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FULL-SCALE TESTING OF SHEAR TAB CONNECTIONS SUBJECTED TO COMBINED AXIAL AND SHEAR FORCES

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Abstract: A common approach to connect steel beams to columns is to use single plate shear tabs. Numerous laboratory test programs of these connections subjected to vertical loading alone have been completed over the past 30 years. However, the effect of axial forces on the shear tab's performance has only recently been the subject of study. If the shear tab were part of a lateral load resisting system, such as a concentrically braced frame, axial forces could develop as earthquake or wind loads are transferred through the horizontal framing structure to the bracing bent. Similarly, beams may be required to stabilize out of plumb columns subjected to gravity loads; in this case the shear tabs will also experience an axial force. The presence of an axial force in the shear tab connection will typically result in the need for multiple rows of bolts, which is not addressed in any Canadian design guide. A series of four full-scale tests were performed on shear tab connections between a W610x140 beam and a W360 x 196 column, as well as a W310 x 60 beam and a W360 x 196 column. The shear tab, which was configured as a double bolt row connection, was subjected to a combined vertical (shear) force and axial tension along with the anticipated rotation of a typical beam-to-column joint. A matching specimen was then tested under shear and axial compression. In general the presence of an axial compression force in the connection increased the shear resistance, while an axial tension decreased the shear resistance, as expected for common length (not extended) shear tabs. This paper will report on the test program and the general findings.

1 RESEARCH PROGRAM

The global research program is aimed toward improving the current design and detailing provisions in Canada used for structural steel shear tab connections. The series of tests described herein was performed as part of a sub-project in which the performance of shear tab connections subjected to combined vertical and axial forces was evaluated. Due to the complexity of testing full-scale specimens that are subjected to combined loading effects (moment, shear, and axial loading), finite element simulation of the connections will also be relied on for this research. However, this paper is limited to a discussion of the laboratory test program. The advantage of using finite element simulation is that the level of loads can easily be changed and more cases can be investigated in less time and with less cost compared to full-scale testing. For this reason only four full-scale tests were selected to be performed, the results of which will be used to better understand the response of the connections to combined loading actions and to calibrate the subsequent finite element models. Shear tab connections have been the subject of many past test programs, as described by Creech (2005), however, limited information is available for these connections when subjected to axial and shear loads (Oosterhof & Driver, 2011).

2 FULL SCALE LAB TESTING

2.1 Test configurations

The global research program comprised different shear tab connection specimens varying in member size, plate size, number and size of bolts, number of bolts per row and support condition. The shear tab connections shown in Figure 1 and described in Table 1 were selected to be tested under combined axial and shear loads because they are commonly used in construction and because previous tests of the same connections under shear loading were carried out by Marosi et al. (2011a,b). One of the methods to increase the axial resistance of shear tab connections is to use multiple rows of bolts, which was also why these connections were selected for testing. Each shear tab configuration was tested once under combined tension plus shear load and once under combined compression and shear load. The results were compared to the findings of Marosi et al. who tested the same shear tabs subjected to vertical shear loading alone.

Table 1. Shear tab test configurations

Test no.	***#1***	***#2***	***#3***	***#4***
Shear tab dimensions (mm)	225x165x10	225x165x10	456x178x16	456x178x16
Shear tab weld size (mm)	6	6	10	10*
Test beam	W310 x 60	W310 x 60	W610 x 140	W610 x 140
Test column	W360 x 196	W360 x 196	W360 x 196	W360 x 196
Bolt size (mm (in))	19 (3/4)	19 (3/4)	22 (7/8)	22 (7/8)
Number of bolts per row	3	3	6	6
Number of rows	2	2	2	2
Axial load type	Compression	Tension	Compression	Tension
Axial load amplitude (KN)	215	215	512	512

* Weld for test #4 was designed to be 10mm but after the test it was measured 5mm

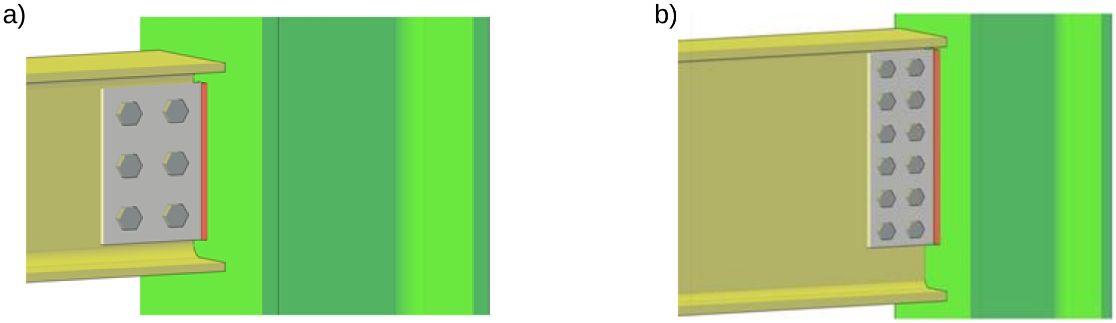

Figure 1. a) Test #1 and #2 shear tab specimens, b) Test #3 and #4 shear tab specimens

2.2 General test setup

An illustration of the full test setup design of test #4, which was subjected to combined tension and shear load, is provided in Figure 2. The shear tabs were shop welded to a W360x196 ASTM A992 Grade 50 (F_y = 345 MPa) column which was connected to the strong floor of the laboratory. Fillet welding was performed on both sides of the shear tab by using a flux-cored arc welding (FCAW-G) process along with an additional shielding gas (CO_2) and an E71T (480 MPa) electrode. ASTM A572 Grade 50 (F_y = 345 MPa) hot rolled plate was used for the shear tab specimens. Transfer of forces from the actuators to the shear tab connection was through an ASTM A992 Grade 50 (F_y = 345 MPa) test beam which varied in size and length for different test configurations (Table 1). ASTM A325 bolts were used to connect the shear tab to the test beam; the shear plane did not intercept the bolt threads, and the holes in the shear tabs and beams were drilled 1.6 mm (1/16") greater in diameter than the bolts.

A displacement based approach was used for loading the test beam in shear. The column member was positioned beneath a 12 MN MTS hydraulic actuator, which generated the main shear force in the connection. Compatibility for free rotation and free friction was achieved by using a half steel cylinder, steel plate and roller system between the MTS actuator head and the test beam’s top flange (Figure 3B). Close to the tip of the test beam, a 269 KN hydraulic actuator was suspended from a reaction frame that was fixed to the strong floor; this actuator was used to control the end displacement of the beam which allowed for the control of the rotation at the connection. In order to prevent lateral-torsional buckling of the test beams, lateral braces were utilized that simultaneously allowed the test beam to move vertically. Figure 2 shows the arrangement of the lateral bracing system with the supporting frame built of double steel angles that were anchored to the strong floor.

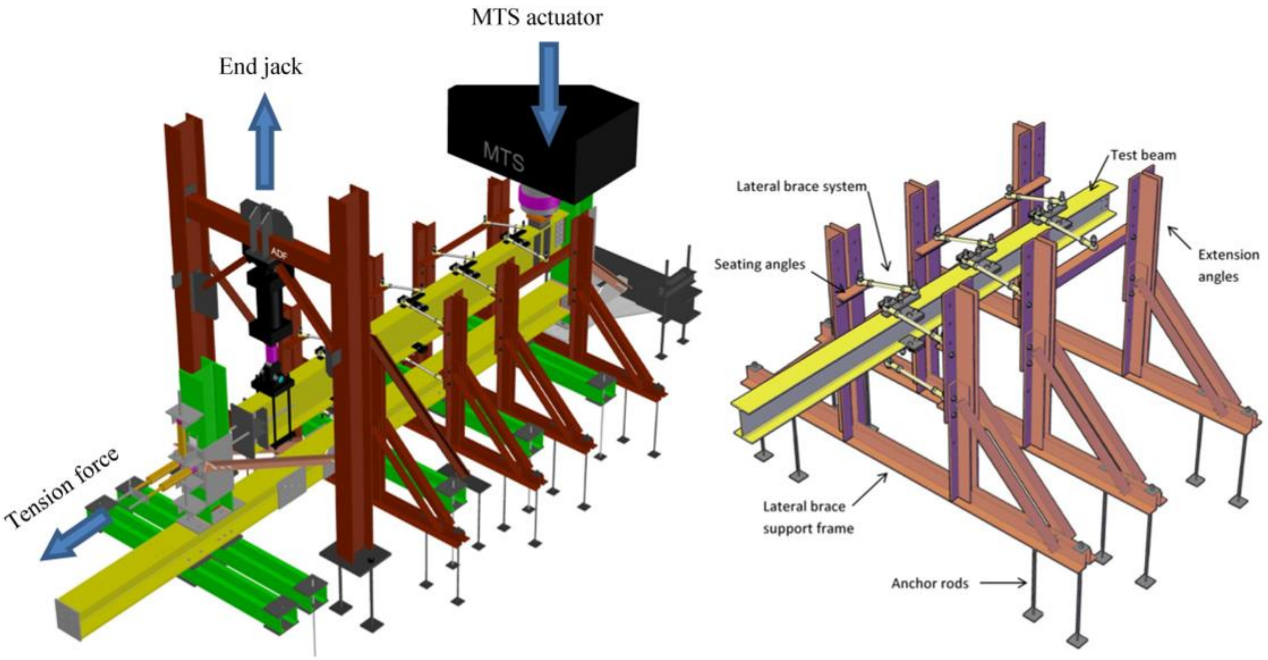

Figure 2. Full test setup for the W610 combined vertical and tension force shear tab test, with details of lateral bracing system and support frame

The Instrumentation was designed to measure horizontal, vertical displacement and rotation of the shear tab, beam and column (Figures 3a & 3b). The displacements were measured by using LVDTs and string potentiometers. Inclinometers were installed on the top flange of the test beam and on the face of the column to measure the absolute and relative rotations of the connection. The connection’s relative rotation was also measured by using two horizontal LVDTs installed on the top and bottom flange of the test beam. Strain gauges were placed at various locations of the shear tab as well as the test beam (Figure 3c). To demonstrate the progress of plastic yielding, a white lime compound was applied on the shear tab specimen and its surrounding region. The connection shear force was measured by the load cells / differential pressure cells in the MTS hydraulic actuators.

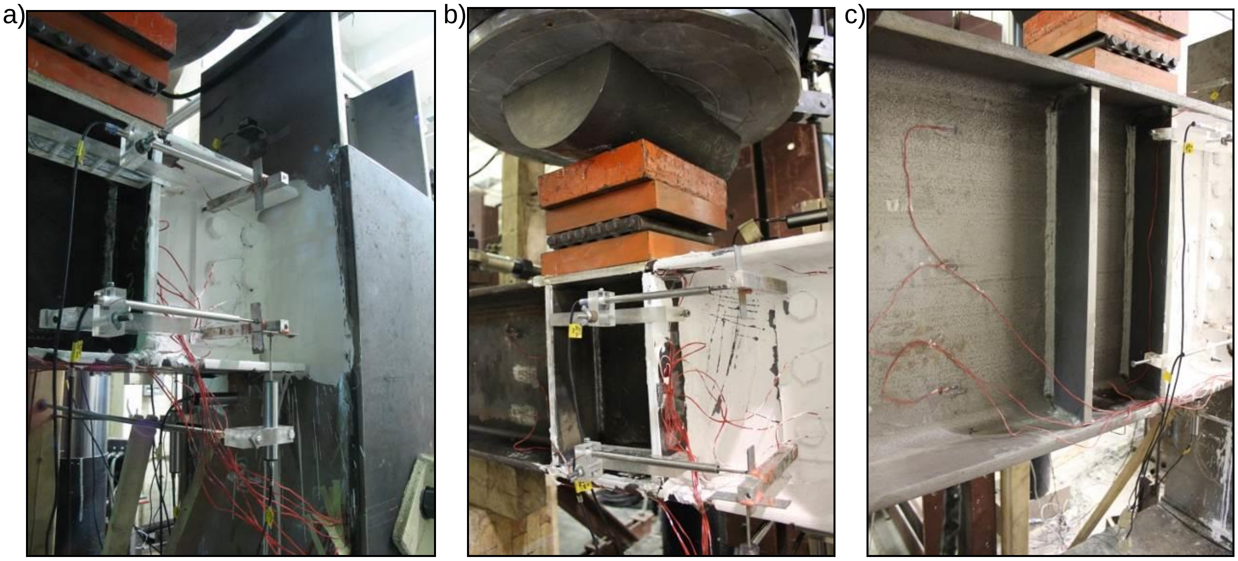

Figure 3. Typical LVDT and strain gauge Instrumentation of the shear tab test specimens

2.3 Loading protocol

In order to have comparable results with the tests of Marosi et al. (2011 a,b), the same vertical displacement based loading protocol was used. Marosi et al. implemented a target rotation of 0.02 rads for the W310 beam connections and a target rotation of 0.015 rads for the W610 beam connections at the predicted ultimate shear resistance of the shear tab specimens using the modified AISC method (2005) recommended by Marosi et al.. A complete description of the modified design method as well as detailed design calculations for the test specimen configurations can be found in the report by Marosi et al. (2011a). In addition to the shear loads a constant axial load was simultaneously applied in order to observe the change in behaviour and shear resistance of the specimens. The concept behind the load protocol for the axial load application was inspired by a typical beam during its lifespan which is normally subjected to gravity service loads until a stage where axial load may occur due to different possible sources such as wind, earthquake or other possible actions. Therefore a service level shear load was selected based on a statistical study and the global force vs. displacement response plots from Marosi's tests. It was observed that the connection mainly behaves elastically before reaching a service load level of 0.66 V_r; where V_r is the predicted ultimate shear resistance of the shear tab calculated using the modified AISC method recommended by Marosi et al. (2011a) and using a resistance factor $\phi = 1$. The point in the protocol when the axial load was applied was selected to be when the shear force in the connection reached the service load level; after which the axial force remained constant until final failure of the shear tab.

2.4 Axial load application system (ALAS)

The axial load application system (ALAS) was responsible for performing two main tasks. First it was required to apply a stable, controlled and constant axial force to the connection in either tension or compression. Second it was necessary to ensure that the axial force remained normal to the cross sectional area of the beam while it both displaced vertically and rotated as the test progressed. The ALAS was built of various components which functioned together to allow the system to perform these two tasks. Figure 4 shows an exploded view of the parts of the ALAS used to apply a tension axial force to the beam and shear tab connection.

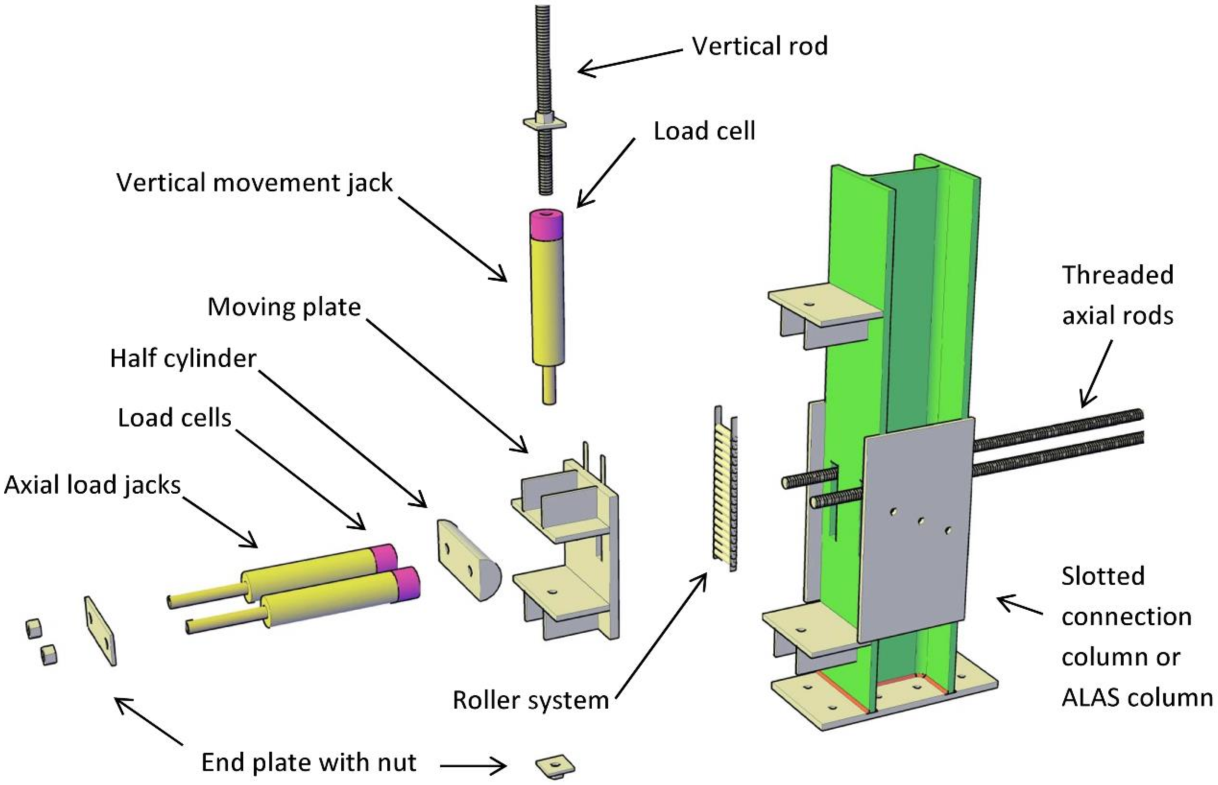

Figure 4. Axial load application system (ALAS) for tension loading

In order to generate the required axial force for the tests, two Enerpac RRH-3010 double acting hollow plunger cylinders were utilized. The force was transferred from these cylinders to a stiffened region on the test beam's web by using two threaded 31.8 mm (1 ¼") steel rods. These rods passed through a slotted column, aside a roller system, through the moving plate, half cylinder, load cells, axial load jacks and lastly were connected by an end plate and nut. For proper axial load transfer these steel rods had to remain in line with the beam which rotated during the testing procedure. To allow free rotation of the rods, a half cylinder steel plate was used to permit the rotation of the axial rods as the beam rotated. The moving plate acted as a moveable support for the half cylinder. The vertical movement of the moving plate was guided and stabilized by means of a vertical 31.8 mm (1 ¼") steel rod which passed through a third Enerpac cylinder, which controlled the vertical position of the moving plate. Load cells were used to monitor the axial force that was applied to the shear tab connection. The system was equipped with two manual hydraulic hand pumps. The first pump balanced the magnitude of the axial load that was applied. A second hand pump was utilized to control the third jack responsible for adjusting the vertical position of the moving plate. A steel roller system was placed between the moving plate and the supporting column eliminating friction and vertical force transfer and allowing only normal force interaction at the interface. Two strips of steel were installed on the moving plate to guide and stabilize its travel under high loads. In case of a contact between the edges of the moving plate and side plates of the column greased Teflon strips were used to eliminate friction between the two components.

The ALAS generates tension in the axial rods; therefore, the installation method for the system to function differs for the compression setup (Figure 5) compared to that used to apply a tension load (Figure 6) to the test beam. In the compression setup the ALAS was directly installed on the test column (Figure 7a).

Slots were placed in the column flanges to allow the axial rods to pass through and connect the stiffened region on the web of the test beams to the ALAS. With the extension of the axial rods and positive rotation of the test beam at the connection, the reaction of the ALAS caused the moving plate to move downward. Therefore the hydraulic cylinder that controlled the vertical travel of the moving plate was positioned below the moving plate to limit excessive movement.

A self-reacting frame that was tied vertically to the strong floor with threaded rods was used for the tension setup (Figure 6), in which the far end of the test beam was essentially pulled away from the shear tab connection. The additional frame also acted as a support for a secondary slotted column at the end of the test beam against which the ALAS was placed (Figure 7b). Unlike the combined shear plus compression force tests, the moving plate would have moved upward as the axial rods were placed in tension based on the geometry of the rotating test beam. It was therefore necessary to install the hydraulic cylinder above the moving plate to force it to move vertically downward as the tip of the test beam was lowered using the 269 kN actuator. In a similar manner to the compression tests the movement of the vertical plate and axial force in the beam were controlled manually based on the displacement and load cell readings, respectively of the ALAS.

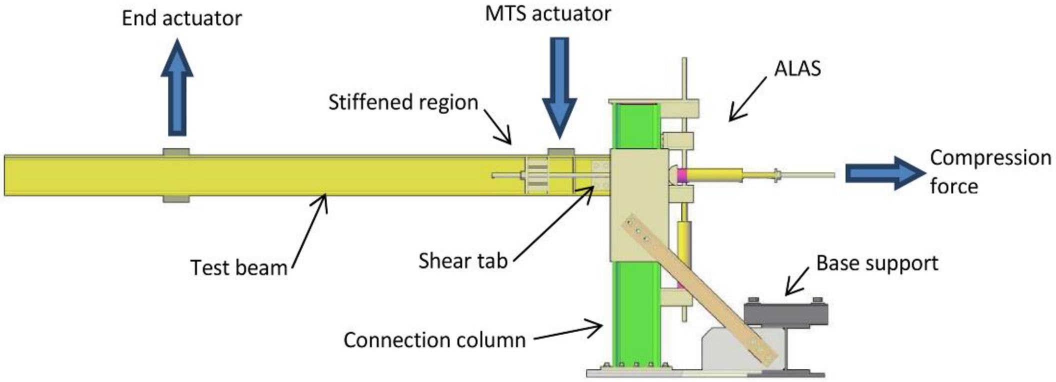

Figure 5. Typical setup used for combined shear & compression force shear tab testing (Test #1 shown)

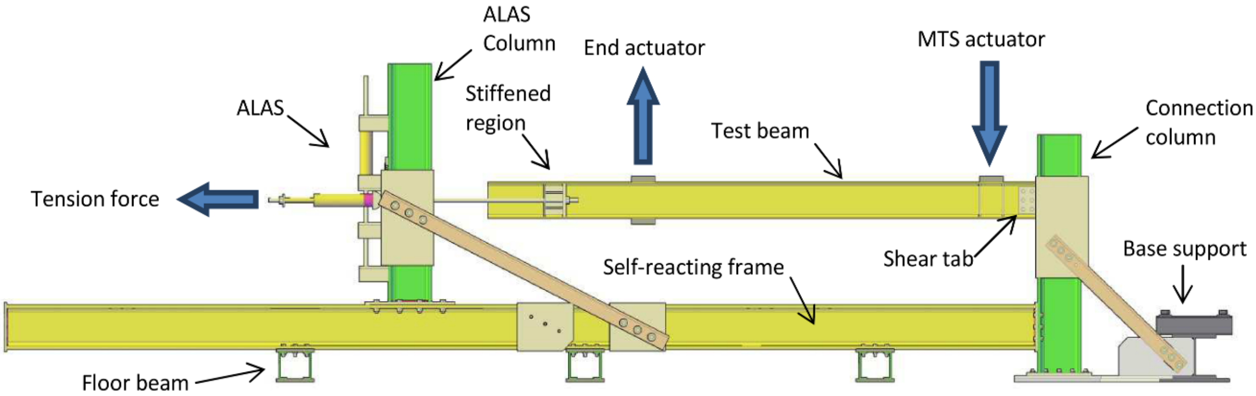

Figure 6. Typical setup used for combined shear & tension force shear tab testing (Test #2 shown)

a) b)

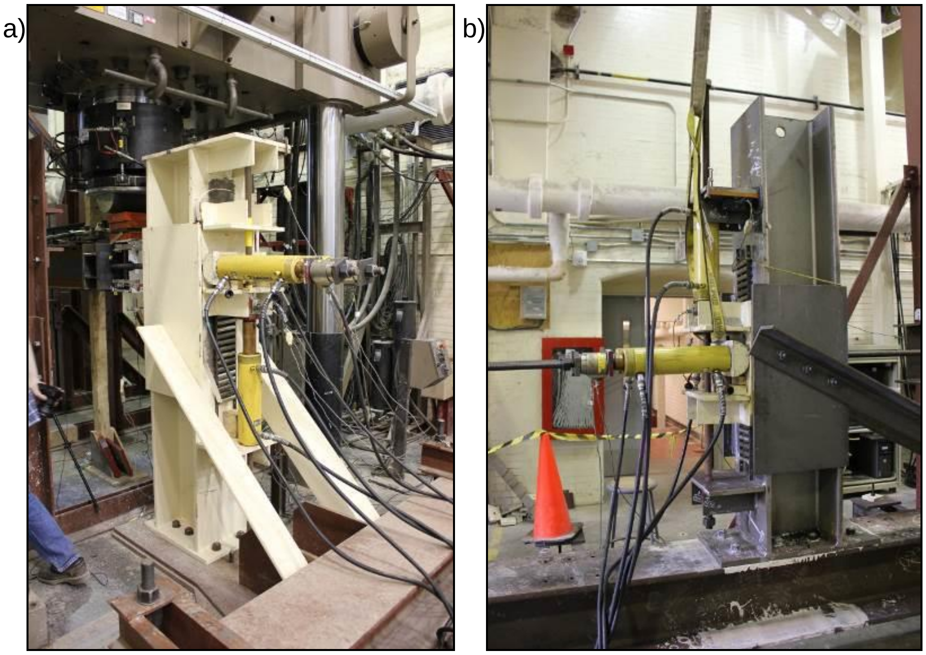

Figure 7. ALAS installation; a) compression tests (Test #1 shown), & b) tension tests (Test #2 shown)

3 TEST RESULTS

Excluding test #4, the damage progression of the tested specimens was similar to the same shear tabs subjected to shear loading alone as described by Marosi et al. (2011a,b). Flexural and shear yielding of the plate was observed in all the shear tab tests, which was followed by the start of a fracture in the connecting plate-to-column fillet weld. Despite the fact that the weld started to fracture, the connection was still able to carry increased loads by redistributing the stresses. Figures 8 and 9 contain photographs of the final deformed shape of each shear tab at the end of testing, including those tested by Marosi et al.. The compression and shear force tests (Test#1 and #3) showed that by continuing the loading protocol after this initial fracture, regions on the first line of bolts on the shear tab strain hardened and additional cracks developed in the net area between the bolt holes. This however, did not occur for the combined tension and shear force tests (test #2 and #4), for which the shear tab's final post-ultimate behaviour was governed mainly by the performance of the connecting plate-to-column fillet weld; fractures along the net area of the shear tab were not observed. In the case of tests #1 and #2 due to the beam tip actuator reaching its stroke limit, the testing had to be stopped soon after the connection shear force started to decrease. Although the same specified material and vertical loading protocol were used for the combined loading tests compared to the Marosi et al. tests, the response of these connections resulted in significant ductility irrespective of whether an additional axial tension or compression force were applied (Figure 10). This was likely caused by the shear tab plates having greater material ductility compared to Marosi et al. tests as indicated by the bearing deformations observed around the shear tab bolt holes. This was not the case for the W610 beam test #3, which exhibited similar ductility to Marosi et al.'s test (Figure 11). Test #4 did not deform as expected and failed by complete fillet weld rupture soon after the full axial tension load had been applied. The reason was later identified to be the undersized fillet weld of the shear tab to the column. It was 5mm instead of 10mm therefore the shear tab did not perform as designed and failed at less than 60% of its true shear capacity which was very close to the service load level.

Table 2. Shear tab connection test results

Test no.	***#1***	***#2***	***#3***	***#4***
Axial load type	Compression	Tension	Compression	Tension
V_r for shear loading (KN) (Marosi et al. (2011a,b))	512	512	1732	1732
V_r for combined forces (KN)	626	468	1898	1031*
Maximum connection rotation for shear loading (rads) (Marosi et al. (2011a,b))	0.042	0.042	0.033	0.033
Maximum connection rotation for combined forces (rads)	0.066	0.049	0.037	0.013*
Maximum shear tab vertical displacement for shear loading (mm) (Marosi et al. (2011a,b))	18.4	18.4	22.6	22.6
Maximum shear tab vertical displacement for combined forces (mm)	28.5	27.6	20.63	7.95*
Change in ultimate shear resistance (%)	+22%	-8.6%	+9.6%	-68% *

* Weld for test #4 was expected to be 10mm but after the test it was measured 5mm

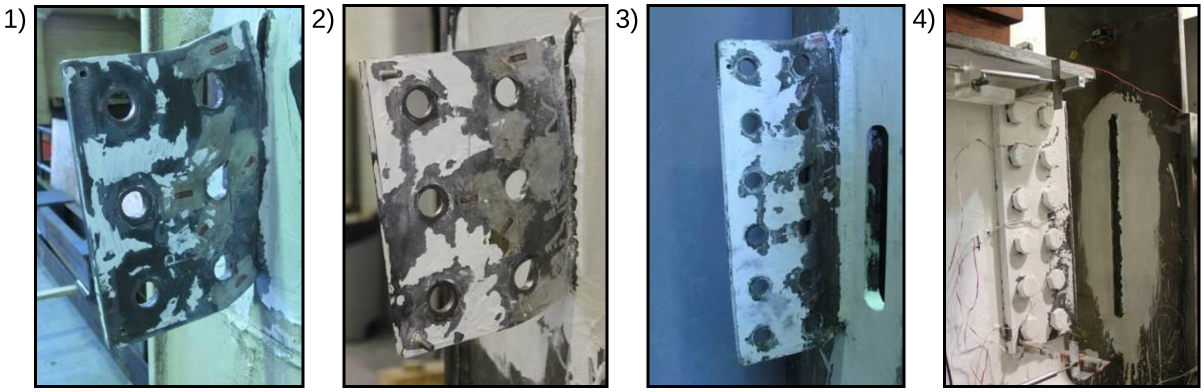
1) 2) 3) 4)

Figure 8. Deformed shape of each of the four shear tab specimens subjected to combined forces

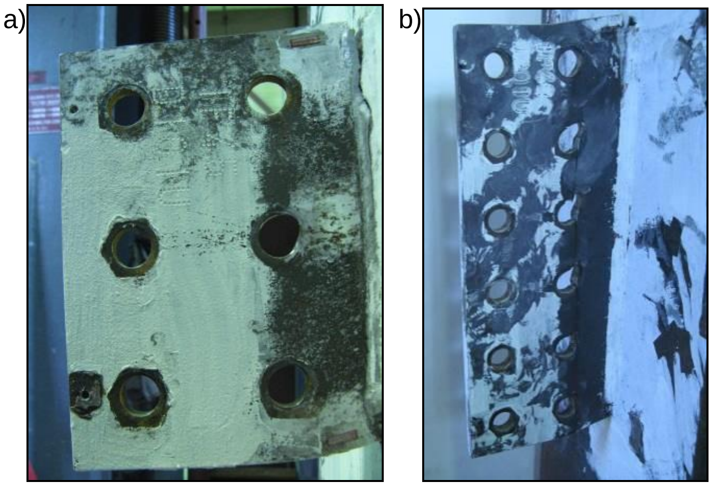
a) b)

Figure 9. Deformed shape of shear tab specimens subjected to shear loads alone (Marosi et al., 2011a)

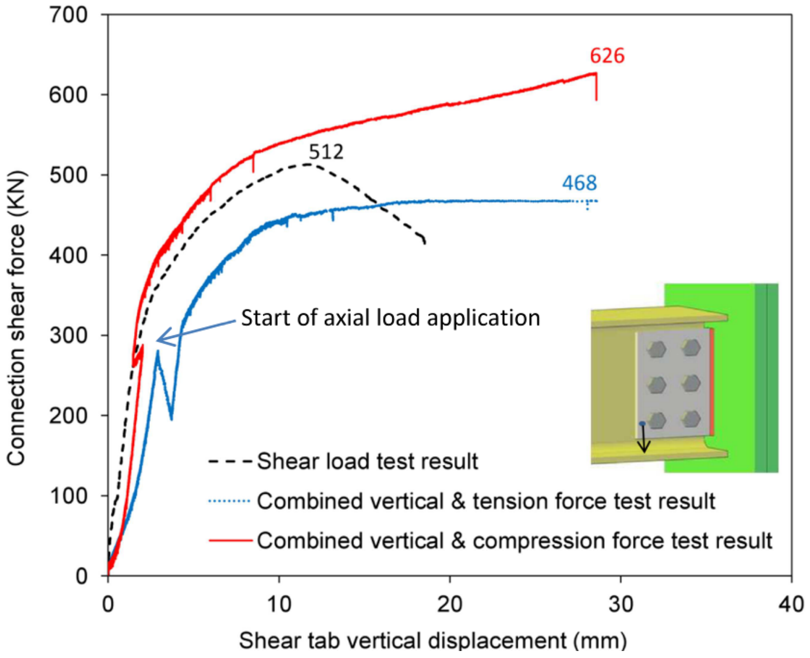

Figure 10. Shear tab connection shear force vs. vertical displacement test results for W310 beam connected by two rows of three 19 mm (3/4") A325 bolts

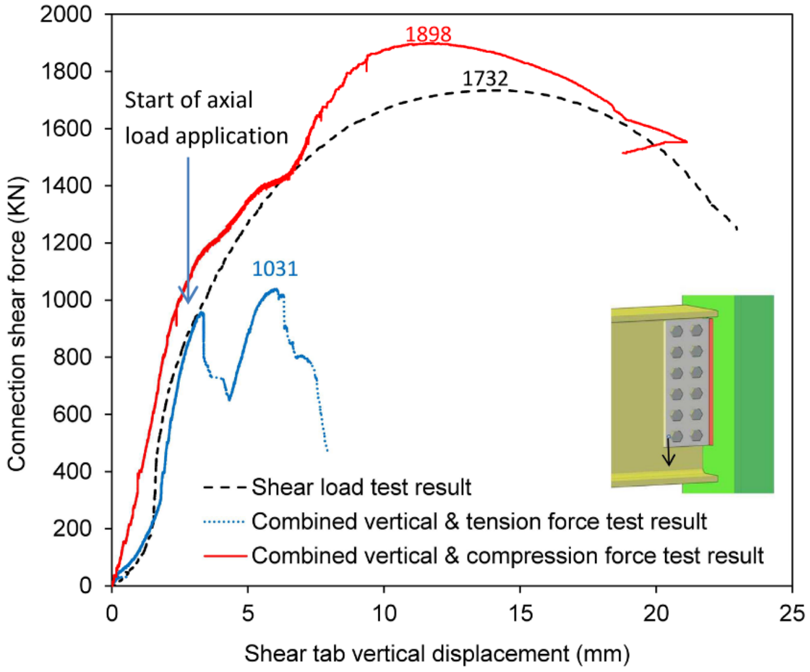

Figure 11. Shear tab connection shear force vs. vertical displacement test results for W610 beam connected by two rows of three 22 mm (7/8") A325 bolts

A comparison of the shear force vs. vertical deflection test results with the Marosi et al. shear tab tests that were subjected to shear loads is shown in Table 2. The shear tabs in tests #1 and #2 vertically deformed almost 1.5 times more than the same connection subjected to shear loads (Figure 10). Unlike the first two tests, Test #3 resulted in similar vertical displacement to that measured by Marosi et al. (Figure 11). In terms of rotation the first three tests experienced a higher rotation level at the end of the test .If properly fabricated, Test #4 would also have been predicted to achieve higher deformations. In general, the application of an axial compression force in the connection increased the shear resistance, whereas a tension force decreased the shear resistance. Further study to develop an appropriate design method for various levels of axial load is ongoing.

4. CONCLUSIONS

A series of four full-scale tests were performed on double row bolted shear tab connections subjected to combined vertical (shear) force and axial tension or compression force along with the anticipated rotation of a typical beam-to-column joint. In comparison with the same shear tab specimens subjected to only shear force conducted by Marosi et al. (2011a,b), the results showed a gain in shear resistance due to the presence of an axial compression force in the connection, while an axial tension decreased the shear resistance. The test specimens, except for #4, performed in a ductile fashion due to flexural and shear yielding of the steel plate, bearing, and ductile weld fracture resulting in a connection within high plastic deformation capabilities. The importance of the connecting plate-to-column fillet weld in the performance of a shear tab connection was witnessed in test #4, which failed suddenly at a load level of about 60% of its predicted shear resistance due to an undersized weld. The results of these tests will be used to calibrate finite element simulation models of shear tab connections such that a range of axial force levels, both compression and tension, can be investigated. The final objective of this study will be to develop a design method for shear tabs subjected to combined shear and axial forces.

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