connection

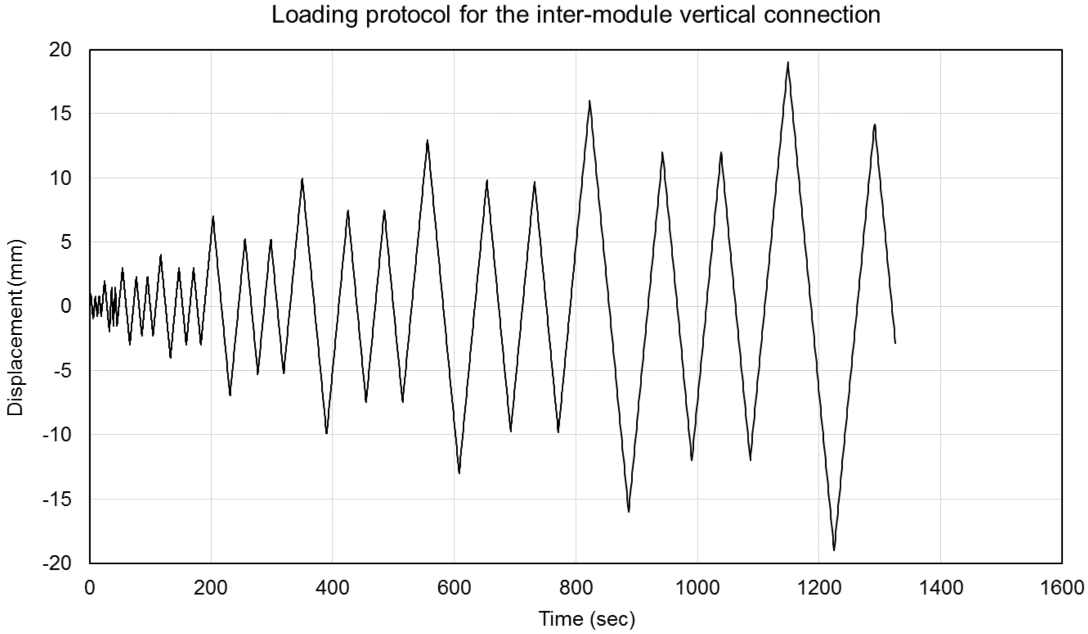

Figure B- 1 Loading protocol for inter-module vertical connection

Table B- 1 Amplitudes of the loading protocol for inter-module vertical connection

Step	Number of cycles		Amplitude (mm)
1	Equal	3	0.8
2	Primary	1	1.8
	Secondary	2	1.5
3	Primary	1	3.0
	Secondary	2	2.3
4	Primary	1	4.0
	Secondary	2	3.0
5	Primary	1	7.0
	Secondary	2	5.3
6	Primary	1	10.0
	Secondary	2	7.5
7	Primary	1	13.0
	Secondary	2	9.8
8	Primary	1	16.0
	Secondary	2	12.0
9	Primary	1	19.0
	Secondary	2	14.3

Appendix C Drawings for the inter-module horizontal connection

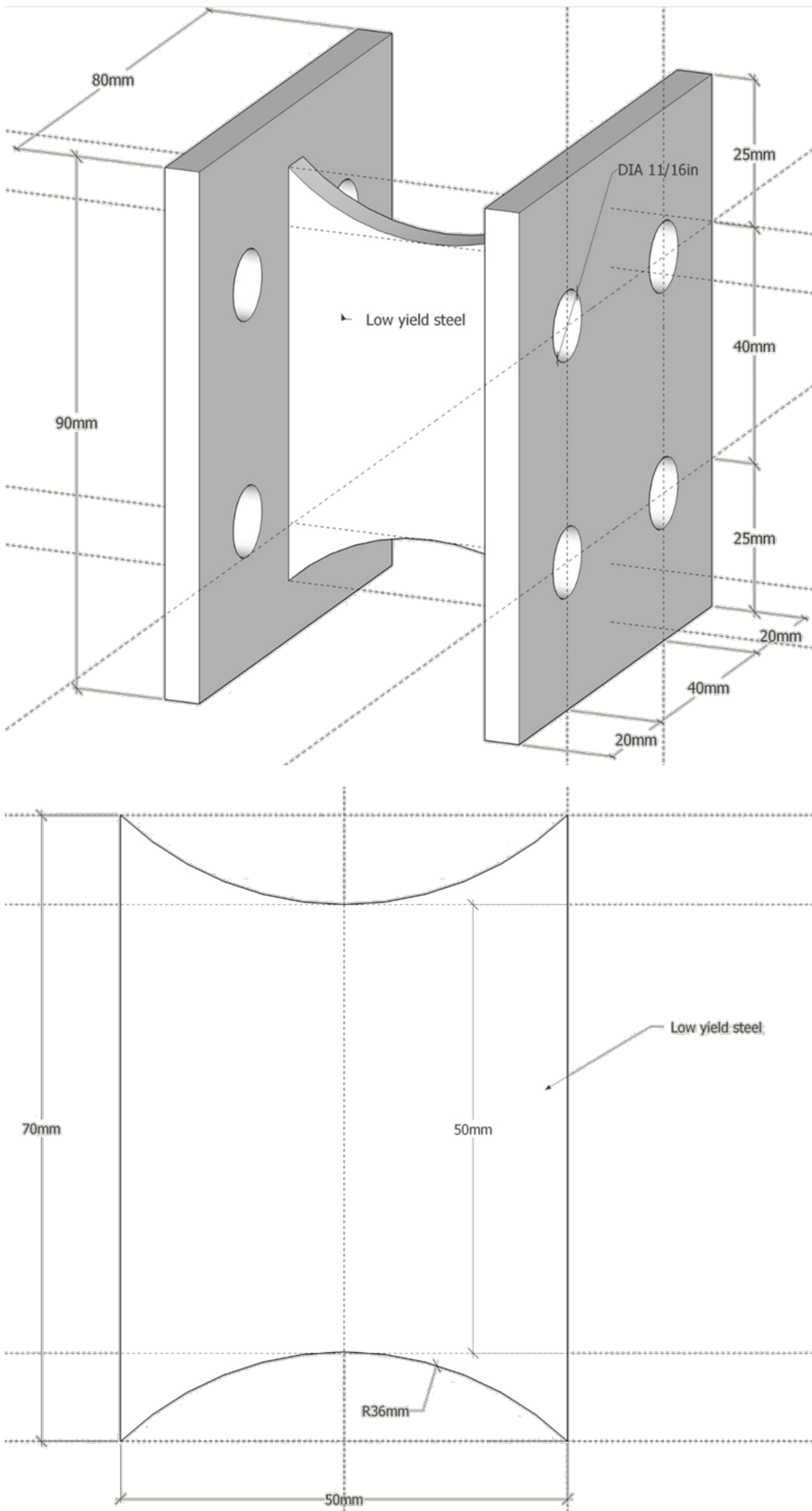

Figure C- 1 Dimensions of the LYS damper

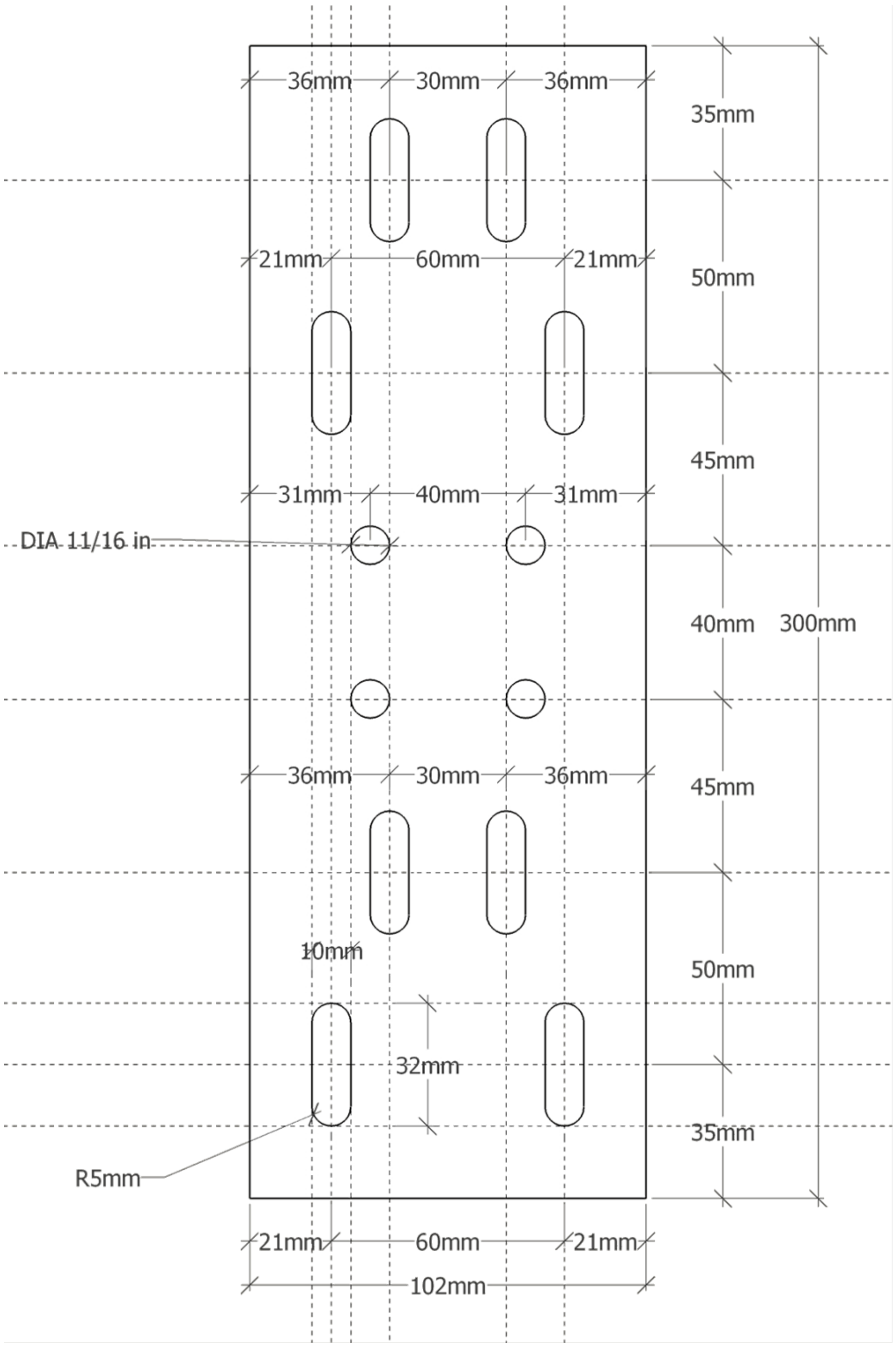

Figure C- 2 Dimensions of the connecting plate for LYS damper

Appendix D Loading protocol for inter-module horizontal connection

Table D- 1 Amplitudes of the loading protocol for inter-module vertical connection

Step	Number of cycles		Amplitude (mm)
1	Equal	3	0.8
2	Primary	1	1.1
	Secondary	3	0.8
3	Primary	1	1.5
	Secondary	3	1.1
4	Primary	1	3.0
	Secondary	3	2.3
5	Primary	1	4.5
	Secondary	2	3.4
6	Primary	1	6.0
	Secondary	2	4.5
7	Primary	2	10.5
	Secondary	2	7.9
8	Primary	2	15.0
	Secondary	2	11.3
9	Primary	2	19.5
	Secondary	2	14.6
10	Primary	2	24.0
	Secondary	2	18.0

THE END