U.K. Loft Boarding LTD.
In Collaboration with University of Central Lancashire

A Critical and Technical Loft-Fixture Product Testing Report

2023 Undergraduate Summer Internship

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DECLARATION

The author confirms that the work submitted has been completed by him/herself and that all findings, data, research outcomes, documentation, and intellectual property resulting from the scientific experiments performed by the employee, during the course of this contract will be the exclusive property of UK Loft Boarding Ltd. and that appropriate credit has been given when in reference to the work of others

ACKNOWLEDGEMENT

This report is prepared in fulfilment of the requirements expressed by U.K Loft Boarding Ltd. I give thanks to U.K Loft Boarding Ltd. for giving me the opportunity to work on this project. I would also like to thank the University of Central Lancashire for allowing the scientific research to be conducted using the Material Testing Labs in Harris Building.

I will also extend my gratitude towards the project supervisor and mentor, Dr. Akinola Adeniyi and Dr. Kirijen Vengdasalam respectively, whose guidance and expertise have been invaluable in steering the project and myself towards success. I also thank other faculty members of the School of Engineering and Computing for their valuable feedback and input suggestions.

The experience of working on this project will surely enrich my technical knowledge and also give me the much needed hands on experience of working on a project to help develop my skill set to a greater extent.

NOMENCLATURE

Symbol	Description	Units
A	Cross Sectional Area	m^2
D	Diameter	m
E	Young's Modulus	Pa
e	Eccentricity	m
F	Force	N
I	Inertial Second Moment of Area	m^4
K	Effective Length Constant	
L	Length of Slender Section	m
M	Turning Moment	Nm
r	Radius of Gyration	m
W	Weight	N
X	axis	
Y	axis	
Z	axis	
Subscripts		
AVE	Average	
B	Block	
C	Compression	
CR	Critical	
f	Friction	
i	Inner	
MAX	Maximum	
O	Outer	
Greek Symbol		
Δ	Deflection	m
ε	Strain	
θ	Angle	$^\circ$
σ	Stress	Pa
π	Constant	

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1. INTRODUCTION

1.1. Purpose

The purpose of this report is to demonstrate and analyse the maximum working capability of Loft-E, the adjustable loft leg. This will be done by an experimental analysis, where the maximum yield stress of the loft leg will be tested at several angles of mechanical loading, which will be verified using a theoretical approach. An analysis of how the loft leg buckles prior to yielding will also be shown.

1.2. Background

U.K. Loft Boarding, to be referenced as “the company”, are specialists in residential loft space construction and upkeep. In 2018, a new product called Loft-E was brought to market in order to meet the new standard for insulation thickness of 270mm, brought into effect in 2003, with it previously being 200mm and 100mm in 1995 and 1985 respectively [1]. as stated in BS EN 13500. Loft-E has been designed with this new standard in mind so that the height of the floorboards can be adjusted to suit each respective loft design, even those with uneven flooring and foundations that have been subject to structural and thermal stresses. As the COVID-19 pandemic occurred, no testing was able to be conducted until 2021, where Lancaster University conducted mechanical and thermal simulations to give credibility to the design [2]. The design also shows potential to solve the issue of plastic loft legs shearing easily under eccentric loads, or from high concentric loads which are currently used in industry. In addition to this, as the plastic loft legs are not adjustable, it is very common for packing pieces to be used to fill the gaps between the insulation and floorboards. The company, in 2023, approached the University of Central Lancashire to perform structural destructive tests of the updated version of Loft-E.

2. METHODOLOGY

Several types of tests could have been performed to check the quality and structural integrity of the LOFT-E adjustable loft leg.

Table 2.1
Potential Qualitative and Quantitative Tests

Qualitative	**Quantitative**
Metrology and Inspection	Charpy Impact Test
Nick-Break Weld Test	Axial Compression Loading
Cross Sectional Weld Test	Eccentric Compression Loading
	Vibration Test
	Drop Test

2.1. CAD and Geometry

The Loft-E geometry has been provided by the company. To allow for compression tests to be done, several blocks have been designed and manufactured. See appendix A.1

2.1.1. Parametric Design

Parametric design is an iterative process that allows the designer to set parameters of a particular model, so that once these parameters are changed the model automatically updates [3]. A variant of this design method can be used when creating parts for assembly that are similar but not congruent, by use of the inbuilt design table feature - available in SolidWorks and other 3D CAD packages. This allows for multiple models to be designed instantaneously once the parameters for each model have been chosen. The main parameter that was changed in the design table was the angle of cut in the XY or ZY plane, varying between 0-15 degrees in each plane, in 5 degree intervals.

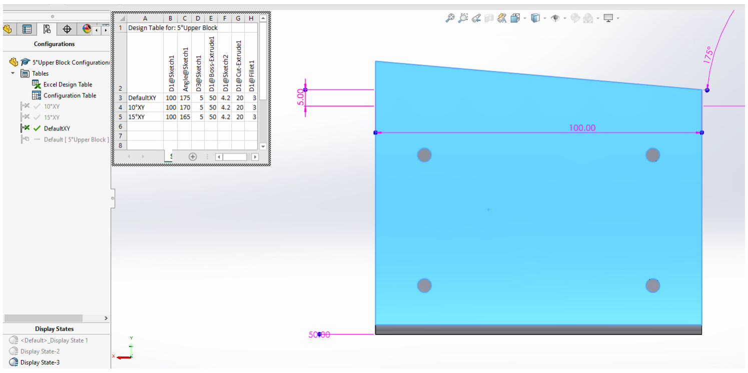
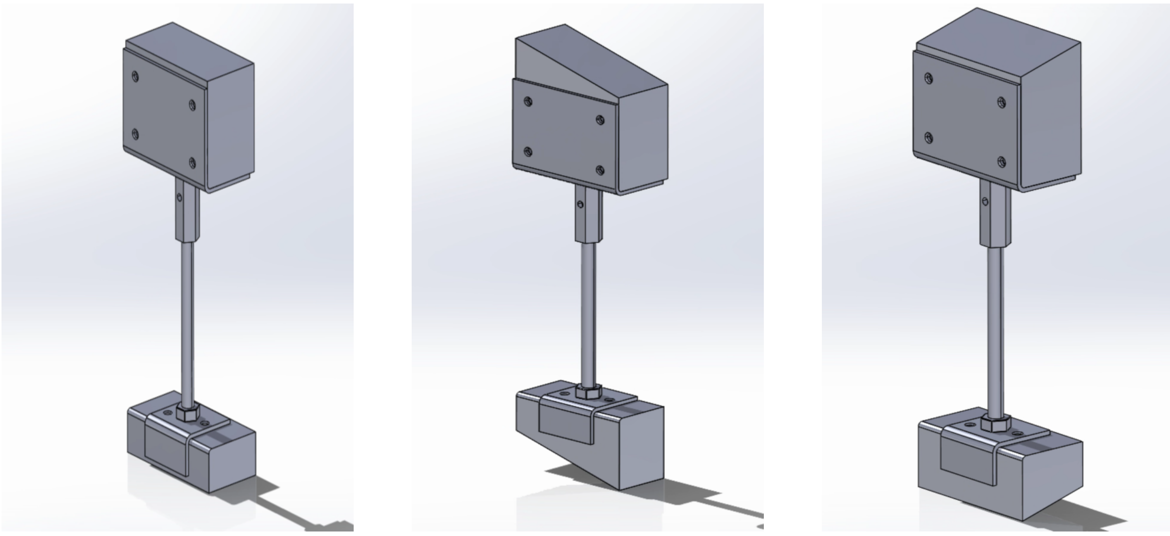


Figure 2.1
Design Table in XY Plane



(a) LOFT-E With Flat Blocks (b) LOFT-E With 15°XY blocks (c) LOFT-E With 15°ZY blocks

Figure 2.2
Three LOFT-E CAD Test Configurations

In total, seven upper blocks and 7 lower blocks were manufactured from mild steel, using a 5-axis milling machine once they had been cut down to the correct sizing. Prior to manufacture, technical drawings were made to the BS8888 drawing standard, which replaced the BS308 standard in the early 2000s, which covers all aspects of technical product specification [4].

2.2. Qualitative Analysis

Qualitative analysis focuses on the use of subjective judgement, based upon the knowledge held by those performing the analysis, which is very often undertaken when the results of the test(s) are difficult to quantify or for when the quality of a manufactured product is to be checked, whether it be in batches or for an entire product line; only if the ratio of test samples to total population is high should the entire line be tested, if not batch testing is sufficient, as otherwise time and financial expenditure incurred will be costly. This contrasts to that of quantitative analysis which is the use of objective judgement, typically through use of numerical results [5].

2.2.1. Visual Inspection Test

A critical part of quality checking a manufacturing process is to visually inspect the products that have been produced. This is to ensure the effectiveness and quality of the parts before they are moved to the next stage of development or assembly, or before they are signed off for final distribution [6]. The method chosen was as follows:

1. Align the test sample in the testing position on a workbench
2. Measure and record the characteristic dimensions (lengths and hole diameters) using a set of vernier callipers and a micrometer
3. Compare these measurements to provided CAD geometry. Are the measurements equivalent to those stated on the technical drawing? If not, are the inaccuracies similar across all samples tested?
4. Assess the uniformity of the welds, are they identical and homogeneous? Are there sections where modular components have not been welded which should have been?
5. Repeat for all test samples, of which there are 26 - 2 of these are to be used to calibrate the hydraulic press with 24 to be used for gathering quantitative data.

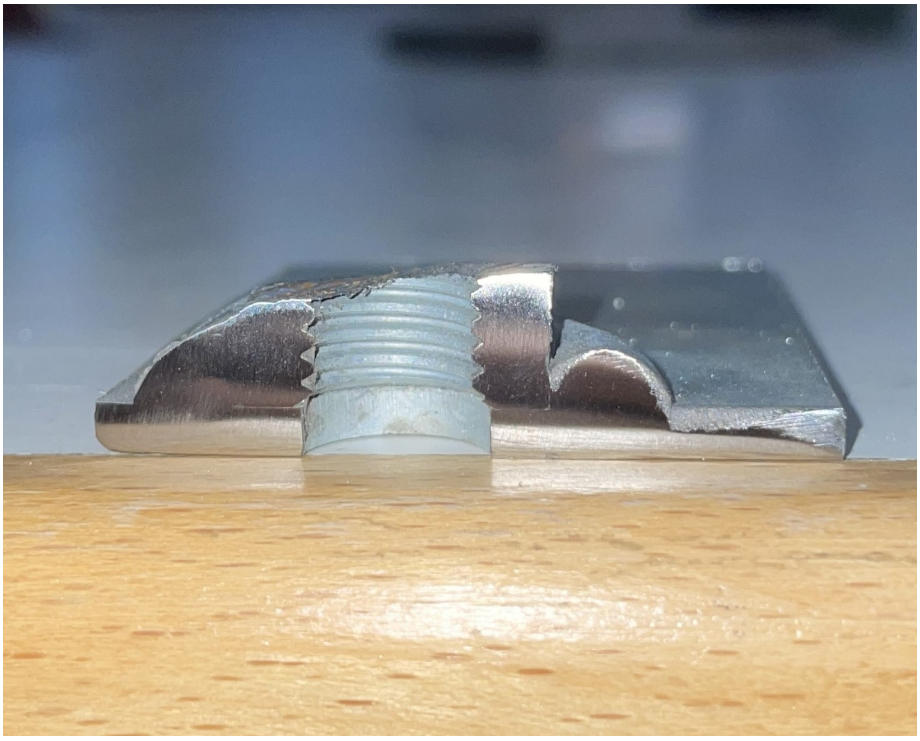
It should be noted that these samples are a batch, as the company produces several thousand adjustable loft legs per calendar month.

2.2.2. Batch Weld Inspection

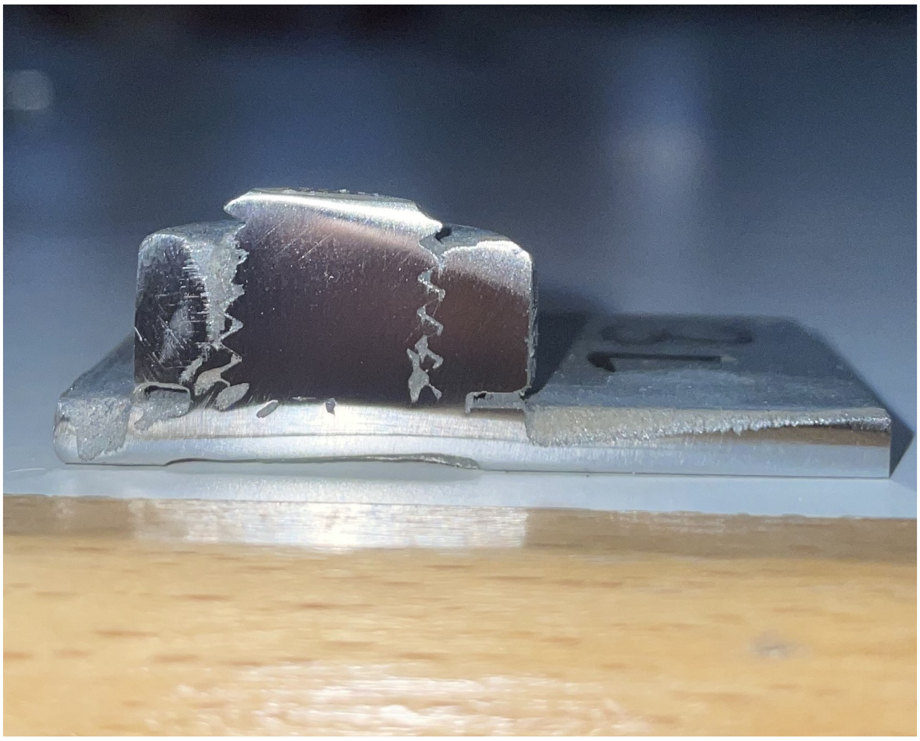
To check if the weld quality of the samples were satisfactory, without doing any metallurgical tests, a visual inspection of the welds.This was done in two stages, the first being a visual inspection test of the welds as they are and the second inspection test is done once the welds are cut in half to view a cross section of a weld. Ideally, a nick-break weld test would have been performed; this type of test fractures the weld length-wise across the entire weld and then broken off with either a hydraulic press or a hammer [7] before then etching the weld, however due to the "length" being a circumference, it would have proved difficult to perform this test. Instead, the test method was carried out as follows:

1. Cut off the vertical sections of the top and bottom L-shaped modules. This was completed using an angle grinder.
2. For the upper section, a hacksaw was used to remove the threaded hex bar - a band saw, or mitre saw would normally be used, however these were not available.
3. Place upper and lower modules into the waterjet cutter[1] so that the water-jet can cut the modules in half.
4. Polish each module to 1000 grade wet and dry paper.
5. Place each module into a dish of ferric chloride ($FeCl_3$) for 15 minutes.
6. Remove any excess ferric chloride, and then inspect for porosity, weld penetration into the substrate material and any cracks or any sections where the weld has not been applied.
7. Repeat for each of the 5 test samples.

[1] It should be noted that each module is placed into the water-jet cutter in the same orientation so that it is cut in the same fashion.



(a) Polished Upper Module Weld



(b) Polished Lower Module Weld

Figure 2.3
Two Polished Weld Samples

2.3. Structural Tests (Experimental)

The structural tests that were to be performed focused on compressing the samples using an Instron 3369 Universal Testing Machine, in accordance to the metal compression standard ASTM E9[2] [8].

2.3.1. Destructive Tests

Three sets of testing were planned to be completed. These consisted of a design point test, and then testing the samples at varying angles in the XY and ZY planes - these planes were determined from the CAD geometry, not the given axes in reality. The tests were completed as follows:

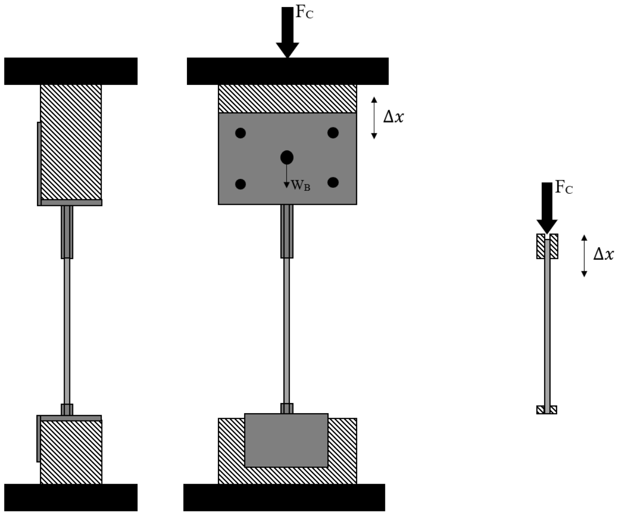
1. Place test sample with attached blocks into the machine.
2. Check that the sample is as close to the centre of compression plates as possible.
3. Lower the upper compression plate until the blocks are in full contact with the machine.
4. Zero the loading on the machine.
5. Begin loading.
6. Stop loading once extension of 3.5mm has been reached.
7. Repeat for all samples.

It can be hypothesised that the mode of failure will be buckling in the M10 threaded bar that connects the upper and lower modules together. Additionally, if it is taken to catastrophic failure, a secondary point of failure could be where the lower M10 nut is welded to the lower plate and M10 threaded bar.

[2] It should be noted that, due to time constraints, instead of performing the test at 0.005inches/min (0.127mm/min) the tests were performed at 0.079inches/min (2mm/min).

2.3.1.1 Design Point

The company was mainly concerned about how much could the LOFT-E adjustable loft leg withstand before failing when under normal compression loading. This was the focus of the testing.



(a) Design Point Schematic

(b) Design Point Preliminary Test

Figure 2.4
Design Point Schematic and Test Piece

Whilst there will be a normal reaction force, F_R, it is not labelled on the schematics due to the way in which the Instron 3369 Universal Testing Machine works in that it only registers the compression force that is being applied by the upper plate, rather than sensing a reaction force from the lower plate. This is so that any force measured, is purely that of which the machine has added. Due to $W_B <<< F_C$ it can be considered negligible and that it would not affect the obtained results in any noteworthy fashion. The entire system can be simplified to a be a vertical column that is fixed at both ends. The company mentioned that they were manufacturing the loft legs from mild steel which was plated in stainless steel, so when it comes to theoretical calculations the value for Young's modulus will be 200GPa [9]. Additionally, as the slender section of the test samples is a M10x1.5 threaded bar, an average diameter of 9.25mm will be taken instead of 10mm or 8.5mm. Also, the length, L, of the slender section is to be taken as 150mm in the design point case.

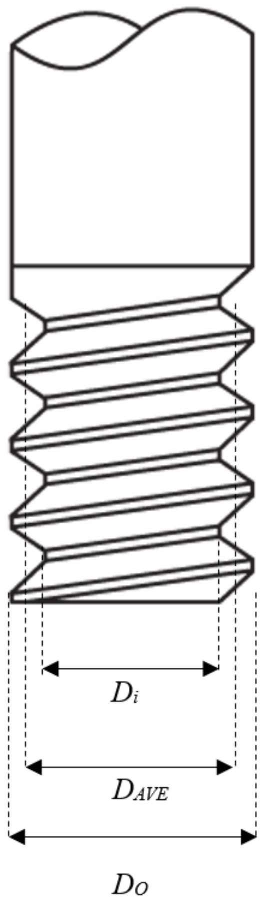


Figure 2.5
Axial Loading Results

To calculate a theoretical value for the critical load, Euler's Theory of Column Buckling was used. It can be derived from the Bernoulli-Euler Beam Equation [10]:

$$EI\frac{d^2\Delta}{dx^2} = -M \tag{2.1}$$

Where $\frac{d^2\Delta}{dx^2}$ is the second derivative of the beam's deflection, Δ, with respect to a position, x, along the beam. M is the internal bending moment at the position x, with E being the Young's modulus of the beam. I is the second moment of inertia. After deriving, the critical buckling load can be calculated as follows:

$$F_{CR} = \frac{\pi^2 EI}{(KL)^2} \tag{2.2}$$

From this the critical buckling stress can be found through rearrangement and substitution:

$$\sigma_{CR} = \frac{\pi^2 E}{(KL/r)^2} = \frac{\pi^2 E}{\left(KL/\sqrt{\frac{I}{A}}\right)^2} \tag{2.3}$$

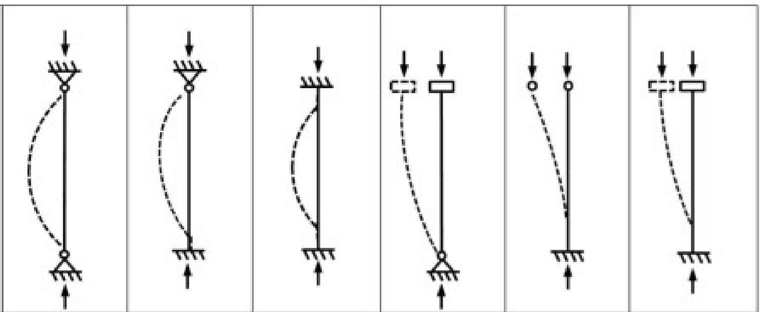
Buckled mode						
Theoretical effective length, k	1.0	0.7	0.5	2.0	2.0	1.0
Recommended effective length, k_r	1.0	0.8	0.65	2.0	2.10	1.2
Symbols for end conditions	= Rotation fixed, translation fixed; = Rotation free, translation fixed; = Rotation free, translation free; = Rotation fixed, translation free					

Figure 2.6
Effective Length

In [10], eq. (2.2 and 2.3) the value of K determines the effective length of the column. This changes depending on the boundary conditions in place. The effective lengths for different fixture types are shown in fig. 2.6[11]

2.3.1.2 Off-Design Point

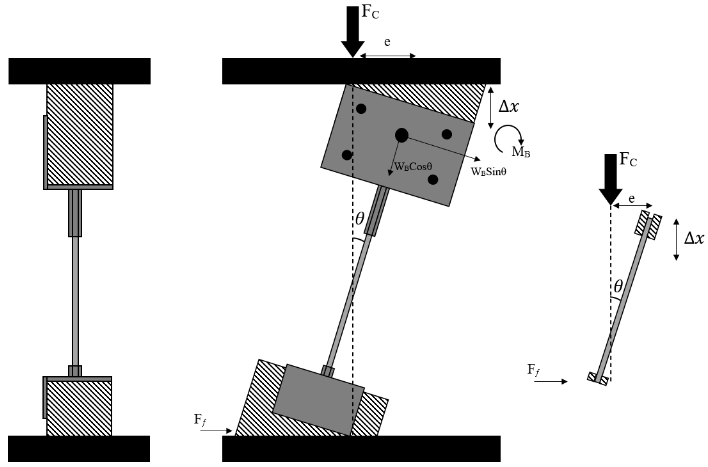
Secondary testing was completed at several different angles in both the XY and ZY plane. This was done by cutting angles of 5°-15° into separate test blocks. The reason behind testing at different angles, was to see how the Loft-E adjustable loft leg would perform when subjected to eccentric and non-perpendicular loads, as wooden beams inside of lofts can undergo warping over time. Whilst, in practice there are typically several dozen loft legs supporting loft beams which would also limit movement of the beam, warping can still potentially occur due to high temperatures and an increased perspiration in the air - a loft is a very humid environment due to insulation and convection currents.

From Euler's Theory of Buckling, equations to calculate critical stress, σ_{CR} and maximum displacement, Δ_{MAX} can be derived.

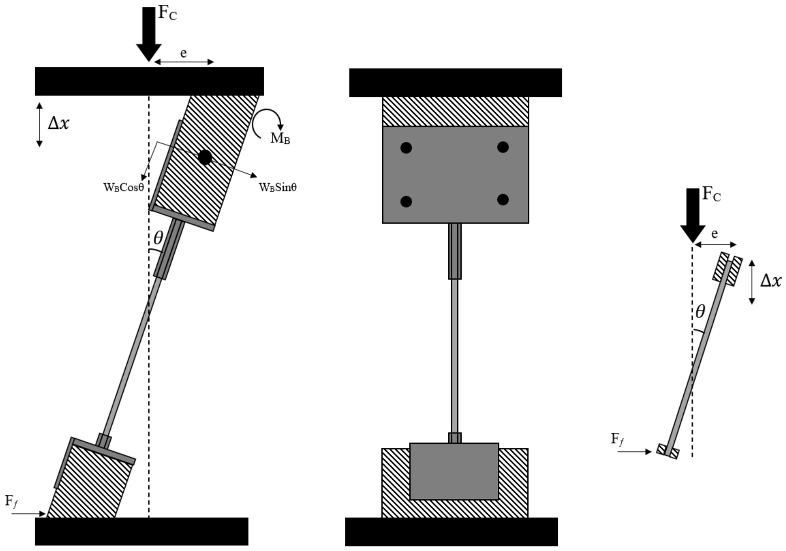
$$\sigma_{CR} = \frac{F_{CR}}{A}\left[1 + \frac{e\Delta_{MAX}}{r^2} sec\left(\frac{L}{2r}\sqrt{\frac{F_{CR}}{EA}}\right)\right] \tag{2.4}$$

$$\Delta_{MAX} = e\left[sec\left(\sqrt{\frac{F_{CR}}{EI}}\frac{L}{2}\right) - 1\right] \tag{2.5}$$

Both of these equations can only be calculated if the value of e is known. On top of that, as the loading is not only eccentric but angled, then forces need to be resolved. Since the off-design point tests did not take precedence in this report, the eccentricity was not measured therefore, causing these results to not be verified mathematically. If further testing was to be done, then this is something that would need to be recorded.



(a) Off-Design in XY Plane



(b) Off-Design in ZY Plane

Figure 2.7
Off-Design Point Schematics

It can be seen that from both off-design point schematics, the angle θ must be taken into account, causing the value L to become $Lsin\theta$. Other variables must also be taken into account such as the frictional force, F_f, a turning moment of the weighted block, M_B and the eccentricity, e - the distance from the centre of the test blocks to where the load is acting.

3. RESULTS and DISCUSSIONS

3.1. Qualitative Tests

3.1.1. Visual Inspection

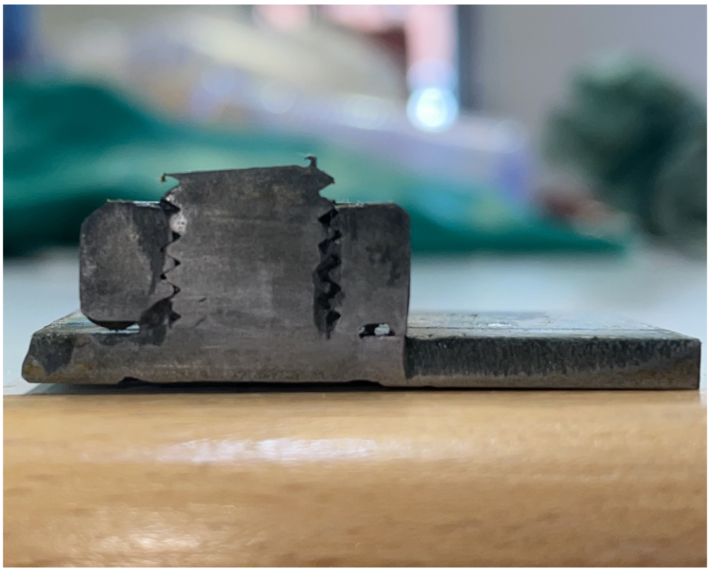
The focus of the visual inspection test was to check whether the samples had been manufactured to the CAD dimensions. It was found that the average standard deviation from the dimensions gathered was 0.0879. The average confidence interval of 95% [12] was found to be "insert dimension here" $\pm$ 0.037mm. However, it has been found that the vertical distance between screw holes on the upper plate when compared to the CAD technical drawing, has an error of between 0.5-1.25mm for each hole, equating to a total error of 2.5mm $\pm$ 0.037mm. Whilst this is not of concern, as it does not affect the integrity of the loft leg, it does highlight that there is an issue with manufacturing.

3.1.2. Batch Inspection of Welds

It was found that when inspecting the upper and lower welded modules of the 5 test samples, all of them had the same issue. This was that whilst the weld was penetrating the substrate L bracket, it was not penetrating the M10 hex threaded bar on the upper module, as well as weld material not being applied all the way into the corners underneath the M10 hex bar and the M10 nut on the upper and lower modules respectively.

In addition to this, the size of the weld was fairly standard and uniform, however it did vary slightly which could be a point of interest for improvement in the manufacturing process. These small issues can be put down to human error, which can potentially be avoided if machine welding is utilised instead. This would, of course, come with financial implications. On one of the lower modules, a small crack became visible once the material had been etched, see fig.3.1a, in between the weld material and the substrate. This could simply be an imperfection in the material or it could have occurred post-weld.

(a) Etched Upper Module Weld



(b) Etched Lower Module Weld

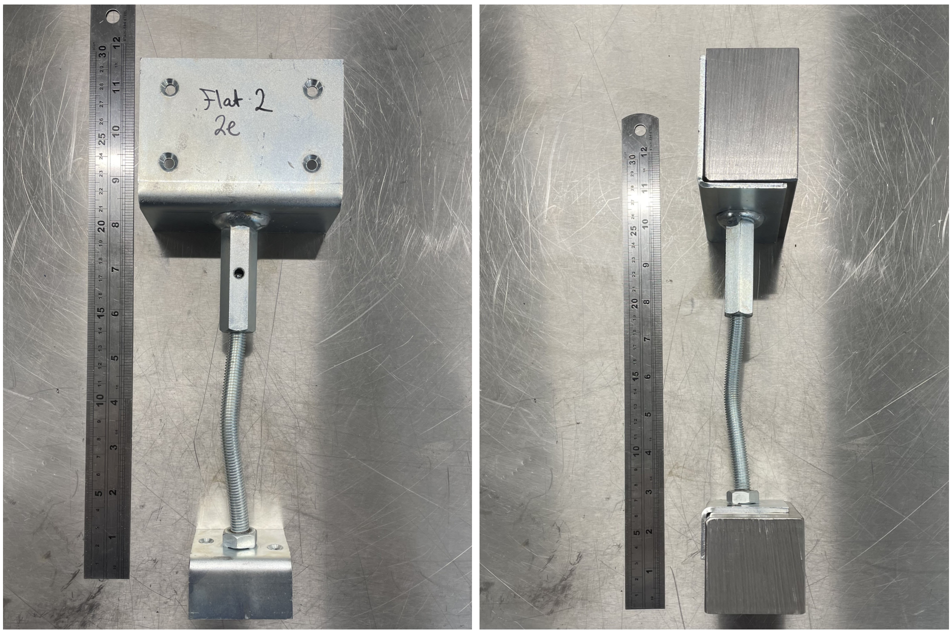
Figure 3.1
Two Etched Weld Samples

3.2. Structural Tests (Experimental)

It is stated within the BS5975 standard that the permissible factor of safety for yield stress is 1.65 and a factor of safety of 2 for failure[13]. It was planned that in the off-design point tests, these would vary between 5°-15° in both the XY and ZY planes. However, due to the weight of the steel blocks the 15° tests in the ZY plane could not be recorded as the turning moment at 15° causing the $M_B >>> F_f$ and so the test piece would fall. The reason as to why this did not happen for the 15° tests in the XY plane, was because of the dimension of the blocks in the X axis was 100mm, compared to 50mm in the Z axis. However useful information was garnered from when the test piece fell over and out of the Instron 3369

Universal Testing machine, this being, that having fallen from a height of approximately 1.2m, the sample failed with the mode of failure being 1st mode buckling, which could be cause for concern as the entire test piece (including blocks) only weighed 7kg. This could prompt further testing to be done, such as impact and drop tests.

3.2.1. Design Point



(a) Critcal Test Front

(b) Critical Test Side

Figure 3.2
Critical Test

The mode of failure for the design point tests was 2nd mode buckling. This occurred halfway down the threaded M10 bar, in all three cases - with case 2 being shown in fig.3.2 This was the expected mode of failure and location. Below shows the theoretical critical load and critical stress, using the assumed value for Young's modulus:

$$F_{CR} = \frac{\pi^2 EI}{(KL)^2} = \frac{\pi^2(200x10^9 Pa)(3.59366x10^{-10}m^4)}{(0.5(0.15m)^2} = 126.108kN \quad (3.1)$$

$$\sigma_{CR} = \frac{\pi^2 E}{\left(KL/\sqrt{\frac{I}{A}}\right)^2} = \frac{\pi^2(200x10^9 Pa)}{\left(0.5(0.15m)/\sqrt{\frac{3.59366x10^{-10}m^4}{6.72x10^{-5}m^2}}\right)^2} = 1.876GPa \quad (3.2)$$

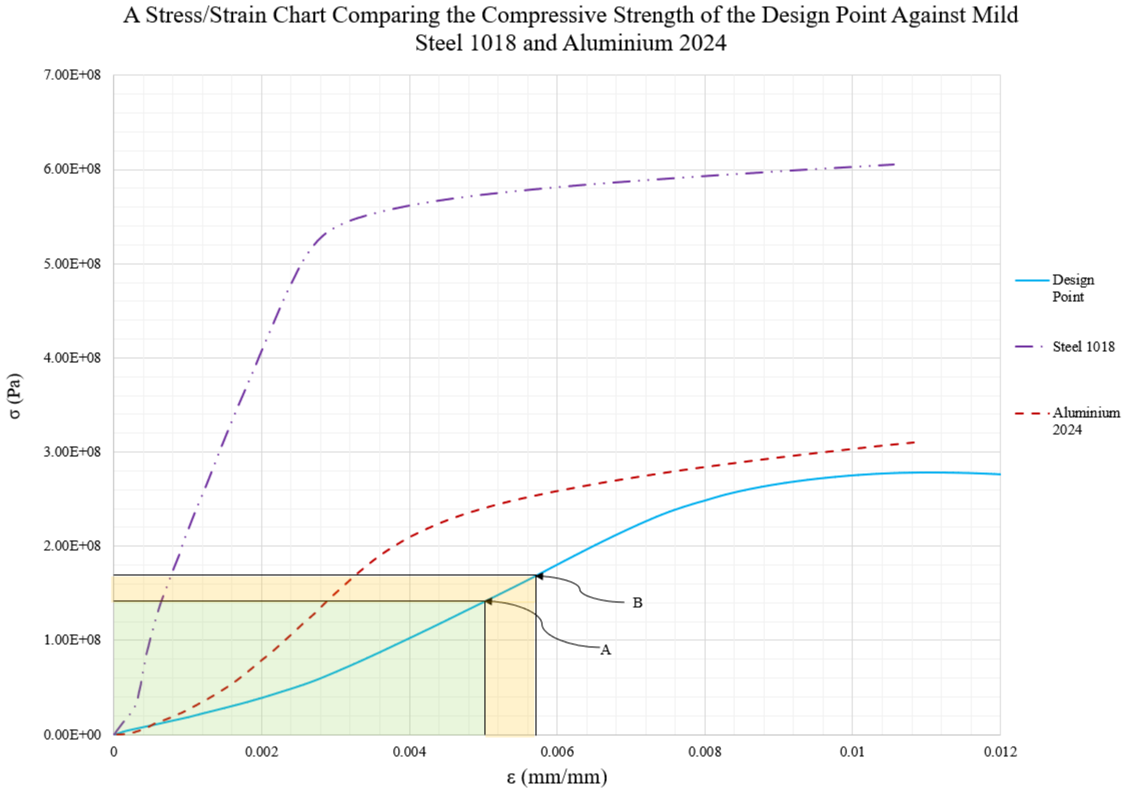


Figure 3.3
Axial Loading Results

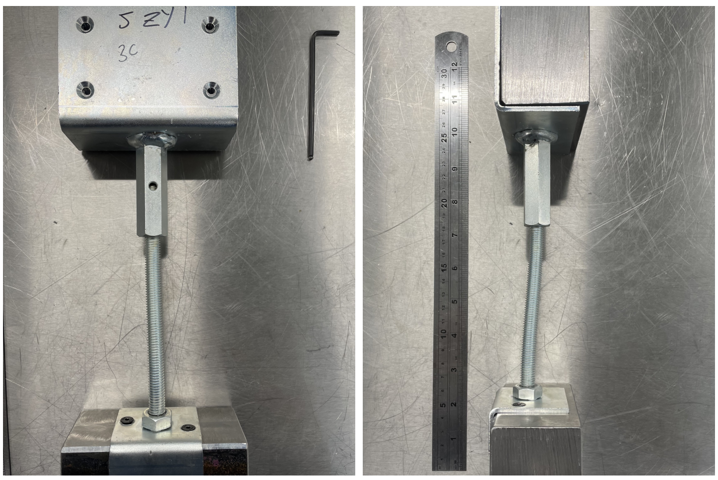
As the recommended factor of safety for yield stress is 1.65 times lower than peak loading, label A shown in fig.3.3, shows that any stress lower than 139MPa is acceptable (highlighted in the green shaded region). Label B, shown in fig.3.3, shows that stresses lower than 168MPa (highlighted in the yellow shaded region) is acceptable. Whilst it would be tolerable to have stresses in this range, it is not recommended as material fatigue can occur at elevated stresses over a lengthened period, even if it is under the yield point, causing the material to fail unexpectedly which would be hazardous for the user. Most failures due to fatigue occur due to the cyclic nature of the load - typically much lower than the yield point - which causes microscopic imperfections in the material to form into a macroscopic crack. Once formed the crack can propagate throughout the material hence resulting in a catastrophic failure of the component that is manufactured from said material [14]. The critical load for the design point was found to be 18.677kN with the critical stress being 277.944MPa. These values are approximately 6.7 times lower than the theoretical values. Looking closer at this stress/strain diagram, it shows that the material used for manufacture of the Loft-E adjustable loft leg, is most likely not mild steel, which the company stated that it was made from, but rather perhaps an aluminium alloy. The compression data for steel 1018 and aluminium 2024 is referenced from the University of Illinois [15]. Both the plotted graph and the actual data implies that the material is not mild steel as it was initially stated to be by the company, if it is, then the quality of the steel should be checked.

3.2.2. Off-Design Point

The mode of failure for the off-design point tests was 1st mode buckling, however when comparing to the different modes of buckling shown in fig.2.6 the shape of the buckle in both the XY and ZY planes, matches the 6th type of buckling where the value of K equals 1 with both ends being fixed - causing rotation to be fixed - but with translation being free.

(a) 5°XY Front (b) 5°XY Side

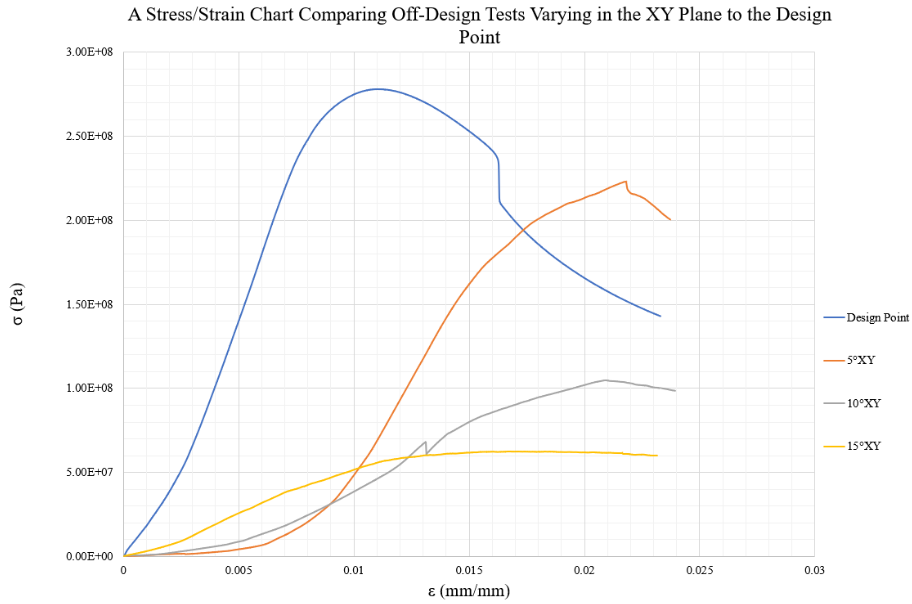
Figure 3.4
5°XY Test



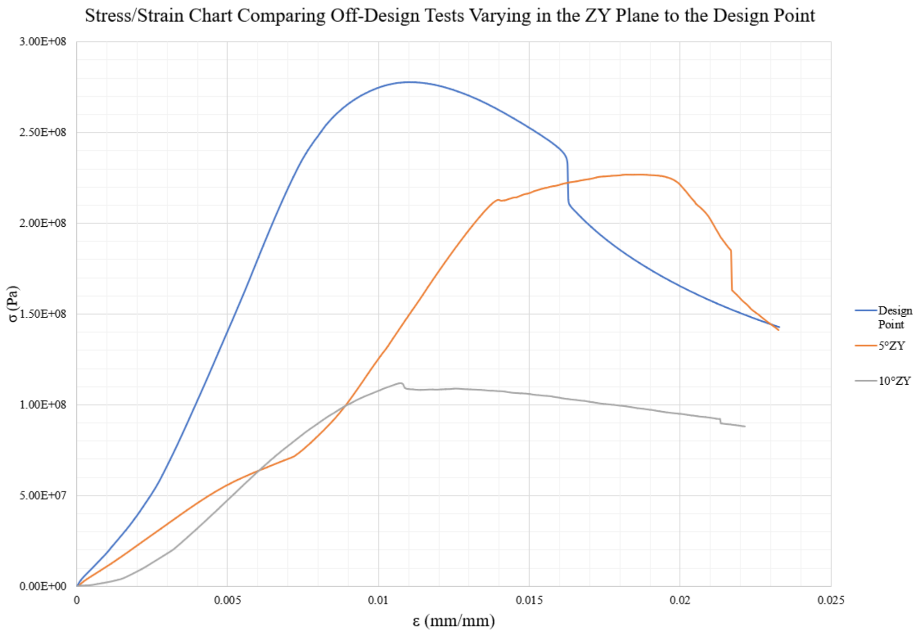
(a) 5°ZY Front (b) 5°ZY side

Figure 3.5
5°ZY Test

It was found that for the off-design XY planar tests, the critical loads for the 5°, 10° and 15° tests were 14.976kN, 7.032kN and 4.187kN respectively. This shows that there is a 20%, 62% and 78% decrease in peak strength respectively in comparison to the design point.



(a) σ/ε Off-Design in XY Plane



(b) σ/ε Off-Design in ZY Plane

Figure 3.6
Eccentric Loading Results

For the off-design ZY planar tests, the critical loads for the 5° and 10° tests were 15.258kN and 7.521kN respectively. This shows that there is an 18% and 60% decrease in peak strength respectively in comparison to the design point.

4. CONCLUSION

To conclude, it has been found that the manufacturing process of the Loft-E adjustable loft leg is fairly standardised for all the samples tested. On the other hand, the manufacturing process makes a consistent error in some of the dimensions when compared to the 3D CAD geometry provided. In reference to the weld testing, it was found that nearly always, the weld material penetrated the substrate steel, however out of the 5 test samples, only one weld was able to penetrate the M10 hex bar and nut, and even this was only partial penetration. The external quality of the welds were typically quite uniform however due to human error there was some differences between them.

The critical load for the design point was 18.677kN and that the mode of failure was 2nd mode buckling. In both planes, XY and ZY, the critical load at 5° decreased by 20% and 18% respectively, with the 10° tests resulting in a 62% and 60% decrease in critical load and the 15° tests in the XY resulting in a 78% decrease in critical load.

Whilst the load bearing capacity significantly decreases at larger angles, it must be said that this is only for 1 loft leg, and not when it is supported by an array of several dozen.

5. FURTHER WORK and RECOMMENDATIONS

It can be noted that due to time constraints on the project, the loft leg was not tested in its modular components. Modular testing of the two welded components that make up Loft-E is required, as this could highlight any failure points in either one of the modules. This is necessary, as if one module fails at a below the minimum factor of safety required then the other module will fail and vice-versa.

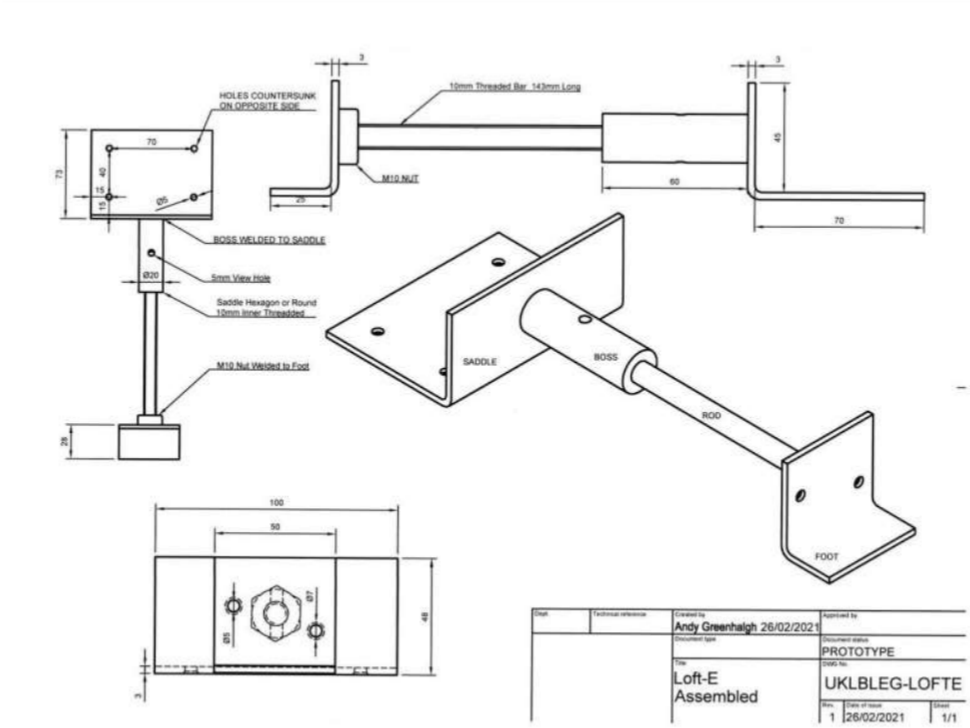
Additional testing through the use of the Charpy impact test, as well as drop testing samples - by dropping loads onto the sample from a given height, instead of dropping the sample itself. This would give a better indication of what would happen if a user dropped an item in their loft.

Further testing that is potentially required, would be to organise a comparison test between the Loft-E adjustable loft leg, and some of the market competitors products.

Due to time and resource constraints, no finite element analysis was completed. In future, it is highly recommended that rigorous simulations would be performed to improve the quality of the loft leg.

A. APPENDIX

A.1.



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