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FINAL YEAR PROJECT

Austerity 90733

Locomotive Horn guide and Frame Re-design

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Austerity 2-8-0 90733

Horn Guide and Frame Re-design

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Abstract

Austerity 2-8-0 locomotive number 90733 was built to aid the war effort. After being sent to the Continent to aid the re-building of the railways it was eventually side-lined and ultimately bought for preservation by the Keighley Worth Valley Railway. After a full overhaul, it ran for a few years until developing rough riding qualities. The wheels were removed for visual inspection and damage was found to have occurred with the axleboxes which act like bearings restraining the axles.

Measurements were taken of the horn guide faces which act as vertical guides for the axleboxes, permitting vertical movement.

Due to the KWVR being a volunteer run charity the expenditure required to repair the damage, impacted greatly on the organisations finances, due to it not being part of their planned maintenance schedule.

The purpose of this study is to therefore create a Computer Aided Design (CAD) model of the locomotive frame that will be tested using Finite Element Analysis (FEA) to determine the areas of high stress and deformation within the horn guides and frame of the locomotive.

Modifications will then be designed and tested to determine whether the displacement in the horn guides has reduced and ultimately resulted in a frame design that is structurally enhanced and adequate to cope with operation on the KWVR.

The overall result from this structural modification will mean that the locomotive will be more financially viable to run and cut down on maintenance time ultimately saving unnecessary expenditure.

The author at the controls of 90733 (Szlatoszlavek, 2017)

Summary

Main actions taken

- Investigate the history of the locomotive.
- Attain dimensions of the locomotive frame.
- Calculate the forces being applied to the locomotive during normal operation.
- Create a computer model within Solidworks Computer Aided Design Software.
- Carry out a meshing procedure to attain the most accurate values.
- Simulate Finite Element Analysis upon the model and evaluate.
- Create several design modifications and re-test comparing each one for improvement and flaws.
- Final design shown.

Investigation into History

Through the authors involvement with the Keighley Worth Valley Railway where this locomotive is currently based, vast amounts of information is already known about its background. This knowledge has been gained through conversing with colleagues on the railway. The author is a qualified steam locomotive operator and so the information obtained about the current condition and operational ability is useful in this section.

Obtain Dimension's

Technical drawings of the locomotive were attempted to be sourced, however sufficient dimensions were not attained. Therefore, the author measured the locomotive using a variety of techniques at Haworth on the KWVR.

Calculation of Forces

Formulae learnt through the authors time at University and earlier education have been utilised along with sourced technical papers and books. Additional assistance has been found through conversing with University and Railway Colleagues.

Create a Computer Model

Dimensions gained from the locomotive at Haworth were used to create a model in Solidworks Computer Aided Design software. Simulations could then be run to attain results of frame deformation.

Carry out a Meshing Procedure

A mesh convergence test was carried out to ascertain correct values which would give the most accurate results.

Simulate Model

Finite Element Analysis was simulated to define areas of movement and weakness within the horn guides and frame.

Creation of Design Modifications

Six frame modifications were created. These showed a gradual improvement in both the frame strength and horn guides. Each design was then compared displaying this improvement.

Final Design

The production of a final design for application on the locomotive.

Acknowledgements

Information included within this report could not have been obtained without the input of several people and sources. Colleagues at the Keighley and Worth Valley Railway have been crucial in the assistance of attaining information of both witness accounts of such locomotives operating in this country during the days of steam but also when the locomotive returned from the Continent. The early years spent running on the KWVR and then the overhaul undertaken after withdrawal from operating service.

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- Stuart Bray
- David Kay

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Many thanks to;

- Julian Stow
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- Sergio Neves

Apart from the people mentioned, much other information has been gathered from a variety of sources. Crucial technical papers were obtained from the Institution of Mechanical Engineers (IMECHE) archives containing complex information and formulas required for the calculation of required forces. The IMECHE must be thanked for the preservation of this information for continued use by future generations.

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1. Introduction

Austerity locomotive number 90733 began its life as War Department number 79257 (Rowledge J. , 1978). Built at Vulcan Foundry, Newton Le- Willows, Lancashire in January 1945 it was constructed to aid the War effort. The locomotive was initially sent overseas, to mainland Europe to provide motive power to heavily damaged railway systems. The Class known as Austerity 2-8-0's were designed in a time when materials and man power were at an all-time low as skilled men were needed to aid the War effort. Constructed using largely the same material throughout the type of locomotive was only designed to last for around 3 years prioritising low cost over design life (WarwickshireRailways.com, n.y). A vast number of this Class remained in this country during the War and more returned from abroad when surplus to requirements. These locomotives were modified extensively to cope with the intense extended running period required by British Railways. However, number 79257 remained on the Continent and received no such modifications.

Eventually purchased by the Keighley Worth Valley Railway the locomotive ran for a few years until overhauling was required, it was then returned to an operationally fit condition. During the overhaul process modifications were made to the original Vulcan foundry drawings and designs. On returning to working condition it was re-numbered 90733, the machine proved to be popular with both visitors and crews. After around 5 years however the ride comfort became worryingly rough and the locomotive was withdrawn from service pending inspection. The findings showed that the horn guides which support the axleboxes were deforming. As a result of those findings this project will require investigation into the stresses being applied to the horn guides and frame, then identify the magnitude and locations of these. Once identified, discover a potential replacement design of horn guide and analyse whether the new design lowers the stress concentrations, at the same time ensuring that these modifications don't apply additional elevated forces elsewhere within the frame.

2. Literature review

To aid the writing of this report several books and papers have been utilised to gain a better understanding of previous and current problems with locomotive horn guides. This section will demonstrate background research into these items of material.

2.1. ILocoE Paper Locomotive Hornblocks- (With a note on Frame Stresses), C. W. CLARKE (1939)

This paper resides in the IMECHE archives. It gives a thorough breakdown of problems and benefits of different horn guide designs. The different types of horn guides are mentioned and each explained in detail. The forces being applied upon the horn guide faces are described for steam, diesel, and electric locomotives. The factors that cause the forces and wear to be applied onto the horn faces are discussed. Due to there being many different designs of steam locomotives produced by the main railway companies each locomotive includes different flaws. A locomotive incorporating an 0-6-0 wheel arrangement, meaning that it has three coupled driving axles will have forces being applied upon 12 axlebox faces. Due to there being two faces per axlebox, a 2-8-0 locomotive such as based in this report will incorporate a forth driven axle and leading non-driven axle. The leading wheelset will not be considered due to not being a fixed structural part of the locomotive frame. Useful equations are included in this paper that demonstrate the required calculations to determine the forces being applied on both the axlebox faces and the resulting horn guide faces. The magnitude being applied on each of the horn guide faces both fore and aft are explained. This will aid in applying loads to the model in Solidworks. The equations given in this report will also be useful in calculating the magnitudes being applied upon the CAD model. Methods in reducing horn guide deformations are described which will give additional exploratory points to investigate.

2.2. ILocoE Paper Axleboxes, E. S. Cox (1944).

This paper explains thoroughly axleboxes fitted to steam locomotives and the forces applied to them when a locomotive is in motion. Two types of locomotive are studied, those with inside motion (where the piston and cylinders are fixed in the middle of the frames) and those with outside motion (where the pistons and cylinders are fixed on the outside of the frames). As this paper was written in 1944 no computer simulations were available to simulate such loadings on axleboxes therefore measuring equipment was fitted to the locomotives being investigated to attain results. The comparison between the two types of motion are compared and various positives and negatives of each design are mentioned. Both the papers mentioned are deemed to be accurate and trustworthy as they have been checked by a number of professionals and is worthy of being part of the archives. Both the papers are the most up-to-date sources of this information.

2.3. British Locomotives of the 20th Century, O.S.Nock (1984)

This book written by a well know railway author describes in detail the background of the majority of locomotives that were in use from around 1930 to the end of steam in 1965. The book doesn't specifically revolve around the WD Austerity designs but does include several detailed diagrams and technical drawings that will help with the creation of the model on Solidworks. Information is also included on the early history of the designs involvement in this country and the testing procedure carried out to determine the efficiency and operativity of the machine. What is interesting is that there is a section describing the ride comfort during trials. It mentions that crews noticed heavy thumping motions in the fore and aft directions. This action would apply large forces upon the horn guides. When travelling at high speeds it was also noticed that lateral sway and oscillation became noticeable, this also would impact on the strength and increase deformation in the frame and horn guides. Written by a well-known railway author this book is deemed a reliable source of information.

2.4. Heavy Goods Engines of The War Department Austerity 2-8-0 and 2-10-0, J.W.P. Rowledge (1978)

This book explains in detail the history of both the 2-8-0 and 2-10-0 designs of the Austerity locomotives. Each number produced is mentioned along with details of their manufacturer, date of build, length of service life and location of operation. The details of their manufacture are mentioned in depth and compared with the current version of LMS 2-8-0 locomotive operating at the time of these new locos. Criticisms of the locomotive are described however nothing is mentioned about any movement with the horn guides or frame. It is quite likely that due to the vast number that were produced for the War effort, once locomotives developed complex issues they were side-lined. This is mentioned in this book, as early as 1945 the British locomotives were becoming redundant in Europe. "This was no reflection on their capabilities for they must have been in better condition than the existing continental engines but it seems to have been the result of the Americans 'dumping' their locomotives as part of the 'Marshall Aid' programme." (Rowledge, 1978). A large section is included in this book explaining the use of these locomotives within the Netherlands where this locomotive served a large amount of its operational life. The different modifications are discussed, explained and the types of operations these locomotives undertook. This book is a complex assortment of information about the lives of the Austerity type of locomotive. It contains useful history about the locomotive and technical information relating to the build and components within the design. It doesn't specifically relate to the frame design, however it does contain details that describe the operation of the locomotive during service while operating on the Continent. The information included within this book has been gained from several sources. The introduction states that the author has no special claim for copyright for the data and material contained within this book. Various sources have been used for the collation of information, these being; published papers, public records and some from the people that corresponded with the author over many years. Details of the locomotives in Holland is the copyright of Mr.R.J.Bayliff who allowed the use of his material within this book. This book is deemed to be an accurate account of this locomotive and all the information included from the book is deemed correct.

2.5. Handbook for Railway Steam Locomotive Enginemen, British Railways (1957)

Information relating to the operation of steam locomotives is displayed within this book. The methods of operating the controls and how to make up the fire for effective steaming is discussed. Each component which makes up the working locomotive system is displayed in detail with intricate diagrams to attempt to make the reader fully understand the systems to which are required to function in a particular way. Due to many designs being developed by separate locomotive builders there are an assortment of different designs for each component such as the type of valve gear fitted. It is this factor that is of most concern to this project as a section has been included discussing how the forces are transmitted from the piston to the horn guide face. Images and information have been used to explain the process the steam takes to provide the movement experienced. Due to this book being written by the British Transport Commission it is deemed to be accurate in the technical processes and information which is used within this report.

2.6. A Defence of the Midland/LMS Class 4 0-6-0, Adrian. Tester (2011)

Although not directly written about the locomotive this report is based upon, this book explains high detail of certain aspects that are common to all locomotives. Problems with frame distortion and failure are mentioned which is of concern to me and this project. Various calculations and diagrams have been used within sections that explain the force application to the axleboxes and horn guides to which have been used to calculate the required forces inputted onto the computer model. Turning the information gained by the author over the 10 years of volunteering at the Keighley Worth Valley Railway into a well-structured description of locomotive systems has proved a challenge. However this book has aided in perfecting the writing into a form which is hoped to be of an interesting and understandable nature. Various sources have been used to create this technical book, including the ILocoE papers also described earlier. The information used matches with parts of these papers indicating the author of this book has carried out thorough research of legitimate sources.

3. History

With the outbreak of WW2, a cheap and easily constructible locomotive was required for the war effort. These necessary locomotives were required to operate on both UK and in mainland Europe.

Due to large amounts of miners leaving to join the forces there was a shortage of a workforce to mine the required coal to power the nation (Johnes, 2014). Adding to the problems French and Belgian coalfields fell into Nazi control cutting off another coal supply (Invicta Media, 2000). These factors caused the designer Robert. A. Riddles to design a locomotive that could burn low quality coal. This lead to a design with a large firebox grate area that was able to produce large amounts of heat through burning the low-quality fuel. (Marsden, Rober.A.Riddles, 2001-2017)

Several manufacturers produced two different designs of War Department Austerities, these being;

- North British Locomotive works
- Vulcan Foundries

The two different designs were differentiated by their wheel arrangements (see appendix 1), one being a 2-8-0 and the other being a 2-10-0. The two generally produced the same power but the 2-10-0 variant benefitted from having a lower overall axle weight. (Herring, 2004)

Initially 79257 was sent to the Netherlands to operate and rebuild their railways destroyed during the War. Other locos of the 935 built were found operating in the UK, across Europe and beyond. The Dutch State Railways upon acquiring 79257 renumbered the machine allocating it 4464 before joining their fleet of existing locomotives. (Rowledge, 1978)

After being surplus to requirement the loco was purchased by the Swedish State railways in 1953 for operation on their network. Before entering service, it was given the classification G11 and rebuilt to cope with the harsh conditions that are often experienced close to the Arctic Circle. Before entering service in 1954 the loco was allocated the number 1931. It saw very little work compared to other locomotives of this type. It was finally withdrawn from active service in October 1956 where the loco was mothballed in a shed located in a secluded forest as part of a strategic reserve. It was stored in a condition where it could be quickly made serviceable if desired. (KWVR, n.y)

It was finally discovered by a group of volunteers from the Keighley Worth Valley Railway in 1972. This group from West Yorkshire visited Sweden to inspect their potential purchase after being made aware of its existence. This type of locomotive had frequented the area around the KWVR during the days of steam operation. Other examples were also known to travel up the line pulling freight to Bradford, Halifax and beyond. After all other examples of the Class had been scrapped the possibility of rescuing the very last example was deemed an opportunity not to be missed.

An assessment was carried out on the machine to determine the operational state and condition. After talks with the Swedish railways, permission was granted to purchase the locomotive and shipment back to the UK was organised. On the 12th January 1973, the locomotive and corresponding tender arrive at Hull docks and unloaded onto a road trailer ready for the final transportation to Haworth locomotive depot on the KWVR. (KWVR, n.y)

The convoy of loco and tender arrived the next day. Due to the care undertaken by the Swedish locomotive engineers and operators, very little work was needed to return the locomotive to operational service. The loco ran on the Worth Valley line until 1976 when it was deemed necessary to carry out a full overhaul due to the run-down state of the engine and tender, discovered after a detailed inspection was carried out. The few years of running on the KWVR had contributed to the deterioration of the mechanical condition. The maintenance facilities at Haworth were poor in the 1970's and engineering work on locomotives would not have been to the same standard as they are today. As the railway was relatively low on funding having only been revenue earning since 1968 the replacement of components on the locomotive became at times financially difficult. This added to the operational condition deteriorating to the point where a full strip down overhaul and rebuild became necessary.

Running in its Swedish guise on returning to UK, its withdrawal from operating service the decision was taken to return the loco to its British outline design. (Marsden, The Riddles O7 (WD) "Austerity" 2-8-0s, 2001-2007)

Further details of the locomotive found in appendix 3.

4. Design

The original designer Riddles closely followed that of William Stanier's 2-8-0, this being one of the most successful locomotive designs being constructed in vast numbers. The locomotives were known to be very reliable and having a high tractive effort resulting in high tonnage trains being hauled with just one locomotive. The rigid construction of these locos also meant that many examples lasted well into the final days of steam. Another Class of locomotive was built to aid the War effort, the USA built S160 locomotives. A similar arrangement to the Austerity UK locomotives being a 2-8-0 wheel arrangement they were built to provide heavy hauling capacity to aid and rebuild War damaged railway systems. This locomotive incorporated bar frames which were found to be far stronger than the UK plate frames. These locos were much heavier than the British designs and damage to weak track was noticed as the locomotives operated in the different countries. (Higgins, 1980)

Due to the War effort, the frame design for the Austerity was significantly different from their predecessors. The reduction in steel production resulted in the designer adopting a value engineered solution achieved mainly through the fabrication of parts rather than casting. This resulted in faster build times and increased productivity. Although this lead to a reduction in the strength of the frame when under load and operating under tractive forces.

It is this factor of reduced strength that is affecting the locomotive to this day. Problems resulting from the frame design became apparent around the midlife of the current overhaul. Lateral sway had developed over time dramatically reducing the ride comfort for the crew when operating. It was deemed necessary to remove the locomotive from operational duties to inspect the condition of the axleboxes and respective horn guides which act as a restraint for longitudinal movement. After removing a driving wheelset using the wheel drop at Haworth (see appendix 2) it was noticed that the white metal top surface on the boxes had sustained heavy damage. Each axlebox was removed in turn from each of the axles for further inspection. It was clear to see once removed from the loco that the forces being applied on the boxes was far greater than initially thought due to the deformation and failure of the white metal surface. This material when agitated peeled off the surface when touched. The decision was made to replace the metal alloy with something more robust to cope with the forces being applied. After calculations were made to estimate the forces being applied by the locomotive's caretaker "a person responsible for the locomotives upkeep at the KWVR" a new material was specified for the axlebox faces. Bronze plates were chosen as an adequate replacement for the white metal. These were subsequently ordered from a manufacturer. On arrival at Haworth the basic plates were machined to new dimensions to suit the horn guides. Checks were made on the horn guides after removing the axleboxes to see whether any deformation had occurred to these faces. A series of methods were used to identify this including utilising micrometres measuring between each horn face to determine whether any deformations had occurred between the width of the guide gap between faces. After countless measurements, it was evident that the faces had deformed, a flat plate was then used with engineer's blue ink to rub against the face to highlight any high spots. These high spots were then ground down to make the face flush again to accept the new manufactured axlebox face plates. This process was highly tedious due to the fact minute amounts of material had to be removed to get the face within a fine tolerance. Hand tools were used in this process due to electric powered grinders being too severe of an action for the minimal removal of material to take place.

4.1. Component Background

An axlebox is basically a restraint for the axle on a locomotive or item of railway rolling stock much like a bearing. The axle is supported in these boxes and is allowed to revolve through a thin layer of oil being present on the surface. The axlebox is positioned between two slide faces called horn guides, these faces restrain the axlebox from longitudinal movement but allows the box to move vertically in the positive and negative Z axis to account for track irregularities. The vertical movement is controlled using leaf springs that are connected to the axleboxes and to the locomotive frame. The springs are designed to cope with the weight of the loco and the spring stiffness set according the weight being applied on each axlebox by the locomotive. Currently the horn guides operate independently from each other, during discussions with the locomotive's caretaker an inspired idea was found. This idea comprised of fixing the horn guides so that the stress from cornering or any lateral movement is shared between each side. This will hopefully preserve the stiffness of the frame and stop any lateral distortion. The outside axlebox face that touches the wheel set transmits the force applied from the wheelset to the horn guides. The Worth Valley comprises of fairly tight radius curves compared to a mainline railway network. Due to the tight radii in the track work large forces are applied onto the axleboxes and horn guides. The amount of material present on the horn guide faces is minimal, therefore the option to direct force away from the side faces should in theory reduce potential damage occurring to these small faces. Currently the axleboxes contain bronze mating faces with the horn guides. It will be interesting to see when the locomotive has finished its current operating period whether the material has coped with the forces being applied. To help with the re-design a force diagram has been used (shown in figure 5) to aid with the FEA, and in understanding the forces being applied when the locomotive is in operation. (For more axlebox information see appendix 5)

The leaf springs are attached at the base of the axleboxes and in turn fixed to the frame using brackets. These brackets are attached to the frame using rivets, these then acting as the secondary restraint for the springs. Lubrication to the axleboxes and horn guides is fed from gravity fed oil pots. The feed pipes run into the top of the boxes allowing the gravity to pass oil into the feed points within the system. Oil is also admitted through an underkeep that rubs on the underside of the axle.

4.2. Existing Horn Guide Problems

Throughout the life of locomotives problems have occurred with frame distortion and horn guide failure. An example of a locomotive heavy on frame breakages was the 0-6-0 type of locomotive. In this case the Fowler 4F. It was known for locomotive repair shops to assemble complete sets of new frames for locomotives suffering with frame flaws. The new sets of frames would be substituted during a heavy general repair. (A repair in which running is affected by the condition of the loco). It was known that axlebox wear generally determined the point of which a locomotive would be admitted into facilities for maintenance called an intermediate repair which was lower priority than a heavy general. (Adrian, 2011) (see appendix 6)

It is noted that in 1948 an example of the Austerity Class was tested between Severn tunnel junction and Acton. This loco being in a very run down condition was noticed to ride very roughly. It was reported that the locomotive footplate conditions were exceedingly poor for the crew with considerable vertical oscillation and bumping experienced. When steam was shut off very bad fore and aft thumping movement was noticed which gradually reduced while the locomotive coasted (Nock, 1984) . This could potentially mean that the horn guides had deformed and hammer blow was occurring between the axlebox and horn guide mating faces. For a locomotive around 5 years old this is surprising although such machines were known to accumulate large mileages during War use. Data collected from the steam era shows that 80% of the Stanier 2-8-0's on which the Austerities were based upon required intermediate repairs after fifty to eighty thousand miles. (Tester, Multiplication and Modification, 2011) The Austerities would have probably received little or no inspection and repair while on the Continent, therefore problems are more than likely only being noticed now as more care is being taken over the condition. After 72 years 90733 has done exceedingly well considering its design lifetime was only around three years.

Tester also mentions that metal fatigue is perhaps the most insidious causes of the loss of strength in a metals structure and represents the cumulative effect of fluctuating loads. This was the overwhelming reason cracks developed in locomotive frames over periods of intense running. Figure 1 displays the locations of frame cracks identified on 134 LMS Class 5 locomotives.

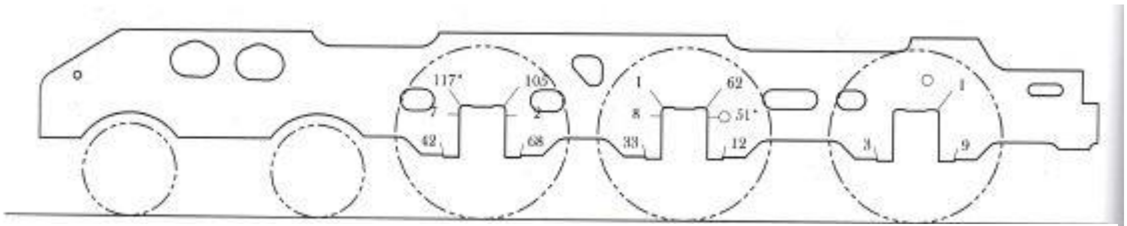


Figure 1 Location of frame cracks (Powell, 2011)

E S Cox stated "the Class 8F 2-8-0 occupies an intermediary position in the scale of frame fracture. It is neither very good not very bad". (Cox, 1947)

Mr C W Clarke explained in 1946 the procedure to test a LMS Class 5 4-6-0 locomotive at low speeds around Derby station. A pair of De Forest recording Scratch extensometers*[1] were fitted to each frame plate on their inner faces near the upper rear corner of the leading coupled axle. After this test had been carried out laboratory tests were conducted using the newly discovered strain gauges on a full size section of a horn gap (Clarke, Distribution of Stress in a frame plate, 1939) much like designed in Solidworks for this project.

*[1] (*an instrument for measuring minute deformations of test specimens caused by tension, compression, bending, or twisting)* (Merriam - Webster, 2017)

4.3. Loads Present in a Locomotive Frame

A locomotives frame is designed to carry the boiler along with all the additional components that make up a locomotive's operating system. It provides a means for attaching the cylinders and maintain the correct position of the axle centres for attachment of the connecting wheel motion rods. The need for the loco to negotiate track curvature is designed into the frames and motion assembly by providing sufficient clearances between the wheel tyre flanges and the rail head, coupling rods and all other motion that provides the transfer of power to the wheel sets. When the locomotive negotiates curvature, the rails ride up or ride down the flanges of the wheels. This feature acts much like a differential on a car as one side of the loco is travelling a shorter distance than the other due to the angle of the fixed tyres on the wheels an example of this is shown in figure 2.

When the loco moves to the right for example the rail rides up the tyre and touches the flange indicated by the well-known squealing sound emitted when travelling over points or curved track work. The rail on the other side however moves down the tyre to the smaller outside diameter of the wheel making cornering possible. This action forces the axleboxes against the horn guide putting pressure on the axlebox flange side, horn guide side and corresponding frame. The locomotive frame incorporates sufficient clearances in-between the wheels, axleboxes and axleboxes/horn guides. This aids the lateral force distribution and process of following a curved railway system. When the locomotive is in operation the frames experience an assortment of complex forces exerted from predominantly the action of the piston thrusts. The force is then transferred through the small end of the motion to the big end (see figure 6). From there the load is transferred by the coupling rods to each of the driving wheelsets.

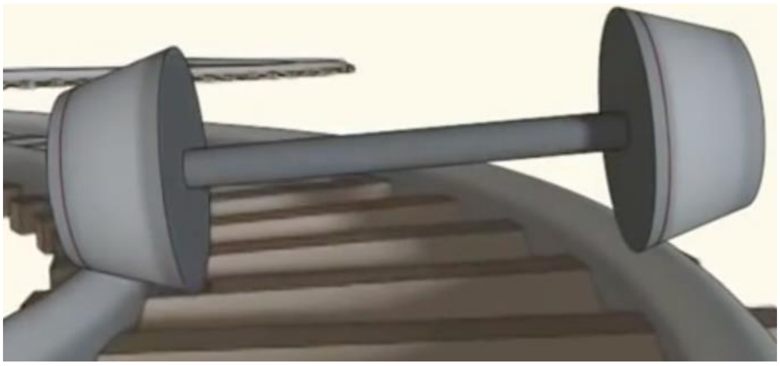


Figure 2 Wheelset negotiating curve (Kumar, 2016)

The forces following the application of a piston stroke are;

- Buffering from unbalanced valve timing & loco motion.
- Drawbar loads exerted from the tender weight and train. The couplings which attach a train to a locomotive are never completely tight, therefore when the weight shifts the train applies another buffering force to counteract the forward momentum applied by the piston.
- Springing forces that occur when travelling over un-even and dipped rail. These are vertical applications of force.
- Braking forces apply a longitudinal as well as a rotational, as brake blocks compress onto the driving and tender wheelsets.

A diagram displaying the stresses applied onto a frame is shown in appendix 8.

There are of course other forces involved, such as in derailments the loco may have to be lifted back onto the railhead. Loads would then be applied at the allocated lifting points at the front and rear of the frame. Loads would also be applied on the horn stays as the wheels lift off the railhead. Horn stays hold horn keeps in position at the base of the horn guides, thus preventing the axleboxes from over travelling and falling out of the base of the frames. These horn stays are often removed to reduce the loads being applied on the frame and the horn stays themselves when lifting.

In most designs of locomotive, including this example, frame plates are of a continuous construction from the front buffer beam to the rear drag box. In the case of 90733 the frame is braced at the front where the smokebox and cylinders are mounted. Further back from this position the frame is braced through the use of frame stretchers.

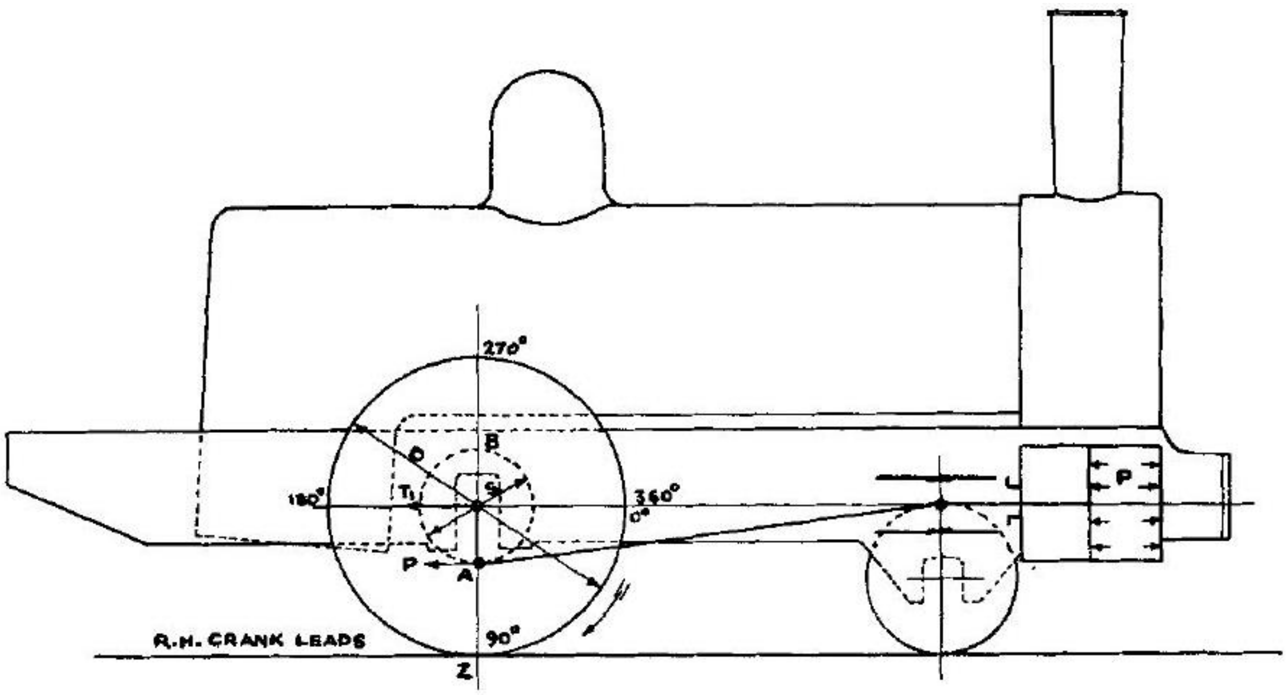


Figure 3 Forces acting upon a driving axlebox (Clarke,1939)

The distance between the centre of the axle and the rail head is equal to half of the driving wheel diameter (D/2) and the throw of the crank (shown on figure 3) equates to one half of the piston stroke.

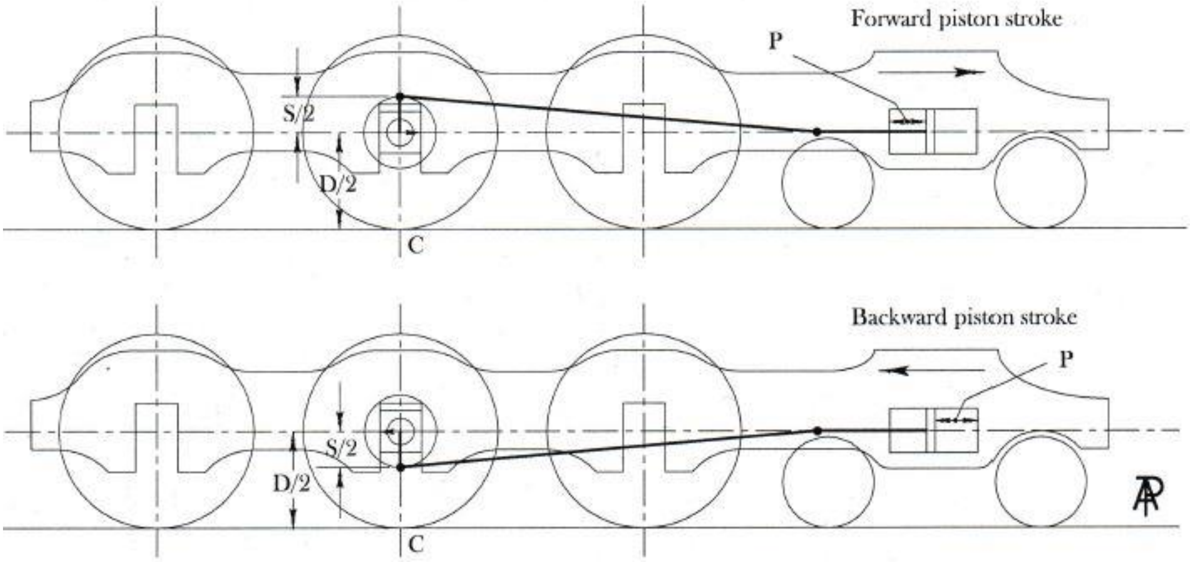


Figure 4 Force action (Tester, How tractive effort is exerted, 2011)

When the loco travels forwards, the piston moves from the rear of the cylinder to the front. In this movement, the steam applies a force (P) upon the piston and via the connecting rod this force acts upon the crank pin. The same force (labelled P figure 4) also acts in a backwards direction on the rear of the cylinder cover. Since the cylinder/cylinders are attached to the frame the front horn cheek is forced against the same axlebox mating surface with the same force. This force applies pressure and forces the axlebox onto the axle. Through the application of the coupled motion rods this is also applied onto all other driving wheelsets. The wheel and the crankpin form a lever that opposes the fulcrum formed at position C the point of contact between wheel and rail. (Tester, How tractive effort is exerted, 2011)

On the backwards stroke of the piston the steam exerts a force P (figure 4) on the front cylinder cover. This action pulls the rear horn face onto the rear driving axlebox face. The force P also acts on the piston but now the crank position has changed and with it the action of the lever formed by the wheel and crank. From the law of levers a force is created that pushes the driving box backwards against the rear horn face. (Tester, How tractive effort is exerted, 2011) This is shown in equation 1.

Equation 1 Thrust force applied on rear horn face (Clarke, Locomotive Hornblocks - with a note on frame stresses, 1939)

$$T_1 = P(D - \frac{S}{D})$$

P= Piston Force D= Driving wheel diameter S= Length of piston stroke.

From this we can see that the driving axlebox exerts pressure on the front horn face causing the locomotive to move forward on the forward piston stroke. When the piston is on its backwards stroke, the force on the front cylinder cover moves the loco forward. An alternate way of looking at this is that as the piston moves through the cylinder on the forward stroke but the cylinder moves over the piston on the backward. (Tester, How tractive effort is exerted, 2011)

High magnitude forces are applied on the front and rear horn faces as these movements take place due to the movement from the piston exerting movement on the driving axlebox on each set of horn guide faces. These forces can cause excessive wear upon the horn guide faces and also the driving axlebox faces. This was shown after removing the boxes around 4 years ago. The white metal faces on the boxes had been compressed to an extent of removing itself from the faces. Once the boxes were removed the remaining white metal fell off the faces in slabs. Thus displaying the high degree of force input on these faces by the horn guides.

A diagram explaining the forces applied is shown in figure 5.

PR= Piston thrust - right hand side

PL=Piston thrust – left hand side

SR= Resistance to motion of other coupled wheels transmitted along Side rods – right hand side

SL = Resistance to motion of other coupled wheels transmitted along Side rods – left hand side

W = Static weight

T = Tractive force

F = Flange force

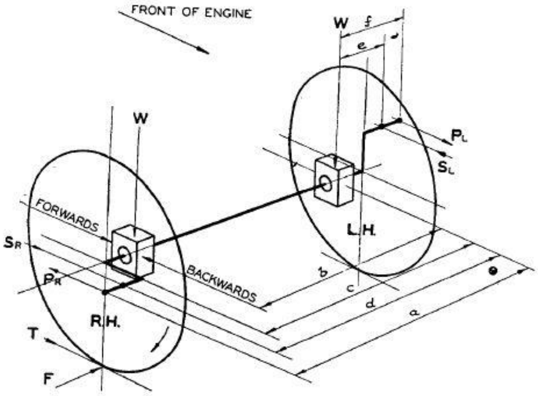


FIG. 2.

AXLEBOX FORCES OUTSIDE CYLINDER ENGINE. RIGHT HAND CRANK LEADING.

(Symbols as on Fig. 1)

FORCES ON R.H. AXLEBOX DUE TO:—

1.	Static weight.	W	Downwards.
2.	Nearside crank, R.H.	$P_R a/b$	Backwards.
3.	Farside crank, L.H.	$P_L f/b$	Backwards.
4.	Nearside coupling rod, R.H.	$S_R d/b$	Forwards.
5.	Farside coupling rod, L.H.	$S_L e/b$	Forwards.
6	Tractive force.	$T c/b$	Forwards.
7.	Flange force.	F	Laterally.

Figure 5 (Tester, Calculation of individual forces acting on an axlebox, 2011)

5. Measuring the Locomotive Frames

To determine the modification process to be carried out on the locomotives frame, a model on Solidworks CAD software needed to be created. Investigations began into acquiring technical drawings, which were potentially available in the archives at the National Railway Museum. These drawings failed to be sourced, therefore the decision was made to measure the locomotive at Haworth by the author. This resulted in a greater understanding of how the machine was put together and weak spots/ flaws in the structure were noted. A list of required sections was created and the process of measuring carried out. Various implements were utilised to gain the data from which a model could be created on the Solidworks software. A tape measure was used for many of the measurements due to the considerably large size of the loco. A pair of large pincers were utilised to measure the connecting rod thickness, required for calculating one of the forces being inputted upon the locomotives horns. Finally, a steel rule was used to measure small distances. To support measurements a general arrangement drawing (see appendix 10) was sourced from a book and scanned, this however only gave minimal dimensions for the frame of the locomotive. However, there were some dimensions that could be utilised.

The different parts that made up the Austerities frame were then modelled using the dimensions taken off the machine. After each part was created they were assembled in the software to build up the structure of the CAD model. The front pony truck of the loco wasn't modelled due to this not being a ridged structural component. This will be considered however when it comes to analysing the results gathered from simulating loads being applied to the frame.

6. Calculating the Loads on the Frame

After creating the frame model the different forces being applied upon the frame had to be calculated. The formula used for the longitudinal piston thrust forces was found within a book by A. Tester shown in equation 1 (p16) explaining about how force is exerted on a horn guide face. This formula took into account the Piston force, the driving wheel diameter and the distance from the Crank pin to the centre of the driving wheel. The driving wheelset was used as the largest point of force application due to this being the point at which the force is initially transferred from the Piston to the rest of the driving wheels through the use of the coupling rods. The force from the Piston is transferred from the Piston itself, down the Piston rod, through the Crosshead, Gudgeon pin and along the Connecting rod and to the Big end (shown figure 4). The big end is connected through the coupling rods to the rest of the wheelsets. The initial force transfer is however through the horn faces on the driving wheel set.

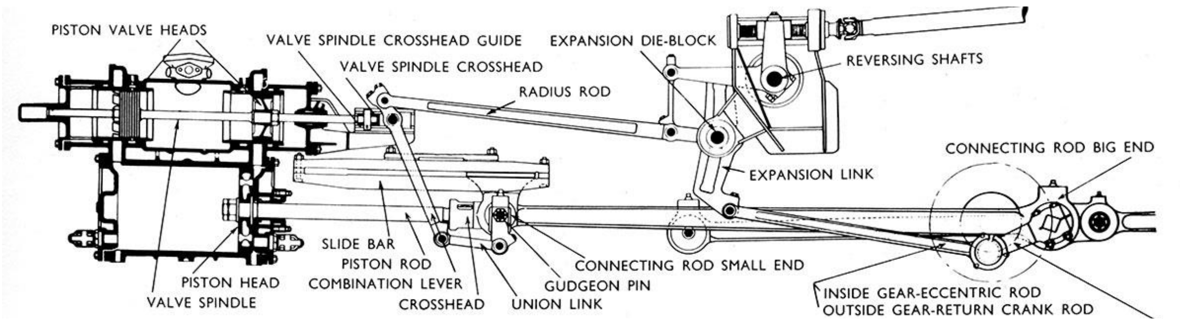


Figure 6 Walschaert's valve gear (Railways, 1957)

Other forces to consider are when the loco negotiates curved track work, the tightest curvature on the KWVR is around the station area at Keighley. Here the speed is restricted to 20mph due to the severe gradient.

The tightest curve through the station area where the speed is lowered to 10mph, an operating rule when arriving into stations. The low speed however may cause lower force applications than negotiating a lower radii curve at a higher speed. The force will be calculated for the tightest curve on the Worth Valley that is run over at line speed (25 mph). The tightest line speed curve was used for the lateral calculations. This curve is not fitted with a check rail. Check rails are laid parallel to running rails that assist locomotives or items of rolling stock negotiate track curvature and points. They prevent derailment by stopping the effect of flange climb where the flange acting on the outside of the curve being negotiated climbs up over the rails inside edge leading to a derailment. These check rails lower the overall force applied upon one flange, therefore a 200m radius curve was used for the calculation as this radius of cure is the minimum radius not requiring a check rail (RSSB, 2011). There are several flange lubricators fitted to curves on the KWVR these lower the friction upon the impact flange to rail interface. However the worst case scenario will be considered where such a device is not in operation.

The weight of the locomotive is transferred to the frames via leaf springs that are attached to compensating brackets fixed to the inside of the loco frames. The compensating system allows smooth transitions of equal force to be applied onto the frame through the locomotives movement over rail. Due to the locomotive being designed to operate in War damaged environments this system was fitted to account for the potential of heavily varying degrees of track quality. From the compensating brackets the spring is fixed centrally to the bottom of the axlebox. As the loco negotiates undulating track the leaf spring dampens the movement allowing for a smoother ride. The leaf springs for each locomotive are designed specifically for use with that machine meaning that each spring is sufficient to cope with each axle weight. The weight was calculated using the maximum service weight of 70 tons. The axle weight for the locomotive is 15 tons this then multiplied by the number of driving axles (4) gives 60 tons. The front of the locomotive is supported by a pony truck which helps the locomotive lead into corners. This therefore taking up the rest of the weight 10 tons. The 60 tons supported by the 4 driving wheel sets is applied onto the frame through the spring hanger brackets. There are 5 brackets along each side of the frame therefore the 60 tons is halved for each side of the frame. The 30 tons is then divided by 5 to find the amount of weight applied onto each bracket. The weights applied are all fully compensated across all 4 axles therefore the weight applied is the same for each support.

Figure 7 spring hanger bracket (Kay,2017)

Figure 7 displays the compensating spring bracket. The springs are attached via a rotating bar allowed to pivot around a central shaft fixed through the bracket. This system allows an equal distribution of the static weight applied when stationary and dynamic weight when the locomotive is negotiating undulating track work.

This feature will be implemented onto the Solidworks model however in a simplified form. The known forces being applied onto the locomotive when in motion is very difficult to calculate as it depends on the condition of the track, the speed and how much water and coal is currently being utilised to generate the steam. Although not a substantial weight when considering the total weight of the locomotive the water and coal within the locomotives boiler can easily add around 3-4 tons to the overall weight. Therefore extensive investigation would be required to calculate such dynamic forces the static weight of the loco will apply. This will be done through attaching a cube around the same size as the bracket to the frame and a downwards force applied to the top. This won't be fully accurate but it should give a result close to what would be expected.

Other forces to consider are the ones from un-even valve setting of the locomotive.

As steam is emitted from the boiler through a value called a regulator (figure 8) it passes through a steam circuit that comprises of passing the (wet steam) back into the boilers superheater flue tubes. This wet steam is then heated again removing a greater amount of the water making for more efficient expansion and use of the generated resource. This now dry steam is admitted into the steam chest to which another valve named as the valve spindle controls the admission into the cylinder. This valve covers two ports through the use of piston heads. Acting very much like the inlet and exhaust ports on an internal combustion engine. These covered ports act as both the inlet and exhaust ports with sequential admission and extraction at both ends of the piston to cause rotation of the driving wheels.

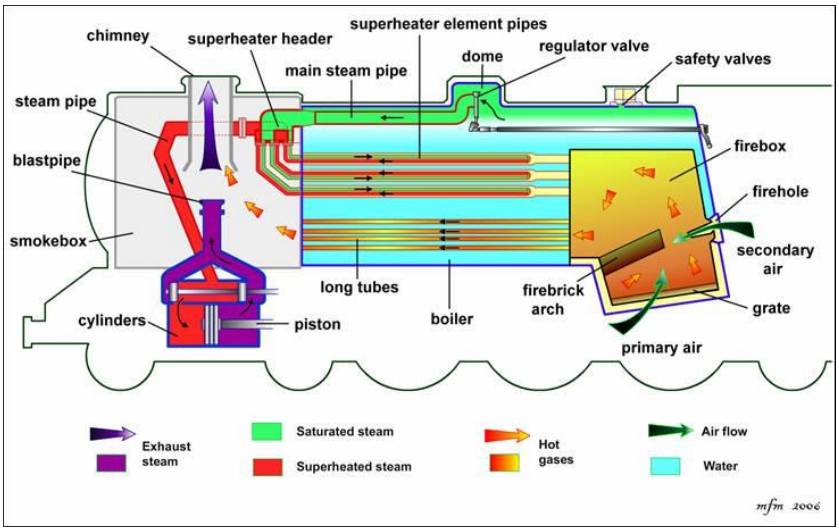


Figure 8 Locomotive steam circuit (Mustaffa, 2006)

The valve spindle setting is controlled by the engine's driver through a reverser in the loco's cab and is very much like a gearbox in a motor vehicle. A reverser controls the amount of steam that is admitted into the cylinder by the valve spindle. Another component of locomotive motion named as the expansion link is the device that is used to convert the driver's input into the valve spindles longitudinal movement. A component within the expansion link named as the die block is connected to the radius rod which in turn is connected to the combination lever and finally valve spindle. The reversing arm which moves the die block within the expansion link lengthens or shortens the travel of the radius rod altering the travel of the valve spindle. Movement is moderated by the forward moving combination lever which is connected to the crosshead through the use of the union link. This combination lever forces the valve spindle to close the admission ports to the cylinder. The point where the radius rod is connected to the combination lever becomes a fulcrum of the motion setup. (The point against which a lever is placed to get a purchase, or on which it turns or is supported (Oxford Dictionaries , 2017).

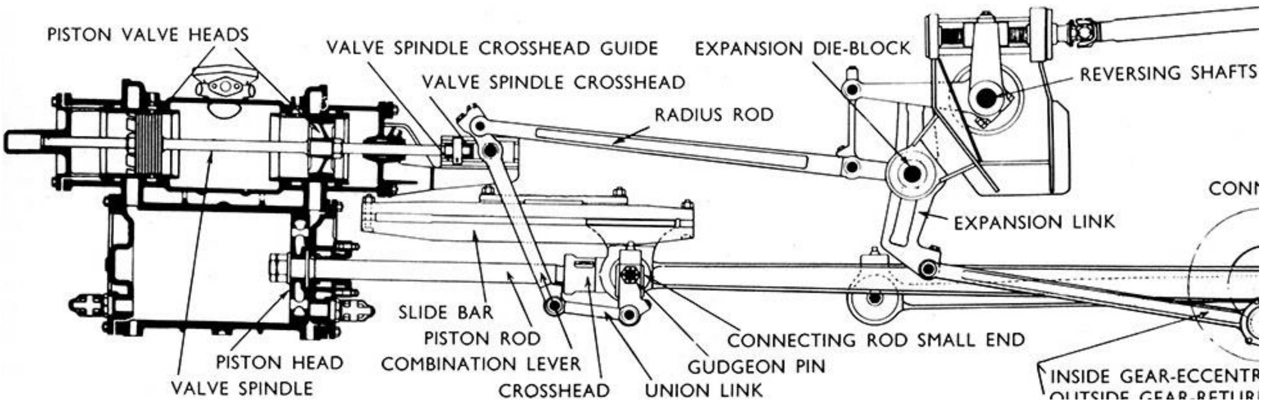


Figure 9 Walschaert's Value gear (Railways, 1957)

Shorter travel means less steam is admitted into the cylinder due to the ports being uncovered less than if the die block was further down or up the expansion link. When the expansion die-block is at the centre of the expansion link both ports are covered whereas if the die block is at the top or bottom on the expansion link the ports are fully open meaning for the full force application of the steam. This is normally only the case when the locomotive is setting off from stationary, applying the largest force upon the horn guide faces. The die block is moved gradually to a central location as the locomotive gains speed and momentum. This is due to less steam being required to maintain movement. (See figure 9)

If the valve timing is not correctly set a hunting periodic motion can occur which applies force thrusts to the frame. This is slightly occurring on this machine but again would require rigorous testing on the locomotive which cannot be carried out currently.

The drawbar weight on the loco will also put a longitudinal force down the frame from the drag box on the rear of the locomotive. This really depends on the length and weight of train being hauled. This force is calculated for the maximum admission of steam being applied onto the piston.

6.1. Lateral Force

Equation 2 Lateral force

$$F_{Total\ Lateral} = \frac{M_{Total} \times v^2}{r}$$

$$F_{Total\ Lateral} = \frac{70000 \times 11.176^2}{200}$$

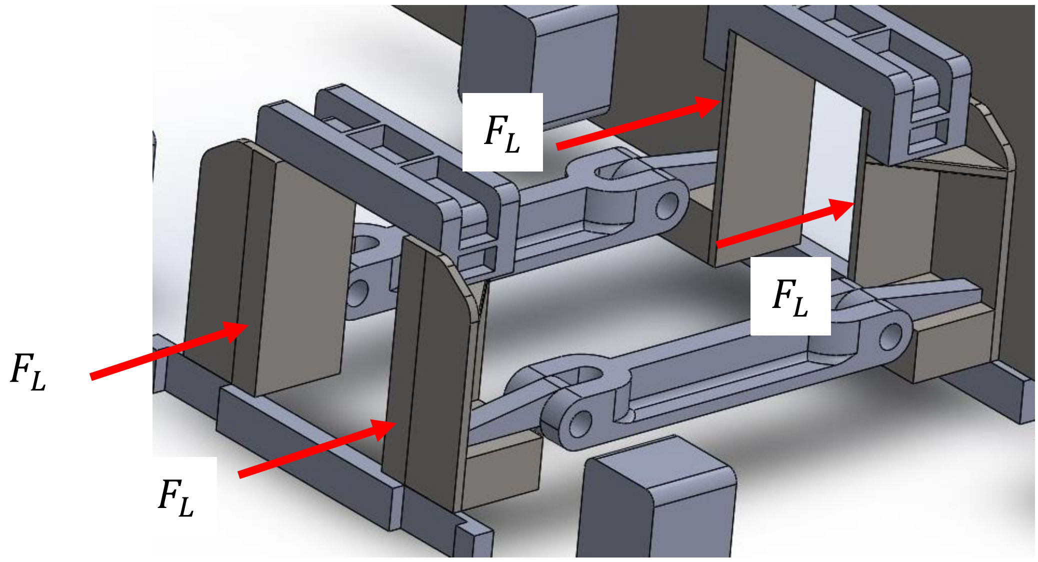
$$F_{Total\ Lateral} = 43716N$$

$$F_{TL}/4 = 10929N$$

$$2F_L = 10929/2 = 5464N$$

$$F_L = 5464/2 = 2732N$$

- M Total is the total weight of the locomotive in kg.
- V^2 = the cornering speed in m/s
- r = The radius of the corner in m
- The total force is divided by 4 across all driving axles.
- This then divided by 2 over each wheel
- Finally, the amount is divided again by two for application onto each of the 4-horn guide axlebox side contact faces.



6.2. Longitudinal Force

Equation 3 Longitudinal Force

$$Piston\ Force\ =\ Steam\ Pressure\ x\ Piston\ Area$$

$$225 \times \frac{\pi \times 19^2}{4}$$

- 225 psi boiler pressure, 19-inch diameter piston.

$$225 \times 283.53 = 63794$$

- Change from lbs to kg.

$$63794lbs = 28936.47kg$$

- Weight to force.

$$28936.47 \times 9.81 = 283866.77N$$

- 30% reduction to account for steam losing energy through steam circuit.

$$283866.77 \times 0.7 = 198706.739\ N$$

- Equation used as shown in equation 1.

$$T_1 = P(D - \frac{S}{D})$$

- P is the piston force, D is wheel diameter and S is the length of piston stroke.

$$T_1 = 198706.739(1.44 - \frac{0.3683}{1.44})$$

$$T_1 = 235315.6958$$

- Thrust force divided by 4 as force shared to 4 coupled wheel sets.

$$\frac{T_1}{4} = 58828.92$$

6.3. Vertical Force

Equation 4 Vertical Force

- Axle weight of locomotive is 15 ton, multiply by 4 axles.

$$F_{Vertical} = 15 \times 4 = 60\text{t}$$

- Weight on 4 driving axles dived by 2 to give weight on one side.

$$F_{Vertical} = 60 \div 2 = 30\text{t}$$

- Weight on one side divided by number of weight compensating pivot points attached to frame.

$$F_{Vertical} = 30 \div 5 = 6\text{t}$$

- Weight multiplied by gravity to find vertical force applied to simplified brackets attached to frame.

$$F_{Vertical} = 6000 \times 9.81 = 58860N$$

Figure 21 displays the forces acting on the model

6.4. Track Cant

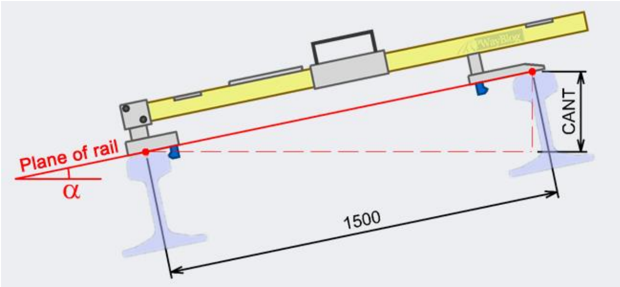


Figure 10 Track cant (Constantin, 2016)

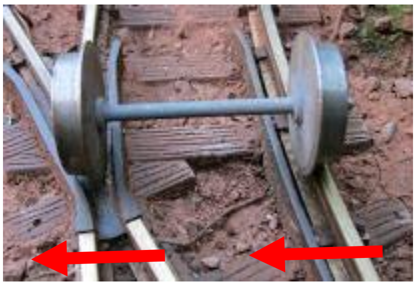


Figure 11 Wheel round check railed curve (Rik, 2012)

Different methods can be applied to the design of track work to reduce the direct lateral force sustained when traversing tight radius curves on a railway system. This method is called applying cant (figure 10). This method increases the angle of the curve to combat the amount of lateral force applied upon railway vehicles. Sleepers are laid at an angle to which the outer rail is higher in elevation than the inner. This change in height must be sufficient however to both reduce the contact to contact fatigue and force but also not compromise the structural balance of the train or locomotive. The maximum line speed for the KWVR is 25mph however there will be several trains that run over such canted curves at lower or in some cases higher speeds. Therefore, passengers will feel greater amounts of lateral force where the designed cant for that radius and speed of curve has been applied. (Railway Technical Web Pages, 2011)

The minimum radius of curve not requiring a check rail is 200m as stated in the Network Rail standards (GC/RT5021 'Track system requirements') and (NR/L2/TRK/2102 'Design and construction of track') (RSSB, 2011) (RAIB, 2013) . Fitting a check rail to a curve further decreases the amount of force being applied upon a wheel set. This being due to the outer-most wheel rubbing against this inside rail ultimately sharing the force. Figure 11 displays the process that occurs, basically the check rail prevents extreme lateral movement that would lead to derailment taking place.

This therefore means that the full force of lateral movement will be applied upon one side of the wheel fitted to the axle giving a worst case scenario.

6.4.1. Cant Calculation

Equation 5 Cant Calculation

$$E = \frac{11.82V^2}{R}$$

Figure 12 Cant Calculation (King, 2011)

$$E = \frac{11.82 \times 40.236^2}{200}$$

= 95.679 divide by 2

=47.839 ≈ 50mm

6.4.2. Lateral Force Calculation with Cant

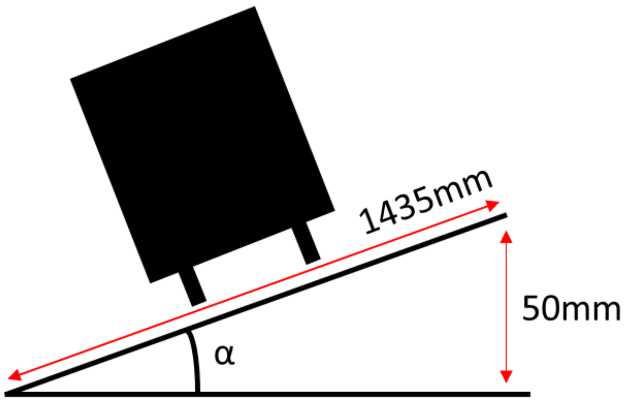
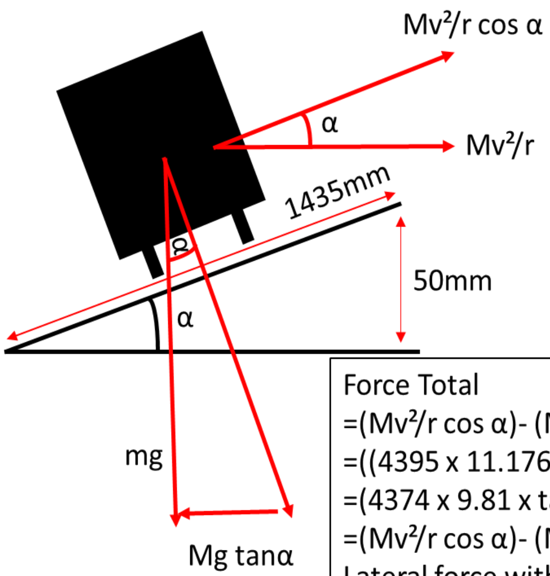


Figure 13 Cant calculation

Equation 6 Angle of cant

$$Sin \propto = \frac{0.05}{1.435} = Sin^{-1} = \propto = 2^{\circ}$$

Figure 13 and shows a simple mock-up of a locomotive or train negotiating a canted curve section of track. The hypotenuse value is the standard track gauge for the UK and majority of the world 4ft 8.5" converted into mm for continuity purposes. The height of 50mm is the amount of cant calculated in the previous section.



Equation 7 Lateral Force equation

Force Total
$=(Mv^2/r \cos \alpha) - (Mg \tan\alpha)$
$=((4395 \times 11.176^2)/(200) \times \cos(2))=2731$
$=(4374 \times 9.81 \times \tan(2))= 1498$
$=(Mv^2/r \cos \alpha) - (Mg \tan\alpha) = 2731 - 1498 = 1233$
Lateral force with cant = 1233N

Figure 14 Lateral force calculation with cant

Equation 6 displays the formula used to calculate the angle of cant applied to a 200m radius curve. Equation 7 includes the maximum intended line speed of 25 mph converted into 11.176 m/s. This calculated value was then used to find the new lateral force applied onto the lateral horn guide faces. Figure 14 displays the method that was carried out to resolve both the forces acting when negotiating the 200m radius curve at 25mph. Compared to value calculated to the value of force applied when cant is not applied ($2732N$) the amount of reduction is surprising.

This therefore shows a large reduction in the lateral force being applied almost 76% difference. With the Worth valley being a light railway i.e. the speed is low at 25mph and bridge weight low the amount of traffic is minimal compared to the mainline network. Weights of trains being conveyed over the route are low and of relatively short lengths. Therefore the levels of cant fitted to the KWVR will be much less than those levels fitted to the mainline network. Current data on the amounts of cant fitted to the KWVR are unavailable however it is known that certain locations do have an amount included. Therefore the calculations have been done to facilitate the inclusion of cant fitted to the minimum radius of line speed curve on the KWVR.

Each modification will be tested and results gained for track geometries with and without the inclusion of canted rail.

7. Solidworks Modelling

Drawings for the locomotive were unobtainable from the KWVR therefore it was decided that self-measurement of the locomotive was the only option. Enquiries were also made at the National Railway Museum as they hold the largest collection of locomotive data, drawings, and pictures in the country. However, no information was made available. Due to the involvement with the KWVR self-measurement was possible and gradually dimensions started to be collected.

A Solidworks model was gradually created however additional measures were required so various visits had to be made to record the necessary dimensions. Due to the locomotives current operating condition, and the locomotives structure, measurement proved difficult. A few of the dimensions taken from the machine have been able to be backed up by a general arrangement drawing (see appendix 10) that I was able to resource from the KWVR. However these dimensions were not sufficiently detailed. If exact technical drawings could be sourced the dimensions obtained could be checked and the model changed to suit.

Initially the entire frame of the locomotive was drawn in detail to try and obtain the most accurate of results for the deformation. From this it was decided to create a simplified model that contained just one set of horn guides for one of the driving wheelsets. This being justified by the locomotives weight and input force being shared equally by each of the driving wheelsets. Various changes to this design were made during preliminary simulations. An initial mistake was made with the horn guides, this being the assembly of them flush to the frame cut-out. This would prevent the axlebox sliding up and down the horn guide face due to the surface not being able to accommodate the shape of the axlebox. The horn guides were therefore moved the required distance away from the frame places in a way that the axlebox would be able to move vertically. Next a horn keep was installed as none was fitted prior to this. The horn keep restrains the frame from longitudinal bowing as weight is applied. This being a crucial part to obtain accurate results.

7.1. Material of Components and Frame

The first required factor was obtaining the correct material for each component that made up the frame formation. After inquiry with a few KWVR colleagues and the locomotive caretaker, (a mechanical engineer that maintains the locomotive) EN8 steel was found to be correct for each part within the assembly. This probably being due to the fact the locomotive was built during the War and material of different kinds and grades being scarce.

8. Simulations

After it was deemed the model reflected current design fitted to the locomotive, simulations were planned. The EN8 Steel material was applied to each component within the model. Mesh was then applied following a mesh convergence to ascertain the correct values. Finally the calculated forces were applied to the frame and simulations run. The process followed is explained below.

8.1. Meshing of Model

This step within the FEA process required several attempts and re-thinks. Initially the whole model was attempted to be meshed with a constant size. However this proved to take far too long to simulate for various results to be obtained. A mesh control method was then envisaged and trialled on the model. The mesh control was applied around the areas in which movement was expected to take place. This would therefore mean that more accurate results would be obtained in these locations. Mesh control was also applied around the areas in which the model was restrained due to these locations also being subjected to forces resultant from the ones calculated and applied.

To determine the correct values for the mesh sizes a convergence study was carried out. This convergence study would hopefully produce two corresponding mesh sizes at which a near to constant displacement would be produced. Several tests were carried out with a different selection of both the global mesh size and the mesh control. After these trials a partnership of mesh size values were attained.

Global mesh size	mesh control size	displacement	1/ mesh control size
4	0.8	7.1472836	1.25
	0.7	7.1819429	1.428571429
	0.6	7.1387687	1.666666667
	0.5	7.2039609	2
	0.4	7.2377839	2.5
	0.3	7.2857637	3.333333333
	0.2	7.3039393	5
	0.1	7.3006802	10

Table 1 Mesh Convergence study

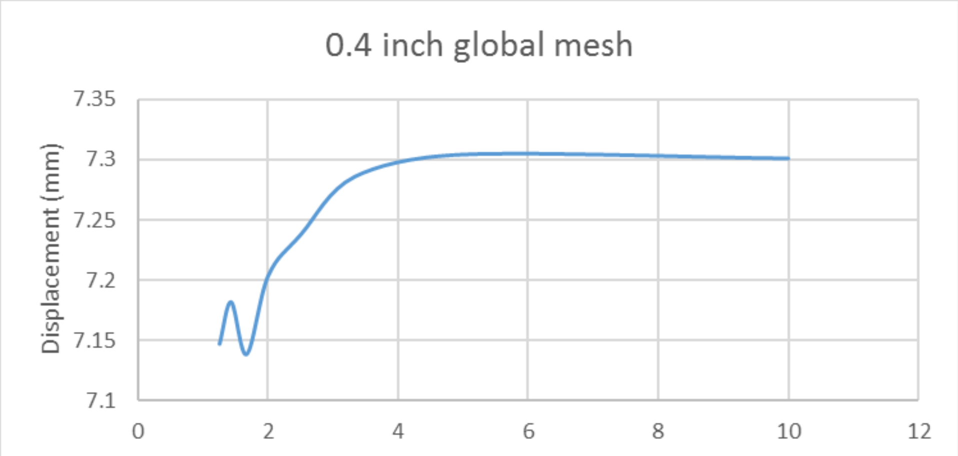
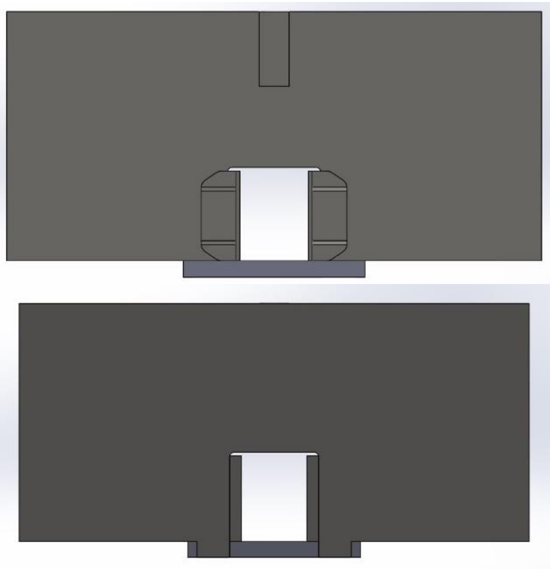


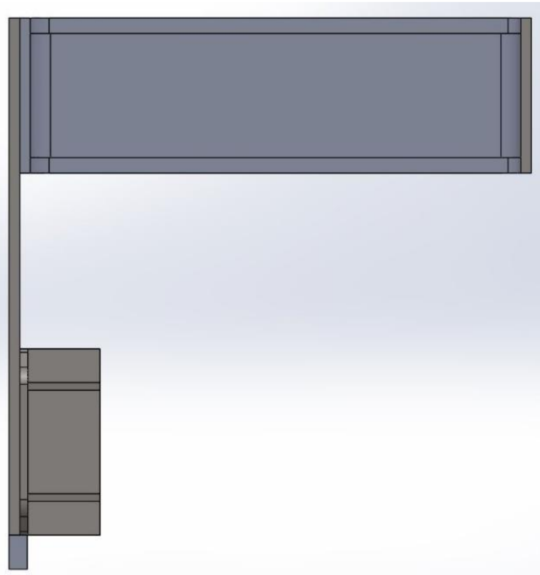
Figure 15 Mesh Convergence

As shown in table 1 and figure 15 a global mesh of 4 inch and a mesh control size of 0.2 inches produce a convergence. Therefore these values will be used for the each of the following simulations to determine the displacements on the 2-8-0's frame.

9. Results

9.1. Current Frame Design





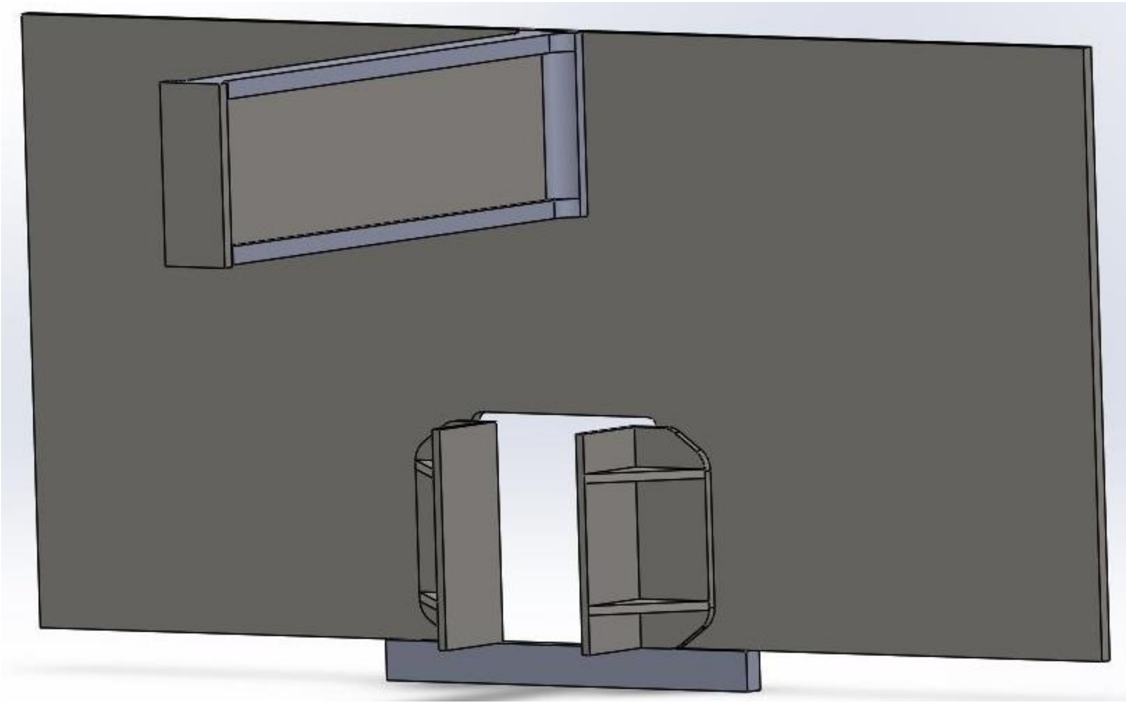


Figure 16 Current Frame Design

Figure 16 displays the current frame and horn guide design fitted to the locomotive. As mentioned previously this simplified version of the frame was used due to all the application forces being equal between each of the driving axles. This therefore means that the forces applied to the horn guide faces and frame sheets will be constant. Resulting in the simulations running quicker and meshing the model is far easier.

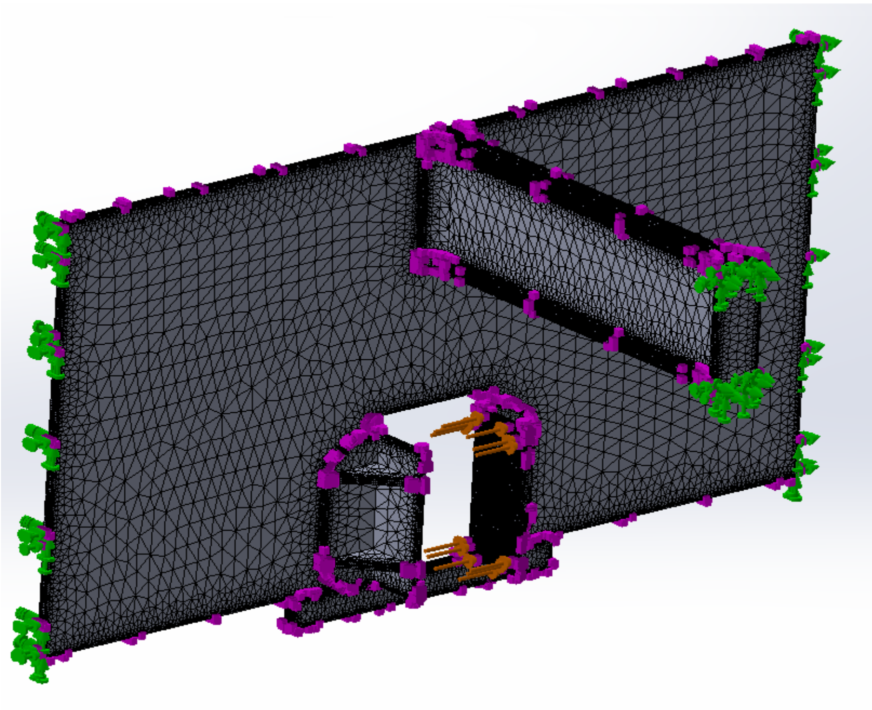


Figure 17 Meshing of model

Figure 17 displays the mesh applied to the model. As mentioned previously the finer mesh control size is applied around the areas in which movement is expected to take place and the areas in which forces are applied to the frame. This method allows the simulations to perform quicker due to the reduced number of elements making up the model compared to if a single small global mesh size was used.

After calculating the static weight force, it was decided that points to apply these forces were required. Therefore, as seen in figure 18 simplified brackets have been attached to the frame assembly to apply these forces.

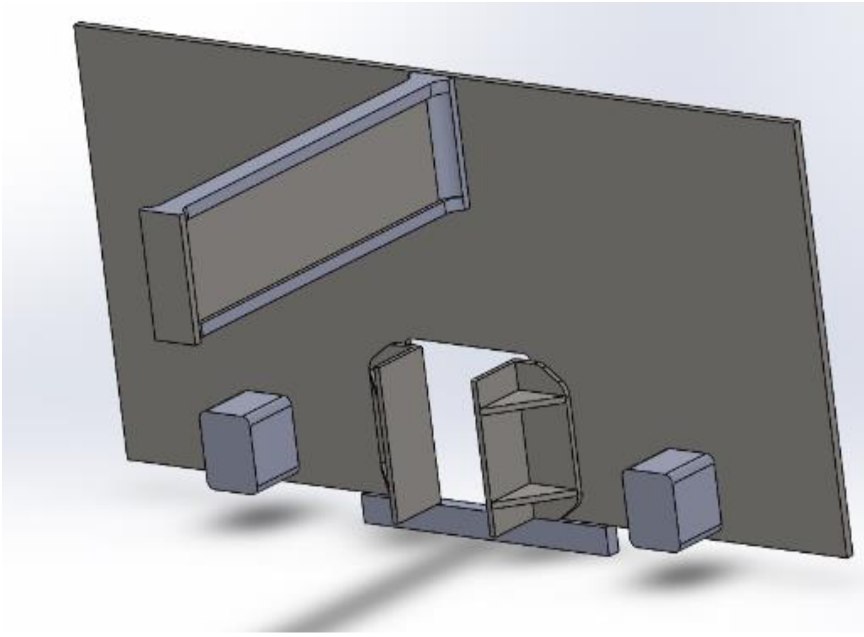


Figure 18 Added spring hanger brackets

9.2. Results from FEA Analysis on Current Frame Design

After simulating the current design fitted to the locomotive it was evident that distortion within this design would be occurring due to the maximum stress showing a value over the yield stress of the material. This is shown through figure 19. When the displacement was scaled up the movement was clearly visible, around the horn guide affected by the longitudinal piston thrust force. The scaled-up image is shown also in figure 20. The stress displayed here was 3.88 x 10^8 N/M^2. Yield strength of material 3.7x10^8N/M^2.

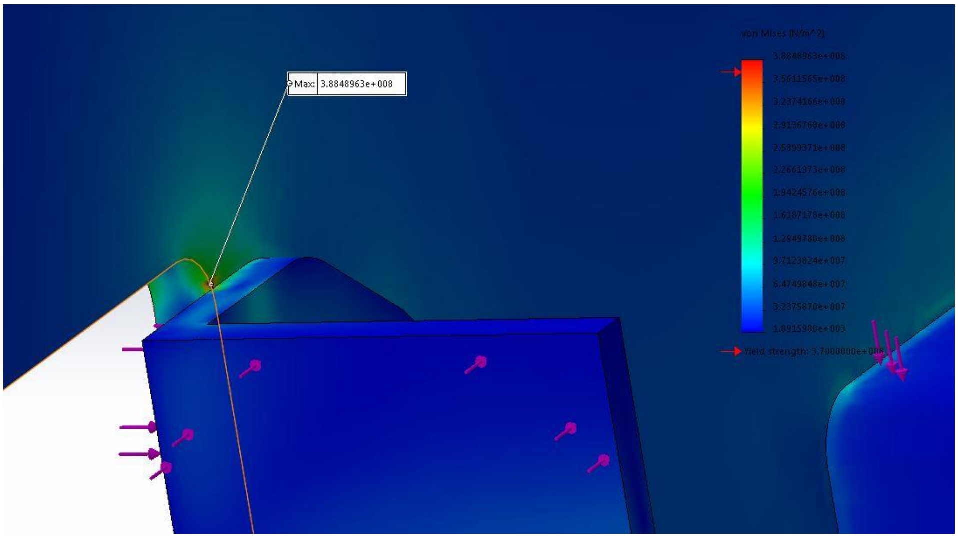


Figure 19 Current frame stress application

Figure 20/21 shows lateral movement being caused by the curvature force being applied to the side profile of each of the horn guide faces. These faces are the ones subjected to the force from the axlebox contact faces. The axleboxes fitted to the driving wheel axles will have an amount of expansive movement along the axle when the locomotive negotiates tight curvature and turnouts for changing tracks.

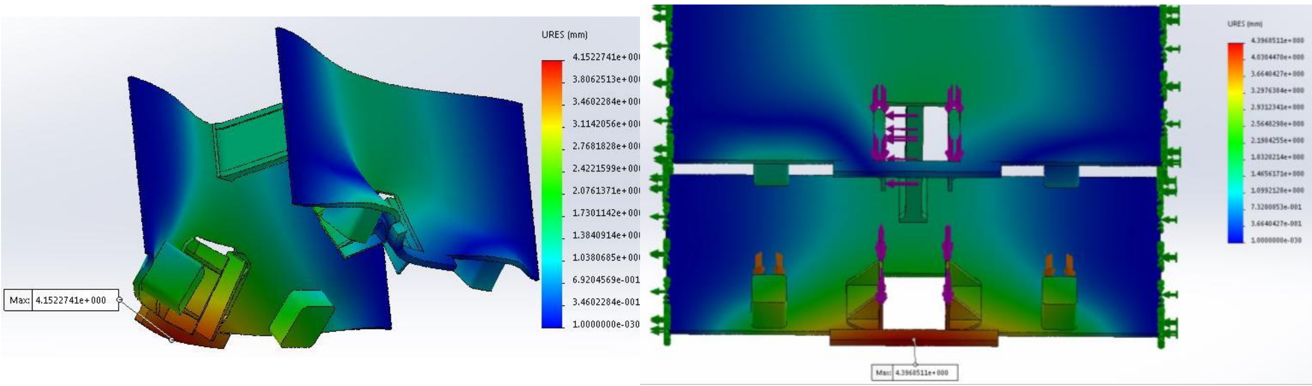


Figure 20 Current frame Max displacement

They are therefore not fixed in static position, the amount of movement is however limited due to the boxes coming into contact with the inner frame face of the wheel.

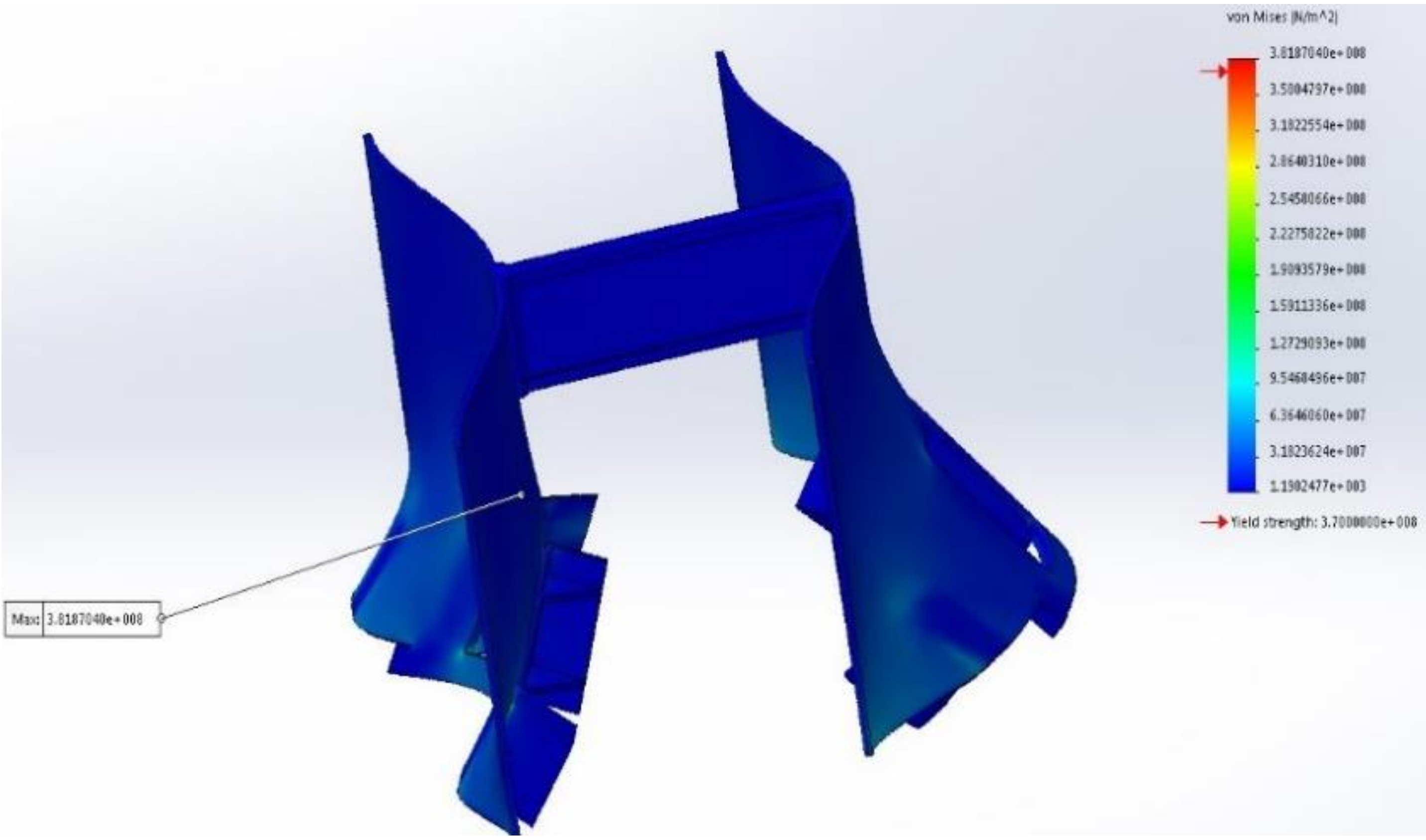


Figure 21 Current frame stress application

An equal force is applied to each resultant side of the horn guides, this shown modelled in figure 20 and displayed in equation 2 in section 6.1. As the locomotive negotiates a curve the weight of the loco boiler and body will be forced out to the outer edge of the curve. This meaning that the frame restraining the main body of the locomotive will apply a force upon the axleboxes and therefore wheels running round the curve. The flange from the wheel set will also be subjected to an opposing force from the inner edge of the outside rail. This producing the common squealing sound heard when trains pass over tight radius track work.

9.3. Current Frame Design with Cant

Figure 22 Current frame max Stress with cant

With cant applied, the stress at the top of the horn guide is shown to be below the yield strength of the material. This value being 3.63 x 10^8 (figure 22). The displacement in the frame shown in figure 23 is 3.46mm indicating a large reduction compared to the un-canted track. The displacement there was 4.15mm. This therefore proves that canting the track benefits the overall force distribution applied onto locomotive frames.

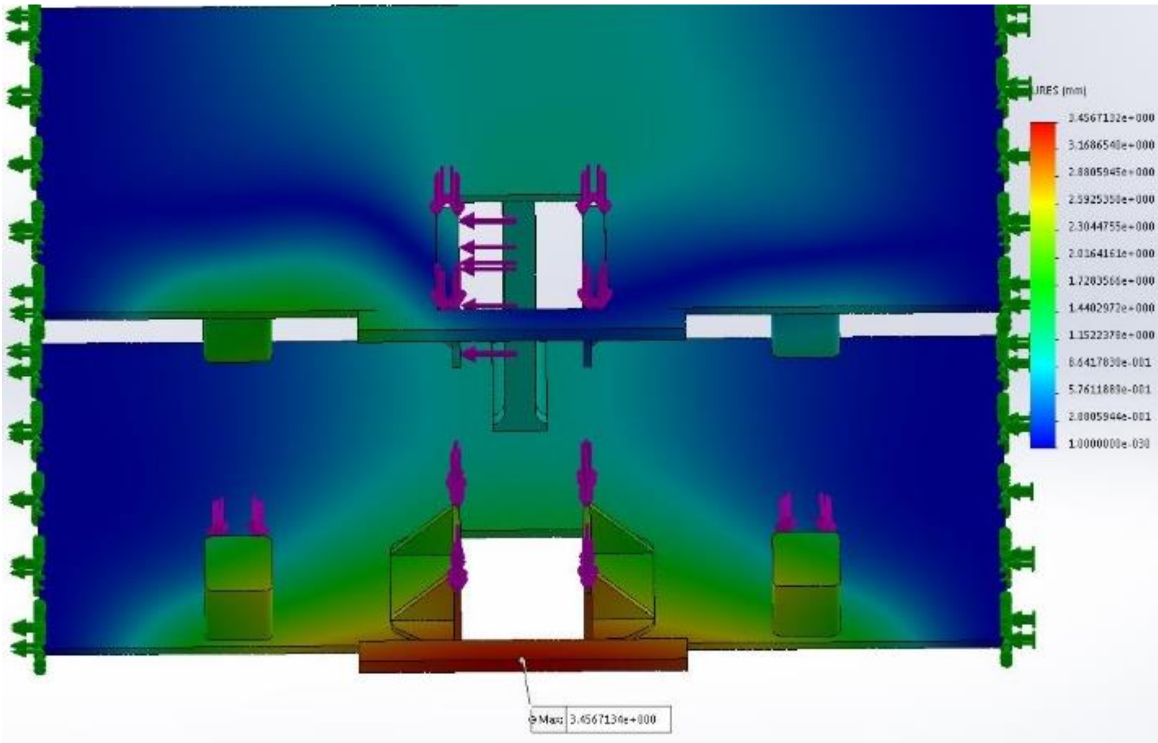


Figure 23 Current design displacement

10. Frame Modifications

The next step is to create a modification in which to lower the stress applied onto the frame to stop deformation occurring around the horn guides. The displacement shown in figure 23 is maximum around the horn keep at the bottom of the frame. Additional stiffness is therefore required around this area to reduce displacement. Inspiration will be taken from locomotives constructed around the same time as the Austerities. Such locomotives being the Ivatt 2-6-2 tank built in 1946 shown in figure 24.

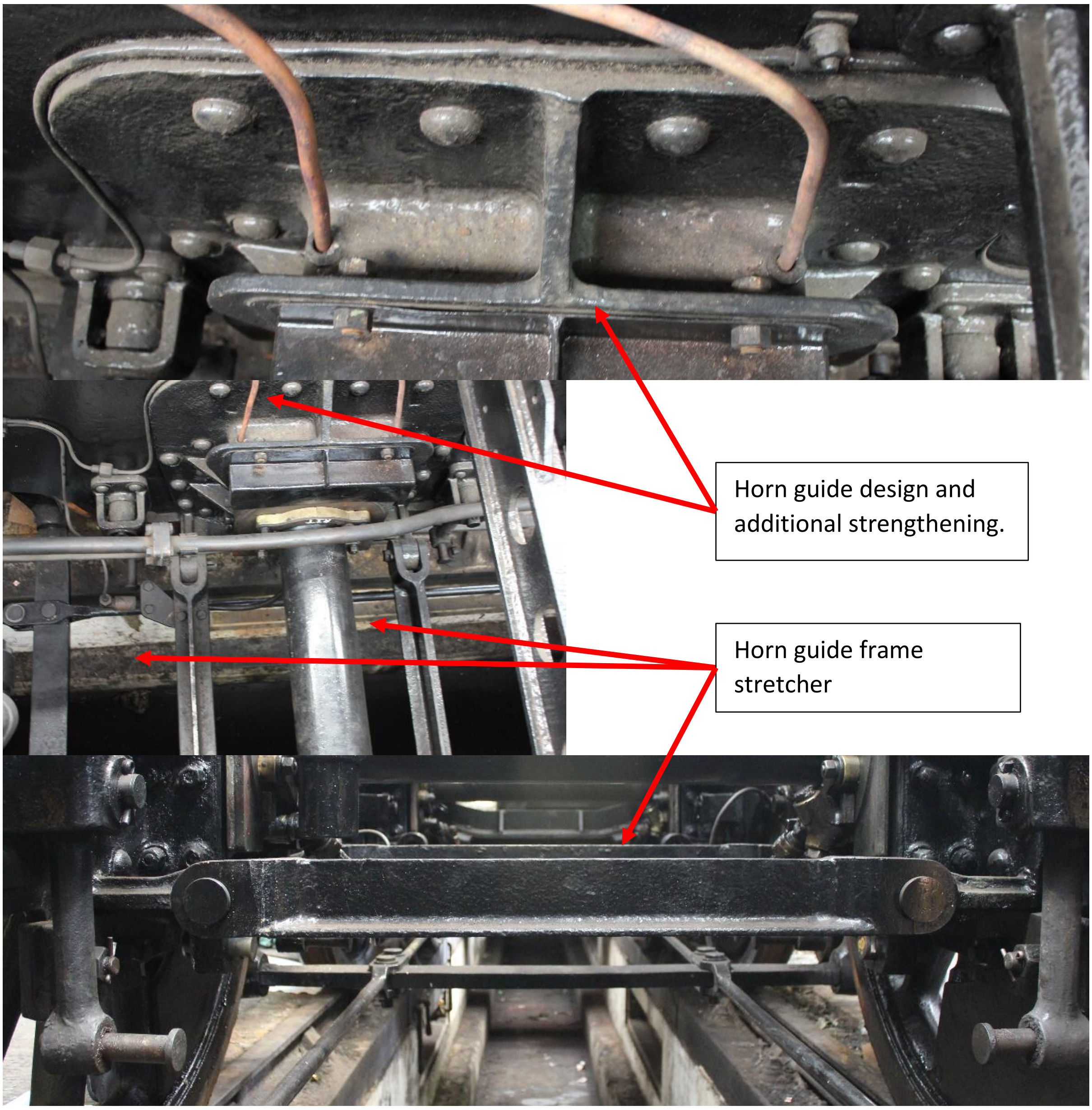


Figure 24 Ivatt 2-6-2 tank Horn Guide design inspiration

Currently at Haworth on the KWVR such an example of locomotive is currently being overhauled. This allowing clear viewing of the horn guides and frame of the locomotive. The frame design shows a much heavier build of horn guide design and assembly with additional thickness and material surrounding the horn guide faces. This however is a casting using far more material to those manufactured for the Austerities.

Also shown are additional stretcher beams connecting the horn guide faces together. This results in the lateral forces being shared between each side of the frame, a current feature not fitted to the 2-8-0.

This locomotive was designed for suburban and branch line use, and as such coped well with the tight radius curve forces sustained from travel over on the KWVR branch line. Therefore this machine is an ideal example to gain inspiration from.

Large castings as fitted around the horn guides are not practicable to be fitted to the Austerity 2-8-0. As the KWVR is a volunteer run charity where man power and finances are limited. However strengthening can be carried out on the current design fitted to the locomotive in the form of new components that could be fairly easily attached to the current frame. Discussions have been made between various locomotive shed staff members and the locomotive caretaker to experiment and develop potential modifications, possibly for fitment when the locomotive finishes its current 10 year operating life. A series of modifications have been developed and tested using the previous FEA techniques to determine whether the stress and displacement in the frame has been reduced to acceptable levels.

10.1. First Frame Modification

To combat the elevated deformation within the frame on the previous design of frame a modification was created to attempt to share the lateral forces between each set of horn guides. This idea in-part taken from the Standard and Ivatt Classes of locomotive as their horn guides share lateral forces using additional stretchers fixed between each of the horn guides.

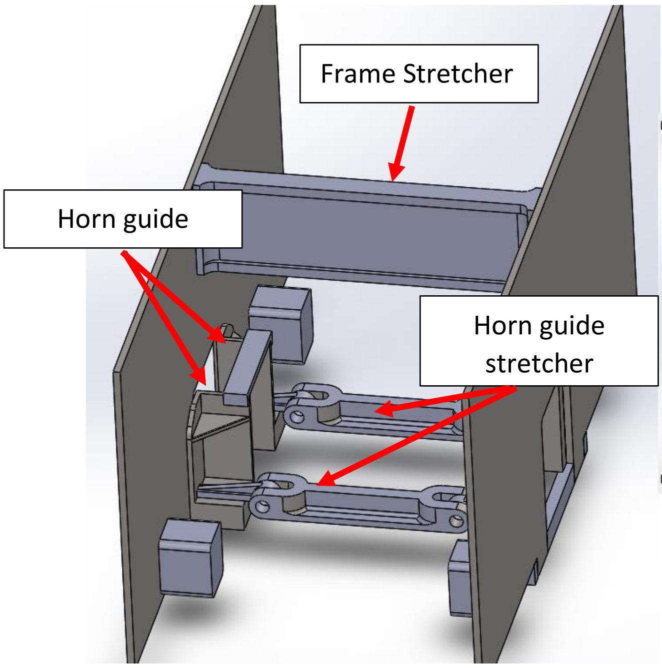


Figure 25 Initial Frame Modification

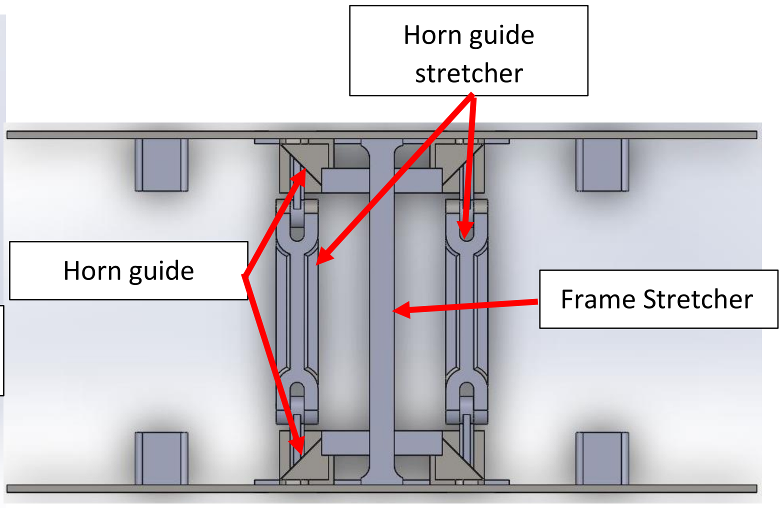


Figure 26 Initial Frame Modification

As shown in Figures 25 and 26 additional stretchers have been added to combat the deformity in the frame due to the lateral curvature being applied. The stretchers have been designed to enable pivoting to occur, this allows a certain amount of movement to take place. This is crucial as if the frames are made too stiff failure will occur.

A certain amount of expansion will occur within the frame due to the heat generated by the boiler and by the external air temperature. Also track irregularities will apply sudden shock loadings upon the loco which will require the frames to incorporate a certain amount of flex. This set up will hopefully account for these factors, tests will be performed however to validate this.

10.1.1. Without Canted Track - Stress

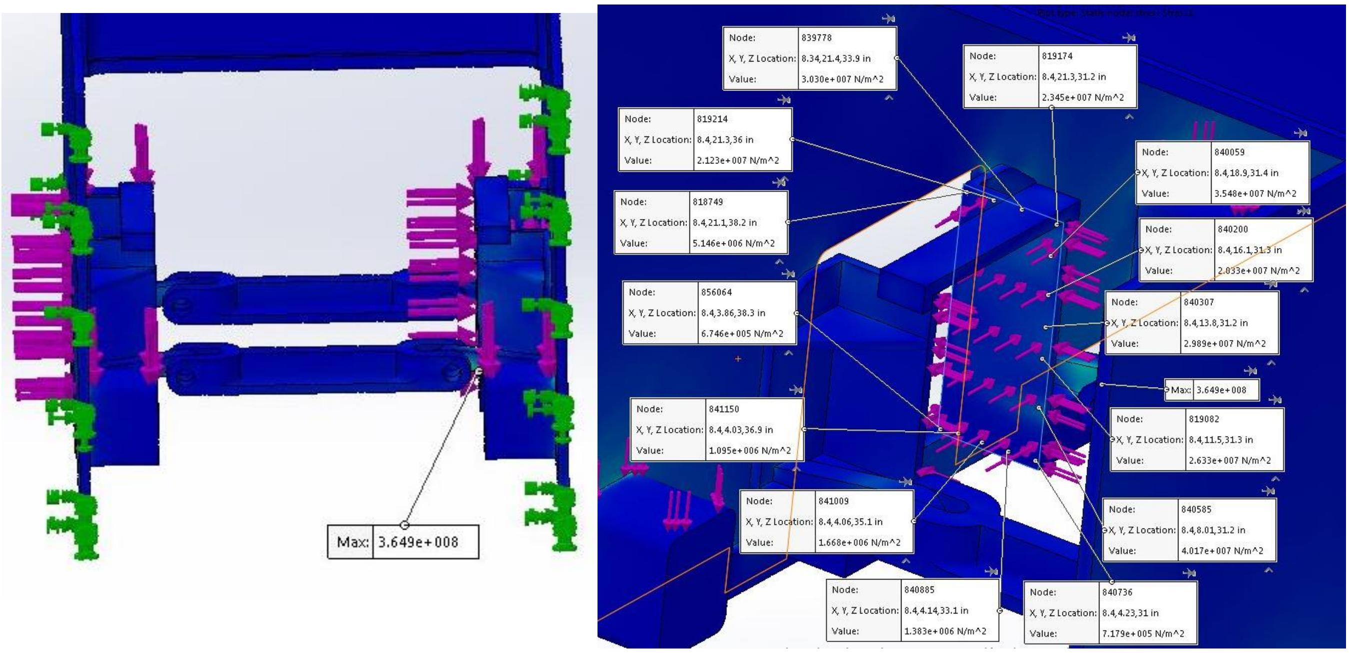


Figure 27 First modification stress applied onto frame and horn guide

The stress applied in figure 27 is shown to move to a bracket attaching one of the stretchers to the horn guide. This is predicted as the movement of the bracket is in a partial longitudinal direction and is influenced by the highest force being applied onto the frame. There is also an element of downwards movement, this being caused by the force exerted onto the spring hanger brackets. The stress distribution is also shown to now be lower than the yield strength of the material. Figure 28 shows a top view of the frame with the bracket shown have the highest stress on the frame. Also the direction of movement is shown to be in the longitudinal direction as mentioned previously.

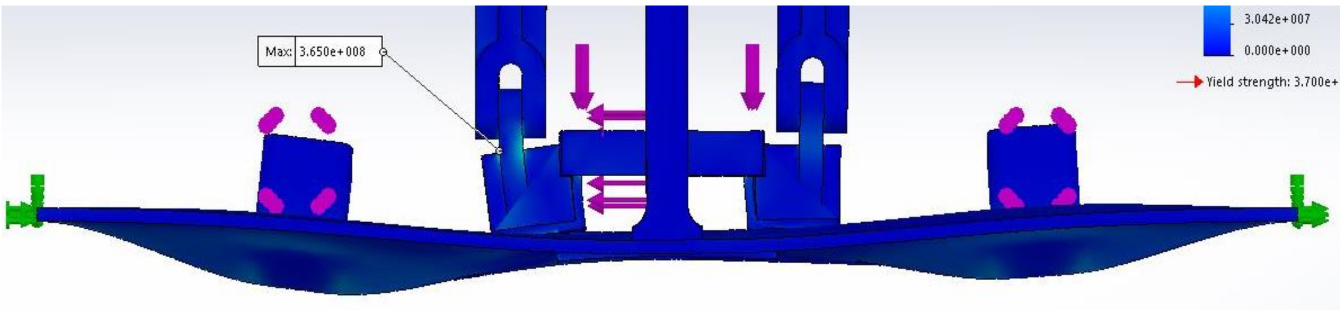


Figure 28 First modification top view stress

10.1.2. Without Canted Track Displacement

Figure 29 highlights the displacement occurring after this modification has been implemented. The displacement in the frames is shown to drastically reduce from a maximum of 4.15mm to 1.566mm.

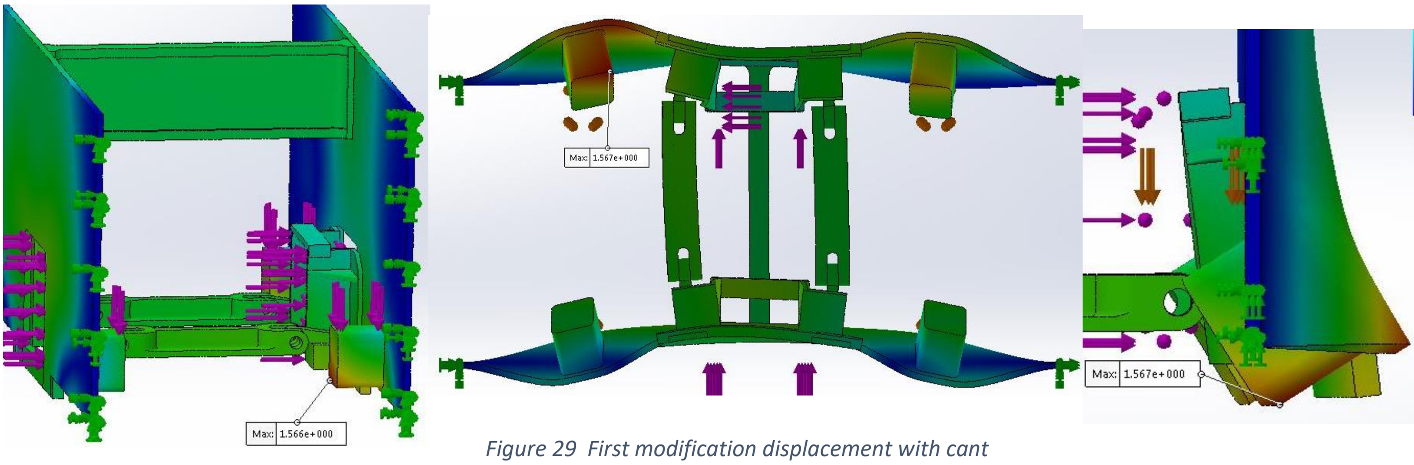


Figure 29 First modification displacement with cant

The maximum value shown is focused around the spring hanger brackets and is in a vertical direction due to the weight of the loco boiler and frames acting on these points. The weight force will be over exaggerated due to the weights including those of the driving wheels therefore the overall weights on these points maybe around 6 tons less, assuming a driving wheel set is around 1.5 tons.

When applying the cant lateral force to the model the displacement went down as expected due to the lowered force being applied, however the stress was shown to elevate to just above the yield strength of the material. An explanation for this could potentially be the force acting upon the horn guide face from the piston having a greater impact than previously. This therefore is not an adequate modification due to the elevated level of the stress being applied. Evidence of this results is shown in figure 30.

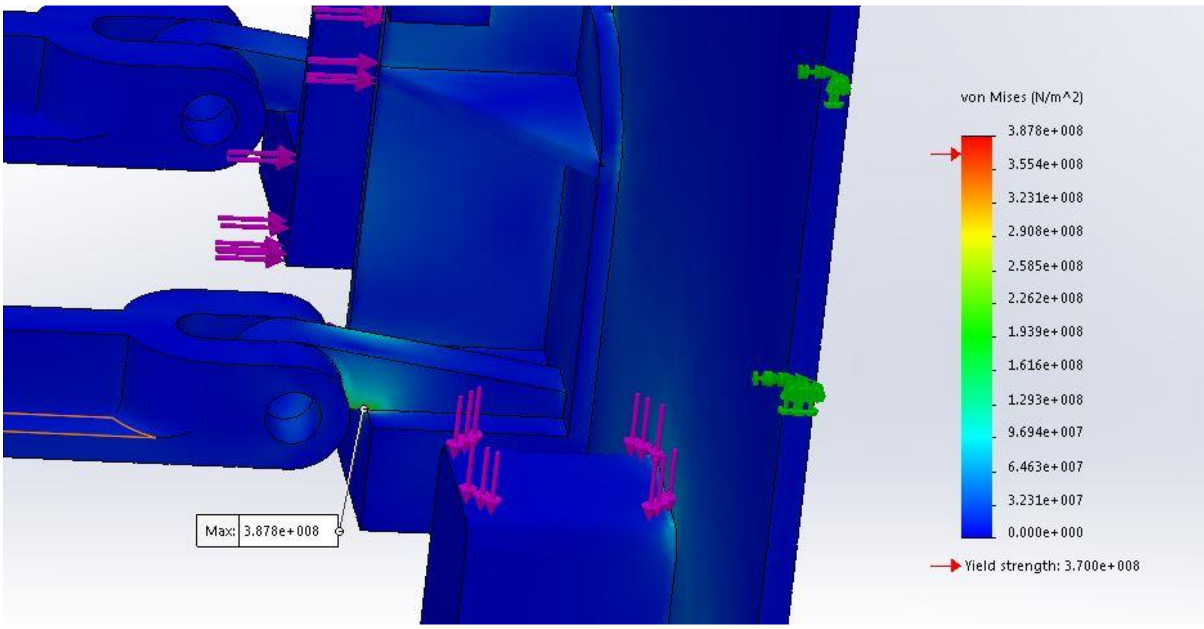


Figure 30 Modification 1 stress applied with cant

10.2. Second Frame Modification

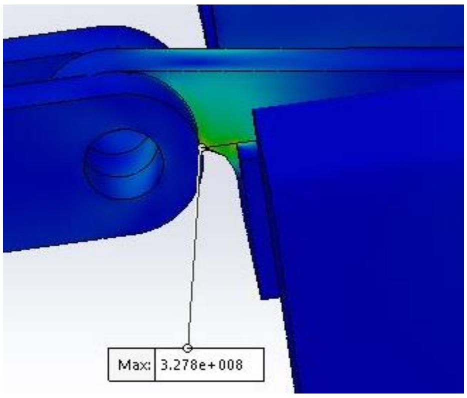


Figure 32 Second mod Stress

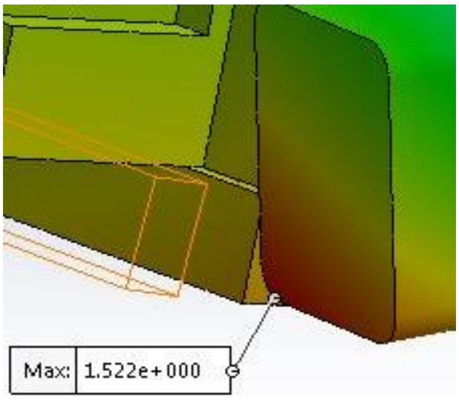


Figure 31 Second mod Displacement

This modification resulted in attaching a support for the stretcher bracket to try and combat the issue of the elevated stress when the loco negotiated canted track. Figure 31 displays the stress with un-canted track and a reduced value is again shown to the previous modification. The displacement shown in figure 32 is also shown to reduce.

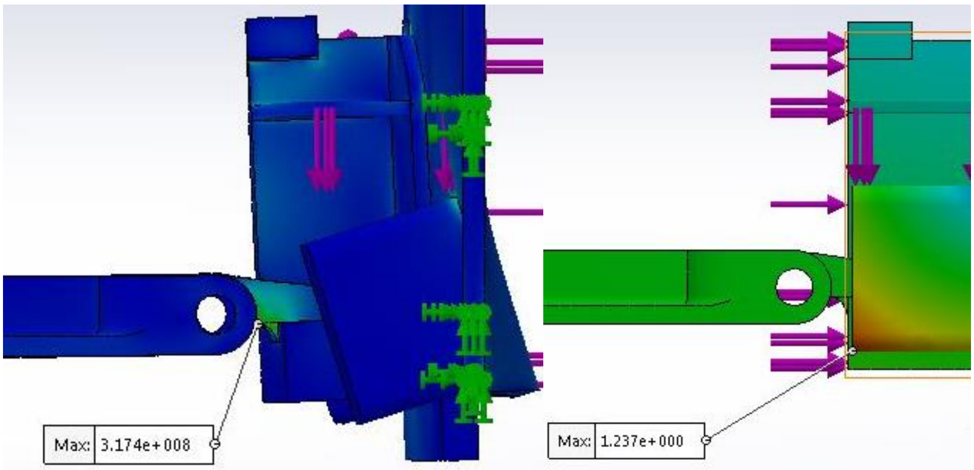


Figure 33 Second modification Stress and Displacement for canted track

Figure 33 displays the results for the second modification. These are surprising as the stress here is lower than the non-canted track test. This opposes the result for the first modification. An explanation for this could be an element of error with the simulation or the way the forces acted on initial modification. However this second modification again shows improvement.

10.3. Third Frame Modification

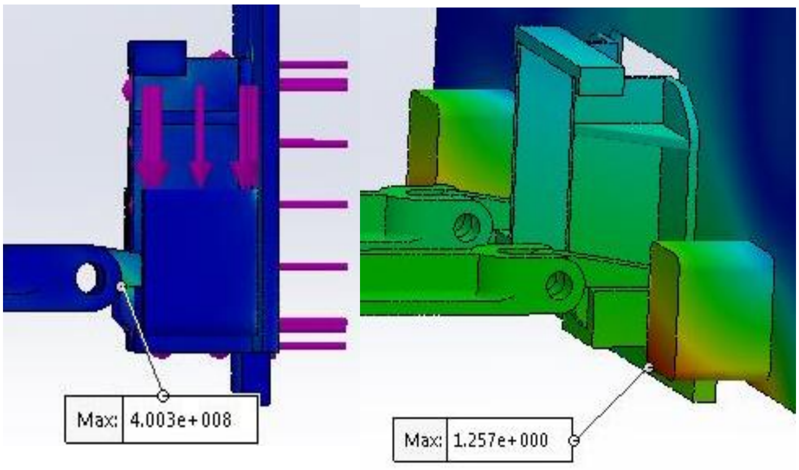


Figure 34 Modification 3 stress and displacement

This modification involved a change of support for the stretcher bracket between horn guides. As shown in figure 34 this change in design has failed to show an improvement for the stress due to now being over the yield strength of the material which means this design can be discounted for use. This change in design attempted to reduce the stress applied at the point shown by having a greater contact area in which to attach to. This in practice has failed my theoretical reasoning. No further testing was carried out on this modification design. A closer view shown in figure 35.

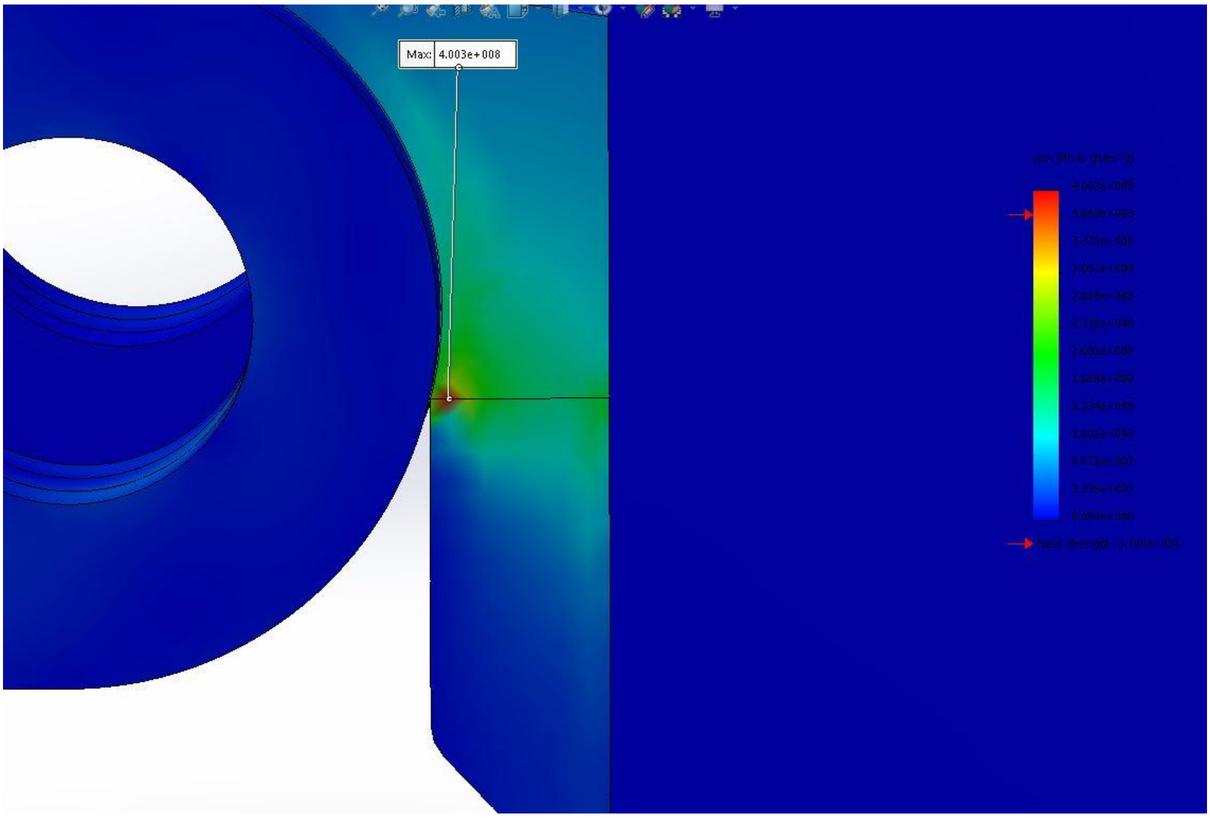


Figure 35 Stress modification 3

10.4. Fourth Frame Modification

After returning to the original support bracket a change was made to the top bracket initially fitted to the first modification to combat the displacement between the horn guide faces. This bracket showed an insufficient design within the first modification but was left due to not showing elevated levels of stress compared to the other parts of the frame. Now these areas of concern have been dealt with this area has been strengthened, showing an improvement compared to the second modification in terms of both stress and displacement (figure 37).

Figure 36 shows the displacement occurring over the horn guide that's subjected to by the piston force. As shown the amount of movement here is now minimal (under 1mm) therefore this design is getting to the stage where it would be an effective change. The spread of displacement is now far more varied meaning less point displacement is occurring.

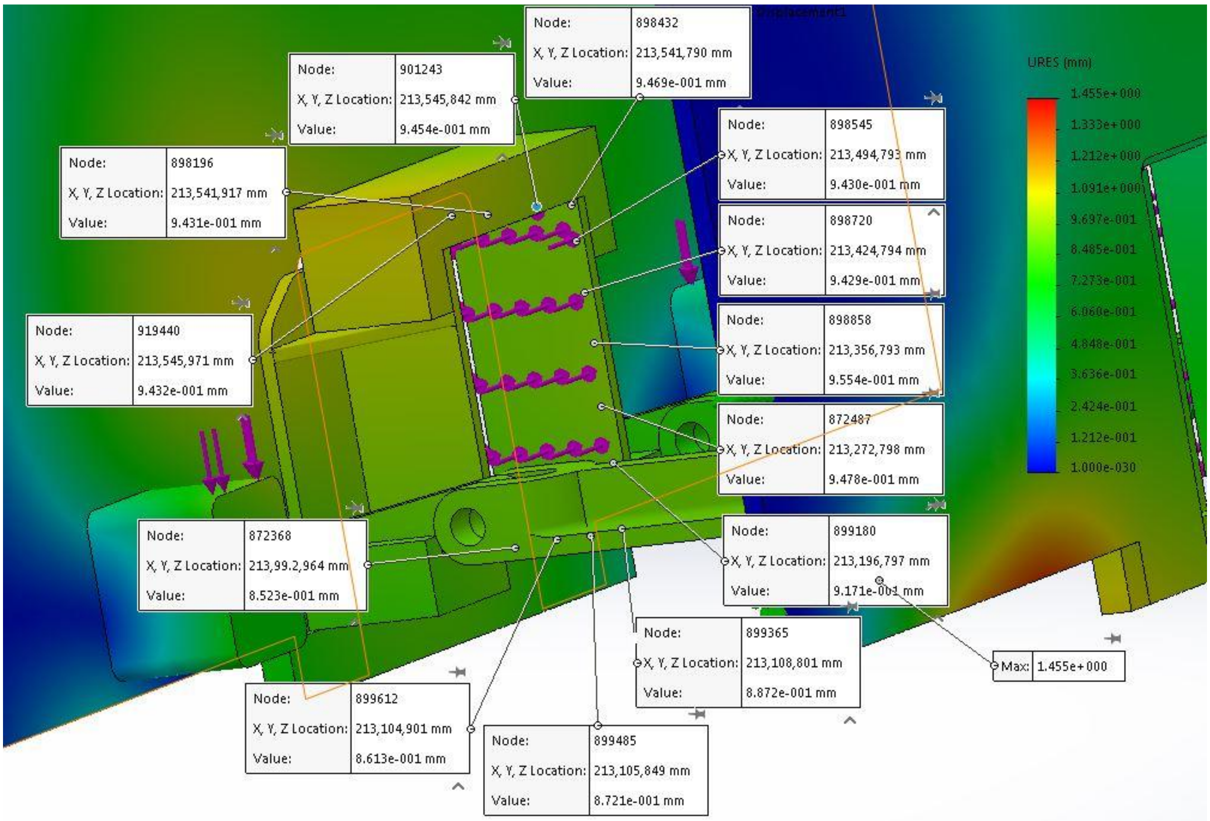


Figure 36 Fourth modification displacement over horn guide

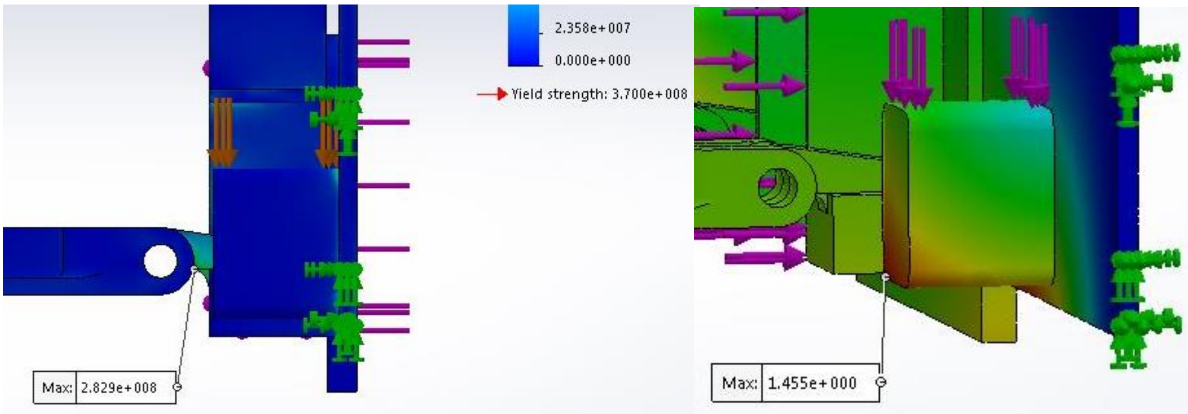


Figure 37 Fourth modification Stress and Displacement

10.5. Fifth Frame Modification

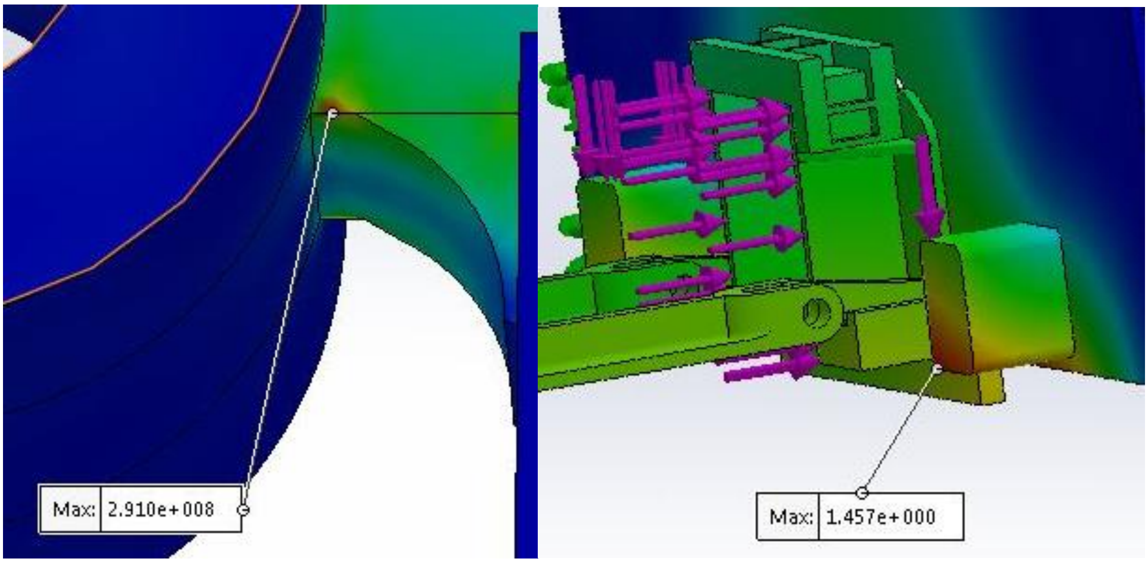


Figure 38 Fifth modification Stress and displacement

Figure 38 displays the modification, showing an increase in both the stress and the displacement. The aim for this modification was to reduce the weight of the top horn keep due to there being initially a large amount of material. The weight of these modifications is currently one of the largest concerns as the weight limit for locomotives on the KWVR is much lower than other railways due to the bridges on the route not being able to accommodate locomotives of heavy axle weights. A further design modification will be carried out to strengthen the current components added to the frame without adding large amounts of additional weight.

10.6. Sixth Frame Modification – Final Design

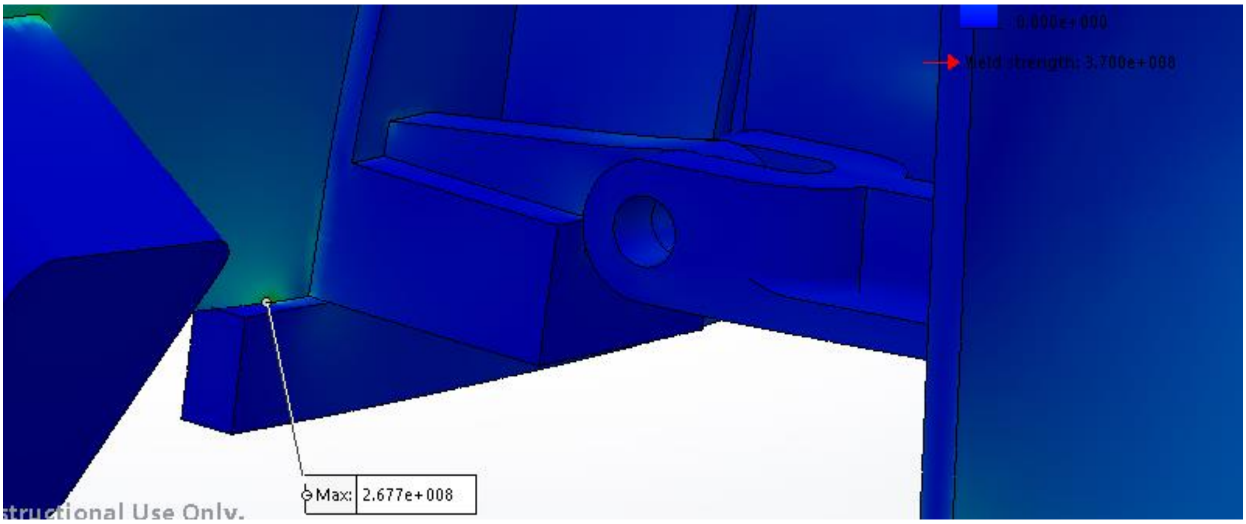


Figure 39 Sixth frame modification - Stress

This sixth modification (figure 39) was trialled with the addition of fillets around the edges of the top horn keep (figure 41). This simple change has shown to lower the stress from 2.9 x 10^8 to 2.677 x 10^8. Meaning a safety factor of around 1.4 has now been attained for the frame design. This is probably the best result that can be attained without heavily modifying the current frame layout, horn guides, and thickness of material.

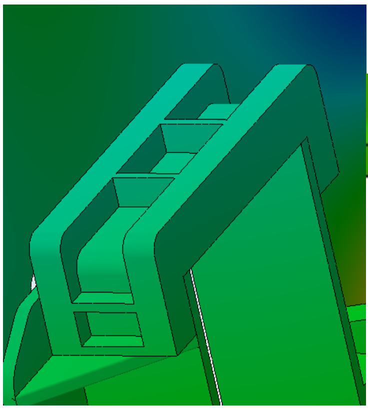


Figure 41 Filleted top horn keep

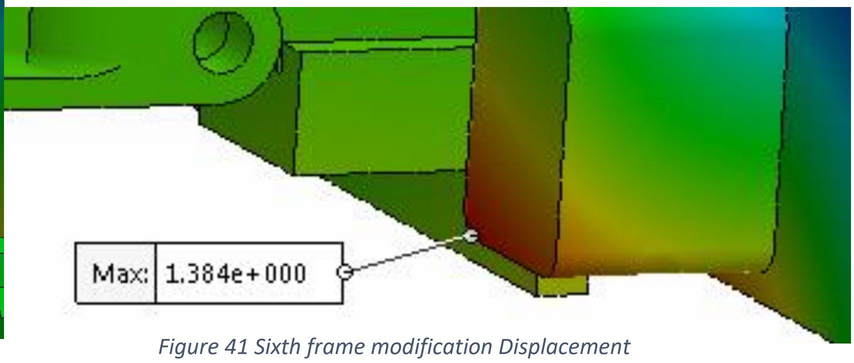


Figure 41 Sixth frame modification Displacement

Due to restricted finances available when such modifications are required to be fitted, a fairly simple design solution has been created. This hopefully reducing material use and man hours required for production. Attachment to the locomotive will also be basic requiring welding or riveting techniques.

When track cant is applied the values for stress and displacement reduce further giving a safety factor of 1.5 (figure 42). However the highest applications of lateral force must be accounted for hence the continued testing for un-canted track.

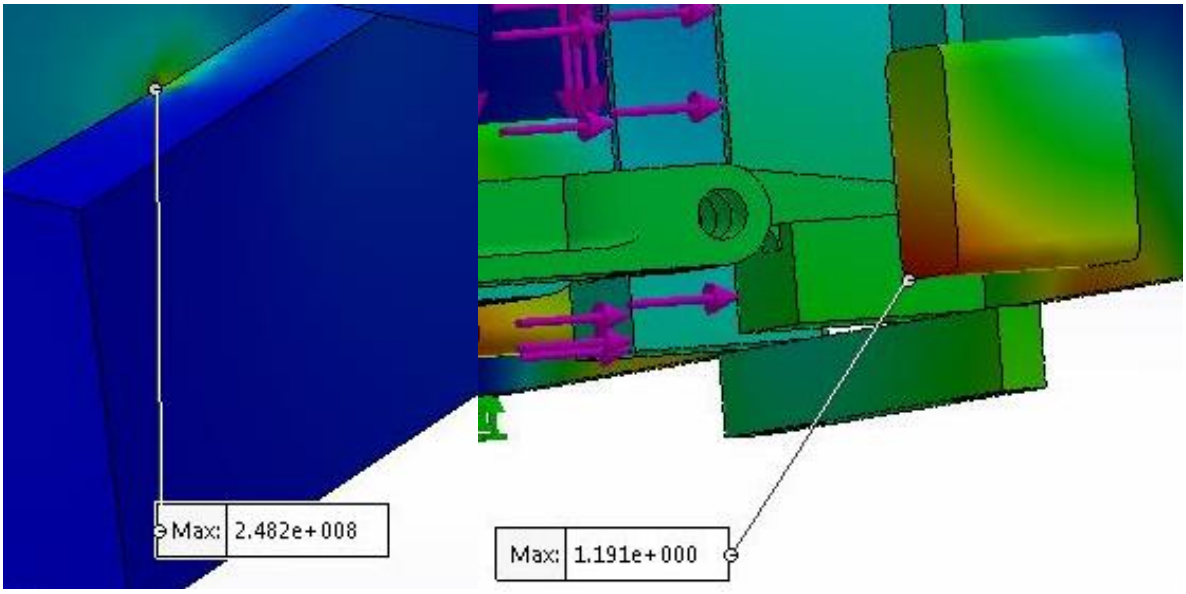


Figure 42 Stress and displacement with cant modification 6

11. Final Design

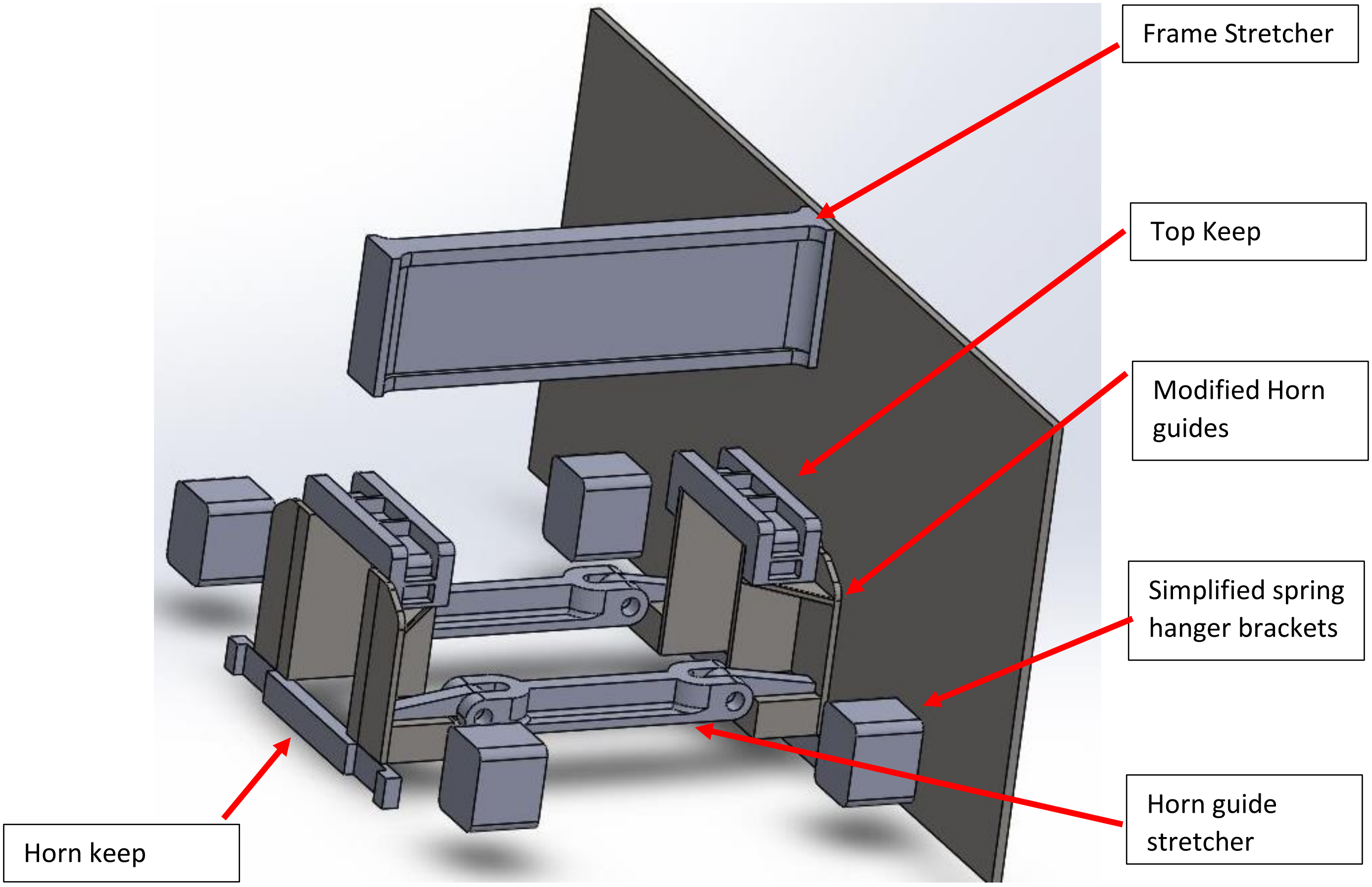


Figure 43 Final design modification

Figure 43 displays my final frame modification. Inspiration was taken from various locomotives such as the Ivatt 2-6-2 tank shown in figure 24, the Standard Class and the LMS Class 5 locomotive shown in appendix 4 & 9. Horn guides on the Class 5's were known to fail therefore a top keep has been fitted to prevent this, improvements were also shown in the simulation results. Space has still been allowed in the frame for movement to occur reducing the chance of stress build up and cracks occurring. The simplified spring hanger brackets made the vertical force applications easier. These would be fully designed if further work was carried out. Testing would be required on the locomotive to determine the exact direction of application of this vertical force within the fully designed brackets. The left-hand frame plate has been removed for easier inspection of the internal component design (inclusion is incorporated in the actual final design model). Weight has been saved through reducing the amount of material in the top horn keeps, additional material could potentially be lost through reducing the thickness of the horn guide stretchers.

12. Comparison of Modifications

Table 2 Frame stresses and displacements

Modification number	With Cant		Without Cant	
	Stress N/m^2 (x10^8)	Displacement (mm)	Stress N/m^2 (x10^8)	Displacement (mm)
Current design	3.631	3.457	3.885	4.397
1	3.878	1.278	3.650	1.566
2	3.174	1.237	3.278	1.522
3	N/A	N/A	4.003	1.257
4	2.849	1.191	2.829	1.455
5	2.914	1.192	2.910	1.457
6	2.482	1.191	2.677	1.384

	Displacement (mm)					
	Mod 6	Mod 5	Mod 4	Mod 2	Mod 1	Current design
	0.96	0.96	0.95	1.27	0.44	1.97
	0.96	0.96	0.95	1.27	0.47	2.16
	0.97	0.97	0.94	1.27	0.48	2.04
	0.96	0.98	0.94	1.27	0.53	1.91
	0.98	0.99	0.96	1.28	0.61	1.85
	0.98	0.97	0.95	1.3	0.67	1.74
	0.96	0.94	0.92	1.3	0.7	1.61
	0.94	0.92	0.89	1.24	0.72	1.5
	0.92	0.9	0.87	1.18	0.77	1.41
	0.9	0.89	0.86	1.14	0.73	1.19
	0.89	0.88	0.85	1.12	0.72	0.94
	0.88	0.96	0.94	1.1	0.71	0.78
	0.96	0.96	0.94	1.09	0.42	1.84
Average	0.94	0.94	0.92	1.22	0.61	1.61

Table 3 Horn guide face displacements

Table two displays the maximum stresses and displacements displayed after simulations were run on the different frame modifications. Modifications were carried out to both reduce the displacement on the horn guide face exposed to the piston thrust force and the rest of the locomotive frame. Through carrying out this process a more ridged frame has been designed and is proved through the results gained. Although the main aim of this project was to produce a stronger horn guide design it was also a requirement to analyse the rest of the frame for deformations resulting from modifications being applied. Through each modification the frame has been analysed and modifications carried out to try and improve the overall structural strength. Table 3 displays the displacements observed on the horn guide face exposed to the piston thrust force for un-canted track. This due to the maximum lateral force being exposed onto the frames with this track geometry feature fitted. It is interesting that the first modification proved to produce the lowest displacement in the guide. However with this modification a number of places within the frame proved to be over the yield strength of the material therefore failure/deformation would occur. The final modification has proved to give a displacement less than 1mm, 0.94mm. This value is shown to have decreased from the current design by 0.67mm. This also being for a lateral force where canted track is not fitted hence a higher lateral force applied. Further images of the simulations can be found in the appendix 11.

13. Cost Analysis

It is difficult to predict the cost of manufacture for each component which make up the final modification design due to the many ways in which parts could be manufactured due to being one-off components. This work would be carried out by an external contractor therefore the work would be sent out to several engineering firms for quotes to be sought.

14. Discussion

The results obtained from the CAD model and FEA simulations show a clear improvement within both the structural strength of the horn guides and of the rest of the frame stiffness. The main priority of this project was to determine the amount of movement of the horn guides and then increase the stiffness of these components. However as found the frame displayed equally if not more amounts of movement and weakness compared to the horn guides. Therefore it has been a challenge to both increase the horn guide rigidity and the rest of the locomotive frame. The results tables however show that this has been achieved through each of the modifications carried out.

There are simplifications within my calculations and model created within Solidworks. For the calculations, it is extremely difficult without doing thorough specialised testing on the locomotive and current Worth Valley track to determine the precise forces applied to the locomotive when hauling trains up and down the line. The track irregularities that are involved within the track joints and general track arrangements are not currently known. Although these irregularities can be backed up with the authors own accounts being a locomotive fireman/operator for the past 6 years on the KWVR. A safety factor of 1.4 is shown to be achieved meaning damage would be prevented if higher forces were applied. This value is deemed satisfactory due to figure 44 displaying the factor of safety values of different devices and components. As the factor of safety for aircraft components is 1.5-2.5 a component on this locomotive will be much lower. This is due to the locomotive has a far less risk of endangering life due to the operating conditions and the speed at which it normally travels.

Equipment	Factor of Safety - *FOS* -
Aircraft components	1.5 - 2.5
Boilers	3.5 - 6
Bolts	8.5
Cast-iron wheels	20
Engine components	6 - 8
Heavy duty shafting	10 - 12
Lifting equipment - hooks ..	8 - 9
Pressure vessels	3.5 - 6
Turbine components - static	6 - 8
Turbine components - rotating	2 - 3
Spring, large heavy-duty	4.5
Structural steel work in buildings	4 - 6
Structural steel work in bridges	5 - 7
Wire ropes	8 - 9

Applications	Factor of Safety - *FOS* -
For use with highly reliable materials where loading and environmental conditions are not severe and where weight is an important consideration	1.3 - 1.5
For use with reliable materials where loading and environmental conditions are not severe	1.5 - 2
For use with ordinary materials where loading and environmental conditions are not severe	2 - 2.5
For use with less tried and for brittle materials where loading and environmental conditions are not severe	2.5 - 3
For use with materials where properties are not reliable and where loading and environmental conditions are not severe, or where reliable materials are used under difficult and environmental conditions	3 - 4

Figure 44 Factors of Safety (The Engineering Toolbox, n.d)

Figure 44 shows the applications in which the ranges of factors of safety are utilised. The material used within the frame is EN8 Steel, this type of steel is very popular and used for a vast number of parts. (KV Steel Services LTD, 2017). As EN8 is a well known material for its strength and wide range of uses, it will reside in the top two boxes of the table in figure 44. This again shows that the factor of safety calculated for the final design modification is sufficient for the intended use on the locomotive.

There are of course other forces that will act upon the locomotive when in operation these are mentioned in section 4.3. These have not been applied because they're theoretically minimal compared to the three forces applied (Static weight, lateral curvature and piston thrust). Also it is difficult to calculate these forces without fitting measuring equipment to the locomotive and running tests with a typical train weight and average speed. As deformation occurs within the horn guide faces a hammer blow longitudinal force will develop from the piston thrust forces. This again has not been applied but must be considered. The locomotive currently is very uncomfortable and rough for the crew when in operation therefore the hammer blow effect is more than likely occurring. During the last modification to the horn guides and axlebox contact faces the damage sustained was alarming indicating this hammer blow was more than likely responsible for the rough riding qualities. It will be interesting when the locomotive is removed from service and disassembled for overhaul in 2018 to discover if such damage has occurred to the new axlebox face material mentioned in section 4.1.

The measurement of the locomotive frame was carried out utilising a tape measure as mentioned previously in this document. This was because sufficient drawings could not be obtained for the parts being re-designed. The general arrangement drawing (appendix 10) was sourced but this only gave basic dimensions such as the distance between wheelset centres, frame thickness and width between each frame sheet. More accurate equipment could be used for future measurements such as laser devices.

A section of the frame was used for the simulations, this section incorporating just one driving axle set of horn guides. The decision to continue with this design was due to the forces being applied to each set of horn guides in theory being identical. This also meant that fewer dimensions were required ultimately allowing more time to be taken in the collection making them hopefully more accurate. The weight of the locomotive as mentioned is fully compensated using the balanced springs and spring hanger brackets. The locomotive hasn't been weighed for a considerable time through the authors current knowledge. Therefore, the axle weights may not be fully equal however this would have to be checked if further work was carried out on this subject. The piston thrust forces should also be identical across all horn guide faces, this being due to each set of driving wheels being connected through the locomotives motion rods. The lateral forces will also be similar, potentially the initial leading set of driving wheels may take the majority of the impact but the full force has been applied to account for the worst-case scenario. The decision to utilise this frame section has assisted the software's simulation time. As this frame design contains less amounts of elements that make up the structure of the frame within the software. The elements of the model give the frame effective substance, modelling the part as if it was a real-life component. The fewer amounts of elements to analyse for deformation the quicker the simulations ran. This was especially crucial when it came to carrying out a mesh convergence study where many simulations were required to ascertain the correct mesh sizes to produce the most accurate results. The fewer elements the less accurate the results, hopefully the best partnership of values have been used giving accurate results.

15. Conclusion

As table 2 and 3 (p43) show my aim to identify the displacement and stresses within the KWVR's Austerity 2-8-0's horn guides has been achieved. The second objective to evaluate the frames overall stiffness and deformation has also been identified. To lower the stresses and deformities within the horn guide design and frame six modifications have been developed and have shown to display a gradual improvement with the amount of displacement and stress levels applied albeit apart from one design. This design failing to show improvement (modification 3) displayed a flaw with a change in support bracket. An attempt was made to lower the stress and increase the structural capabilities further, however this design proved insufficient to complete this. This however was potentially a good result as it prompted a series of further modifications that showed further improvement on the values to the final design that will be presented to colleagues at the KWVR for potential fitment to the locomotive when time comes to modifying the current design.

A horn guide drawing was ultimately found for the locomotive but proved too unreliable for the required dimensions to be copied for use on the CAD model. If further time was permitted a visit to the National Railway Museum would be undertaken to search their achieves for drawings they may hold that would be of use with this project. The calculations of the forces applied upon the CAD model have been as accurate as possible using assumptions of potential losses and gains where appropriate. It is difficult to allocate truly accurate values without fitting the locomotive with testing data equipment that would be sufficient to measure the multitude of potential forces that could be applied while the locomotive is in operation. The Advanced Steam Trust (AST) organisation are known to the author and involvement has been undertaken with this group in the past. Potentially contact could be made again with the AST and measurement gear developed that could be of use to the requirements stated here. Data collected through accurate means could then be fed into different computer models to show the dynamics of a vehicle while in motion. Results could then be validated with those recorded from the locomotive with the data recording equipment. Measurement gear could also be placed upon a rail mounted trolley to survey the track structure and formation to apply correct cant and lateral forces to the frame. The vertical weights of the locomotive could be changed while movement over dipped track rail joints. These locations and magnitude could also be recorded with the use of rail mounted travelling equipment.

Overall the locomotives current operating condition is shown to be in relatively good order in relation to accounts of locomotives back in the days of steam running on the national network. The amount of mileage run every year is minimal compared to what this Class used to accumulate back in the days of steam. It is evident though that the locomotive would benefit from improvement. By just observing the locomotives frame it shows to lack structural strength compared to other locomotives built around the same time. Stiffness is predominantly focused around the top of the frame through the aid of frame stretchers with little in the centre of the locomotive to support the force applications lower down around the axles and wheelsets. This is therefore one of the reasons that additional stretchers have been inputted between the sets of horn guides. These are shown to both resist the lateral applications from cornering and reduce the overall deformation within the frame. Considerations have been made toward the finances available for modifications to the locomotive. As mentioned previously the KWVR is a volunteer run charity therefore man power and expenditure is low compared to other railway companies and locomotive operators. Complexed design changes have been kept to a minimum to accommodate these factors.

15.1. The Next Steps

The next steps for this project could include an assortment of different investigations and improvement to the final design created. The main areas for further research will be;

- Calculation of greater accuracy force values.
- Technical drawings gained.
- Installation of final design on complete locomotive model.
- Evaluation to identify any other points of weakness or high stress points.
- Dynamic simulations carried out, identifying how design performs when in operation.
- Calculation of cost of production and installation on locomotive.

15.2. Final Comment

This subject has been of vast interest to the author as his interest in railways and steam locomotives began at a very early age. The opportunity to include his hobby within his studies has been fantastic and made the task of writing this report highly enjoyable. It has been an honour to be able to work with the Institute of Railway Research and alongside some of the highest of skilled professionals currently in the field of railway engineering. The aim to create a modification that should both benefit the locomotive to which the author has had considerable involvement in over the years is greatly satisfying and should hopefully preserve its running ability for many years to come. Hopefully this paper will give inspiration to other railways and locomotive owners to design components that will improve these ageing beasts allowing them to continue running for future generations to enjoy.

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18. Appendix

1) <u>Wheel Arrangements</u> (THE-RAILWAYMAN'S-POCKET-BOOK, 1909)

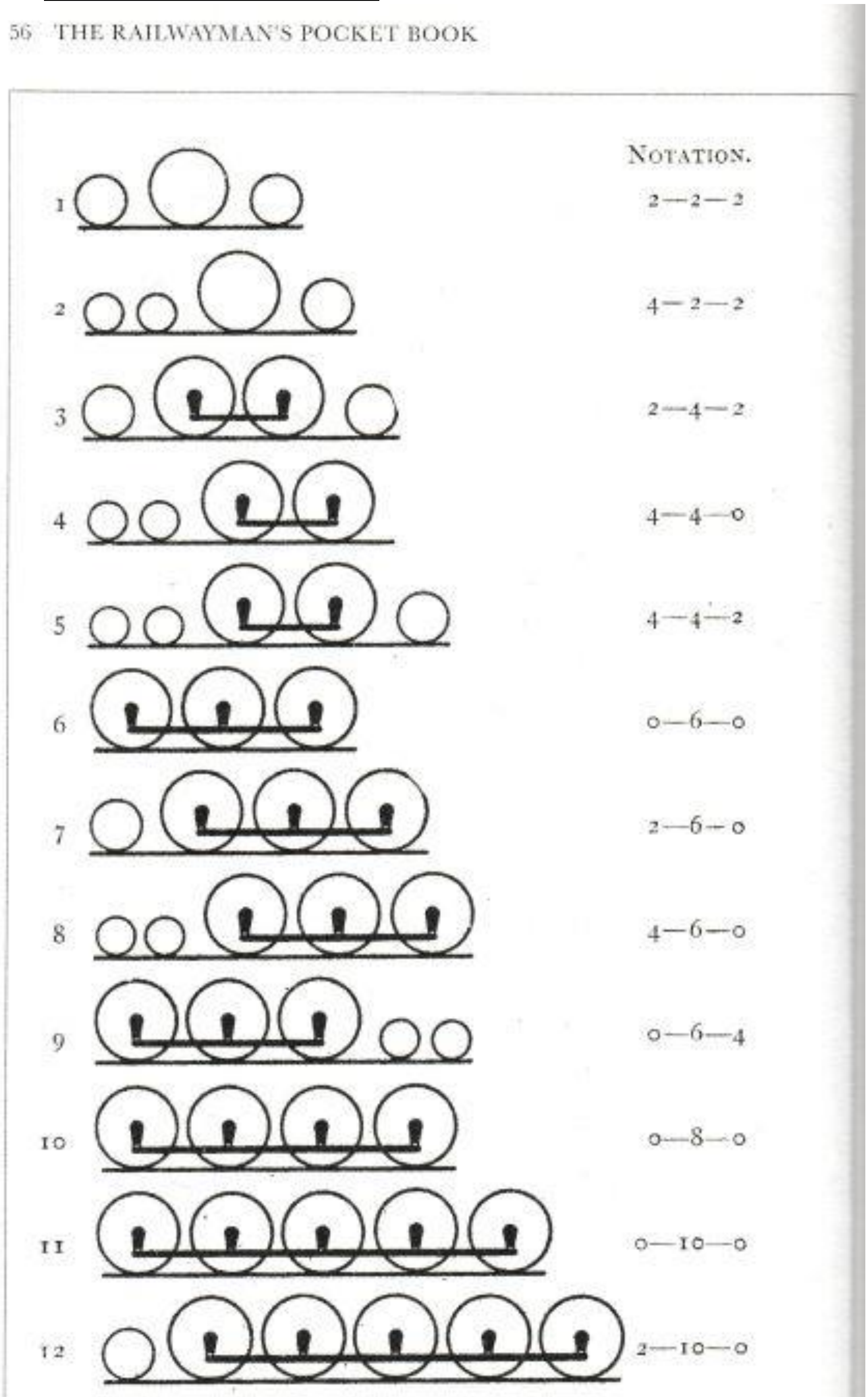
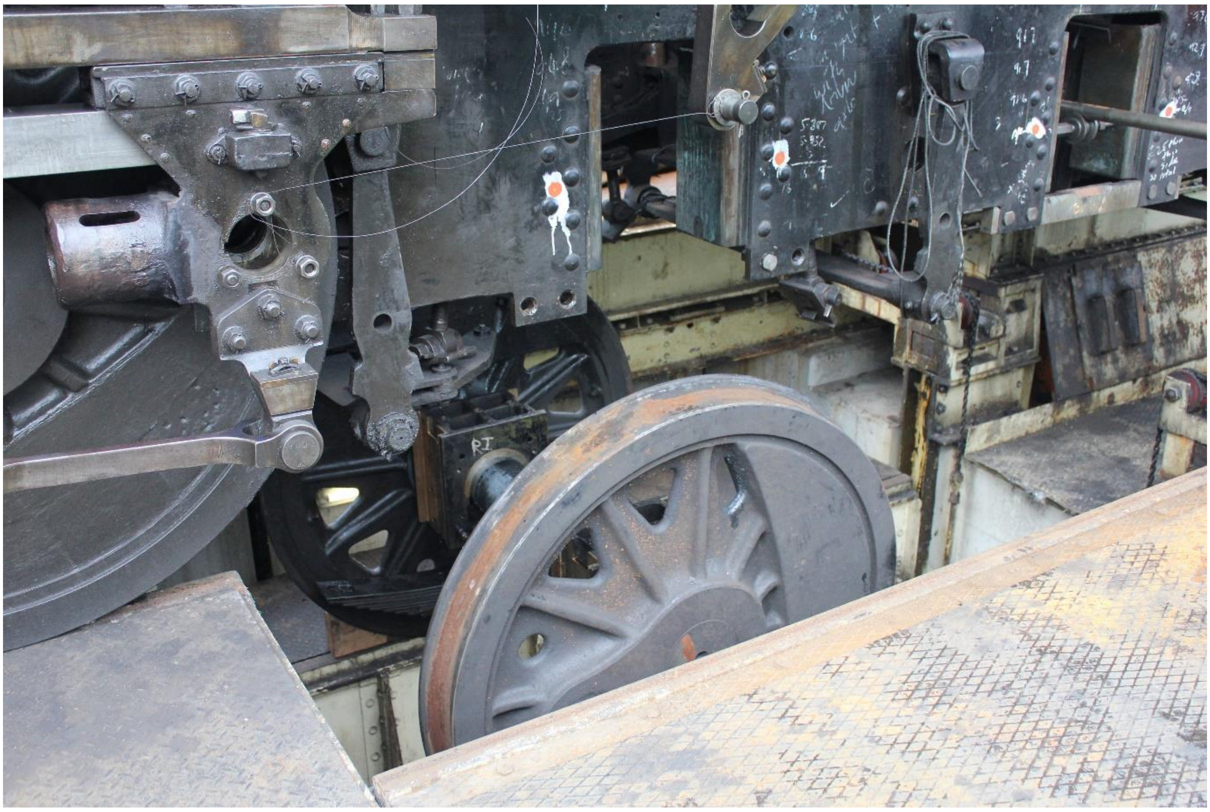


FIG. 1.—WHEEL ARRANGEMENTS OF ENGINES.

2) Using the Wheel Drop at Haworth (Tom Kay)



3) Locomotive Details and Modifications Carried out on the KWVR

Adorned with an enclosed cab, electric lights, taller chimney, snow ploughs and more, much had to be done to return the loco to a UK specification. Many mechanical components also had to be made new or reconditioned to meet the current insurance agreements and running specifications set by the KWVR. Large amounts of boiler work were carried out by external contractors. The bottom end of the loco which included all the connecting motion also required a full strip down and reconditioning. The Frames had to be checked for deformation along with each set of horn guides. Cylinders were inspected for wear and machined to suit new piston rings.

All this work was carried out within the Haworth locomotive works which by then had been improved to make this a much less onerous task. Before this time most of the work would have been undertaken outside with little in the way of protection from the elements. A new shed was constructed and new machines acquired that aided the overhaul of this locomotive plus others in the fleet.

The tender also received large modifications due to it being the wrong design to what was originally manufactured. Having only three axles compared to the initially designed 4 and a shortened tender an enquiry was sent out to find a replacement chassis conform to original build specifications . A new tender tank was also ordered for manufacture from a local firm. A chassis was located at a steelworks being used as a carrying vehicle for the produced steel. This chassis was found to be the exact match for the locomotive, amazing to think that one had survived until this time. The new tender tank was then manufactured and placed on the acquired frame. Once the locomotive was re-assembled it was steamed again in 2007 and re-number 90733 taking the next number on from the last Austerity locomotive produced 90732.

4) Standard Class locomotive (Tom Kay)

5) Axlebox Further Information

Figure 72 shews a simple form of axlebox suitable for a carrying axle. The journal *J* is in contact with the brass *B*, which was rigidly retained in the box. The brass *B* carries nominally a constant vertical load when running normally, but when braking the journal could make contact on the auxiliary surfaces *A* and *A′* present in the axlebox body beyond the ends of the brass. When passing over crossings and rail joints the brass and journal were liable to part company momentarily, thereby temporarily disrupting the oil film. The lubricant, oil in this instance, was contained in the keep *K*, which depending on the design could be readily removed for cleaning and inspection. Oil was raised from the keep to the journal by continuous capillary action (syphoning) by means of a pad *P* of porous material together with a wick *W*, attached to the underside of the pad. The wick was partially or wholly immersed in the lubricating oil with the whole assembly of pad and wick supported by and held in contact with the underside of the journal by a spring *S*.

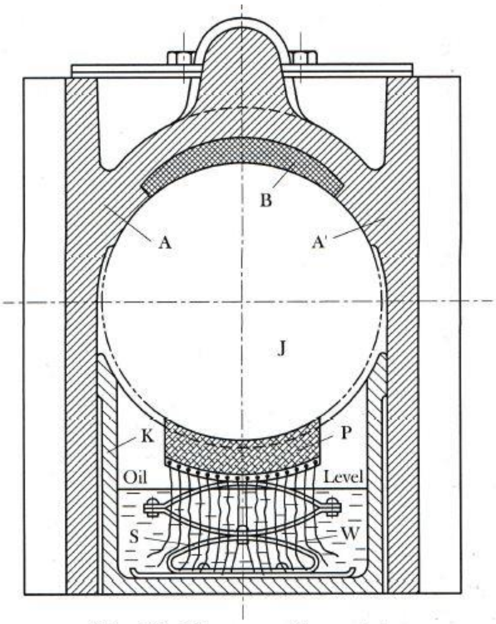


Fig. 72 - Diagram of an axlebox

(Tester, Midland Railway manganese bronze driving axlebox, 2011)

Early version of the 'Stanier' axlebox as used on the 2-6-4T introduced in 1934. This Great Western inspired design comprised a steel body with a pressed-in circular brass, large keep containing an auxiliary spring-loaded oil pad. This was intended as a back up to the main feed from the mechanical lubricator thereby ensuring continuity of supply. The slide-out keep could be removed for inspection. The white metal was only shrouded at ends but the brass was provided with serrations to improve bonding.

Oil from the mechanical lubricator entered through the top of the axlebox, whence it reached the journal via two internal passages and two oil grooves located at 40° to the vertical centre line. Later practice was to reduce the thickness of the white metal and to groove the back of the brass so permitting oil delivery on the horizontal centre line. However, this arrangement although providing a bearing surface undisrupted by oil grooves, was not successful in boxes having high bearing loads in the region of oil delivery. For them a reversion was made to the arrangement shewn here.

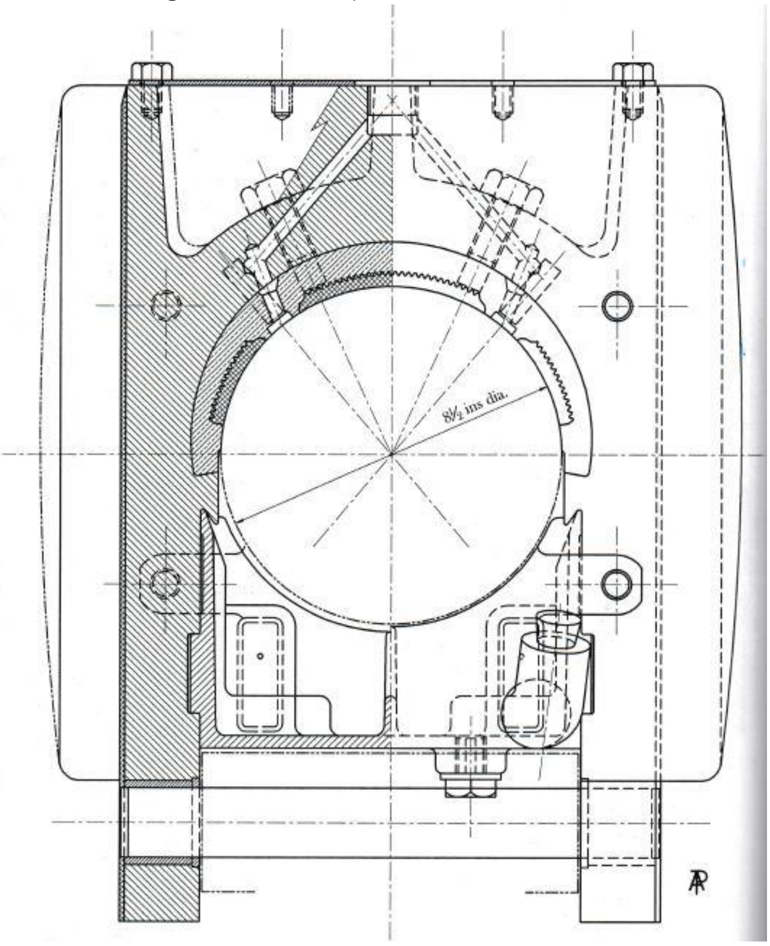


Fig. 35 - LMS 'Stanier' steel axlebox with pressed in brass (scale - quarter full size)

(Tester, LMS 'Stanier' steel axlebox with pressed in brass, 2011)

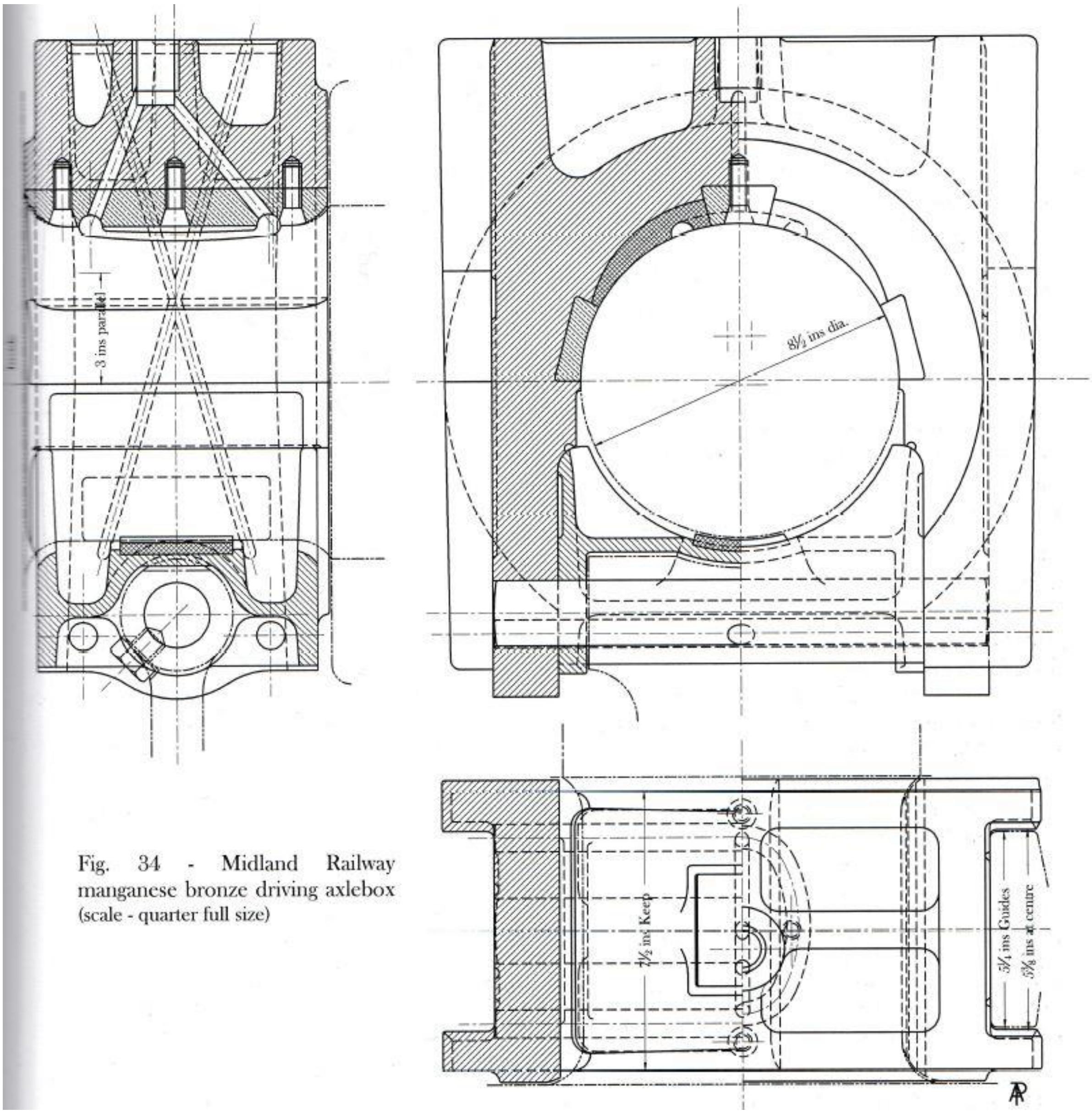


Fig. 34 - Midland Railway manganese bronze driving axlebox (scale - quarter full size)

(Michell, 2011)

6) Type of Repairs

General repairs were a complete overhaul following which the locomotive would have the same performance as a new engine. Intermediate or service repairs were defined as attention to tyres, axleboxes and other such details that would permit the engine to give another six month's service. (Adrian, 2011) (RailUK, 2014)

7) Comparison of 4F and WD 2-8-0

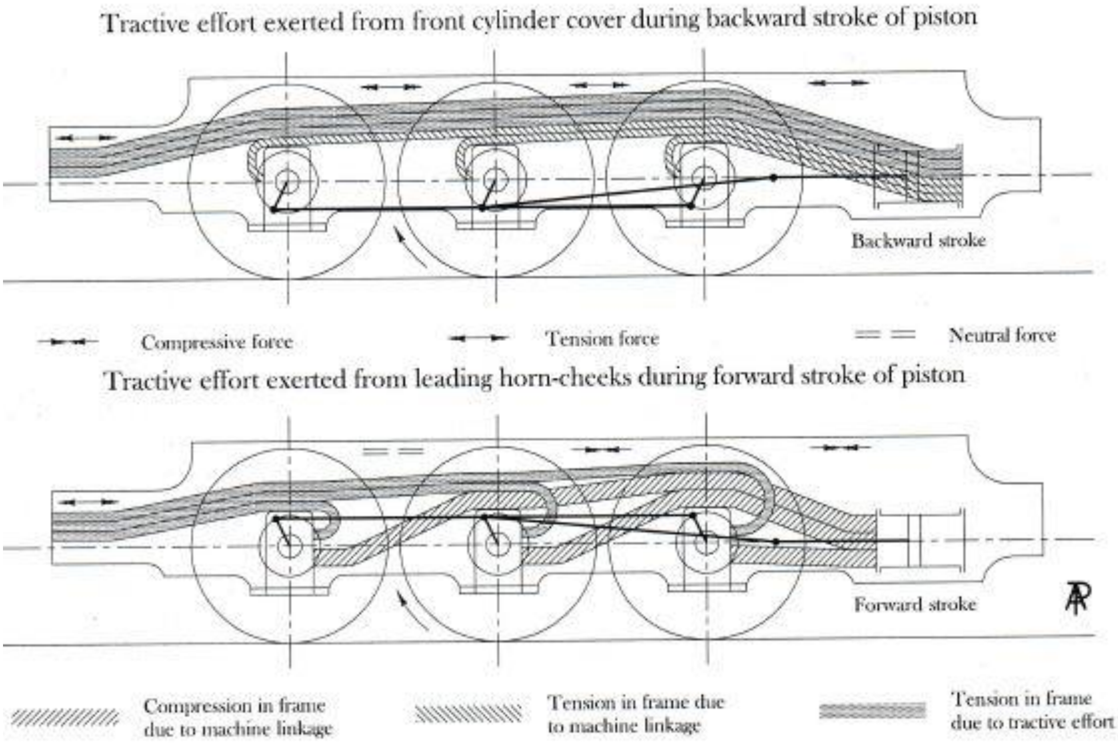
(Tester, Comparison between ex-LMS Class 4F 0-6-0 and WD Austerity CLass 8F 2.8-0, 2011)

Table XXXVII – Comparison Between ex-LMS Class 4F 0-6-0 and WD Austerity Class 8F 2-8-0

		Class 4F 0-6-0	WD 2-8-0
Engine weight	tons	48.75	70.25
Drawbar horsepower (level)		720	1,010
Drawbar horsepower per ton		14.8	14.4
Tractive effort	lbs	24,555	34,215
Drawbar pull at 22mph on the bank	lbs	10,200	14,300
Drawbar pull ÷ tractive effort		.415	.418
Drawbar pull at 22mph on the level	lbs	12,273	17,216
Drawbar pull ÷ tractive effort		.50	.50
Weight of train	tons	301	422
Weight of train ÷ weight of engine		6.17	6.01

8) Stresses in Frame

(Clarke, Tractive Effort Exerted , 1939)



9) Horn Guides and Hornblocks Fitted to LMS Class 5 4-6-0

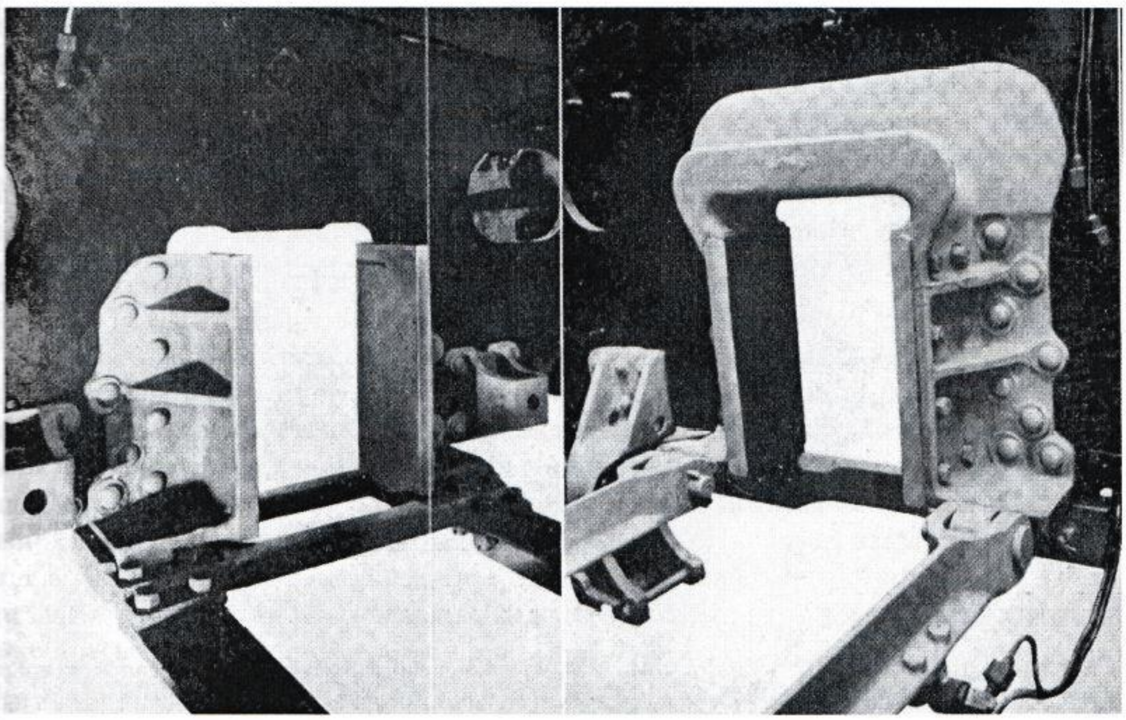
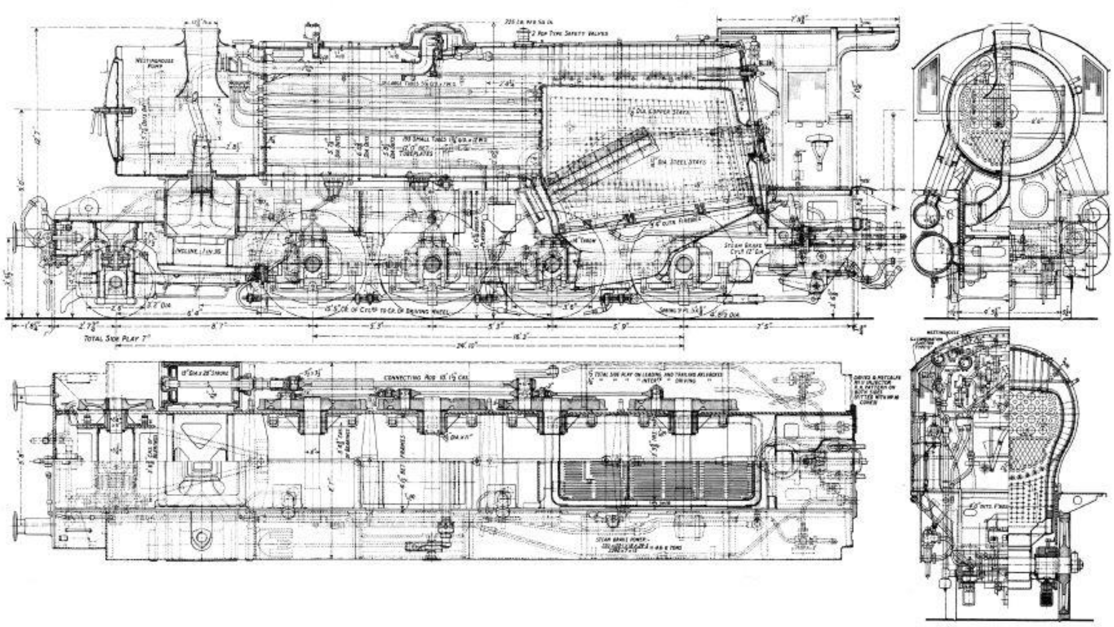


Fig. 15 – Horn guides and hornblocks fitted to LMS Class 5 4-6-0s

(Tester, Horn guides and hornblocks fitted to LMS Class 5 4-6-0, 2011)

10) General arrangement drawing

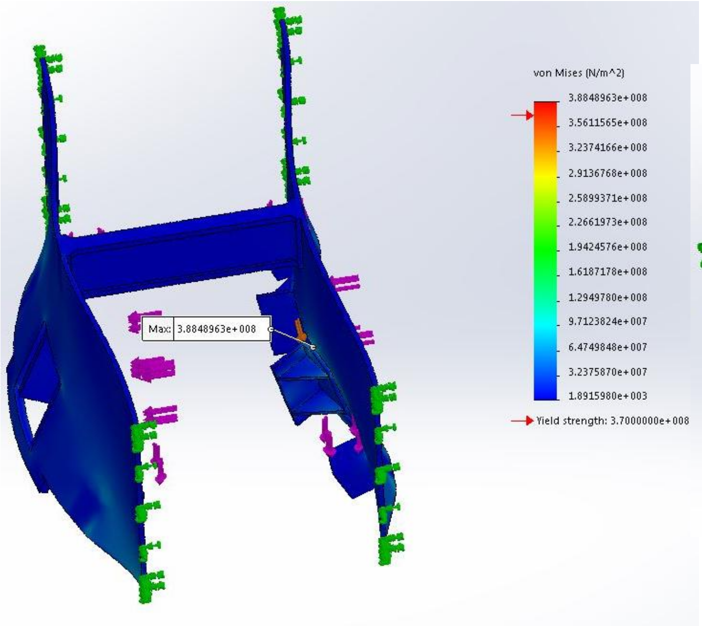
(British Railways, 1984)

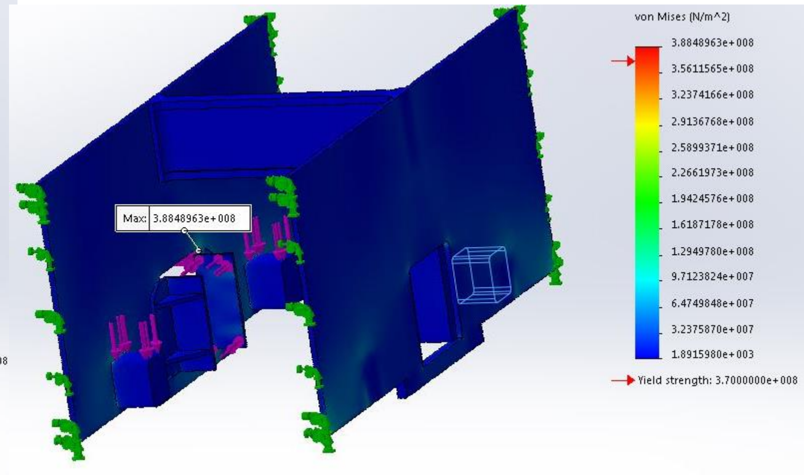


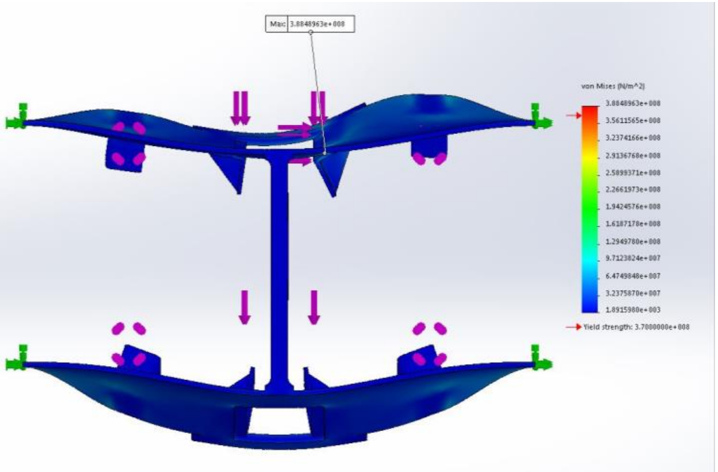
11) Further Screenshots of Simulations

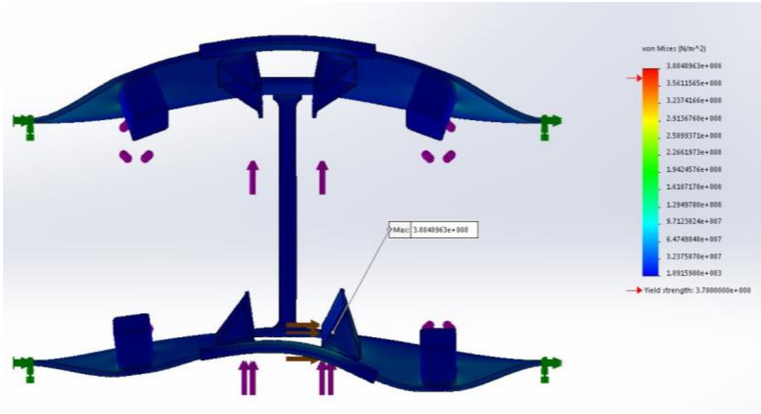
Current Design of Horn Guide

Without Cant Applied – Stress

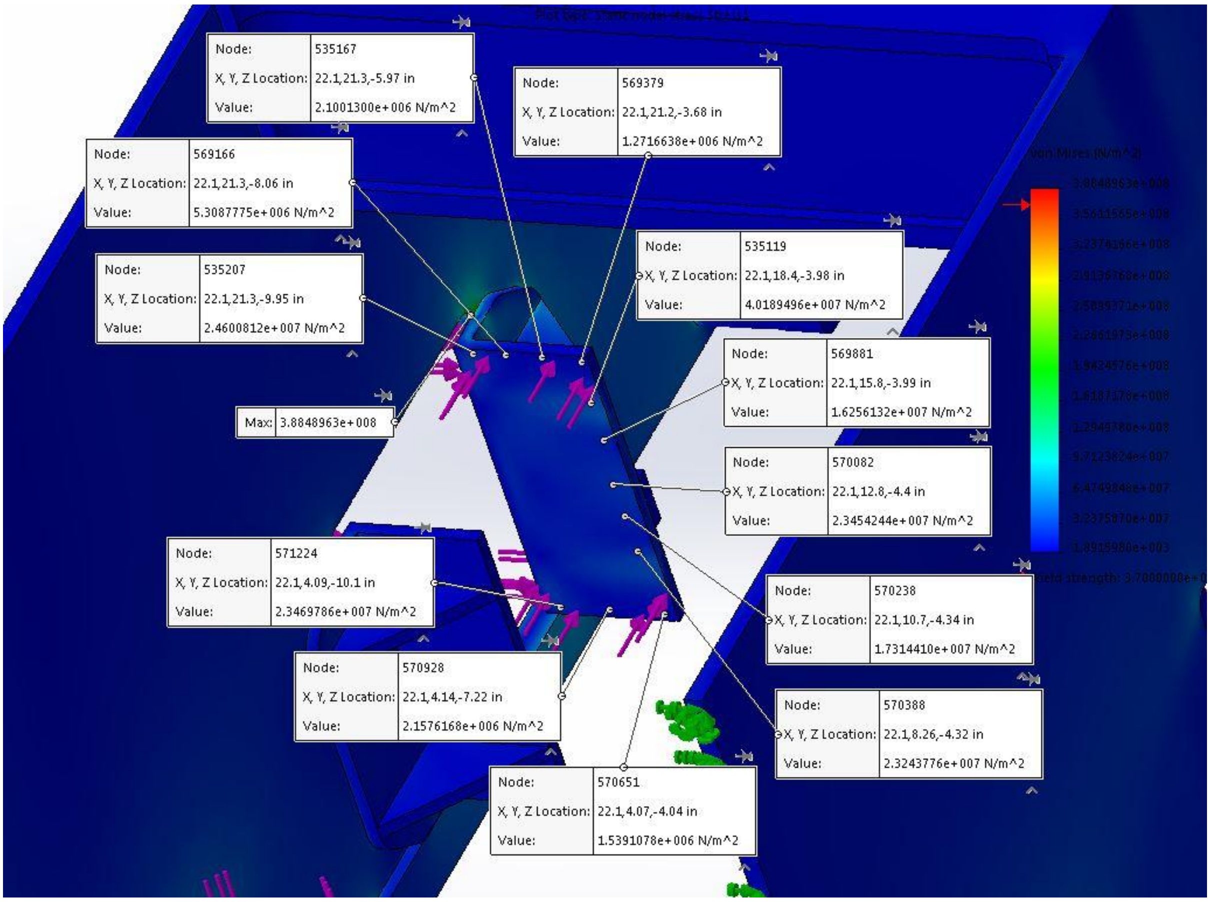






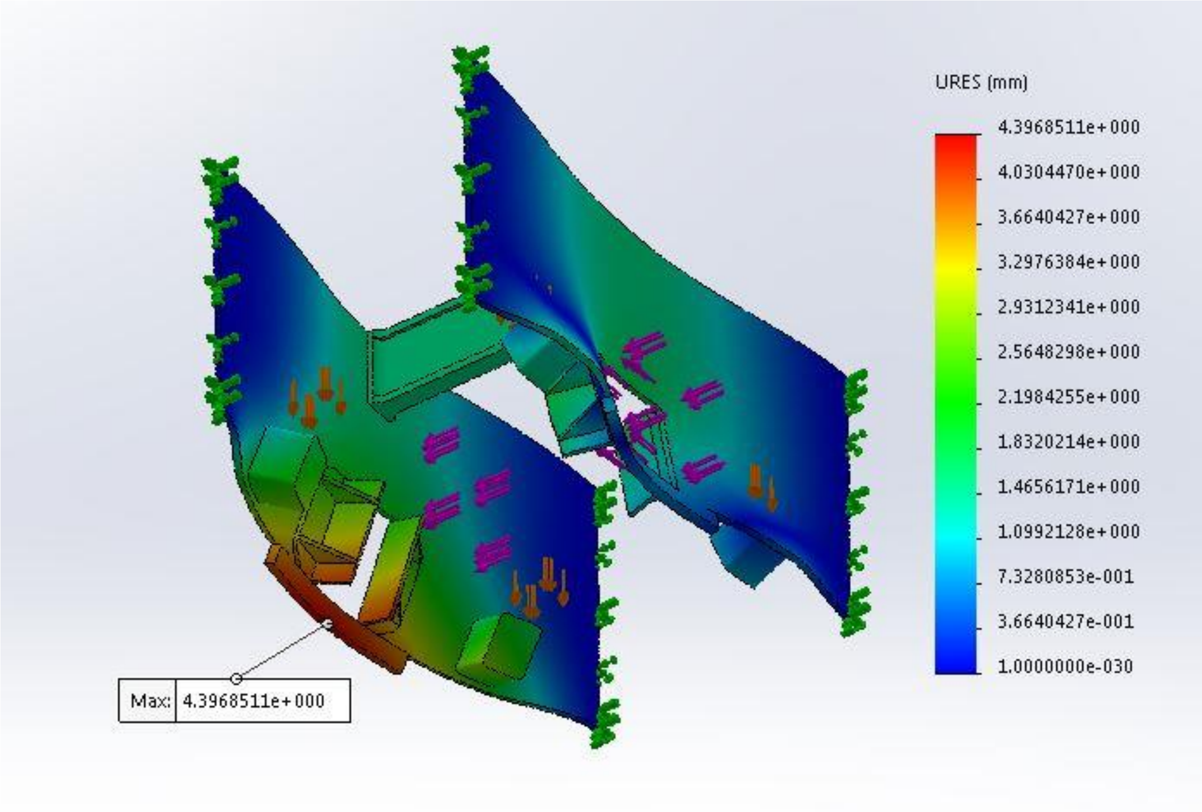


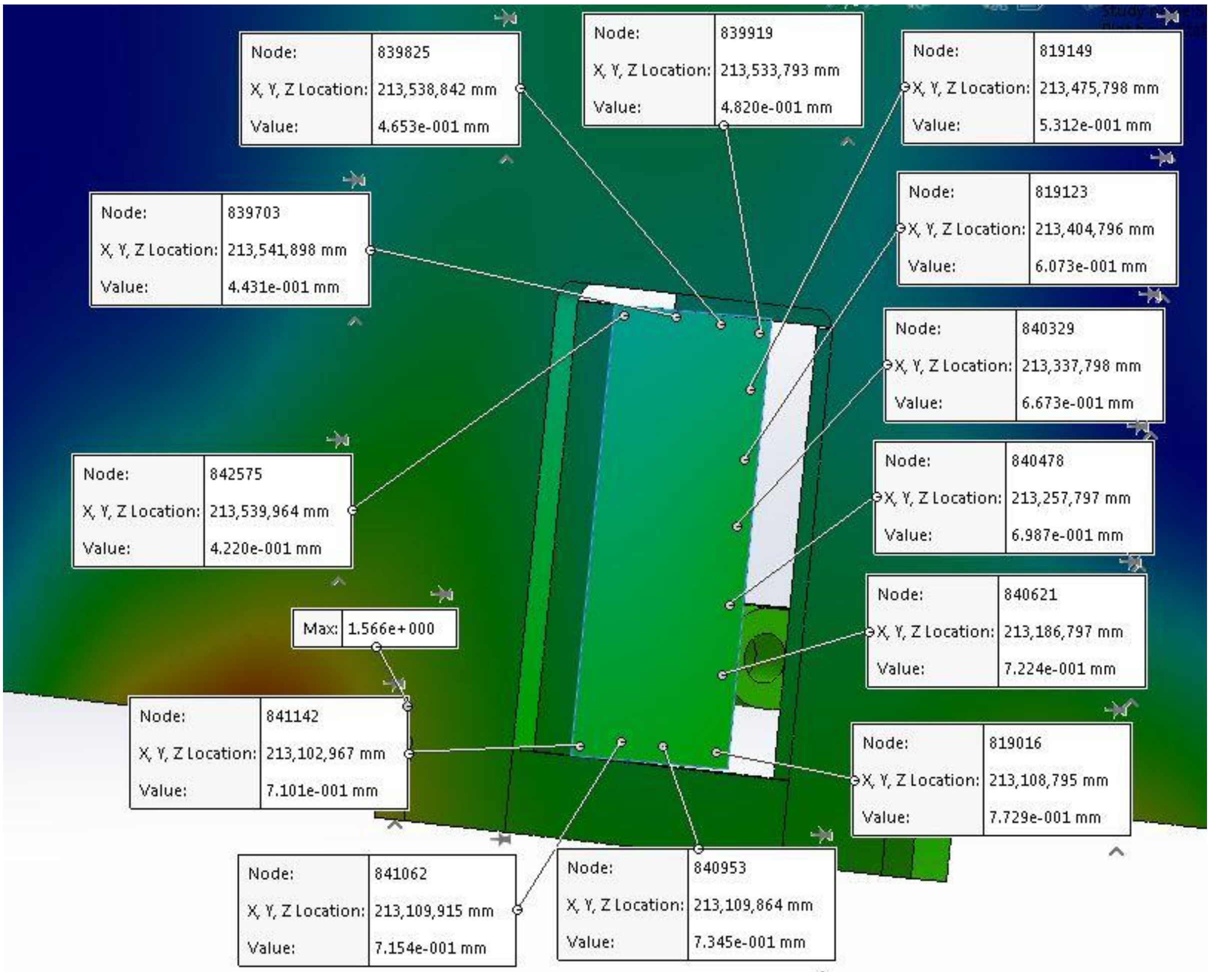
Stress Top & Bottom Views



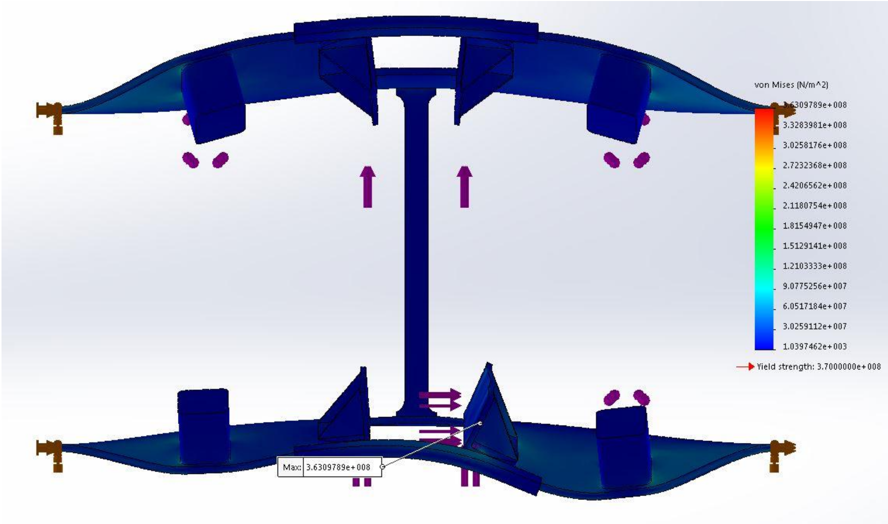
Stress Distribution over Horn guide Face

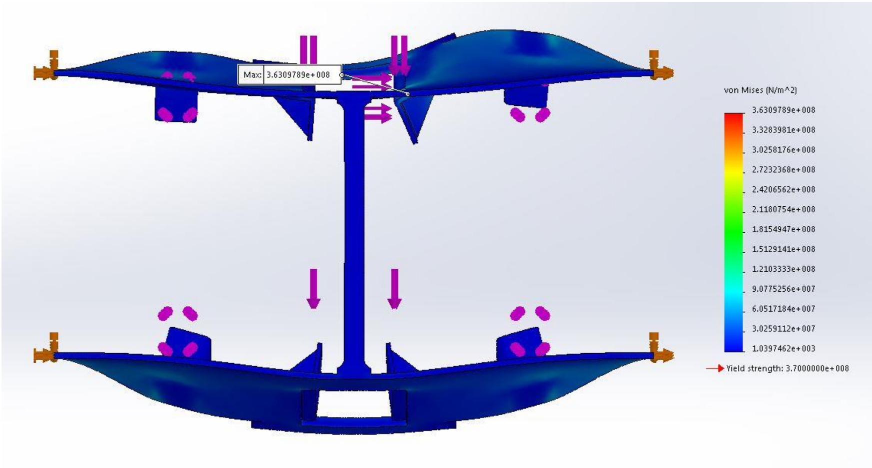
Displacement

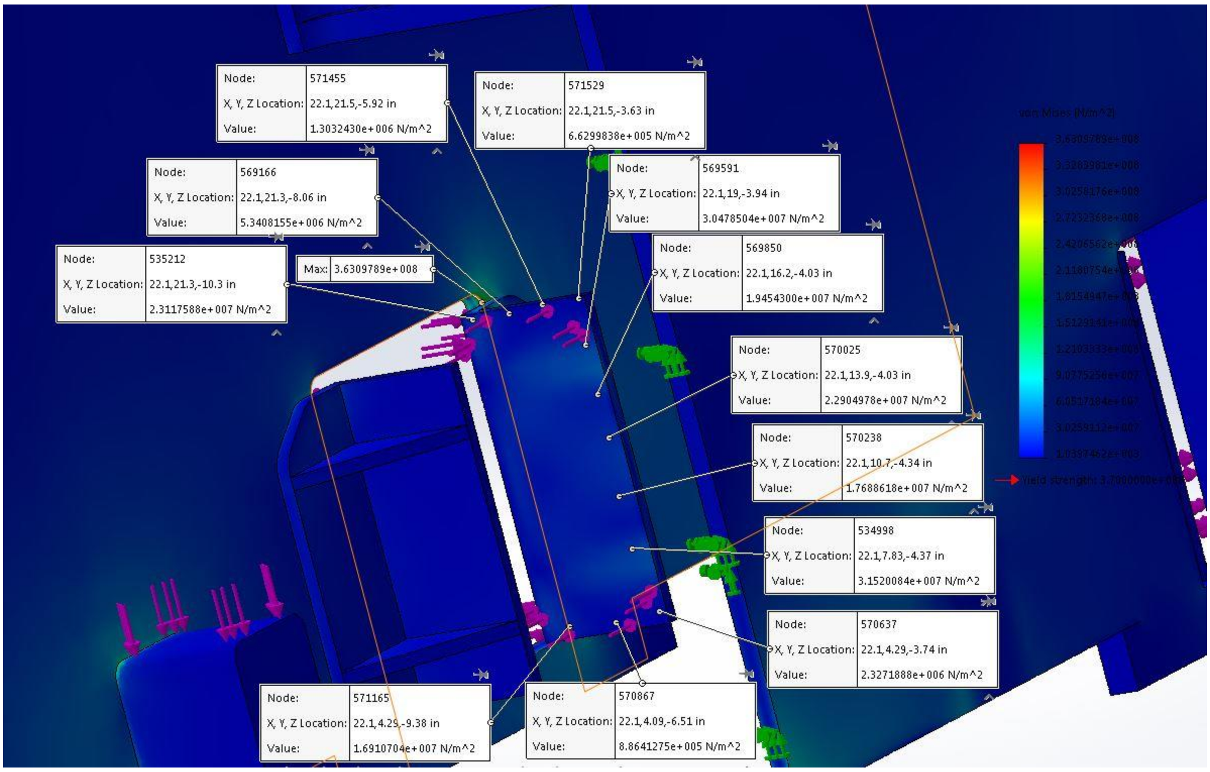




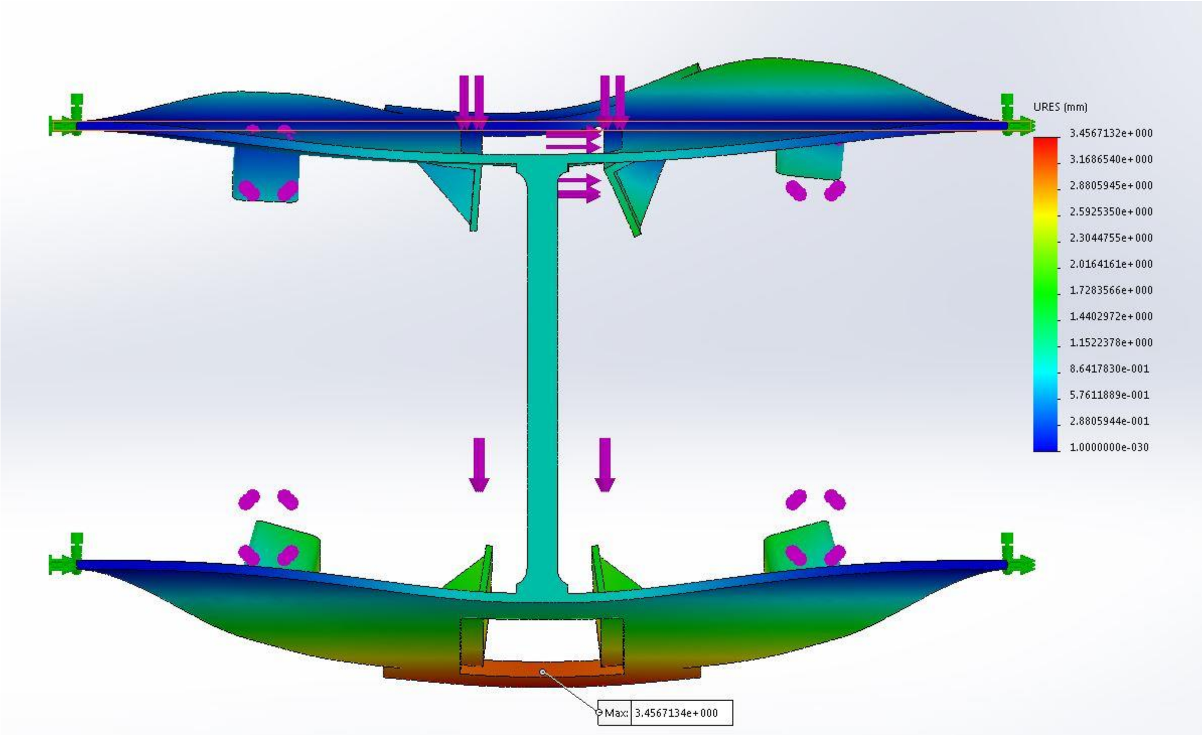
With Cant - Stress

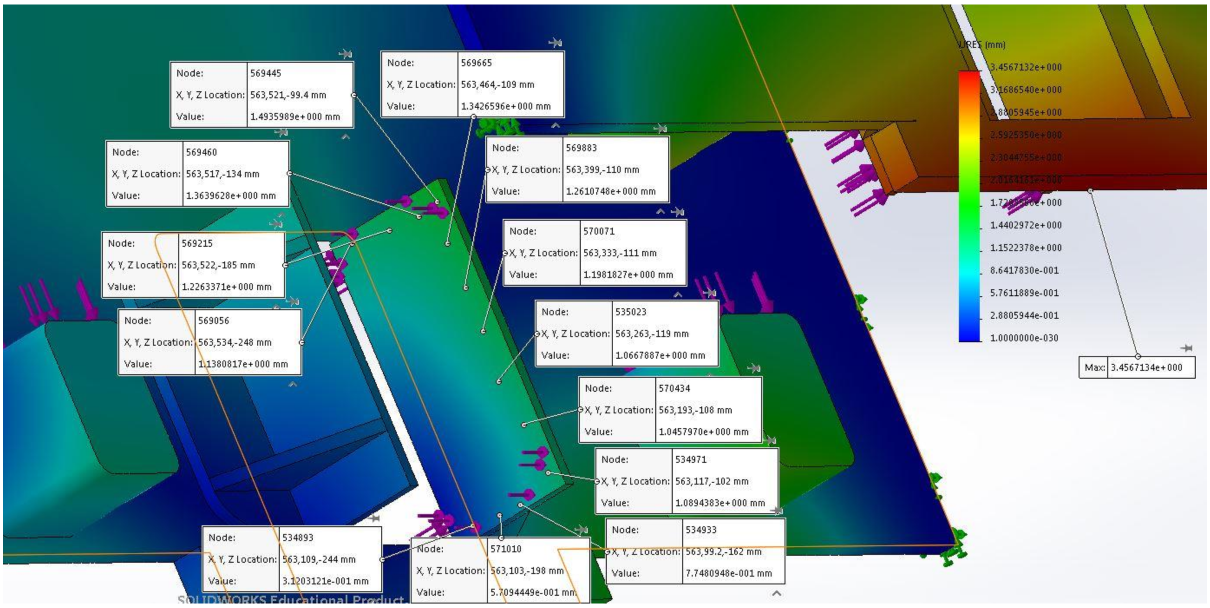




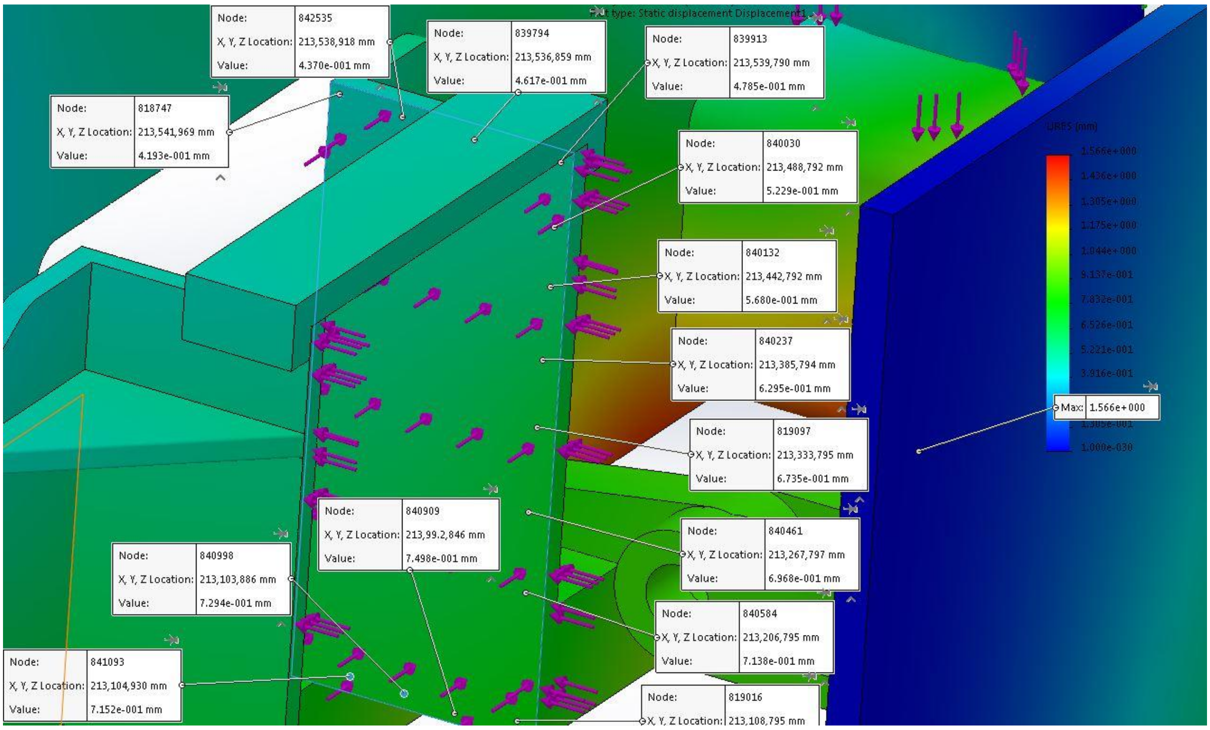


With Cant – Displacement

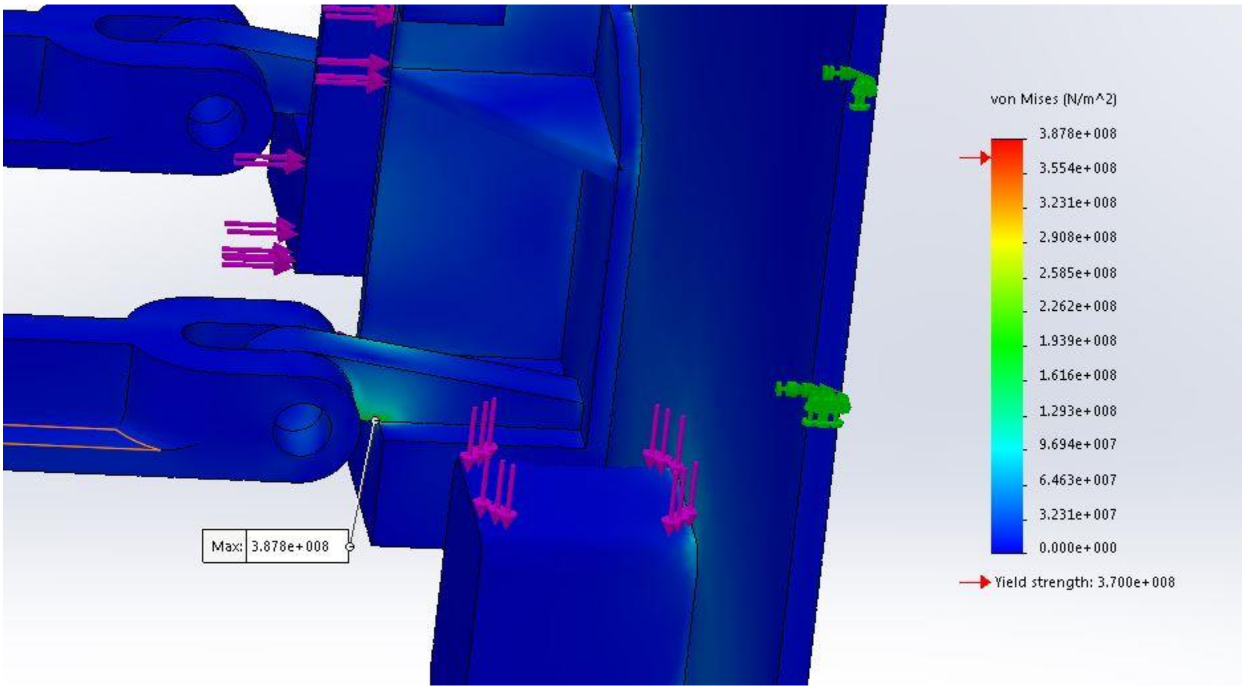


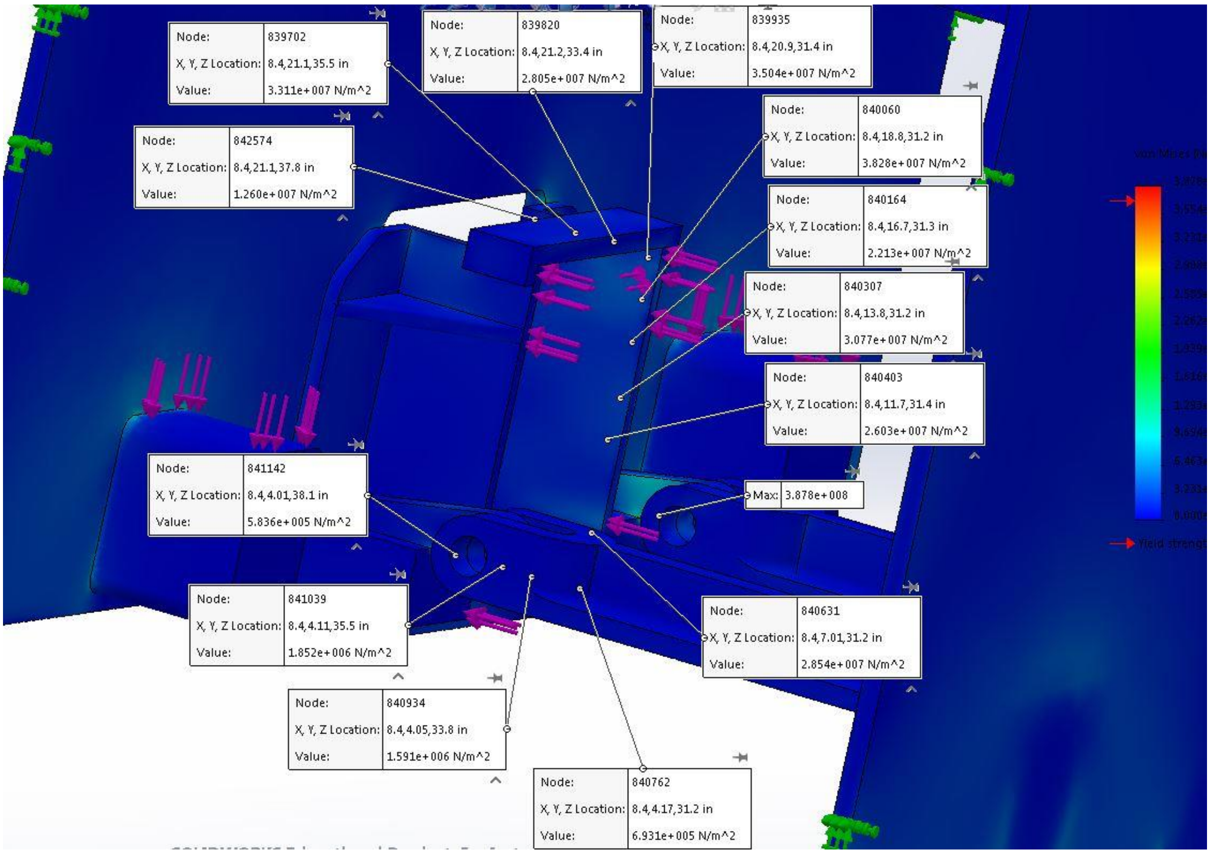


Modification 1 Without Cant – Displacement



With Cant – Stress

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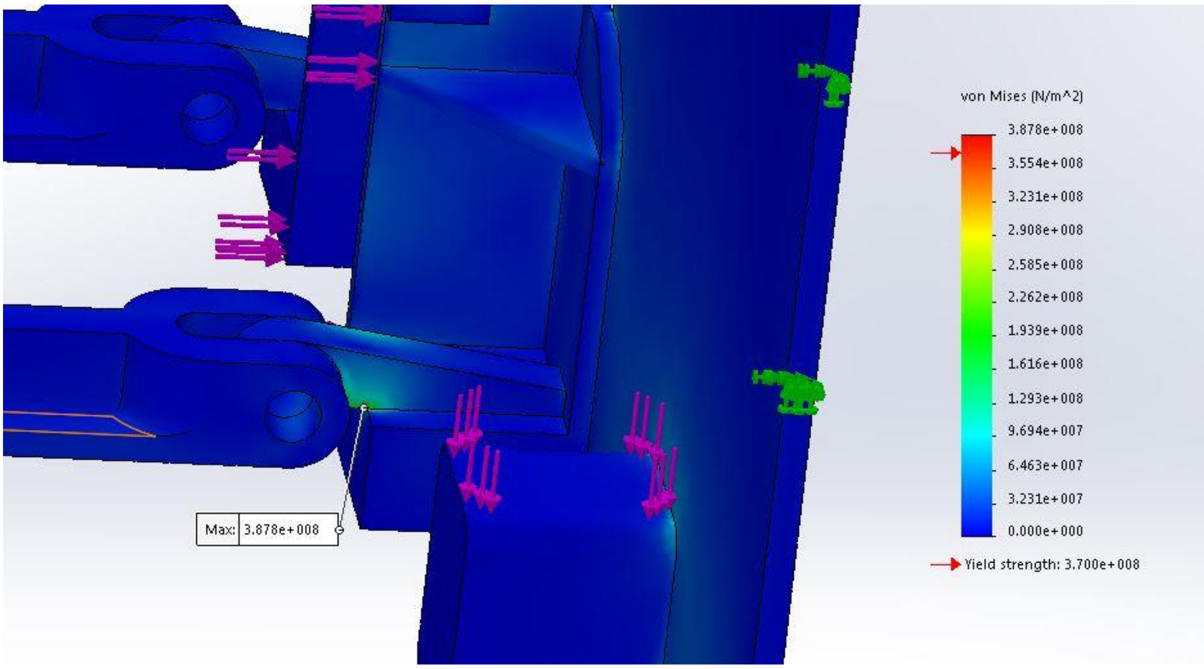
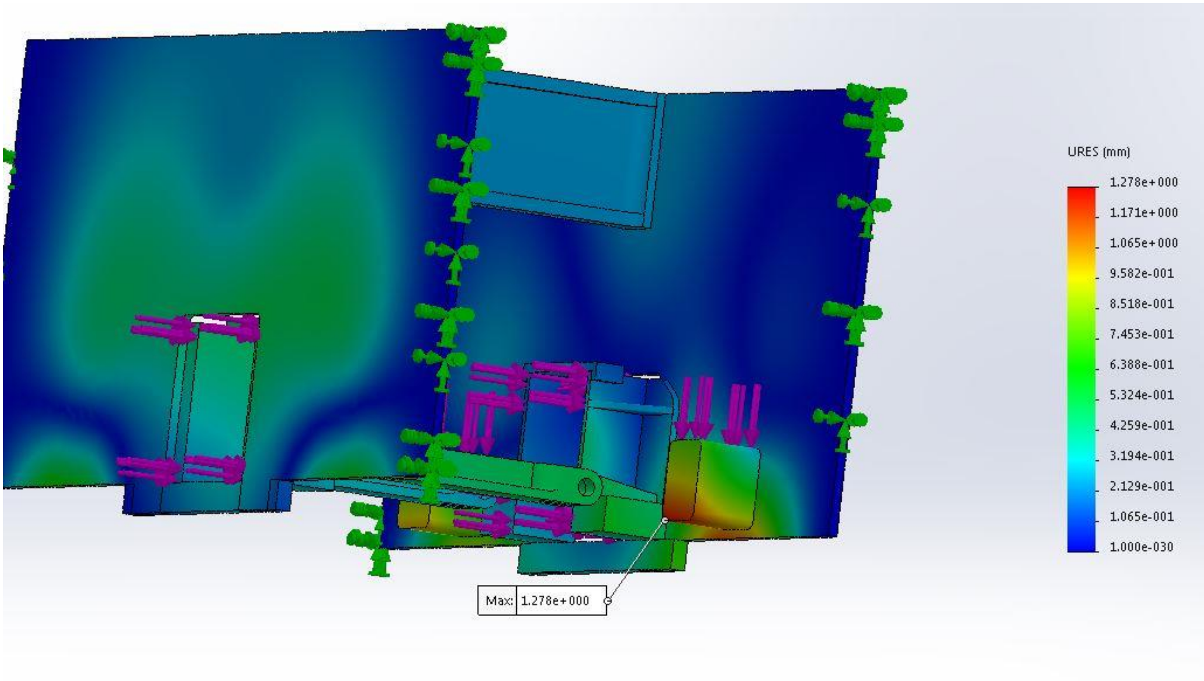
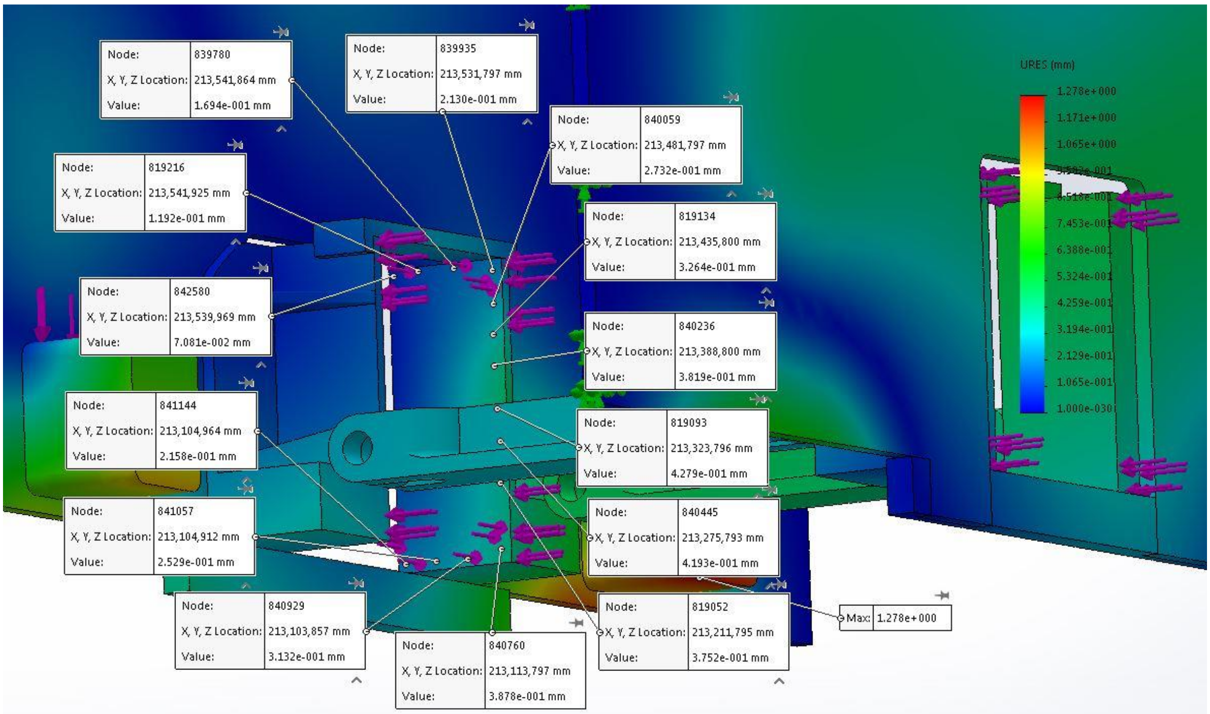
X, Y, Z Location: 8.4,21.1,35.5 in
Value: 3.311e+007 N/m^2
Node: 839820
X, Y, Z Location: 8.4,21.2,33.4 in
Value: 2.805e+007 N/m^2
Node: 839935
X, Y, Z Location: 8.4,20.9,31.4 in
Value: 3.504e+007 N/m^2
Node: 842574
X, Y, Z Location: 8.4,21.1,37.8 in
Value: 1.260e+007 N/m^2
Node: 840060
X, Y, Z Location: 8.4,18.8,31.2 in
Value: 3.828e+007 N/m^2
Node: 840164
X, Y, Z Location: 8.4,16.7,31.3 in
Value: 2.213e+007 N/m^2
Node: 840307
X, Y, Z Location: 8.4,13.8,31.2 in
Value: 3.077e+007 N/m^2
Node: 840403
X, Y, Z Location: 8.4,11.7,31.4 in
Value: 2.603e+007 N/m^2
Node: 841142
X, Y, Z Location: 8.4,4.01,38.1 in
Value: 5.836e+005 N/m^2
Max: 3.878e+008
Node: 841039
X, Y, Z Location: 8.4,4.11,35.5 in
Value: 1.852e+006 N/m^2
Node: 840631
X, Y, Z Location: 8.4,7.01,31.2 in
Value: 2.854e+007 N/m^2
Node: 840934
X, Y, Z Location: 8.4,4.05,33.8 in
Value: 1.591e+006 N/m^2
Node: 840762
X, Y, Z Location: 8.4,4.17,31.2 in
Value: 6.931e+005 N/m^2


von Mises (N/m^2)
3.878e+008
3.554e+008
3.231e+008
2.908e+008
2.585e+008
2.262e+008
1.939e+008
1.616e+008
1.293e+008
9.694e+007
6.463e+007
3.231e+007
0.000e+000
Yield strength: 3.700e+008
Max: 3.878e+008

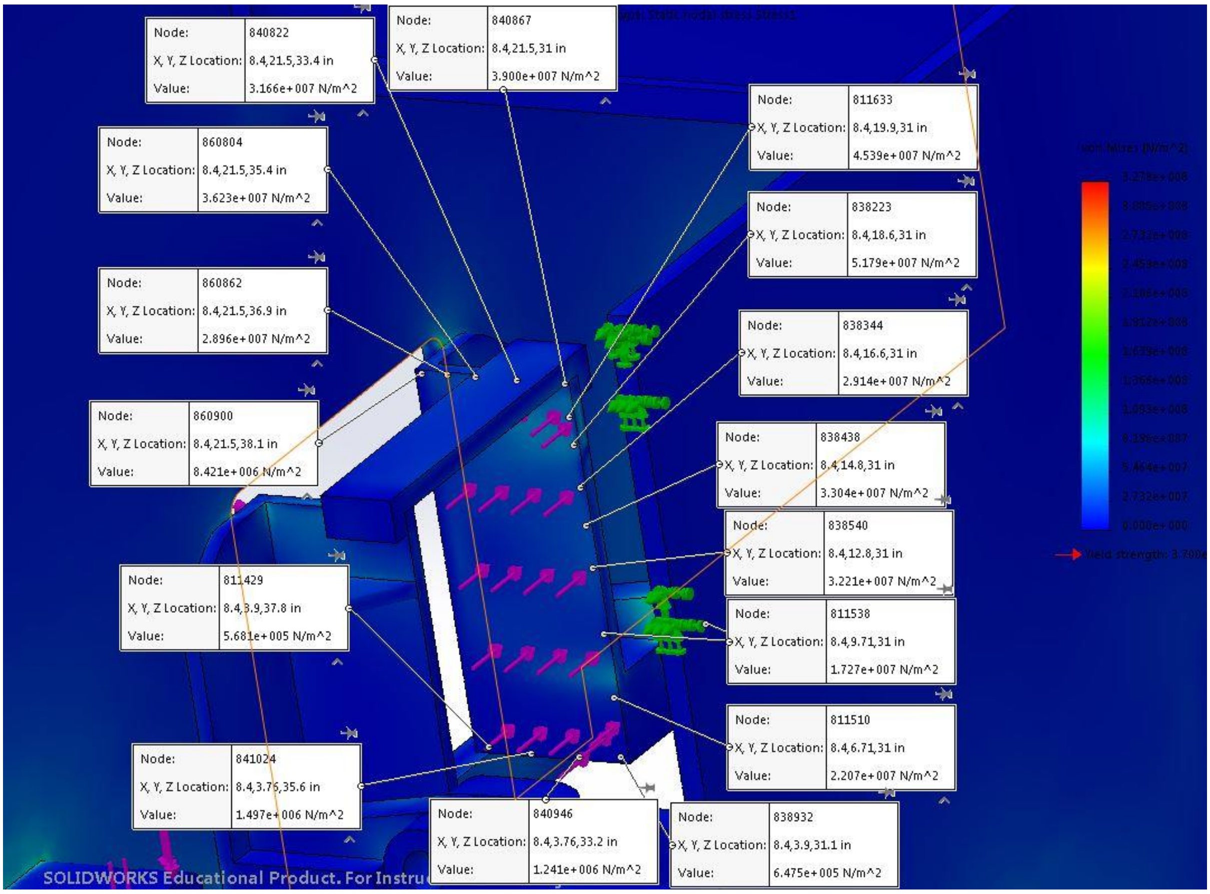
Displacement



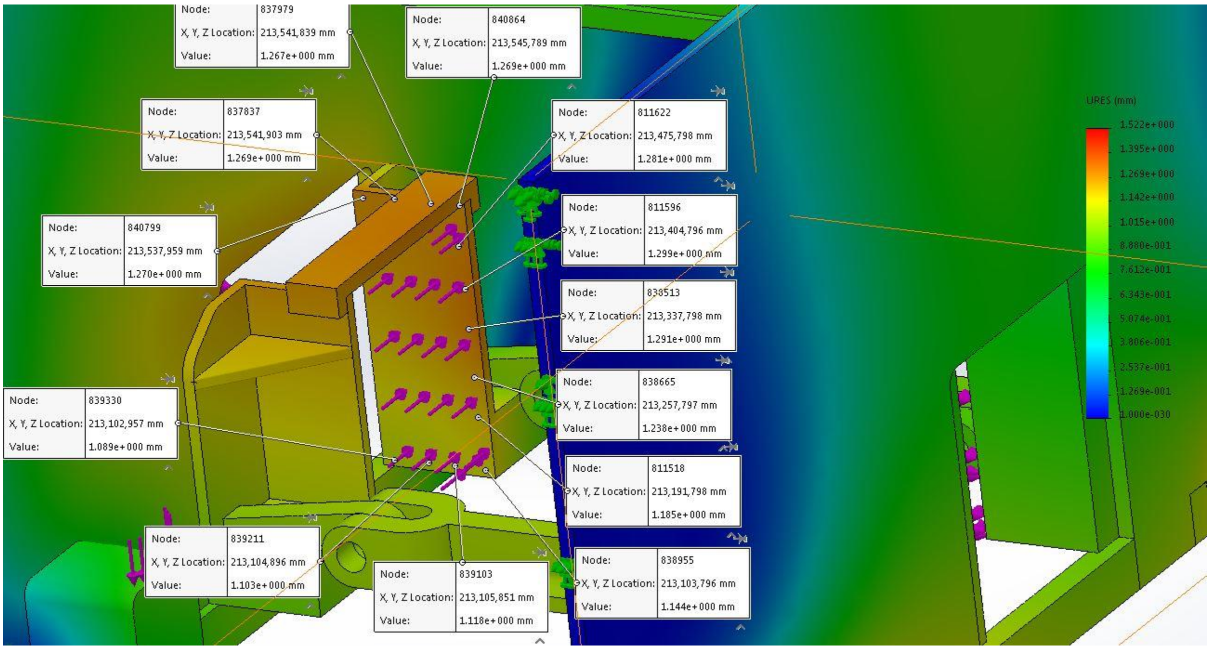


Mod 2 Without Cant

Stress

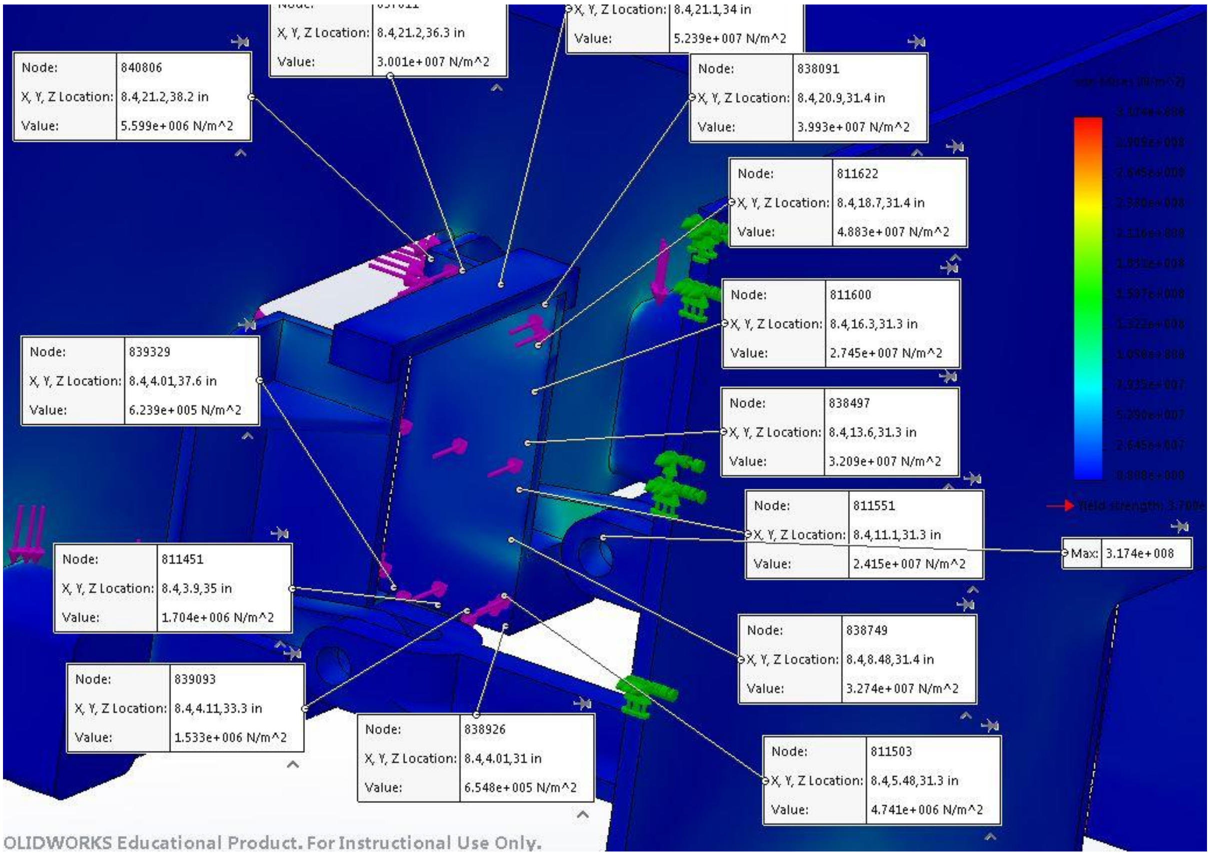


Displacement

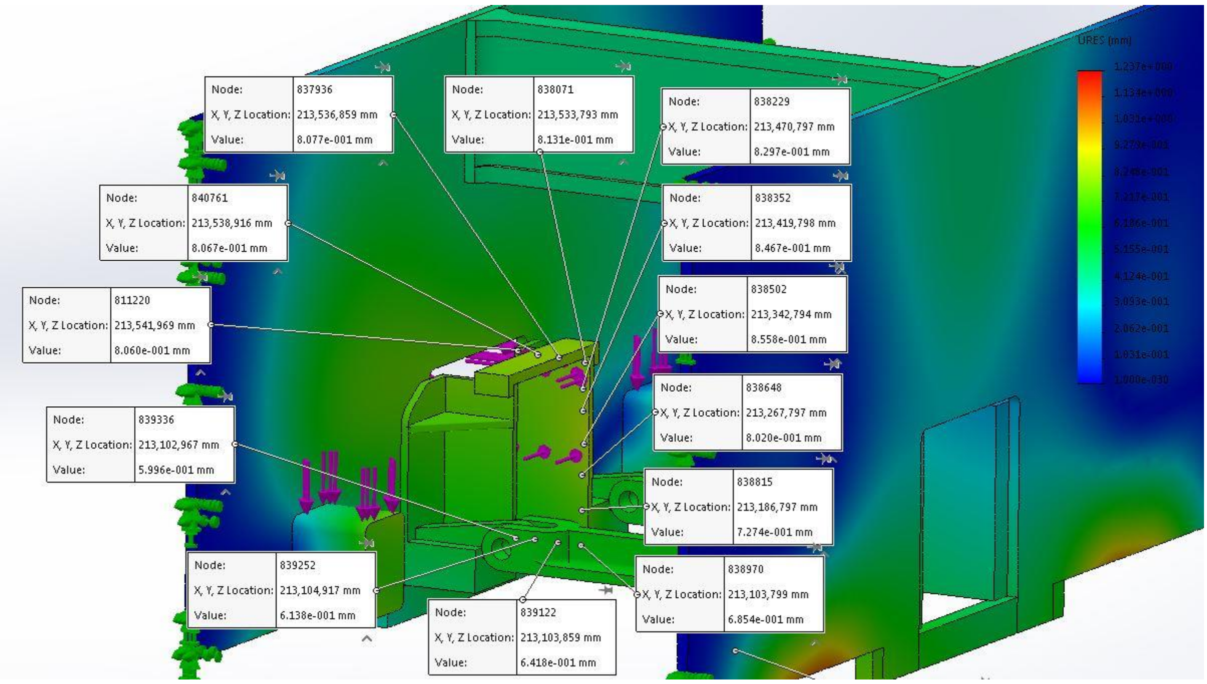


Mod 2 With Cant

Stress



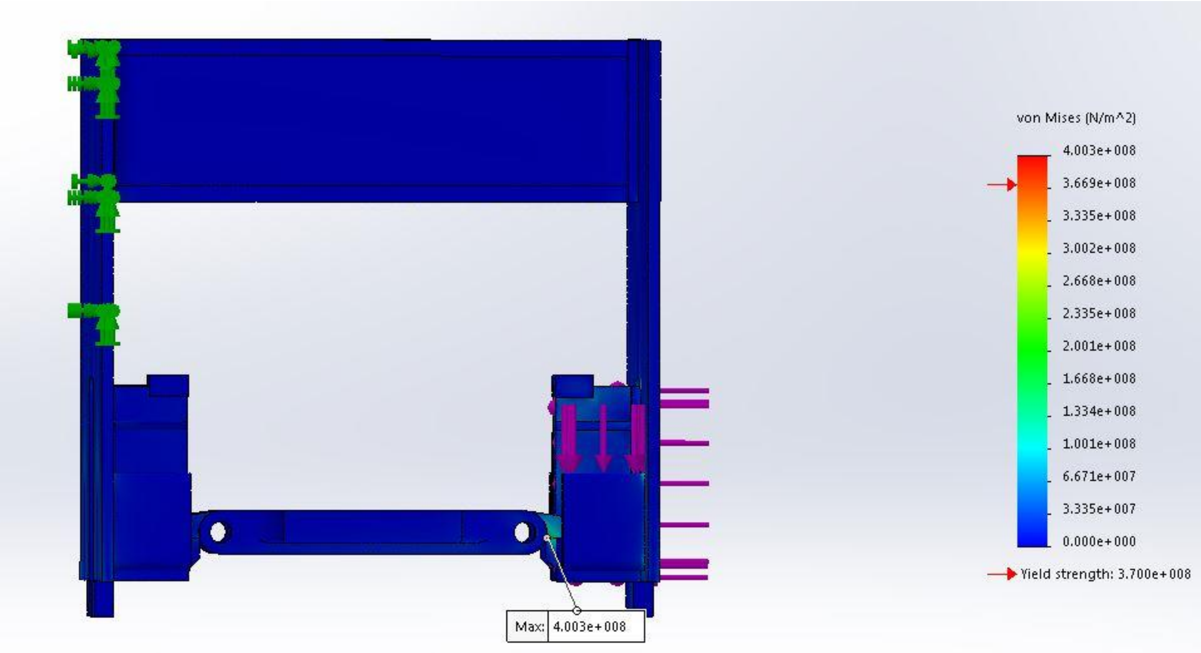
Displacement



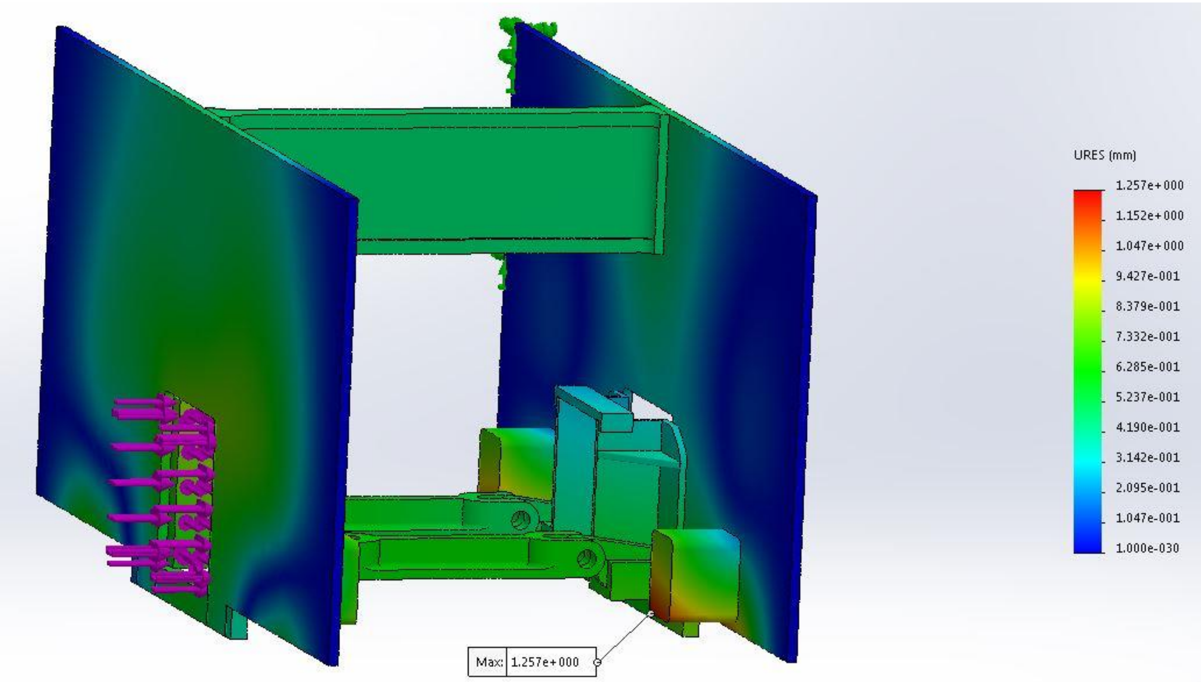
Mod 3

Without Cant

Stress

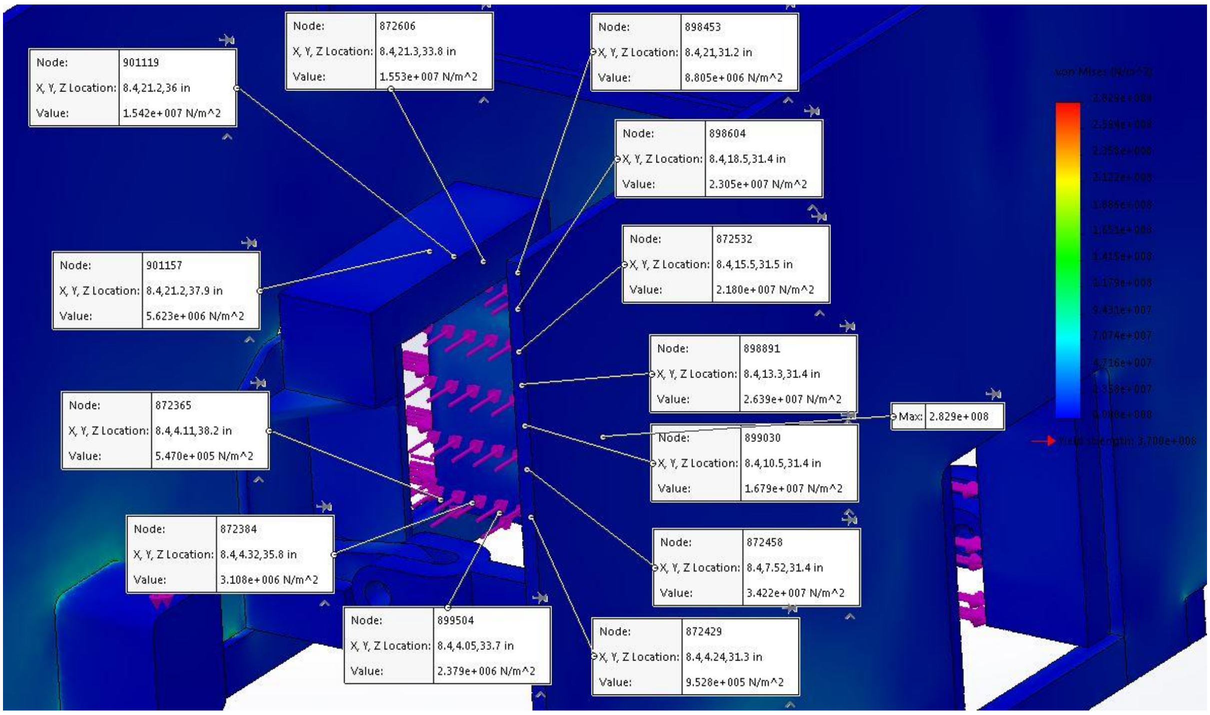


Displacement

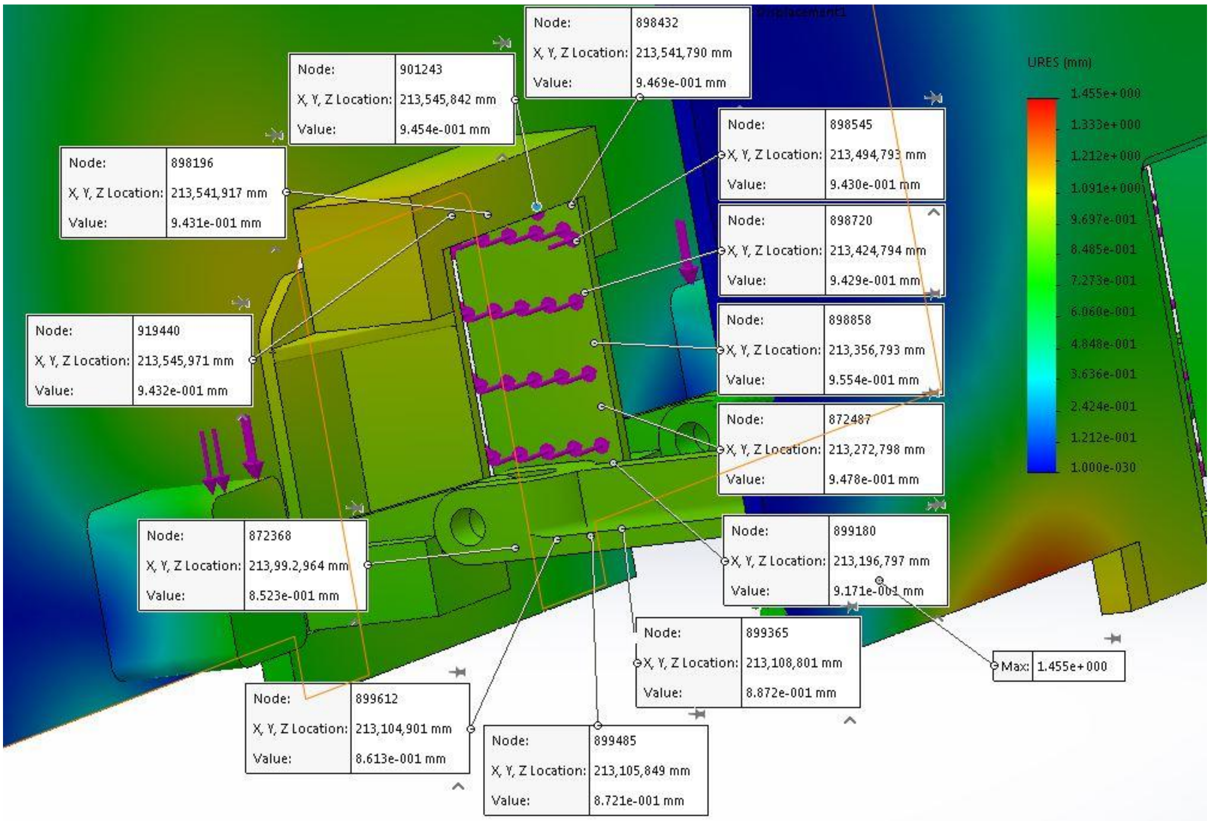


Mod 4 – Without Cant

Stress

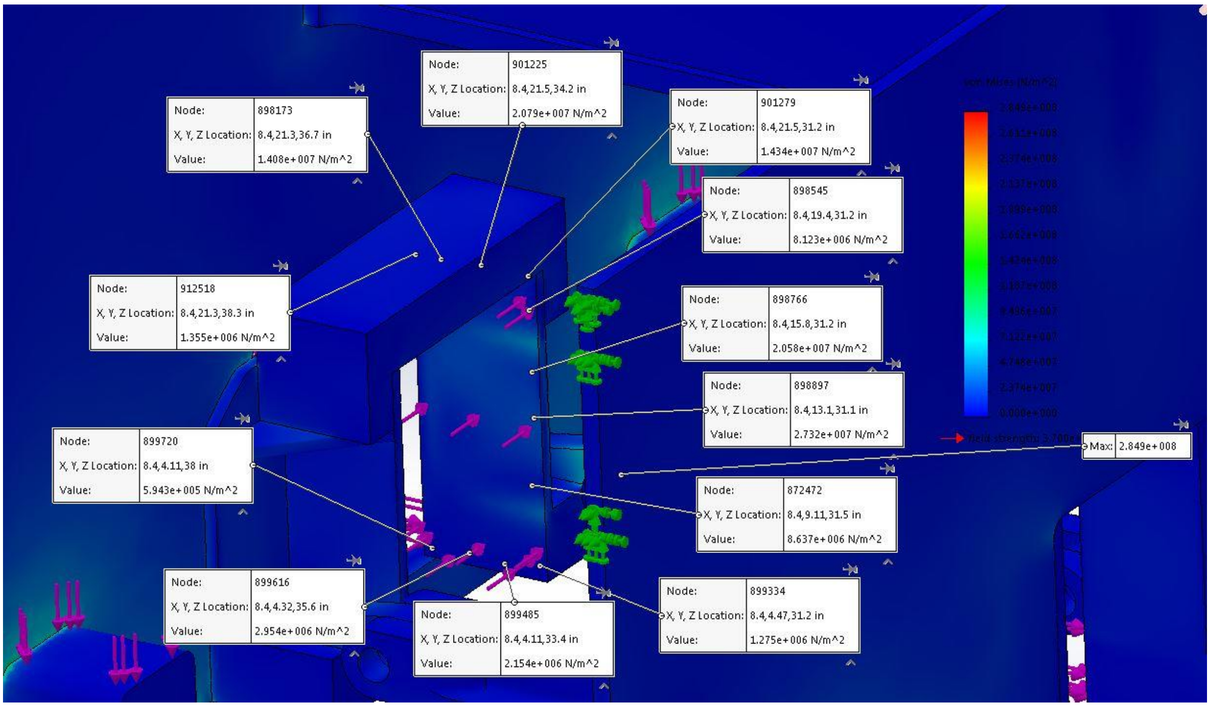


Displacement

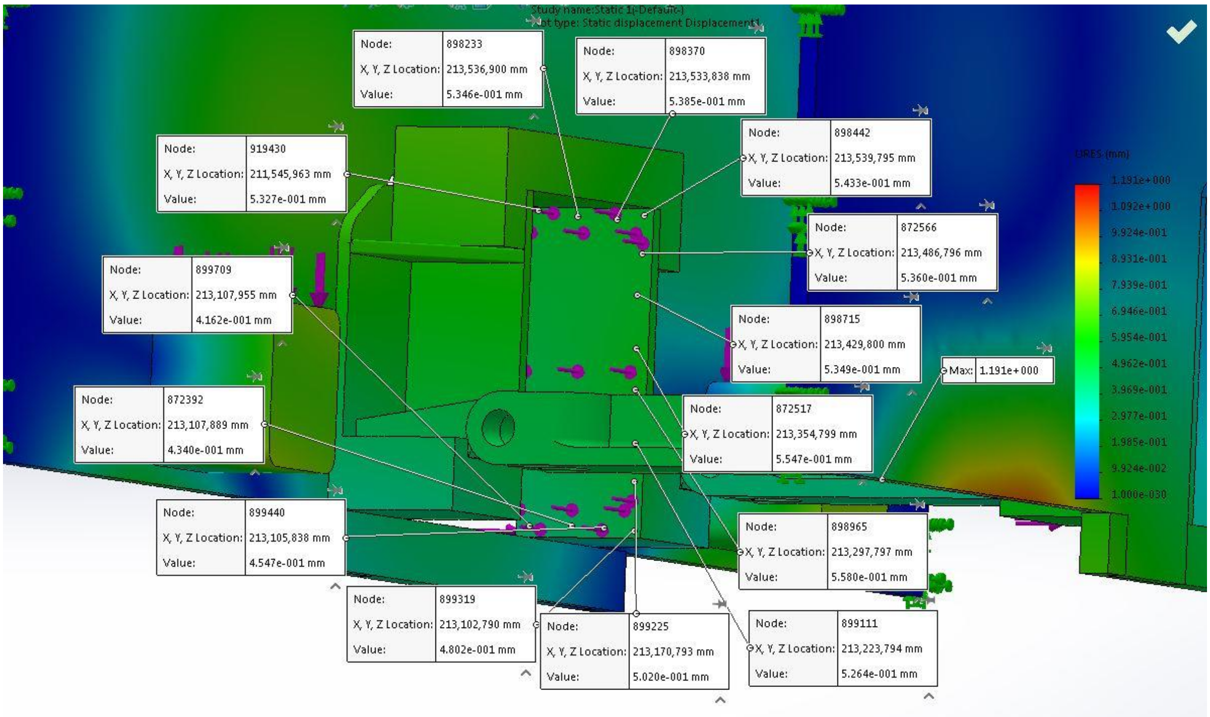


With Cant

Stress

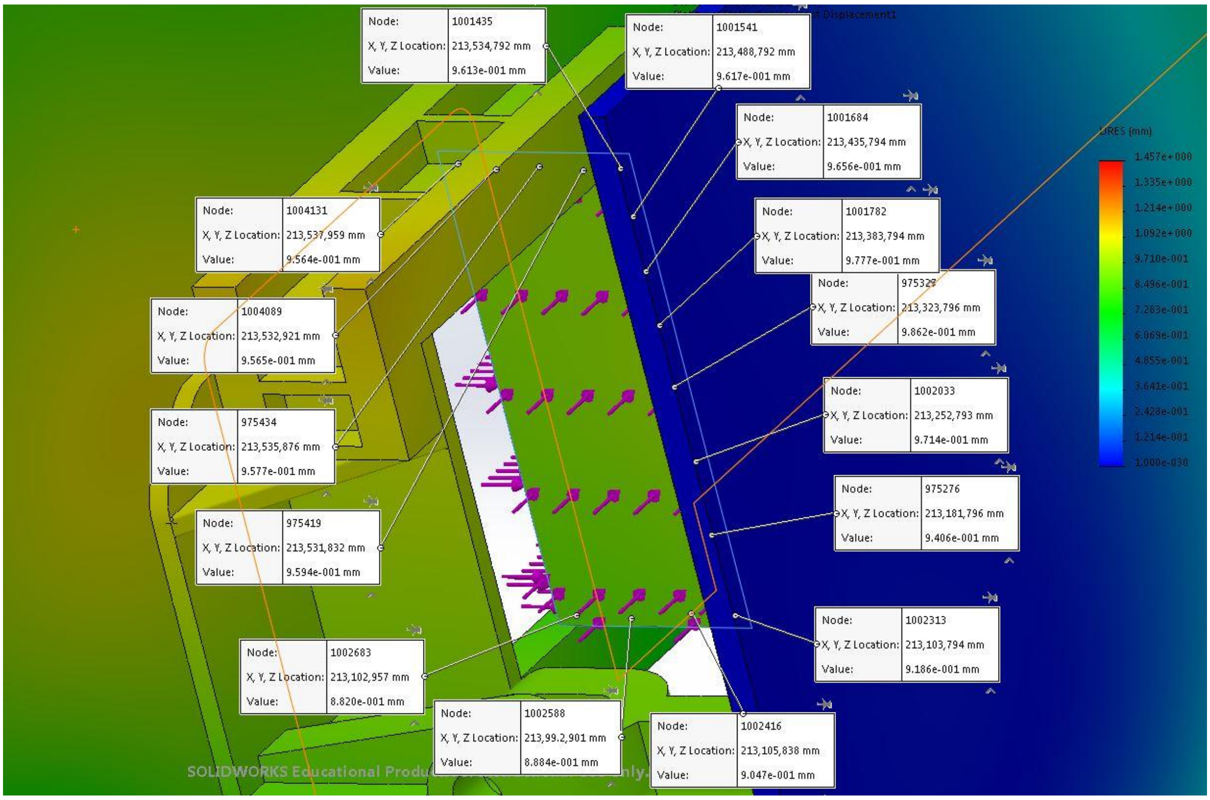


Displacement



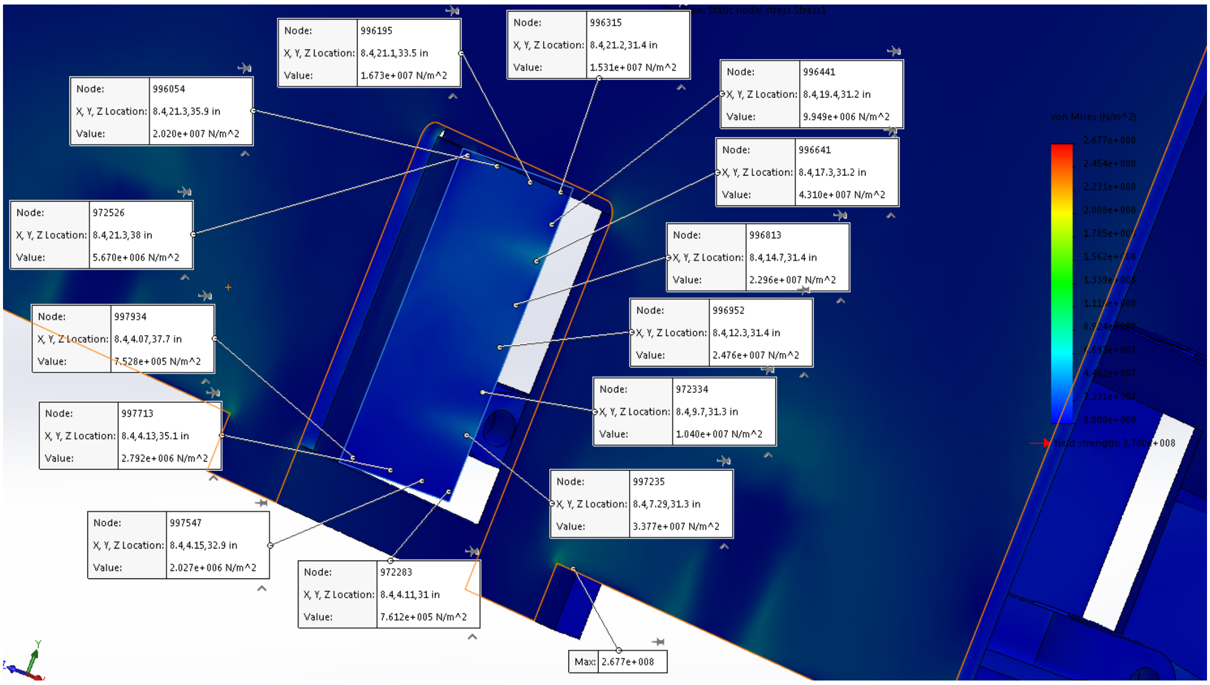
Mod 5 – Without Cant

Displacement

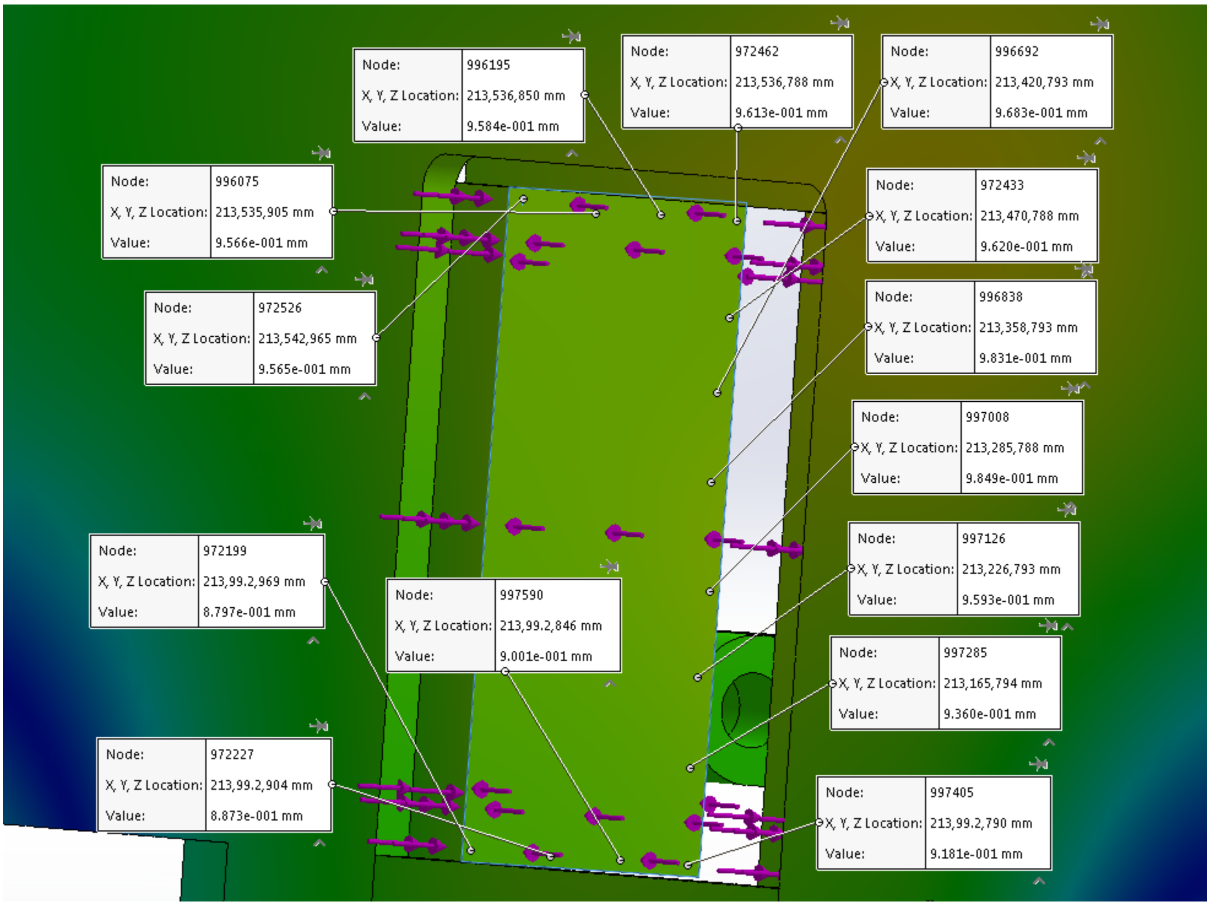


Mod 6 – Without Cant

Stress

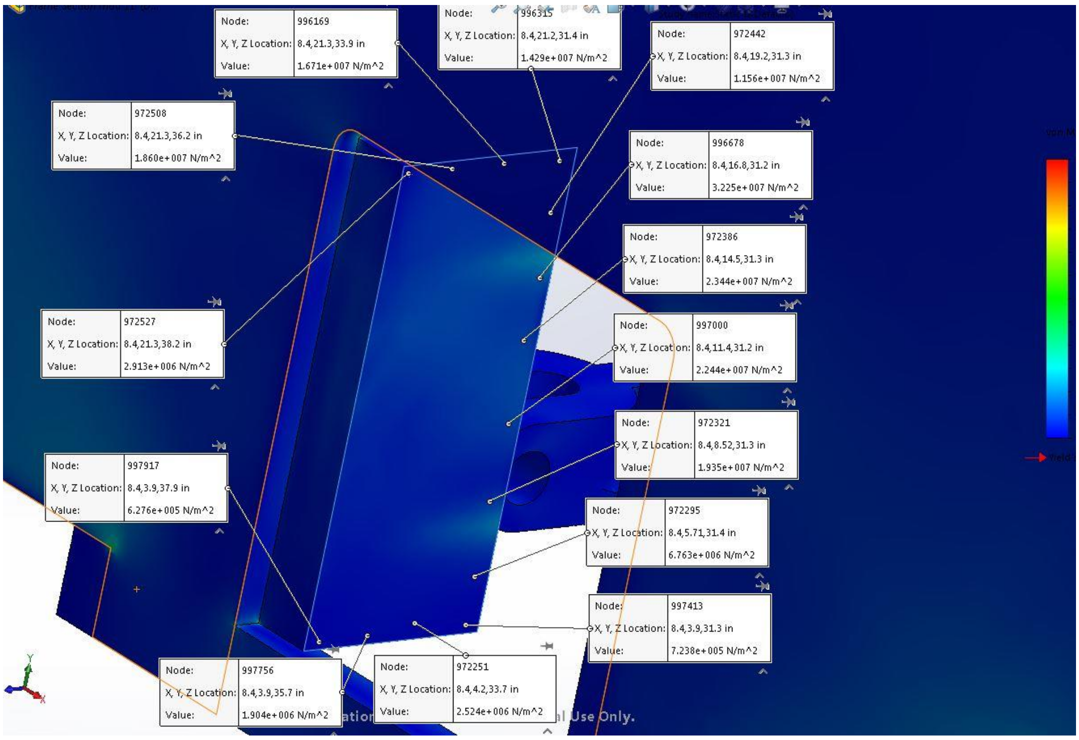


Displacement



With Cant

Stress



Displacement