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BRE Test Report

WikiHouse Structural Testing

Prepared for: Clayton Prest
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1 Introduction

Open Systems Lab, the Client, in collaboration with the University of Edinburgh, Real Living Homes, Three Create and Leeds Becket University, and supported by Innovate UK's Sustainable Innovation Fund, are working on an open R&D project (WikiHouse) to look at how digital and offsite manufacturing technologies and methods can help transform the UK construction industry. As part of this project the Client requested that BRE undertake a programme of large-scale structural testing to build on knowledge from preliminary element and connection testing carried out by the University of Edinburgh. This report covers structural testing of component panels and a full module of WikiHouse. This report covers the racking testing undertaken on 4 No. 5.4m wide x 3.1m high timber panels; 2 No. solid construction and 2 No. with apertures, as well as horizontal loading of 1 No. 5.3m x 5.3m x 3.1m high module (all dimensions have been advised by the client and were not verified by BRE).

This testing was carried out under BRE Proposal P120099, which was accepted by Clayton Prest on behalf of Open Systems Lab Ltd on 1st April 2021 on an emerging scope basis. The scope of testing was developed and agreed as the test programme progressed, with the details described within this report.

Open Systems Lab arranged for delivery and install of the first test specimen at BRE's Watford site on 1st June 2021. The setup and testing were undertaken between 26th May – 16th June 2021.

This report provides details of the testing carried out and the results obtained.

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2 Test programme

The test programme covered two types of testing: racking strength and stiffness of two-dimensional panels and a three-dimensional module test.

2.1 Racking Strength and Stiffness of Two-Dimensional Panels

Four racking tests were carried out:

- 1 No. panel without openings, without coincident vertical load
- 1 No. panel without openings, with coincident vertical load
- 1 No. panel with 2 No. 1.2m square openings, without coincident vertical load
- 1 No. panel with 2 No. 1.2m square openings, with coincident vertical load

The client advised that the dimensions of the test panels were 5.4m long and 3.1m high and weighed approximately 400kg each (these dimensions were not verified by BRE). A sketch showing a typical set up and location of loads and displacement transducers can be seen in Figure 1.

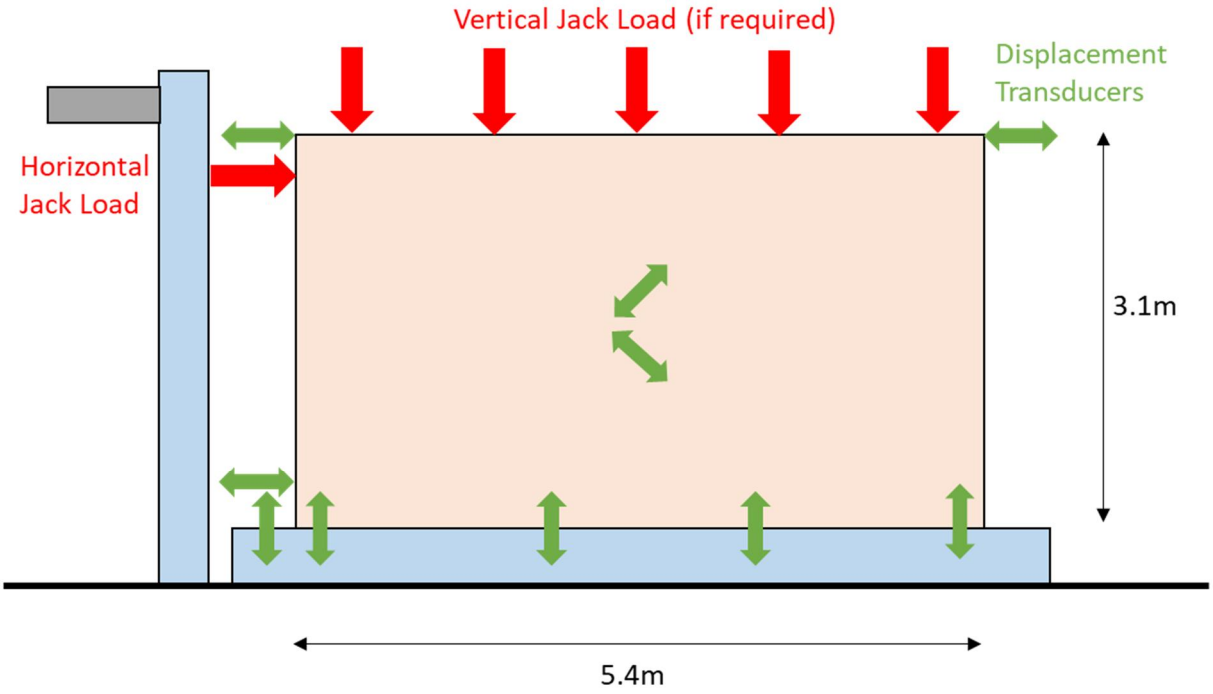


Figure 1 - Set up for 2D Racking Panels

The test panels were fixed to the BRE large structures laboratory strong floor through a hot rolled steel beam that was supplied by the Client. The horizontal load was generated using 1 No. hydraulic jack reacted off a steel column fixed to the strong floor and first floor balcony ring beam. Based on preliminary estimates of capacity made by the client, the target racking load Fmax adopted for this testing was 80kN. The load was applied as per the following:

- Load applied up to 0.1 Fmax and maintained for 30 seconds and unloaded
- Load applied up to 0.4 Fmax and maintained for 30 seconds and unloaded
- Load applied up to Fmax or failure

For tests where a vertical load was required in addition to the horizontal load, the vertical load was applied to the top of the panel as five point loads at nominal 1143mm centres. This was equivalent to a line load of 8.3kN/m and was generated using hydraulic jacks fixed to the strong floor. This load was applied to the top of the test panel through a series of tie rods and steel spreader beams. A timber header beam was added across the top of the wall to span between the steel spreader beams. PTFE shims were installed between the steel spreaders and the timber header beam to minimise friction. Both the racking and vertical loading were measured using calibrated load cells. A photo of the set up with and without the vertical loads can be seen in Figure 2 and Figure 3 respectively.

Lateral restraint was provided to the top of the panel through two struts fixed back to the first floor laboratory balcony, with connections to allow sliding and rotation.

Displacement was measure using 10 deflection transducers installed in the positions shown in Figure 1.

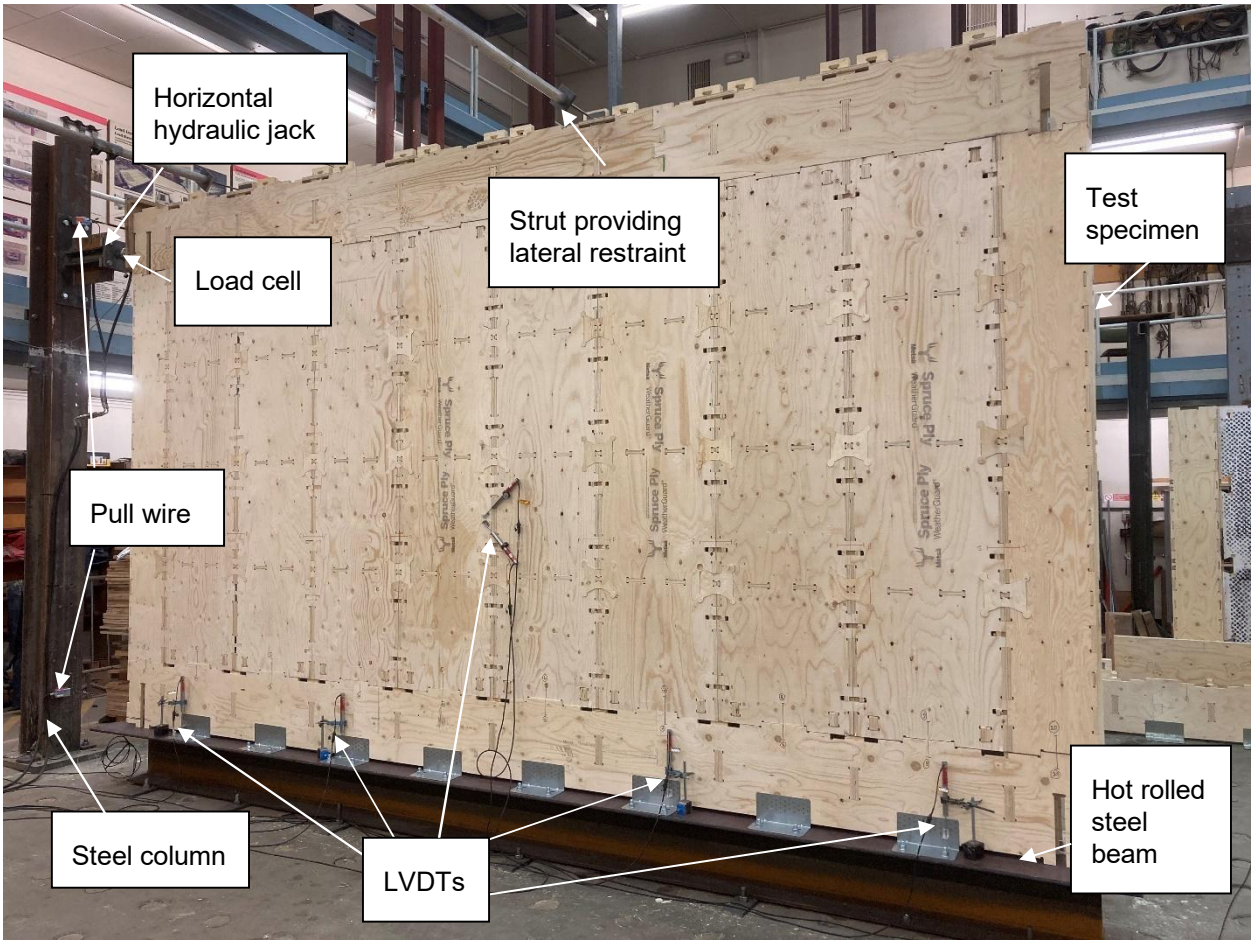


Figure 2 - Set up for 2D Racking Panels without Vertical Load

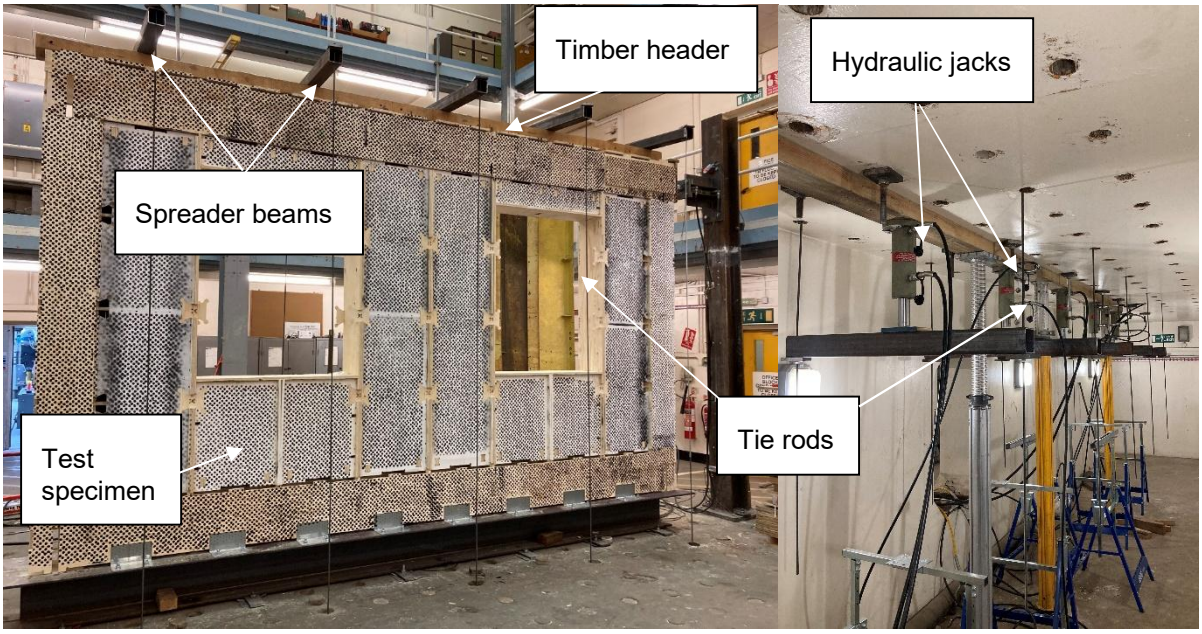


Figure 3 - Set up of 2D Racking Panels with Vertical Load.

2.2 Three-Dimensional Module Test

One three-dimensional module test was carried out on a one-storey module structure, which the client advised had dimensions 5.3m long, 5.3m wide and 3.1m high (these were not verified by BRE). The three-dimensional module was delivered to BRE in panels and assembled inside the large structures laboratory to accommodate the size of the laboratory door openings. The construction was carried out by the Client and BRE. The test module was fixed to the laboratory strong floor through an assembly of hot rolled steel beams and steel plates.

The horizontal load was generated using two hydraulic jacks reacting off steel columns fixed to the strong floor and first floor balcony ring beam. The load was applied mid-storey height (approximately 1.5-1.6m above FFL). The load from the jacks was spread into the wall of the test module using a 1100mm x 2300mm x 8mm thick steel plate. Two 580mm x 190mm x 90mm timber spreaders were installed between the jack and the steel plate. The target racking load Fmax that was used for this testing was 50kN per jack. The load was applied as per the following:

- Load applied up to 0.1 Fmax and maintained for 30 seconds and unloaded
- Load applied up to 0.4 Fmax and maintained for 30 seconds and unloaded
- Load applied up to Fmax or failure

A vertical uniformly distributed load of 1.6kN/m^2 was applied over the roof area. This was applied as a static load using 45kg weights on a square grid spaced at 525mm centres in two orthogonal directions and was applied before horizontal loading began.

Displacement was measure using 19 deflection transducers installed in the positions shown in Figure 4 and Figure 7 on the east face, Figure 5 on the north elevation (and mirrored on the south elevation) and 4 on the roof.

A buffer structure was erected on the opposite side of the module to that horizontal jack to minimise the risk of a collapse of the test module, and can be seen in Figure 6.

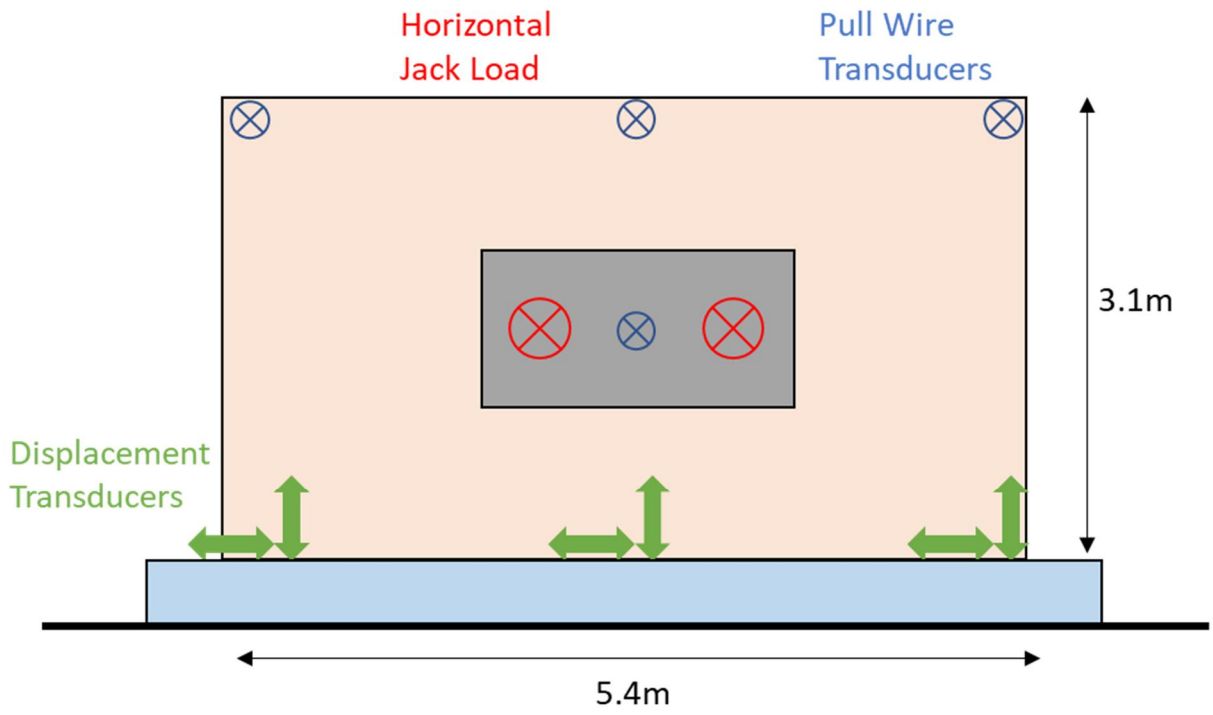


Figure 4 - Set up of 3D Module showing East Face

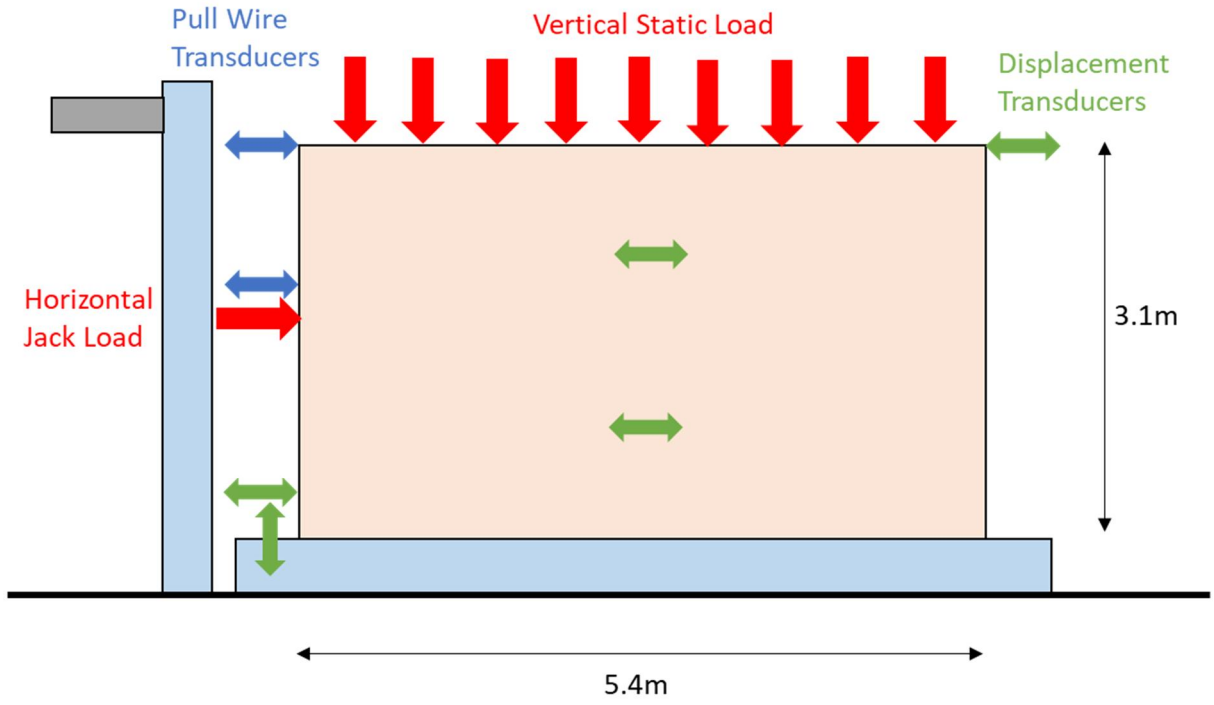


Figure 5 - Set up of 3D Module showing North Face

Figure 6 - 3D Module showing Roof Loading and Buffer Structure

Figure 7 - 3D Module Test Showing East Face

3 Test results

3.1 2D Panel Tests

3.1.1 Window Wall – No Vertical Load

Based on preliminary estimates of capacity made by the client, the target racking load Fmax adopted for this testing was 80kN.The displacement transducer locations can be seen in Figure 8. The positive direction of movement as shown in the graphs below are upwards and to the right. These are indicated by the arrow directions in Figure 8.

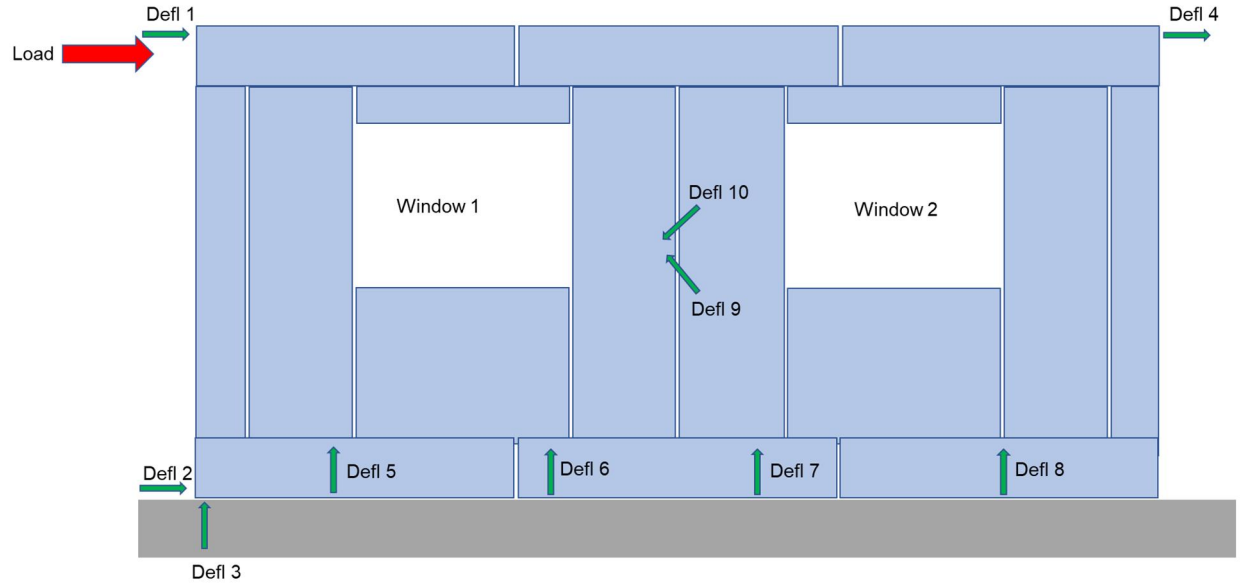
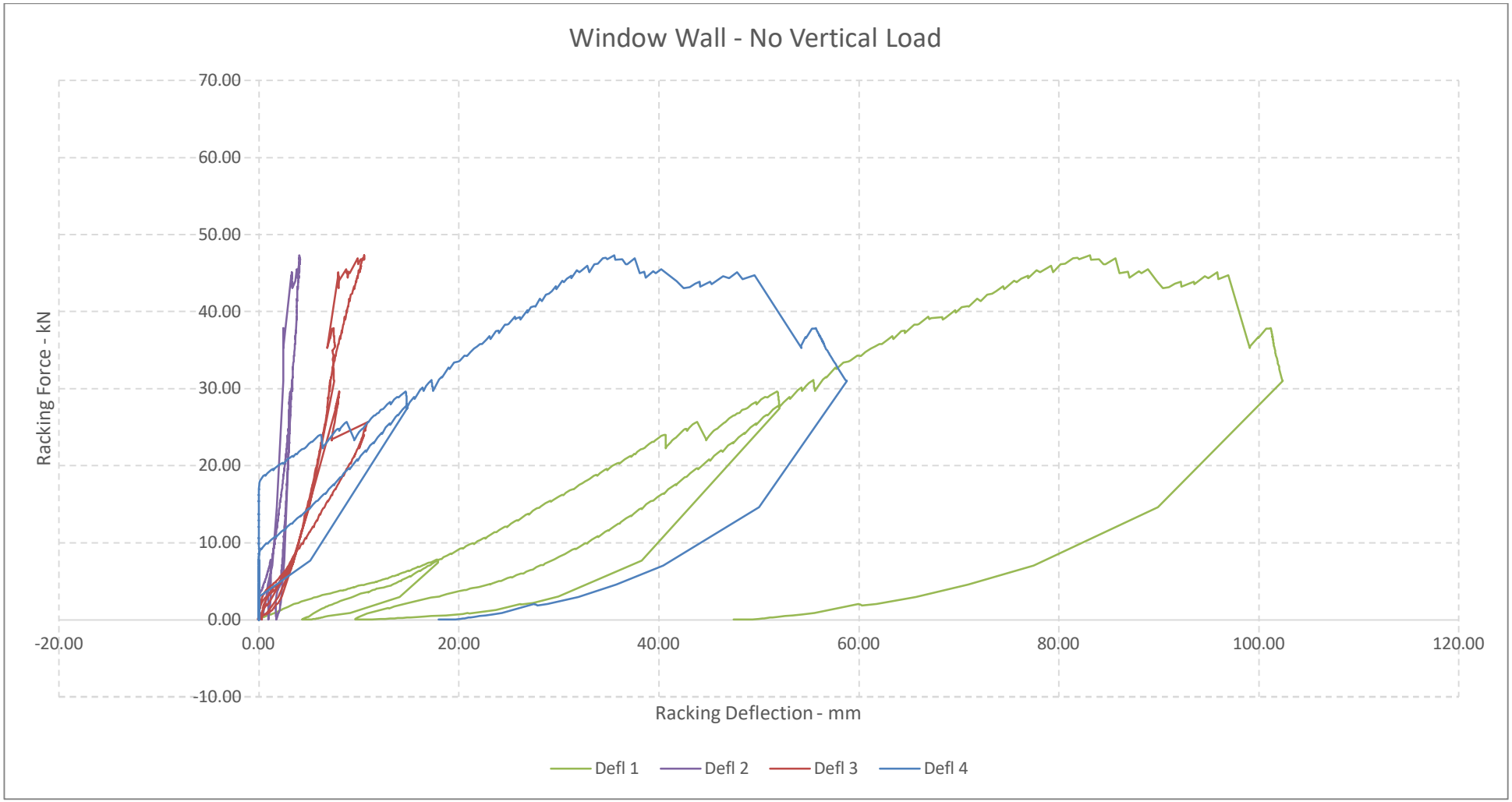


Figure 8 - Displacement Transducer Locations for 2D Window Wall test without Vertical Load

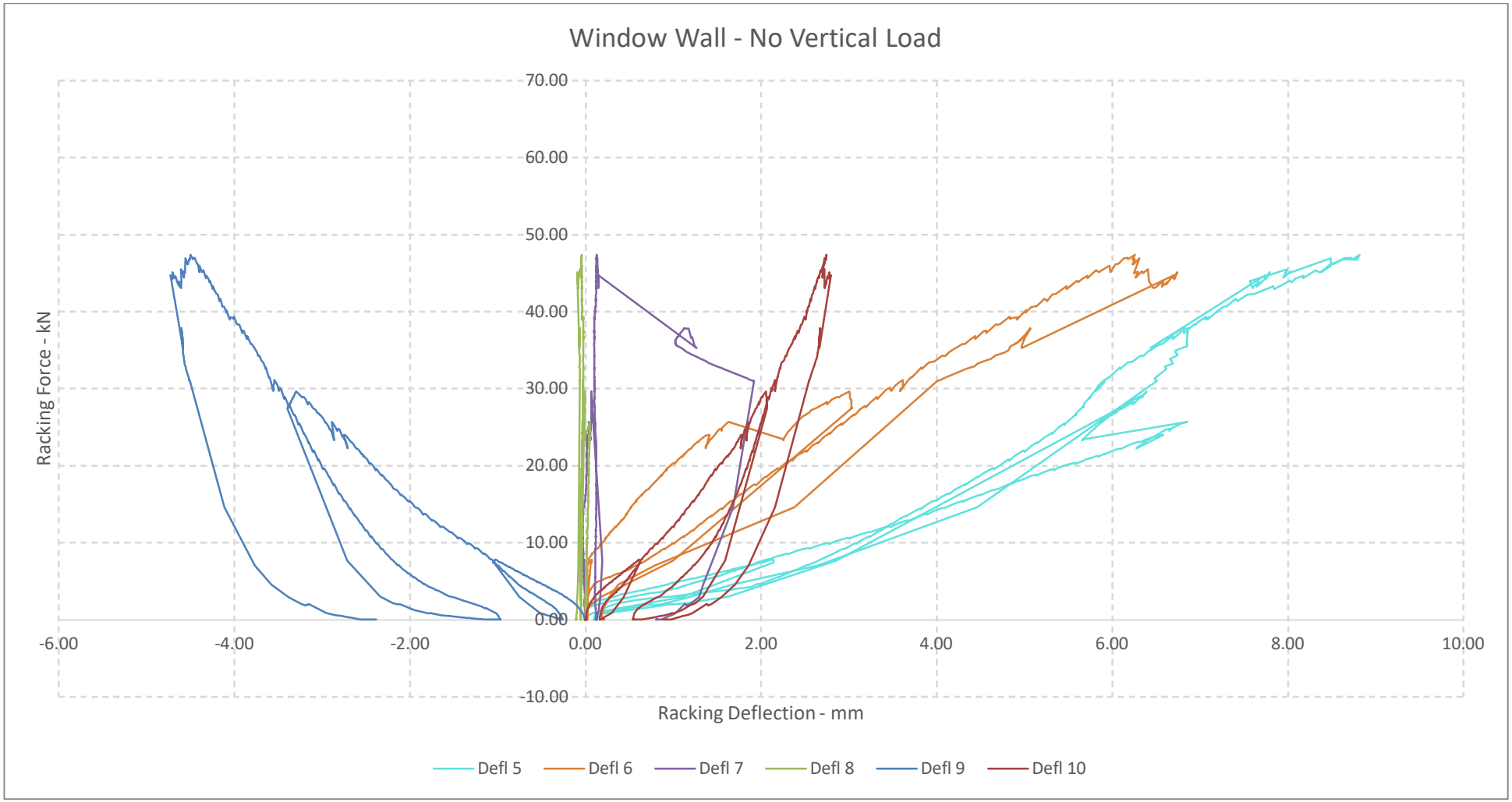
The first cycle was to 0.1F or 8kN and the load was applied gradually to peak then held for 30 seconds before release. There was no obvious damage or other problems.

The second cycle was to 0.4F or 32kN, as before load was applied gradually to peak then held for at least 30 seconds before release. This second cycle caused movement of wall components but there were no obvious signs of damage.

The third cycle was to 0.4F then failure, the load was raised to 32kN as for previous cycle and held for at least 30 seconds then increased until failure. There was eventual failure of the bow tie plates between the wall elements at bottom right corner of window 1 and between the two full height units between windows. At approximately 47 kN there appeared to be a drop in the load sustained by the specimen. Loading continued, however a significant increase in the magnitude of the applied load was not achieved and so the load was removed. The through wall peg between the wall units and foundation beam almost disengaged at the loaded end of wall due to uplift induced movement between units. This failure can be seen in Figure 9 - Figure 12.



Graph 1 – Window Wall without Vertical Loading: Deflections 1-4



Graph 2 – Window Wall without Vertical Loading: Deflections 5-10

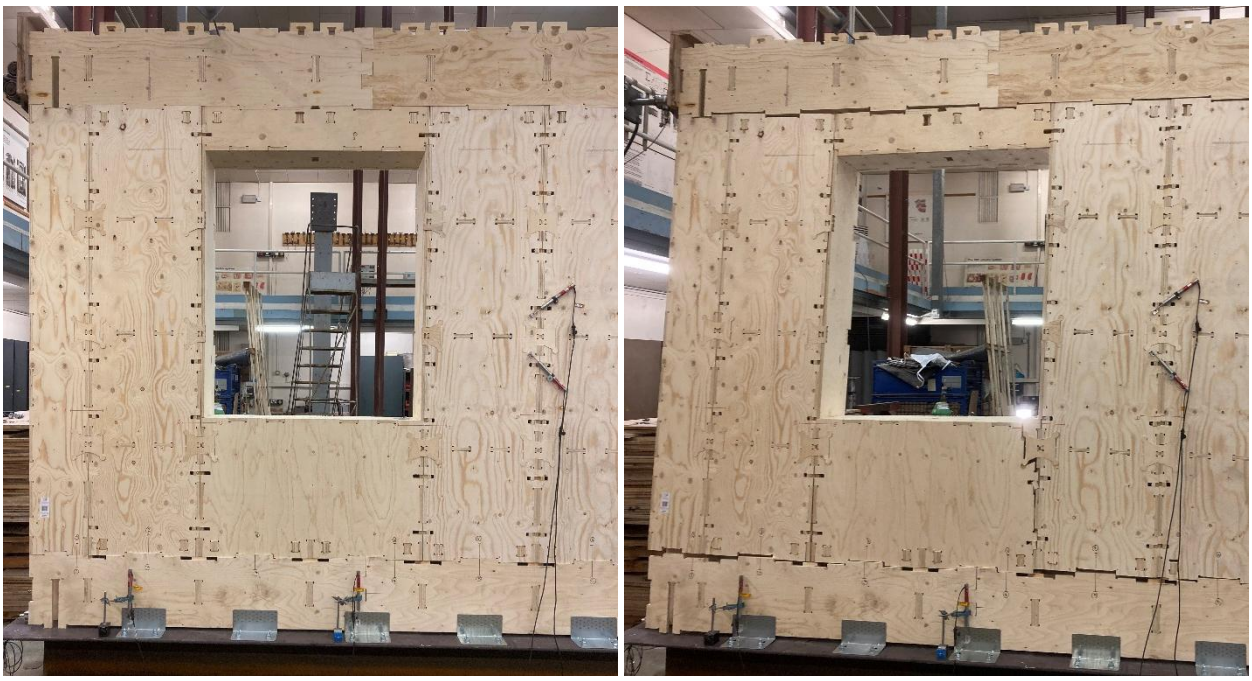


Figure 9 – LHS of Window Wall without Vertical Load Before (L) and After (R) Test

Figure 10 – RHS of Window Wall without Vertical Load Before (L) and After (R) Test

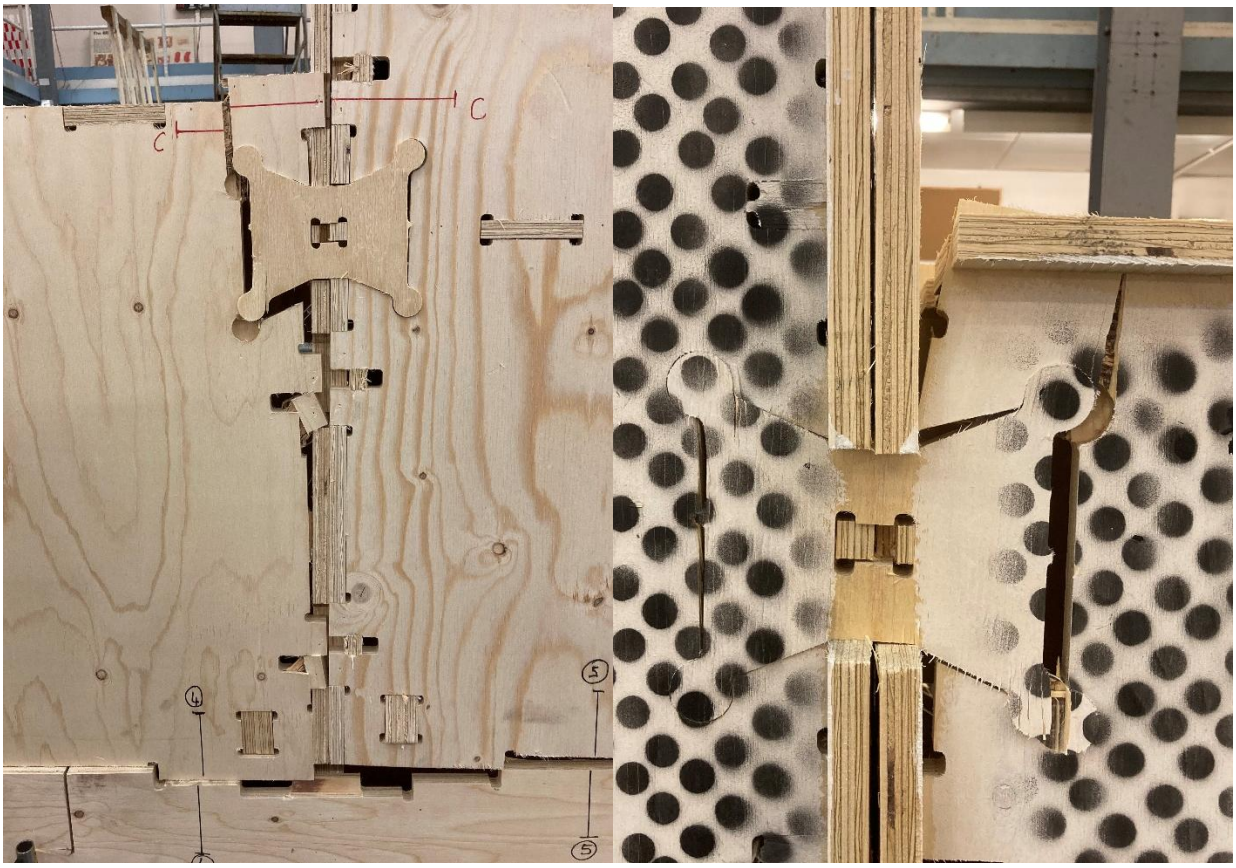


Figure 11 - Failure of the Bow tie plates

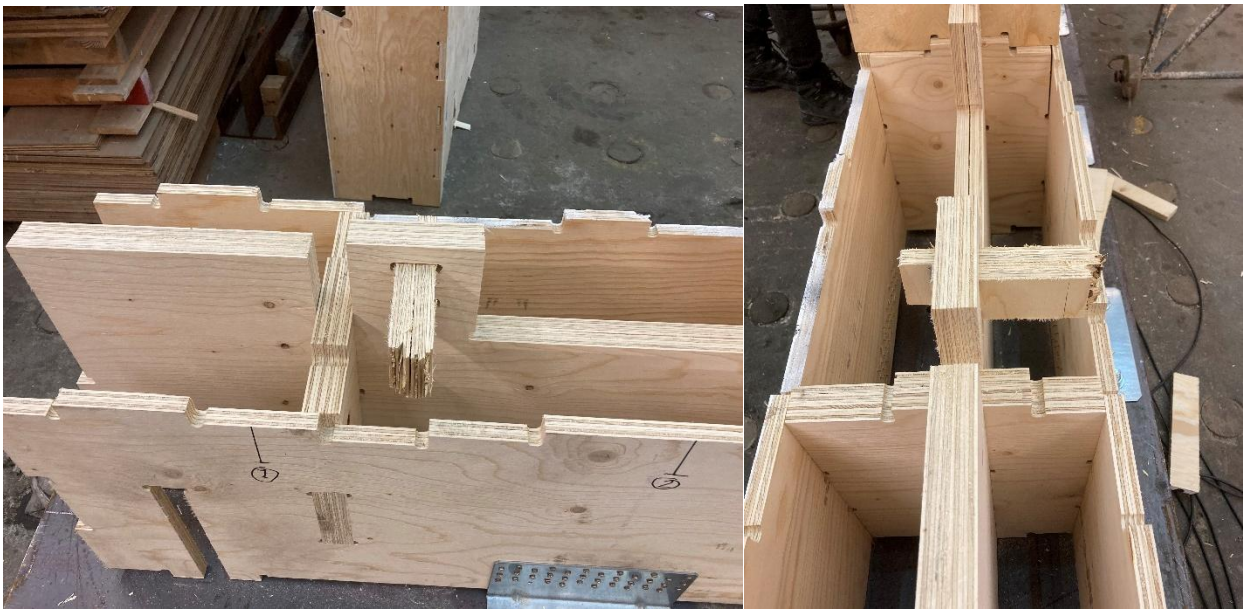


Figure 12 - Broken Pin at the Through wall peg

3.1.2 Solid Wall – No Vertical Load

Based on preliminary estimates of capacity made by the client, the target racking load Fmax adopted for this testing was 80kN.The displacement transducer locations can be seen in Figure 13. The positive direction of movement as shown in the graphs below are upwards and to the right. These are indicated by the arrow directions in Figure 13.

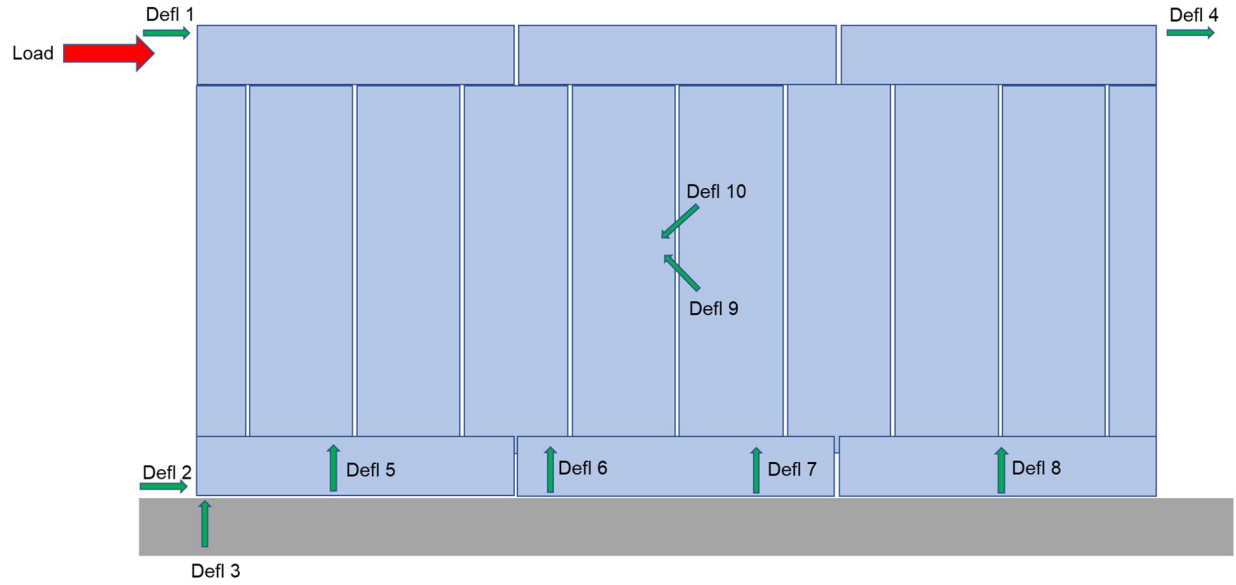


Figure 13 - Displacement Transducer Locations for 2D Solid Wall test without Vertical Load

3.1.2.1 Attempt 1

The first cycle was to 0.1F or 8kN and the load was applied gradually to peak then held for 30 seconds before release. There was no obvious damage or other problems.

The second cycle was to 0.4F or 32kN, as before load was applied gradually to peak then held for at least 30 seconds before release. This second cycle caused movement of wall components but there were no obvious signs of damage.

The third cycle was to 0.4F then failure, the load was raised to 32kN as for previous cycle and held for at least 30 seconds then load reduced to 0.1F before increase until failure. This final cycle led to localised compressive failure of the wall under the racking load. This failure can be seen in Figure 14 and Figure 15.

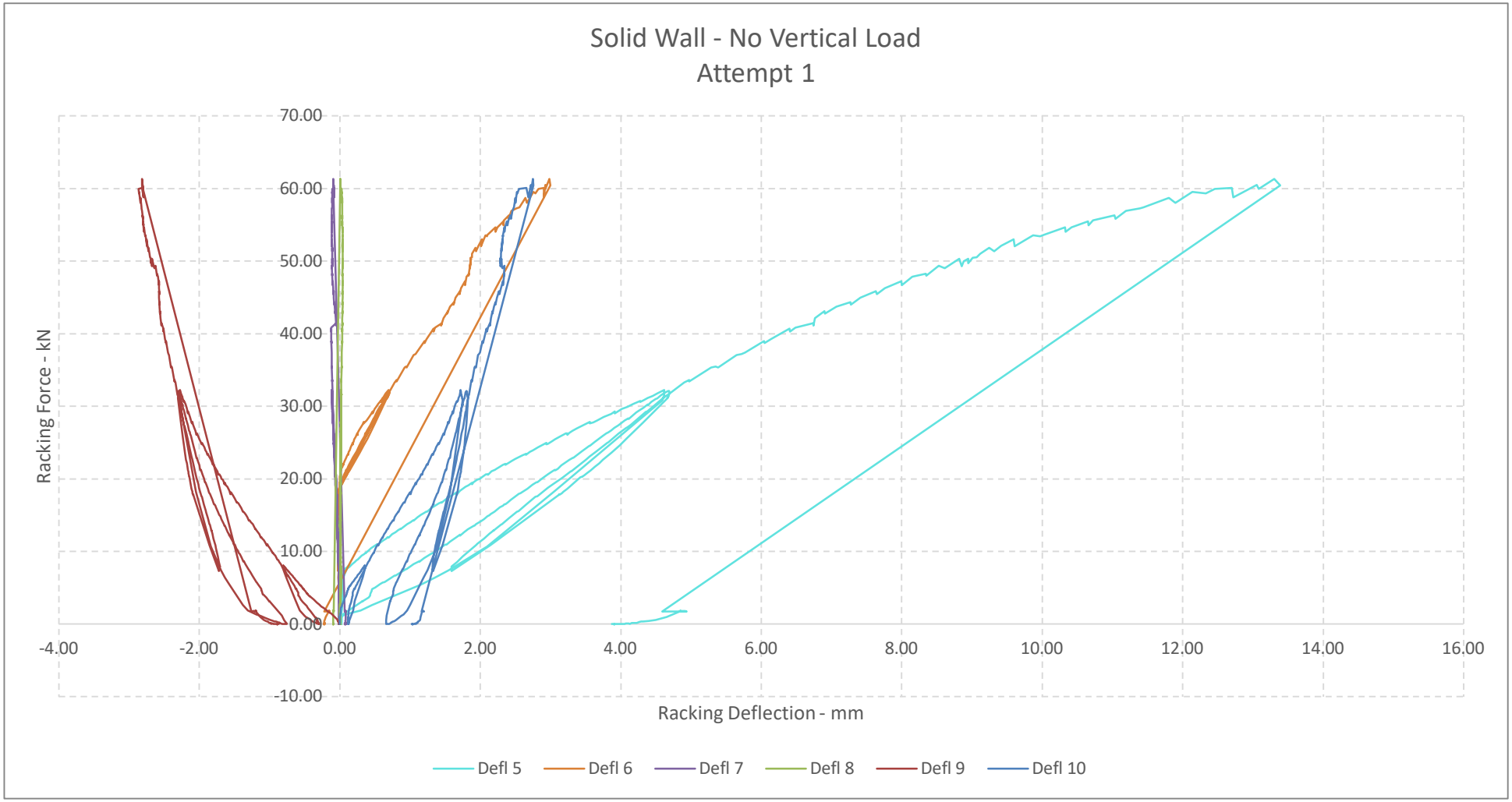
3.1.2.2 Attempt 2

After the first three cycles, the wall was repaired at the loading point and then loaded direct to failure without the intermediate steps outlined above. There was no reset of datums after the first failure attempt. This loading led to localised collapse of the sample at the loading point again.

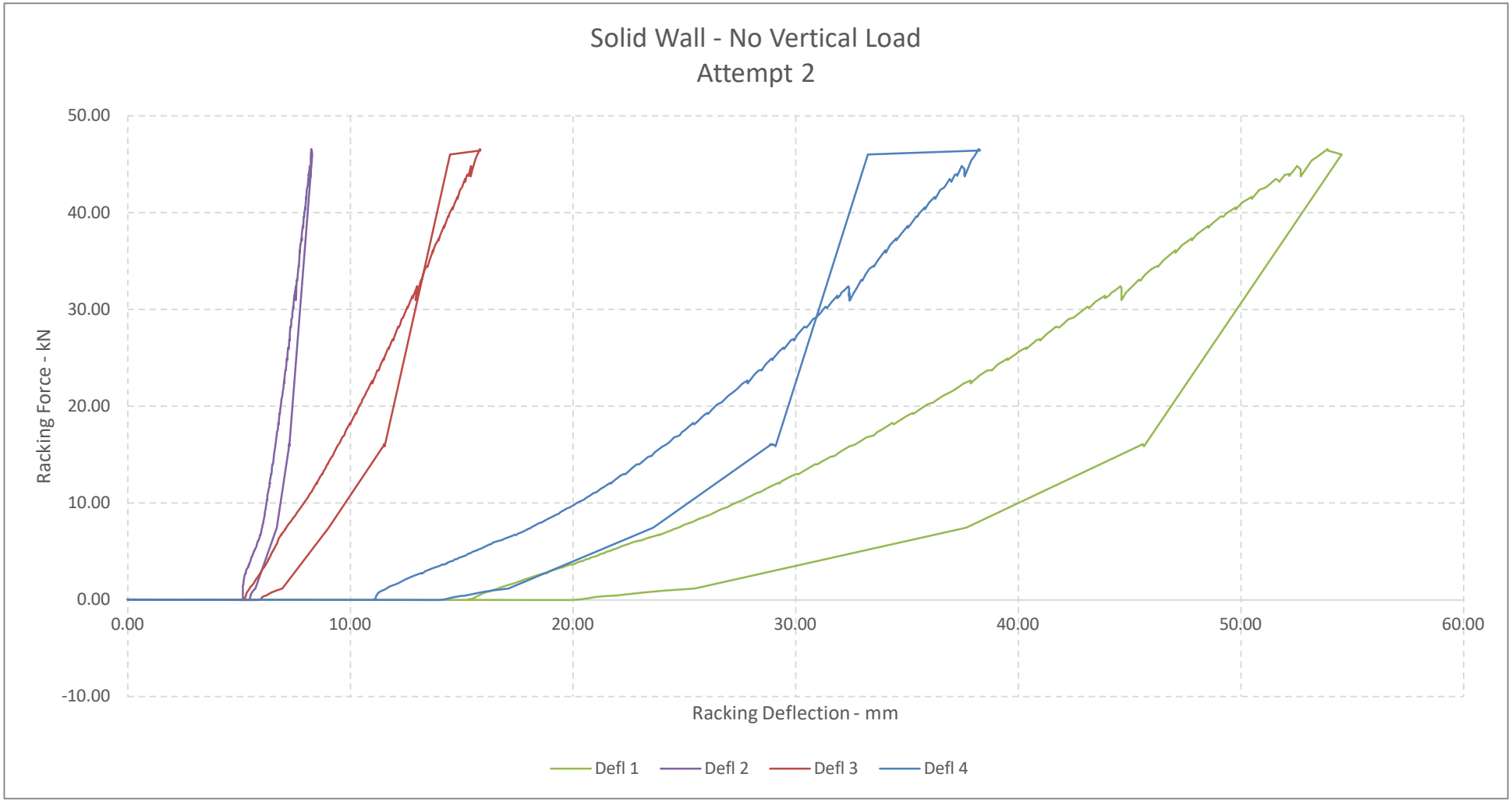
3.1.2.3 Attempt 3

After attempt 2, the wall as repaired at the loading point with components from the previously tested window wall and then loaded direct to failure without the intermediate steps outlined above. There was no reset of datums after first failure attempt. During attempt 3, there was abrupt failure of the wall to foundation beam uplift connection and bow tie plates.

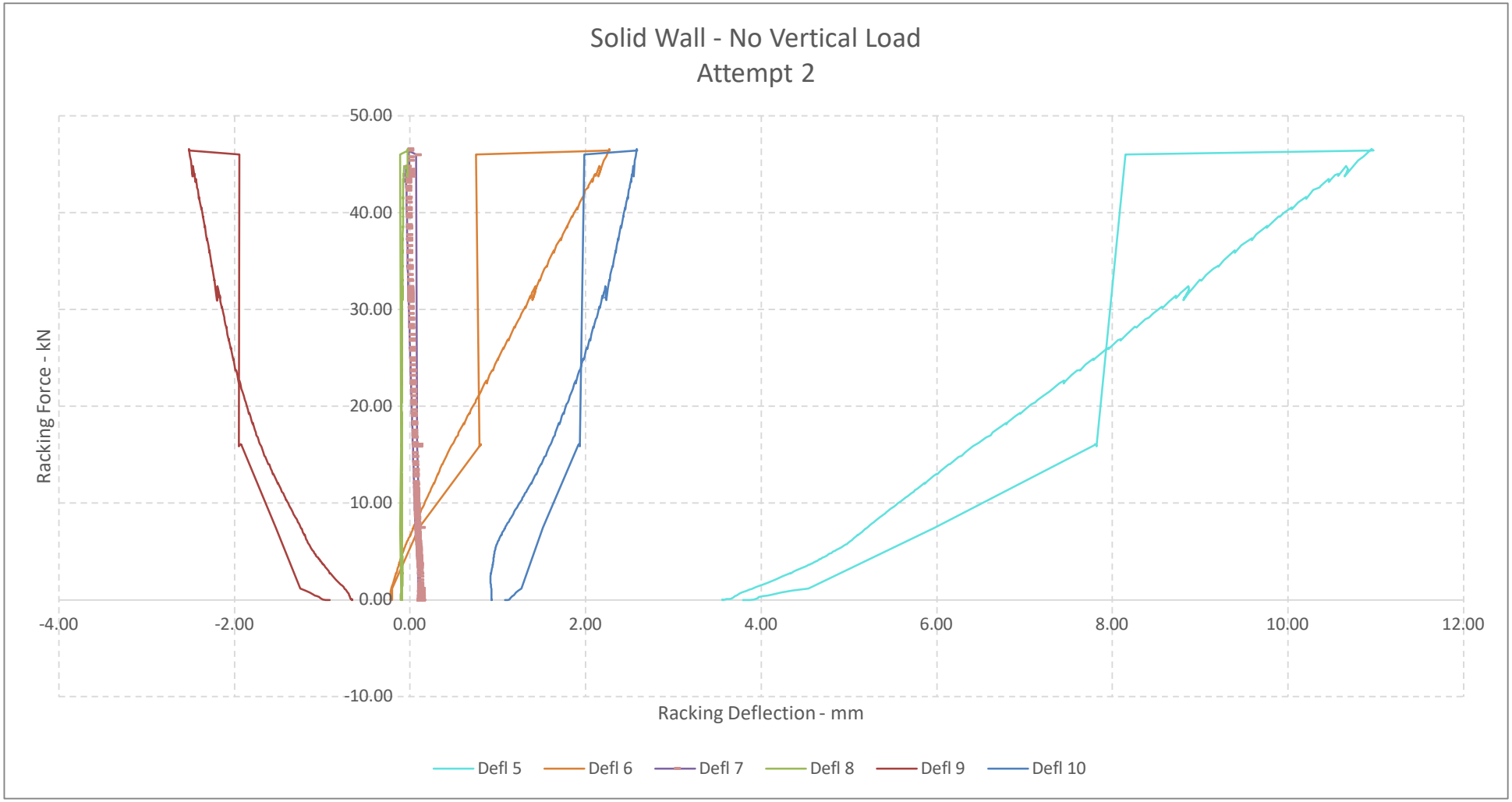
Graph 3 – Solid Wall without Vertical Loading Attempt 1: Deflections 1-4



Graph 4 – Solid Wall without Vertical Loading Attempt 1: Deflections 5-10

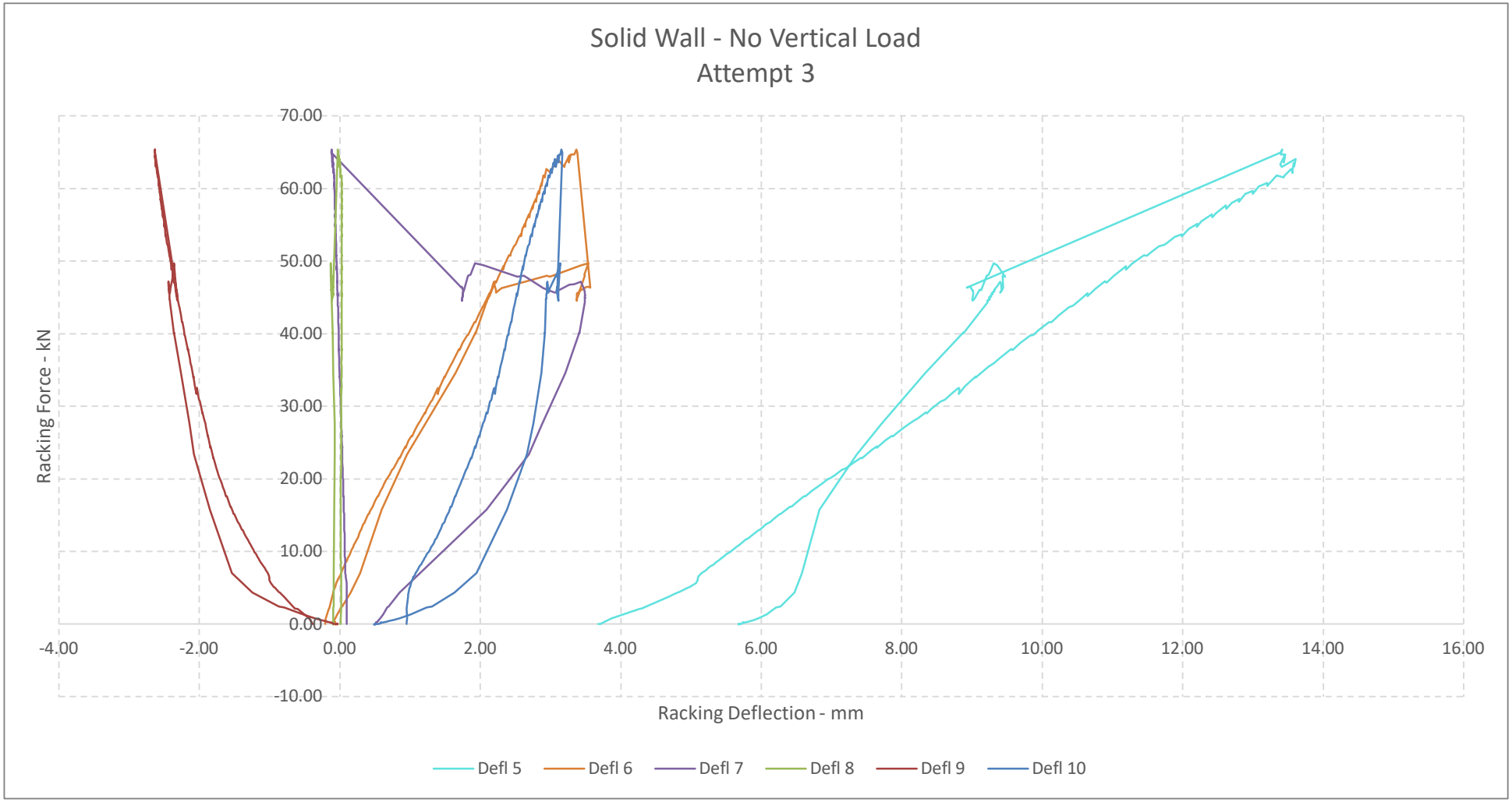


Graph 5 – Solid Wall without Vertical Loading Attempt 2: Deflections 1-4



Graph 6 – Solid Wall without Vertical Loading Attempt 2: Deflections 5-10

Graph 7 – Solid Wall without Vertical Loading Attempt 3: Deflections 1-4



Graph 8 – Solid Wall without Vertical Loading Attempt 3: Deflections 5-10

Figure 14 - Solid Wall without Vertical Load Sample Before Attempt 1

Figure 15 - Localised Compressive Failure of the Wall at the Loading Point on Attempt 1

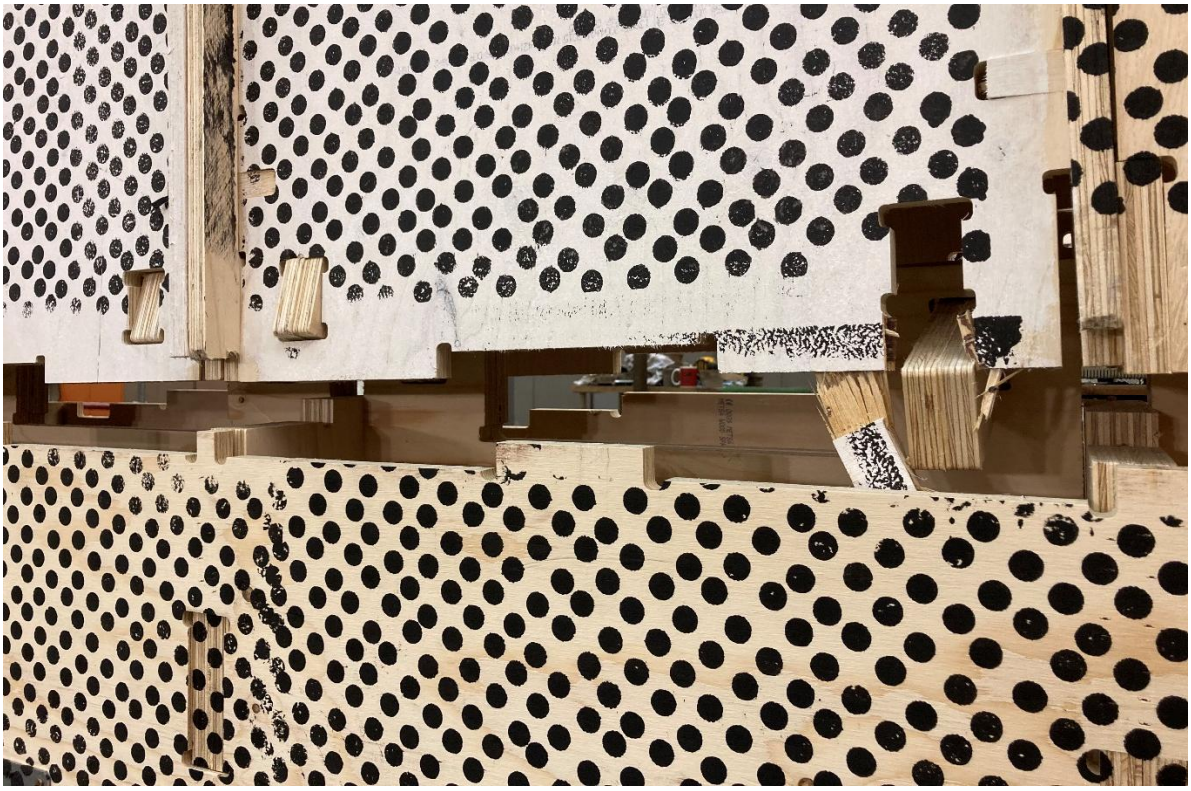


Figure 16 - Failure of the Wall to Foundation Beam Uplift Connection

Figure 17 – Failure of the Wall to Foundation Connection (L) and of the Bow Tie Plates (R)

3.1.3 Window Wall – Vertical Load

Based on preliminary estimates of capacity made by the client, the target racking load Fmax adopted for this testing was 80kN.The displacement transducer locations can be seen in Figure 18. The positive direction of movement as shown in the graphs below are upwards and to the right. These are indicated by the arrow directions in Figure 18.

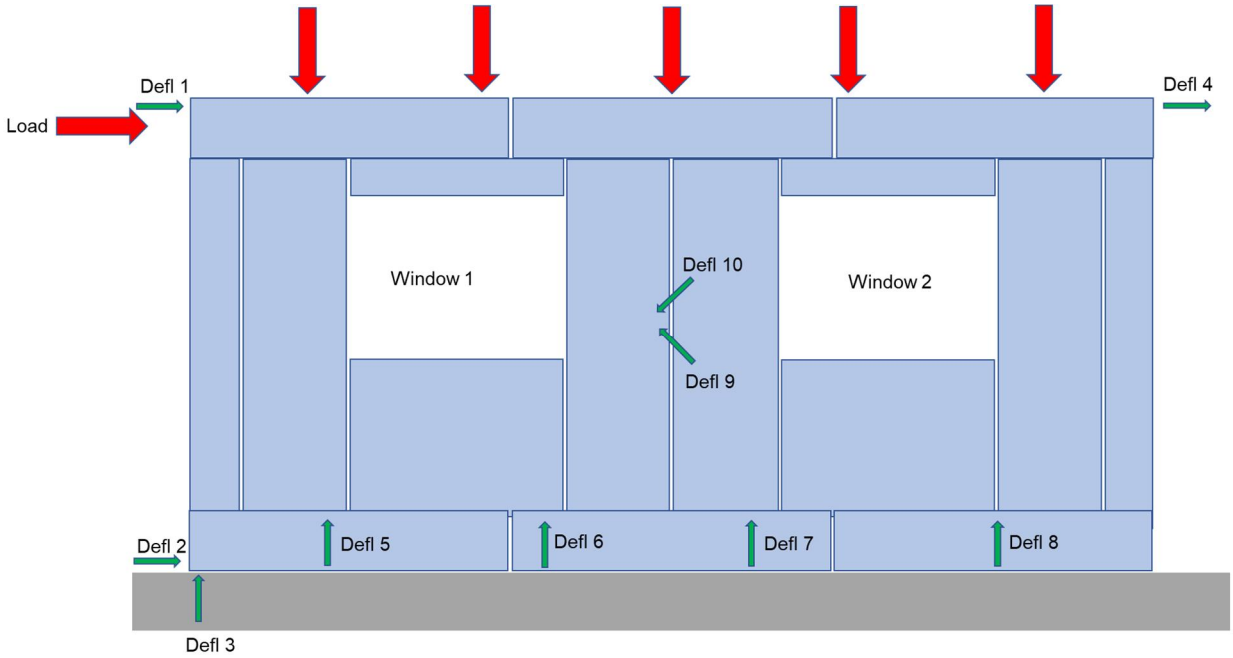


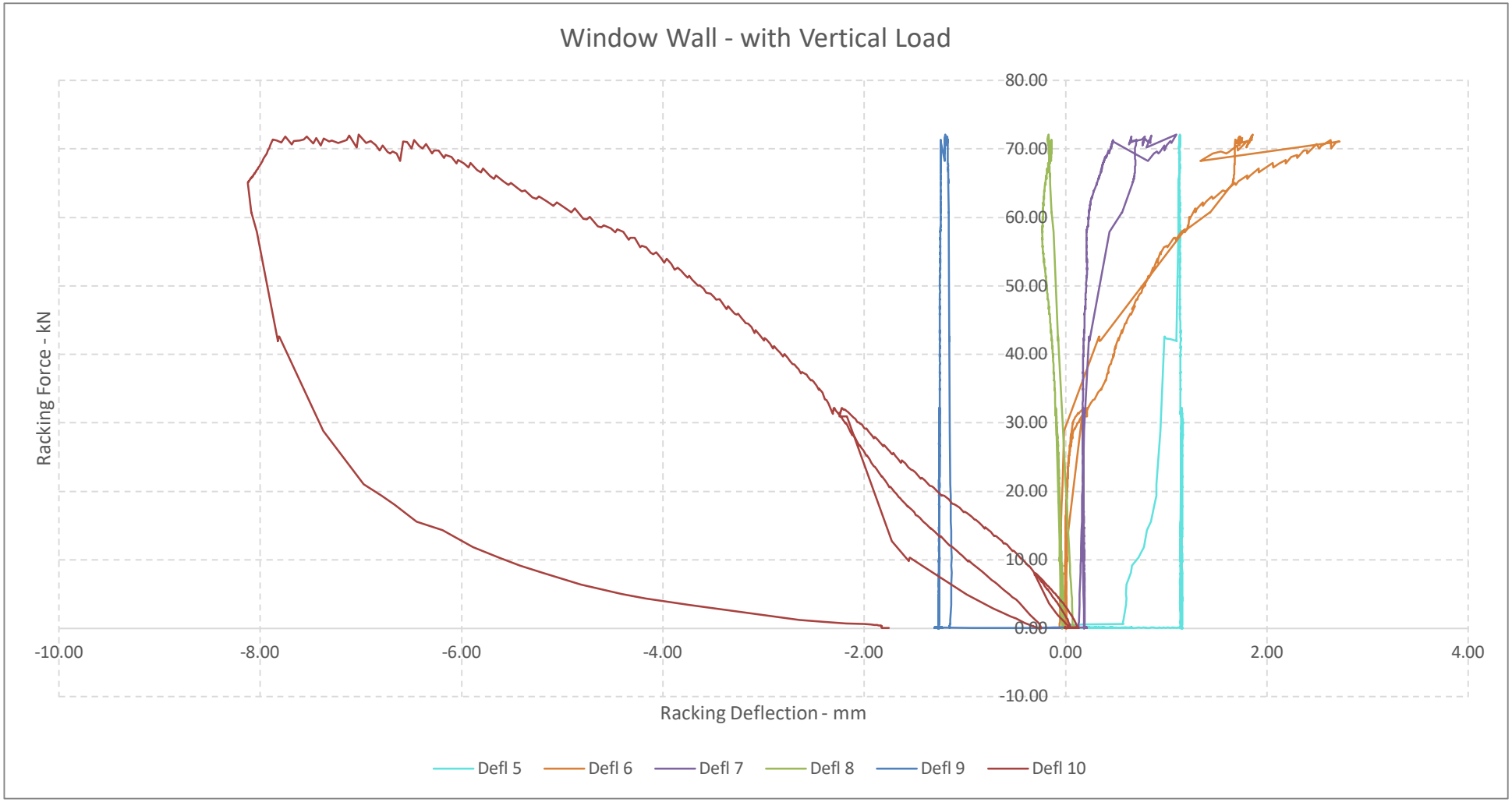
Figure 18 - Displacement Transducer Locations for 2D Window Wall test with Vertical Load

The first cycle was to 0.1F or 8kN and the load was applied gradually to peak then held for 30 seconds before release. There was no obvious damage or other problems.

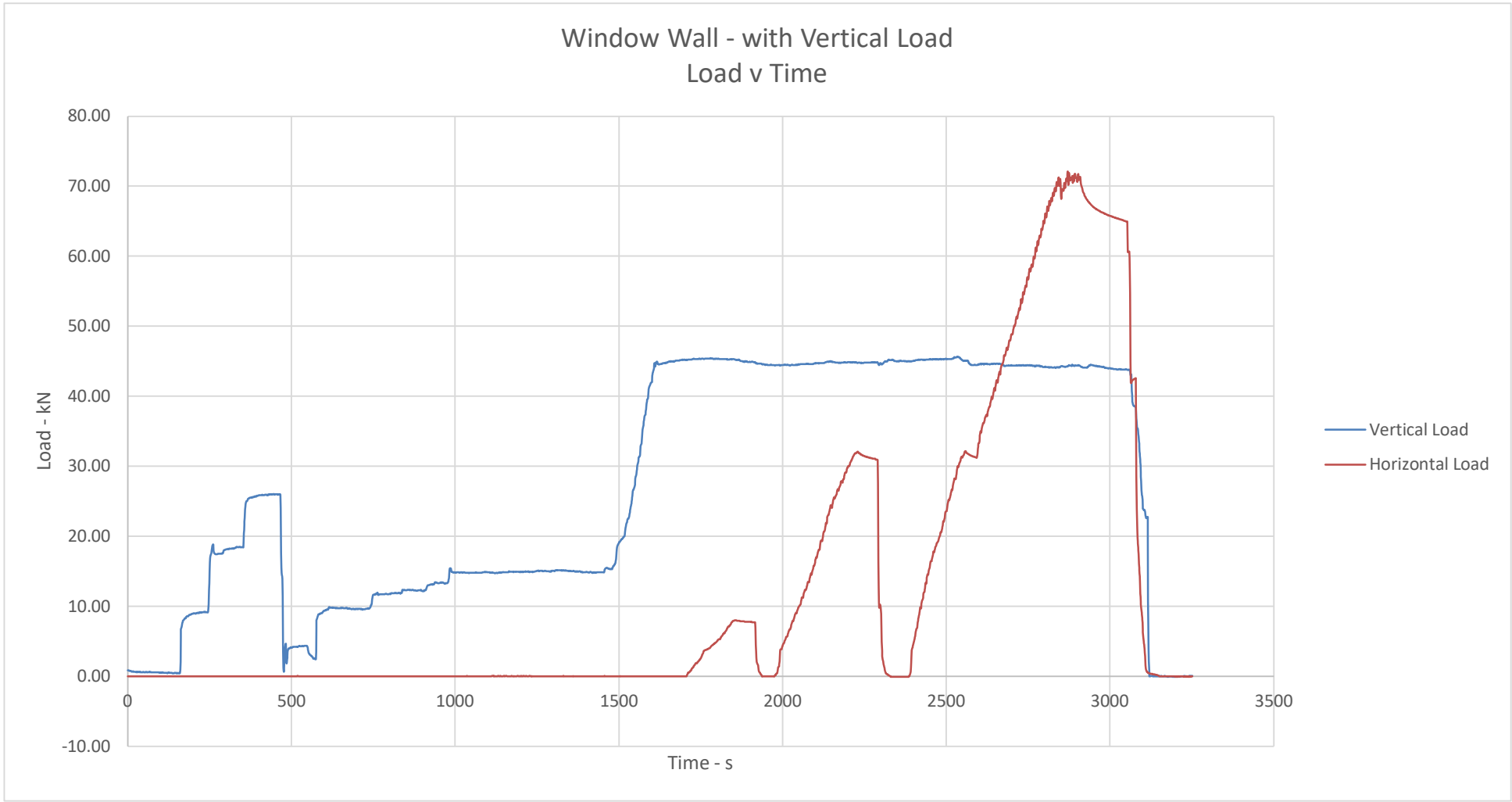
The second cycle was to 0.4F or 32kN, as before load was applied gradually to peak then held for at least 30 seconds before release. This second cycle caused movement of wall components but there were no obvious signs of damage.

The third cycle to 0.4F then failure, the load was raised to 32kN as for previous cycle and held for at least 30 seconds then increased until failure. At approximately 72 kN horizontal load there appeared to be a drop in the load sustained by the specimen. Loading continued, however a significant increase in the magnitude of the applied load was not achieved and so the load was removed. There was eventual failure of the bow tie plates between the wall elements at the bottom right corner of window 1 and between the two full height units between windows. This failure can be seen in Figure 19.

Graph 9 – Window Wall with Vertical Loading: Deflections 1-4



Graph 10 – Window Wall with Vertical Loading: Deflections 5-10



Graph 11 – Window Wall with Vertical Loading: Load v Time

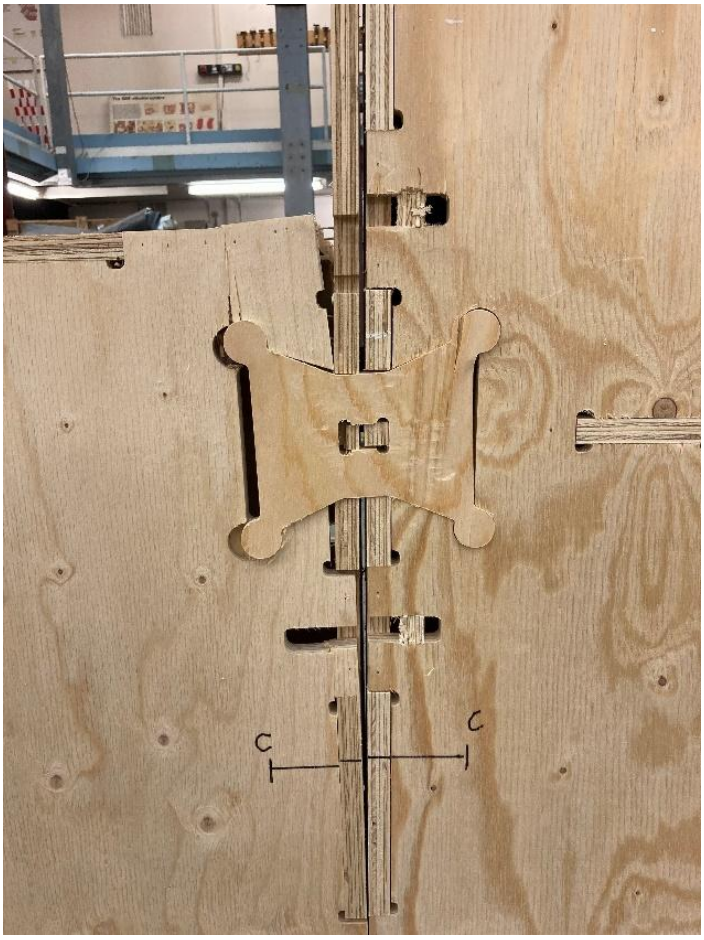


Figure 19 - Failure of the Bow tie plate

Figure 20 - Movement in Through wall peg

3.1.4 Solid Wall – Vertical Load

Based on preliminary estimates of capacity made by the client, the target racking load Fmax adopted for this testing was 80kN.The displacement transducer locations can be seen in Figure 21. The positive direction of movement as shown in the graphs below are upwards and to the right. These are indicated by the arrow directions in Figure 21.

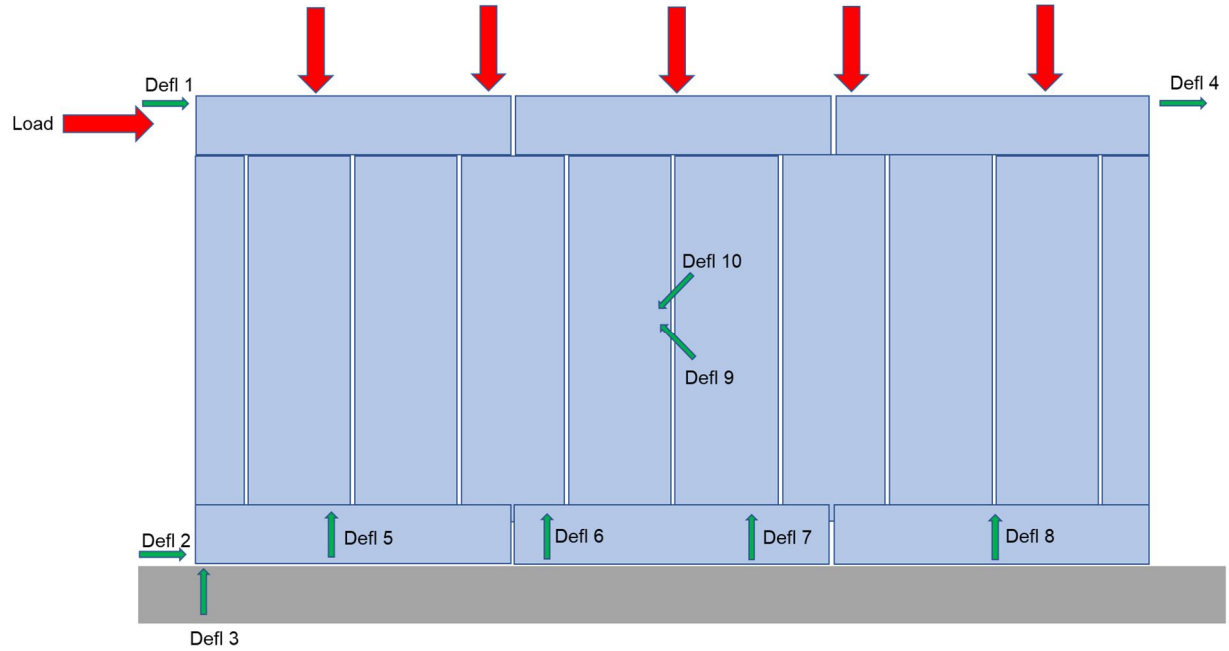


Figure 21 - Displacement Transducer Locations for 2D Solid Wall test with Vertical Load

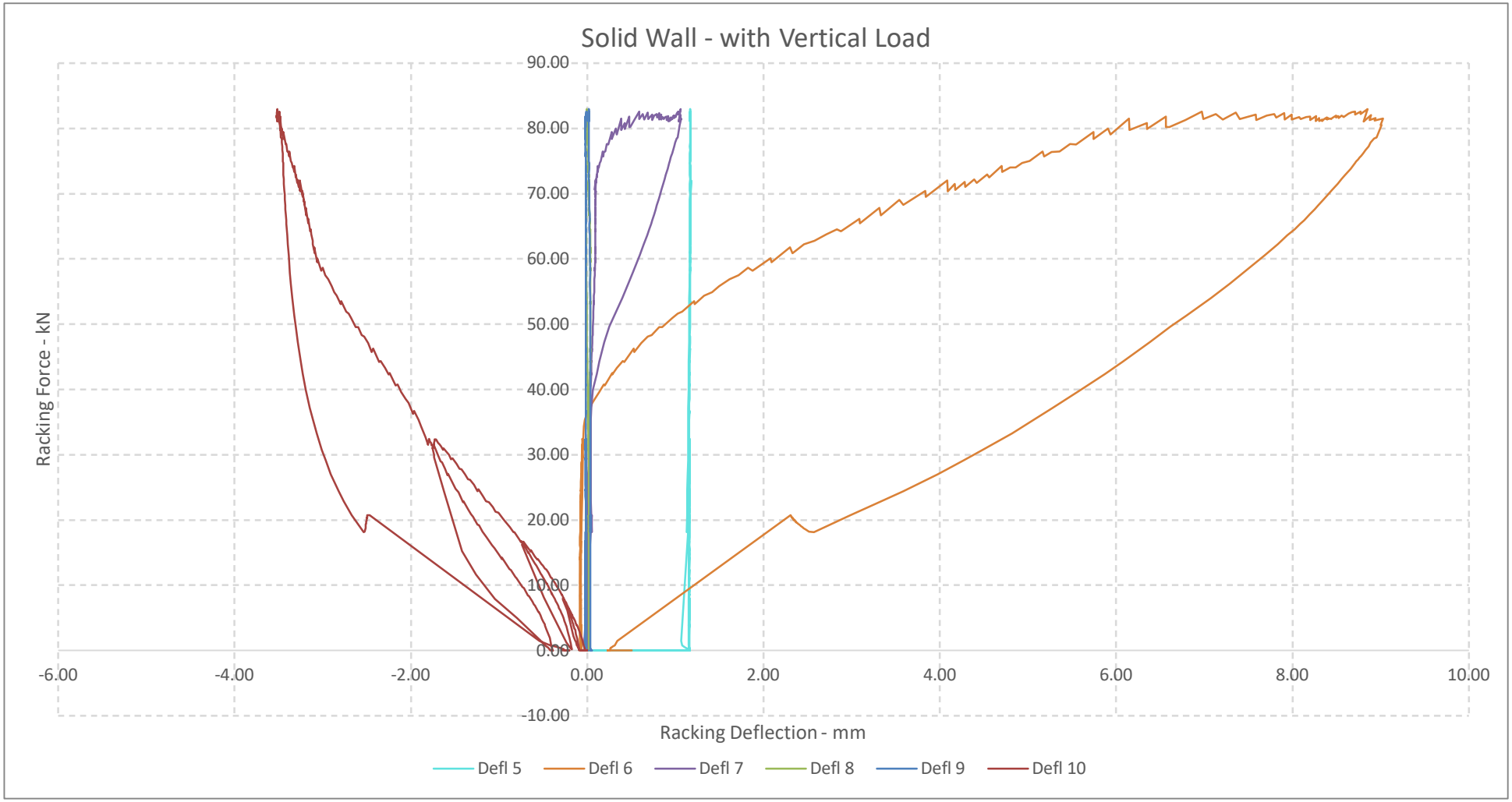
The first cycle was to 0.1F or 8kN and the load was applied gradually to peak then held for 30 seconds before release. There was no obvious damage or other problems.

It was observed that there was an issue with the deflection sensors at location Defl 2 and Defl 3 so these were reset for cycle 2.

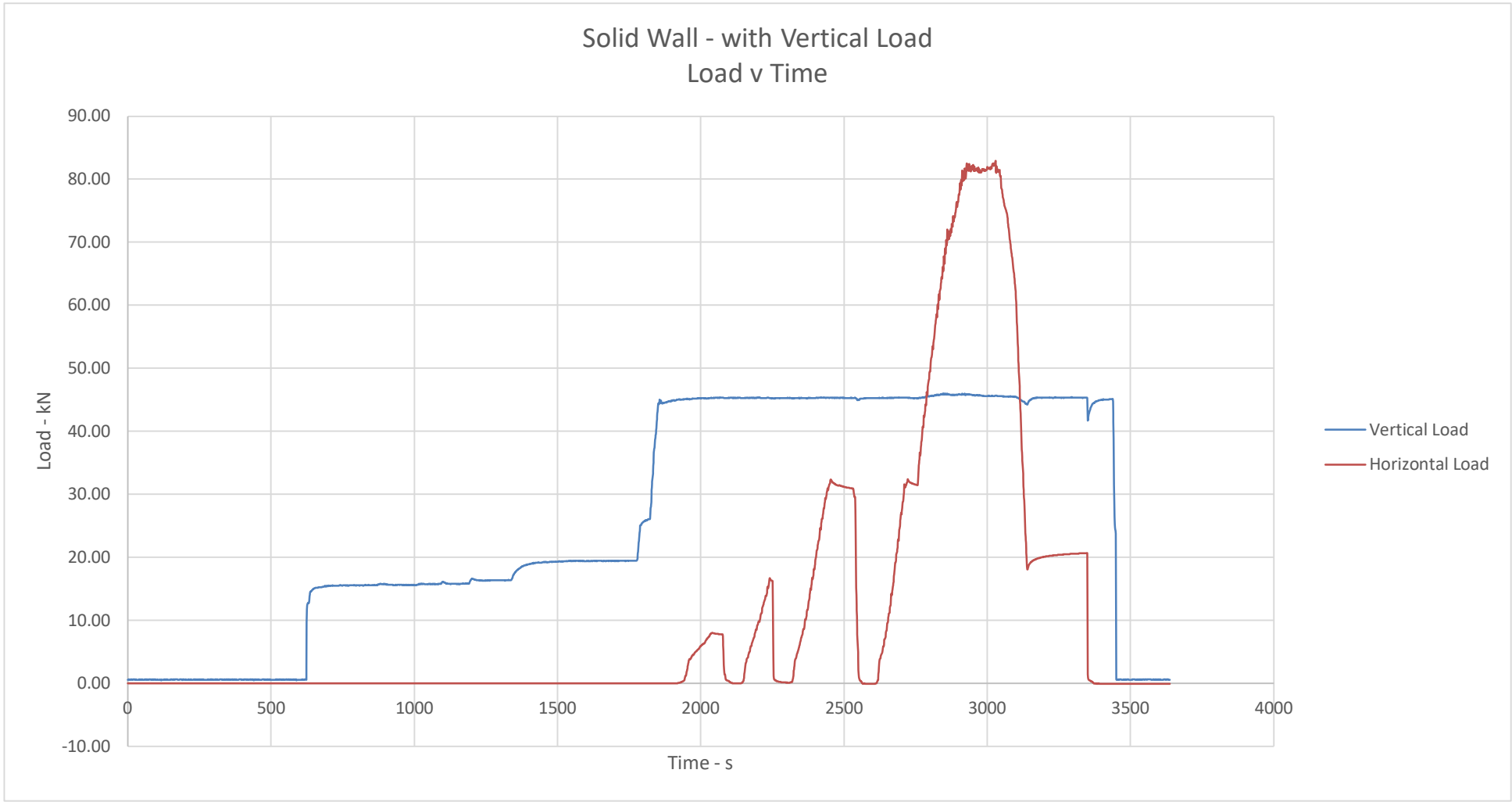
The second cycle was to 0.4F or 32kN, as before load was applied gradually to peak then held for at least 30 seconds before release. This second cycle caused movement of wall components but there were no obvious signs of damage.

The third cycle to 0.4F then failure, the load was raised to 32kN as for previous cycle and held for at least 30 seconds then increased until failure. The test was stopped due to the wall twisting out of plane as the installed lateral restraints buckled. There was also differential movement between the base and the wall beams, which can be seen in Figure 23.

Graph 12 – Solid Wall with Vertical Loading: Deflections 1-4



Graph 13 – Solid Wall with Vertical Loading: Deflections 5-10



Graph 14 – Solid Wall with Vertical Loading: Load v Time

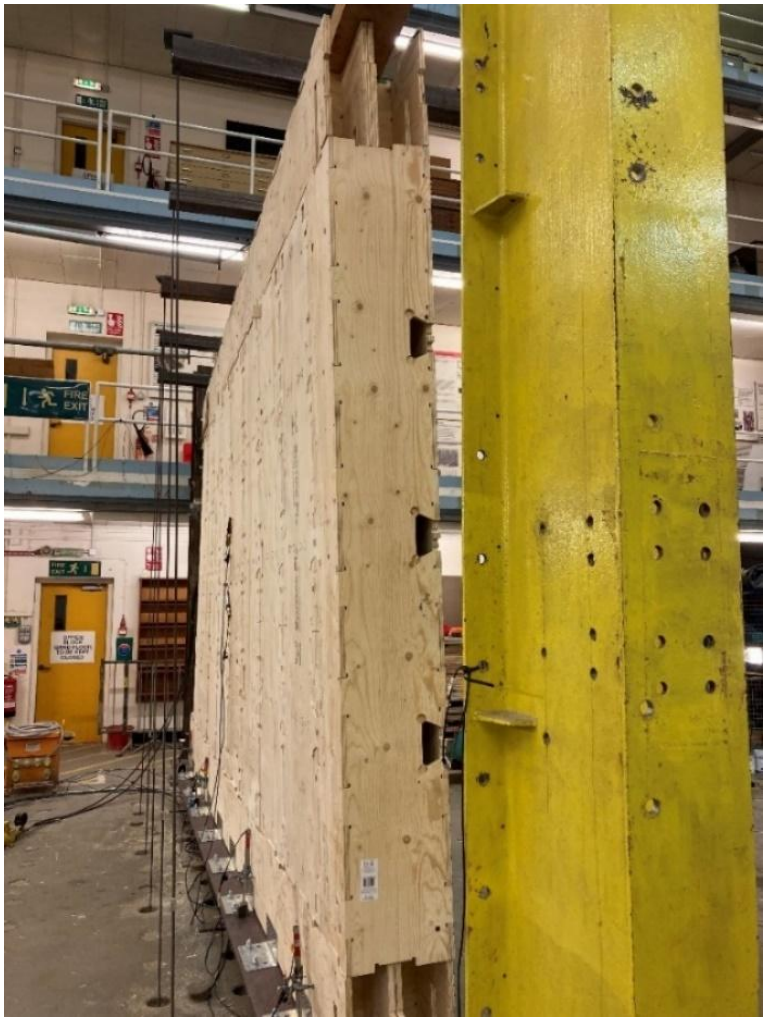


Figure 22 - Solid Wall Twisting Out of Plane

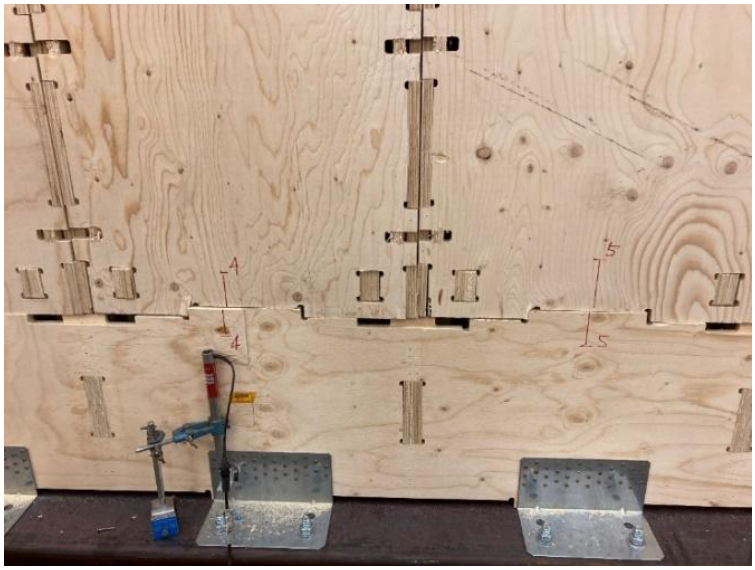


Figure 23 – Differential Movement between the Base and the Wall Beams

3.2 3D Module Test

The target racking load Fmax that was used for this testing was 50kN per jack. A dead load of 1.6kN/m2 was applied to roof using nominal 45kg weights on a square grid spaced at 525mm centres in two orthogonal directions. The deflection transducer locations can be seen in Figure 24 - Figure 27. The positive direction of movement as shown in the graphs below are upwards and to the right. These are indicated by the arrow directions in Figure 24 - Figure 27.

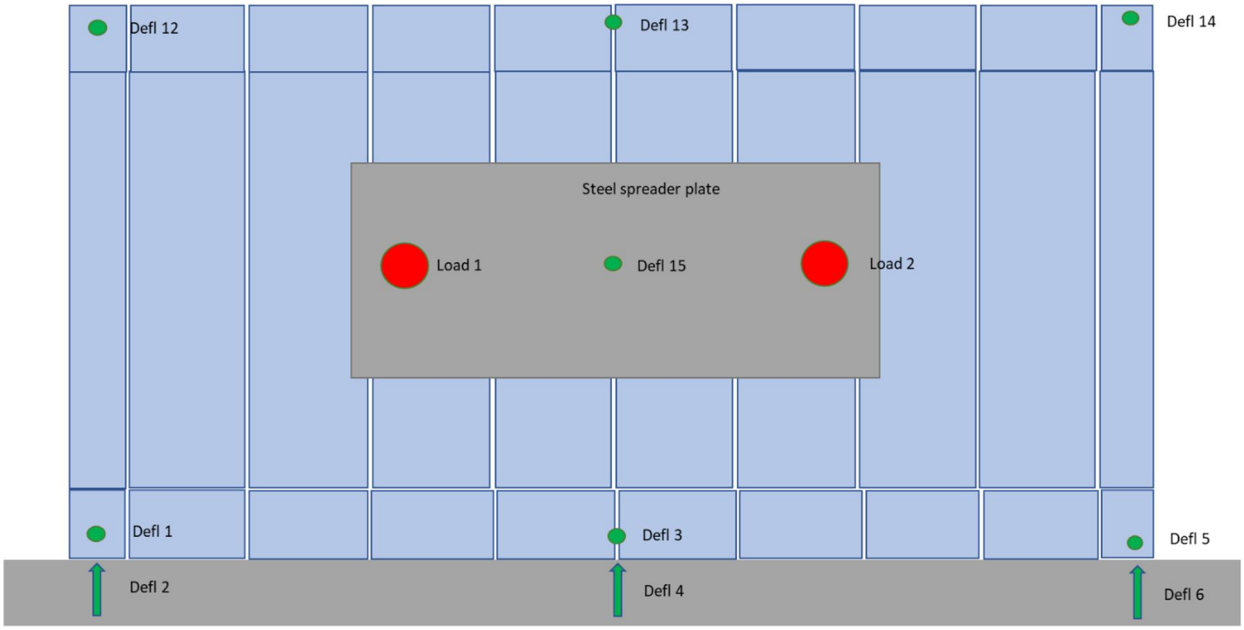


Figure 24 - Displacement Transducer Locations for East Face of the 3D Module Test

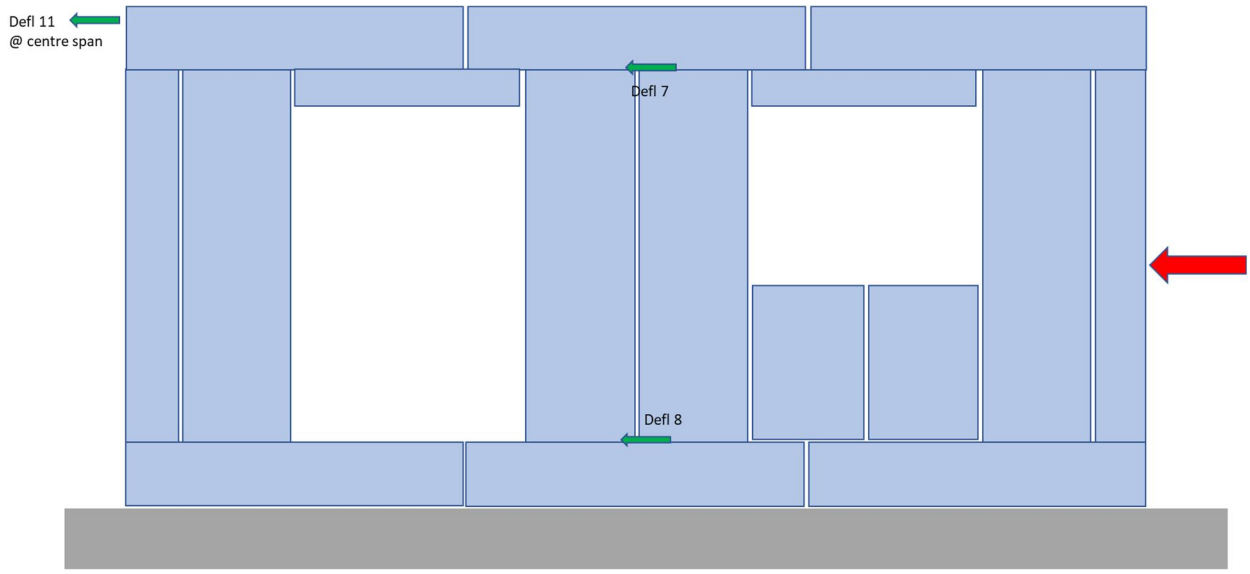


Figure 25 - Displacement Transducer Locations for South Face of the 3D Module Test

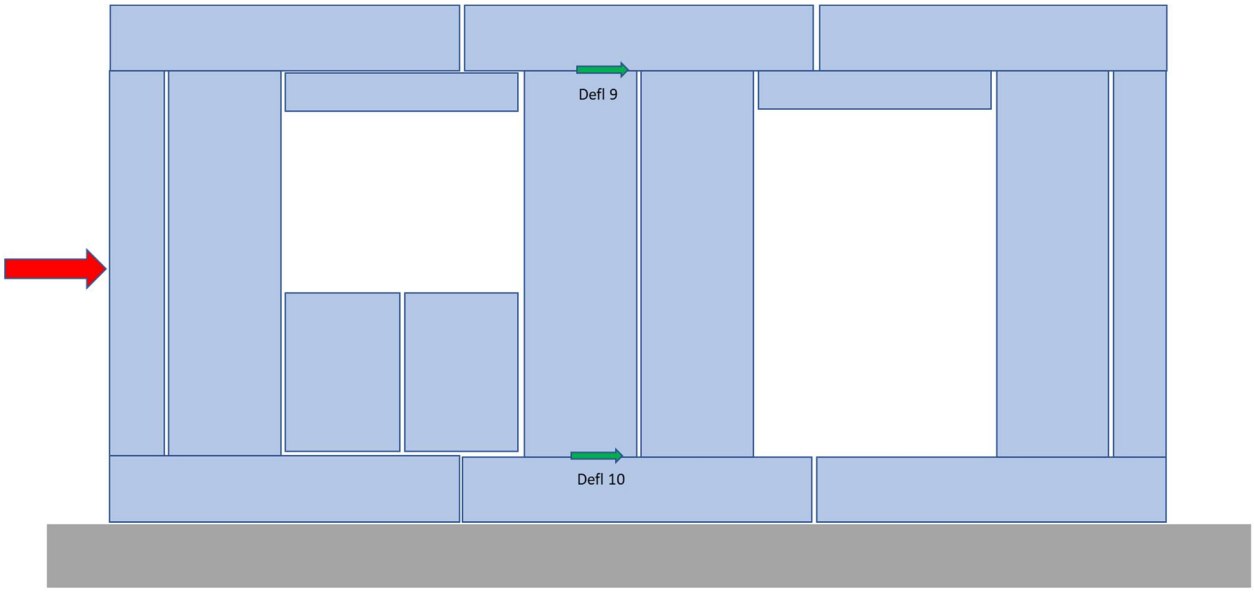


Figure 26 - Displacement Transducer Locations for North Face of the 3D Module Test

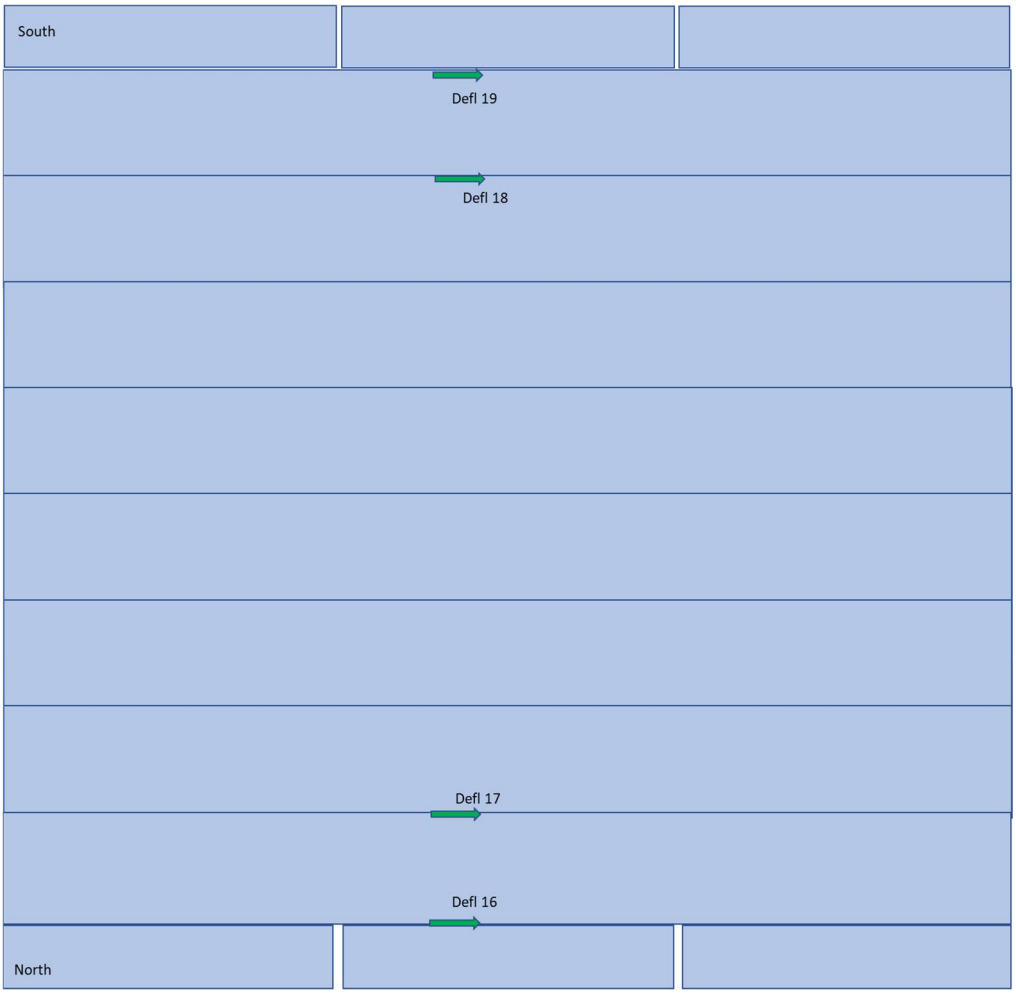


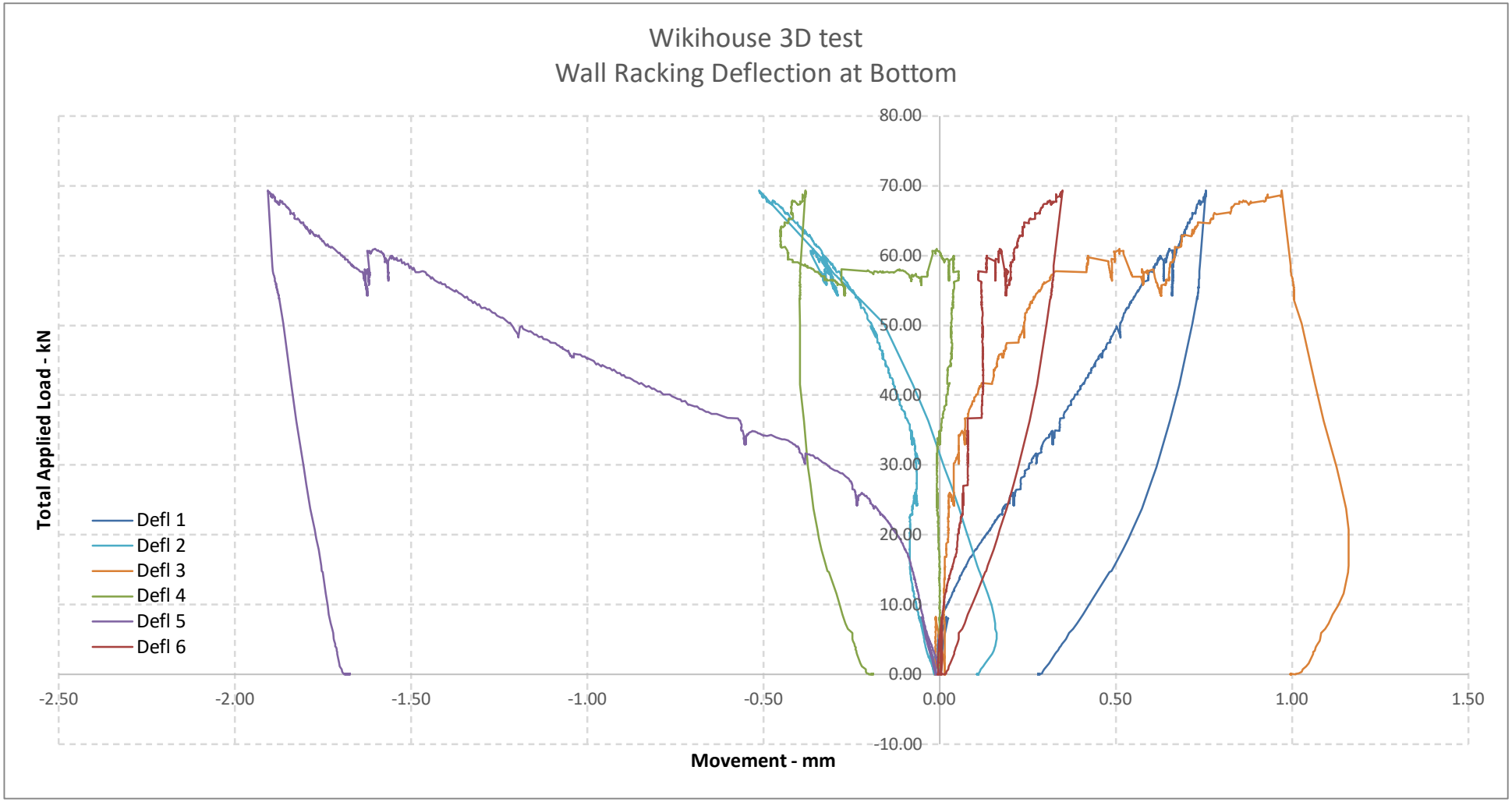
Figure 27 - Displacement Transducer Locations for Roof of the 3D Module Test

The first cycle was to 0.1F, or 5kN per jack, and the load was applied gradually to peak then held for 30 seconds before release. There was no obvious damage or other problems.

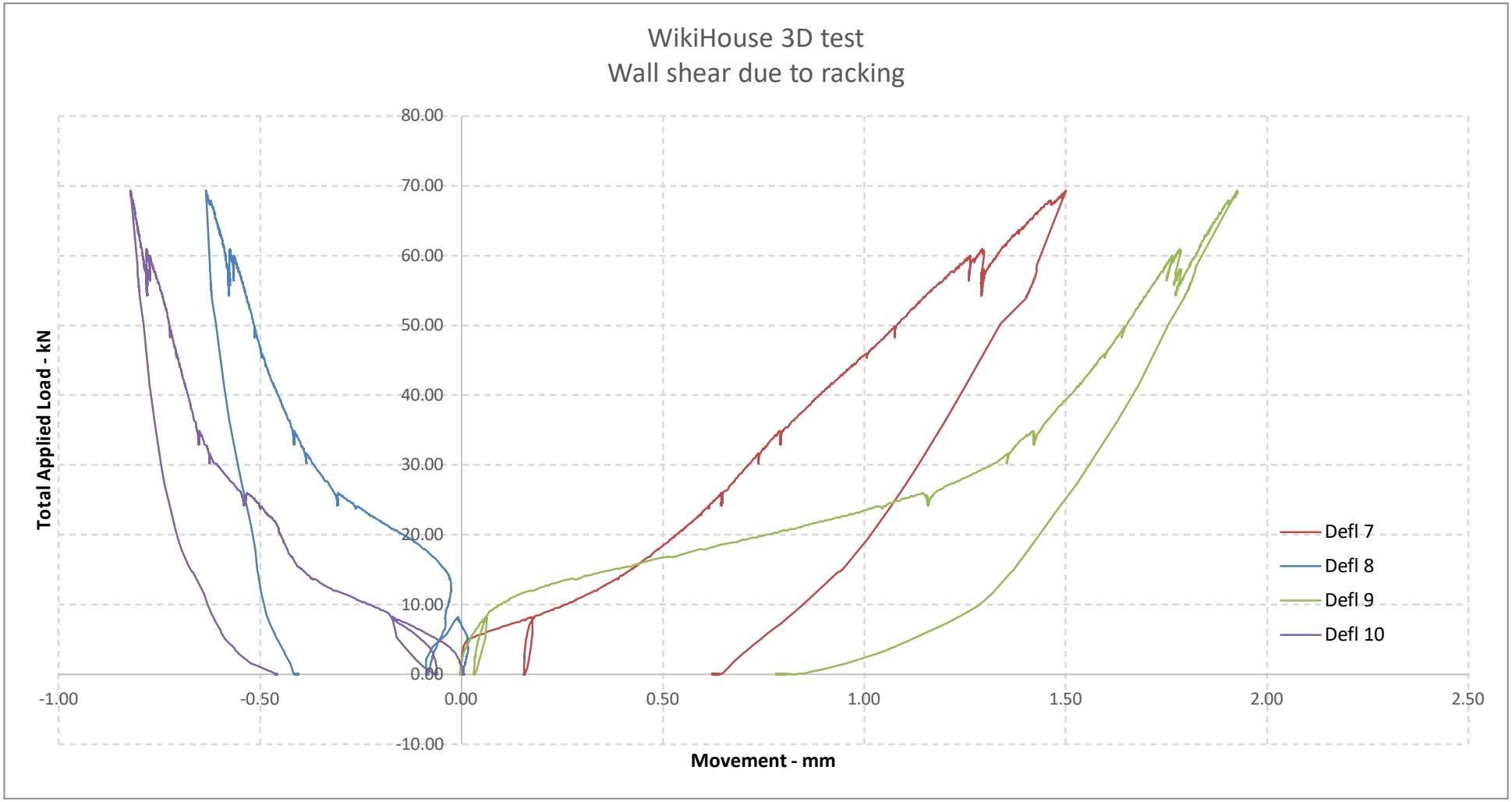
The second cycle was to 0.4F, or 20kN per jack, but stopped at ~0.3F as a shear tie near the top right of the steel spreader plate snapped and there was concern about the plate punching through the wall. At this point the load applied to the wall was gradually allowed to decay. The wall was then loaded up to 0.4F and held for 30 seconds before being allowed to decay. At this point the through wall peg at the top of the wall had disconnected (see Figure 28). Differential movement was observed between the panel being loaded and the panel to the right-hand side. There was also cracking noted internally on the face of the panel in the equivalent spot on the outside face where the shear tie had broken[1].

For the third cycle, the module was loaded up to failure. At failure the through wall peg had become disconnected at the bottom on the right-hand side of the plate. In this test, the module was considered to have failed when there was loss of 20% or greater of the load. Photos of the east facing wall at the failure load can be seen in Figure 29 - Figure 31.

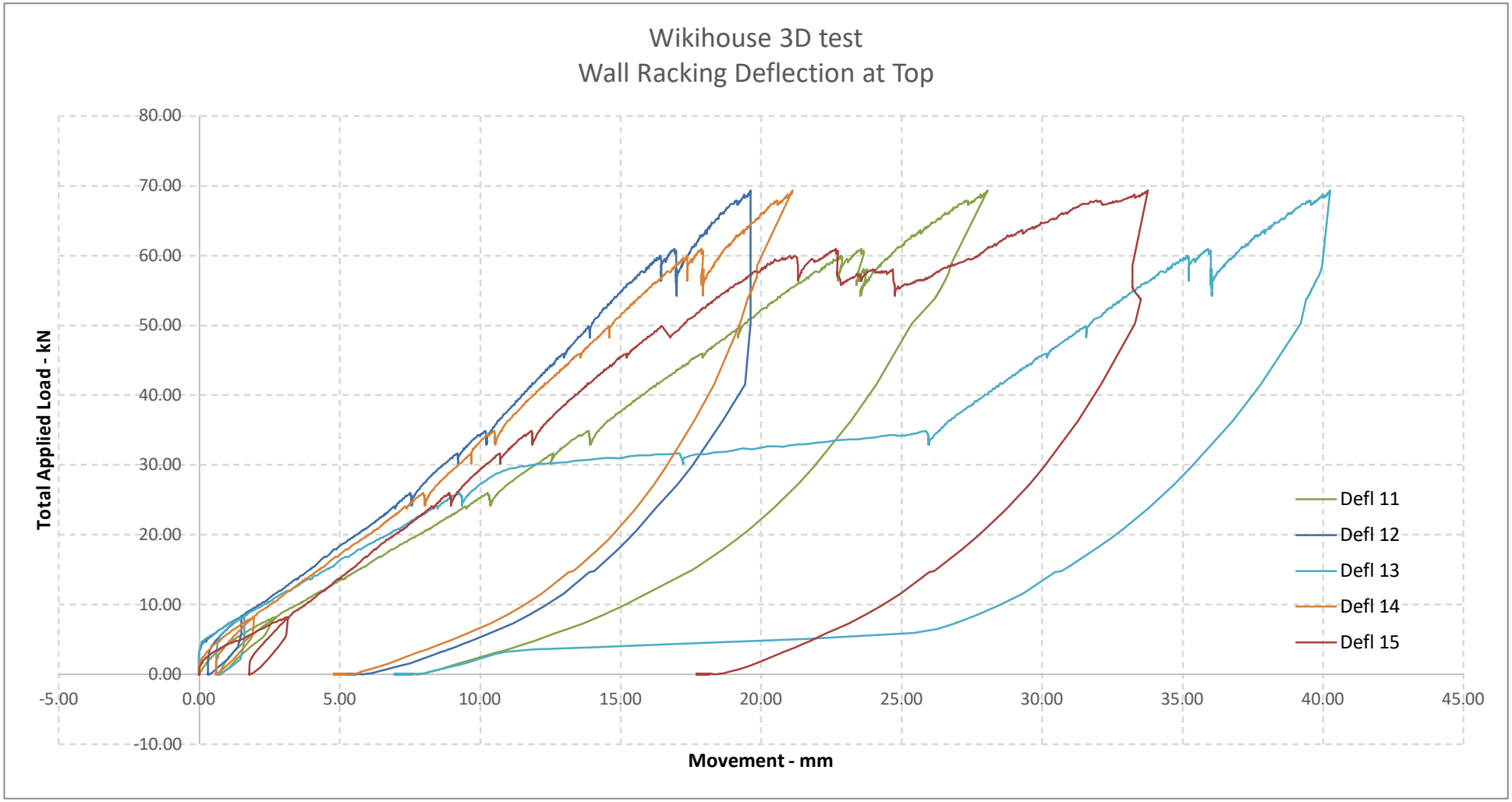
[1] Upon inspection of photos later, it was found that this cracking was present before testing began.



Graph 15 – 3D Panel: Deflections 1-6



Graph 16 – 3D Panel: Deflections 7-10



Graph 17 – 3D Panel: Deflections 11-14

Graph 18 – 3D Panel: Deflections 16-19

Figure 28 - Damage to the East Wall at 0.4F Loading showing Broken Bow tie plate (L) and Internal Cracking (R)

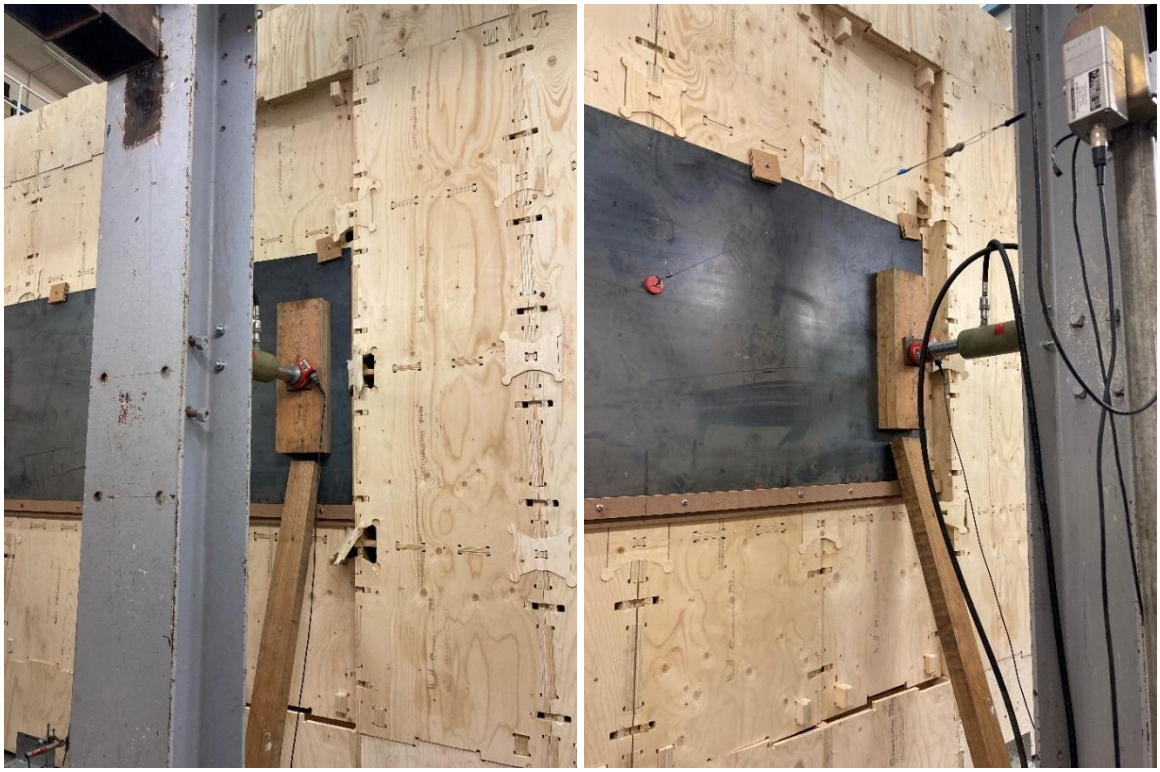


Figure 29 - Damage to the East Wall at Failure Loading

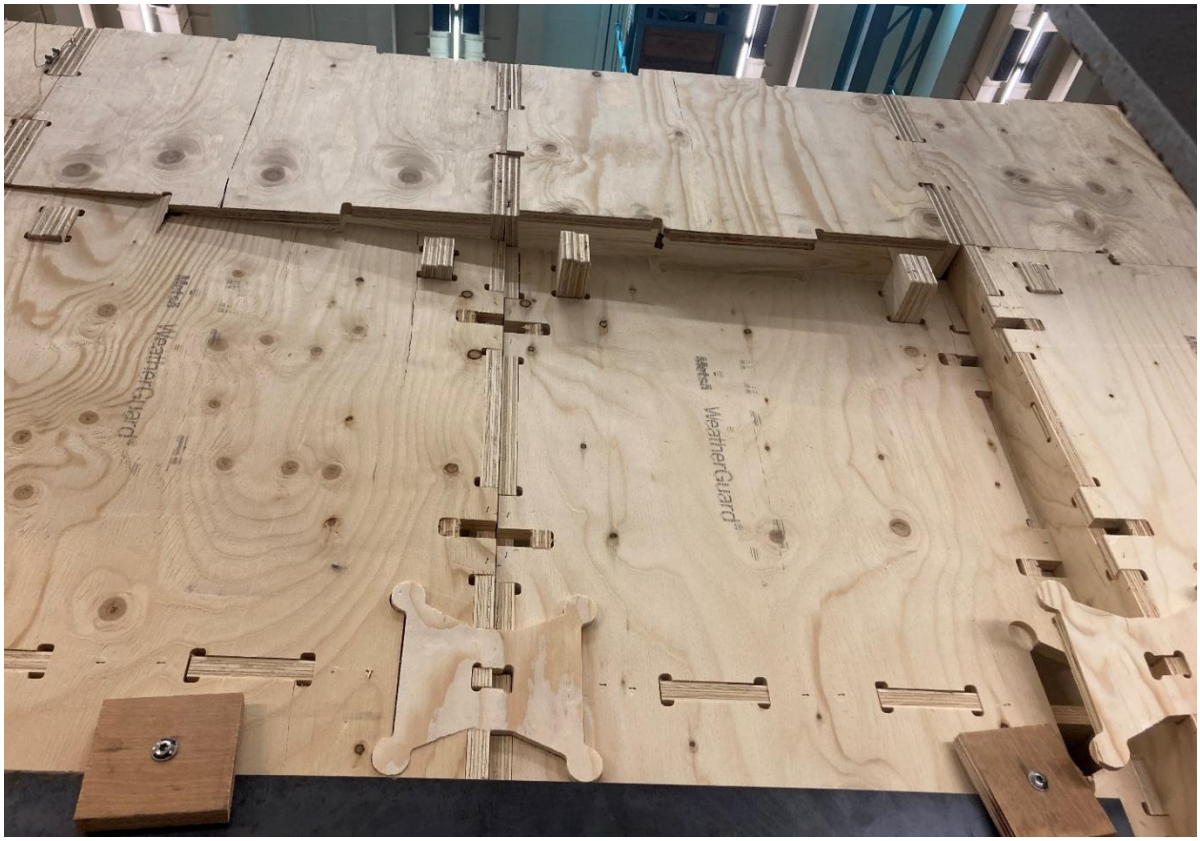


Figure 30 - Top Through wall peg at Failure Load

Figure 31 - Internal Elements on East Wall After Testing

Report Ends