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# Monotonic and Cyclic Performance of Self-tapping Screws for Cross-laminated Timbers with Steel Side Plates

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## ABSTRACT

The recent changes of National Building Code of Canada and the International Building Code allow mass timber construction represented by cross-laminated timber (CLT) to be used in buildings with taller heights, more stories and greater allowable areas. These new changes in the building codes on both sides of the border would remove many hurdles in the jurisdiction level to promote the use of timber in mid-rise and high-rise buildings. As typical CLT buildings heavily rely on the connections from self-tapping screws (STS), structural behaviour of these connections is important. This work reports the laboratory experiment of STS connections with steel side plates under monotonic and cyclic loadings. The goal of the work is to explore potential technology for CLT and other MTC to further exhibit strong and ductile behaviour under disastrous loads. Five-ply CLT samples are used in the study. The STS from two manufacturers with the nominal diameter of 8 mm are tested for their shear capacity in CLT samples under monotonic and reversed cyclic loading. Eight replicates of each type of connections are performed. The test results indicate that the screw connections can develop a mean ultimate strength of 25.6 kN for one pair of screws. The peak loads from the cyclic tests are similar to the monotonic ones. These peak load values have a low COV, which indicates that the results are very consistent. The ductility ratio is found to range between 1.59 and 2.10, depending on the screw types and the reference methods. The ductility ratio values have significant variations, represented by large COV values. The maximum strength and energy dissipation for each cycle are also reported. With these results, the parameters for hysteretic models can be obtained, which can be used to predict the performance of different configurations of STS connections.

Keywords: Cross-laminated timber, self-tapping screws, cyclic performance, ductility, mass timber construction.

## INTRODUCTION

Mass timber construction (MTC) has been used as a traditional construction technology all over the world with a long history. This type of construction has not only observed in many ancient countries from Asia to Europe, but also in some relatively new countries after the Industrial Revolution including Canada and USA. Even nowadays, it is not uncommon to find some commercial, institutional and industrial buildings in many cities of North America that was built with old growth Douglas fir over a hundred years ago.

During the past two decades, MTC has regained the interest of many stake-holders in the construction industry. Many non-residential buildings have been built with various types of mass timber mainly from engineered lumbers. Among these materials, cross-laminated timber (CLT) has extended the use of wood to many commercial and institutional buildings that are traditionally dominated by concrete and/or steel, which is considered to be a prominent application in this section.

The wide use of CLT in the non-residential buildings has encountered many hurdles, mainly in the limit of the jurisdictions. The recent changes of National Building Code of Canada and the International Building Code allow CLT and mass timber to be used in buildings with taller heights, more stories and greater allowable areas. These new changes in the building codes on both sides of the border would remove many hurdles in the jurisdiction level to promote the use of timber in mid-rise and high-rise buildings.

As typical CLT buildings heavily rely on the connections from self-tapping screws (STS), structural behaviour of STS connections is important. Hossain et al. [1] reported their work on the performance of different types of CLT panel assemblies connected with STS under quasi-static monotonic and reversed cyclic loading. Shen et al. [2] reported their comprehensive test and numerical model assessments for uniaxial cyclic behaviors of standard bracket connections for CLT.

This work reports the laboratory experiment of STS connections with steel side plates under monotonic and cyclic loadings. The goal of the work is to explore potential technology for CLT and other MTC to further exhibit strong and ductile behaviour under disastrous loads. Two brands of STS were examined for their monotonic and reversed cyclic tests. Each type of the tests has eight replicates in order to examine their statistical behaviour and potential probability analysis. The key parameters are summarized for their essential parameters.

## EXPERIMENTAL CONFIGURATIONS

### Materials

The tests used three-ply and five-ply CLT panels fabricated by Kalesnikoff, a timber supplier located in BC. According to ANSI/APA PRG-320 [3], the CLT panels are close to grade E2 with 35 mm thick Douglas fir as the main material. Two types of partially threaded STS were used in the study. One is ASSY 4 Combi screws provided by Wurth Canada Ltd. The other is HECO Topix-plus screws provided by SFS Group USA Inc. The specific diameter of both types of screws is 8 mm. 120 mm-long screws of both types were used in the preliminary study. 140 mm-long screws of both types were closely examined with their detailed results reported here. This paper publishes the results without disclosing their brands. Instead, they are listed as type A and type B screws.

### Configurations

The steel side plates used in the tests were 6 mm thick with a yield strength of 300MPa. In order to minimize the eccentricity of the loading to the test machine and the measuring equipment, two STS screws with steel side plates were in-stalled from opposite sides and staggered to a distance of minimum seven times of the screw diameter (Figure 1). From several trial tests and the visual inspection of the cut samples through the screw holes, this staggered distance is deemed to be sufficient to minimize the eccentricity. The steel plates from the opposite sides were welded to a cross-plate reinforced with fins, which forms a U-shape plate assembly that can be installed to the test machine, as shown in the top side of Figure 1. The loaded end distance was seven times the diameter of the screws, while the penetration length is the length of the screws subtracting 1.6 mm gap between the steel plate and the wood member. The displacement of the screws relative to the steel plates were recorded using a linear transducer at a rate of 20 samples per second.

*Figure 1. Test configuration*

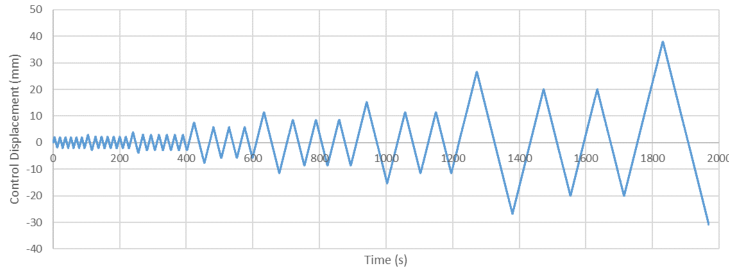


*Figure 2. The CUREE cyclic loading protocol*

### Test Protocol

The tests mainly follow ASTM D1761 [4] in the displacement control. In the monotonic tests, the loading frame moves in a displacement controlled mode at a rate of 20 mm/min. During the cyclic tests, the loading frame moves at a rate of 30 mm/min in order to complete one test in a reasonable time. The cyclic tests follow the CUREE loading protocol (Figure 2) for wood frame structures [5].

## TEST RESULTS

### Data Processing

The monotonic test results were processed to obtain the peak load ($P_{max}$) at its corresponding displacement ($\Delta_{Pmax}$) and the ultimate displacement ($\Delta_u$) defined at 80% of the peak load after that. Two data processing methods were used to obtain the stiffness: the equivalent energy elasto-plastic (EEEP) method as defined in ASTM Standard E2126 [6] and the CEN method [7]. The yield strength ($P_{yE}$) with EEEP is calculated from the energy calculated the load curve until the ultimate displacement and the stiffness ($K_E$) from the secant line at the 40% of the peak load. With the yield strength, the yield displacement ($\Delta_{PyE}$) can be determined from the load displacement relationship. The CEN method determines the stiffness ($K_C$) from the secant line between the 10% and the 40% points of the peak load. The yield strength ($P_{yC}$) in the CEN is calculated from the secant stiffness K and another line going through the peak load, which concept is briefly illustrated in Figure 3. The yield displacement ($\Delta_{PyC}$) can be determined thereafter from the curve. With the above parameters, the ductility ($\mu_E$ or $\mu_C$) can be calculated from the ratio of the ultimate displacement to the yield displacement, respectively. Overall speaking, the subscript E denotes the results for the EEEP method while the subscript C denotes the results for the CEN method. The results from both methods are reported together so that the results can be justified for future use.

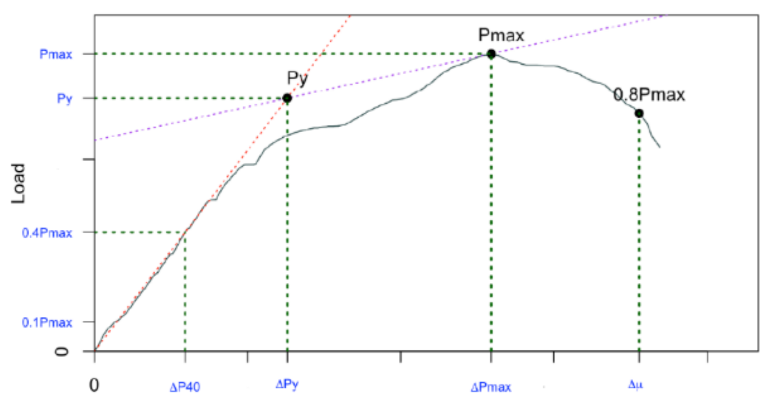


*Figure 3. Determination of parameters for monotonic tests (the CEN method shown)*

### Monotonic Test Results

The load displacement behaviour of eight monotonic tests for type A STS are shown in Figure 4. In this figure, two of them show straight decrease of the load after the peak load due to the breakage of screws near the screw head. Other tests show a relatively smooth decrease of the load after the peak, which are considered to be relatively ductile.

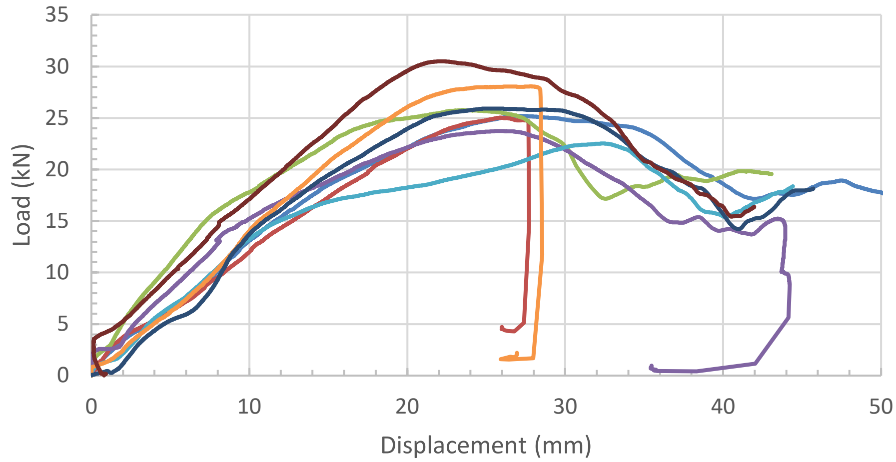


*Figure 4. The load displacement relationship of monotonic tests for type A screws*

*Table 1. Summary of monotonic test results for type A STS based on the EEEP and the CEN methods*

| Test No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Mean | COV |
|---|---|---|---|---|---|---|---|---|---|---|
| $P_{yE}$ (kN) | 23.7 | 23.4 | 23.5 | 21.4 | 19.7 | 28.1 | 24.9 | 27.8 | 24.1 | 0.11 |
| $P_{yC}$ (kN) | 24.1 | 24.0 | 22.2 | 22.2 | 18.4 | 26.9 | 24.3 | 29.3 | 23.9 | 0.13 |
| $P_{max}$ (kN) | 25.2 | 25.0 | 25.8 | 23.7 | 22.5 | 28.1 | 25.9 | 30.5 | 25.8 | 0.09 |
| $\Delta_{yE}$ (mm) | 18.7 | 19.6 | 10.7 | 13.1 | 15.3 | 21.3 | 20.1 | 13.4 | 16.5 | 0.22 |
| $\Delta_{yC}$ (mm) | 21.1 | 23.5 | 11.0 | 17.5 | 13.3 | 20.3 | 17.6 | 20.8 | 18.1 | 0.22 |
| $\Delta_{Pmax}$ (mm) | 27.4 | 25.9 | 23.5 | 25.9 | 32.3 | 27.8 | 25.8 | 21.3 | 26.2 | 0.12 |
| $\Delta_u$ (mm) | 38.2 | 27.7 | 30.7 | 33.2 | 37.2 | 28.4 | 35.3 | 32.4 | 32.9 | 0.11 |
| $K_E$ (kN/mm) | 1.26 | 1.26 | 1.26 | 1.26 | 1.26 | 1.26 | 1.26 | 1.26 | 1.53 | 0.25 |
| $K_C$ (kN/mm) | 1.14 | 1.02 | 2.02 | 1.27 | 1.38 | 1.33 | 1.38 | 1.40 | 1.37 | 0.20 |
| $\mu_E$ | 2.04 | 1.41 | 2.86 | 2.53 | 2.43 | 1.34 | 1.76 | 2.42 | 2.10 | 0.25 |
| $\mu_C$ | 1.81 | 1.18 | 2.79 | 1.90 | 2.79 | 1.40 | 2.01 | 1.55 | 1.93 | 0.29 |

The essential parameters for type A screws can be extracted from the load displacement behaviour and reported in Table 1. The maximum peak for one pair of screws can reach 30.5 kN, with the average value of 25.8 kN. The coefficient of variation (COV) of the peak loads is 0.09, which indicates that the results are very consistent. The ultimate displacement ranges between 27.7 mm and 38.2 mm, with the average of 32.9 mm and the COV of 0.11. This result is considered to be consistent as well. The yield point is based on the definition of the methods. In order to compare the impact of the methods, the yield strength, yield displacement, stiffness and the ductility ratio are shown for both methods. The average yield strength from the EEEP and the CEN method is 24.1 kN and 23.9 kN for two screws. With the COV of 0.11 and 0.13, the result of the yield strength is consistent. The ductility ratio is 2.10 and 1.93 for the EEEP and the CEN method, respectively. The COV of 0.25 and 0.29 for the ductility ratio from both methods indicates that the results of the ductility ratio have relatively great variations.

The load displacement behaviour of eight monotonic tests for type B STS are shown in Figure 5. It can be observed that the behaviour of type B screws is very similar to type A ones. In order to further quantify the performance, the key parameters are extracted and listed in Table 2. The average peak value of this type is 25.6 kN with the COV of 0.07, which is very similar to type A screws. The ultimate displacement is 36.4 mm with the COV of 0.12. This result may indicate that type B is more ductile. However, type A monotonic tests have seen two screws broken their head that reduced the mean peak displacement. The broken screws may attribute to the newly fabricated steel plates and the smooth holes at the beginning of the tests. Further test examination is needed to explore the differences of the peak displacement. The low ductility ratio of 1.59 ~ 1.80 compared to type A screws may be explained as the relatively lower stiffness and thus greater yield displacement values. The relatively large COV values (0.37~0.39) indicate the results are not very consistent.

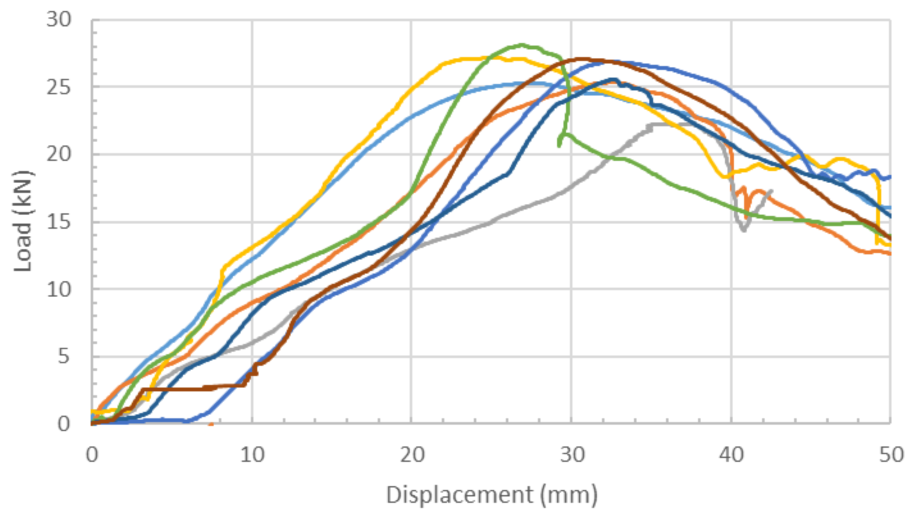


*Figure 5. The load displacement relationship of monotonic tests for type B screws*

*Table 2. Summary of monotonic test results for type B STS based on the EEEP and the CEN methods*

| Test No. | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | Mean | COV |
|---|---|---|---|---|---|---|---|---|---|---|
| $P_{yE}$ (kN) | 23.2 | 23.5 | 18.9 | 24.1 | 28.7 | 23.9 | 21.2 | 25.6 | 23.6 | 0.11 |
| $P_{yC}$ (kN) | 24.0 | 25.7 | 21.4 | 23.9 | 25.5 | 27.0 | 24.5 | 22.5 | 24.3 | 0.07 |
| $P_{max}$ (kN) | 25.3 | 26.8 | 22.3 | 27.2 | 26.6 | 28.1 | 25.6 | 23.4 | 25.6 | 0.07 |
| $\Delta_{yE}$ (mm) | 18.3 | 10.2 | 28.3 | 18.1 | 30.4 | 24.0 | 26.4 | 23.9 | 22.4 | 0.27 |
| $\Delta_{yC}$ (mm) | 19.9 | 32.1 | 31.5 | 12.9 | 27.1 | 28.0 | 25.6 | 22.3 | 24.9 | 0.24 |
| $\Delta_{Pmax}$ (mm) | 27.1 | 26.6 | 35.5 | 24.9 | 26.1 | 27.0 | 32.6 | 20.5 | 27.5 | 0.16 |
| $\Delta_u$ (mm) | 43.2 | 34.1 | 40.1 | 37.1 | 36.6 | 29.7 | 40.3 | 30.2 | 36.4 | 0.12 |
| $K_E$ (kN/mm) | 1.27 | 2.31 | 0.67 | 1.33 | 0.94 | 0.99 | 0.80 | 1.07 | 1.17 | 0.41 |
| $K_C$ (kN/mm) | 1.20 | 0.80 | 0.68 | 1.85 | 0.94 | 0.96 | 0.95 | 1.01 | 1.05 | 0.32 |
| $\mu_E$ | 2.36 | 3.35 | 1.42 | 2.05 | 1.21 | 1.24 | 1.53 | 1.26 | 1.80 | 0.39 |
| $\mu_C$ | 2.17 | 1.06 | 1.27 | 2.88 | 1.35 | 1.06 | 1.57 | 1.35 | 1.59 | 0.37 |

**Cyclic Test Results**

For both type A and B screws, eight replicates were used in the reversed cyclic tests. The load displacement behaviour of one test with a pair of type A screws can be found in Figure 6. The mean peak load of eight tests is 26.0 kN with the COV 0.082. This result indicates that the peak load of the cyclic tests is very consistent with the monotonic ones, which is considered to have a great potential for energy dissipation for earthquake loading. The backbone curves of all eight replicates of type A are shown in Figure 7. In each cycle, the strength change of the screws can be recorded, as shown in Figure 8. It can be found that the strength for the trailing cycles is significantly lower than the primary cycles. Figure 9 shows the energy dissipation of the type A STS connection over all cycles. This figure further confirms that the energy dissipation or the resistance to the potential earthquake loading rely on the primary cycles. The maximum energy dissipation per cycle before failure is 363 kN.mm, with the COV of 0.278. This large variation of the results can be explained that one test failed in an early cycle, without showing significant energy dissipation. All these results are based on a pair of screws.

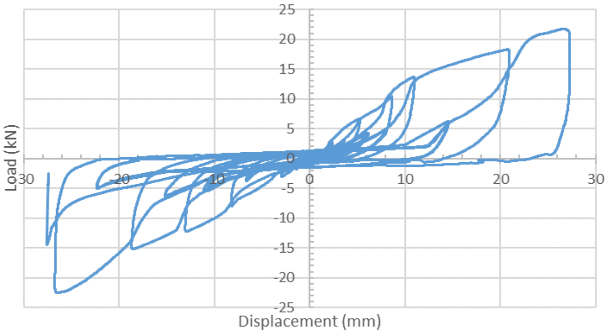


*Figure 6. Typical cyclic test result for the connection with one pair of type A screws*

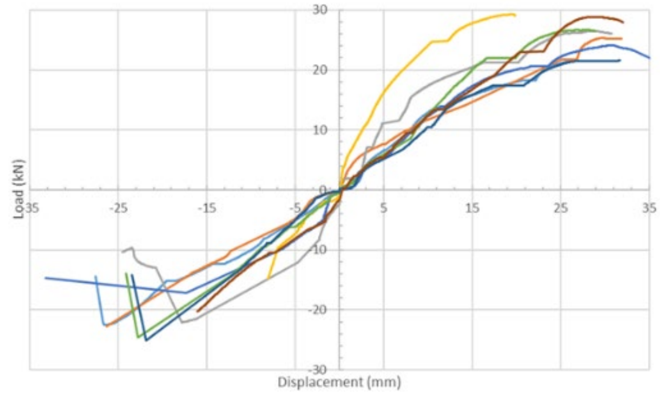


*Figure 7. Backbone curves of cyclic tests for type A screws*

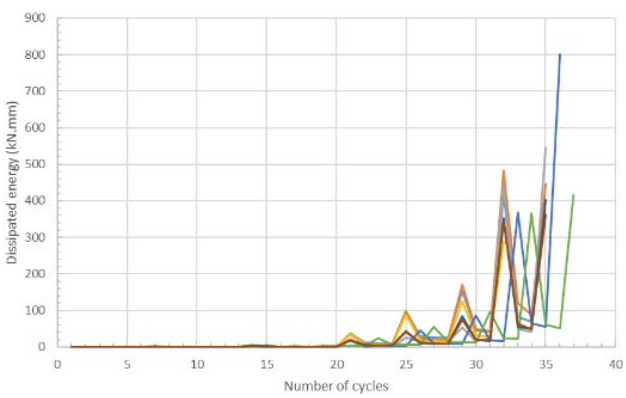


*Figure 8. Strength change per cycle of cycle tests for type A screws*

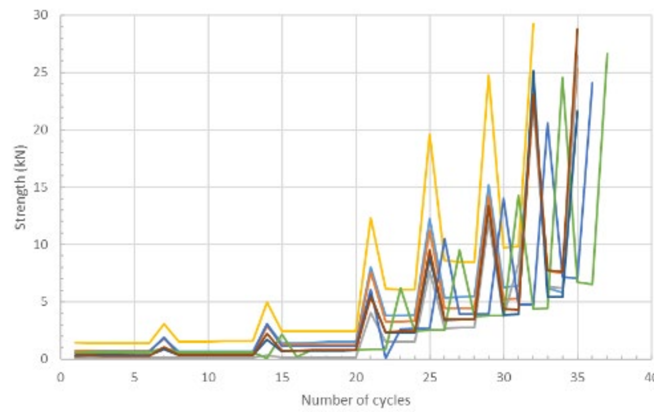


*Figure 9. Energy dissipation per cycle of cyclic tests for type A screws*

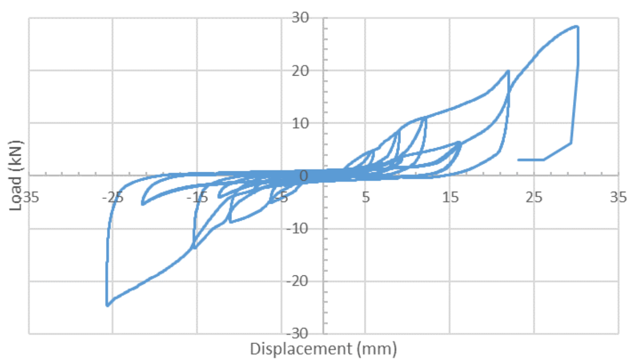


*Figure 10. Typical cyclic test result for the connection with one pair of type B screws*

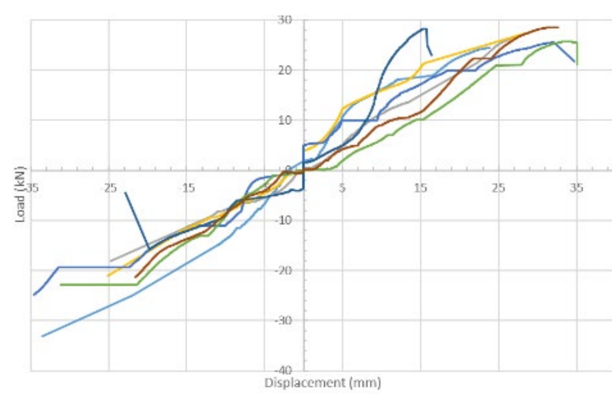


*Figure 11. Backbone curves of cyclic tests for type B screws*

The results for type B screws are similar to those of type A. A typical load displacement curve is shown in Figure 10. The mean peak load of the tests is 28.9 kN. A low COV of 0.057 for the peak load was observed, which indicates the results are consistent. This peak load is 13 greater than the monotonic results. The comparison of the backbone curves of all eight replicates of type

B screws can be found in Figure 11. The strength change in each cycle is recorded as shown in Figure 12. The energy dissipation in each cycle can be found in Figure 13. The maximum energy dissipation per cycle is 418 kN.mm with a COV of 0.232.

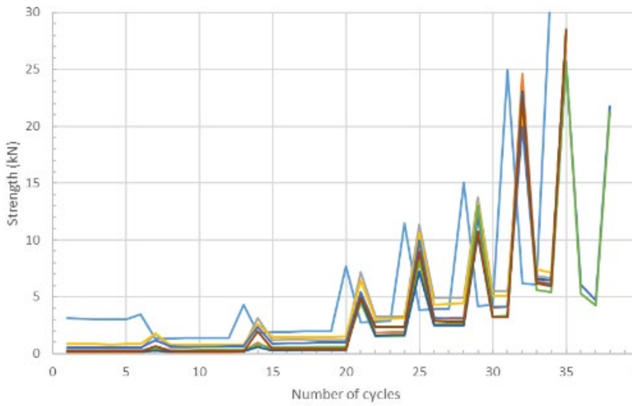


*Figure 12. Strength change per cycle of cyclic tests for type B screws*

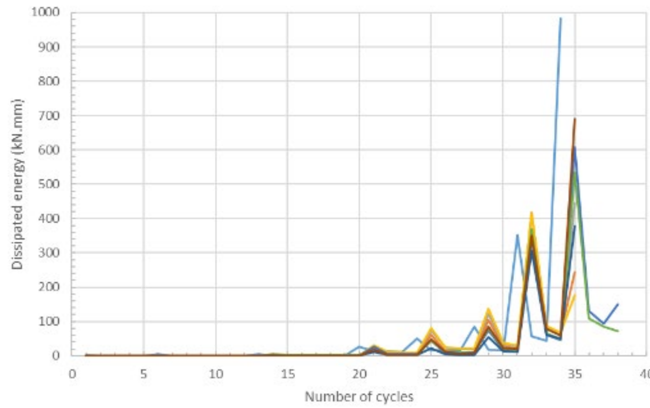


*Figure 13. Energy dissipation per cycle of cyclic tests for type B screws*

**Failure Modes**

In about 10% of the monotonic tests, both types of screws broke near the end of the head where the steel plate holes bends the screws (Figure 14). Although both types of screws have a large diameters at this location, the weak point still occurs. The most other screws  did not fail. Instead, they gradually pulled out from CLT during the monotonic (Figure 15) and cyclic tests and can be taken out after the tests (Figure 14). In one of all test samples, one screw (type B) was broken in the threaded portion, which may be explained as a fatigue failure during the cyclic test.

*Figure 14. Some screws after tests*

*Figure 15. Screws pull-out during the tests*

## CONCLUSIONS

The paper introduces the experimental studies to examine the lateral resistance of STS used in CLT construction with steel side plates. Monotonic and reversed cyclic tests were conducted to study their load displacement behaviour. Two brands of STS of 14 mm long screws were used in the tests. Each type of tests has eight replicates, in order to examine the potential impact to the probabilistic behaviour for seismic loading. Both types of screws have an average of peak strength above 25.6 kN from the monotonic tests. The peak loads from the cyclic tests are similar to the monotonic ones, which implies the great potential for energy dissipation under seismic loading. The test results for the peak load have a low COV, which indicates that the results are very consistent. The ductility ratio is found to range between 1.59 and 2.10, depending on the screw types and the reference methods. The ductility ratio values have the significant variations, with the COV of 0.25 ~ 0.39. The maximum strength and energy dissipation for each cycle are also reported. With these results, the parameters for hysteretic models can be obtained, which can predict the performance of different configurations of STS connections. These parameters can also be used to explore the potential new applications in structural components that can develop ductile structural response for gravity and lateral loads.

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