



Mass Timber Connections Fire-Resistance Testing

For Nordic Structures

December 16, 2022

CHM FIRE CONSULTANTS LTD.
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A handwritten signature in black ink, appearing to read 'R. Michels'.

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TABLE OF CONTENTS

1	Introduction	4
1.1	Objectives of Research/Testing	4
2	Test Specimen Descriptions	4
3	Test Procedure	10
4	Test Results	10
4.1	General.....	10
4.2	Test 1.....	10
4.2.1	Wood Charring.....	15
4.2.2	Steel Temperatures.....	16
4.2.3	Other Thermocouple Measurements	20
4.2.4	Deflection.....	22
4.3	Test 2.....	23
4.3.1	Wood Charring.....	28
4.3.2	Steel Temperatures.....	30
4.3.3	Deflection.....	34
5	Conclusions	35

Attachment A: Beam Assembly Plans

1 INTRODUCTION

CHM Fire Consultants Ltd. (CHM) has been retained by Nordic Structures to assist in the testing of mass timber beam-to-column connections for their fire-resistance rating in order to satisfy code requirements for the fire-resistance design of mass timber construction.

Two fire-resistance tests were conducted at Southwest Research Institute's (SwRI's) testing laboratory in San Antonio, Texas, July 14 and July 19, 2022, and witnessed by Dr. Craft with CHM.

The two connections tested consisted of a glued-laminated timber (glulam) beam to column connection with a CLT floor slab. The connection was loaded by placing an axial load on the CLT floor slab a short distance from the column.

This report is intended to accompany the SwRI Testing Reports^{1 2}.

1.1 OBJECTIVES OF RESEARCH/TESTING

The objective of the fire tests was to determine the fire-resistance ratings of a knife plate connection and a bearing plate connection in accordance with ASTM E119 *Standard Test Methods for Fire Tests of Building Construction and Materials*, and CAN/ULC-S101, *Standard Method of Fire Endurance Tests of Building Construction Materials*. In particular, the two connections were tested for a 2-hour fire-resistance rating.

2 TEST SPECIMEN DESCRIPTIONS

Fire-resistance tests were conducted on two test specimens, as described below. Refer to Attachment A for Assembly Plans for the two connections. Test 1 was conducted with a knife plate steel connector and a 5 mm gap between the end of the beam and the column. Test 2 was conducted with a bearing plate steel connector and a 3 mm gap between the end of the beam and the column.

The materials were received by SwRI on July 5, 2022, and the assemblies/specimens were constructed between July 11-19, 2022. For more information on the construction of the test specimens, refer to SwRI's test reports.

1. Knife Plate Connection (Test 1 in Assembly Plan)

A general description of this test assembly is as follows:

- 346 x 699 glulam beam.
- 395 x 395 glulam column.

¹ Southwest Research Institute. Fire Performance Evaluation of Glulam Loaded Doweled Steel Knife Plate Beam-to-Column Connection with a CLT Panel Floor, Tested in General Accordance with ASTM E119-20, *Standard Test Methods for Fire Tests of Building Construction and Materials*. SwRI Project No. 01.26260.01.704. October 25, 2022.

² Southwest Research Institute. Fire Performance Evaluation of Glulam Loaded Steel Bearing Plate Beam-to-Column Connection Assembly Column with a CLT Panel Floor, Tested in General Accordance with ASTM E119-20, *Standard Test Methods for Fire Tests of Building Construction and Materials*. SwRI Project No. 01.27009.01.413. October 25, 2022.

- 5 mm gap between beam and column.
- 350W steel bracket:
 - Fastened to column with total of 14 screws,
 - Fastened to beam with 21 zinc dowels 170 mm long with 19 mm diameter. Protected with 88mm long wood plugs.
- Wood blocking 346 mm wide, 353 mm long and 82 mm thick was used to protect the bottom edge of the knife plate. The blocking was screwed and glued to the beam.
- 175 mm 5-ply CLT floor panel on top.
- A total of 19 thermocouples were added to the connection and two thermocouples placed in the beam in order to measure temperatures during the fire test.

Figures 1 and 2 below show the knife plate connection before and after the beam was installed.

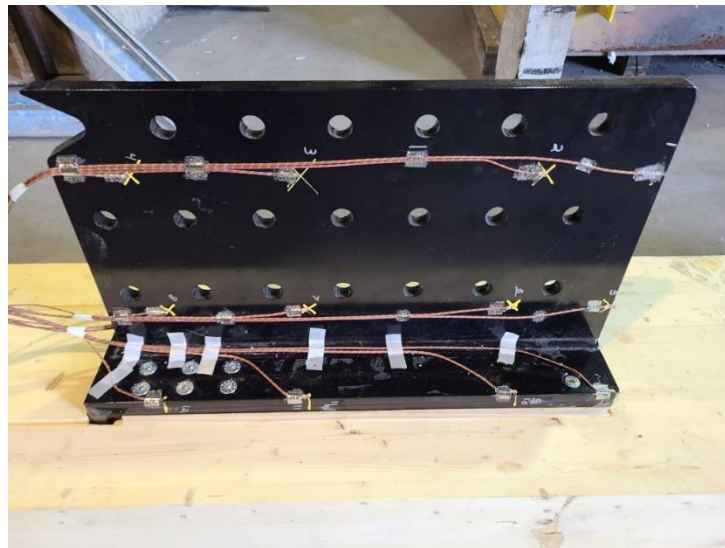


Figure 1: Knife Plate with Thermocouples Installed.



Figure 2: Beam (vertical) and column (horizontal on floor) during installation of wood plugs.

Thermocouples were installed in the following locations as shown in Figures 3 and 4 that follow:

- 16 thermocouples fastened directly to the knife plate beam hanger (TC 1-16).
- 2 thermocouples inside the beam inserted from the top, down predrilled holes (TC 17-18).
 - One in each side, installed from the top side 1068 mm from column face, 63 mm from the side of the beam, 305 mm from the top of the beam.
- 3 thermocouples between the beam and the wood blocking (TC 19-21).
 - TC 19 – approximately 16 mm from edge
 - TC 20 – approximately 82 mm from edge (same depth as wood blocking)
 - TC 21 – approximately 82 mm from the opposite edge

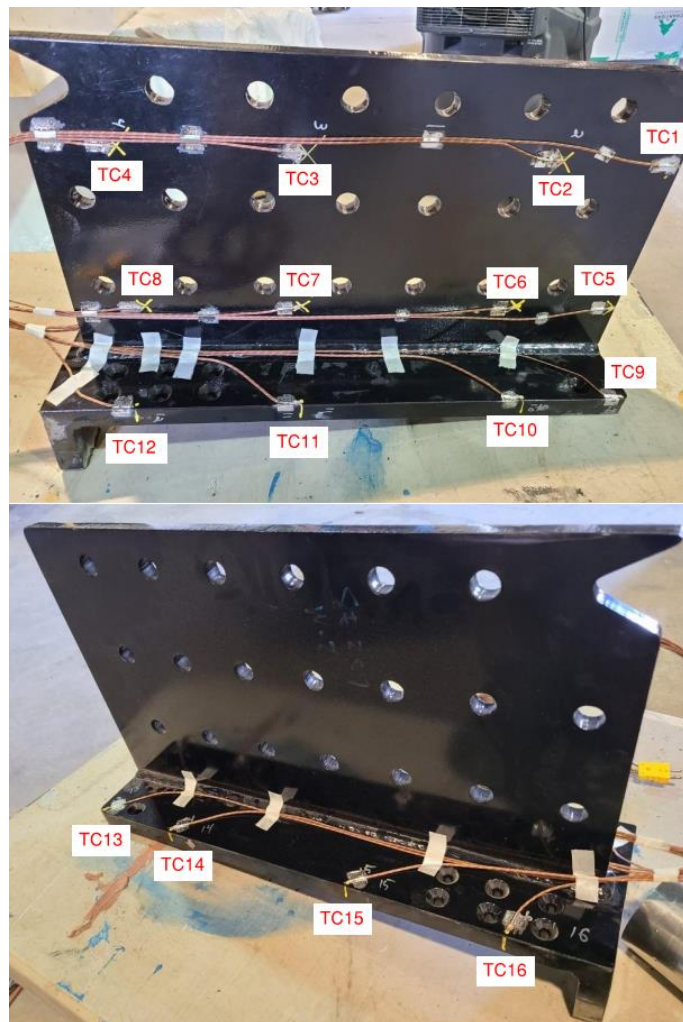


Figure 3: Thermocouples for Test 1 on steel knife plate.



Figure 4: Thermocouples for Test 1 between beam and wood blocking

2. Bearing Plate Connection (Test 2B in Assembly Plan)

A general description of this test assembly is as follows:

- 346 x 699 glulam beam.
- 395 x 395 glulam column.
- 3 mm gap between beam and column.
- 350W steel bracket with bearing plate:
 - Fastened to column with total of 14 screws,
 - Fastened to beam with 2 zinc dowels 170 mm long with 19 mm diameter. Protected with 88 mm long wood plugs.
- Wood blocking 346 mm wide, 410 mm long and 82 mm thick was used to protect the bottom edge of the bearing plate. The blocking was screwed and glued to the beam.
- 175 mm 5-ply CLT floor panel on top.
- A total of 17 thermocouples were added to the connection and two thermocouples placed in the beam in order to measure temperatures during the fire test.

Figures 5 and 6 below show the bearing plate connection before and after the beam was installed.



Figure 5: Bearing Plate with Thermocouples Installed



Figure 6: Beam (vertical) and column (horizontal) prior to installation of wood blocking

Thermocouples were installed in the following locations as shown in Figure 7:

- 17 thermocouples fastened directly to the bearing beam hanger (TC 1-17).
- 2 thermocouples inside the beam inserted from the top, down predrilled holes (TC 18-19).
 - One in each side, installed from the top side 1068 mm from column face, 63 mm from the side of the beam, 305 mm from the top of the beam.

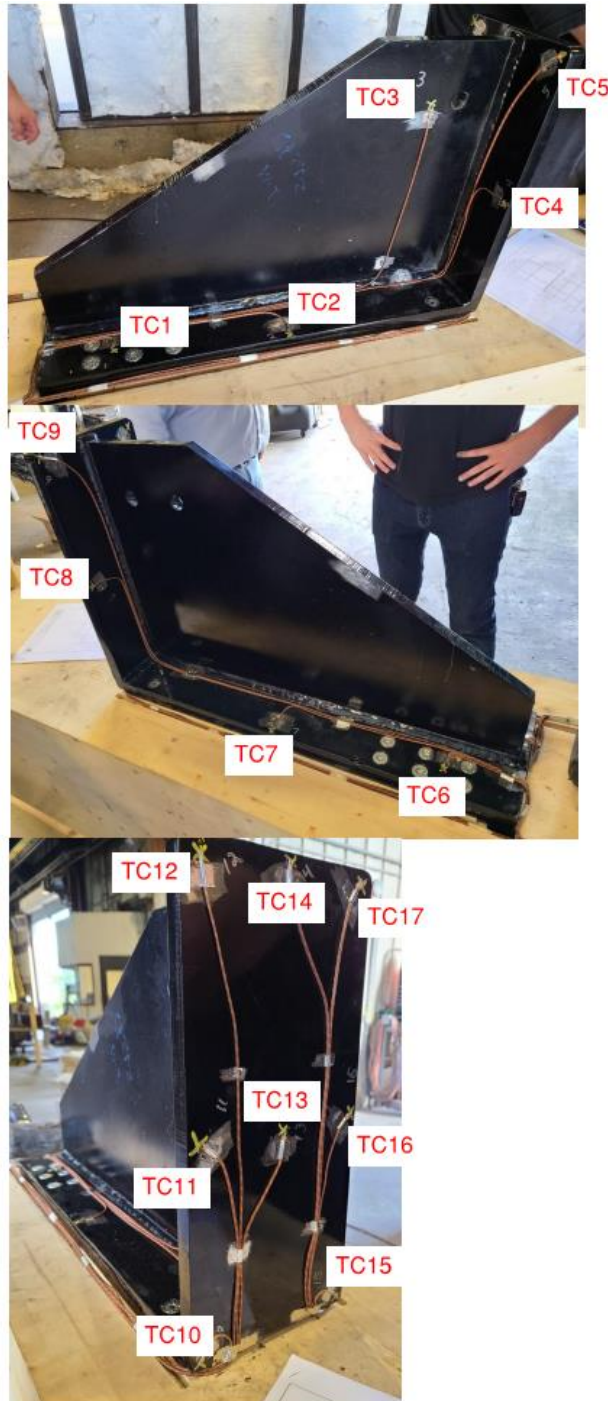


Figure 7: Thermocouples for Test 2 on bearing plate

3 TEST PROCEDURE

The two tests were conducted in the full-scale test furnace at SwRI's laboratory in San Antonio, Texas on July 14 and 19, 2022 in accordance with ASTM E119 and CAN/ULC-S101.

The test assemblies were placed in the full-scale test furnace and were loaded using a hydraulic cylinder. For application of the load, a 12" x 12" x 1" steel plate was placed on top of the CLT panel directly over the beam and the load was applied to the steel plate 218 mm from the column. The load applied was 35.8 kips. The load was applied in 25% increments the fire test started 30 minutes after full load was reached in accordance with CAN/ULC-S101.

The tests were each run for 2 hours (120 minutes).

4 TEST RESULTS

4.1 GENERAL

Limited visual observations were possible during the tests as the test specimen was inside the furnace and no windows were present to see into the furnace. A video camera which relies on compressed air for cooling was placed in the furnace for the first test to provide a view of the connection during the fire test. However, it was requested to remove the camera approximately 10 minutes into Test 1 since it was apparent the air used for cooling of the camera was impinging on the test sample which would have had an impact on char oxidation during the 2-hour test.

Both test specimens passed the test to achieve a 2-hour fire-resistance rating.

The temperature data collected in the test has been analyzed in order to provide insights into the performance of the assemblies.

4.2 TEST 1

The ambient temperature and humidity in the laboratory before the test were 29°C (84°F) and 76%. The moisture content of the beam prior to testing was measured as 9.5% and the column was 9.8%

The photos below show the assembly before, during, and after the test (Figures 8 through 16).

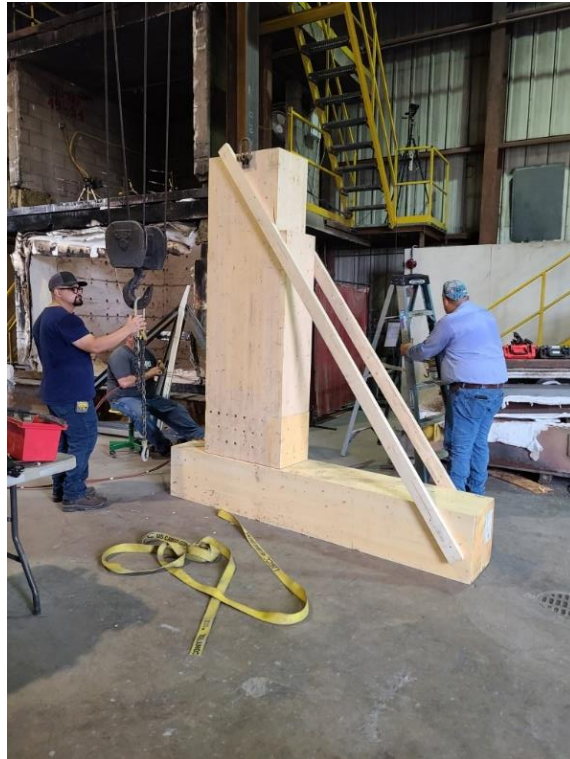


Figure 8: Beam (vertical) and column (horizontal) before hoisting



Figure 9: Test assembly in furnace



Figure 10: Furnace during testing



Figure 11: Test assembly being lifted out of furnace



Figure 12: Test assembly post-test



Figure 13: Beam remaining cross-section post-test



Figure 14: Column remaining cross-section post-test



Figure 15: Knife plate-column connection post-test

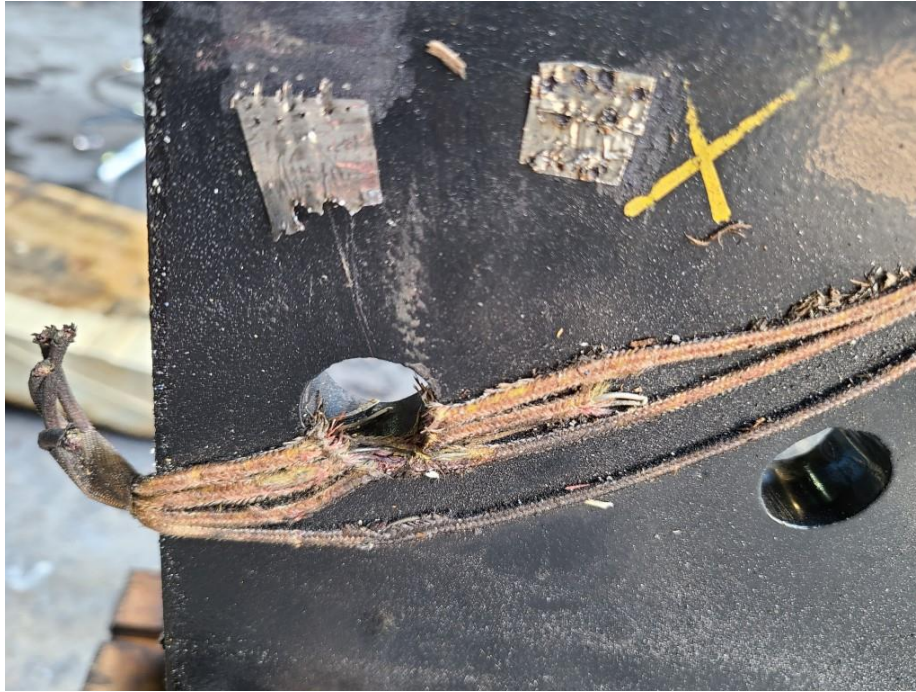


Figure 16: Photo showing damage to TC wires due to tight construction tolerances during fabrication (from top to bottom, TC1, TC4, TC2, TC3).

4.2.1 Wood Charring

As the thermocouples for this test were primarily used for measuring the steel temperature, charring rates at different times during the test cannot be calculated. However, the average charring rates over the 2-hour fire exposure are calculated and discussed below.

Beam

The beam was exposed to 3-sided fire exposure. The initial cross-section of the beam was 346 mm wide x 699 mm deep. After the fire exposure, the remaining cross-section (after removing char) was approximately 190 mm x 590 mm. As such, the average charring rates are:

- Width: $(346-190)/(2 \times 120) = 0.65 \text{ mm/min}$
- Depth $(699 - 590)/120 = 0.91 \text{ mm/min}$

As can be seen in Figure 14, which shows the bottom of the beam where it meets the steel plate, there was no charring between the end of the beam and the steel plate. The 5 mm gap which existed between the beam and column is no longer present as that wood was converted to char. However, it is clear from the remaining cross-section that no accelerated charring occurred on the end of the beam, or char contraction took place opening up the gap between the beam and column.



Figure 17: Photo showing remaining wood at end of beam on each side. The areas where wood remains between beam and column is consistent with the end gap of 5 mm between beam and column.

Column

The column was exposed to 4-sided fire exposure. The initial cross-section of the column was 395 mm x 395 mm. After the fire exposure, the remaining cross-section (after removing char) was approximately 216 mm x 216 mm. As such, the charring rate was the same in both cross-sectional dimensions. The average charring rate is:

- $(395 - 216)/(2 \times 120) = 0.75 \text{ mm/min}$

These charring rates are within the expected rates for this type of standard fire exposure scenario. The somewhat higher charring rate in the depth direction for the beam (0.91 mm/min) may be a result of multiple factors, such as the effect of corner rounding and the relatively narrow width of the beam, or location in the furnace (which may not be completely uniform in temperature throughout).

4.2.2 Steel Temperatures

The primary concern with respect to temperatures in a fire-resistance test of steel mass timber connections is the temperatures of the steel connections. At elevated temperatures, steel begins to lose its strength. In particular, it loses approximately half its strength at approximately 550°C. As a safety factor of 2 is typical for design of structural elements for loading, steel components can be expected to fail in a standard ASTM E119 test at approximately the time that the steel reaches this temperature, as a rule of thumb.

Charring of wood at the steel/wood interface can also be problematic. Another important temperature to consider is 300°C, the temperature at which wood is assumed to convert to char. When the steel reaches 300°C, it will begin to char the wood with which it is in contact. Under loaded conditions, this may lead to structural failure if enough of the wood is charred.

Further, as these full-scale tests included loading, joint movement could be impacted in areas where wood is under compression and temperature is between 100-300°C.

Figure 18 below is a graph of the temperatures of the 8 thermocouples on the knife plate in Test 1 (TC 1-8). The peak temperature reached at the bottom of the knife plate was at TC5, which reached 218°C at 120 minutes. While TC5 reached a peak temperature of 218°C, TC6 directly above reached a peak of 134°C which shows the relatively high temperature gradient in the steel knife plate. This is most likely a function of the relatively thick steel plate (19 mm).

Figure 19 below is a graph of the temperatures of the 8 thermocouples on the back plate in Test 1 (TC 9-16). The temperatures for the most part stayed below 200°C for the duration of the test. The one exception was TC 13 which was on the bottom corner of the back plate attached to the column. It is not surprising the temperature was highest at this location where the peak reached approx. 375°C given the proximity to fire temperatures in two directions (bottom and side). Again, given the relatively thick steel (25 mm), the temperature at TC 14 just above TC 13 didn't reach 200°C.

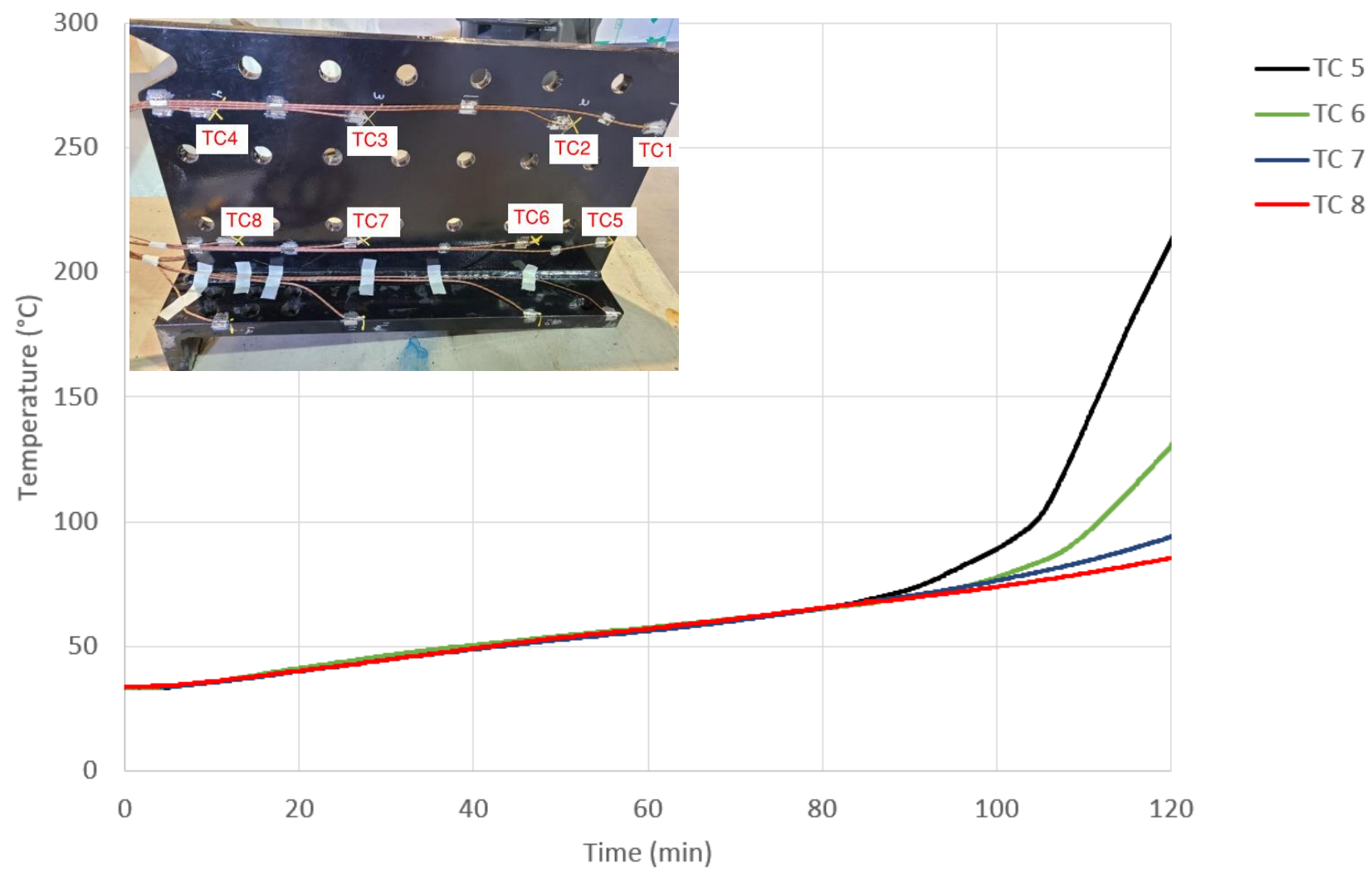


Figure 18: Test 1 Steel Temperatures – Knife Plate (Note TCs 1-4 were damaged and therefore not included in the graph).

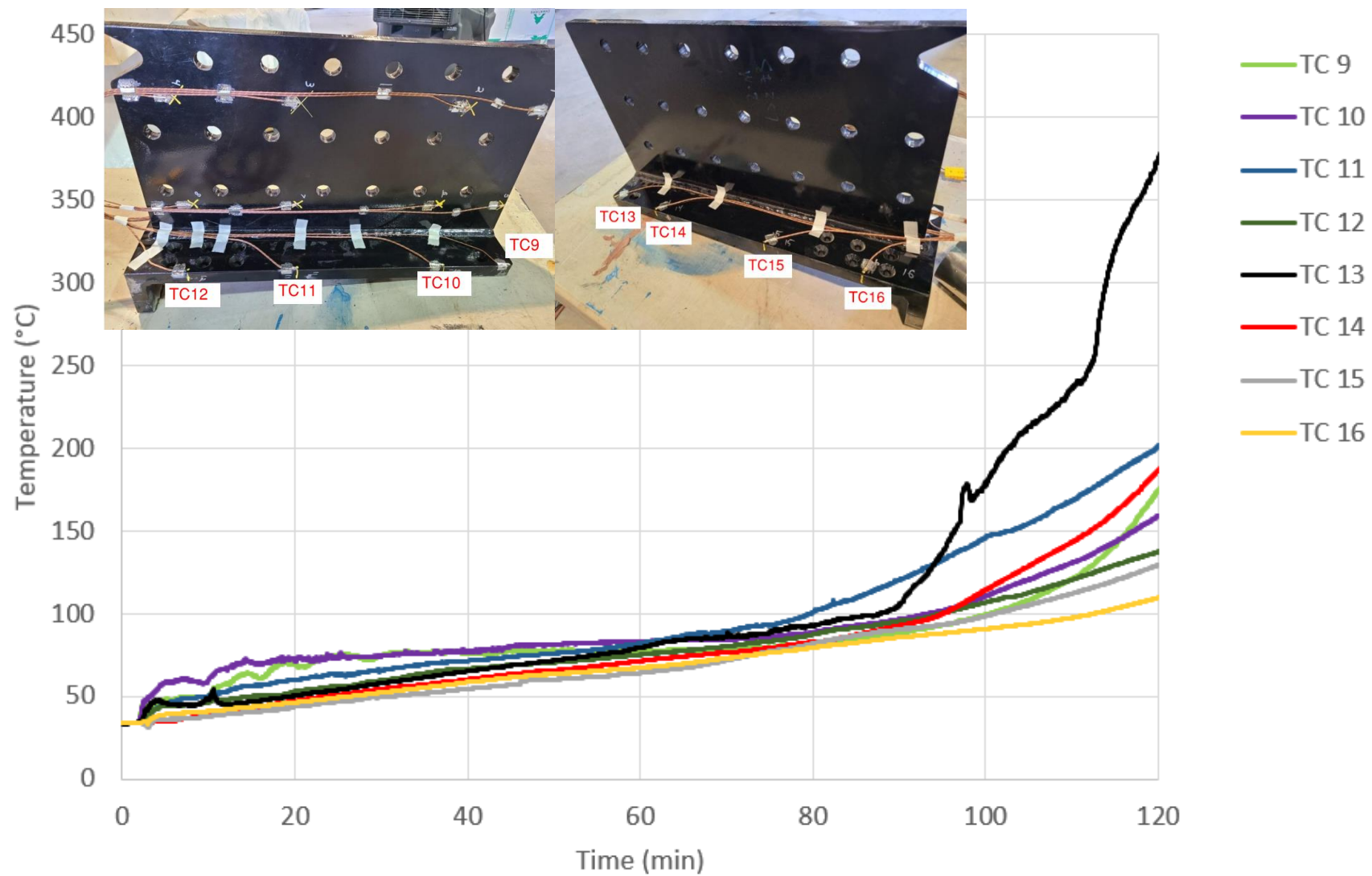


Figure 19: Test 1 Steel Temperatures – Back plate attached to column

Based on the relatively low temperatures measured and the ability of the thick steel to not heat up significantly at some distance from areas where it was more exposed to fire, it is not surprising that the connection performed so well in the fire test.

4.2.3 Other Thermocouple Measurements

Figure 20 below shows the thermocouple data between the beam and the wood blocking. Given the temperatures measured are somewhat below the furnace temperature ($\sim 1027^{\circ}\text{C}$ at 2 hrs), it is likely the charred wood block remained in place providing some level of protection from the radiation in the furnace (dominate form of heat transfer given the high temperatures) long after it was fully charred.

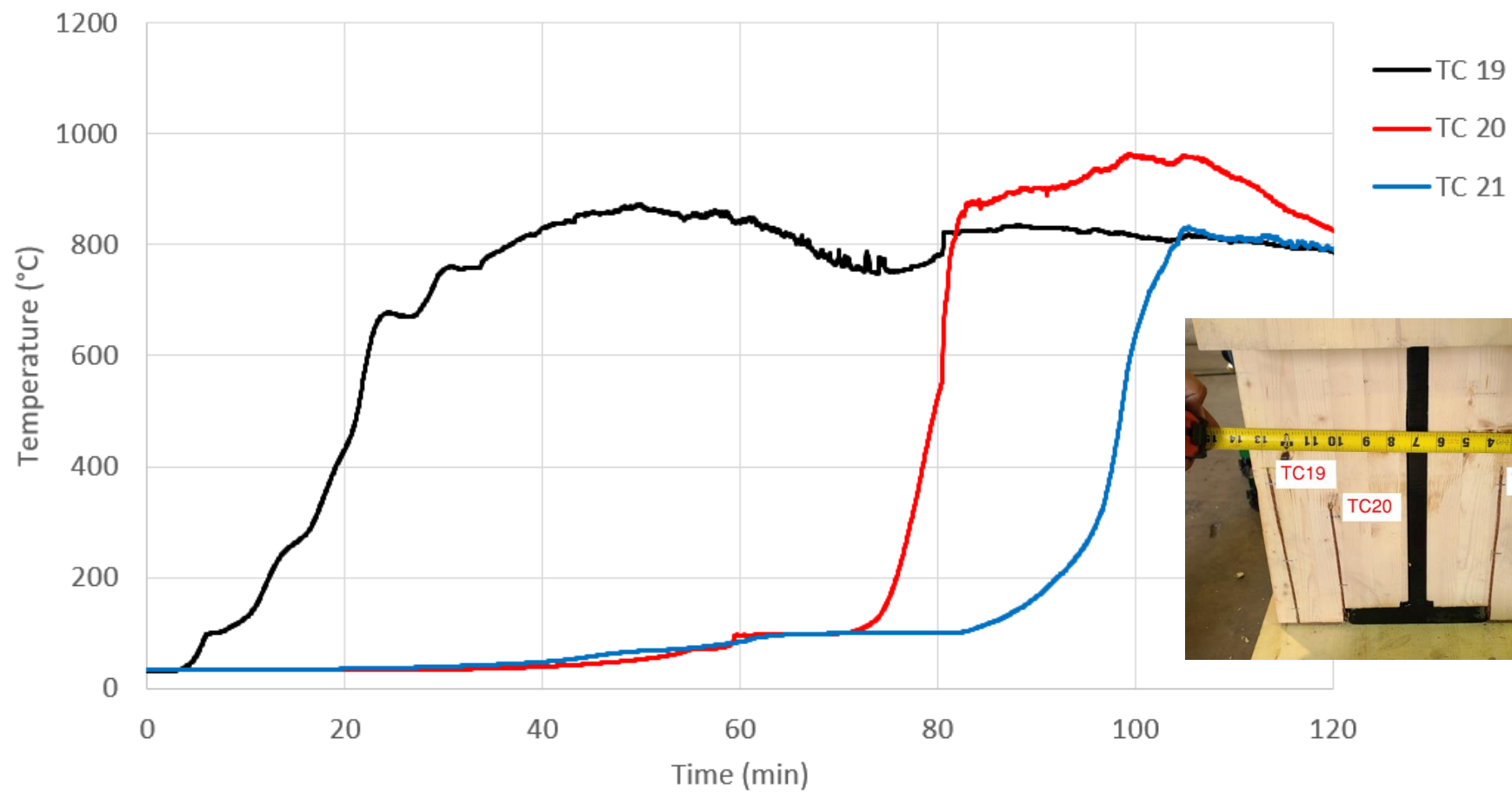


Figure 20: Thermocouple data – between beam and wood blocking – Test 1

4.2.4 Deflection

Figure 21 below shows the deflection throughout Test 1. The deflection when the load of 35.8 kips was applied was 9.2 mm. The maximum deflection measured after 2 hours was 11.8 (0.465") including the initial deflection. Therefore, deflection during the fire test was 2.6 mm which is only 28% of the initial deflection and is considered extremely little deflection to take place during a fire test.

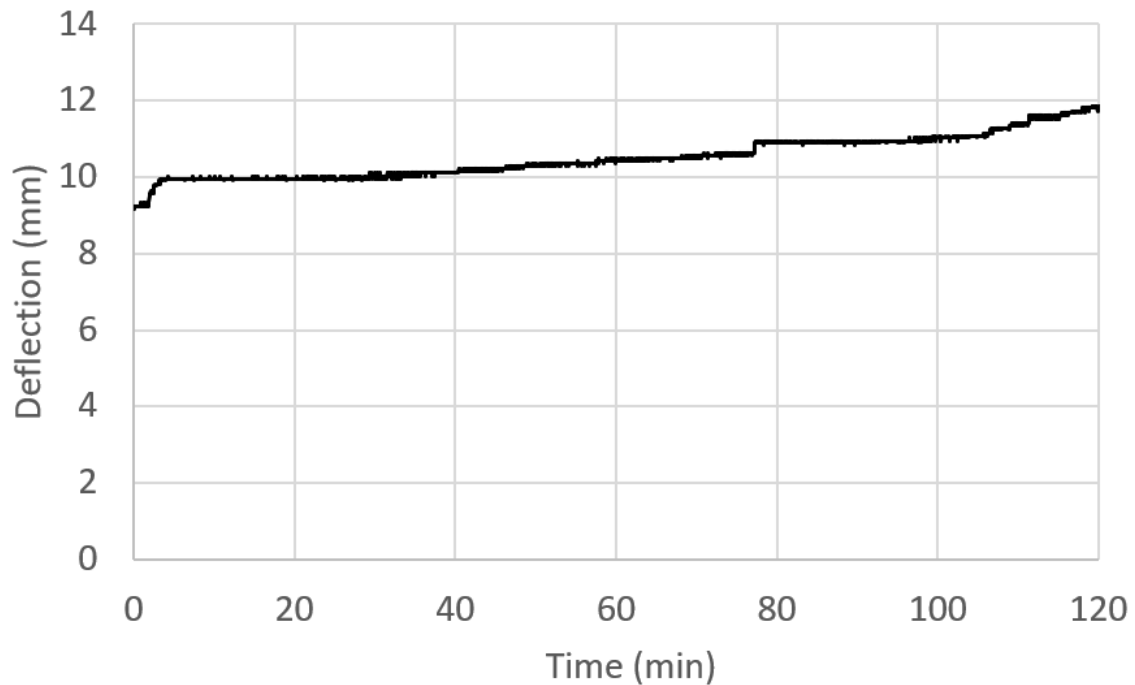


Figure 21: Deflection - Test 1

4.3 TEST 2

The ambient temperature and humidity in the laboratory before the test were 29°C (84°F) and 76%. The moisture content of the beam prior to testing was measured as 9.6% and the column was 8.9%

The photos below show the assembly before, during, and after the test (Figures 22 through 31).



Figure 22: Beam (vertical) and column (horizontal) before hoisting

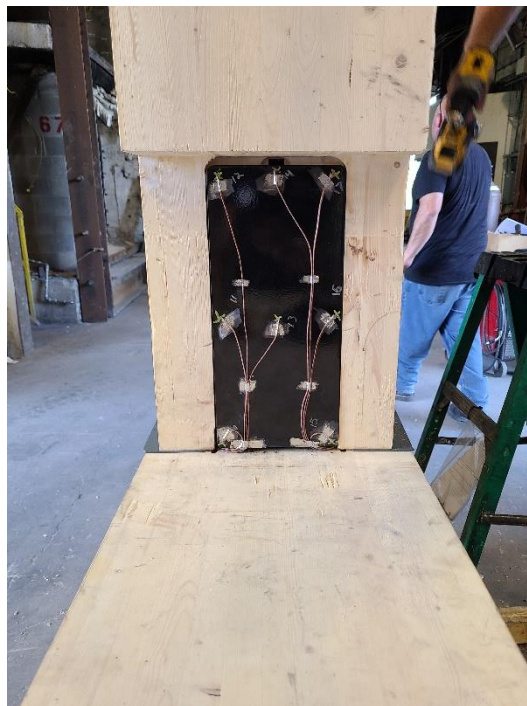


Figure 23: Bearing plate connection view from bottom prior to wood blocking



Figure 24: Test assembly in furnace



Figure 25: Furnace during testing



Figure 26: Test assembly being lifted out of furnace



Figure 27: Test assembly post-test



Figure 28: Bearing plate post-test



Figure 29: Beam remaining cross-section post-test



Figure 30: Bottom of beam post-test



Figure 31: Column remaining cross-section post-test

4.3.1 Wood Charring

Beam

The beam was exposed to 3-sided fire exposure. The initial cross-section of the beam was 346 mm wide x 699 mm deep. After the fire exposure, the remaining cross-section (after removing char) was approximately 180 mm x 590 mm. As such, the average charring rates are:

- Width: $(346-180)/(2 \times 120) = 0.69 \text{ mm/min}$
- Depth $(699 - 590)/120 = 0.91 \text{ mm/min}$

As can be seen in Figure 30, which shows the bottom of the beam where it rested on the steel bearing plate, there was no charring of the wood between the beam and the bearing plate. Figure 29 shows the end of the beam which terminates at the steel plate attached to the column. Again, no significant charring took place on the end of the beam. The 3 mm gap which existed between the beam and column is no longer present as that wood was largely converted to char. However, it is clear from the remaining cross-section shown in Figure 32 below (circled portion) that no accelerated charring occurred on the end of the beam, or char contraction took place opening up the gap between the beam and column.



Figure 32: Remaining cross-section of beam with small amount of wood showing 3 mm gap did not expand significantly.

Column

The column was exposed to 4-sided fire exposure. The initial cross-section of the column was 395 mm x 395 mm. After the fire exposure, the remaining cross-section (after removing char) was approximately 220 mm x 220 mm. As such, the charring rate was the same in both cross-sectional dimensions. The average charring rate is:

- $(395 - 220)/(2 \times 120) = 0.73 \text{ mm/min}$

The char depth was similar in test 1 with an average char rate of 0.75 mm/min which suggest the repeatability of the furnace exposure and response of the mass timber is very similar between tests.

These charring rates are within the expected rates for this type of standard fire exposure scenario. The somewhat higher charring rate in the depth direction for the beam (0.91 mm/min) may be a result of multiple factors, such as the effect of corner rounding and the relatively narrow width of the beam, or location in the furnace (which may not be completely uniform in temperature throughout).

4.3.2 Steel Temperatures

Figure 33 below is a graph of the temperatures of the thermocouples on the bottom of the steel bearing plate in Test 2. The peak temperature reached on the steel bearing plate was at TC14, which reached 726°C at 120 minutes. While this temperature is well above that of charring of wood (300°C), it is notable that the wood above the bearing plate did not char. Again, this is an indication of the temperature gradient in the relatively thick steel plates (19 mm).

Also, note that since there is such a large difference in the temperatures measured on the bottom of the bearing plate to the top of the plate (between the wood and steel), it may be that some of the thermocouples were not in full contact with the steel plate on the bottom after the wood block was fully charred. If the TCs were not in full contact with the steel, the temperature measured would be higher since the air temperature around the steel would no doubt be significantly higher than the steel temperature.

Some of the temperatures in Figure 33 drop early in the test and take a long time to reach the temperature at the start of the test. The testing lab was unable to identify the reason for this drop, and therefore, the temperatures measured should be considered along with all the other measurements to avoid drawing improper conclusions.

Figure 34 below is a graph of the temperatures of the 4 thermocouples on the top of the bearing plate in Test 2. The temperatures for the most part stayed below 100°C for the duration of the test (with the exception of some fluctuations late in the test likely due to noise in the signal). The low temperatures are somewhat confirmed by the lack of charring of the wood on the bottom of the beam which rested on the bearing plate.

Figure 35 below is a graph of the temperatures of the thermocouples on the back plate connected to the column, and the knife plate in Test 2. For the most part the temperatures stayed below 100°C with the exception of an anomaly in the measurement which saw the temperature climb up above 120°C, only to drop quickly shortly after 100 minutes into the test. The 3 mm gap did not let any significant amount of heat into the joint.

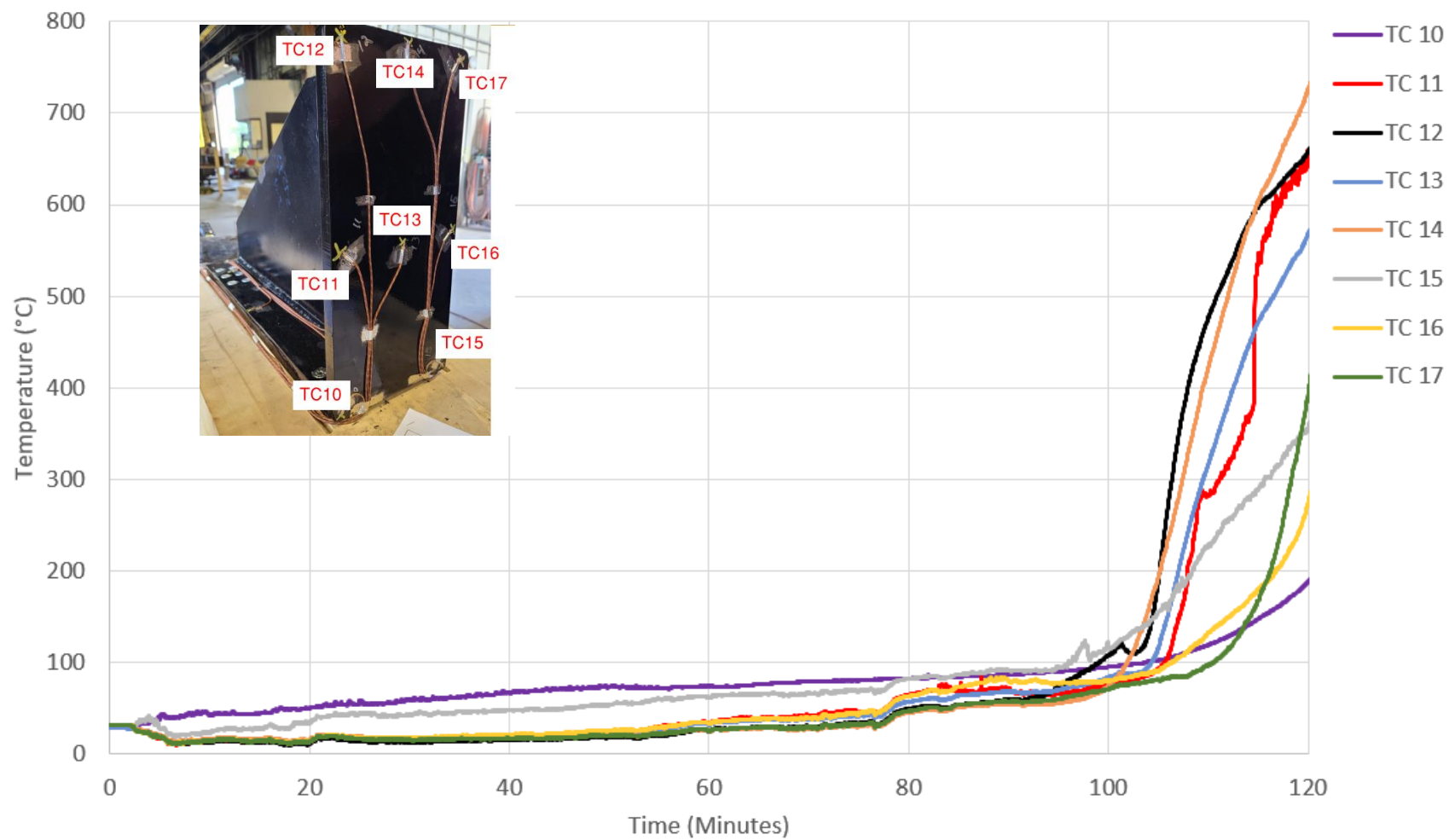


Figure 33: Test 2 Steel Temperatures – Underside of Bearing Plate

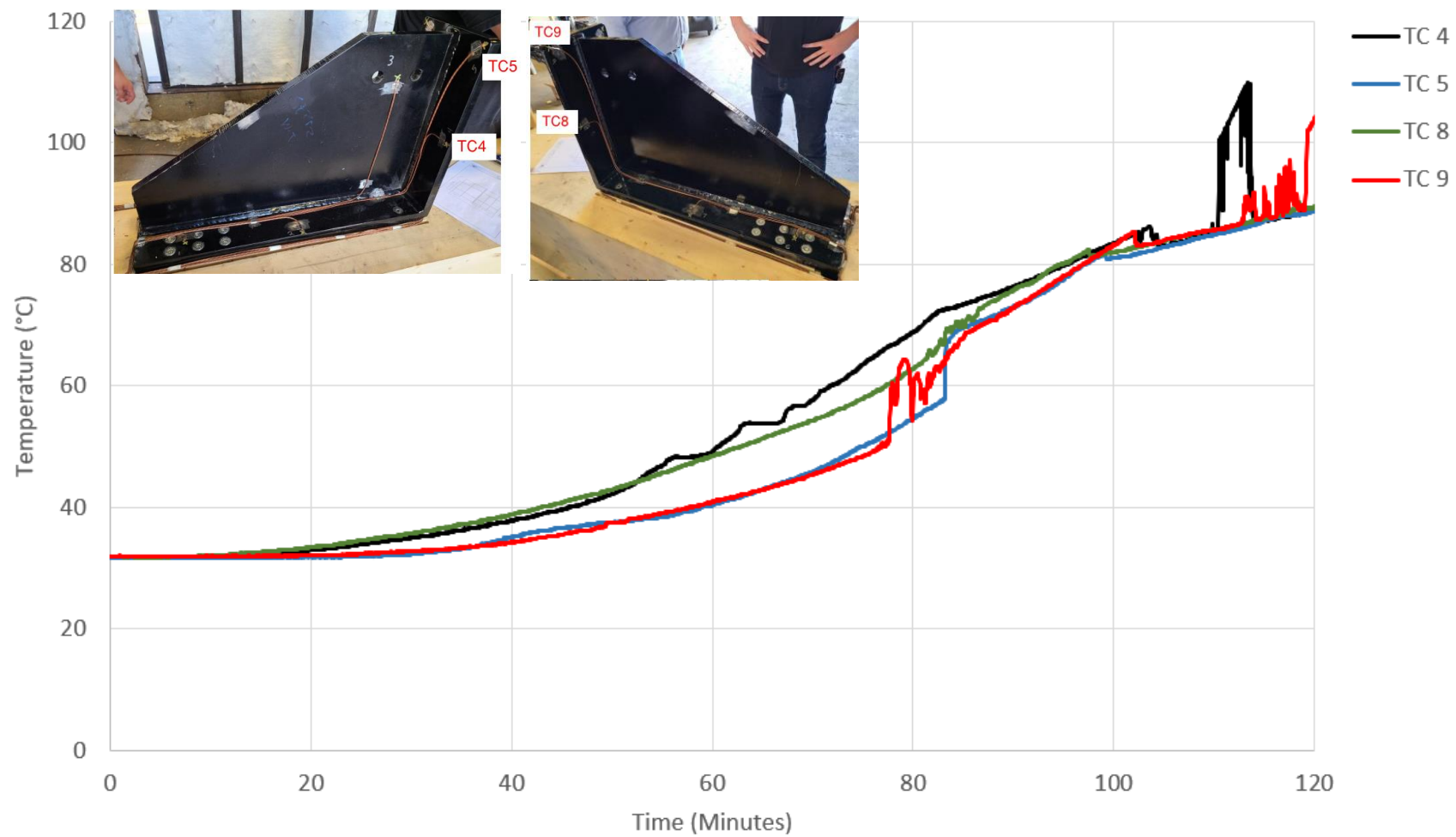


Figure 34: Test 2 Steel Temperatures – Top side of Bearing Plate

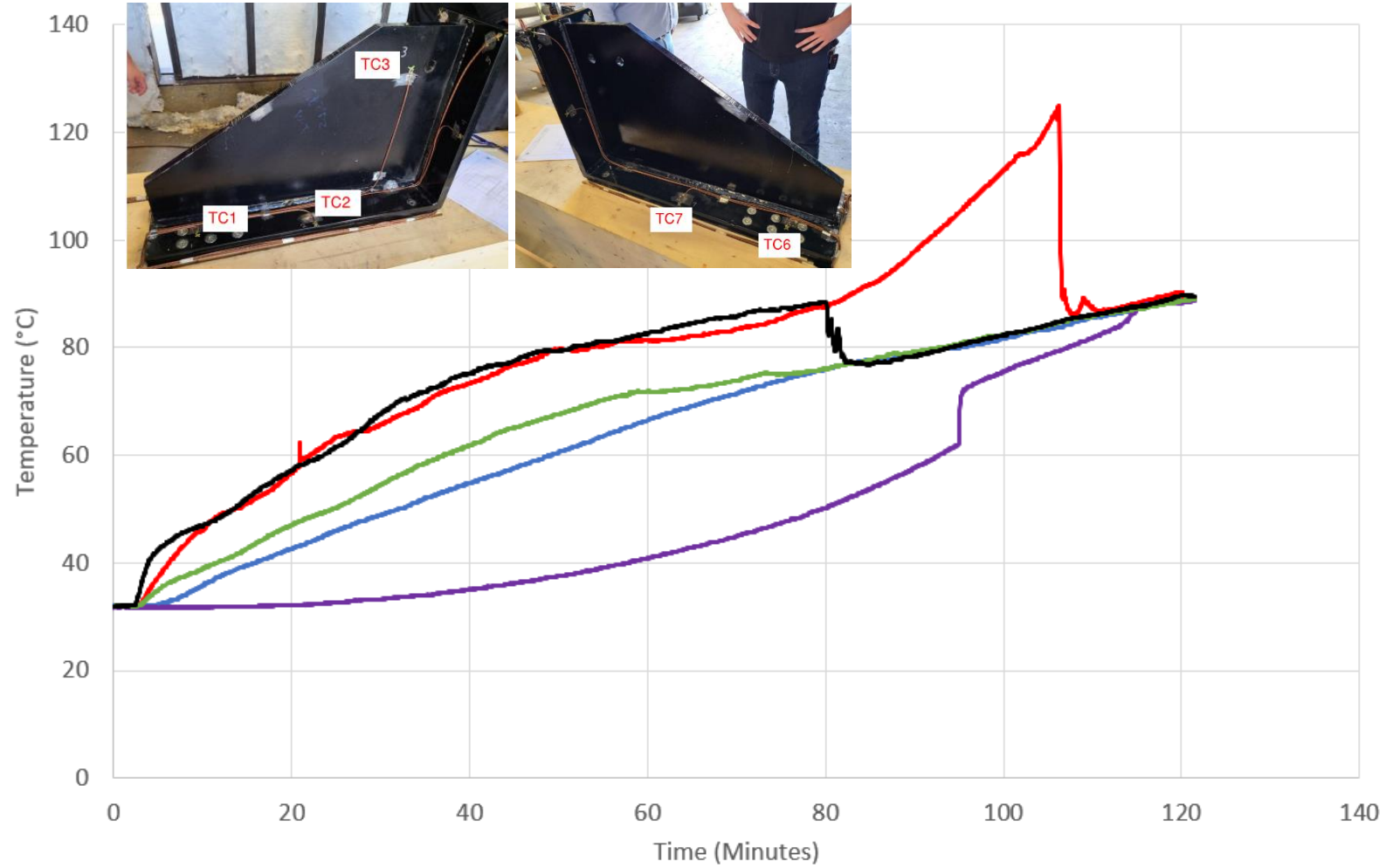


Figure 35: Test 2 Steel Temperatures – Back plate and knife plate

4.3.3 Deflection

Figure 36 below shows the deflection throughout Test 2. The deflection when the load of 35.8 kips was applied was 9.2 mm. The maximum deflection measured after 2 hours was 17.3 mm (0.682") including the initial deflection. Therefore, deflection during the fire test was 8.1 mm which is 88% of the initial deflection and is considered a relatively small amount of deflection to take place during a fire test.

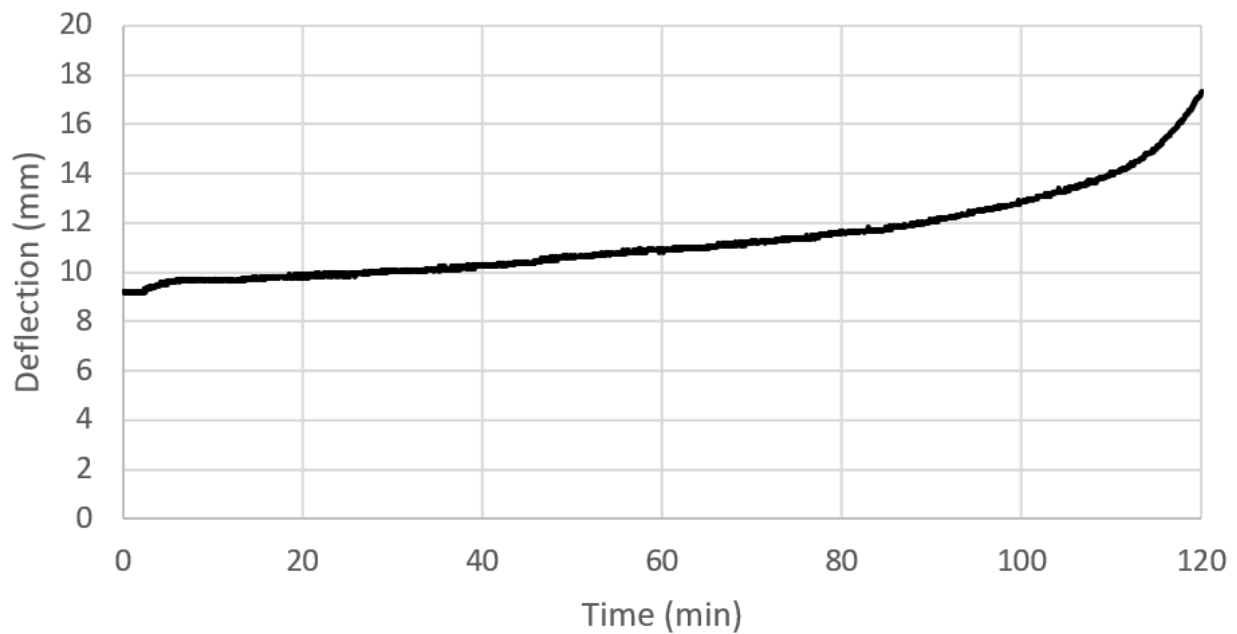


Figure 36: Deflection - Test 2

5 CONCLUSIONS

Based on the data collected and the analysis herein, the following conclusions can be made:

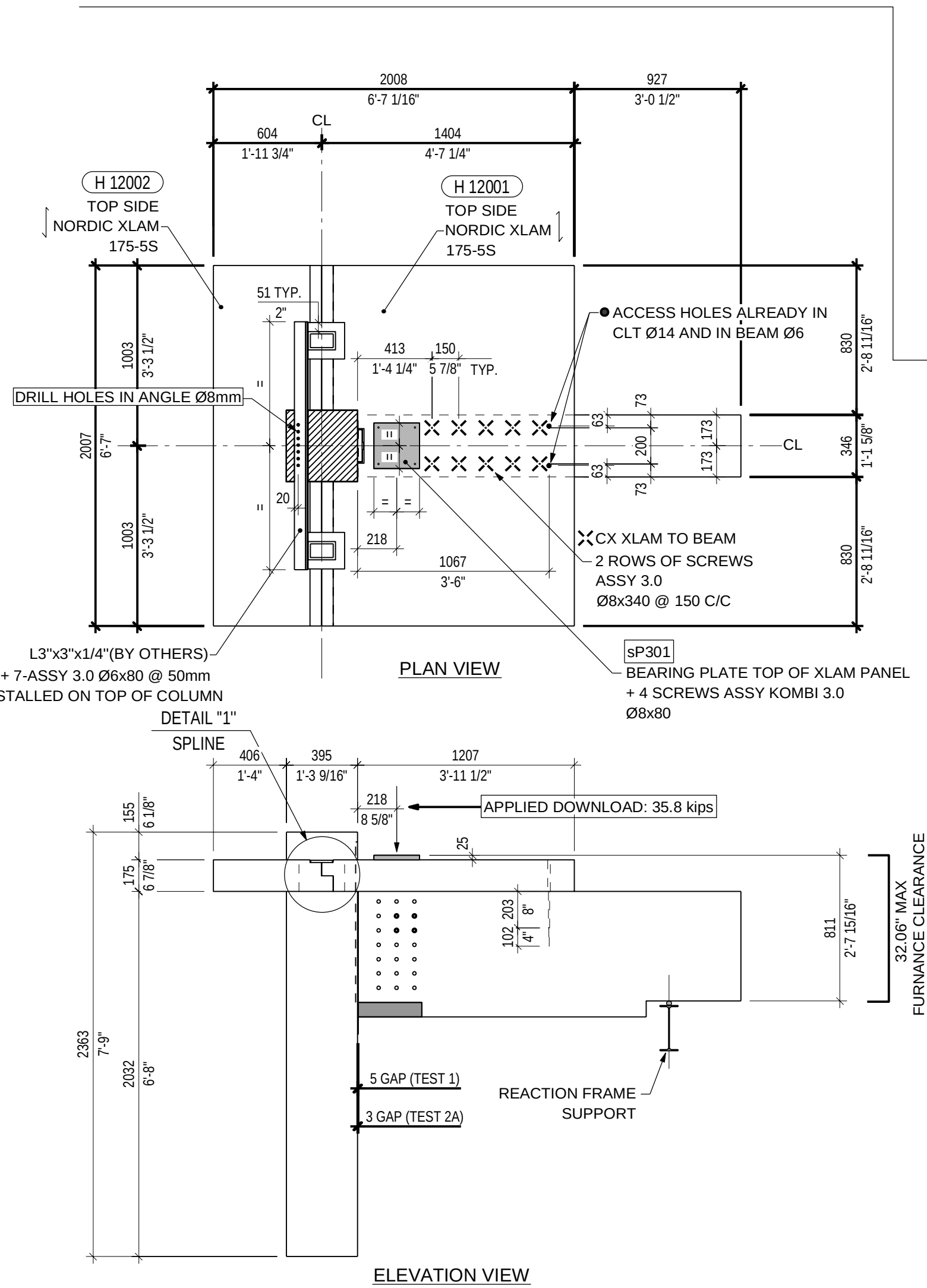
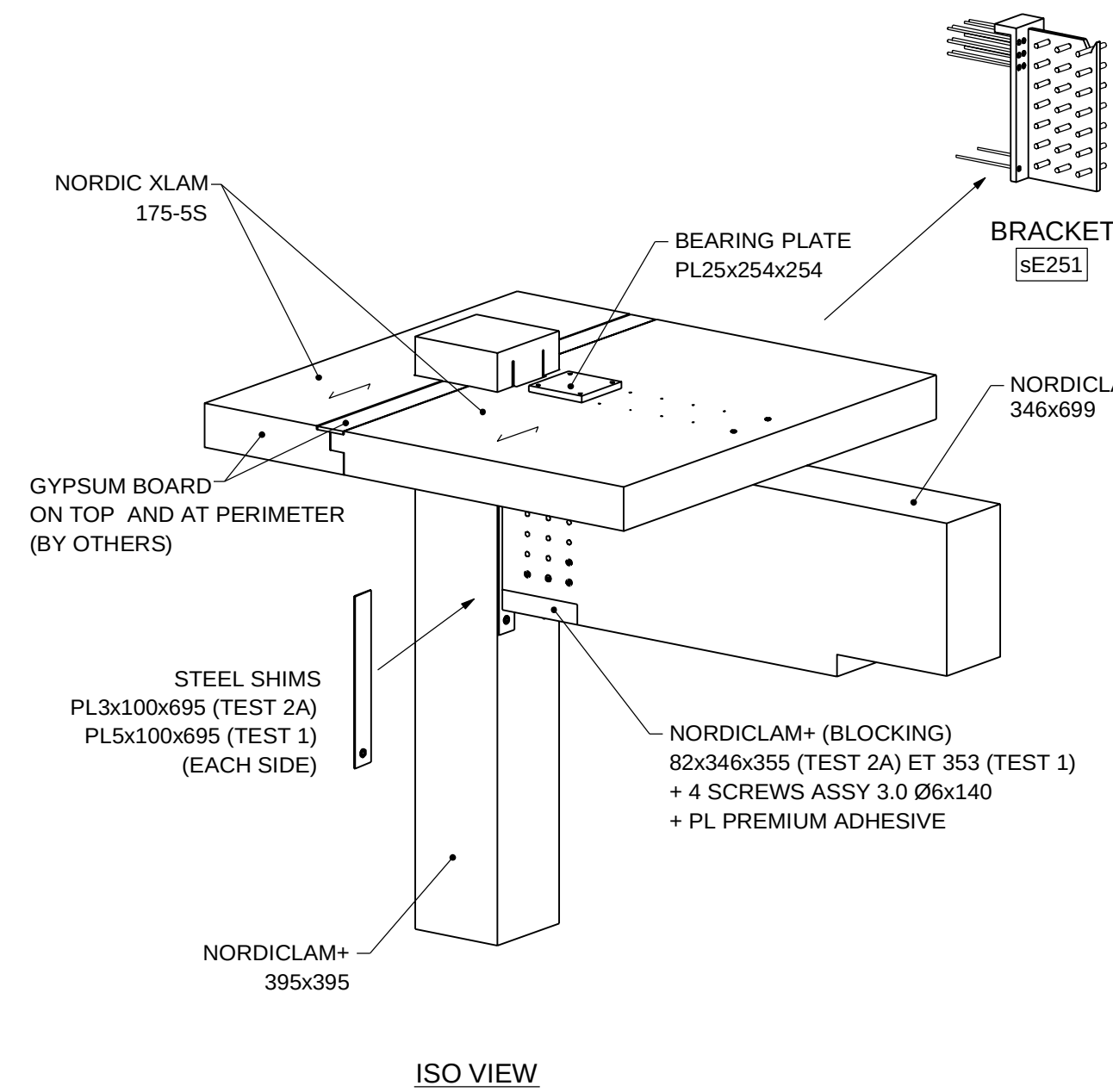
1. The fire-resistance test methodology used successfully exposed the mass timber connection a standard-time temperature curve as specified in ASTM E119/ULC-S101. The exposure was more severe on the bottom of the beam due to the furnace fire dynamics where the burners are near the bottom of the furnace. This is expected due to the test set-up with the connection fully immersed in the test furnace.
2. Both mass timber connections tested achieved a 2-hour fire-resistance rating.
3. The 88 mm wood plug covers are adequate to protect steel components such as dowels for a full 2 hour standard fire exposure.
4. For the connection tested in Test 1, the presence of a 5 mm gap between the end of the beam and the column did not seem to significantly affect the fire performance. This can likely be attributed to the 5 mm gap not significantly affecting the char rate and the fact that char remained in place protecting the steel plate. No evidence of char contraction on the end of the beam was observed in Test 1.
5. For the connection tested in Test 2, the presence of a 3 mm gap between the end of the beam and the column did not seem to significantly affect the fire performance. This can likely be attributed to the 3 mm gap not significantly affecting the char rate and the fact that char remained in place protecting the steel plate (both on the sides and on the bottom). No evidence of char contraction on the end of the beam was observed in Test 2.
6. The thickness of the steel connection plates (knife plate, base plate and bearing plate) is likely an important parameter in the fire performance of the connections. Therefore, application of these test results should be limited to connections similar to that tested.

Attachment A

Beam Assembly Plans

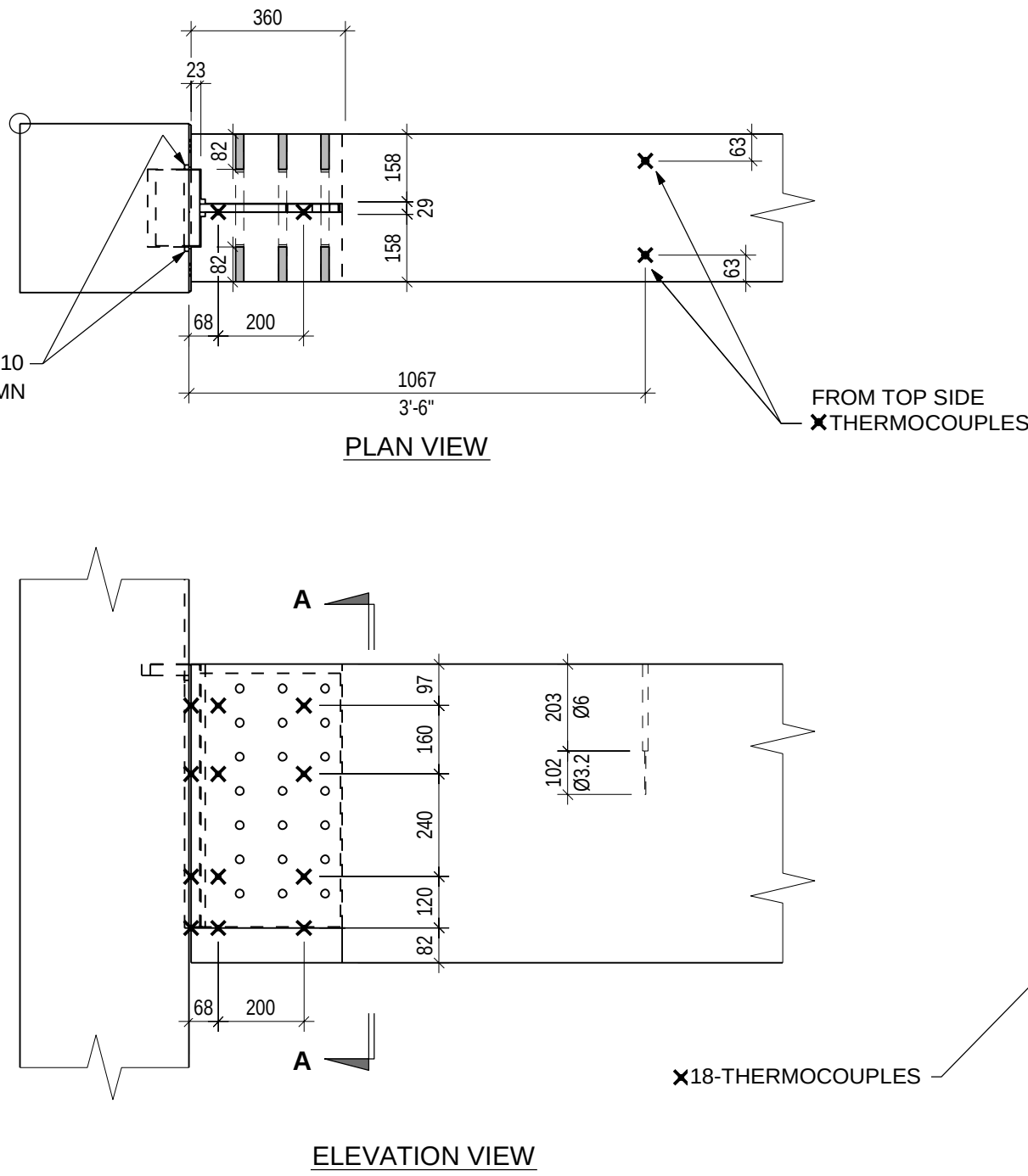
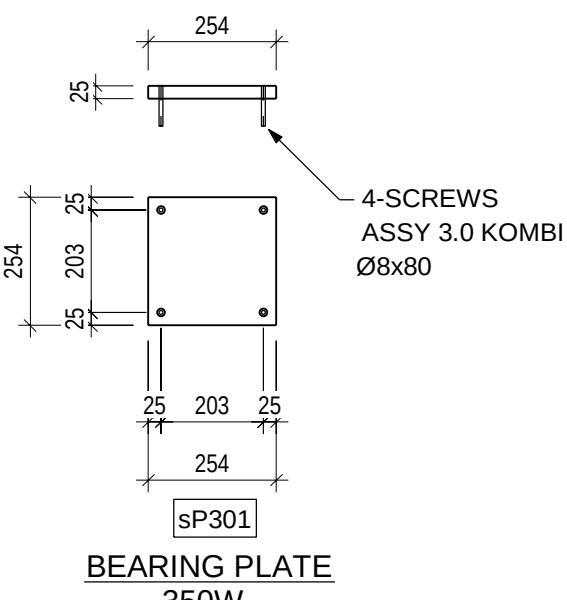
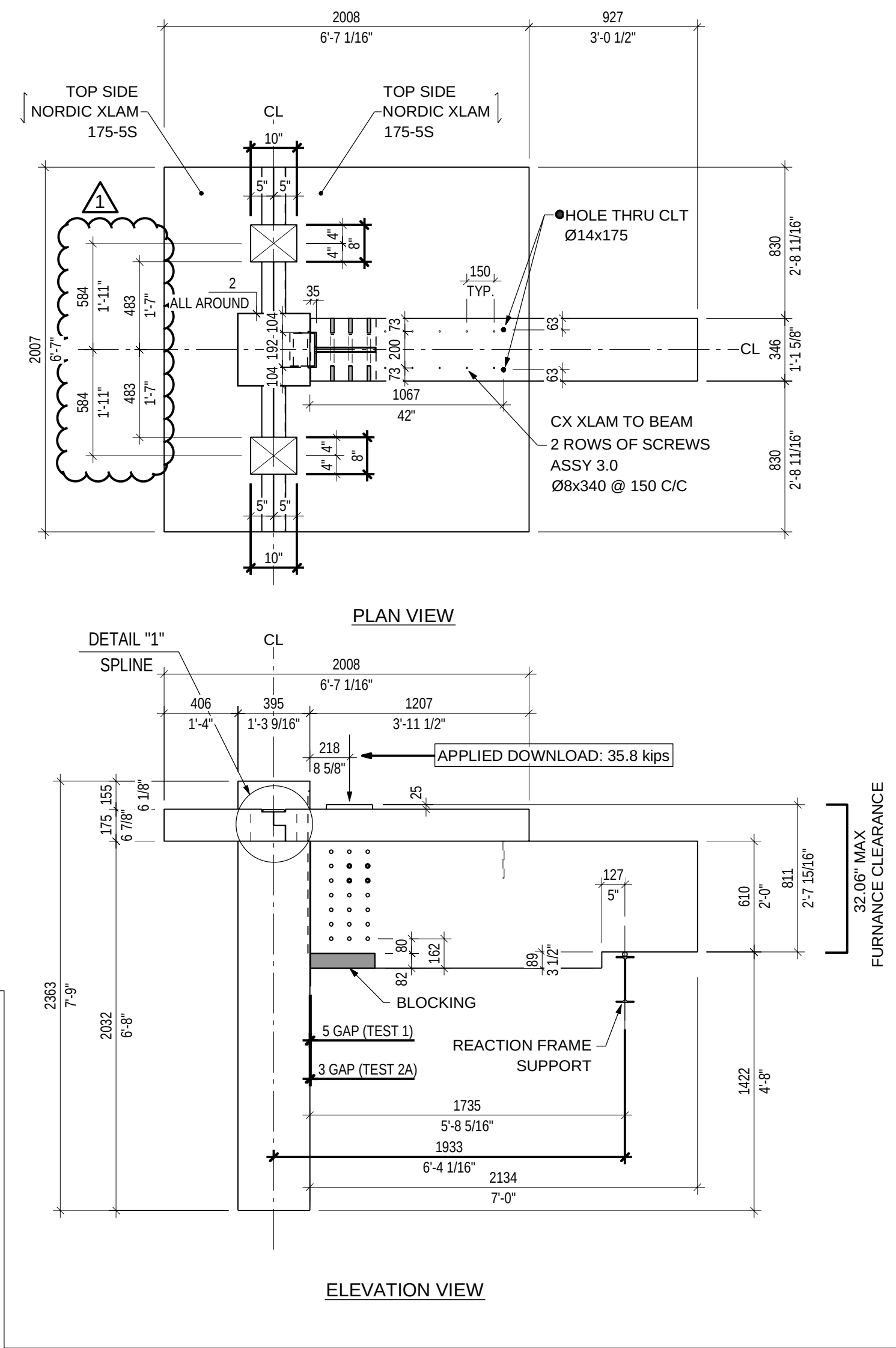
TEST 1 - GAP 5mm (13/64")

TEST 2A - GAP 3mm (1/8")



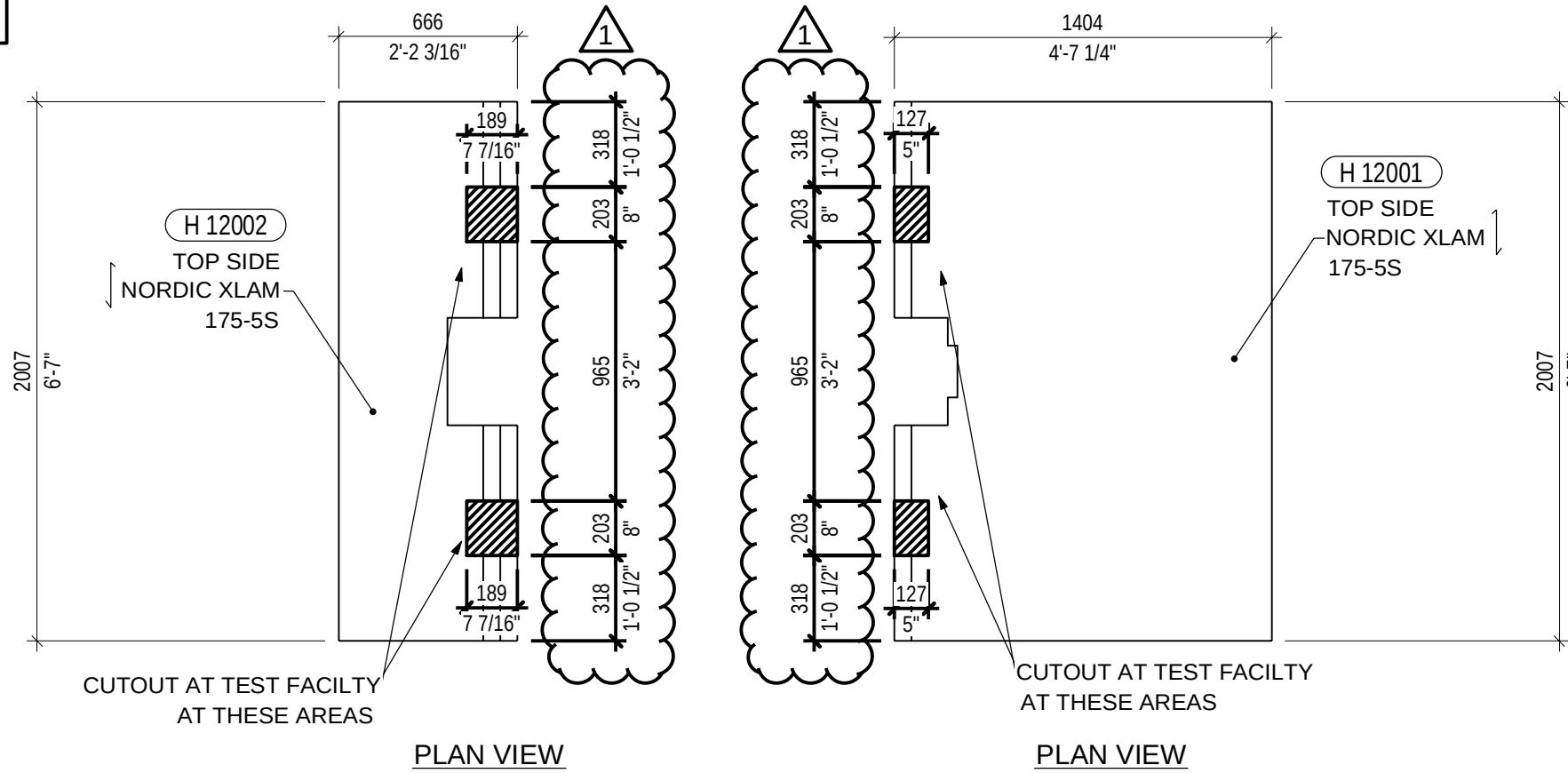
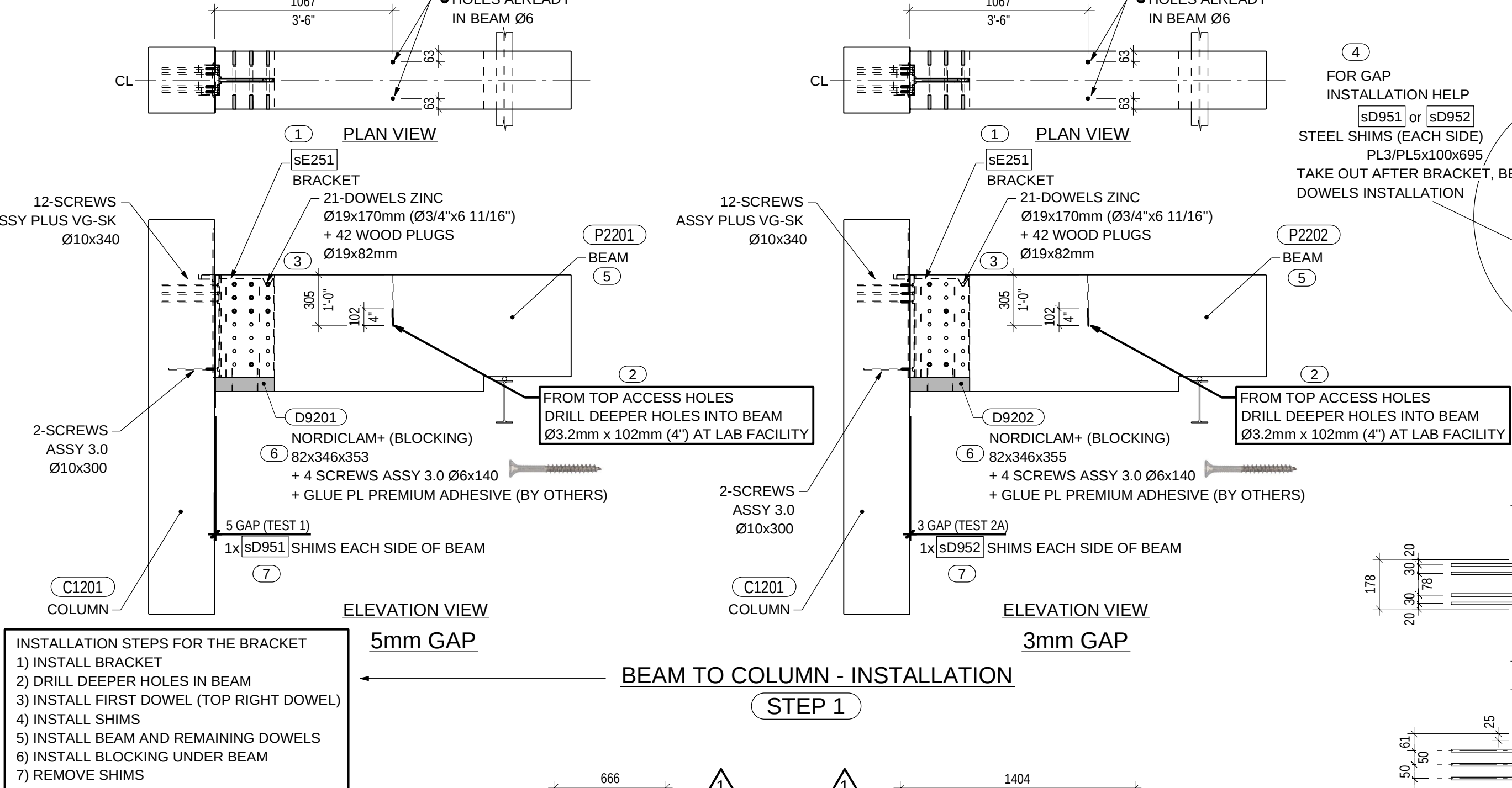
ASSEMBLY OF WOOD AND STEEL PARTS

STEP 3



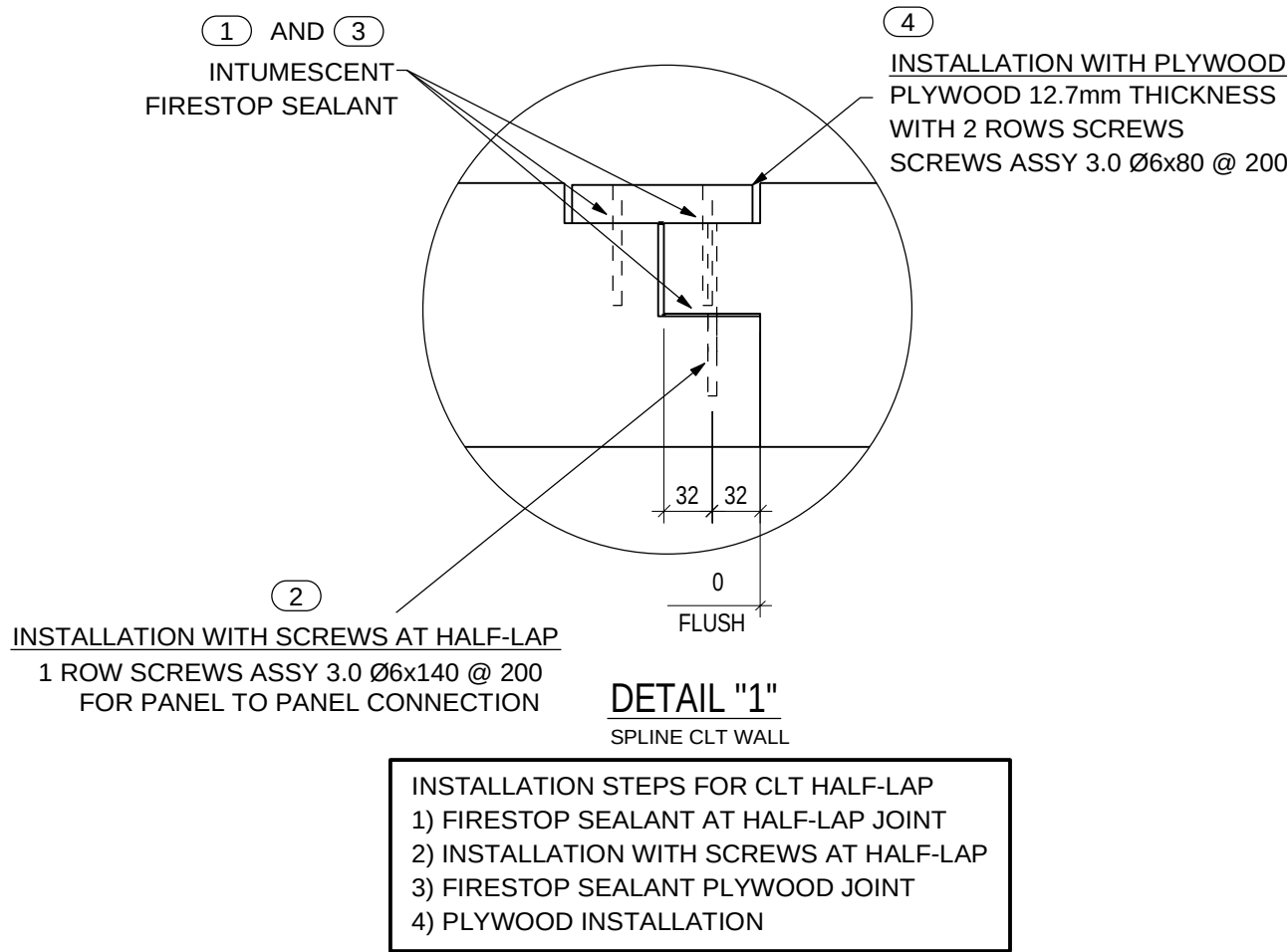
THERMOCOUPLES POSITION

STEP 4

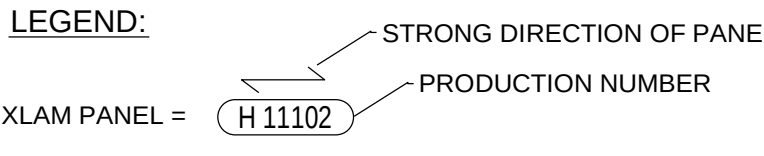


XLAM PANELS - CUT-OUTS TO DO AT TEST FACILITY

STEP 2



LEGEND:



ADDITIONNAL MATERIAL BY NORDIC

- 6 TUBES OF HILTI FS-ONE MAX
- 100 WOOD PLUGS Ø19 x 82mm

1	FOR REFERENCE	2022-07-13
0	FOR CONSTRUCTION	2022-07-05
B	FINAL MARK-UP	2021-06-23
A	FOR APPROVAL	2021-06-03
Rev.	Description	Date

EMISSION / REVISION

NORDIC STRUCTURES

T 514-871-8526
1 866 817-3418

nordic.ca

100-1100, av. des Canadiens-de-Montréal
Montréal (Québec) H3B 2S2

Project

SwRI - FIRE TEST
PHASE 2
TEST 1 - GAP 5mm (13/64")
TEST 2A - GAP 3mm (1/8")

Title

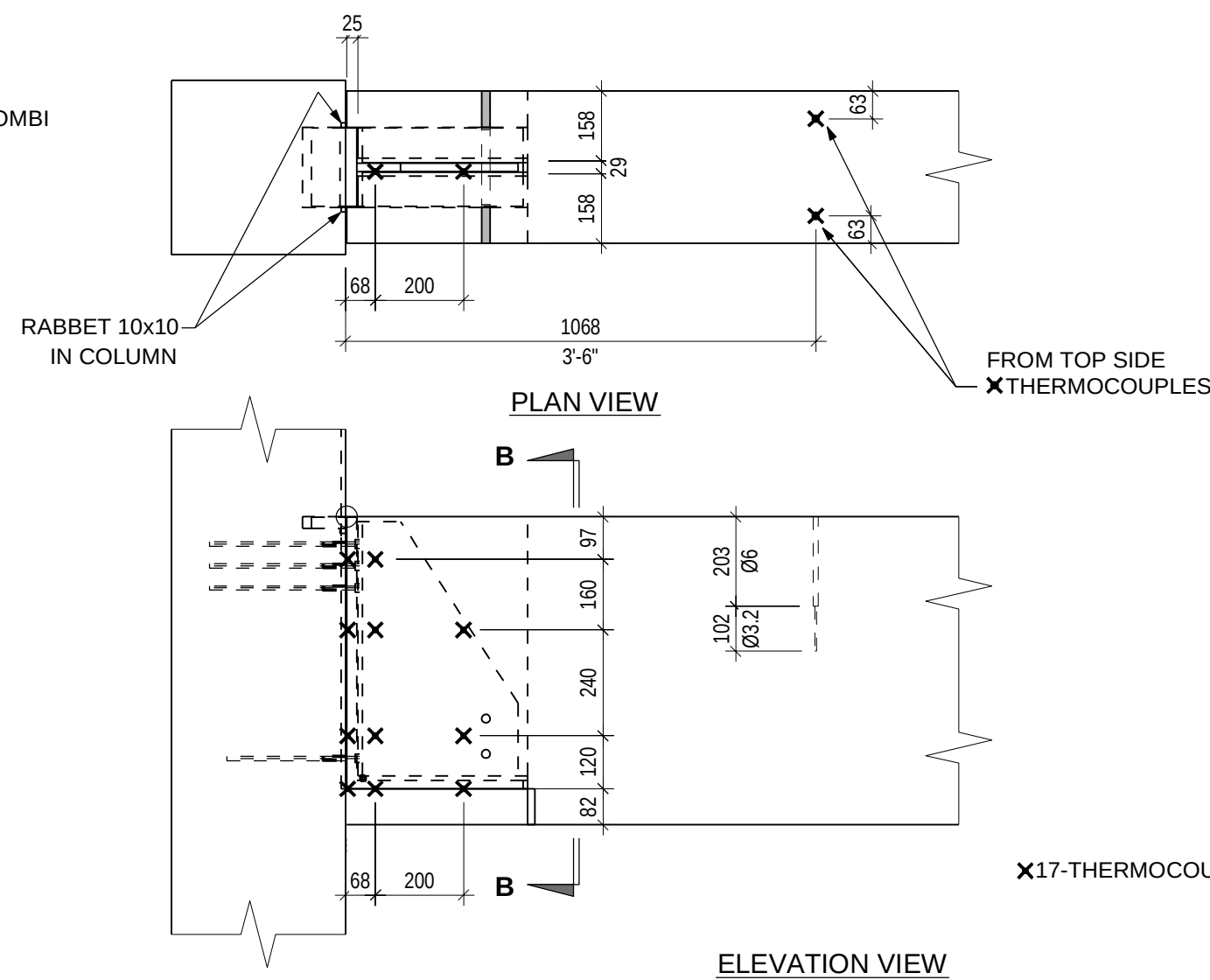
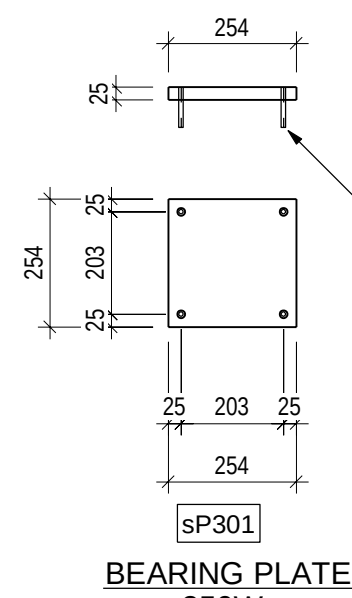
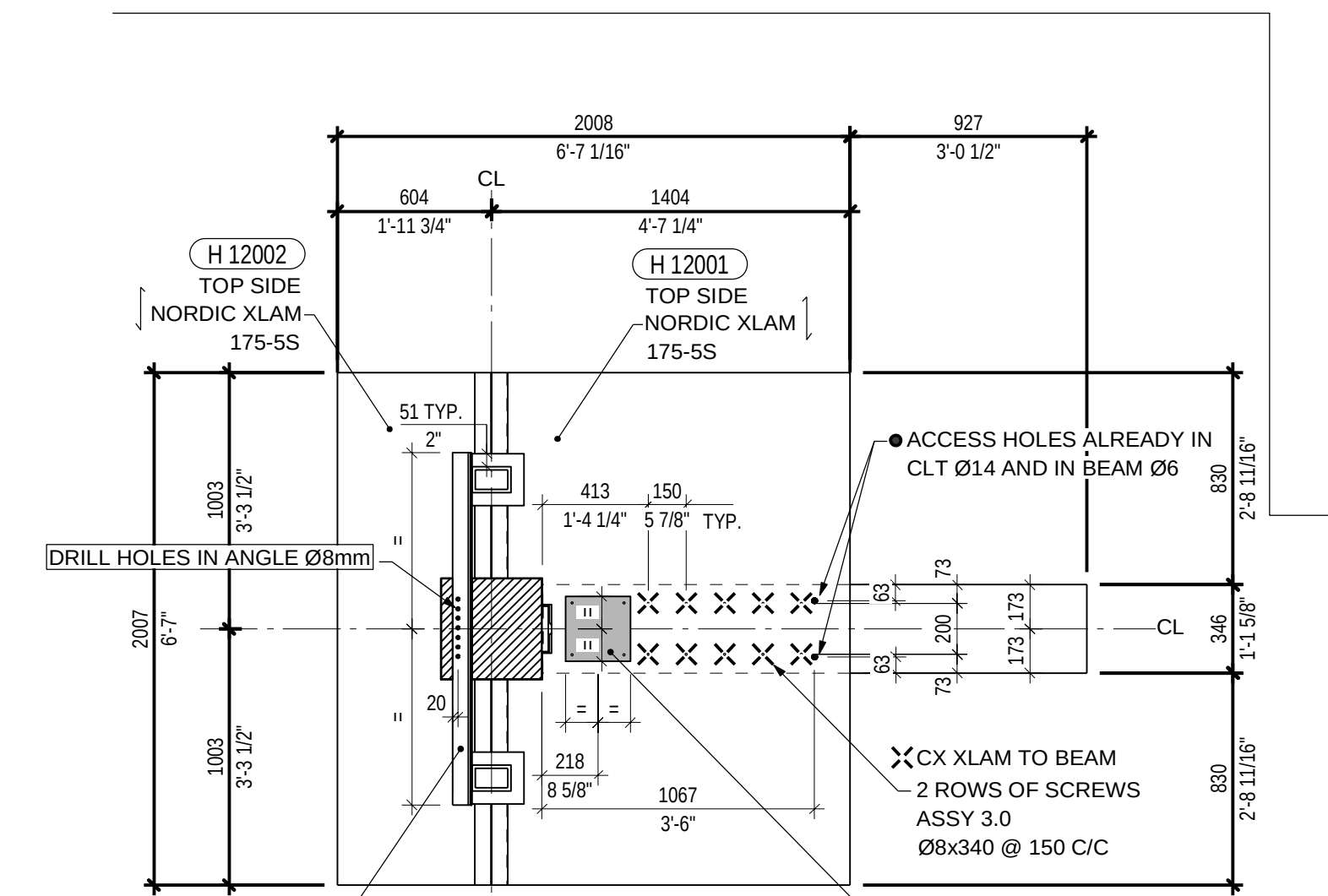
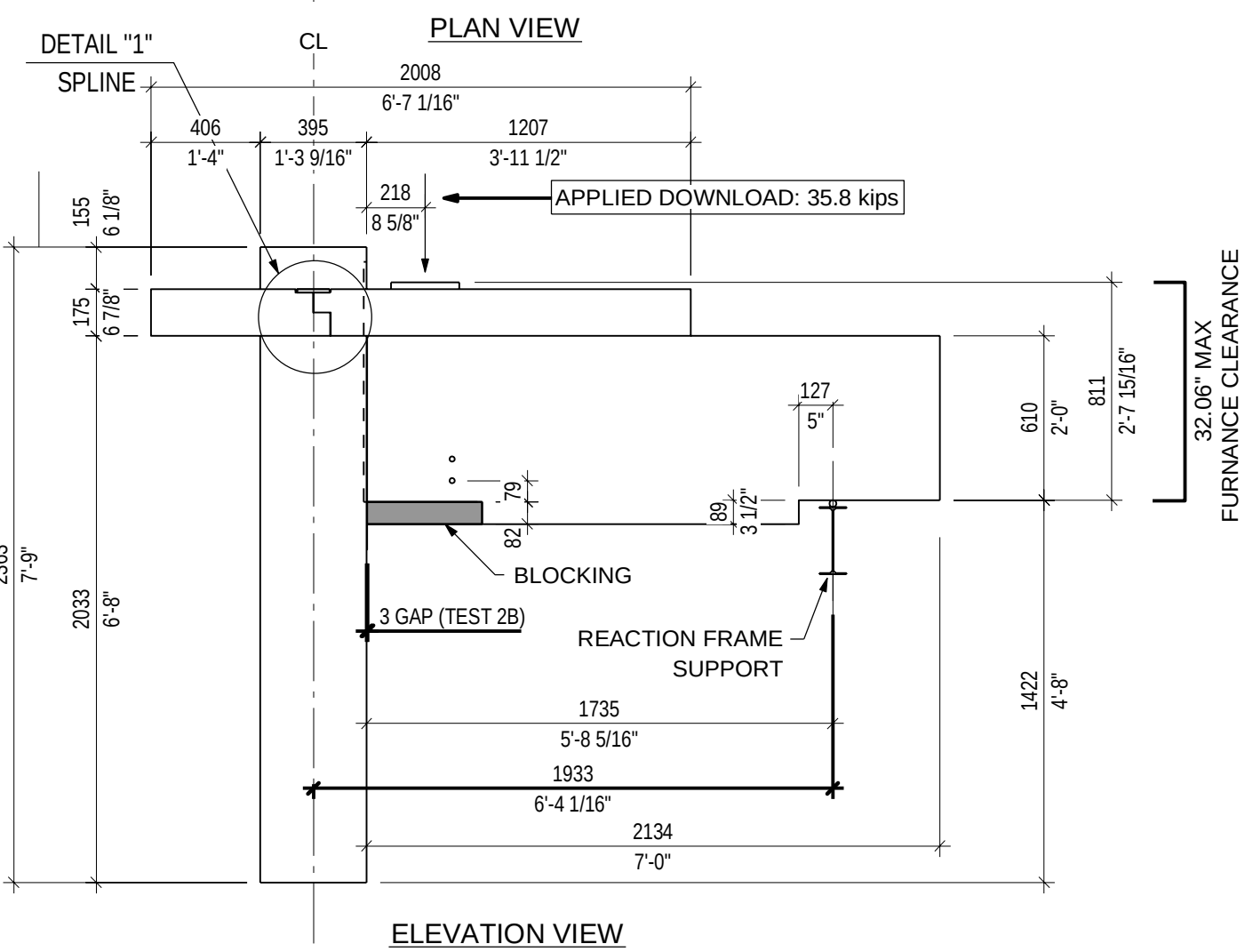
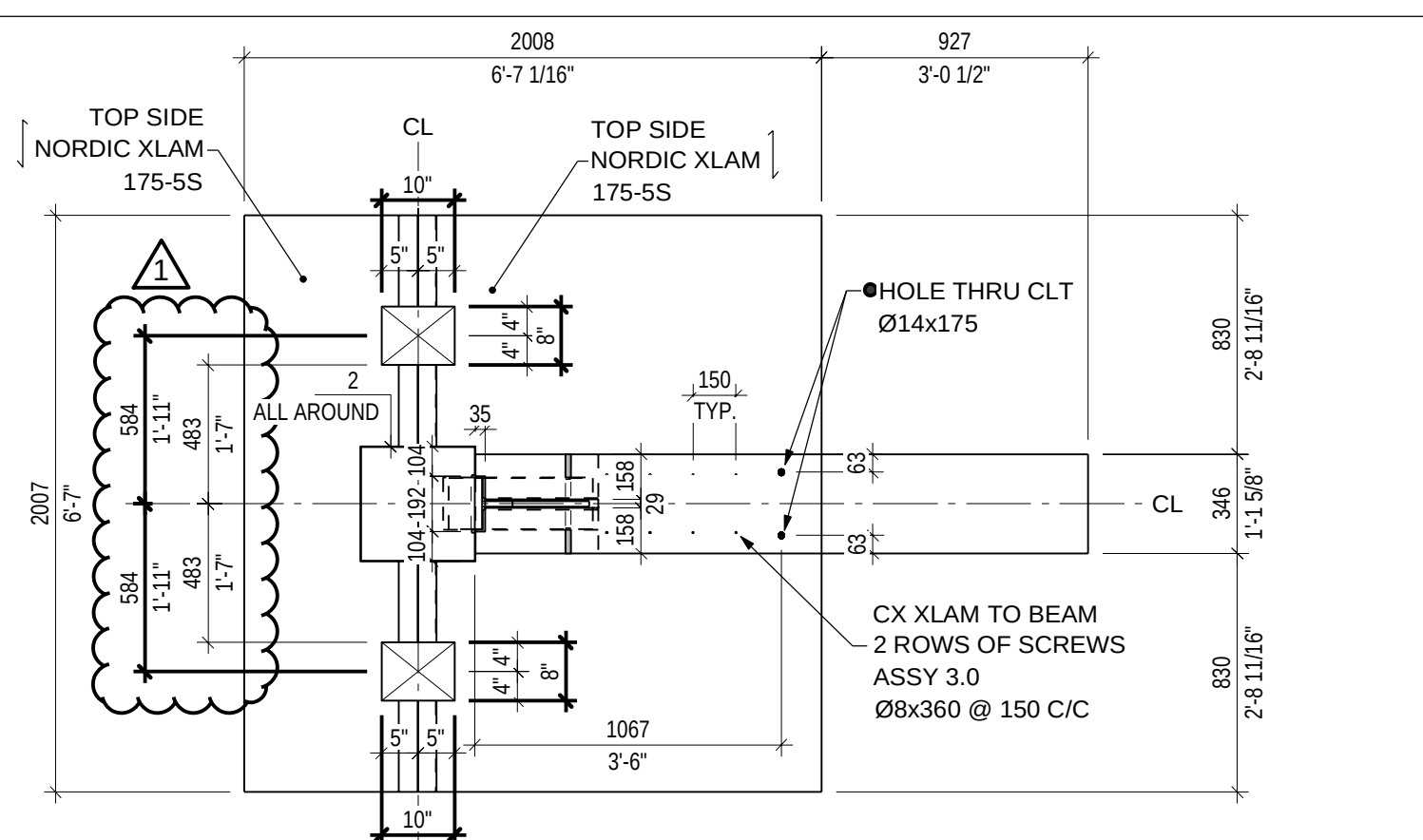
REFERENCE
REFERENCE - ASSEMBLY
PLAN

Drawn by	CPD	Phase	-
Checked by	DPC	Date	2022-06-02
Project No.	2947	Drawing Number	R 001

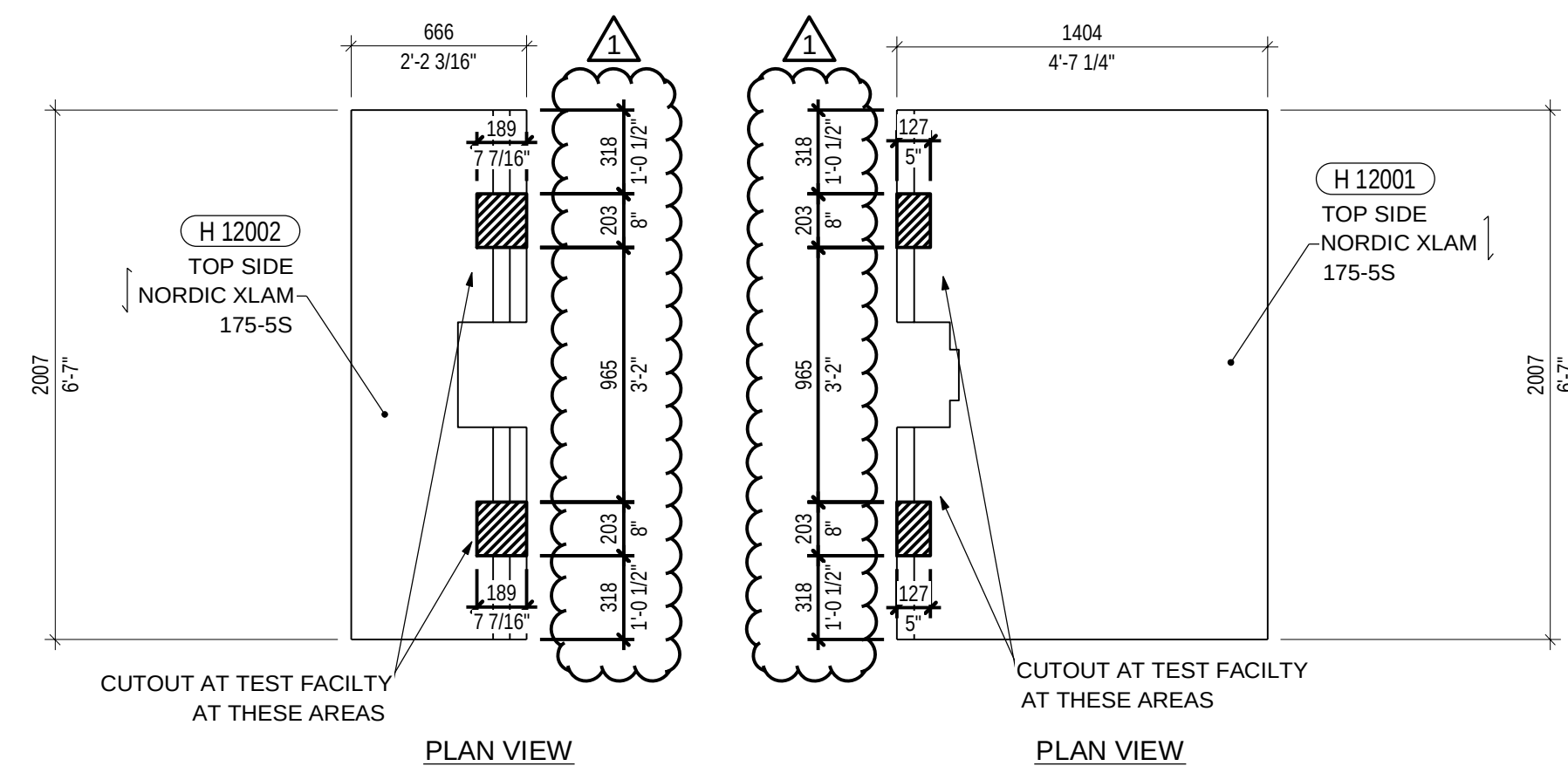
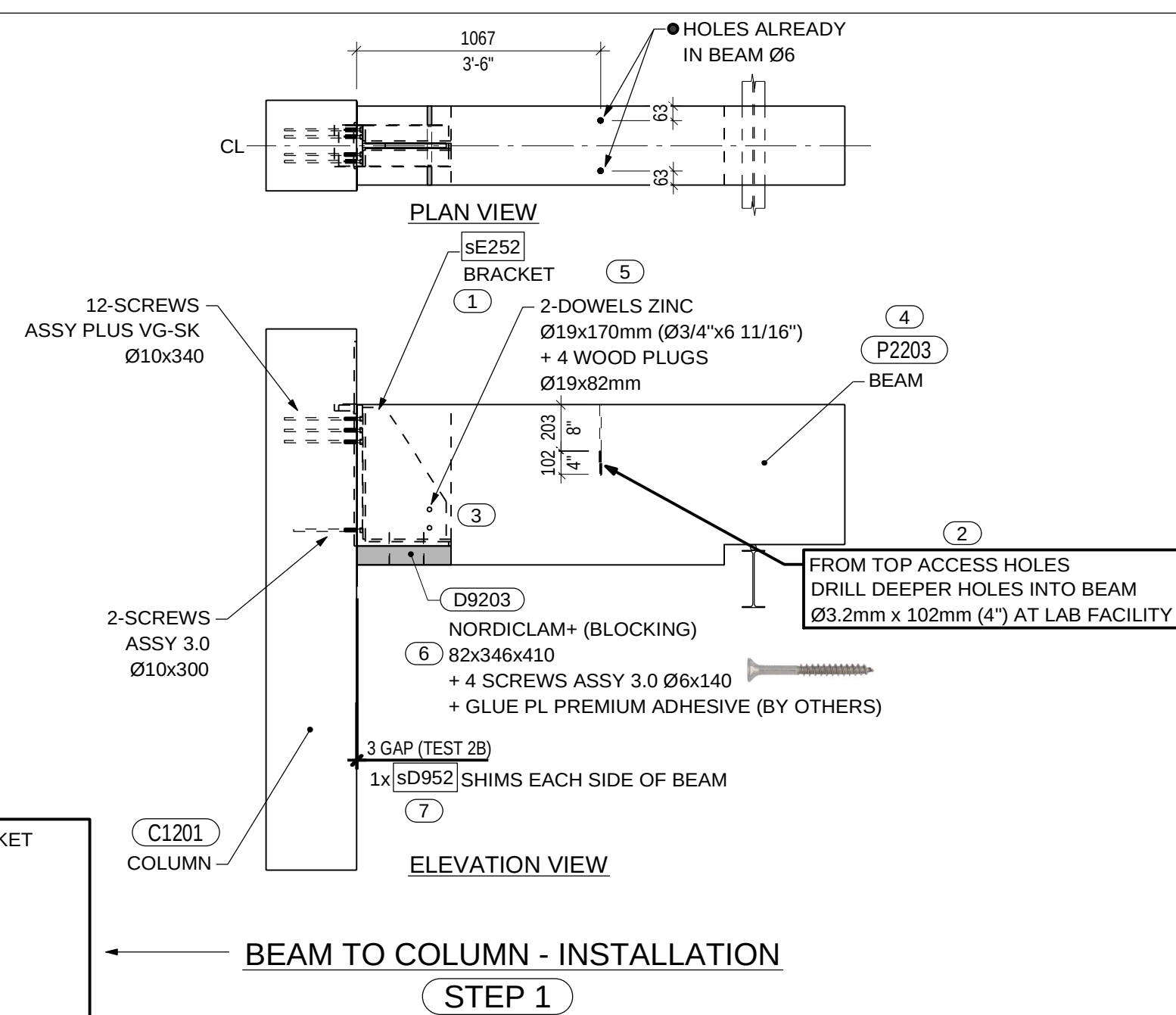
ISO VIEW

Diagram illustrating the assembly components and sequence for the ISO VIEW:

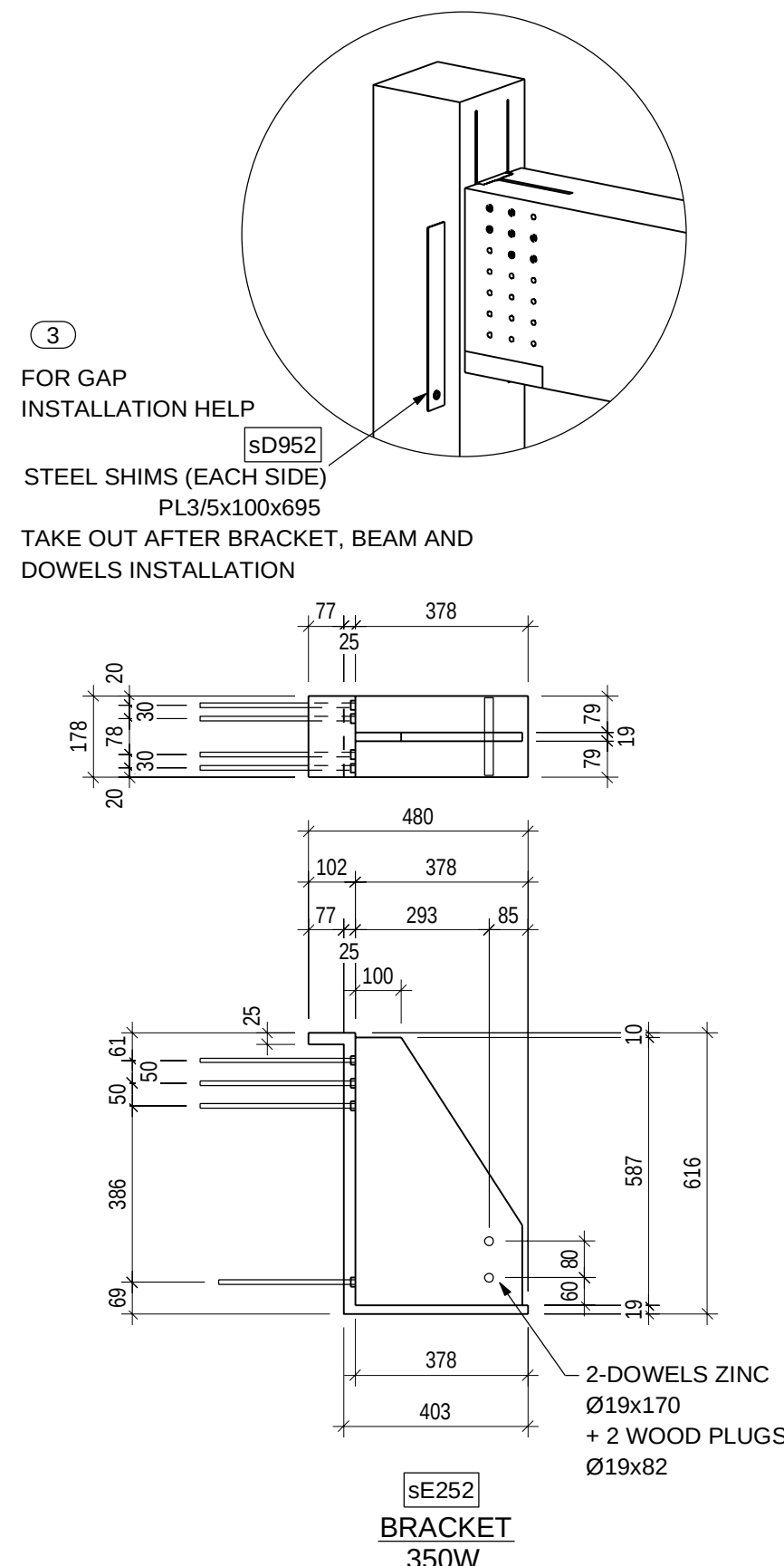
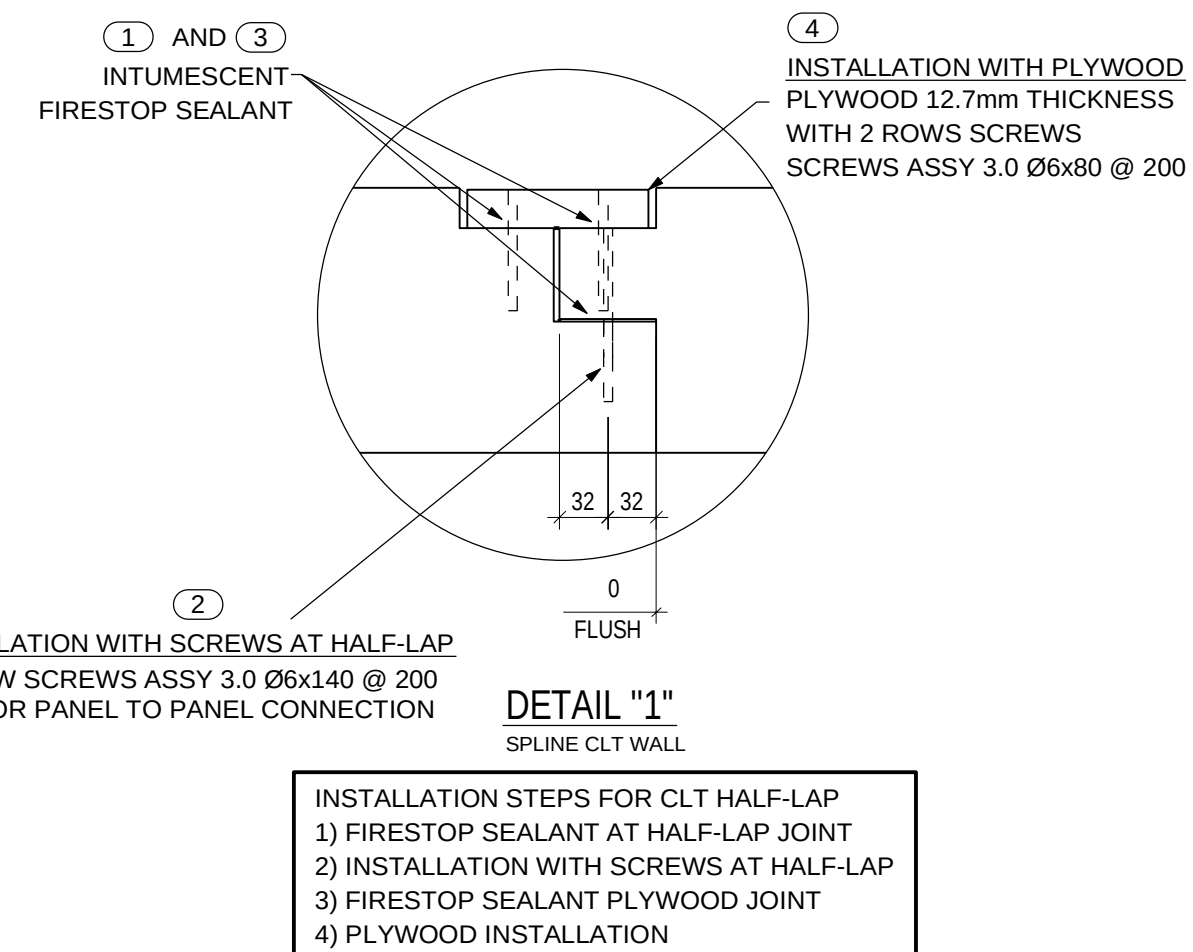
- BRACKET** (sE252)
- BEARING PLATE** (sP301) PL25x254x254
- NORDICLAM+ 346x699**
- NORDICLAM+ 395x395**
- STEEL SHIMS** (sD952) PL3x100x695 (EACH SIDE)
- NORDICLAM+ (BLOCKING)** 82x346x410
 - + 4 VIS ASSY 3.0 Ø6x140
 - + PL PREMIUM ADHESIVE
- M BOARD** (sP301) AND AT PERIMETER (OTHERS)
- NORDIC XLAM 175-5S**



STEP 3



STEP 2



1	FOR REFERENCE	2022-07-13
0	FOR CONSTRUCTION	2022-07-05
B	FINAL MARK-UP	2021-06-23
A	FOR APPROVAL	2021-06-03
Rev.	Description	Date

NORDIC
STRUCTURES

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1 866 817-3418

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Title

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Drawn by	CPD	Phase	-
Checked by	DPC	Date	2022-06-30
Project No.	Drawing Number		
2947	R	0	02

Imprimé le 13-07-2022 pour format d'impression (22"x34")