The Stress and Deformation Analysis and Comparison of two Portaledge Designs

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Certificate of Authorship

I, Edward Bennett, hereby certify that I am the author of this report. All results and analyses are entirely my own, except where otherwise acknowledged. All sources of information and literature that were used are indicated and cited in the report. Any assistance received during the project and preparation of the report is duly acknowledged and disclosed.

I also certify that the work used in this report has not been previously submitted for assessment in another course or university degree, except where otherwise stated or acknowledged.

1/11/2021

Acknowledgements

I would like to thank John Middendorf for his ongoing support and enthusiasm throughout the development of this paper. I appreciate his guidance, his advice, and the time he has put forth towards this project. John also fabricated and sent the Portaledge samples for testing, in which this project couldn't have progressed without.

I also appreciate the continuing support and enthusiasm from Adrian McCallum, who has continued to guide me through this process. He has provided positive reinforcement at all milestones and has been willing to help wherever possible along the way.

It couldn't have been done without you gents!

Contents

1 – Summary

A new design of Portaledge frame has recently been developed, where the corners use curved aluminium, instead of aluminium blocks, and the tubing has a hybrid diameter. The project aimed to compare two Portaledge designs: the A5 Alpine Double block corner ledge and the updated D4 curved corner design of similar size. It sought to determine which design is superior in terms of strength, rigidity and weight. It was hypothesised that the curved corner design will surpass the block corner design in all sections. The testing was limited to analysis of the two Portaledge's frame, such no testing was conducted on other elements of the design, such as the fly, canvas or carabiners. A literature review was developed, justifying the project, and researching various applicable concepts and methods that were used in the testing. Then, the project's methodology, timeline, resource requirements and risk factors were planned, before progressing to the testing phase.

The testing was conducted with a series of simulations, followed by physical testing. A 3D model was formulated in SpaceClaim, and imported to ANSYS Mechanical for FEA. These simulations tested the Portaledges' capabilities in terms of deformation and maximum stress in three different loading scenarios: Pure loading (where the Portaledges are hanging from a singular point above the centre of the frame), centre loading (where a point load is applied to the centre of the longest edge of the frame) and transverse loading (where the frame is twisted by applying a load to the opposite corner from the support). It was determined that the D4 model was more rigid and had both a higher yield strength and strength to weight ratio in pure loading and centre loading, while the A5 design is slightly lighter and had a higher rigidity and yield point in transverse loading.

The simulations were followed by physical testing of an A5 block corner segment and a D4 curved corner segment. This testing compressed each corner, revealing that the D4 curved corner segment design had a significantly higher ultimate strength compared to the A5 block corner segment. It was also determined that failure occurred at points of high stress concentration within the corners, such as sharp edges and material imperfections.

2 – Project Aims and Objectives

The objective of the project is to determine which Portaledge design is superior in terms of strength to weight ratio, rigidity and general ergonomics. It is expected that the updated, D4 curved corner design (Figure 1) will be superior to the original design (Figure 2): the A5 Alpine double ledge. It is hypothesised that the curved corner design will prove more rigid by resisting deformation and it will have larger force bearing capabilities despite a lighter weight.

Figure 1 – The updated, D4 curved corner design.

Figure 2 – The A5 block corner design's aptly named block corners.

3 – Scope

The scope of the project will be limited to the testing of the Portaledge frame, and elements such as ropes and carabiners will not be investigated. The investigation will be limited to the two proposed designs: the updated, D4 curved corner design and the A5 Alpine double ledge design. This means that two frame shapes with the same materials will be tested, and no changes can be made to them prior to testing.

The project will start with an extensive review of literature relevant to the design of Portaledges. The mechanical properties of the materials in use will be investigated, to determine how each corresponding material will react to the applied load. These properties will be constrained to realistic conditions that the product will be exposed to, such as mild temperatures and pressures. The force distribution on different shapes of design will also be investigated. This will be limited to practical designs, to keep the Portaledge as compact and lightweight as possible. Furthermore, likely causes of failure will be investigated, limited to what is expected will occur in the Portaledge.

The testing of the Portaledges will then be planned and conducted. The tests will be conducted initially with FEA analysis software (such as ANSYS), before progressing to physical testing. The testing will be completed considering relevant forces. This will include the weight force of the user and their belongings, as well as exterior forces that may be imposed by nature. These tests will aim to identify which designs operate the most effectively in the given conditions. The points of maximum equivalent stress and deflection of the Portaledges will be tested, followed by an assessment of their fatigue life.

The results of the testing will be analysed and compiled into a legible and useful format. The results will be used to determine the maximum capabilities of each ledge, and their performances will be compared and contrasted. It will be determined whether the aim and objectives of the project were achieved, and whether the outcomes and results were beneficial to the field of practice and engineering discipline.

4 – Review of Literature

4.1 – Project Justification

Rock climbing is an inherently hazardous sport, which is part of the thrill that draws athletes to it. For this reason, alongside the skill of the climber, climbing safety equipment is widely available to minimise (although not eliminate) the risk involved. Typically, climbers will be attached by rope to anchor points on the cliff face, so that if a fall occurs, they will be caught by the rope before they fall a dangerous distance (Vogwell and Minguez, 2007). In the Engineering Failure Analysis Journal, it was assessed that a weight of 0.5kN could result in a 3kN peak force in the rope almost instantaneously when dropped (Vogwell and Minguez, 2007). With this practice comes the increased risk of mechanical failure due to a falling load drastically increasing the strain on equipment once the rope becomes taught. The safety of the climber comes down to the weakest link within their equipment, as often several elements will be linked together, such as the anchor nut, karabiner, rope and harness (Vogwell and Minguez, 2007). If one component fails, the results can be catastrophic.

Despite the vast array of safety equipment available, the most effective way to stay safe on a rock wall is to not fall. This may seem obvious, but as the number of mistakes increases, so does the risk to the climber. In the International Journal of Environmental Research and Public Health, it was noted that the most rock climbing injuries occurred due to errors, inattentiveness or environmental measures (Rugg et al., 2020). A large contributing factor to errors and inattentiveness is the fatigue level that the climber is experiencing. Ineffective recovery may lead to reduced climbing ability, more frequent losses in concentration and increased vulnerability to physical injuries (Magiera et al., 2019).

On multi-day big wall climbs, a Portaledge is a necessity to gain rest at night-time and take a break during the day. Several factors determine how restful a night in a Portaledge can be. The size of the Portaledge can be a double-edged sword. If you are sharing with a partner, a larger Portaledge will likely lead to a more pleasant sleep. Unfortunately, larger will often mean it is both heavier and bulkier, making it more difficult to climb with (Raleigh, 2000). Bed tensioners are also important in setting the firmness of the bed, which can contribute to a good night's rest. The ease of the setting up process can also be important for reserving energy and reducing stress after a long climb (Raleigh, 2000). The strength to weight ratio is important in allowing the user to conserve energy where possible, as a lighter design will be easier to transport up the wall. Finally, the design can be modified to make the Portaledge more stable against the rock wall. Optimising these factors is a critical part of ensuring that the user is relaxed and safe in their bed and can recover effectively between climbs. This effective recovery can drastically reduce the risk of accidents and injury, making it a worthwhile improvement.

The project will seek to answer some questions derived from this justification: How can a precisely engineered Portaledge design make improvements on previous designs with regards to strength to weight ratio, rigidity and stability? Will minor changes in the frame provide a worthwhile improvement that will increase the safety, productivity and quality of multi-day climbs?

4.2 – Introduction to Updated Design

The primary difference in the updated Portaledge frame design is the use of rounded tube corners, rather than the original aluminium block corners. This is intended to increase strength through properly distributing the stresses in the frame, increase rigidity through removing the risk of the frame buckling to a parallelogram, and decreasing the net weight (Middendorf, 2019). The tubing used varies in diameter, to increase strength where required, and save weight in sections that do not bear substantial loads. The frame joints used are 'bullet joiners' which utilise the varying tube diameters, and are situated along the straight sections of the frame. The updated design uses Aluminium 2024, which boasts a greater hardness and tensile strength than its 6061 counterpart, but is slightly denser (Juvinall and Marshek, 2012). An annotated schematic of one version of the updated design can be seen in figure 3.

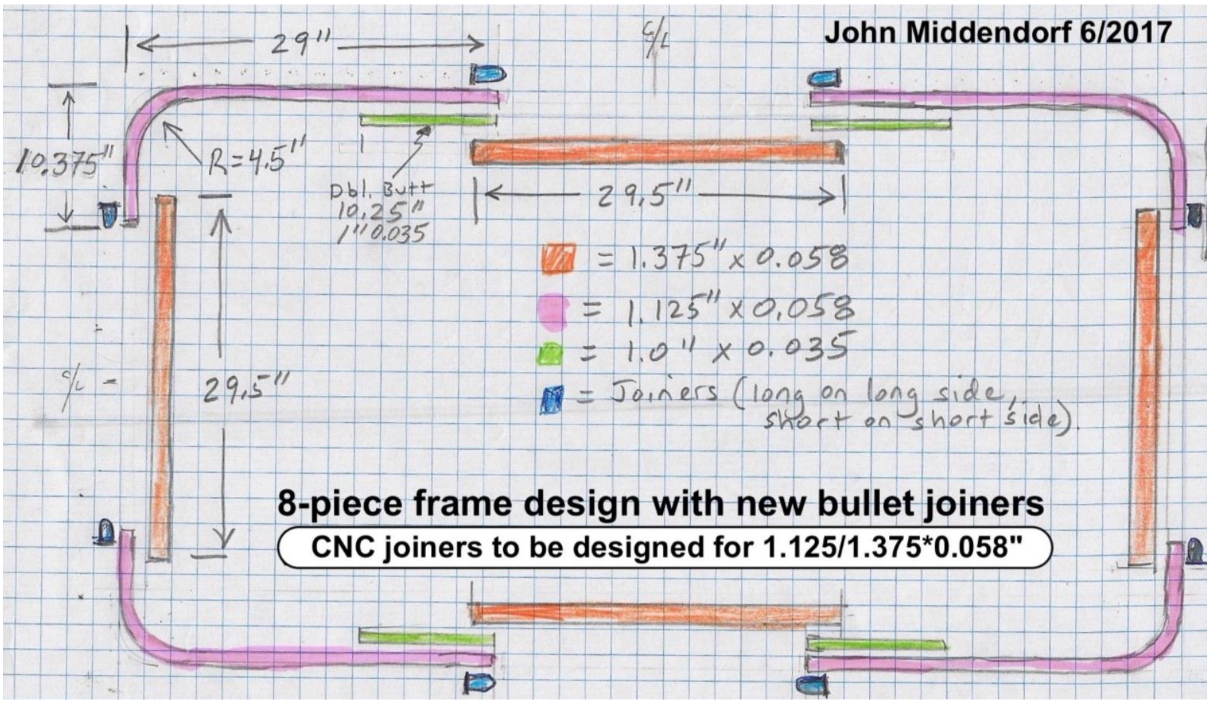

Figure 3 shows an annotated schematic of the updated Portaledge design, developed and drawn by John Middendorf (2017).

There are many elements to consider when optimising the design of the Portaledge. Primarily, the weight bearing properties and overall strength are pivotal in ensuring that the Portaledge performs successfully. A high Factor of Safety (F.O.S.) is desirable, whilst maintaining a low net weight. It is also desirable to have a design which is stable and rigid when assembled on the wall and is compact and easy to handle when dismantled.

4.3 – Analysis of Current Solutions

To establish how to make improvements most effectively on Portaledge designs, current designs should first be investigated. The A5 block corner designs are regarded as the first frames to be developed with engineering tools to optimise its strength, weight and rigidity (Middendorf, 2019). This design has been successfully used in the field for several decades, although no significant improvements to the product's strength to weight ratio, function and packed size have been made.

The A5 designs incorporate 1.125-inch (25.575mm) OD 6061-T6 Aluminium Tubing for the frames, and exact tolerance milled block 6061-T6 Aluminium corners (A5 Adventures Big Wall

Outfitters, 1989). Most designs created since the A5 block corner design incorporate the block corners and aluminium tubes, making the A5 a good benchmark for comparison against newer designs (Middendorf, 2019).

Aluminium 6061 is commonly implemented in boats, rail cars, trailers and hang gliding aircraft, due to its ability to resist corrosion and be welded with ease (Juvinall and Marshek, 2012). When untreated, it provides relatively poor mechanical properties. Untreated Aluminium 6061 has a Brinell Hardness of 30, ultimate tensile strength of 125MPa, and yield strength of 55MPa (Juvinall and Marshek, 2012). The A5 block corner design uses aluminium that has undergone T6 temper heat treatment, providing drastically increased mechanical properties. The Brinell Hardness of T6-6061 is 95, ultimate tensile strength is 310MPa and yield strength is 275MPa (Juvinall and Marshek, 2012).

4.4 – Criteria for successful design

The aim for the new design is to provide a solution with an advantageous strength to weight ratio, increased rigidity and stability, and a smaller and more ergonomic packed size. The piping in the frame will need to withstand constant weight forces, both highly distributed and focussed, considering the user(s) may be standing or lying on the Portaledge. Adverse weather will also need to be factored into force calculations. The frame will need to be designed to resist failure due to fatigue under a fluctuating load. The magnitude and analysis of these loads on Portaledges are not highly researched or published, so further research and testing into this subject would be beneficial.

The shaping of the frame will be important for proper distribution of stress, and avoidance of stress concentration hotspots at critical points. The maximum stress concentration in designs often occurs at sharp edges and irregularities within the shape. This can be mitigated by replacing sharp corners with filleted corners (where the greater radius distributes the concentration more effectively) and using gradual transitions in designs (Nagpal et al., 2012). Additionally, relief notches can be incorporated near areas of high stress concentration to alleviate a portion of the stress (UNSW, n.d.).

The design will be required to perform effectively under different climates and weather conditions where it is used. Mechanical properties of materials often vary with temperature and pressure, and the stability of the design will be affected by the magnitude and direction of wind in the vicinity. Aluminium 6061 is considered moderately effective in resisting corrosion, which is a pivotal design feature for any material that will exposed to the rain (Juvinall and Marshek, 2012). Notably, the materials are likely to be scratched regularly in their use, so a corrosion resistant coating would not be effective. Aluminium can operate within a range of temperatures without having a decrease in mechanical properties. Aluminium is able to reach a high temperature of 150°C before risking property degradation (Summers et al., 2015), and can reach extremely low temperatures without losing any strength and ductility or becoming brittle (Zajac, 2018). This is due to its Face Centred Cubic structure, which has reduced sensitivity to low temperatures (Zajac, 2018). This reinforces that aluminium is a good choice of material for a Portaledge to resist both warm and cold climates.

4.5 – Material Strength and Failure Theories

The Portaledge will be required to maintain its integrity and strength under constant use. Several failure theories are pertinent for determining whether each design is suitable.

4.5.1 – Yield Strength, Ultimate Strength and Fracture

Stress–strain curves are developed to measure the yield strength, ultimate yield strength and fracture point of materials. At the yield strength, the plastic deformation begins to occur, where the material begins to deform irreversibly. At the ultimate yield strength, the mechanical properties of the material begin to fail (Juvinall and Marshek, 2012). Figure 4 shows the true stress–strain curve of aluminium 6061 and 2024. In this case, the 6061's yield point occurred at about 250MPa of stress, whereas the 2024's yield point occurred at 300MPa of stress (Jena et al. 2017). The ultimate yield strength of aluminium 6061 and 2024, occur at roughly 310MPa and 500MPa respectively, suggesting that if the maximum stress reaches these values, a component will fail drastically (Jena et al., 2017).

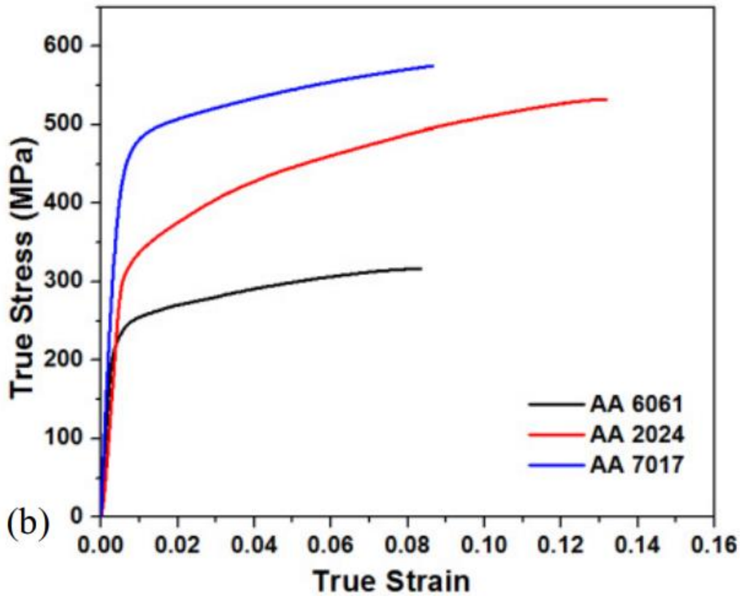

Figure 4 – Stress strain relationship between different varieties of aluminium, including 6061 and 2024 (Jena et al. 2017).

4.5.2 – Fatigue

Fatigue fracture refers to the gradual degradation of a component after numerous cycles of use, eventually leading to fracture (Juvinall and Marshek, 2012). When calculating fatigue strength in a mechanical component, testing is the most accurate method of obtaining data. However, expected results can be obtained using equation 1 (Juvinall and Marshek, 2012):

Equation 1:

$$S_n = S'_n C_L C_G C_S C_T C_R$$

Where: C_L *= Load factor*

C_G *= Gradient factor*

C_S *= Surface factor*

C_T *= Temperature factor*

C_R *= Reliability factor*

S'_n *= R.R. Moore, endurance limit*

The S_n value from this equation can be applied to an S-N curve for the appropriate materials to identify the expected lifetime. An S-N curve plots how many cycles of use a material can withstand against its corresponding stress. Some metals, namely steel and iron, are considered to have an infinite life under fatigue once they are engineered to surpass 10^6 cycles of use (See plot A, Figure 5) (Taneja, 2018). However, some non-ferrous metals, such as aluminium alloys, do not possess this property. Instead, these components will continue to degrade, until inevitably breaking (see plot B, Figure 5). Notably, this can occur after a very large number of cycles, with experimental data suggesting that some aluminium can withstand up to 10^{10} cycles (Nwachukwu et al., 2017).

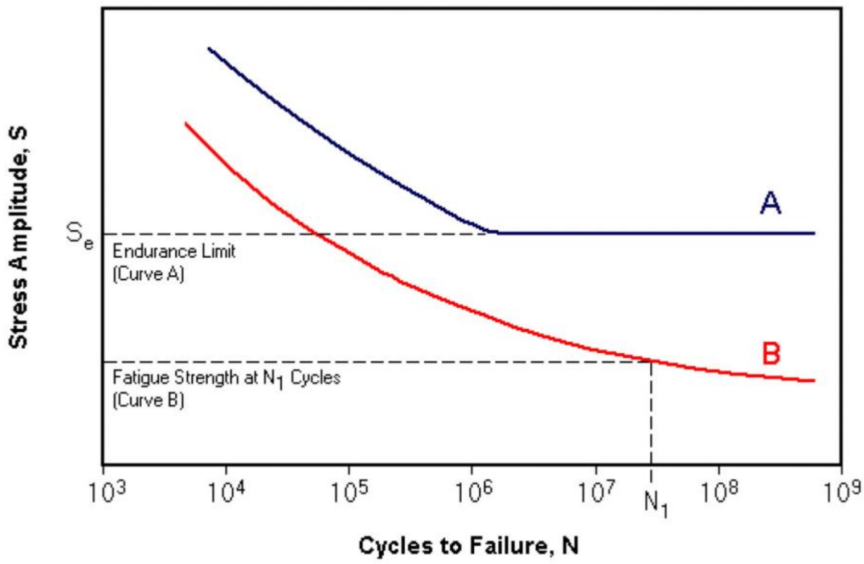

Figure 5 – S-N curves of materials with (Plot A) and without (Plot B) endurance limits (Taneja, 2018).

Experimental data is the most reliable way to determine a component's fatigue life, but estimations may be made by inspecting existing S-N curves of the same material. Bai et al. (2014) developed an S-N curve of 6061-T6 Aluminium Alloy, shown in Figure 6. This may be referred to when estimating how many cycles of use a component can have before succumbing to fatigue failure.

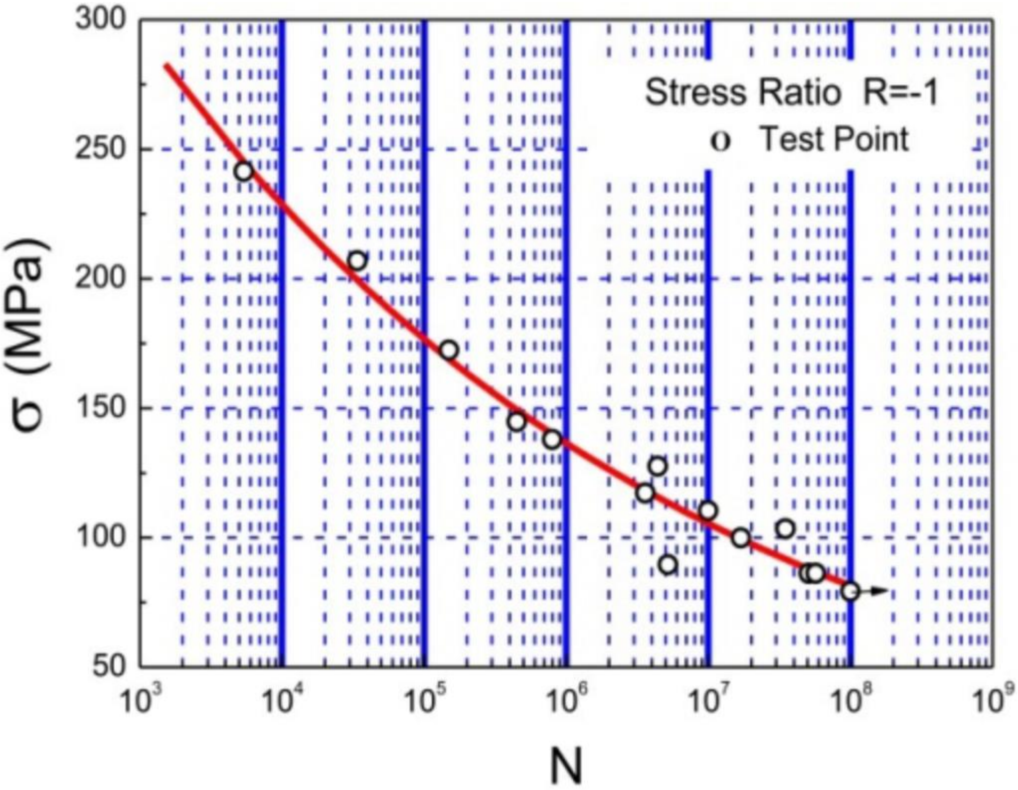

Figure 6 – Experimentally obtained S-N curve for 6061-T6 Aluminium Alloy (Bai et al., 2014).

4.5.3 – Fracture Mechanics

The underlying assumption of fracture mechanics is the inevitable imperfections in all materials (Juvinall and Marshek, 2012). The weight force imposed on the Portaledge will induce strain on the tubes. It is possible that minute cracks may also form due to impacts on the tubes in general use, so there is potential that fracture mechanics will be pertinent. Figure 7 can be used to identify the stress intensity factor for such cracks, and consequentially determine the critical stress for the tube.

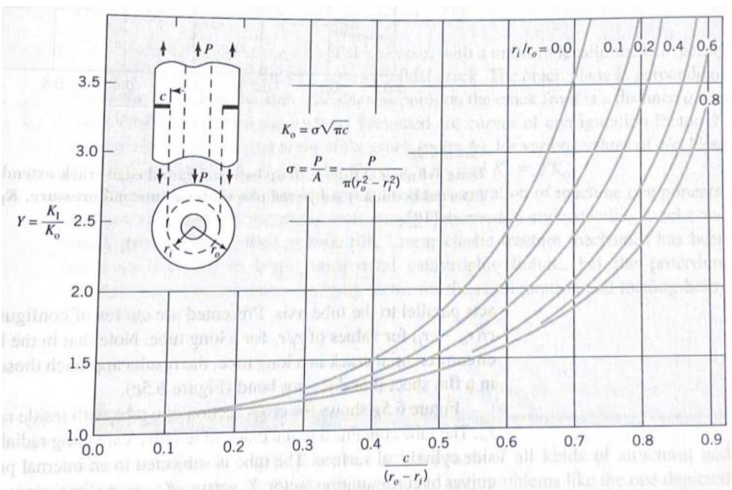

Figure 7 – Graph for determination of stress intensity factors in tube under uniaxial tension (Rooke and Cartwright, 1974).

4.5.4 – Deflection

When a load is applied to an object, it will cause said object to warp by an amount dependant on the load. The magnitude of this deformation is known as deflection (Designing Buildings, 2020). The amount of deflection that occurs is dependant on a structure's rigidity, thus strengthening elements by reinforcement or a change in material can help minimise deflection.

Deflection in Portaledge members is likely to occur most prominently in the beams in the frame. Considering them as hollow circular beams under uniformly distributed loads, the following equations can be used to predict the magnitude of maximum deflection:

Equation 2 (MechaniCalc, n.d.):

Moment of inertia:

$$I_{Hollow\ Cylinder} = \frac{\pi\ (r_o^4 - r_i^4)}{4}$$

Equation 3 (MechaniCalc, n.d.):

Max. Beam Deflection Hollow Cylinder Simply Supported:

$$\delta_{max} = \frac{5wL^4}{384EI}$$

The maximum deflection described in equation 3 will occur in the centre of the beam.

5 – Management Strategy

5.1 – Timeline

To ensure that the projects final objectives are met in ample time, the project was divided into a series of smaller goals. These have been compiled in a Gantt chart (located in appendices 1) which outlines the timeline allowed for each minor goal. Adhering to this schedule will ensure that the project is completed in due time.

The major steps are as follows: Project registration, project proposal, research plan, intermediary project report, portfolio, testing, data analysis and thesis finalisation. The minor steps and their respective dates are covered in the Gantt chart.

5.2 – Resource Requirements

To conduct the testing stage of the project, a variety of equipment and software will be required:

- Access to 3D modelling software (SpaceClaim, Autodesk Inventor)
- Access to Finite Element Analysis software (ANSYS Workbench, Autodesk Fusion)
- Shimadzu compression testing equipment, with rounded piston attachment for top piston
- Vice compatible with Shimadzu compression equipment, for keeping corner piece secure
- Software for quantitatively analysing compression and bending test results
- A5 Alpine Double design corner piece
- D4 Curved Corner design corner piece

Depending on the availability of existing ledge components, additional resources may be required:

- CNC Machine to model block corners for A5 design
- Pipe Bender for D4 design

5.3 – Risk Analysis

Correct and proper methods should be employed to ensure that the project is completed safely and without endangering anyone. A preliminary risk assessment was conducted to identify what may be hazardous, and how to mitigate or remove the risk (Figure 8). Throughout the project, as activities arise, additional risk assessments will be conducted more thoroughly, and submitted to governing bodies for approval.

Identify the hazard	**Assess the risk**	**Control the risk**	
What is the hazard?	What might go wrong? Who might be harmed and how?	Priority or risk level (low, med, high) *	What do you need to do to control the risk?
Portaledge failure during testing	Portaledge components may fail explosively, discharging shrapnel. Puts operators and viewers at risk	Medium	Ensure guards on testing devices are fitted properly, wear PPE (ie goggles) and do not test Portaledge beyond expected capabilities.
Use of CNC machine for component manufacturing	User may be injured if they interfere with CNC machine whilst it is operating	Medium	CNC machine safeguards should be used and adhered to, an experienced and properly trained user should operate machine, machine should not be interfered with while in use.

Figure 8 – the preliminary risk assessment conducted to identify potential hazards and risks in the project, their severity, and how best to control them.

6 – Methods

6.1 – Finite Element Analysis Simulations and Testing

6.1.1 – Model Formulation and Preparation

To conduct FEA on the two models of Portaledge, it was first required to create accurate 3D models of each Portaledge. SpaceClaim was chosen to produce the 3D models, as it is effectively transfers into ANSYS Mechanical for FEA. Both models were created as individual components, which were then assembled. The A5 model consisted of 7 different part designs, which made a total of 20 components in the assembly (see 7.1 for annotated A5 Model). The D4 model only consisted of 4 different part designs, which also made a total of 20 compoennts in assembly (see 7.2 for annotated D4 Model). For the purpose of accurately depicting the method of supporting the D4 Portaledge, an additional component was added to all four corners (Figure 9). This sleeve fit with exact tolerence, and was not included in any stress, deformation or fatigue calculations in FEA, as it was simply used as a support anchor. It was critical that all components of both designs were fully constrained, and fit with exact tolerencing to one another. This prevented critical errors with the FEA stage.

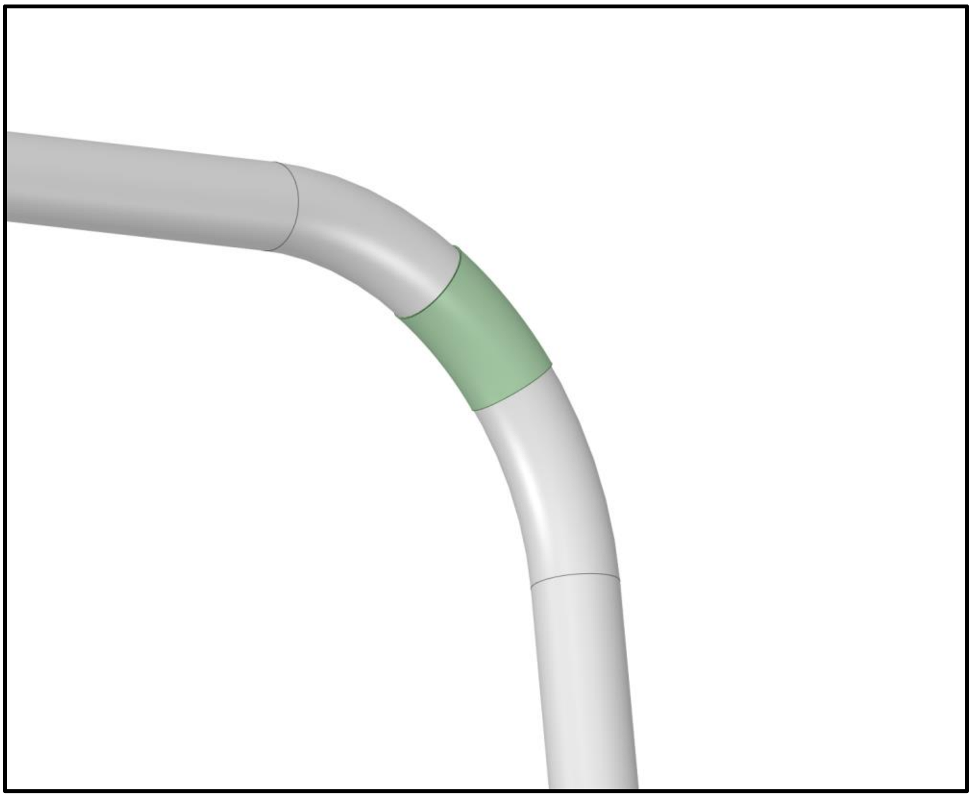

Figure 9 – Additional support component added to the D4 Design, used as a support in FEA (green sleeve in picture).

The 3D models were then imported into ANSYS Mechanical APDL for FEA. The first step was to assign engineering material properties to each design. ANSYS Material Library incorporates Aluminium 6061-T6 for basic most basic properties, however it lacked the inclusion of an S-N curve for fatigue calculations. This needed to be imported from investigated literature. The FEA was then set up. Initially, each component was assigned to be Aluminium 6061-T6. Then, a mesh was produced on each design. Due to the considerably large size of the frames, the element size of each node was set to 0.01m. This resulted in roughly 100 000 nodes for each design.

6.1.2 – Pure Loading Setup

Three different loading scenarios were tested for each Portaledge. The first was Pure Loading, which investigated the Portaledge's ability when hanging. For this test, the four corner supports were bound to a remote displacement, which was located 1.5m above the centre of the frame (see point A, Figure 10). This allowed the model to act as a hanging load. In general use, when the user is on the material section of the Portaledge, the forces applied to the ledge comes from where the material is connecte to the poles. The angle of this force is dependent on the taughtnes of the material, and the magnitiude of the load. To simulate this, distributed loads were applied to each side, for the entire duration of the pole length. The force vectors were directed downwards and inwards, at an angle of 53° from horizontal (See points D, E, F, G, Figure 10). This angle was chosen by analysis of images of highly loaded Portaledges. It was seen that they would flex inwards at this angle. Standard Earth Gravity was also incorporated, to account for the weight of the ledges. In the first test, a total combined force of 1kN was imposed on the frame. In the first setup, each side underwent 250N of applied load, broken into components of 200N downwards, and 150N inwards (see figure 12).

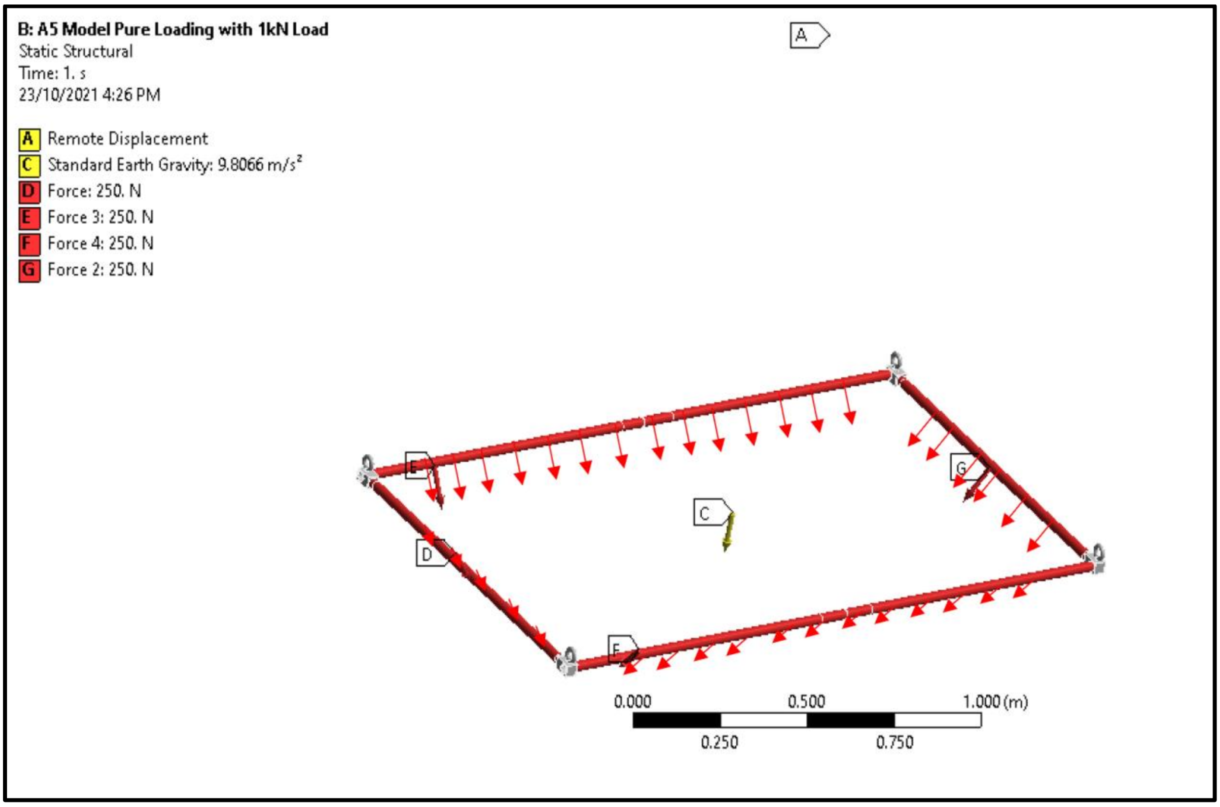

Figure 10 – Isometric view of FEA setup for A5 Pure Loading scenario, with 1kN load.

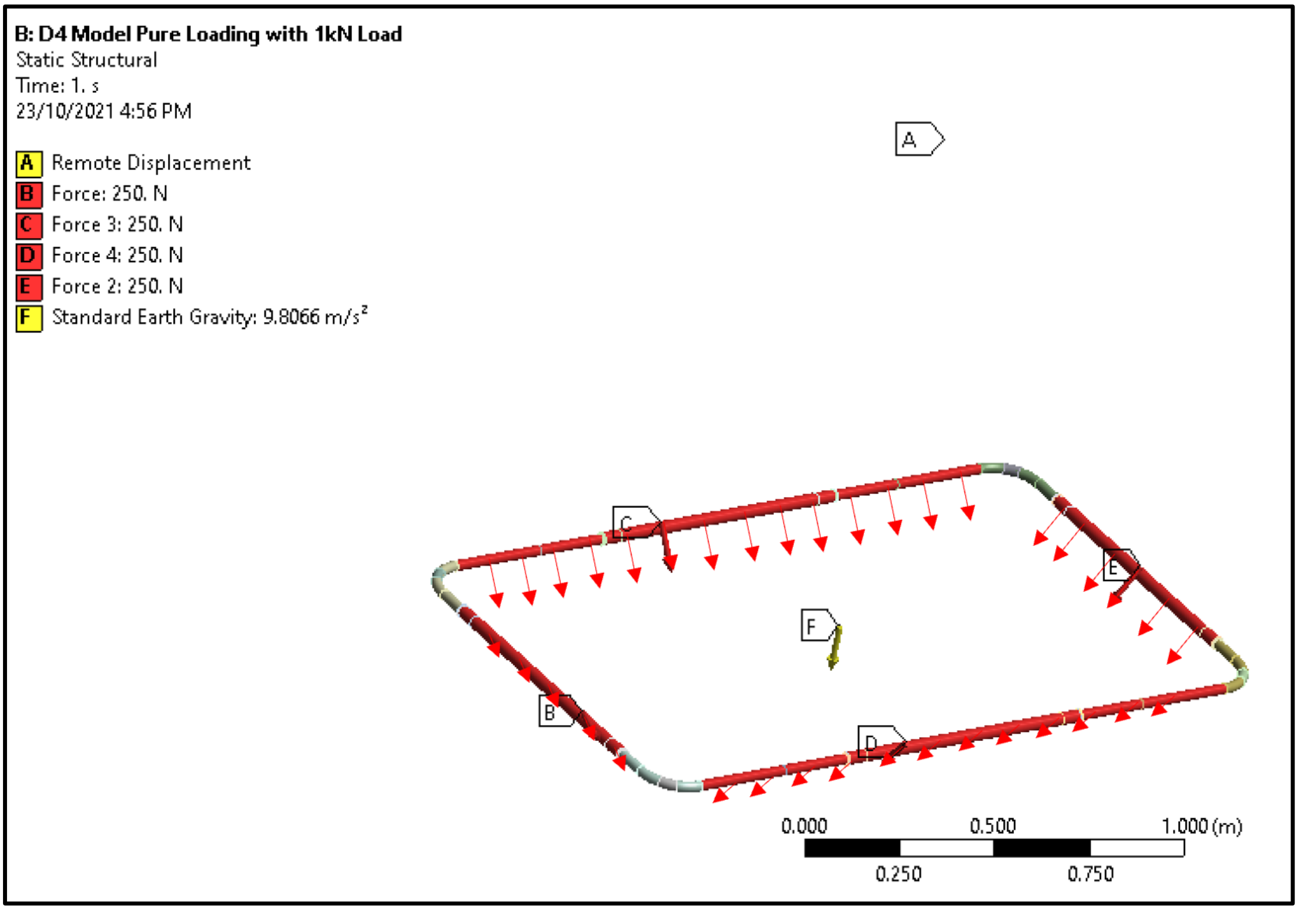

Figure 11 – Isometric view of FEA setup for D4 Pure Loading scenario, with 1kN load.

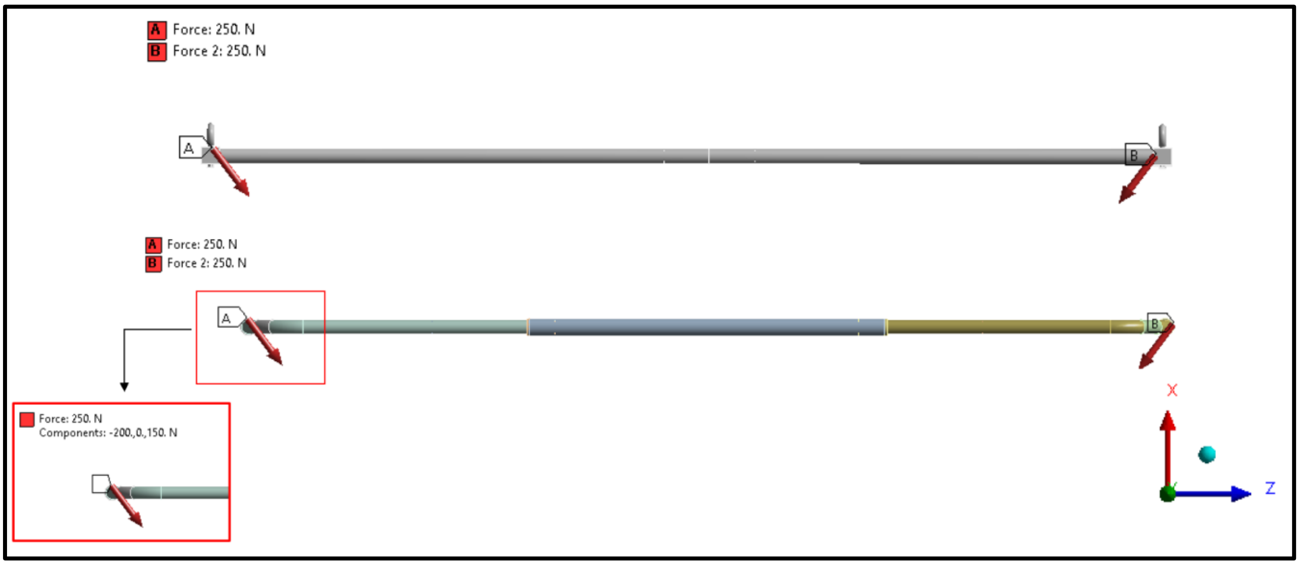

Figure 12 – Front view of setup for A5 (top) and D4 (bottom) ledges, showing two of four applied forces on the ledges, as well as their components.

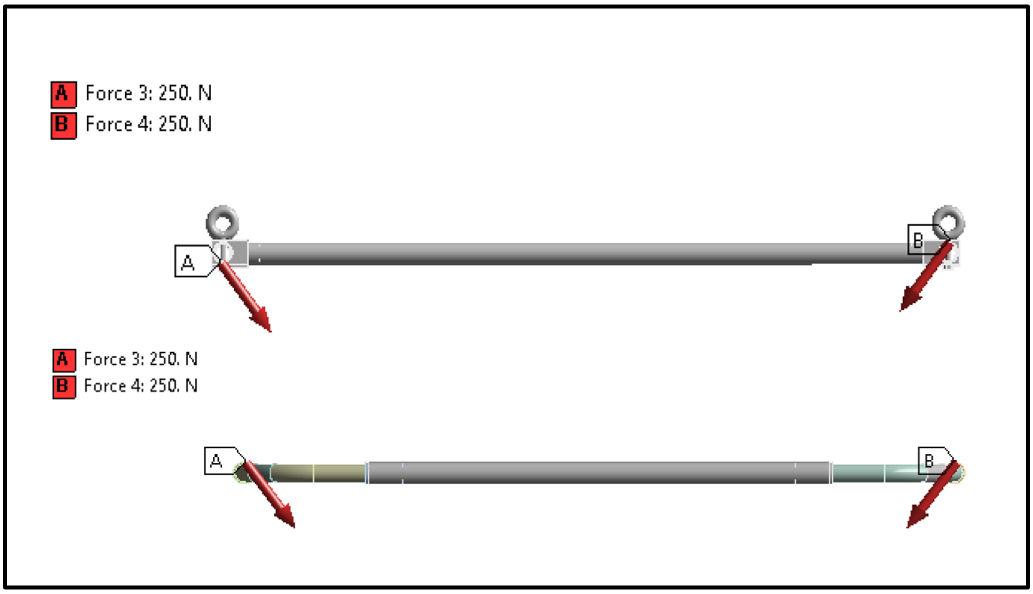

Figure 13 – Side view of setup for A5 (top) and D4 (bottom) ledges, showing two of four applied forces on the ledges.

The simulation for Pure Loading was also run with a 2.5kN total force and a 5kN toal force. For the 2.5kN loading, each side had a 625N distributed load, which was broken into components of 500N downwards and 375N inwards (Figure 14). For the 5kN loading, each side had a 1250N distributed load, which was broken into components of 1000N downwards and 750N inwards (Figure 15).

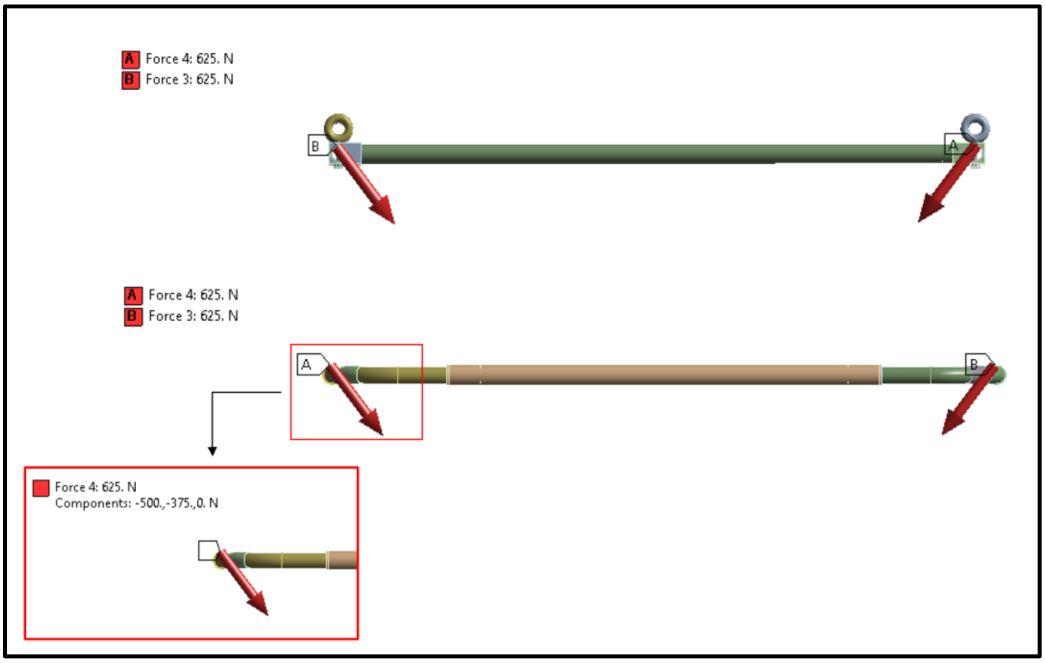

Figure 14 – Side view of setup for A5 (top) and D4 (bottom) ledges with 2.5kN total loading, showing two of four applied forces on the ledges, as well as their components (where the positive 'x' component is upwards).

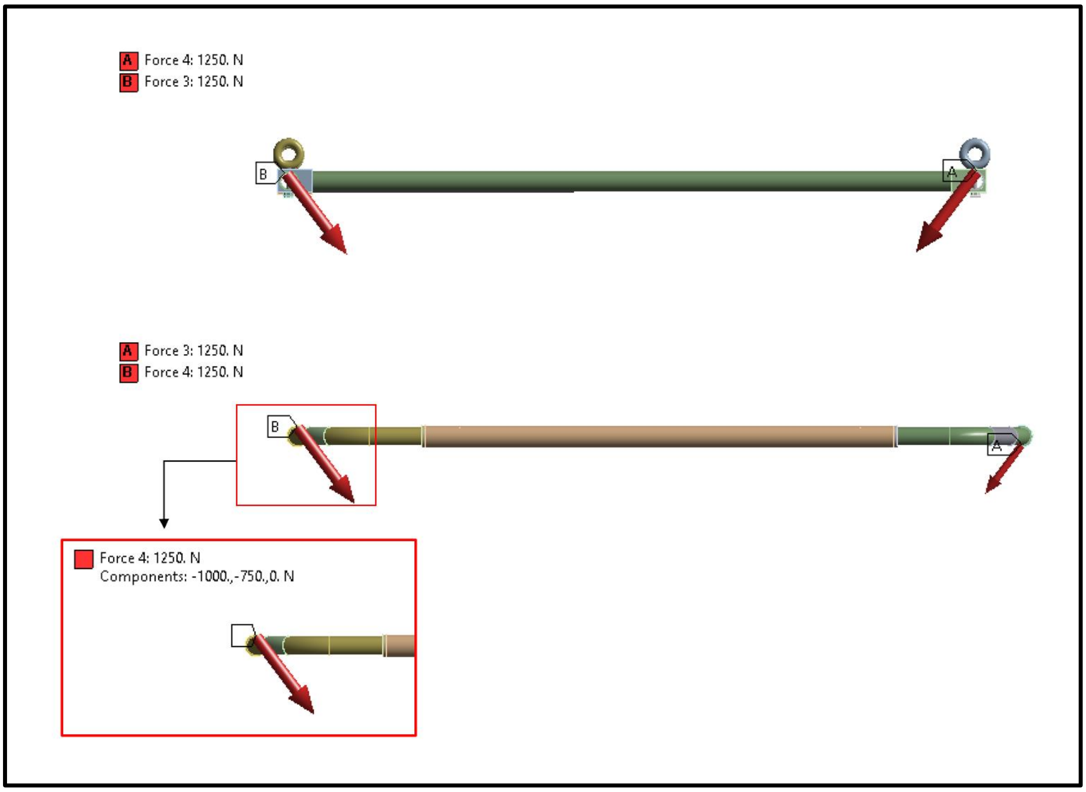

Figure 15 – Side view of setup for A5 (top) and D4 (bottom) ledges with 5kN total loading, showing two of four applied forces on the ledges, as well as their components (where the positive 'x' component is upwards).

6.1.3 – Transverse Loading Setup

The following simulation was for transverse loading, which investigated how the Portaledges performed when twisted in the longitudal axis of the poles. This was conducted by applying a 1kN force in one corner, perpendicular to the short edge, and setting a fixed support in the opposite corner. Figure 16 and 17 provide diagrams on the transverse loading setup for the A5 and D4 ledges respectively.

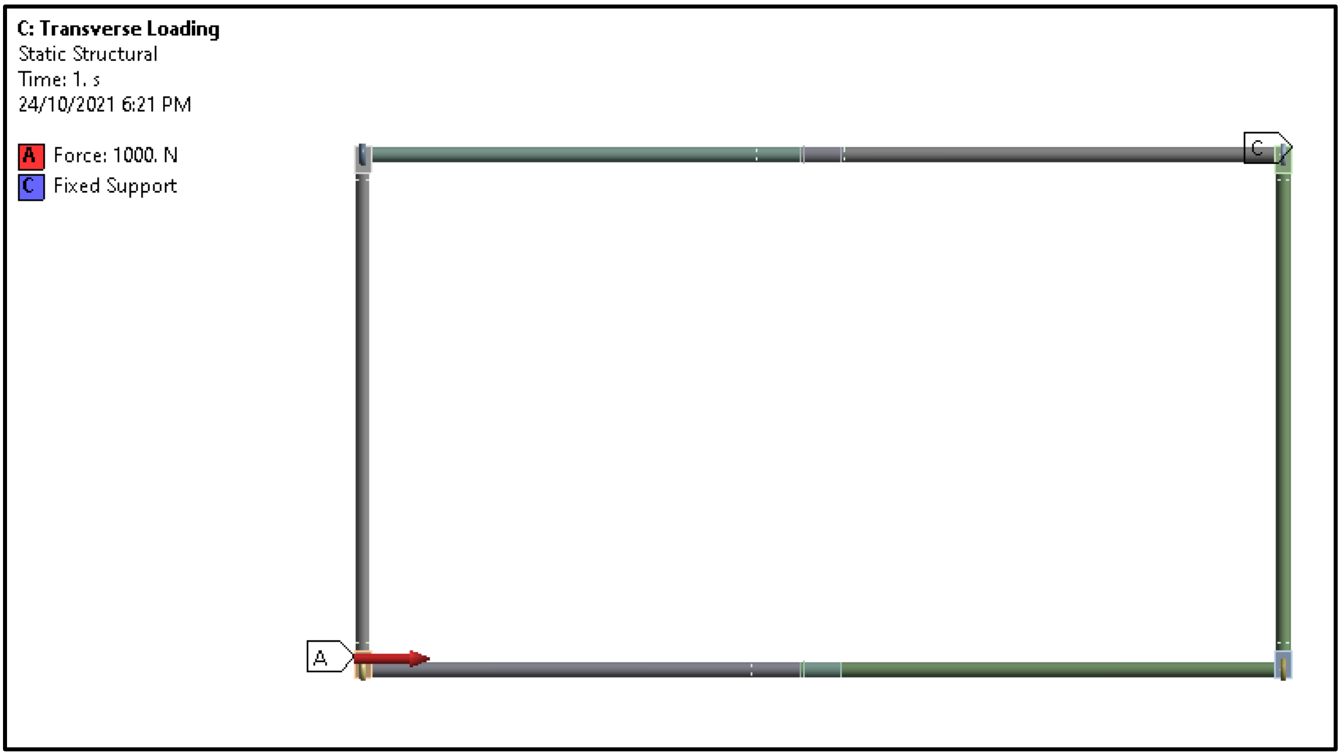

Figure 16 – Top view of A5 Model setup for transverse loading with a 1kN applied force, showing the applied force (point A) and fixed support (point C) in opposite corners.

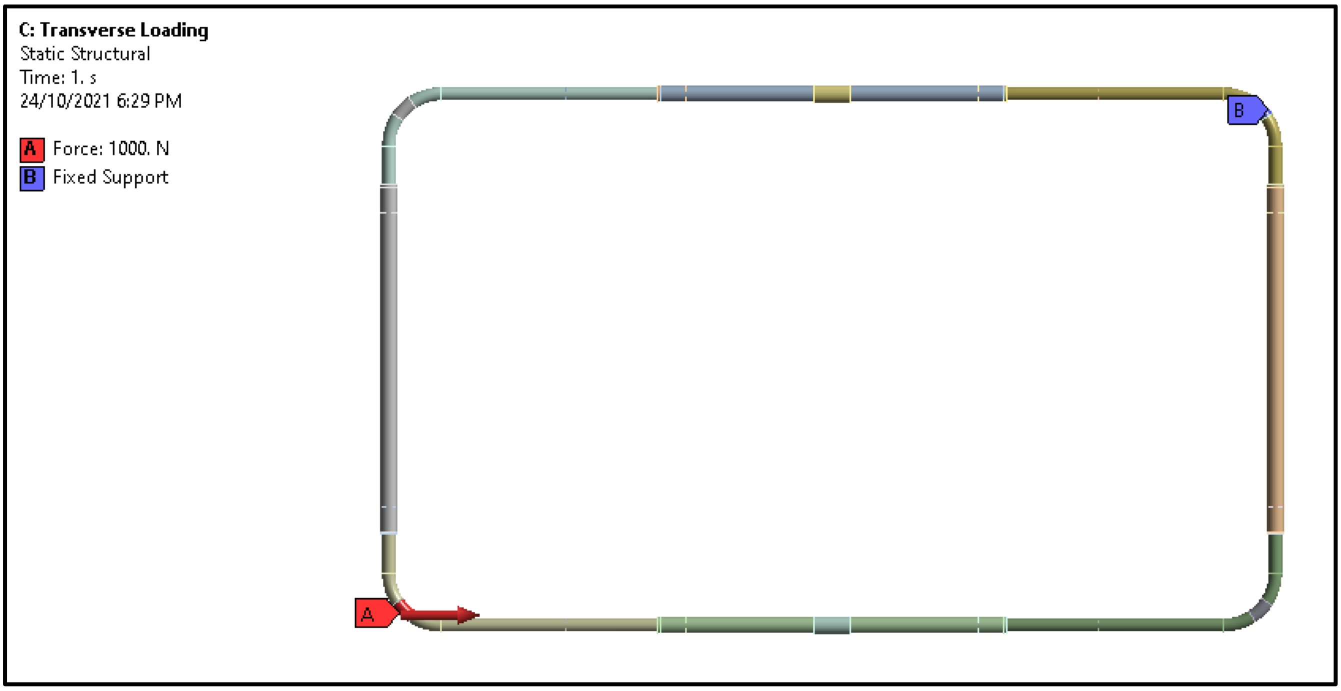

Figure 17 – Top view of D4 Model setup for transverse loading with a 1kN applied force, showing the applied force (point A) and fixed support (point B) in opposite corners.

6.1.4 – Centre Loading Setup

The final simulation was for a centre loading, to examine how the Portaledges respond when setup against a small edge, such as a tree, or pointed rockface. In this simulation, a 1kN force was applied to the centre support of one long tube, directed inwards and perpendicular to the tube. A fixed support was positioned on the centre support on the opposite long tube. Figure 18 and 19 provide diagrams on the centre loading setup for the A5 and D4 ledges respectively.

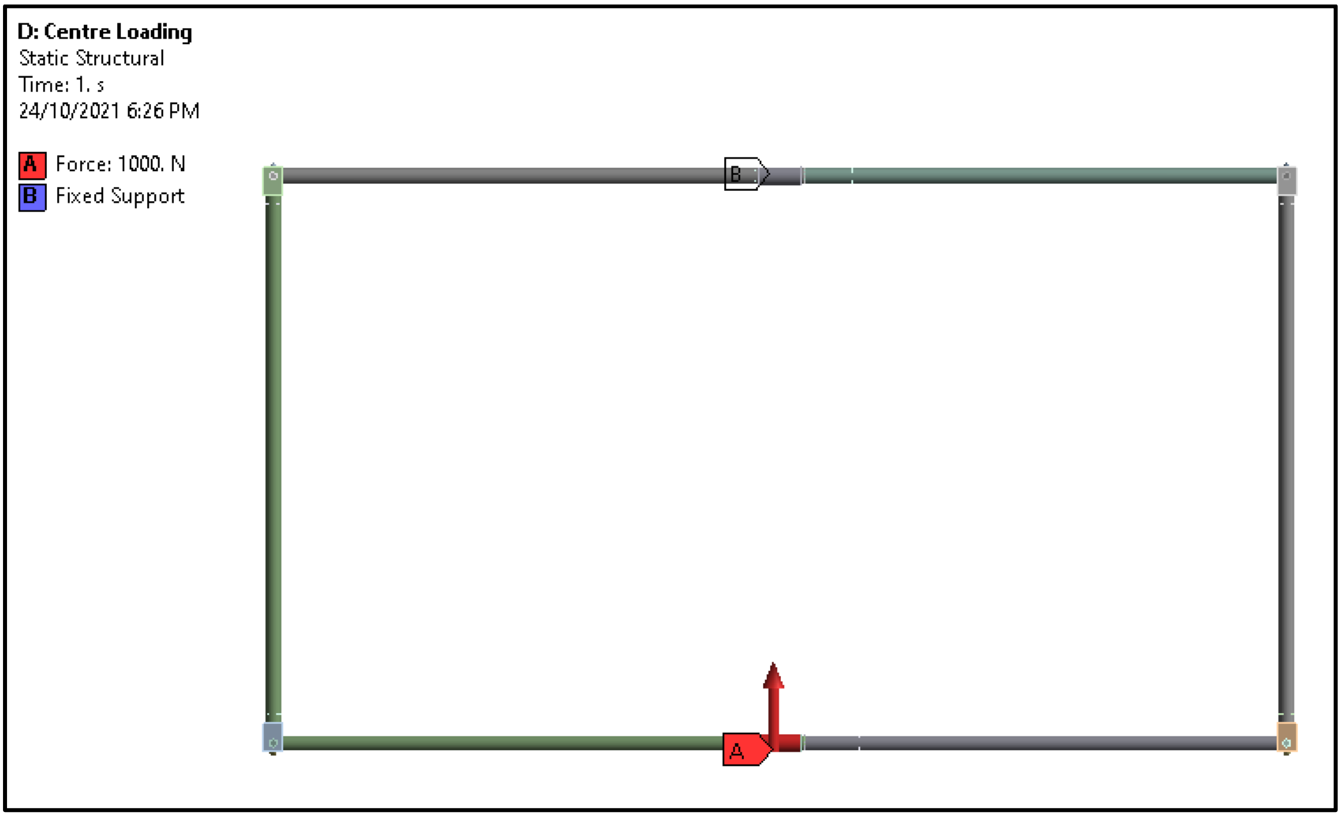

Figure 18 – Top view of A5 Model setup for centre loading with a 1kN applied force, showing the applied force (point A) and fixed support (point B) on opposite centre supports.

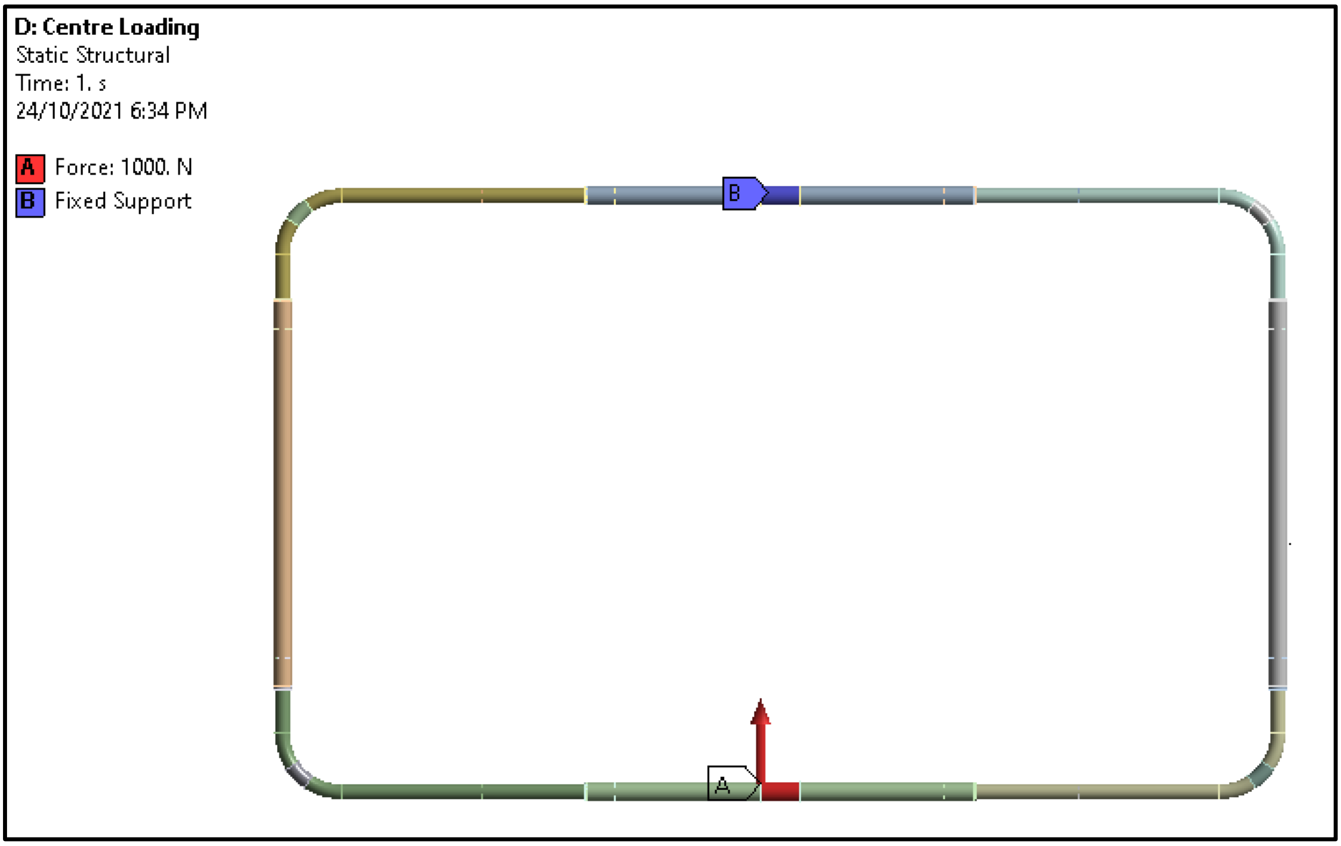

Figure 19 – Top view of D4 Model setup for centre loading with a 1kN applied force, showing the applied force (point A) and fixed support (point B) on opposite centre supports.

6.2 – Physical Compression Test

To gain real experimental data, and support the results gained from the FEA, physical compression tests were conducted on corner pieces of the two designs. A bending test was also conducted on a straight member of the D4 design, testing the performance of the joiner under pressure.

6.2.1 – Corner Piece Compression

The Shimadzu Compression Testing machine was used for the testing of the corner pieces. The shorter tube of each corner was fixed into a vice at the base of the compression apparatus, so that the top piston connected 150mm away from the outside of the corner. The top piston was fixed with a 6mm diameter curved head attachment and layered with 5mm thick foam tape to minimise the likelihood of slippage occurring. The corner pieces for testing both consisted of 1.125” OD tubes, with 0.058” walls. The shorter length of tube measured 10” from the end of the tube to the outside of the corner. Figures 20 and 21 provides annotated diagrams of the setups for the A5 and D4 Corner piece tests respectively.

Prior to the test, the top piston was manually lowered to be lightly touching the horizontal member, without applying force on it. The piston was then set to lower at 12mm/min and record time, stroke (deflection) and force 100 times per second.

The test was started, and run until the corner piece completely failed, or deflected to the point at which it touched the base plate. Each set of data was saved as a text file for analysis.

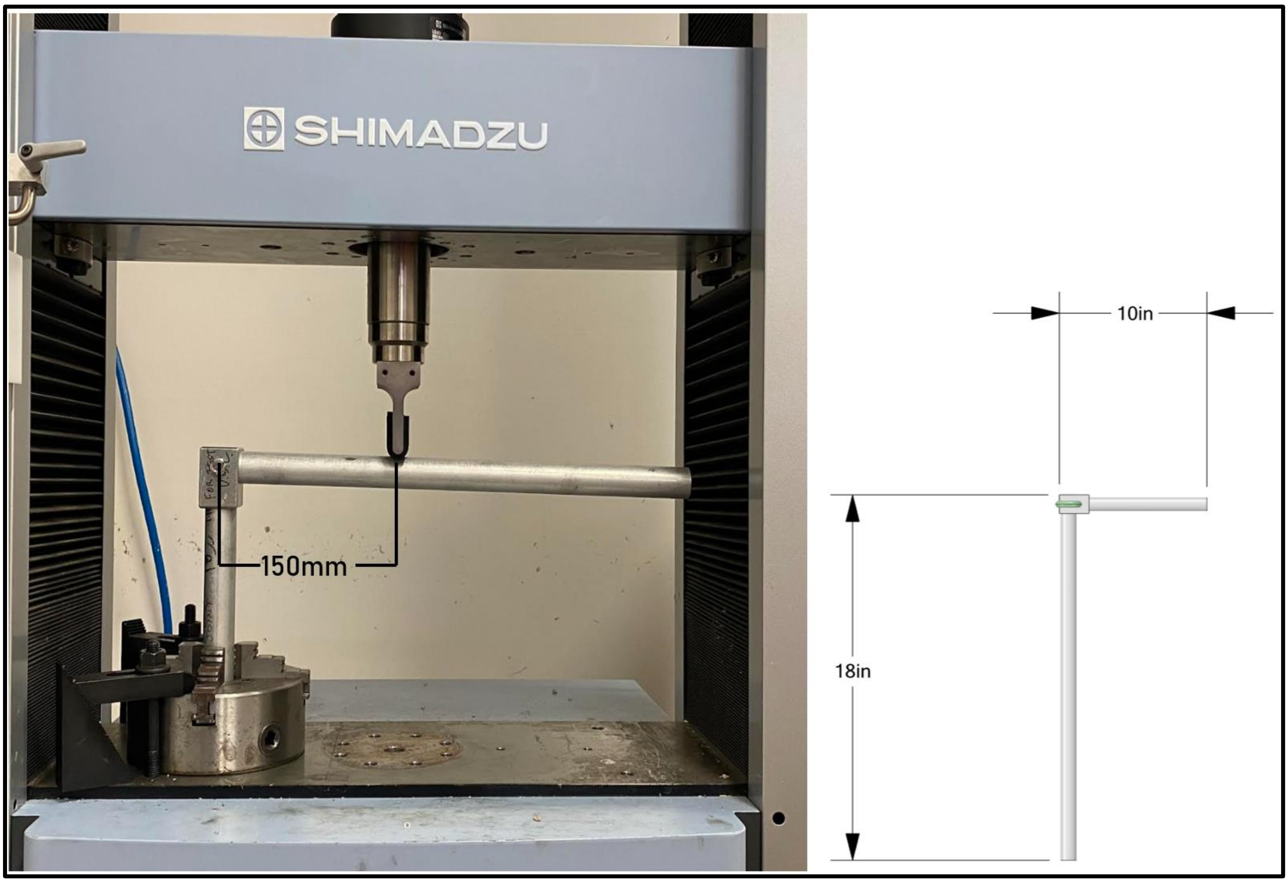

Figure 20 – Corner Piece Compression test setup for A5 Corner piece, with dimensions (Block corner and diameter dimensions included within Part 7 – Detailed Model of Designs).

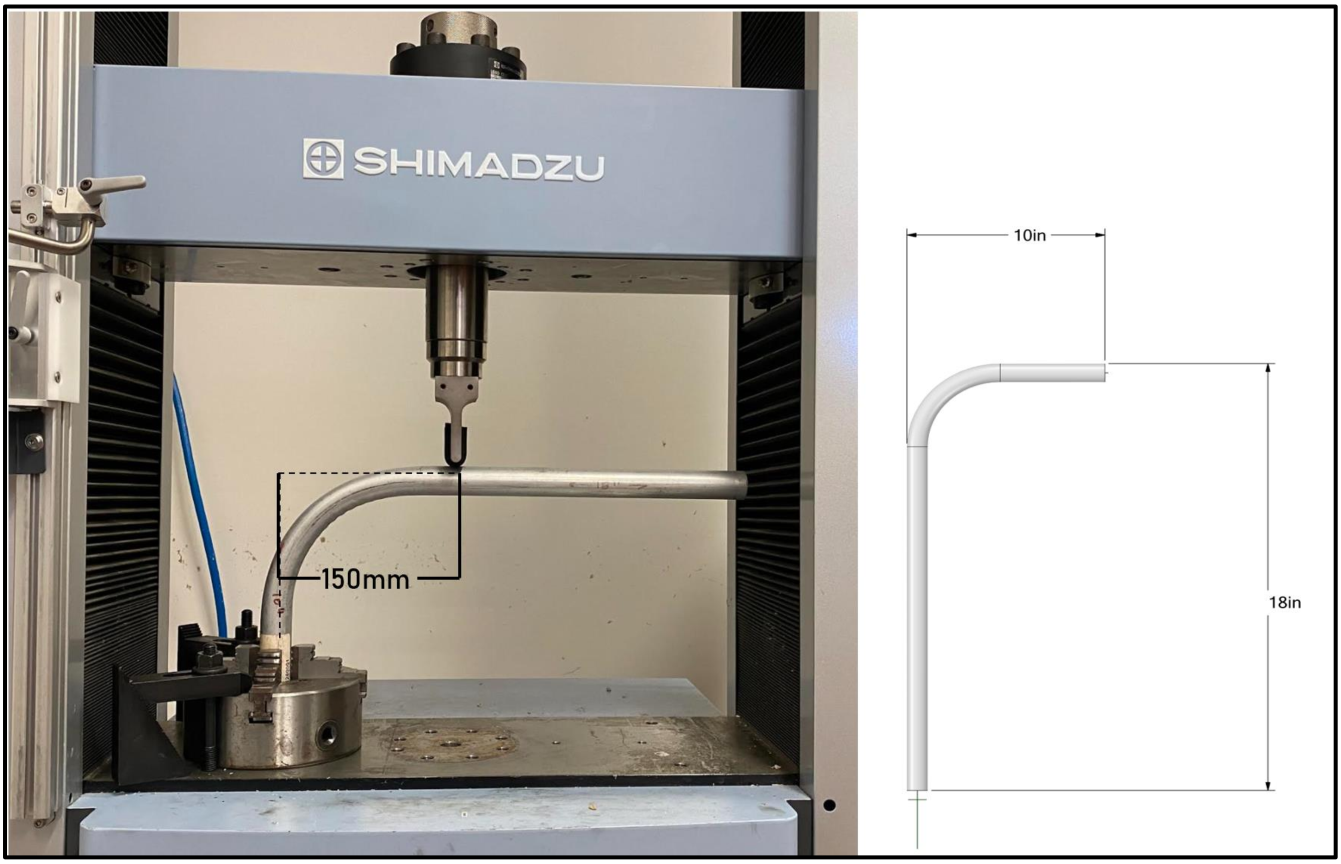

Figure 21 – Corner Piece Compression test setup for D4 Corner piece, with dimensions (Corner radius and diameter dimensions included within Part 7 – Detailed Model of Designs).

6.2.2 – Straight Tube Three Point Bending

The Shimadzu Compression Test machine was used for the three-point bending test of the straight member with a D4 Joiner. The tube was rested upon two tubes, 300mm apart. The top piston was fixed with a 6mm diameter curved head attachment and layered with 5mm thick foam tape to minimise the likelihood of slippage occurring. It was positioned to compress the tube in the centre of the two bottom supports.

Prior to the test, the top piston was manually lowered to be lightly touching the horizontal member, without applying force on it. The piston was then set to lower at 12mm/min and record time, stroke (deflection) and force 100 times per second.

The test was started, and run until the piece failed. Each set of data was saved as a text file for analysis.

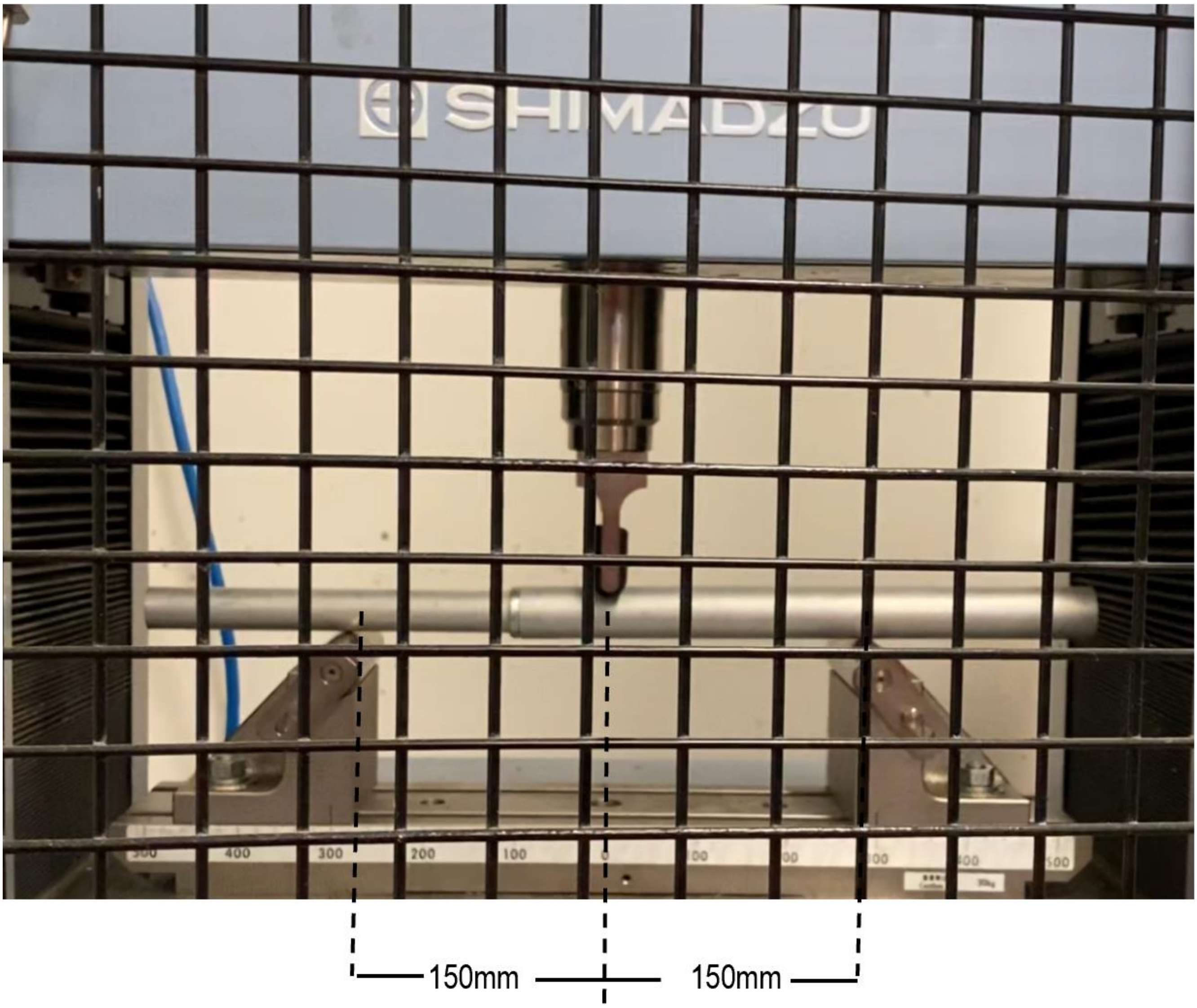

Figure 22 – Straight Tube Three Point Bending test setup for D4 connection piece, with dimensions. Sample included a 1" OD with 0.058" wall thickness pole, a 1.25" OD pole with 0.049" wall thickness, connected to each by a bullet joiner (Bullet joiner dimensions included within Part 7 – Detailed Model of Designs).

7 – Detailed Model of Designs

7.1 – Original Design – A5 Alpine Double Ledge

The A5 Alpine Double Ledge is designed with machined aluminium corner blocks (Figure 23), and straight aluminium tube edges. This variety of A5 design was chosen to compare against the updated D4 curved corner design due to the similar sizing. Upon construction, the A5 Alpine Double Ledge frame is 42.48” × 75”. The A5 design is comprised of 7 different varieties of parts, with a total of 20 components. The parts list is:

- Part 1: 4× Block Corners (Figure 24)
- Part 2: 2× Large Connector Pole – 1.0” OD, 0.083” wall thickness (Figure 25)
- Part 3: 2x 40in. Pole – 1.125” OD, 0.058” wall thickness (Figure 26)
- Part 4: 2x 39.25in. Pole – 1.125” OD, 0.058” wall thickness (Figure 27)
- Part 5: 2x 35.75in. Pole – 1.125” OD, 0.058” wall thickness (Figure 28)
- Part 6: 2x Small Connector Pole – 1.0” OD, 0.083” wall thickness (Figure 29)
- Part 7: 4x M8 Eye Bolt

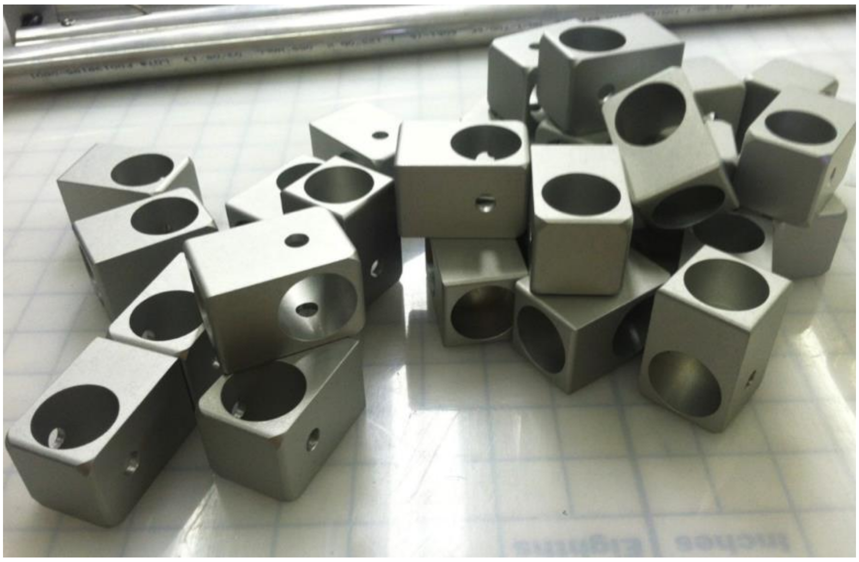

Figure 23 – Aluminium block corners for A5 Alpine Double Ledge

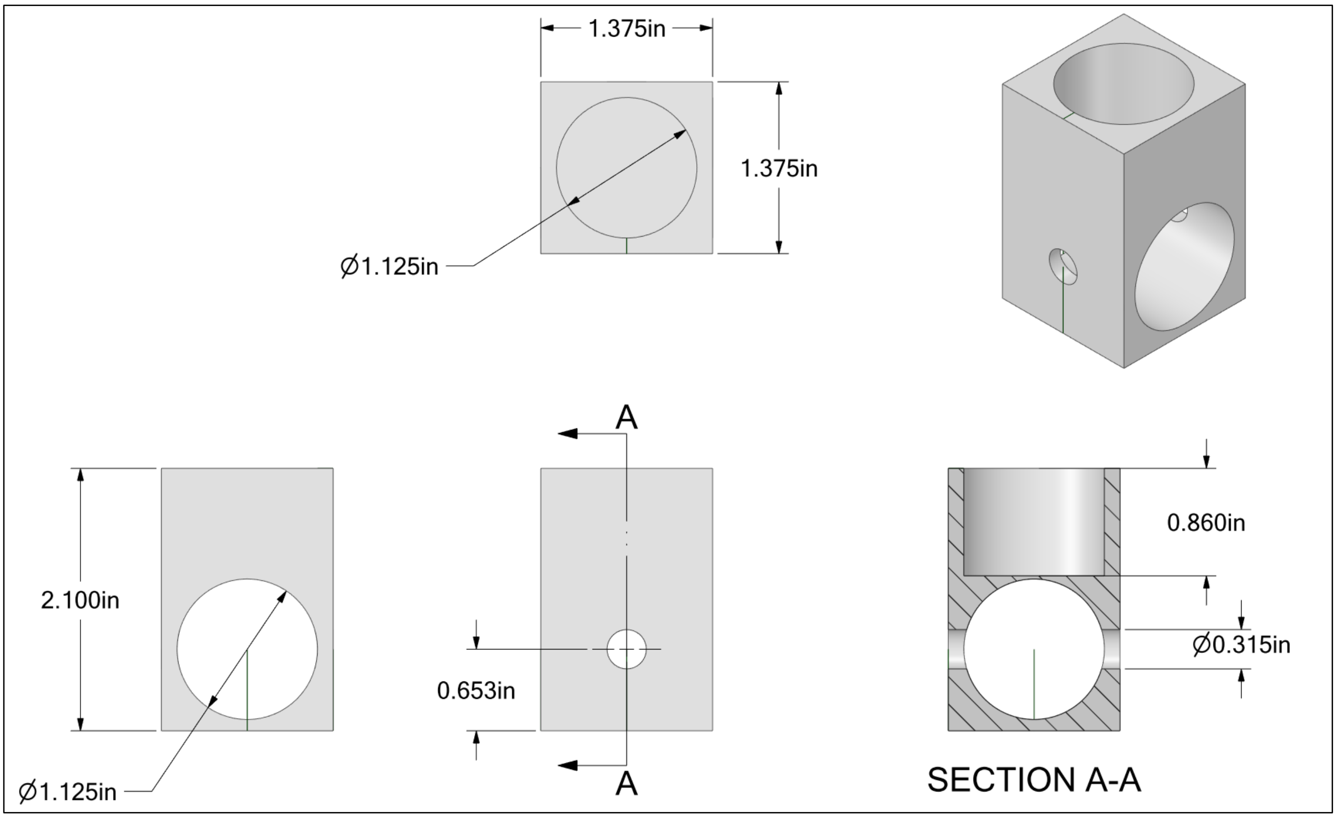

Figure 24 – Annotated Model of Block Corner from A5 Design

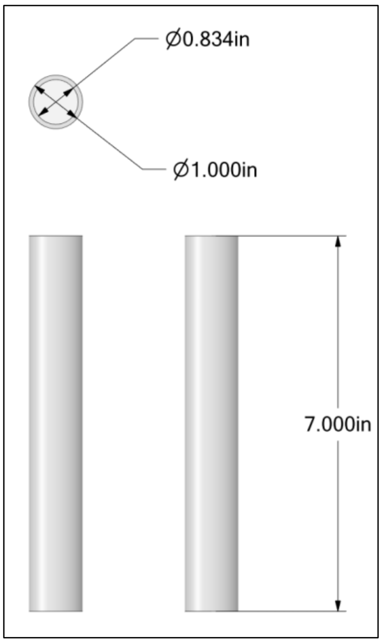

Figure 25 – Annotated Model of Pole Connector (Large) from A5 Design

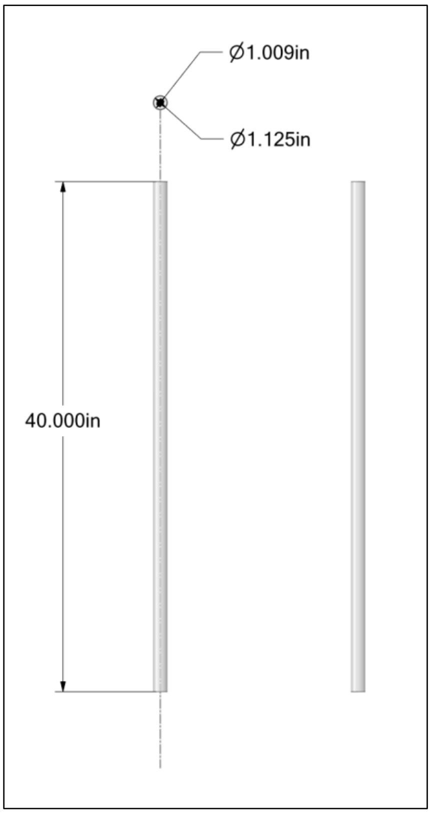

Figure 26 – Annotated Model of 40in. Pole from A5 Design

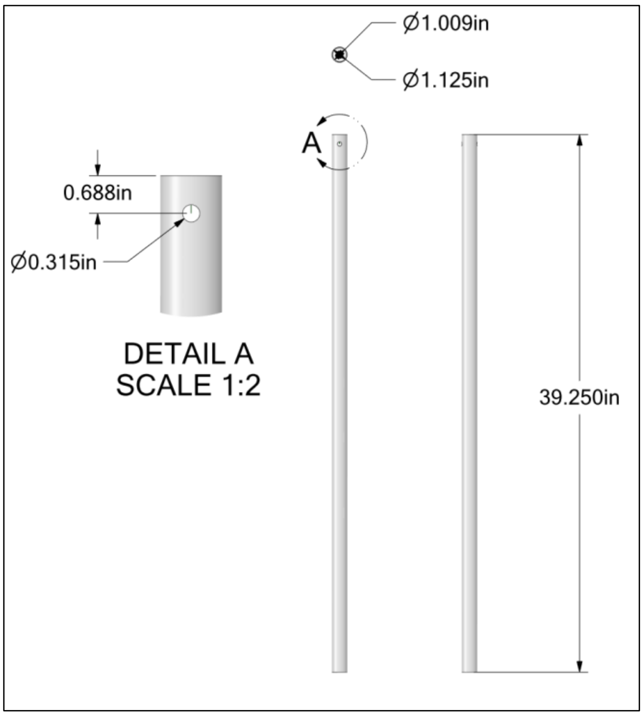

Figure 27 – Annotated Model of 39.25in. Pole from A5 Design

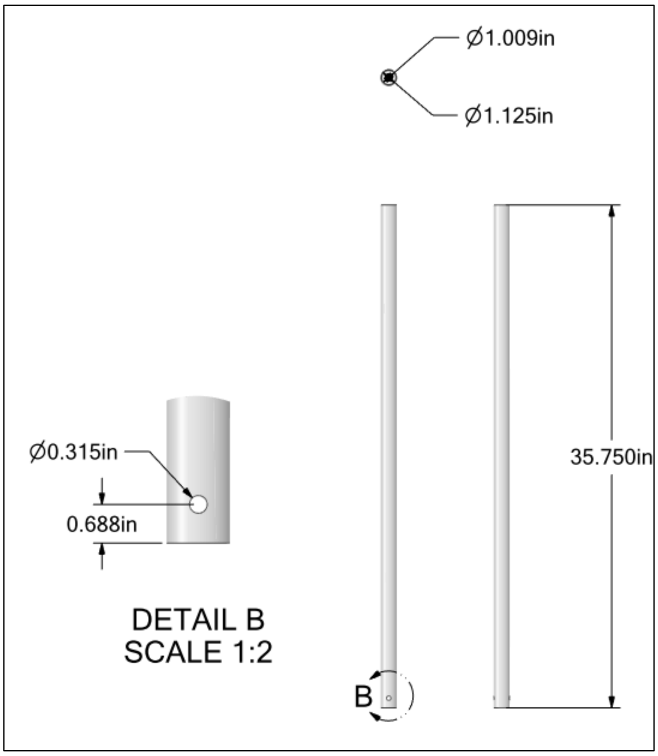

Figure 28 – Annotated Model of 35.75in. Pole from A5 Design

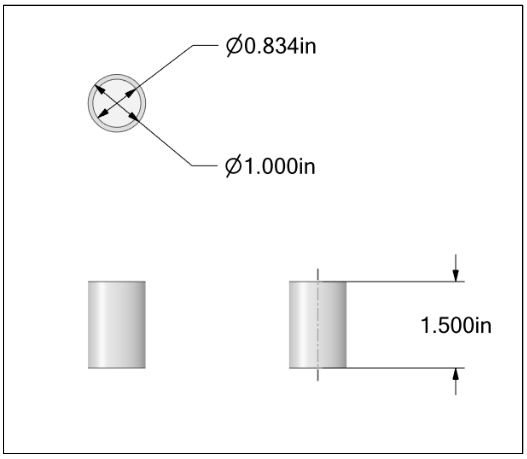

Figure 29 – Annotated Model of Pole Connector (Small) from A5 Design

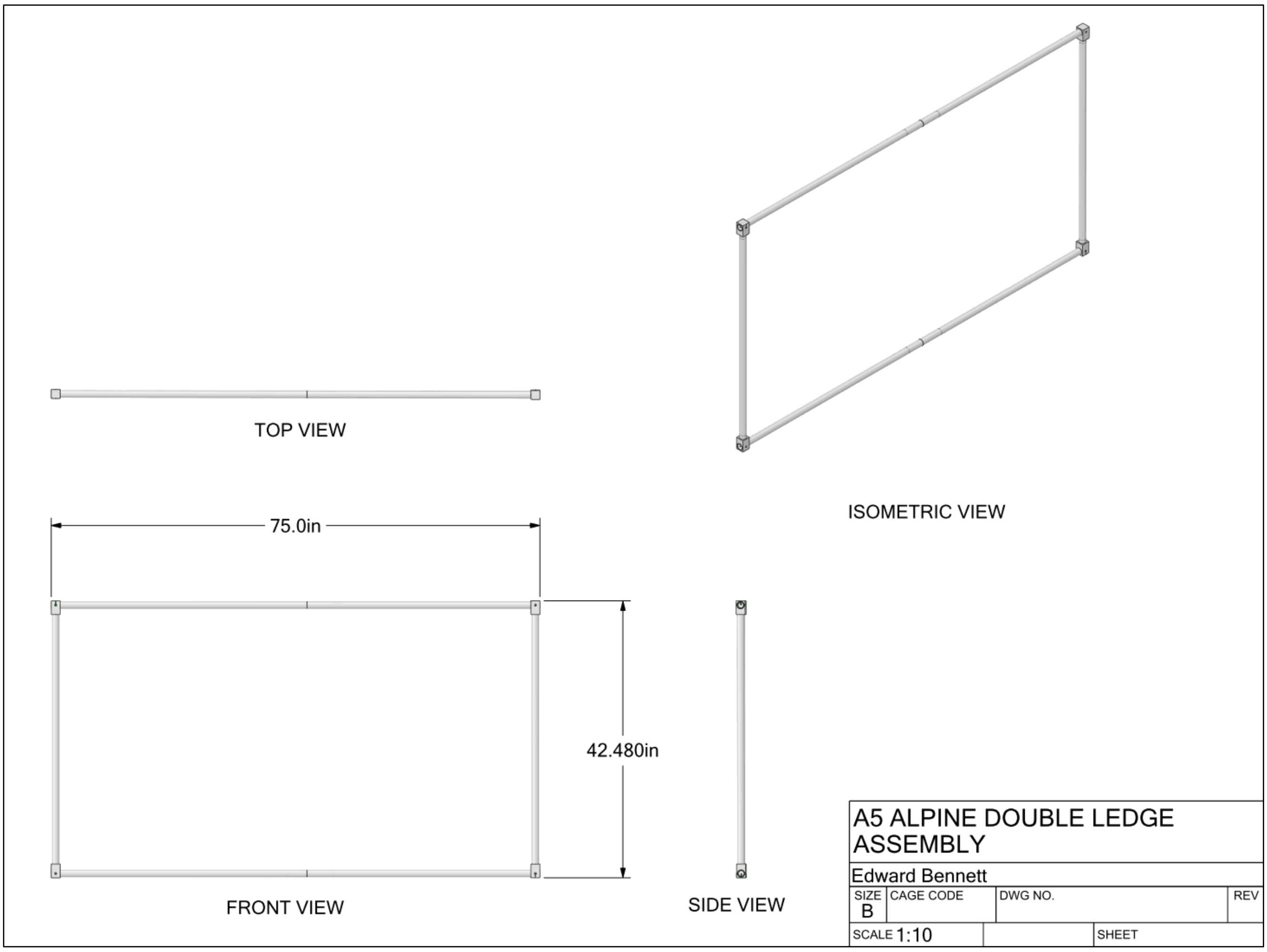

Figure 30 – Assembled A5 Frame

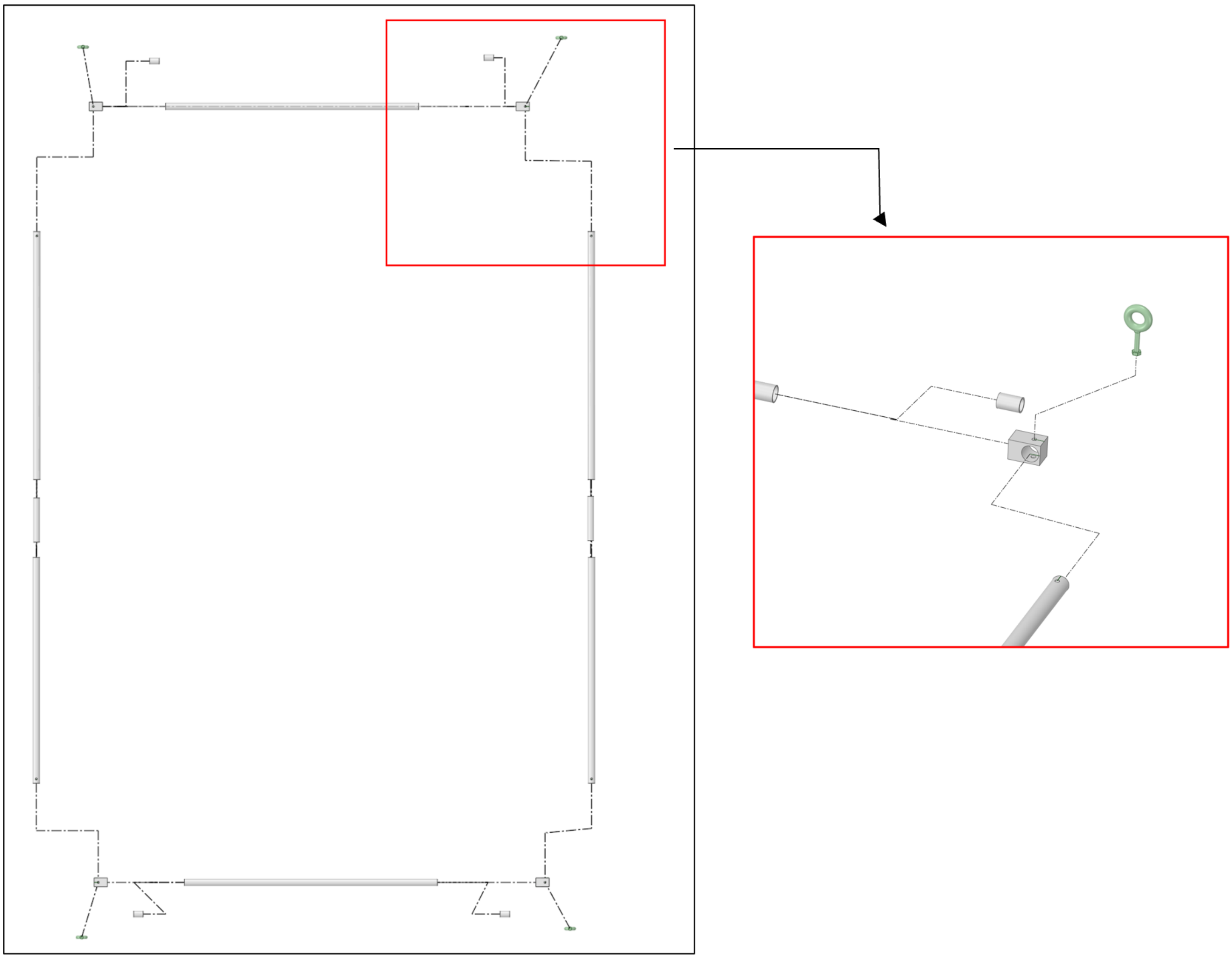

Figure 31 – A5 Exploded View

7.2 – Updated Design – D4 curved corner design

The D4 curved corner design is comprised of 4 different varieties of parts, with a total of 20 components. The parts list is:

- Part 1: 4× Straight Tube – 1.375” OD, 0.058” wall thickness (Figure 32)
- Part 2: 4× Corner Tube – 1.125” OD, 0.058” wall thickness (Figure 33)
- Part 3: 4× Inner Tube – 1.000” OD, 0.035” wall thickness (Figure 34)
- Part 4: 8× D4 Joiners (Figure 35)

Figure 15 demonstrates the method in which the four parts interlock. Exact tolerancing of the D4 Joiners uses friction to grip the pieces together. Upon construction, the frame amasses to 45.5” × 76”, with the maximum height being equivalent to the thickest pipe – 1.375” (Figure 14). When folded, the packing is 27” tall. All components are made with 2024 aluminium in reality but were set as 6061-T6 aluminium for the simulation.

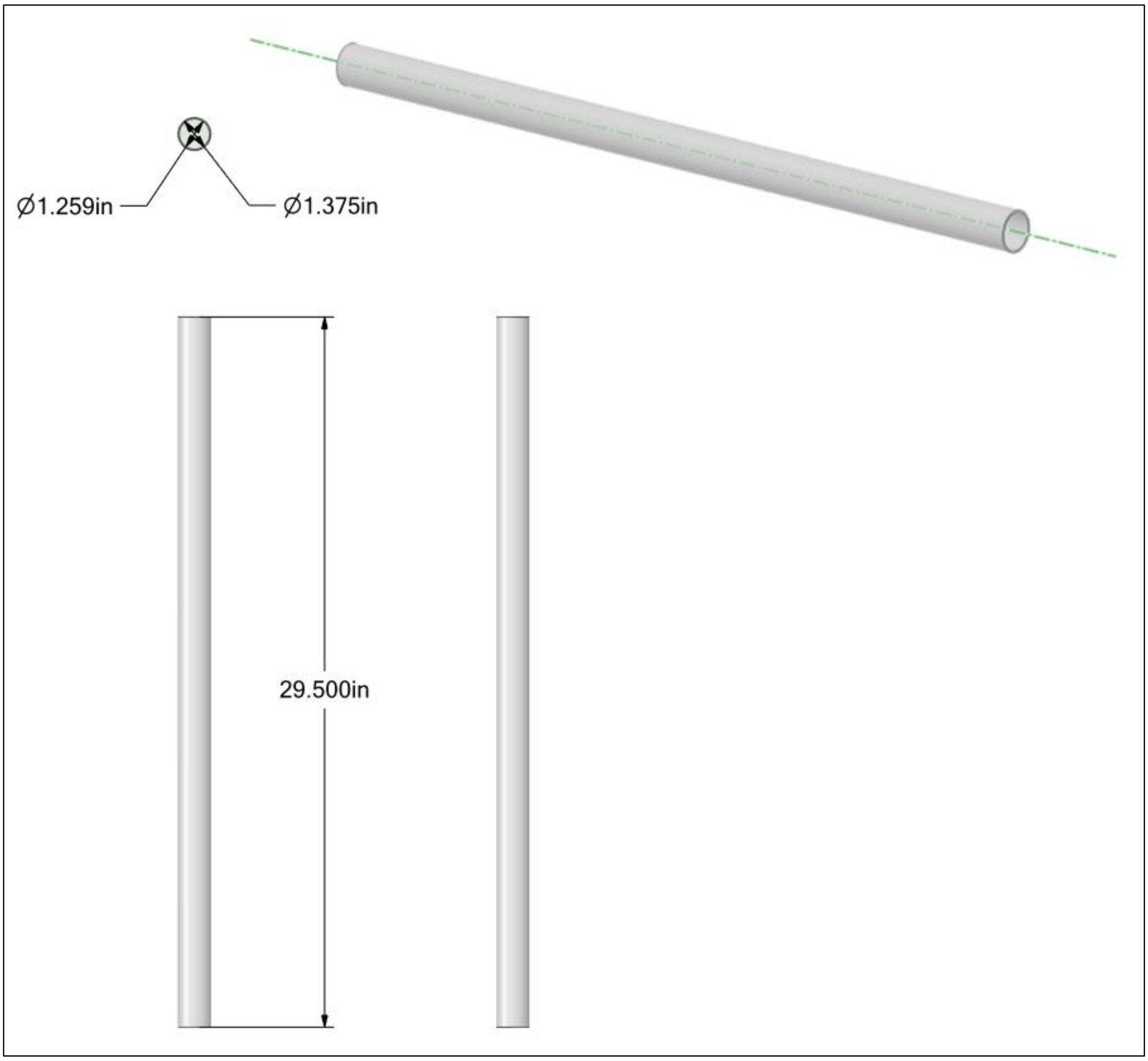

Figure 32 – Annotated Model of Straight Tube from D4 Design

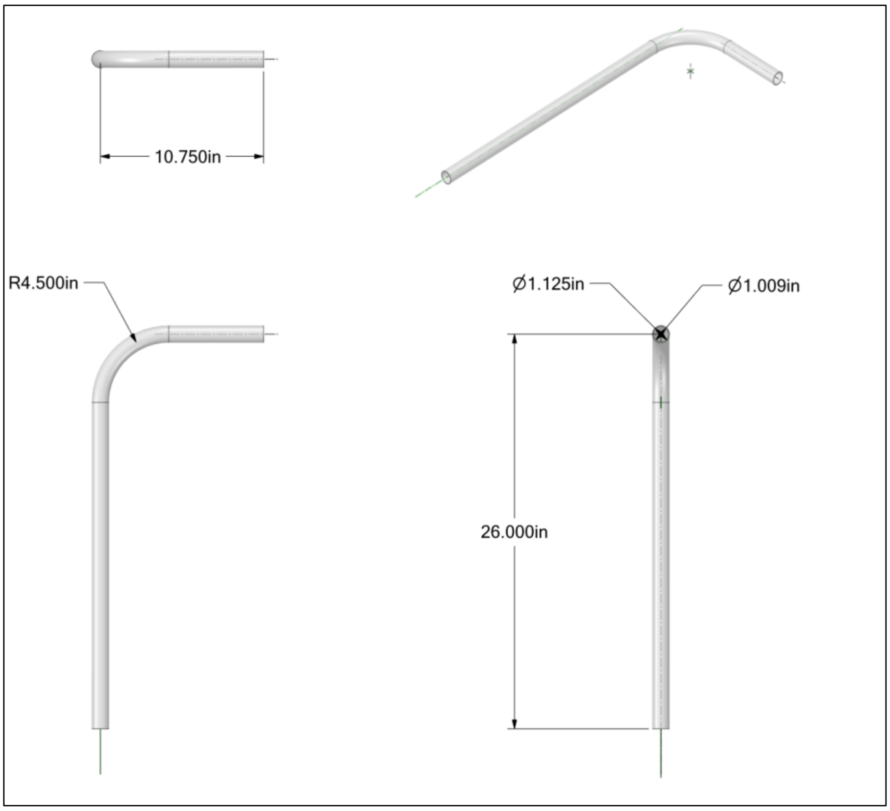

Figure 33 – Annotated Model of Corner Tube from D4 Design

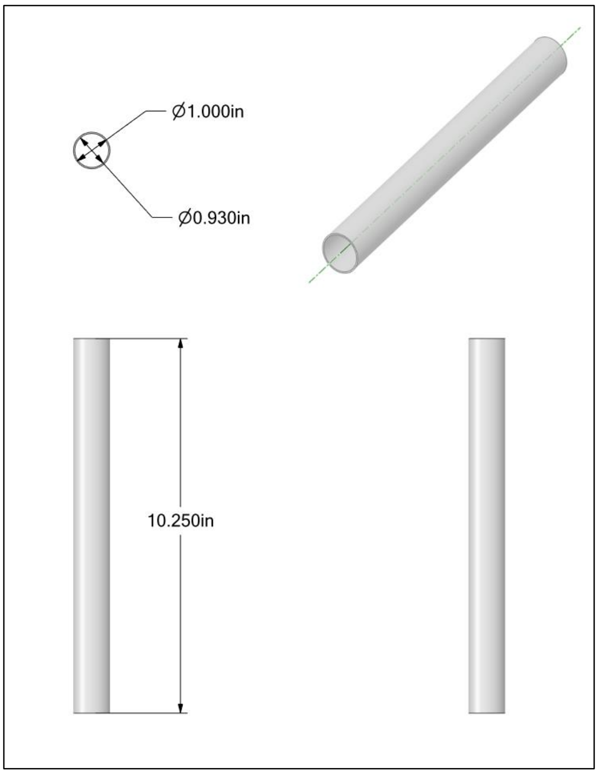

Figure 34 – Annotated Model of Interior Tube from D4 Design

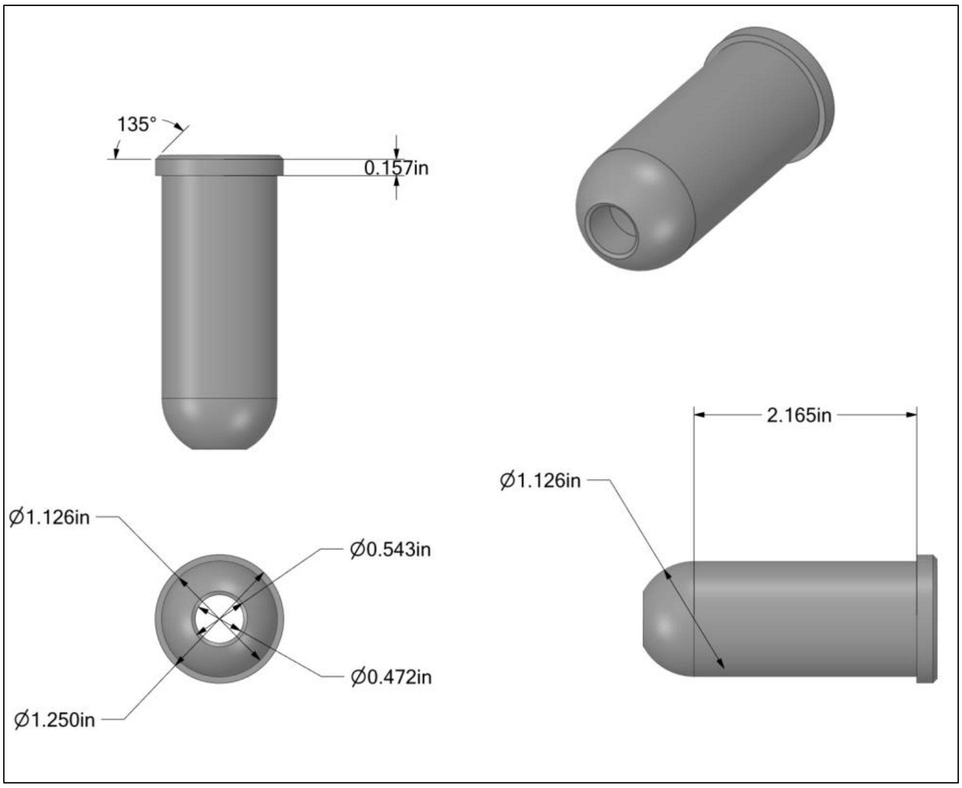

Figure 35 – Annotated Model of Joiner from D4 Design

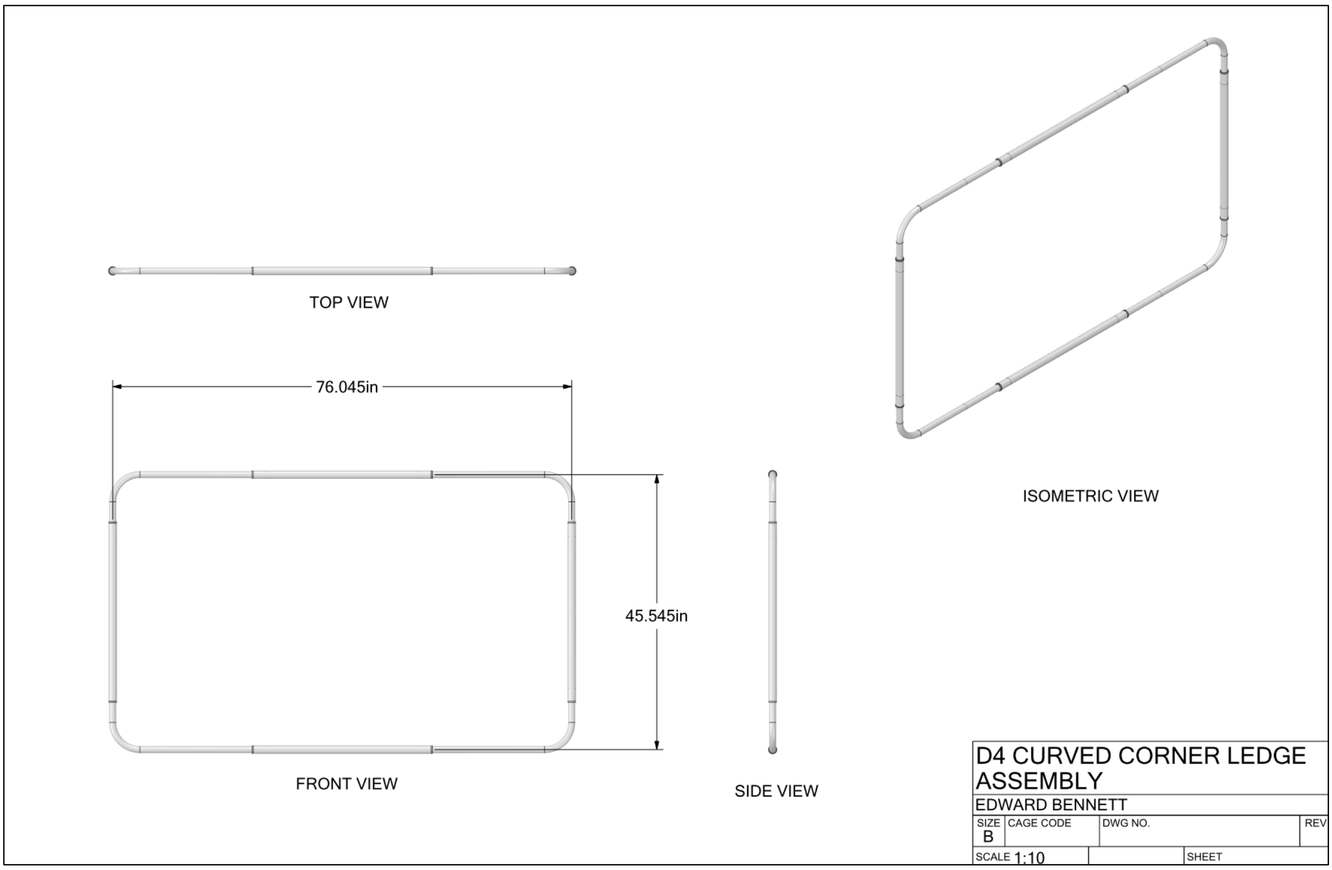

Figure 36 – Assembled D4 Frame

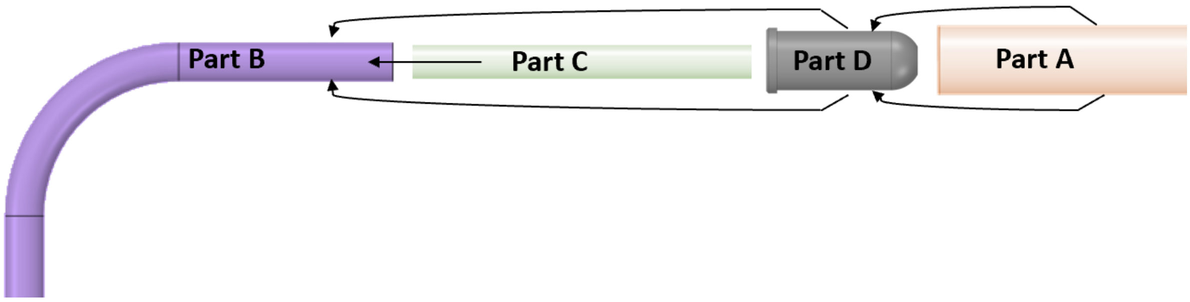

Figure 37 – Corner Assembly Example

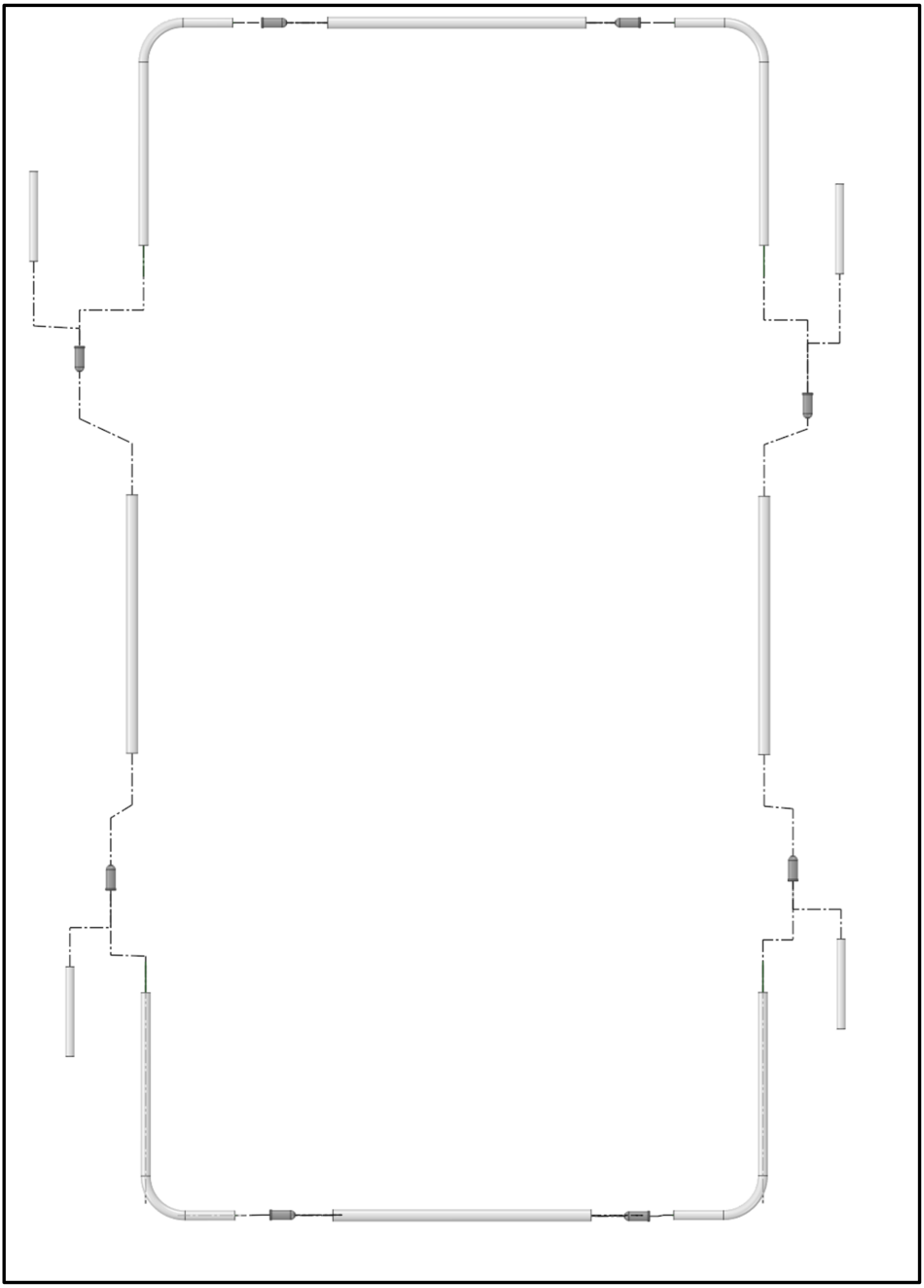

Figure 38 – D4 Exploded View

8 – Results

8.1 – 3D Modelling and Finite Element Analysis

8.1.1 – Mass

A5 Model (Aluminium 6061-T6)				
Item Number	Part Name	Quantity	Individual Mass (g)	Combined Mass (g)
1	Block Corner	4	100.02	400.08
2	Long Connector Pole	2	74.06	148.12
3	40in. Pole	2	344.01	688.02
4	39.25in. Pole	2	337.63	675.26
5	35.75in. Pole	2	307.53	615.06
6	Short Connector Pole	4	15.87	63.48
7	Eye Bolt Support	4	61	244
Total		20		2834.02

Table 1 – A5 Parts List with component masses and total mass of assembly, when constructed with Aluminium 6061-T6. The total mass of this model is 2834.02g, as calculated with SpaceClaim's material property library and based off 3D model of design.

D4 Model (Aluminium 6061-T6)				
Item Number	Part Name	Quantity	Individual Mass (g)	Combined Mass (g)
1	Straight Tube	4	313.22	1252.88
2	Corner Tube	4	289.84	1159.36
3	Inner Tube	4	48.57	194.28
4	D4 Joiners	8	34.36	274.88
Total		20		2881.4

Table 2 – D4 Parts List with component masses and total mass of assembly, when constructed with Aluminium 6061-T6. The total mass of this model is 2881.40g.

D4 Model (Aluminium 2024)				
Item Number	Part Name	Quantity	Individual Mass (g)	Combined Mass (g)
1	Straight Tube	4	322.5	1290
2	Corner Tube	4	298.43	1193.72
3	Inner Tube	4	49.55	198.2
4	D4 Joiners	8	35.38	283.04
Total		20		2964.96

Table 2 – D4 Parts List with component masses and total mass of assembly, when constructed with Aluminium 2024. The total mass of this model is 2964.96g.

8.1.2 – Deformation

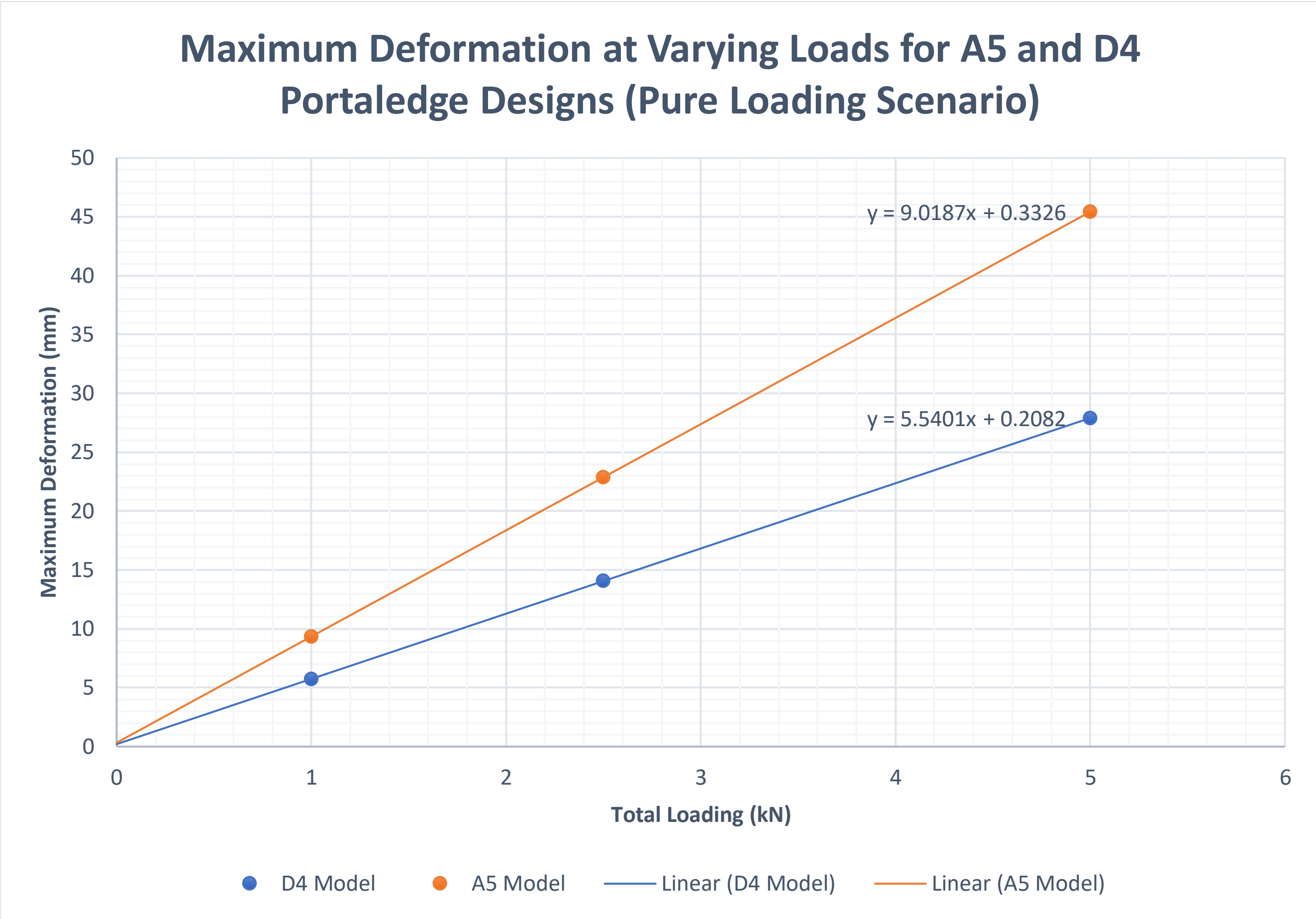

Figure 39 – Graph outlining the maximum magnitude of deformation in the A5 and D4 designs, at given loads, when simulated in the 'Pure Loading' (hanging) scenario.

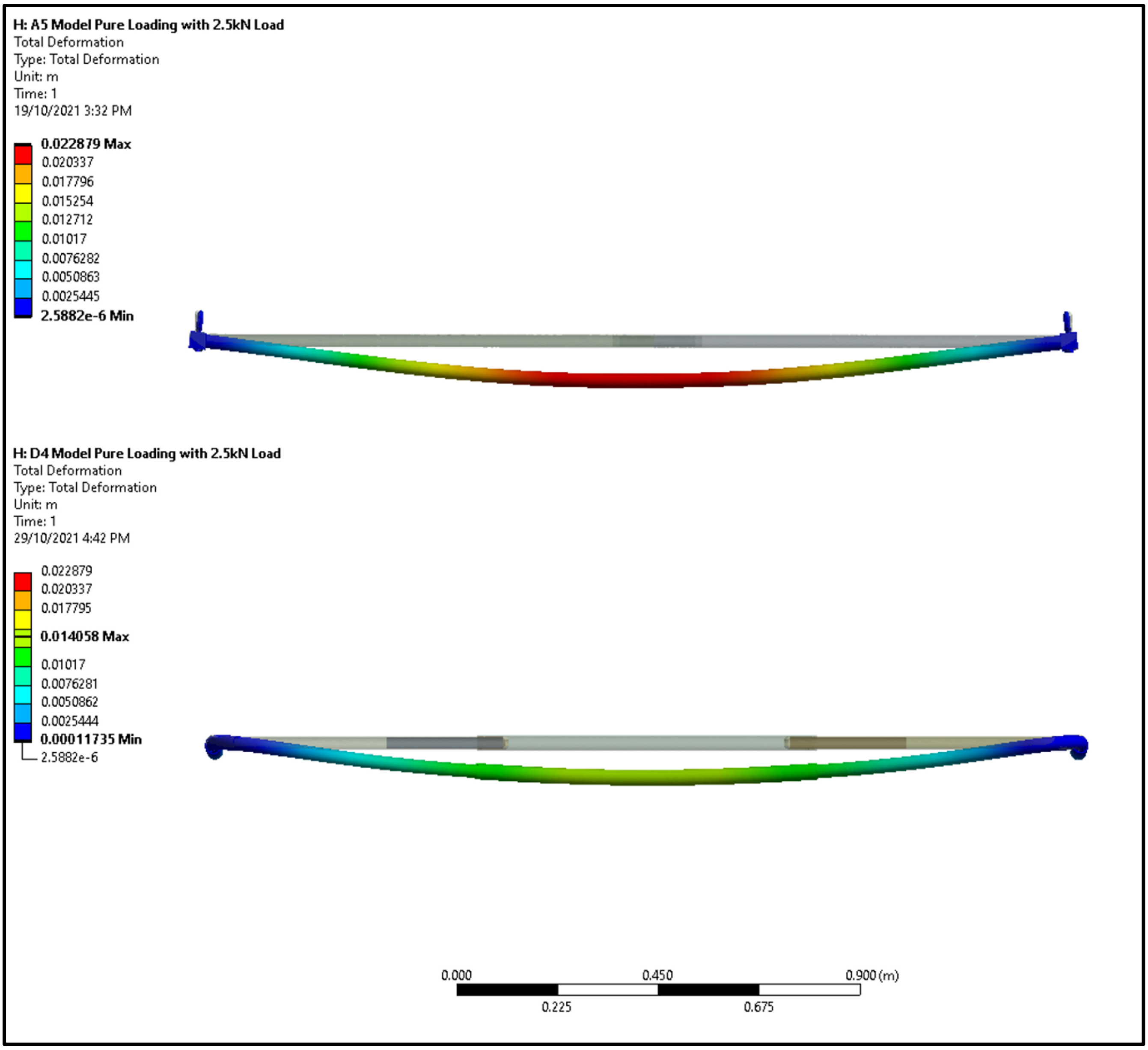

Figure 40 – Front view for deformation of A5 and D4 respectively Portaledge under Pure Loading Scenario (6.3x scale exaggeration).

Figure 41 – Side view for deformation of A5 and D4 Portaledge respectively under Pure Loading Scenario (6.3x scale exaggeration).

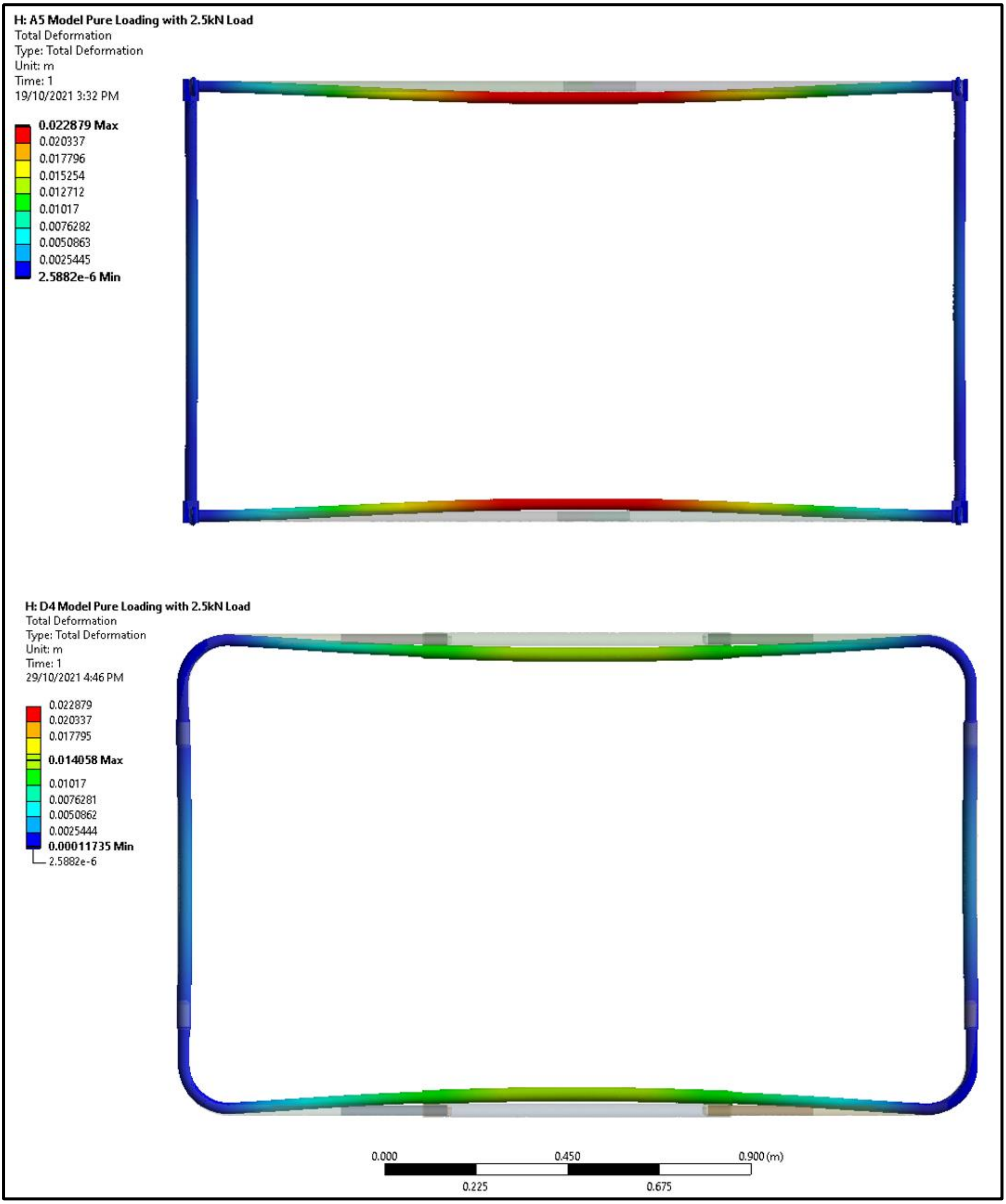

Figure 42 – Top view for deformation of A5 and D4 Portaledge respectively under Pure Loading Scenario (6.3x scale exaggeration).

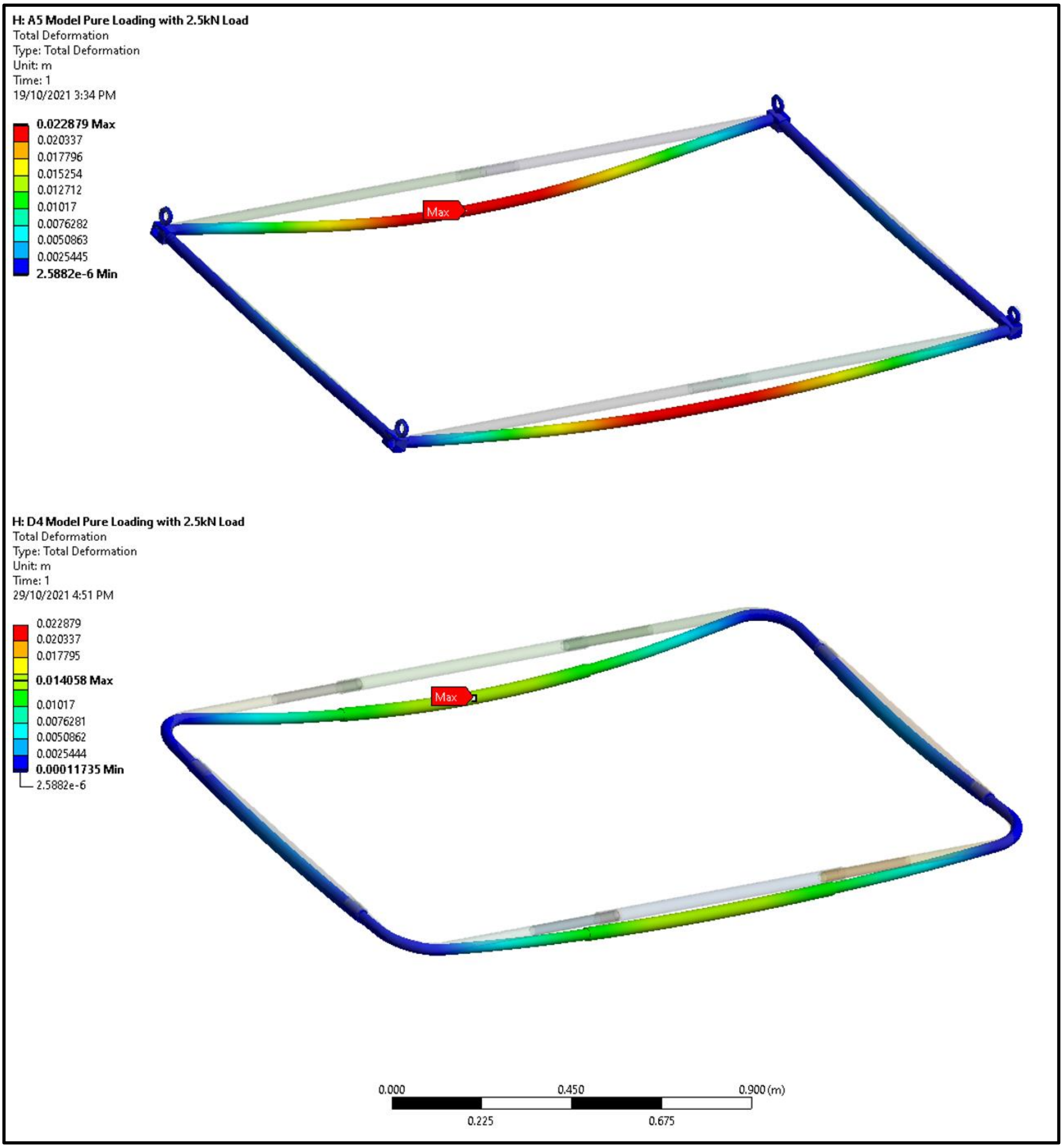

Figure 43 – Isometric view for deformation of A5 and D4 Portaledge respectively under Pure Loading Scenario (6.3x scale exaggeration).

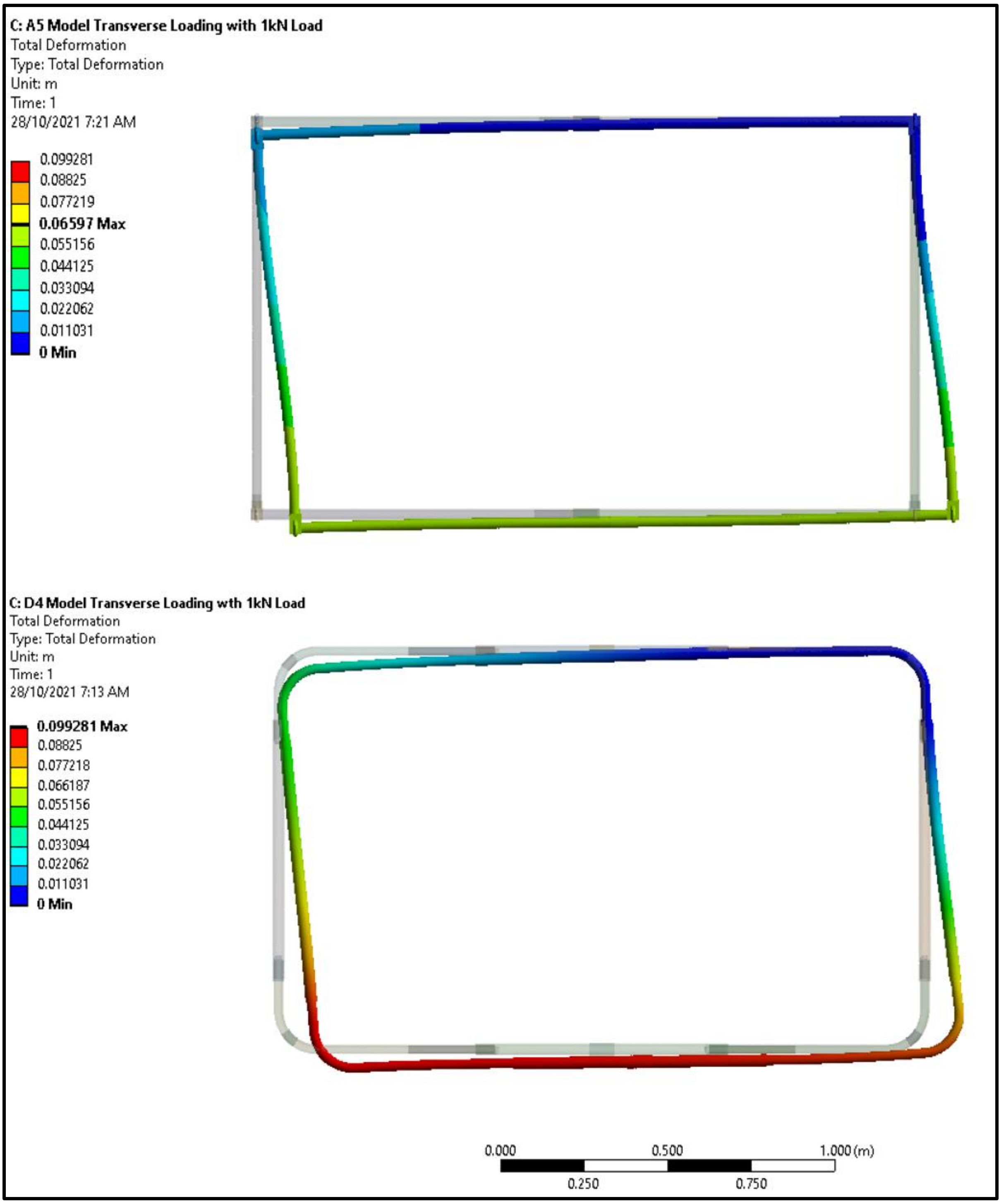

Figure 44 – Top view for deformation of A5 and D4 Portaledge respectively under Transverse Loading Scenario .

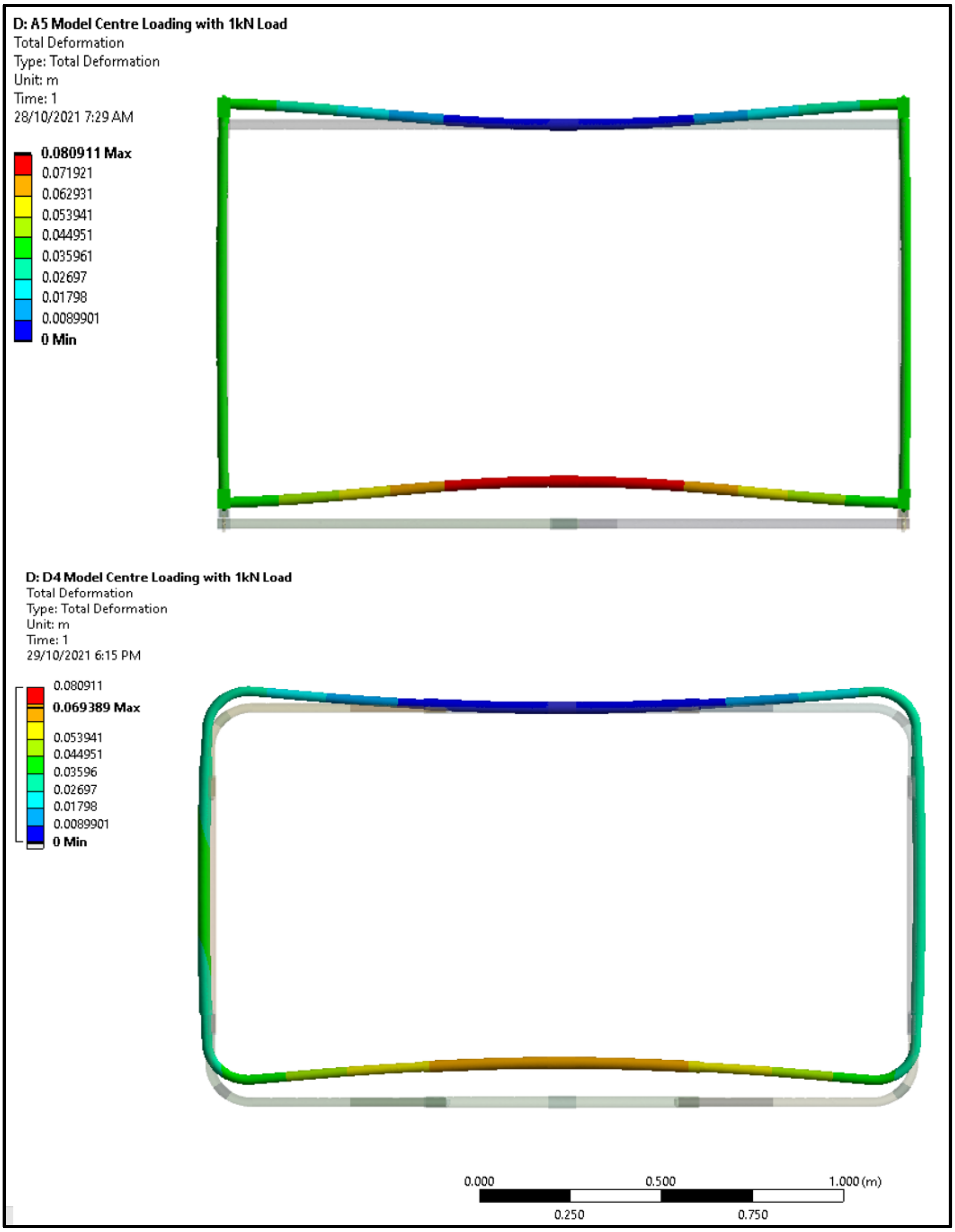

Figure 45 – Side view for deformation of A5 and D4 Portaledge respectively under Centre Loading Scenario.

8.1.3 – Equivalent Stress

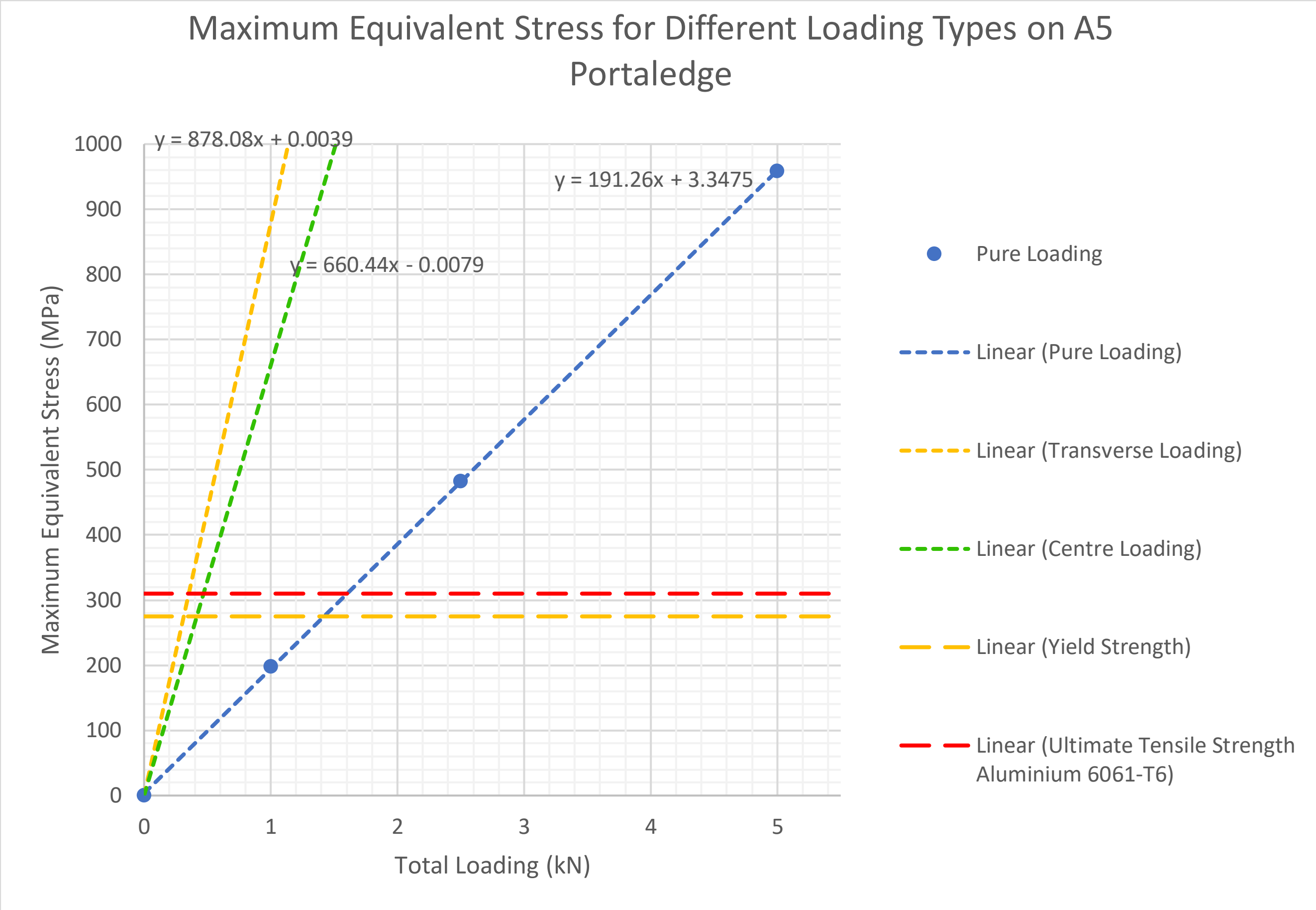

Figure 46 – Summary of maximum equivalent stress in the A5 Portaledge at different loads, and how they compare to the yield strength and ultimate tensile strength of Aluminium 6061-T6. Simulations of three loading scenarios are included.

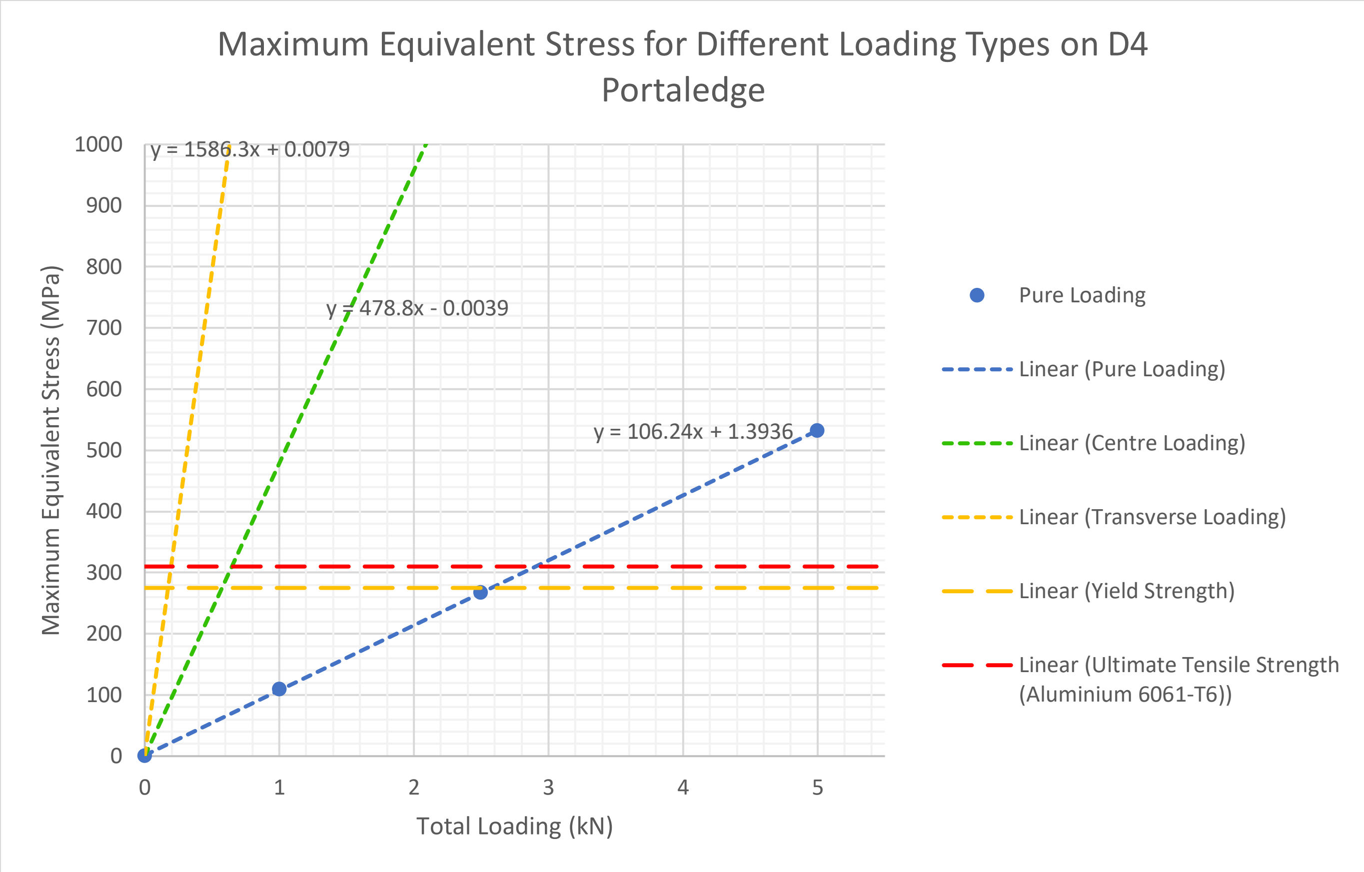

Figure 47 – Summary of maximum equivalent stress in the D4 Portaledge at different loads, and how they compare to the yield strength and ultimate tensile strength of Aluminium 6061-T6. Simulations of three loading scenarios are included.

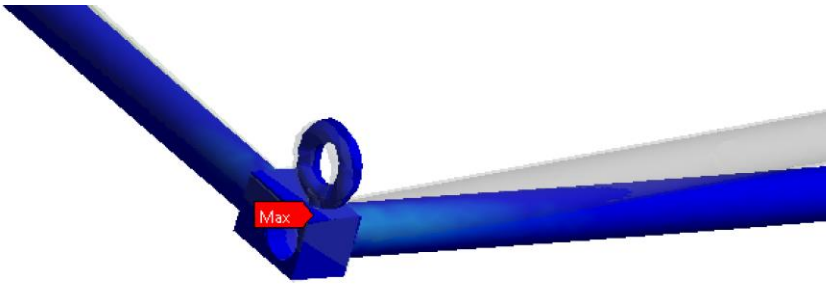

*Figure 48 – Maximum Stress Location in **A5 Pure Loading** Scenario, located on the end of the 40" Pole, where it connects with the block corner.*

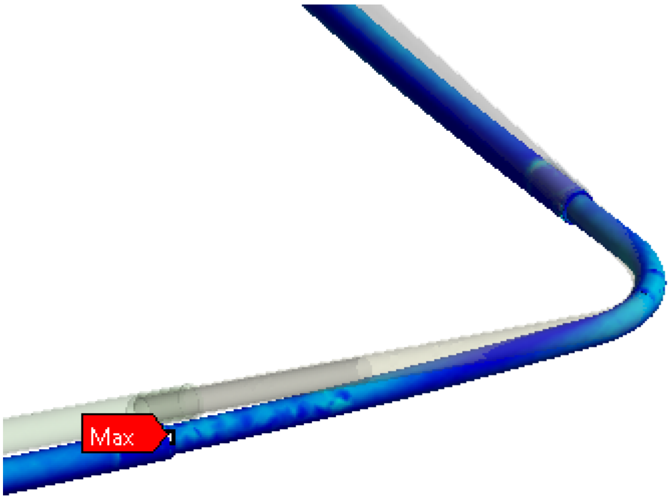

*Figure 49 – Maximum Stress Location in **D4 Pure Loading** Scenario, located on the end of the Straight Pole, where it overlaps the joiner component.*

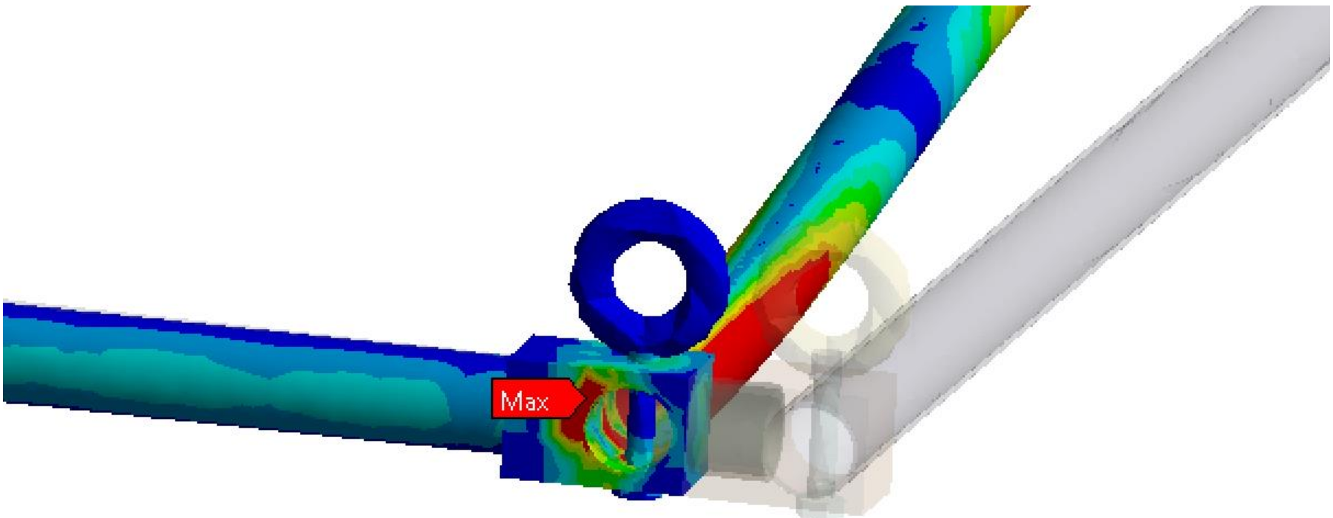

*Figure 50 – Maximum Stress Location in **A5 Centre Loading** Scenario, located on the 1.5" connector pole, within the block corner.*

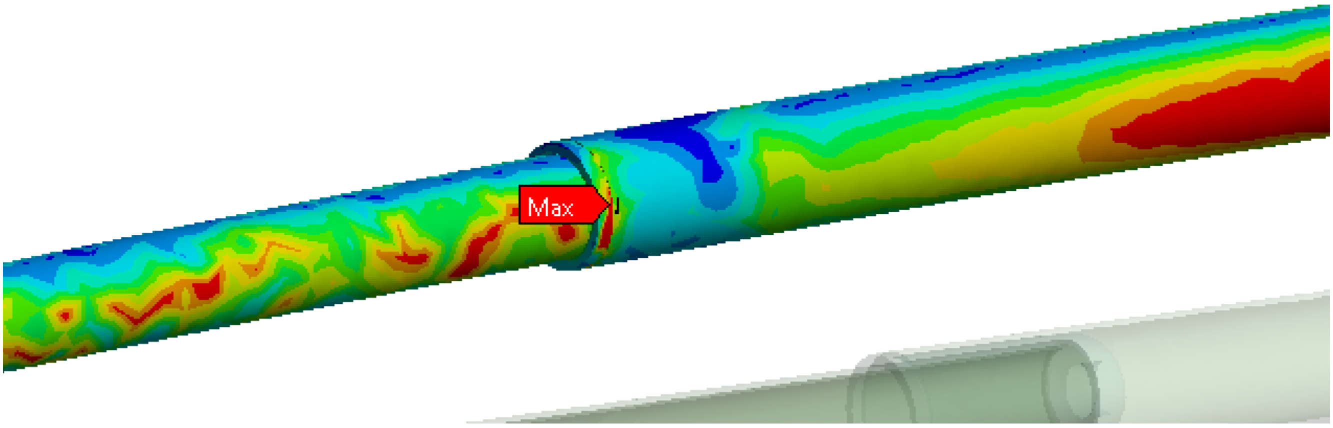

Figure 51 – Maximum Stress Location in ***D4 Centre Loading*** *Scenario, located on the end of the Straight Pole, where it overlaps the joiner component.*

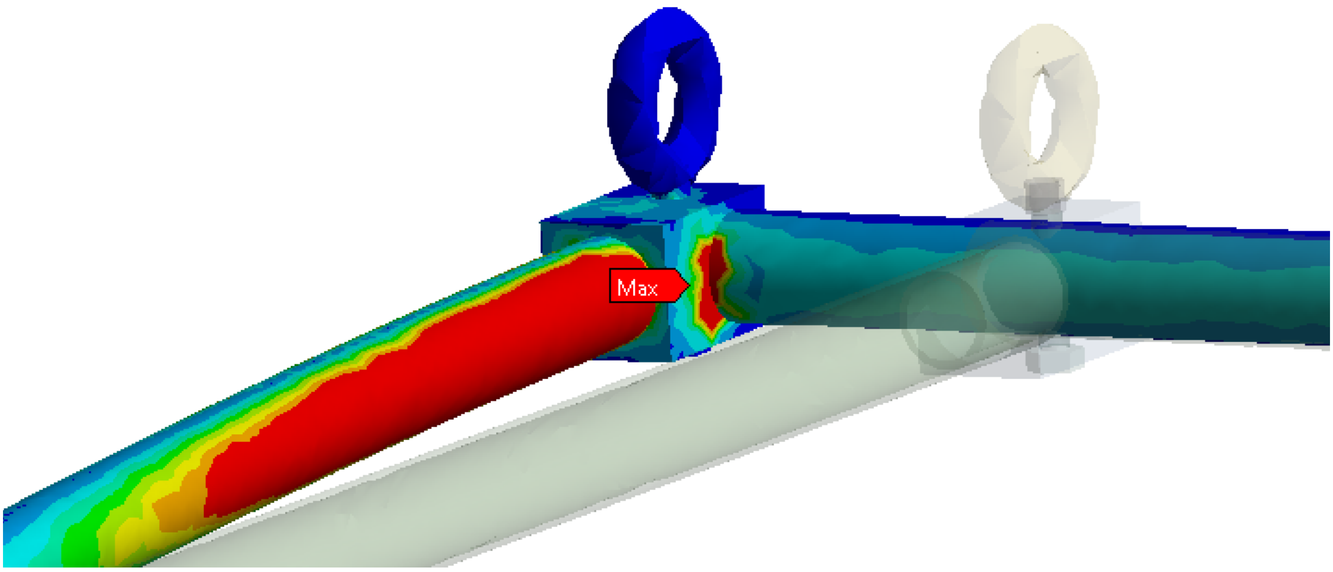

Figure 52 – Maximum Stress Location in ***A5 Transverse Loading*** *Scenario, located on the Block Corner. Additional severe stress concentration points are located where the two poles enter the block corner.*

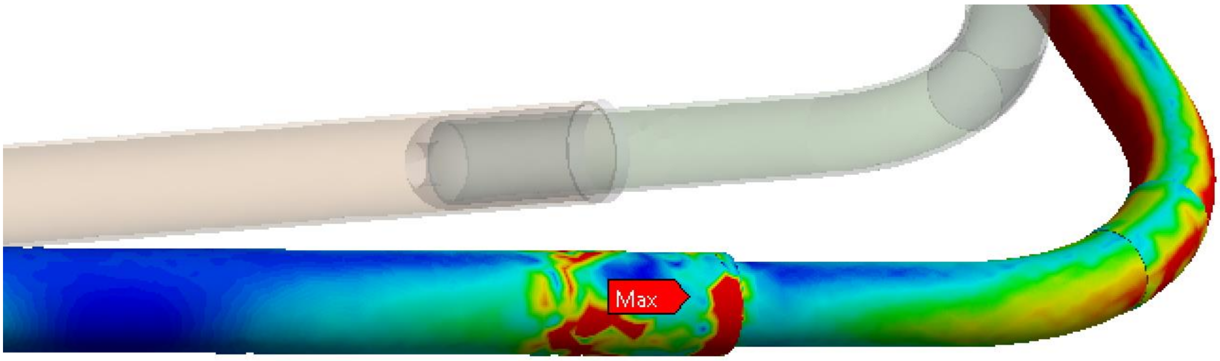

*Figure 53 – Maximum Stress Location in **D4 Transverse Loading** Scenario, located on the end of the Straight Pole, where it overlaps the joiner component. Additional point of high stress occurred on the inside of the corner piece.*

8.1.4 – Fatigue

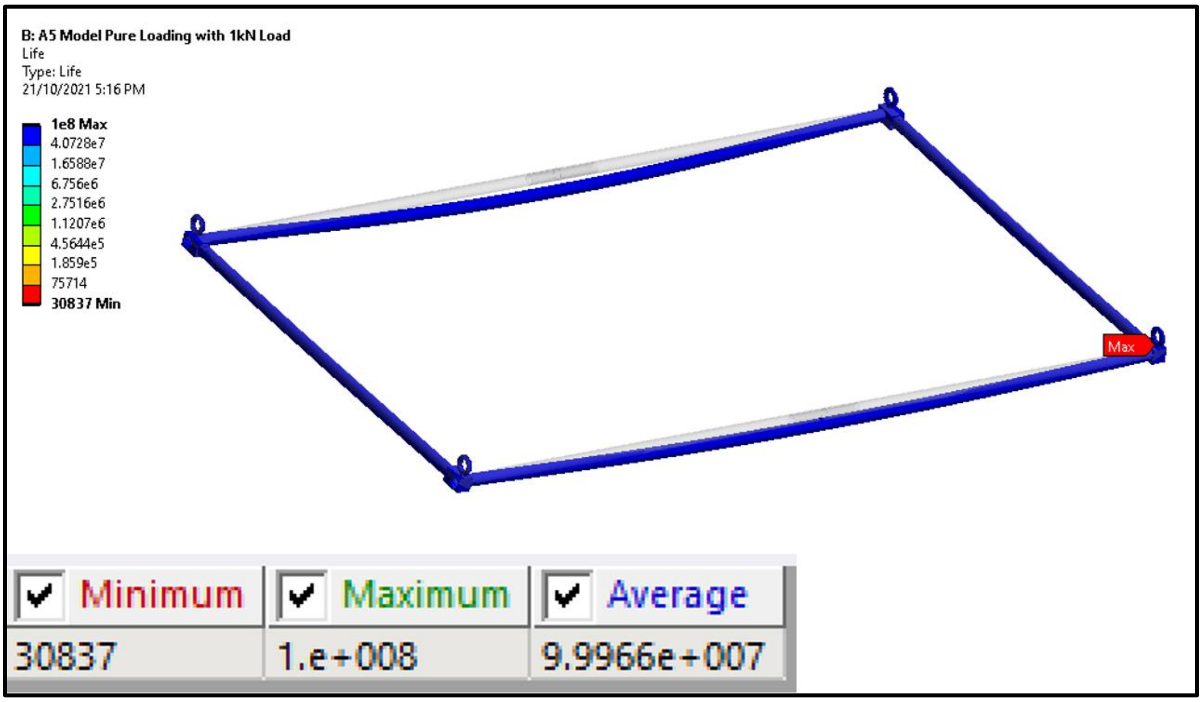

Figure 54 – Expected fatigue life of A5 Portaledge, calculated to be 30837 uses at the point of highest stress with ANSYS' fatigue tool. Result is based off maximum stress at 1kN for Pure Loading scenario.

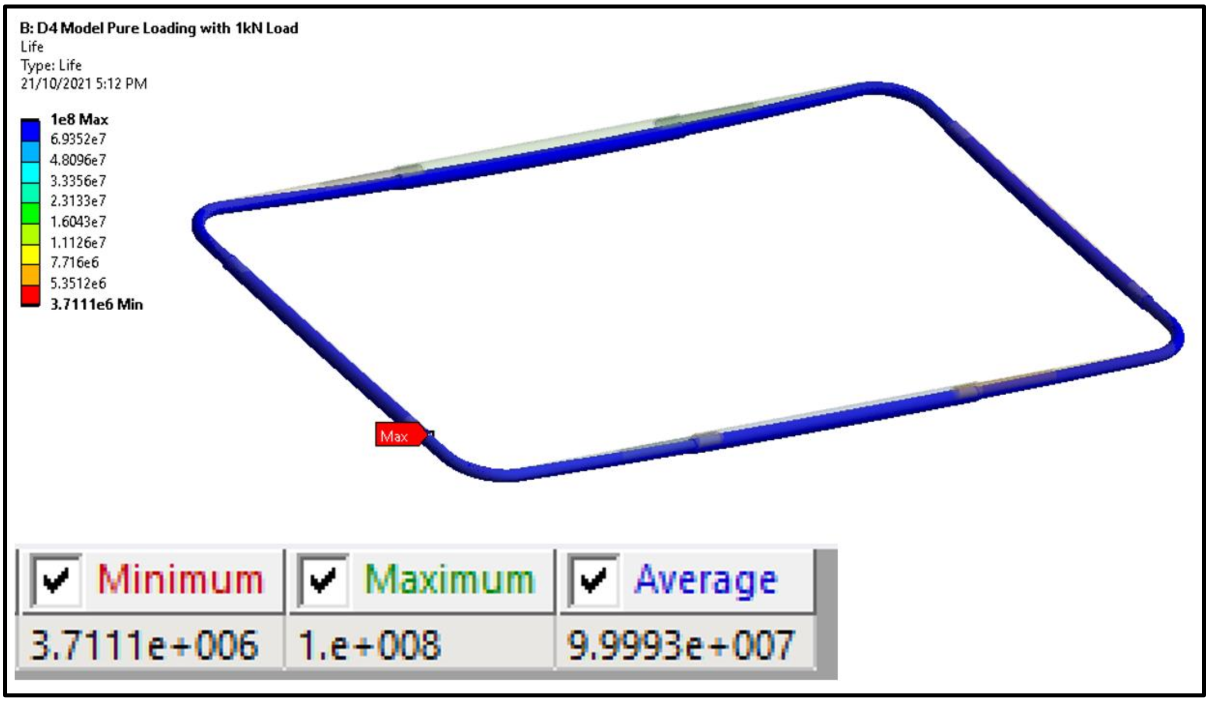

Figure 55 – Expected fatigue life of D4 Portaledge, calculated to be 3.7111 × 10^6 uses at the point of highest stress with ANSYS' fatigue tool. Result is based off maximum stress at 1kN for Pure Loading scenario.

8.2 – Physical Compression Testing of Corner Pieces

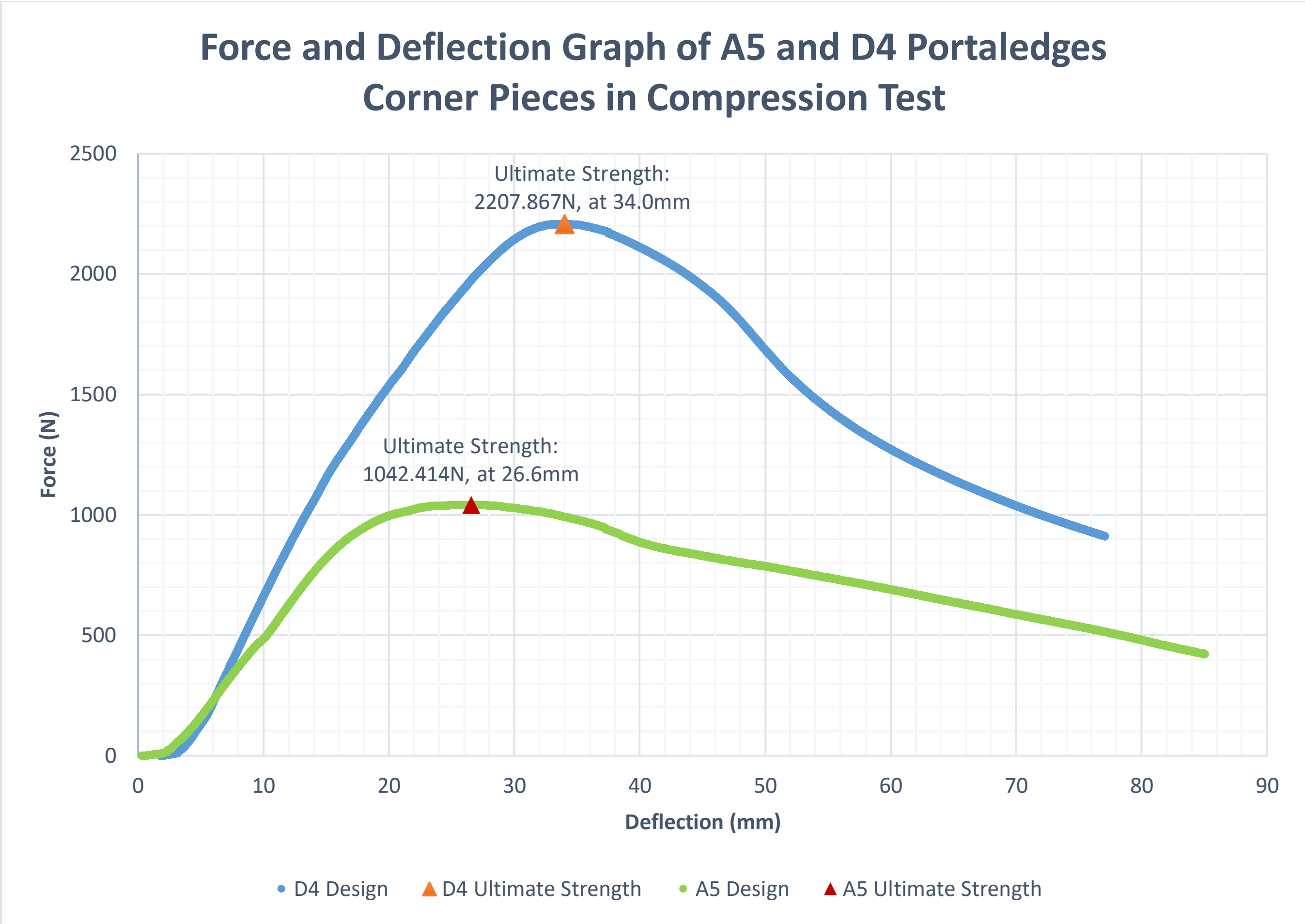

Figure 56 – Resultant graph from compression test on A5 and D4 Portaledge corner pieces, denoting the deflection steps and corresponding force at each step, as well as the points of maximum load.

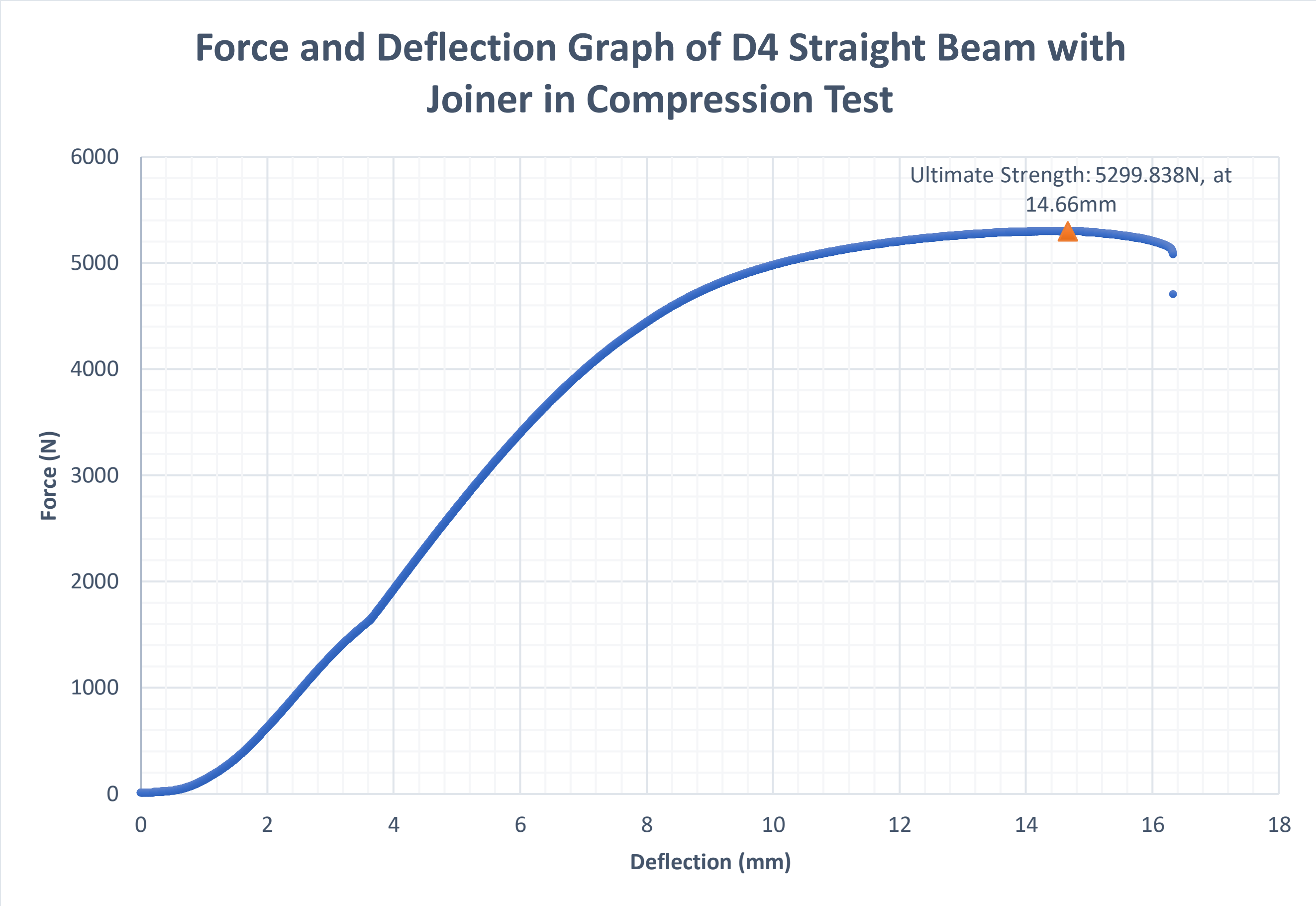

Figure 57 – Resultant graph from compression test on D4 Portaledge straight beam with joiner, denoting the deflection steps and corresponding force at each step, as well as the point of maximum load.

9 – Discussion

9.1 – 3D Modelling and Finite Element Analysis

9.1.1 – Mass

The mass of each Portaledge is an important practical property. Climbers must transport the ledge up the cliff as they climb, so the heavier a ledge is, the more energy it will require to transport. However, reinforcing critical points with more mass can often be used to strengthen a component's weight bearing capacity. Therefore, it is critical to find a balance between the strength and weight of the Portaledges – the strength to weight ratio. Effective stress distribution is key for maximising the strength to weight ratio of a design.

The D4 Model is normally produced with Aluminium 2024, which has a greater density than Aluminium 6061. However, for the purpose of fair testing, all simulations and tests were conducted on a D4 model made with Aluminium 6061. The D4 Model was calculated to weigh 2964.96g when comprised of Aluminium 2024 (Table 3), while it was 83.56g lighter when comprised of Aluminium 6061, weighing 2881.4g in total (Table 2). The A5 design, which is constructed with Aluminium 6061, was calculated to weigh 2834.02g (Table 1), which is 47.38g lighter than the D4 model of the same material. This difference is almost negligible but could be attributed to the D4 being 1" longer and 3" wider than the A5.

9.1.2 – Deformation

To maximise comfort and safety, minimal deformation is desired within the Portaledge designs. The 'pure loading' simulations were designed to replicate how the Portaledges would operate in standard, everyday use. Generally, a double Portaledge will bear 100-160kg in use, when considering one or two users plus their belongings. The Pure Loading simulation was run with a total load of 1kN, 2.5kN and 5kN. This was to investigate standard, everyday loadings, as well as heavily loaded and overloaded circumstances. Figure 39 shows that as the applied load increases, the magnitude of deformation in both Portaledge designs also increases. As seen in *equation 3*, the magnitude of deflection (δ) is directly proportional to the load (w). In figure 39, this is evident in the linear relationship between the two variables. With this clear relationship, a valuable equation for each design was formulated, allowing a user to calculate the maximum magnitude of deflection anticipated at any loading:

A5 Deformation-Loading relationship:

$$\text{Maximum Deformation (mm)} = 9.0187 \times \text{Total Loading (kN)} + 0.3326$$

D4 Deformation-Loading relationship:

$$\text{Maximum Deformation (mm)} = 5.5402 \times \text{Total Loading (kN)} + 0.2082$$

Evidently, the maximum magnitude of deformation in the D4 Portaledge is roughly 60% of that in the A5 with the same load, making the D4 design a more rigid body in a hanging scenario. However, the relationship between the two ledges is not a perfect ratio, due to the slight difference in the mass of each frame.

9.1.3 – Equivalent Stress

The finite element analysis of the Portaledges identified the location and magnitude of the maximum equivalent stress within each model, for each loading scenario. This allows the location of failure within the components to be identified. By cross refencing the results with the yield strength (275MPa) and ultimate tensile strength (310MPa) of the aluminium 6061-T6, the maximum load can also be identified. Figure 46 and 47 demonstrates the performance of the A5 and D4 design, respectively, in each loading scenario. As stress is directly proportional to force, maximum equivalent stress and total loading can be considered to have a linear relationship. The gradient describes each loading scenario's susceptibility to applied loads.

The pure loading scenario is notably the most effective at withstanding loads for both models. In the A5 design, the most vulnerable component of the ledge will likely begin to yield at a 1.42kN load, or when there is a 144.78kg weight on the Portaledge. As seen in figure 48, the location of this maximum stress is in the 40" Pole, where it is fixed by the eyebolt to the block corner. In the D4 design, it is predicted that yielding will begin to occur at a 2.57kN load, or with a weight of 262.52kg. This will likely occur in the straight pole, where it overlaps with the joiner component (see figure 49). For pure loading scenarios, the D4 design can withstand 180% of the load of the A5 design before beginning to yield, making it the more effective Portaledge design for general use. Considering the weight of each design, the A5 design had a strength to weight ratio of 0.501N/g, while the D4 design had one of 0.892N/g. Thus, despite only being 47.38g heavier, the D4 design effectively used variable tube diameters as reinforcement at high stress locations and curved corners to avoid stress concentrations to provide a far superior strength to weight ratio than the A5 counterpart.

In the centre loading scenario, the maximum load applied does not directly equate to the maximum load of the ledge. This simulation is designed to replicate the Portaledge's abilities when assembled against a small edge, such as a tree. The load applied in the simulation is the opposing moment to a downwards force on the ledges (see figure 58).

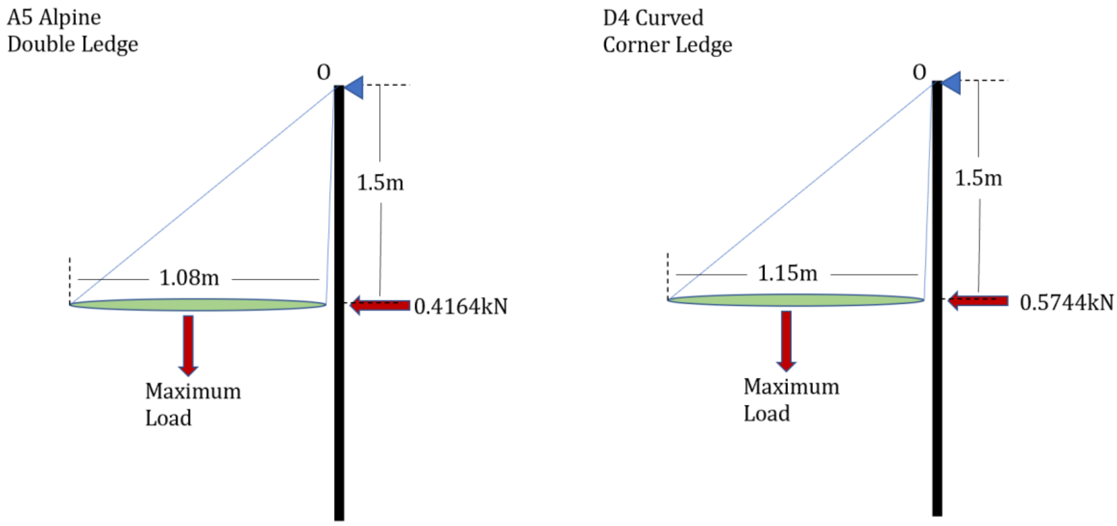

Figure 58 – Free body diagrams for A5 and D4 designs under centre loading scenario. Assume that the Portaledges are assembled against a tree, where only the centre is in contact. The applied loads

are equivalent to the load where it is expected that yielding will occur, calculated from figures 46 and 47.

Using this free body diagram, the expected maximum loads can be calculated:

A5:

$$\Sigma M_O = 0$$

$$1.5 \times 0.4164 = 0.54x$$

$$x = 1.156kN$$

D4:

$$\Sigma M_O = 0$$

$$1.5 \times 0.5744 = 0.575x$$

$$x = 1.498kN$$

The A5 design withstood 0.4164kN before reaching its yield point, while the D4 design withstood 0.5744kN. This converts to a maximum downwards force of 1.156kN on the A5 Portaledge and 1.498kN on the D4 Portaledge. The D4 design can withstand 129.6% of the force that the A5 can withstand before reaching its elastic limit. The A5 ledge's point of maximum stress occurs at the end of the 1.5" connector pole within the block corner (figure 50), while in the D4 model it will occur at the end of the straight pole, where it overlaps the joiner (figure 51).

The transverse loading scenario was the most susceptible to applied forces, with the steepest gradient in figures 46 and 47. However, it is also the least likely scenario to be exposed to large forces. This testing was conducted due a known failure mode in the A5 Portaledge, where it may lose its integrity when a force is applied to a corner, warping the frame as seen in figure 44. Despite this, the A5 design began to yield at an applied force of 0.313kN, whereas the D4 began to yield when exposed to 55% of this force; 0.173kN. This suggests that users should be cautious when using the Portaledge frames, to ensure that minimal force is applied to the corners, and transverse loading scenarios are avoided. Certain limitations exist within the simulation of transverse loading, as some connections within the frame are tolerance fit, and applying forces in this plane may affect the effectiveness of these connections. The simulation software does not consider the possibility of parts moving in relation to each other, so in reality results may vary.

It is worth noting that simulations within ANSYS do not consider failure if a material's elastic limit is surpassed. Rather, it will continue to calculate the stresses within the components as if though they are completely intact. For this reason, in figure 46 and 47, it is likely that after a Portaledge's maximum stress surpasses the yield strength, the line will become shallower, until reaching the material's ultimate tensile strength. From this point, the material will begin to completely fail. Thus, points above the ultimate tensile strength line are strictly theoretical and will not occur due to material failure. For this reason, it is important and necessary to conduct physical tests on components to gain a thorough understanding of how the Portaledge's will operate in reality.

9.1.4 – Fatigue

The consequence of failure of Portaledges can be dire, thus it is expected that all designs should not fail due to fatigue in a lifetime of use. Using the Ansys fatigue tool and the maximum stresses calculate in the simulations, the expected lifetime of each Portaledge in the pure loading scenario when exposed to a 1kN load was calculated. The results were based off the ASME Elliptical Stress Theory, as it assumes failure at the material's elastic limit, rather than the ultimate yield strength. The A5 Portaledge design is anticipated to last for 30837 uses at its point of highest stress. While this is low for a machine component, Portaledges are used at a relatively low frequency. If the A5 ledge were to be once every day, it would last for 84 years. This is ample time for this product to last under fatigue. Additionally, the average fatigue life throughout the entirety of the ledge is 9.997×10^7 uses, with the assumption in ANSYS that 1×10^8 uses is an infinite life. Although this is not strictly accurate, for the frequency of Portaledge use, it could be considered infinite. The D4 design was calculated to last a total of 3.7111×10^6 uses at its point of highest stress, with an even higher average than that of the A5 design. This is a very ample figure, suggesting that the D4 design is unlikely to ever fail due to fatigue in while hanging with a load of 100kN.

9.2 – Physical Compression Testing of Corner Pieces

To support findings from the ANSYS FEA simulations, a corner piece from each Portaledge design was compressed at a rate of 12mm per minute, recording the applied force at each step. The nature of testing was most similar to the transverse loading scenario, as the force was only being applied in the horizontal axis of the ledge. Figure 56 displays the findings of the two tests. It was found that the A5 design reached an ultimate strength of 1042.414N, while the D4 design reached an ultimate strength of 2207.867N. This means that the D4 corner piece withstood 211.8% of the force that the A5 design withstood. In the transverse loading simulations, it was anticipated that the A5 model would fail at the corner, while the D4 model would fail at a connection. In figure 59, it is evident that both models failed at the corner, and neither straight length of aluminium sheared.

Figure 59 – Image of A5 and D4 Corner pieces after failure.

Upon disassembly of the A5 corner (figure 60), it is apparent that failure occurred when the edge of the block corner created a concentration of stress on the pole, causing it to buckle. As this occurred, the block corner crushed the other side of the pole as the corner piece failed. In figure 52, which displays the points of maximum stress within the A5 design under transverse loading, two clear points of stress concentration exist at the inside of the corner piece, where the block corner's corner meets the poles. This is verified within the compression test, as this is where failure eventually occurred.

The D4 corner piece appears to have eventually buckled in one of the ridges present from the original bending of the pole (figure 61). The integrity of this ridge was seemingly compromised, eventuating in this section failing. In figure 53, where the points of stress concentration within the D4 model under transverse loading are displayed, there is a spot of stress concentration throughout the inside of the curved corner. Although this was not recorded as the point of maximum stress, the 3D model did not include material flaws, such as said dimples on the inside of the corner. These ridges likely exacerbated the stress concentration in the corner, leading to failure. Despite passing their ultimate strength substantially, neither test resulted in a severe fracture, rather deforming to the point of touching the bottom plate of the testing apparatus. This suggests that the corner designs will not fail drastically, prior to a substantial amount of deflection, which is a positive reassurance if either ledge is pushed over its limits.

Figure 60 – Closer inspection of failure within the A5 Design corner piece

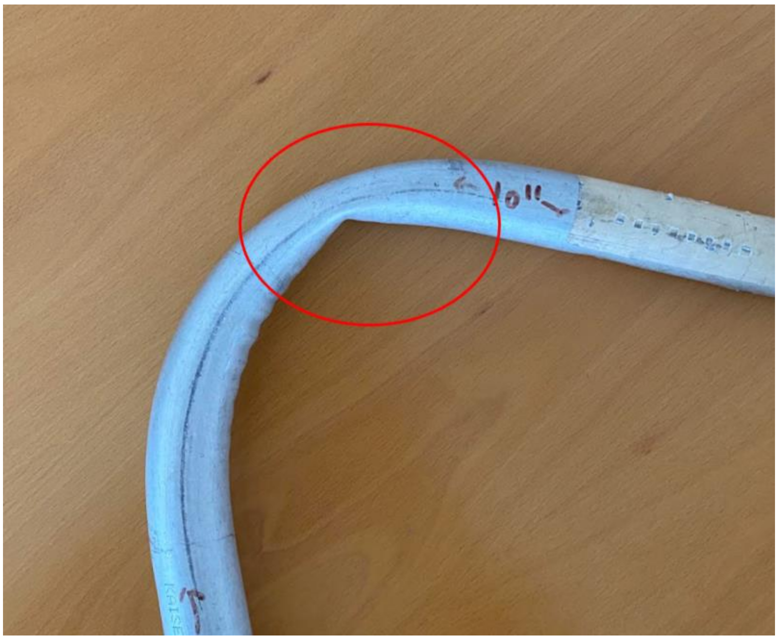

Figure 61 – Closer inspection of failure within the D4 Design corner piece

A final compression test was conducted on a joint assembly from the D4 model. It included a 1" OD with 0.058" wall thickness pole, a 1.25" OD pole with 0.049" wall thickness, connected to each by a bullet joiner. Figure 57 shows that the piece reached its ultimate strength at a force of 5299.838N, while only deflecting by 14.66mm. It then deflected minimally before completely failing. In figure 62a, it can be seen that the larger aluminium tube fails by shearing on the side in tension. In 62b, it can be seen that the compressed side of the tube buckled. These failures occurred at the curved tip of the bullet joiner was, suggesting that the joiner acted as reinforcement at a point of high stress concentration before then. This is supported in figure 53, where it is evident that a one of the greater concentrations of stress occurs at this point in transverse loading scenarios.

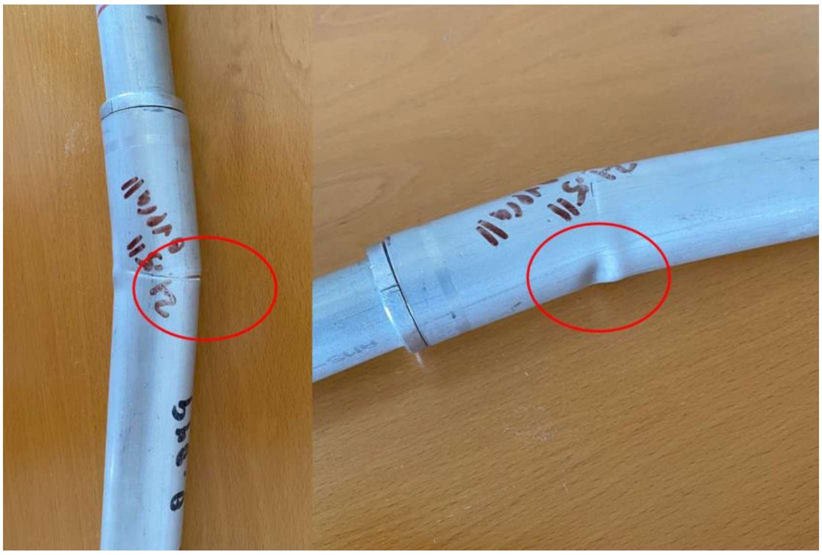

Figure 62a & 62b – Closeup image of failure points in D4 straight beam with joiner.

10 – Conclusions

To determine whether the A5 Alpine Double ledge or the D4 curved corner design is superior in terms of strength, rigidity and weight, a series of simulations and physical tests were conducted. Initially, 3D models were developed in SpaceClaim, to be imported to ANSYS for FEA simulations. These simulations tested the Portaledges' capabilities in terms of deformation and maximum stress in three different loading scenarios: Pure loading, centre loading and transverse loading. The following points were found:

Pure Loading:

- The D4 design was more rigid, deforming by about 40% less than the A5 design
- The most vulnerable component of the A5 design will begin to yield at a 1.42kN load, while the D4 design can withstand 180% of this load, beginning to yield at 2.57kN
- The D4 design weighs 2881.4g and has a strength to weight ratio of 0.892g/N, while the A5 design weighs 47.38g less, but has a strength to weight ratio of 0.501N/g. This is attributed to effective use of variable tube diameters in high stress locations for reinforcement, and curved corners to minimise stress concentrations in the D4 curved corner design.
- When exposed to a 1kN force, the critical component of the A5 Portaledge will last for 30837 cycles of use, will the critical component of the A5 Portaledge will last for 3.7111×10^{6} cycles of use.
-

Centre Loading:

- The A5 design withstood 0.4164kN before reaching its yield point, while the D4 design withstood 0.5744kN.
- When considering the induced moment from this reaction force, this converts to a maximum downwards force of 1.156kN on the A5 Portaledge and 1.498kN on the D4 Portaledge
- The D4 design can withstand 129.6% of the force that the A5 can withstand before reaching its yield point

Transverse Loading:

- The A5 design began to yield at an applied force of 0.313kN, whereas the D4 began to yield at 0.173kN.
- The D4 design's yield point occurred at 55% of the force that the A5's yield point occurred at.
- Users of both Portaledges should work to avoid forces than induce transverse loading scenarios, as it causes particularly large stresses within key components.

To further reinforce the findings in ANSYS, a corner piece of each ledge was tested, as well as a connection point from the D4 design, which included the bullet joiner. The testing was conducted with a Shimadzu compression testing apparatus, by using a rounded piston head to apply a force, testing the rigidity and strength of each corner. The D4 connection point was tested with two supports, in a 3 point bending test. The following results were found:

- A5 design reached an ultimate strength of 1042.414N, while the D4 design reached an ultimate strength of 2207.867N
- The D4 corner piece had an ultimate strength that was 211.8% of the A5 design's.

- At the A5 design's ultimate strength, the D4 design had deformed by approximately 12.5mm less, suggesting that the D4 corner is more rigid in this loading scenario.
- The A5 corner failed due to buckling in one tube, with simulations and observations suggesting it was caused by a point of stress concentration imposed by the edge of the block corner.
- The D4 corner failed due to buckling in the curved corner, with simulations and observations suggesting it was caused by a build up of stress in a ridge, which existed due to the manufacturing process of bending the tube.
- The D4 connection point reached its ultimate strength at a force of 5299.838N, while only deflecting by 14.66mm
- The D4 connection point failed severely due to shearing in tension and buckling in compression. This occurred at the wider tube, where it overlapped the end of the bullet joiner.

There are countless ways in which Portaledges could be acted upon by forces, and minute changes can vary how effective a Portaledge is at supporting weight and remaining rigid. For example, the tightness of the fabric in between the frame will affect the angle of the vectors in pure loading, or users may stand at any point(s) on the frame, causing a unique set of stresses within the frame. However, the methods chosen to test these designs are standard uses of Portaledges and known causes of failure and provide a valuable insight into how the two designs perform in given circumstances. With these results, it is suggested that the D4 design is superior in terms of its strength to weight ratio and rigidity in pure loading and centre loading, while the A5 design is superior in terms of strength and rigidity in transverse loading, as well as a lighter frame. Finally, the physical tests show that the D4 curved corner has a considerably higher ultimate strength and rigidity than the A5 block corner. It is suggested that to validate and further the results, tests should be conducted on fully assembled Portaledges. This will require additional components and testing equipment, but will be effective at addressing certain ambiguities, such as how each frame will truly react to transverse loading.

11 - Benefits

Testing and comparing the two Portaledge designs will assure users of the limits and capabilities of each design. It will also highlight potential weaknesses that can be improved upon in future iterations, to further optimise the strength, weight and rigidity of these designs. As Portaledges are often the largest and heaviest items that climbers carry, optimising their weight will enable climbers to take more strenuous routes in shorter times than possible in the past. A stronger and more rigid design will decrease the risk of Portaledge failure and injury, as well as support the user's peace of mind.

Developments in engineering on Portaledge frame designs could potentially be impactful on other applications of rectangular frames. For example, rescue stretcher frames have similar requirements to a Portaledge; a necessity for being strong, lightweight, and rigid. A conventional rescue stretcher frame can be made from a single polymer body, but for niche applications where a design needs to be compact and able to be dismantled, the Portaledge design could be applied. This may be useful in sports like spelunking, where tights crevices are prevalent.

As an academic topic, Portaledges have received minimal attention. A large number of resources on Portaledges are simply descriptions and reviews of their use, as opposed to quantitative data. This increases the significance of this project, as it can provide more quantitative data in this field. It can give users of the A5 Alpine Double and D4 curved corner designs a greater understanding into the capabilities of their equipment, and a comparison of the engineering effectiveness of each design.

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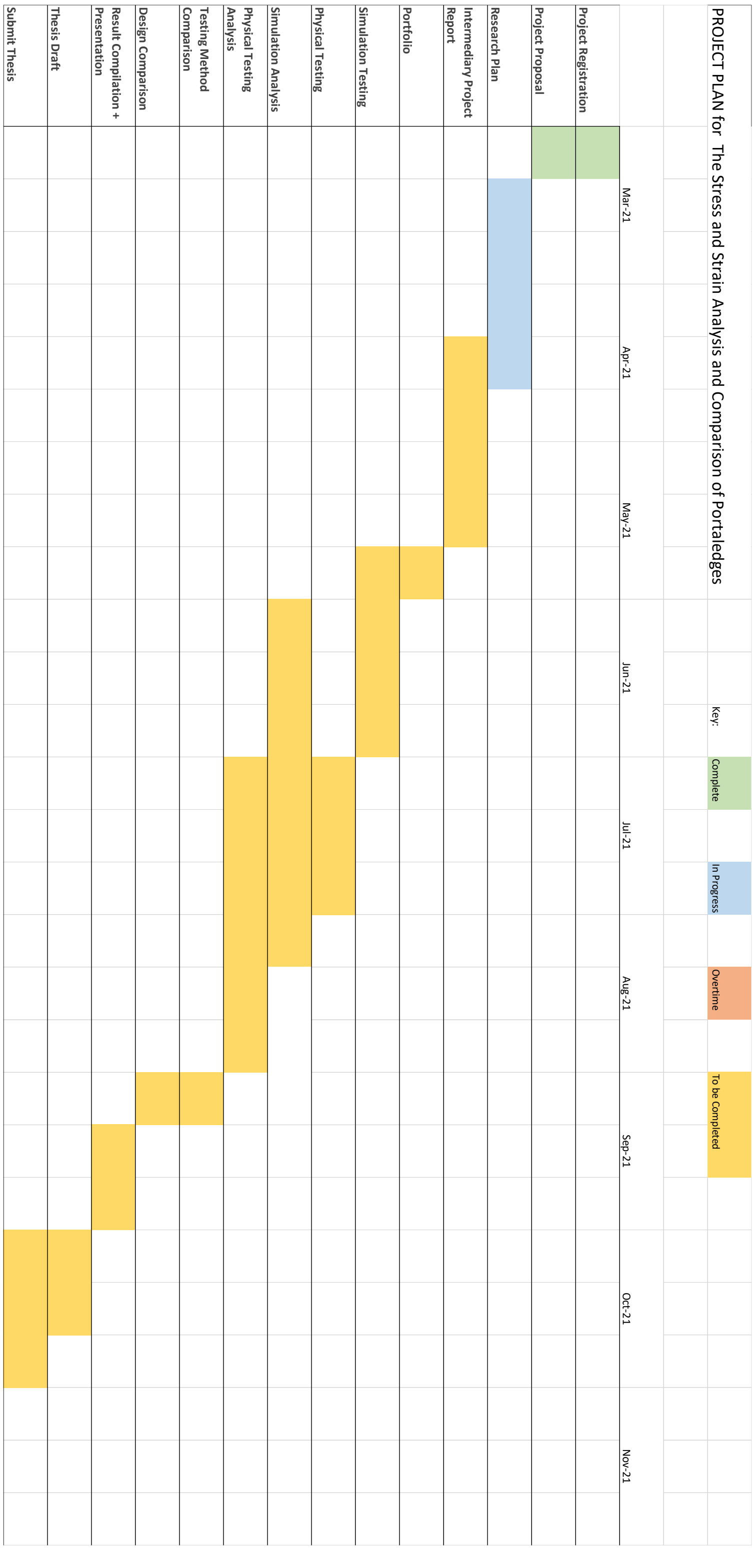
13 – Appendices

Appendices 1 – Gantt Chart



Appendices 1 – Gantt Chart outlining expected timelines for each minor project task