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APPLICATION OF A TUBE CONNECTOR FOR CATENARY ACTION IN CLT FLOORS

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ABSTRACT: Multi-storey buildings require provisions to avoid disproportionate consequences after unexpected events, e.g. explosions or human error during design and construction. To prevent failure progression in the structure after an initial damage (loss of load-carrying elements), alternative load paths, like catenary action, should be provided. Catenary action supports the sagging structure after element loss by transferring the loads horizontally to the adjacent elements; this mechanism requires the connections to remain ductile under high load. Conventional dowel-type connectors in timber structures have limited potential to develop catenary action in beams or floors. A previously developed tube connector exhibited desirable behaviour to develop catenary action in cross-laminated timber floors; however, the tube exhibited and undesirable failure mode. In the present study, the behaviour of a newly designed variant of the tube connector was experimentally investigated under catenary action. The new connector design was tested in varying configurations, at both the component level and full-scale floor level, in Canada and Sweden. The results show that a more desirable behaviour of the adapted connector could be achieved compared to the previous design, with respect to catenary action.

KEYWORDS: Disproportionate collapse, Progressive collapse, Structural robustness, Alternative load paths

1 INTRODUCTION

1.1 BACKGROUND

Multi-storey timber buildings can provide living space for many occupants. The more occupants, the more severe are the possible consequences if unforeseen events lead to a damage and a subsequent collapse. Disproportionately large collapses, in relation to their original cause, e.g. an explosion, a vehicle accident or human errors during design and/or construction, must be avoided. Often, a disproportionate collapse occurs because the progression of an initial component failure cannot be halted, which is then usually referred to as a progressive collapse. Some building codes, e.g. Eurocode 1 [1], require that a progressive collapse shall be avoided for buildings taller than four storeys or with a certain number of occupants.

A building can be designed to resist a progressive collapse by providing alternative load paths (ALPs) after certain components have failed. [2]. Examples of ALPs in floors after the loss of a support include compressive arching action for small deflections, and catenary action or membrane action for large deflections [3]. In catenary action, the beams or floors support the sagging structure by acting like a chain and transferring the loads mainly by in-plane tension to the surrounding undamaged structure.

1.2 FLOOR CONNECTORS AND CATENARY ACTION

In timber structures, catenary action can be developed in beams in post-and beam systems, or in cross-laminated timber (CLT) floor panels. Currently available dowel-type connectors do not allow for large deformations of beam or floors, e.g. tests of timber post-and-beam systems found that conventional connectors failed prematurely and could not develop catenary action; however, a double slotted-in steel plate connector, with elongated holes to allow joint rotation, was able to develop catenary action [4]. Support-removal tests in [5] on lap-jointed solid timber floors and walls in platform-type construction, including CLT floors, found that conventional screw connections were not able to develop catenary action.

In contrast, tube connectors [6] were able to support substantial catenary forces under large displacements in CLT floors [5]. In a numerical optimisation of the original design [7], the most influential parameters were found to be the tube diameter, the tube thickness, and the coupler diameter. The original tube design used a welded coupling nut on the inside of the tube; this was a weak spot where brittle rupture occurred, as shown in Figure 1.

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***Figure 1**: Original tube connector with welded coupler*

In a numerical study [8], 3D finite element (FE) models were developed, and parameter variations were conducted reflecting a building situation to study both traditional screw connections and the tube connector in a support-removal scenario. The study found that catenary action was the dominant ALP and confirmed the suitability of the tube connector for catenary action.

1.3 OBJECTIVE

Given the simplicity of the tube connector regarding manufacturing and installation, and its suitability to develop catenary action under large floor rotations, it was deemed worthwhile to investigate further adaptations to improve its performance. The goal of the present study was to investigate the behaviour of a newly designed variant of the tube connector with a hammerhead under catenary action in CLT floors.

2 MATERIAL & METHODS

Tests were conducted at the Wood Innovation Research Lab in Prince George, Canada, and the lab of the Research Institutes of Sweden (RISE) in Skellefteå, Sweden.

2.1 MATERIALS

In Canada, 100 mm thick 5-ply CLT panels with 20 mm thick layers made of Norway Spruce (*Picea abies*) of strength class C24 [9] were used. The boards were edgewise bonded. All cutting and milling was done in the test lab. In Sweden, 200 mm deep 5-ply CLT panels with 40 mm thick layers of Norway Spruce of strength class C24 [9] were used. The edges of the boards were not glued. The panel geometry including the cut-outs for the tube was cut and milled at the manufacturing site.

The outer diameter of the tubes was 3'' (76,2 mm). The steel for the Canadian tubes was A/SA 106 Grade B (minimum yield strength 240 MPa) and for the Swedish tubes was S355 (minimum yield strength 355 MPa). In Canada, the length of the tube was 100 mm and the thickness was 3 mm, and in Sweden, the length was 140 mm and thicknesses of 4 mm and 5 mm. Two holes on opposing sides were cut at mid-length of the tube for passing through the rod. In Canada, two circular holes were cut, but in Sweden one of the holes was cut as an elongated slot to not restrict the rod movement in certain test variations.

Instead of the welded coupler used in [5], a conically shaped steel part with a cylindrical base was used, herein referred to as the *hammerhead*, and it was held in place by a standard nut. The hammerhead pushed onto the outside of the tube instead of pulling on the inside. In Canada, a hammerhead with an outer diameter (D_1) of was 1,5'' (38,1 mm) and a height (h) of 0,5'' (12,7 mm) was used, with the conical base facing away from the tube, see Figure 2b. The hammerhead was mild steel grade ASTM A36, while for the threaded 5/8" (19,9 mm) rod, grade ASTM A193 Grade B7 was used (minimum yield strength 720 MPa). In Sweden, a hammerhead with D_1 = 50 mm and h = 20 mm was used and it was positioned with the cylindrical base towards the tube, see Figure 2a. A standard M20 threaded rod with strength class 8.8 (minimum yield strength 640 MPa) was used together with a class 12.9 nut.

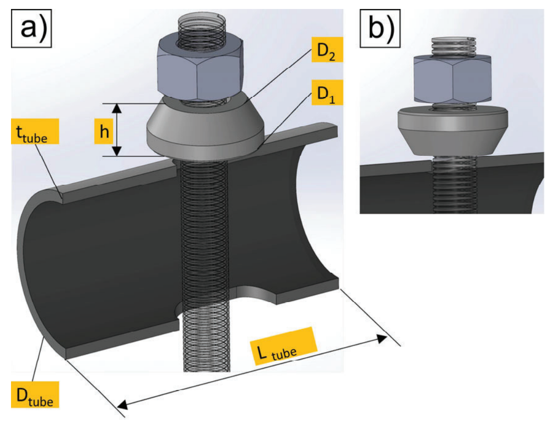

***Figure 2:** Tube connector with hammerhead; a) Swedish and b) Canadian version*

2.2 TUBE PRE-TESTS

Tensile tests on the tube connector, embedded in CLT, were performed by applying a displacement-controlled, quasi-static load along the axis of the rod. The insights gathered during the pre-tests were used for final adjustments of the connector designs to be used on tests in full floor elements.

For the Canadian tests, the CLT samples were 350 mm wide and 800 mm long, see Figure 3. The cut-out to embed the tubes was machined through the full depth of the panel and the part for embedding the rod was machined to a depth of 60 mm (3 layers). A symmetric loading setup with two tubes being tested simultaneously was chosen. The relative displacement between CLT panel and tube edge was measured by two linear variable differential transformers (LVDT) positioned on a thin metal plate locked by nuts to the end of the rod. The load was applied displacement-controlled at 10 mm/min.

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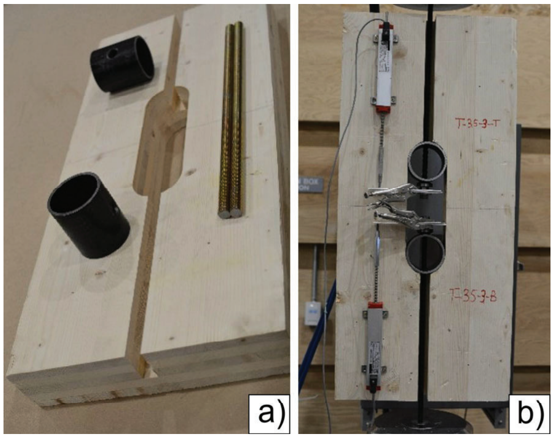

Figure 3: *Canadian pre-tests of the tube connector*

For the Swedish pre-tests, the CLT samples were 400 mm wide and 600 mm long, see Figure 4. The circular part to embed the tube was machined to a depth of 170 mm and the part to embed the rod was machined to 130 mm depth, see Figure 4a. Only a single tube was used in each test repetition, while the rod was fixed at approximately half its length to a rigid steel frame. The other side of the CLT sample was fixed by nine fully-threaded self-tapping screws (STS) with diameter 13 mm and length 200 mm [10] to customised steel parts which provided a rotation-free connection to the pulling hydraulic cylinder, see Figure 4b. The STSs were inserted using a 45-degree angled washer of type VGU [10]. The displacement in the hydraulic cylinder was increased by 6 mm/min and the resulting load was recorded. The total displacement was measured at the edge of the panel facing the fixed point of the rod using a LVDT. Additionally, the relative displacement between the CLT panel and the customised steel parts was measured to control for slippage.

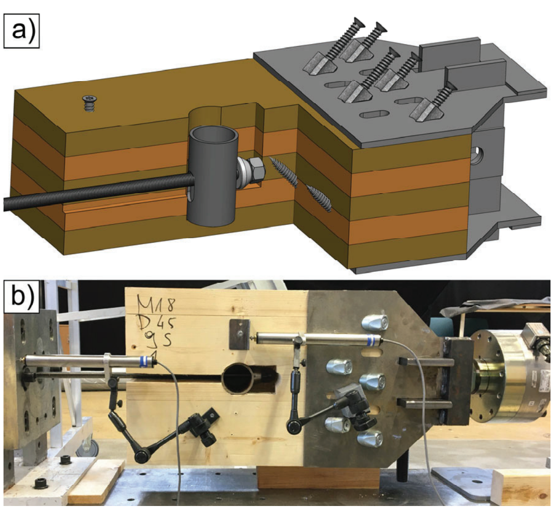

Figure 4: *Swedish tube pre-test; a) tube placement and b) test setup*

2.3 FLOOR ELEMENT TESTS

To evaluate the performance of the tube connector under catenary action in the lengthwise direction of the floor panels, pushdown tests were conducted with full-length CLT panels over a removed wall support, as shown in Figure 5 for the Canadian tests.

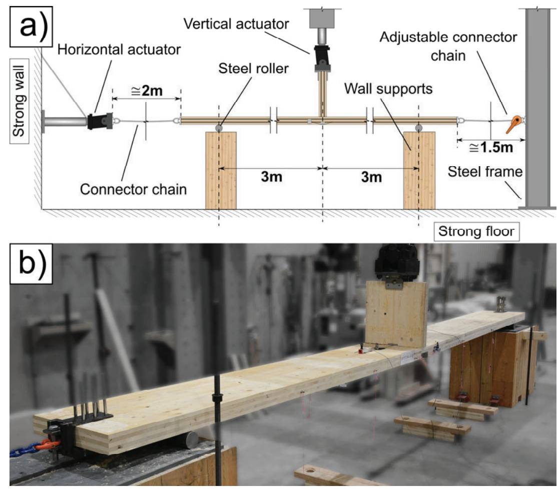

Figure 5: *Canadian floor element tests; a) idealised and b) lab setup*

For the Canadian tests, a single span of 3 m was assumed, i.e. the nominal length between the supports in the tests was 6 m. The CLT panels were 600 mm wide and butt-jointed lengthwise (Figure 6). The tube connector was inserted in pre-milled cut-outs in the panels. The screws used for the butt connection were 140 mm SWG fully threaded STS [11] installed at 45° angle. To prevent the rod of the tube connector from rising above the surface of the CLT panels, the loading was applied via a CLT wall section on the centre of the joint. A steel stopper was manufactured to fit underneath the load application wall to prevent the rising rod from compromising the wall-to-floor contact. Since the pushdown actuator had a maximum stroke of 500 mm, the test was conducted in two stages to fully deform the tubes; firstly, a 600 mm tall wall section was used up to approximately 300 mm extension of the actuator, and after unloading and exchanging the wall with an 800 mm section, the loading was continued. The vertical supports were long steel rollers, and the horizontal displacement was fixed by running chains from strong wall to the sample on both sides. These were fixed onto steel C-clamps with 6 steel ¾” (19,1 mm) bolts. One of the chains ran to a horizontal actuator which allowed for pre-tensioning of the chains to take out slack while acting as a load cell. Thanks to this setup, compressive arching was omitted as only tensile forces could be transferred through the chain and the friction of the rollers was negligible.

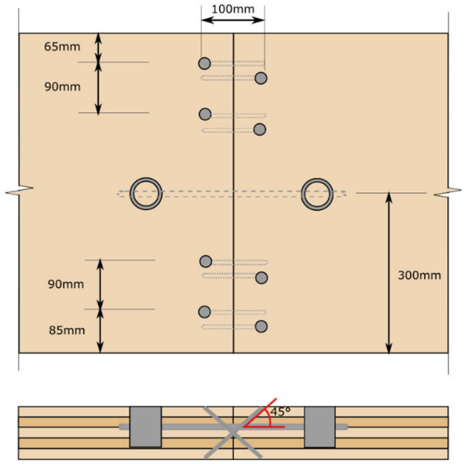

Figure 6*: Butt joint and tube connector alignment in Canadian floor tests*

For the Swedish tests, the test setup was adapted for an inverted load application, see Figure 7, to allow the use of the full hydraulic cylinder stroke. The panels were flipped, and the tubes were thus inserted from below to connect the panels. The custom steel plate connectors from the pre-tests were slightly adapted and used for rigidly fixing the panels horizontally. Rotation was free at the ends which was achieved by a pinned connection between the end connection and the rigid frame. Effectively, the span was 200 mm larger due to the connector. An additional hydraulic cylinder with a load cell was attached to one of the end connections to measure the horizontal tie force and to apply a 0.5 kN pre-load on the tube connector to prevent it from slipping out of the cut-out.

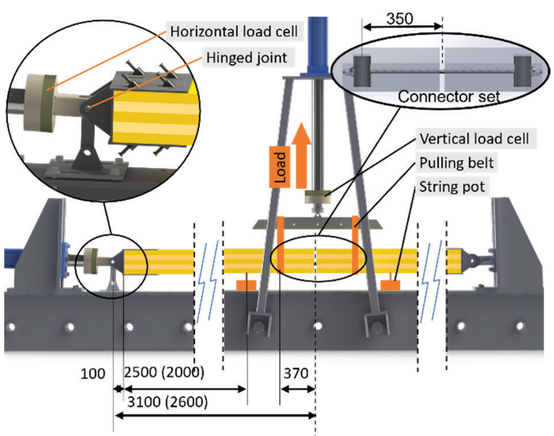

Figure 7: *Swedish test setup for the floor element tests (mm)*

The panels used were machined symmetrically such that a cut-out for the tube was provided in both ends. After initial tests with a length of 3 m, 500 mm were cut off from the end used in the experiment and the remaining panel was reused at a length of 2.5 m, i.e. a length of 5 m between the supports. For the 2.5 m panels, the tube was inserted as indicated in Figure 4a, i.e. with the slot hole restricting the motion of the rod during rotation, and for the 3 m panels, the tube was inserted in a flipped orientation to allow rod movement during pushdown. For reference, floor elements without a tube connector, but with four angled double-threaded 8.2 mm × 280 mm STS [10] were tested.

The floor system was pushed down (i.e. pulled up) by applying a displacement-controlled quasi-static load via a spreader beam and straps, see Figure 7. The vertical pushdown force and the horizontal tie force were recorded. The pushdown displacement was recorded using string potentiometers. Since the horizontal fixture of the floor was unable to provide noticeable compliance, compressive arching action as in [8] was expected to occur between the panels. Since this resistance mechanism was not of interest for this study, and to single out the effects of catenary action, an initial 20 mm gap was provided between the panels. For the tests with STSs only, no initial gap was provided since a gap was expected to disproportionately affect the performance of the screw connection negatively.

3 RESULTS & DISCUSSION

3.1 PRE-TESTS

A typical development of the tube deformation during the Canadian pre-tests is shown in Figure 8 and the corresponding force-displacement curves in Figure 9. After an initial elastic phase (Figure 8a), tube yielding (8b) and hardening occurred until the ultimate load was reached (8c) and subsequent yielding led to softening (8d). The tubes predominantly engaged in a folding mechanism along a line along the tube length during yielding.

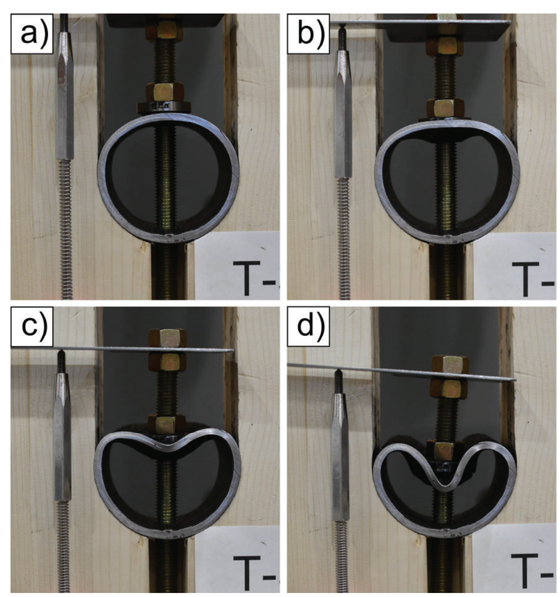

Figure 8*: Pre-test of the Canadian tubes showing the tube deformation from unloaded to loaded state (a-d)*

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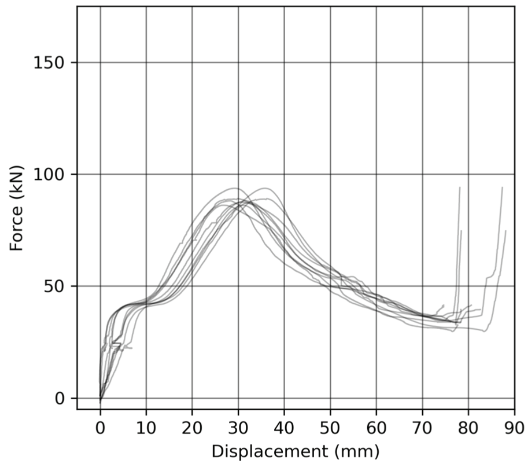

***Figure 9**: Force-displacement curves of 10 Canadian pre-tests.*

The Swedish pre-tests showed that the folding mechanism of the tubes during yielding was dominated by the more point-wise circular impression of the hammerhead (see Figure 10) than the Canadian tests due to the increased tube length. It was observed that the 5 mm tubes induced timber failure before the ultimate load of the tube could be reached. The 4 mm tubes reached their ultimate load consistently without timber failure if hammerheads with $D_1 = 50$ mm were used, see Figure 11. Additional tests with hammerheads of $D_1 = 45$ mm resulted in the hammerhead being pulled through the hole of the tube during yielding before tube folding was completed.

***Figure 10**: Deformed tube from the Swedish pre-tests*

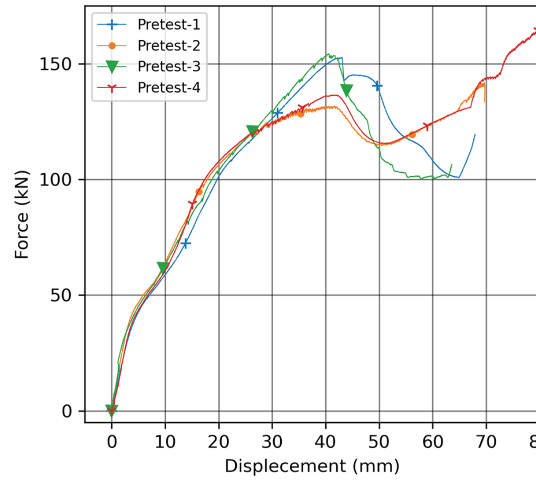

***Figure 11**: Force-displacement curves of the Swedish pre-tests for 4 mm tubes with hammerheads with 50 mm diameter.*

3.2 FLOOR ELEMENT TESTS

Figure 12 shows the pushdown and tie force curves of the Canadian floor element tests. The initial gradual increase in slope proves to be proportional to the geometrical deformation as expected of the steadily increasing catenary response with no compressive arching present. The failure of the butt joint is indicated by load plateau at approximately 350 mm pushdown, after which all load is transferred to the tube connector. Two clear peaks at approximately 10° and 13° floor rotation and subsequent load drops represent both tubes buckling at separate times.

The three-point testing may have affected the redistribution of forces in the connector as the metal stopper (Figure 13b) under the wall forced the deformation in the tubes on both sides to be in line with the panels. This setup might also have caused tube buckling to occur at corresponding lower pushdown distance than in the Swedish four-point tests (see below) because the displacement of the hammerhead was larger in order to conform with the enforced bent shape of the rod. The benefit of this wall configuration however is that the rod alignment remains normal to the tube walls, which could make the tube behaviour more predictable as it can be correlated more directly to the pure tension tests. This may furthermore reduce the risk of punching failure through the tube wall.

Despite the additionally provided actuator stroke, none of the specimen failed completely, after having deformed both tubes fully, see Figure 13c. Given the results of the Swedish tests (see below), it seems likely that the tube connectors in the Canadian tests reached their maximum load at the second buckle peak and that failure would occur not long after.

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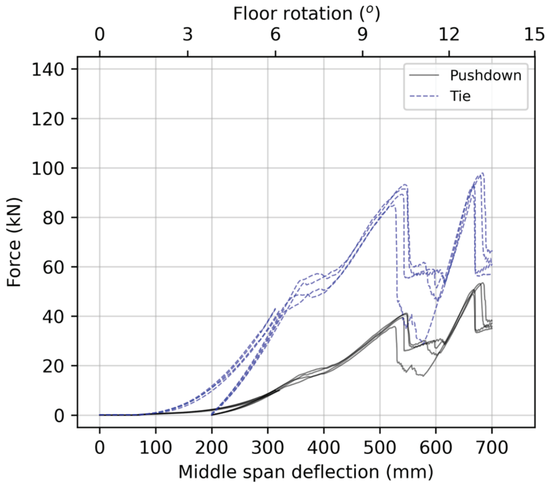

Figure 12*: Force-displacement curves of the four Canadian floor element tests*

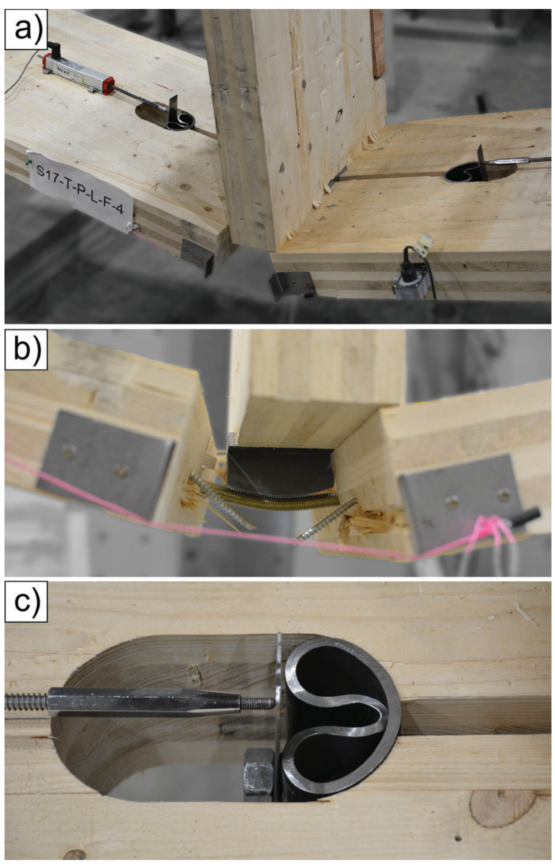

Figure 13*: Canadian floor level tests during large floor rotations; a) wall section pushing on the floor panels, b) metal plate bending the rod of the tube connector and c) deformed tube connector*

The pushdown and tie force curves for the Swedish floor element tests with tube connectors in 3 m panels are shown in Figure 14 and for the 2.5 m panels in Figure 15.

After an initial dead phase caused by the gap between the panels, catenary action developed and could be sustained up to at least 10° of floor rotation. The dip in force at approximately 570 mm of pushdown deflection in Figure 14 was due to shear failure in the tube since the large rotation led to a load concentration at the hammerhead, see Figure 16a, which was aggravated by the slot hole. This effect was not as pronounced for the 2.5 m panels, because the flipped orientation of the slot kept a straighter pushing direction of the hammerhead onto the tube.

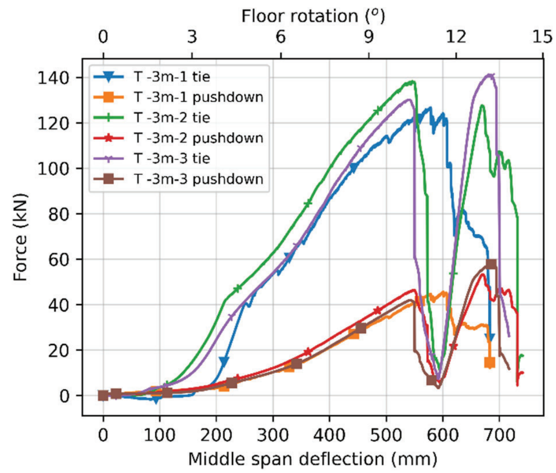

Figure 14*: Force-displacement curves of the Swedish 3 m floor element tests with tube connectors*

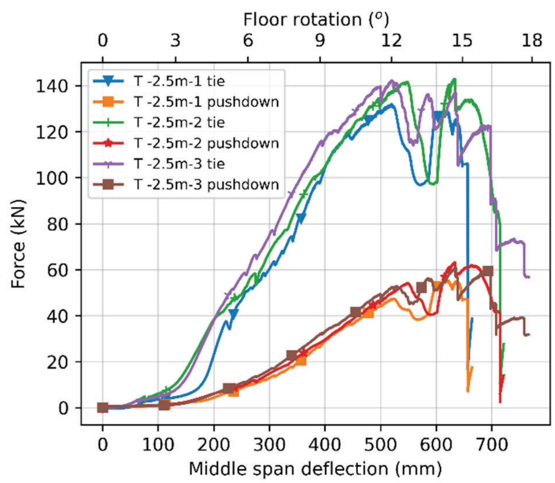

Figure 15*: Force-displacement curves of the Swedish 2.5 m floor element tests with tube connectors*

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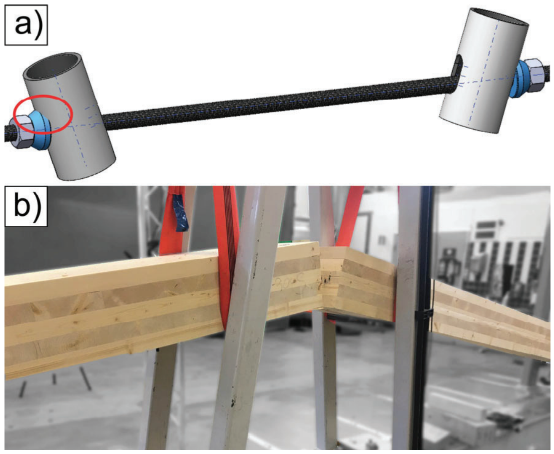

Figure 16: *Swedish floor element test; a) load concentration in the tubes and b) pushed-down floors*

Figure 17 shows the mean pushdown and tie curves of three Swedish floor element tests each with the screw connection. Since no gap existed between the panels, no dead phase occurred and instead, compressive arching action developed below 200 mm of pushdown deflection. Catenary action could not be sustained as the screws were bent and extracted from the CLT, see Figure 18.

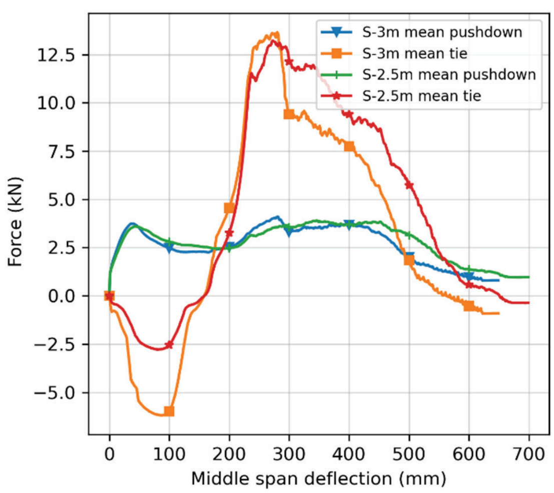

Figure 17: *Force-displacement curves (means) of the Swedish floor element tests with screw connections*

Figure 18: *Screw failure during pushdown in the Swedish tests*

3.3 COMPARISON TO PREVIOUS RESULTS

Previously conducted tests of the original tube connector design in [6] tested 3’’ diameter tubes (variant T3) of 3 mm thickness in CLT in a similar loading configuration as the pre-tests in the present study. The used steel grade of the tubes had a yield strength of approximately 400 MPa. The results for the monotonic tests in [6] showed an ultimate load of approximately 50 kN at 24 mm displacement in the tube, which are both lower than the corresponding results in the present study. The development of the tube deformation and the characteristic shape of the load-displacement curves were similar in both studies.

The previous tests in [5] used the original tube connector design, as specified above, in similar pushdown tests as in the present study. Two connectors were used in CLT panels of a single span of approximately 2 m. The ultimate load of the tubes was not reached due to limited pushdown displacement and the maximum pushdown force for a single tube connector was approximately 15 kN at a floor rotation of approximately 7.2°. The models in [8] simulated larger pushdown displacements at slightly different boundary conditions for the tests in [5] and predicted an ultimate pushdown force of approximately 24 kN at a floor rotation of 12° for a single connector. The results of the present study indicate higher pushdown forces at corresponding floor rotations.

4 CONCLUSION

A new design of a tube connector for sustaining catenary action after a support removal in CLT was explored. Instead of using an internally welded coupler which may exhibit brittle weld failure, an external hammer pushed onto the tube and plastically deformed it during large joint rotations. The new connector design was tested in varying configurations, at both the component level and full-scale floor level, in Canada and Sweden.

The results indicate that the adapted tube connector could sustain higher catenary forces than the previous design at similar joint rotations. While variants with 4 mm tubes and slot holes which allow a changing direction of load application in the hammerhead could lead to abrupt load decreases due to shear failure, the new design did not exhibit a tendency for brittle failure. The conducted tests provided consistent results although slight variations existed in the material and test setups.

Compared to the initial design, a larger cut-out in the CLT was required to embed the connector. Nevertheless, the new design provides a more independent separation of the design components of the tube connector. The hammerhead geometry may further be adapted to produce a desired plastic deformation mode of the tube under load. With this design flexibility, alternative load paths in a damaged structure may be customised as desired.

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