



University of Wales Trinity Saint David
School of Engineering

Analysis And Recommendations For
The Minimisation Of Material Failures

Michael Anderson
P151178

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Mechanism of Materials Failure
ACEA 7010

Phil Holden

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1. Introduction

An investigation was conducted into the mechanical failures of a wishbone/control arm component within a road vehicle suspension system. This report will research the different shapes of wishbones, impacting both the forces exerted onto the component and its construction procedure.

Both material selection and failures will be analysed to determine their cause and recommend preventative measures to ensure a long lifespan, satisfying both customers and consumers. Case studies will be reviewed to comprehend their methodology and results of topological optimisation and failure analysis within wishbone designs in the automotive and motorsport industry.

2. Component Selection & Analysis

Modern suspension systems can trace their roots back to horse and oxen-drawn carts used within mines, quarries for the removal of their respective raw unrefined substance and personal transportation. The concept derived from the requirement to separate the valuable cargo from damage incurred from harsh terrain as roads were often bumpy, uneven and of excessive/adverse gradient/incline, if existent at all.

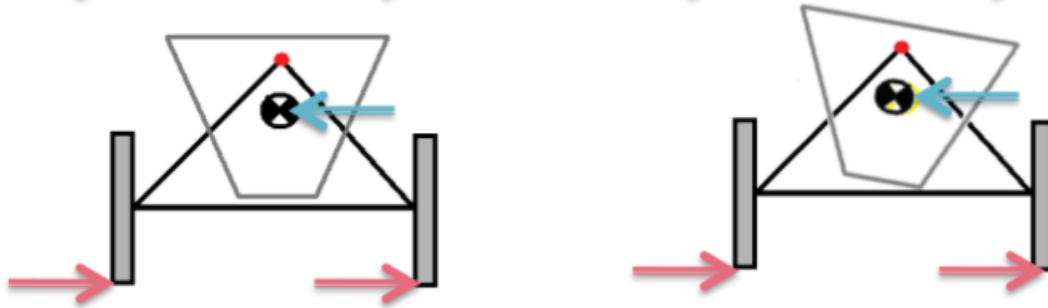


Figure 1 – Demonstration Of Motion Incurred By A Mine Cart Engaging In A Right Hand Corner (Tudor, 2020)

The cargo was suspended originally by iron chains, then evolving into leather straps (through braces), allowed the ability for the 'unsprung mass' to pivot relative to the terrain, gradient or centripetal cornering forces. (Figure 1) This system severed the direct link between terrain surface and the cargo, providing damage control to goods and comfort for passengers.

Suspension systems have developed significantly in proportion to the human understanding of metallurgy and our ability to manipulate metallic elements to suit our provocative. The Romans replaced through braces with multiple stacked flat wood planks, over time, spring steel bars replaced wood to prolong their lifespan against rotting. Each bar could vary on their independent elastic properties, allowing the impact transferred from the terrain to the unsprung mass to be softened to a desired rate. Of course, this would be designed in accordance to the weight differential between unladen and fully laden loadings to prevent bottoming-out. (EvansTire, 2017)

An important part of any road vehicle is the suspension system, where there are many different variations of design depending upon the application. Most modern passenger vehicles make use of either a MacPherson strut or a double wishbone independent suspension systems on the front of the vehicle. A common structural component between these systems is a lower 'control arm', also referred to as a wishbone/control arm, (Figure 2).



Figure 2 – MacPherson Strut vs Double Wishbone Suspension System (Left) (Stevens, 2020), Diagram Of Wishbone Connections (Right) (Testing Autos, 2020)

The wishbone structurally connects the unsprung mass to the chassis of the vehicle. It translates the independent vertical linear motion/disturbance of the unsprung mass, into rotational movement. Two rubber bushings act as pivot points which both endure forces through six degrees of freedom within three-dimensional space. (M. Sridharan, 2016)

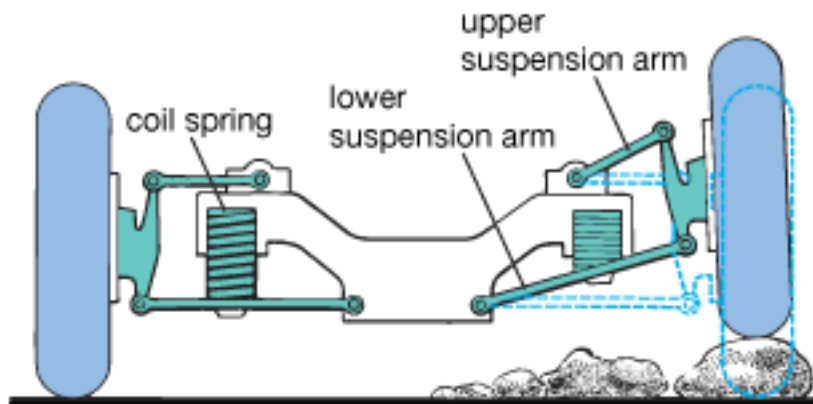


Figure 3 – Diagram Displaying Motion Of Suspension System Encountering A Bump (Encyclopædia Britannica, Inc., 2010)

The individual rigidity of these bushings have a significant influence on the handling of the vehicle. “The bushing in line with the wheel can be kept relatively stiff to effectively handle cornering loads while the off-line joint can be softer to allow the wheel to recess under fore-aft impact loads.” (Suresh, 2013)

This means that the wishbone and subsequent fixings are all subjected to numerous forces that must be considered, understood and incorporated into the design to prevent component failure, either due to environmental material degradation (rust/corrosion) or a sudden impact causing ductile failure/second moment of area of the component (breaking/bending). (Philippa Moore, 2015) This can pose a danger to the driver by causing further damage should the component fail. (Oards Automotive Hub, 2020)

Each suspension design has its own advantages & limitations due the effects each system has on the handling of the vehicle. E.g. a disadvantage of the MacPherson strut relates to the small camber change as a consequence of the vertical motion of the suspension being extended/ compressed when cornering. This results in less contact between the tyre and the road surface, negatively impacting the handling of the vehicle. (Shoaib Khan, 2017)

The design and shape of the wishbone directly correspond to how flexible you wish the component to be. If the wishbone is allowed to flex slightly, this may improve comfort for road applications, but not ideal for racing. This leads to the two main shapes for a wishbone; ‘A’ & ‘L’, Figure 4.



Figure 4 – Examples Of Wishbone Designs, A-Shape (Left) (Kashyap, 2020), L-Shape (Right) (Energized Customs, 2021)

For racing applications, an A-shaped is preferred for rigidity, where performance overpowers the comfort requirement. Two bushings connect each wishbone to the chassis horizontally to restrict movement to a purely vertical motion. The classification of racing has considerable impact on the available budget, thus consequently, on the manufacturing process of construction. An A-shaped wishbone can range from two singular tubes welded together, or a singular structure through die casting or CNC machining.

Whereas, the passenger vehicles on the road will not be subjected to such high cornering speeds and weight transfer. Therefore they would favour an L-shaped wishbone to allow slight component deformation, optimising between comfort and handling. Generally machined or die casted into a single element, with fixtures connected by bolts and bushings press fitted into place. (Figure 4 – Right)

Most manufacturers currently producing wishbones for the automotive road vehicle have leant towards using low (AISI 1018) to medium-carbon steels (AISI 4130), for a compromise between strength, stiffness and comfort. (S. Lakshmi Sankara, 2018)

With a reduced Young's Modulus inducing elasticity and deformation, a wishbone must not only be strong enough to withstand the forces applied through it in terms of vertical loading, but also have resistance to twisting and buckling that would occur during cornering or other dynamic forces acting throughout the operation of the vehicle. (GÜLER, 2006). The denser the population of carbon within a steel structure, the harder it becomes, but with the added side effect of becoming brittle, Figure 5.

Plain Carbon Steel

Low carbon	Medium carbon	High carbon
• Good formability and weldability • Strengthening by coldwork • Structure usually pearlite and ferrite	• Can be quenched to form martensite or bainite • Compromising structure between ductility and strength	• Low toughness and formability • Good hardness and wear resistance • Can form martensite by quenching but risk of cracking
Compare to other engineering materials • High strength and stiffness, reasonable toughness, easy to recycle and low cost • Rust easily, require surface protection		

Figure 5 – Comparison Between Low, Medium & High Carbon Content Steels (Naik, 2017)

Mild or Pressed Steel, Aluminium or Chromoly are the material of choice for mass production cars. Whereas, within racing applications and the motorsport industry as a whole, components are made to order on a limited run so the equivalent cost of manufacturing 1000 mild steel wishbones could be allocated to more exotic materials, processing, tooling and labour of a singular, more experimentally manufactured component, such as; Carbon Fibre, (Figure 6 – Left).

Cost is a major factor when selecting a material for component manufacture. The budget much account for not just for material purchase cost, but also the machining process, equipment, consumables, labour and general overheads. These can vary significantly material to material and would incur drastic consequences should the cost outweigh the profit.



Figure 6 – Experimental Formula 1 Carbon Fibre Wishbone (Left) (Garvey, 2011), Basic Mass Production Design (Right) (Elise Parts, 2021)

3. Mechanical Failures

As with any component subjected to external forces, the wishbone will endure fatigue, ablation and general wear throughout its lifetime, which if left unchecked, will lead to inevitable failure. Whether two identical wishbones, manufactured at the same time, with no prior defects within them, will last the same duration before failure, relies heavily on its use. A suspension system that is designed for smooth roads and occasional speed bumps will inevitably fail prematurely, if regularly driven on a rough off-road environment. (Popely, 2017)

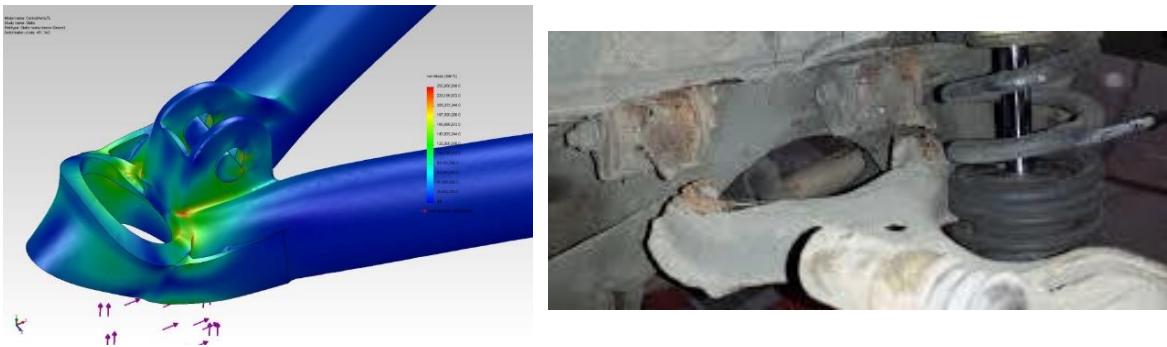


Figure 7 – Wishbone Ball Joint Fixing Failure, (Left) (Ludemann Engineering, 2012), Polly Bushing Failure Due To Corrosion (Nedski, 2013)

Not only does the structure of the wishbone itself have to be strong, but also the joinings to the other components must withstand the same forces and environmental impact without failure or deformation, (Figure 7).

Damage may occur on any of the individual components within a wishbone (Figure 8), such as;

1. Wishbone Arms – May fracture or buckle under excessive stress.
2. Welding – Subject to corrosion or weld decay resulting in breakage.
3. Bushings – Degradation of the rubber will induce excessive free movement or slack.
4. Ball joint – Degradation of rubber causing slack or corrosion seizing movement.
5. Drop Link (ARB) – Fast fracture may occur snapping the hoop used for fixture.

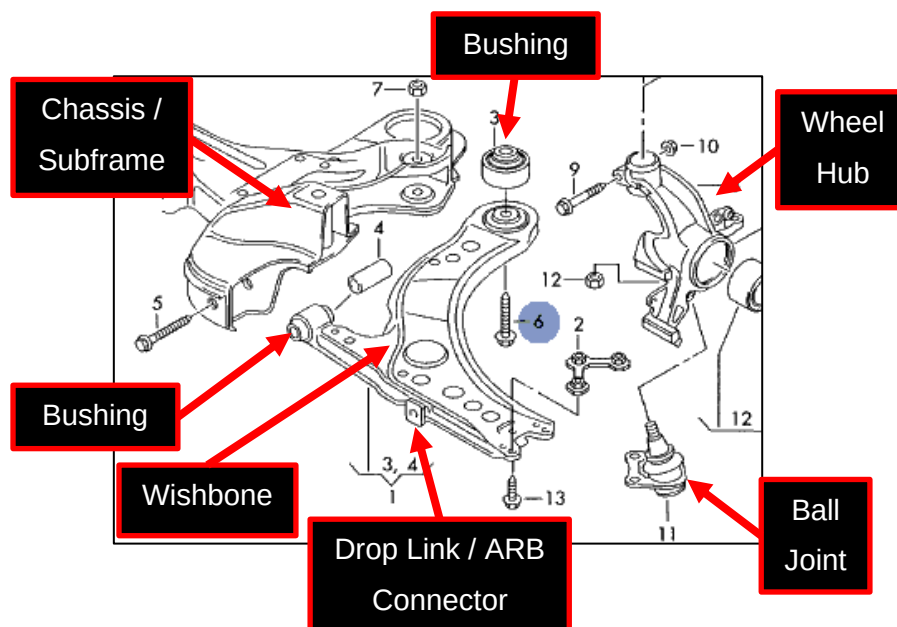


Figure 8 – Breakdown Of Components & Connections Between The Wishbone & The Vehicle (vw-parts-international, 2021)

Due to the vast range of climates around the world, a component must be designed to be suitable to those of the demographic within the automotive market. E.g. a Land Rover Defender is designed to tolerate harsh off-road environments, climbing rocks or wading through rivers. Hence, the wishbone would be of stronger design and ideally more corrosive resistant in either material or coating. Compared to those of a Nissan Micra, aimed at primarily city drivers that will encounter rain, sun, wind, but rarely to any extreme. (Figure 9)



Figure 9 – Project Viper Custom Land Rover Defender (Left) (Smith, 2017), Nissan Micra K11 (Right) (Honest John, 2018)

The nature of the environment due to the local climate is incredibly important regardless of desired road application. Those two same cars could be owned by persons living in Moscow, Russia or Dubai, United Arab Emirates, two cities but with completely opposing environments.

The cars in Moscow would experience a freezing cold environment where a slight crack or recess can house water droplets potentially subjecting the component to ‘freeze-thaw’ or ‘thermal cracking’. (Fangzhi Zhu, 2016) This occurs as the metal loses its ductility and becomes stiffer at cold temperatures, compared to standard room temperature (20°C), breaking instead of bending. (Clifton Steel, 2021)

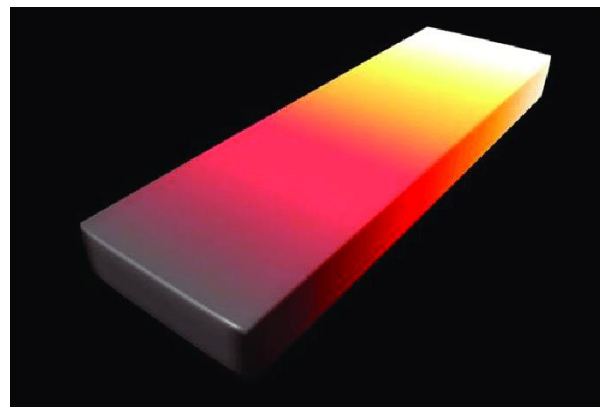


Figure 10 – Frost Developing On Metal In A Cold Environment (Left) (Maes, 2021), Various Colours Stages That Change With Temperature Within Iron Based Metals (Kellie, 2021)

While those in Dubai would need to cope with hot temperatures, direct sunlight and sand, which all negatively impact the life span of any component. The heat would make the metal more ductile and the rubber bushings/gaiters to deteriorate, increasing the chance of splits occurring. (Robert Keqi Luo, 2015)

“If the rubber is presented in a high-temperature environment, then the long chains of polymer shorten cause the rubber to contract. While in a low-temperature environment, rubber can expand. Temperature and entropy are in a correlated relationship. Therefore, the higher the temperature is then the higher the entropy will be.” (COI Rubber, 2020)

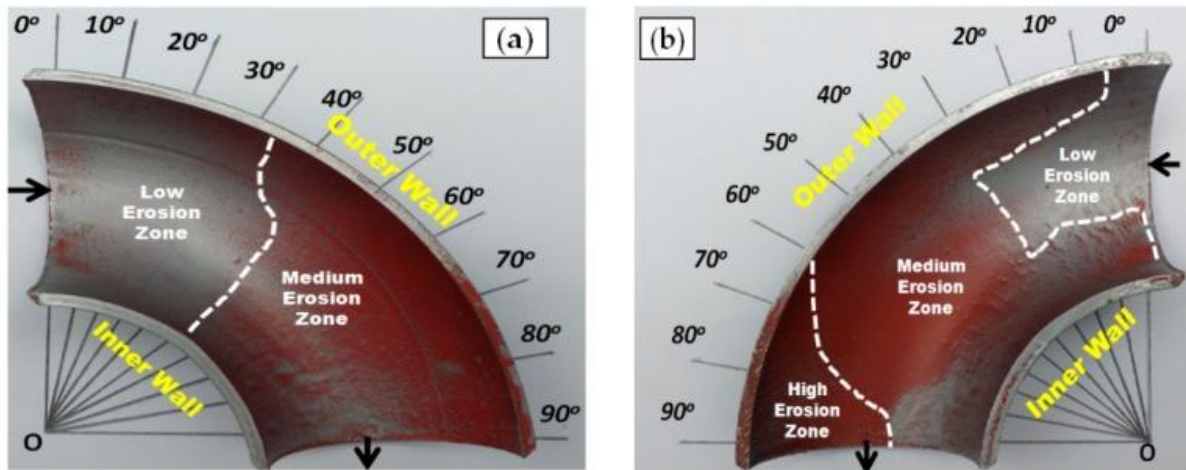


Figure 12 – Cross-Section Of Slurry Pipes Displaying Wear From Flow Of Sand (Rehan Khan, 2019)

Sandstorms, which frequent the region, can erode both the rubber seals and the metal's protective coating, leaving undesired areas open to the elements, instigating further corrosion onto the metal itself. Aminul Islam (Md. Aminul Islam, 2013) studied the effect of erosion-corrosion on surface roughness within API X-70 steel elbow pipelines at varying corner angles. They agreed with John Postlethwaite (Postlethwaite, 1981) stating that in the presence of erosion, the corrosion noticed within the components as a result of surface coating loss, almost doubles, (Figure 12). Rehan Khan et. al provide recommendations to reduce a wide angle where possible to reduce erosion-corrosion within carbon steel elbow pipes. (Rehan Khan, 2019)



Figure 11 – Drop Link Fixture Fracture (Left), Drop Link Dust Cover (Gaiter) Failure (V10 SPM, fatboy18, 2016)

As a result of rubber degradation, water/sand/dirt is allowed to enter sensitive components that would otherwise be protected. (Figure 11) shows the effect of fracturing occurring the fixing between the drop link and the wishbone. This is caused by a redox reaction, the combination of two chemical processes (reduction & oxidation) where oxygen molecules within a fluid (air & water), alter the molecular structure of the metal component by exchanging electrons. This is further aided by the presence of an electrolyte solution (water), accelerating the flow of electrons between the molecules. (LibreTexts, 2020)

Unfortunately, this process severely inhibits the metals structural integrity over time, becoming a soft flaky powder-like substance, making it significantly weaker. Should the component then encounter outside disturbance, the oxidised section would either shatter and blow away with the wind, causing imminent failure. (University of Illinois - Department of Physics, 2020)

The presence of saltwater within the air along coastal areas has been known to aggravate the effect of corrosion through oxidation of vehicle components as opposed to air further inland. This is caused by a higher concentration of dissolved ions significantly increasing the transfer of electrons within the redox reaction. (Gillespie, 2018)



Figure 13 – Effect Of Salt Water Rusting Away Metals Containing Iron (Left) (Redazione, 2014), (Right) (Gillespie, 2018)

Should a component become weakened due to such corrosion, they would be particularly vulnerable to fail via impact loads. Whether caused by potholes, speed bumps or mounting the curb, this sudden and unexpected shock has been well documented to damage the suspension systems of vehicles and has caused public uproar over road surface quality. (RAC, 2020) (LV Car Insurance, 2020)

Prevention of decay and degradation is an important criteria when designing any component, the easiest solution is applying a protective coating, such as; galvanising, nickel coating or powder coating. The surface coating has an extraordinary effect on the lifespan of a component, but both its material and intended application severely impact which protective coating is adequate.



Figure 14 – Application Of Protective Coatings, Powder Coating (Left) (Ronquillo, 2021), Galvanising Steel (Right) (Sperrin Galvanisers, 2021)

Powder coating can be applied to any metal by conducting electricity. The coating is applied by spraying dry powder with a positive electrostatic charge, onto a component of negative charge, gaining instantaneous adhesion, then left to cure within an oven. This can be an excellent process of quickly and cheaply protecting metals against corrosion as opposed to paint, with significantly less curing time, overhead and consumable costs. It is easily able to resist corrosion, chemical stains and the adverse effects caused by the weather but can be broken down by UV rays. (McHone Industries, 2019)

Although it has ability to bend along with the component, it is known for chunks to chip off when tightening nuts/bolts against the surface. This causes concentrations of stress on the coating surface from the combined clamping and twisting force applied by the bolt's surface but could be aggravated due to inadequate spraying/curing processes or a contaminated substrate. (Windridge, 2006) Most modern race cars make use of power coating when using steel wishbones as a cheap process for protecting parts as they are not mass produced. (MCR Race Cars, 2021)

Galvanising is the manufacturing process of applying a zinc coating to a metal component to act as a sacrificial anode, corroding itself before the steel, ensuring a longer component lifespan. (National Material Company, L.P., 2021) This is because of the higher reactivity of the zinc compared to steel or iron it is protecting. (BBC Bitesize, 2021) Even though galvanising can boost the structural integrity of a component, the drawbacks come at the cost of this process, a downside where a limited budget is concerned. While resistant to red rust, white rust has been known to develop on galvanised metals when exposed to moisture. (Saskarc, 2019)

Aluminium components can either be anodised or coated with nickel, processes which leave a residue deposit on the surface of a component, protecting against corrosion. Nickel is a surface coating, adding weight and an increase in outer dimensions of the component, whereas, anodising grows both into the component and a thin outside layer. (Ahmad, 2006) It must be noted that by repeating the anodising process on the same component, it can destroy

Nickel Plating vs. Aluminum Anodizing

	Nickel Plating	Aluminum Anodizing
Appearance	Clean, smooth finish that can be re-done when needed	Comes in a multitude of colors, though may not come out as nice on uneven surfaces
Weight	Makes components much heavier and can change outer dimensions. Just a surface coating	A big advantage of aluminum anodizing is since it builds up half into the part and half on the surface, it stays a lot lighter
Strength	Nickel plating undoubtedly makes a part stronger and more durable therefore increasing overall life span for that part	Of the three types of anodizing, Type III is the hardest, but nickel plating still beats it out

Figure 15 – Comparison Between Nickel Plating & Anodising Aluminium (PFI Inc., 2019)

There are corrosion resistant paints, but they are usually a last resort if any of the other above processes are not available as painting can be costly and lengthy process. Paint can add an appealing aesthetic element to the component, but subject to use, performance outweighs aesthetics. Paint is more likely to chip and fade over time compared to powder coating, but touch-ups can be applied in the field, rather than requiring specialist tools/equipment to perform. (Saskarc, 2019)

4. Experimental Procedures

It is possible to simulate the forces acting upon a wishbone within a virtual environment to optimise its design to either suit the desired application, for the reduction of stress concentrations, mass and wasted material. Software packages allow simple simulations of these expected forces to be undertaken to aid the design team comprehend if the component is structurally sound or whether it needs to be redesigned.

Should a component fail the simulation, it is vital that appropriate action is taken to optimise the design in such a way to as to prevent the specific/numerous failures that occurred. E.g. some A-shape wishbones feature a brace bar between the individual arms to prevent twist occurring. If the simulation showed that this brace bar buckled under load, it would be adequate to increase the thickness/diameter of the brace bar to increase the distance to the neutral axis ('d' within Figure 16 – Right). Thus, increasing the second moment of area and its resistance to deformation about that axis. (OpenStax CNX, 2020) (Figure 16)

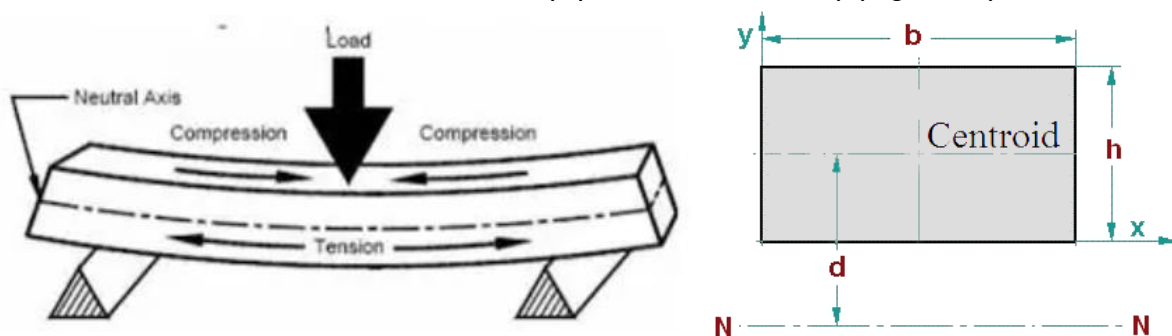


Figure 16 – Diagram Emphasizing Moments About the Neutral Axis (Left) (Joshi, 2017), Dimension for 2nd Moment Of Area (Right) (MDME: MANUFACTURING, DESIGN, MECHANICAL ENGINEERING, 2021)

Different materials can be applied to a component easily within FEA packages to quickly compare the strengths of each compound. R. R. Varpe undertook an analysis of an automotive lower wishbone arm in hopes to optimise the integrity of the component through material substitution by means of Finite Element Analysis (FEA). (Figure 17 – Left)

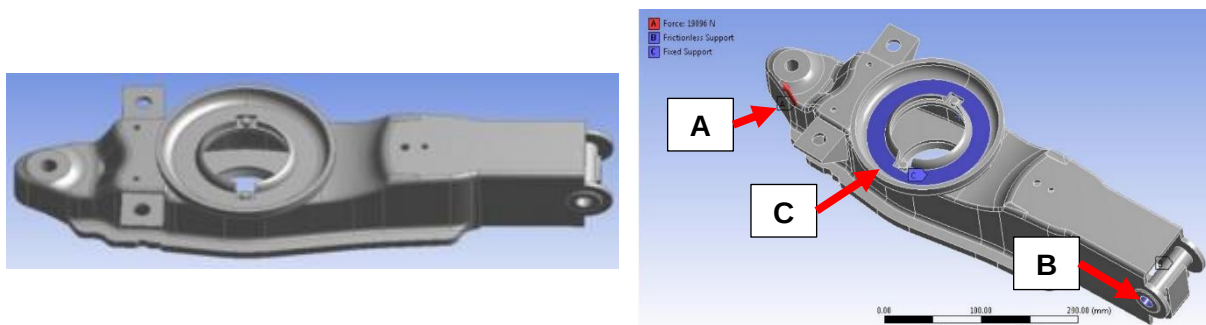


Figure 17 – CAD Model Of The Wishbone Analysed Using FEA (Left), Boundary & Loading Conditions (Right) (Varpe, 2019)

Figure 17 – Right shows boundary and loading conditions applied to the wishbone, duplicating its external geometry within 3D space. Point 'C' was fixed to replicate the resistive force of the coil spring, while a frictionless support pivoted around point 'B', mimicking the bushing and its connection to the chassis. A force of 19096N was then applied to point 'A', considering the vehicle mass was encountering an assumed bump at 20kmh. (Varpe, 2019)

The construction material was changed from mild steel to Ethylenediamine-N,N'-disuccinic acid (EDDS), with the properties displayed within Table 1. EDDS features a slightly higher poissons ratios and bulk modulus but display a lower shear modulus. This means that EDDS is more resistant to deformation and compression forces, but less resistant to shear stress/strain.

3.5 Material Properties of lower wishbone arm

Table No. 3.1 Material Properties

Density (kg/m ³)	Young's Modulus (Pa)	Poisson's Ratio	Bulk Modulus (Pa)	Shear Modulus (Pa)
7850	2e11	0.3	1.6667e11	7.6923e

Table No. 3.3 Mechanical Properties of EDDS

Density (kg/m ³)	Young's Modulus (Pa)	Poisson's Ratio	Bulk Modulus (Pa)	Shear Modulus (Pa)
7850	2e11	0.35	2.22e11	7.4e10

Table 1 – Material Properties Used On The Wishbone FEA, Mild Steel (Left), EDDS (Right) (Varpe, 2019)

Three plots were analysed on the component for each material; Equivalent Stress (Von-Mises), Maximum Shear Stress and the Total Deformation.

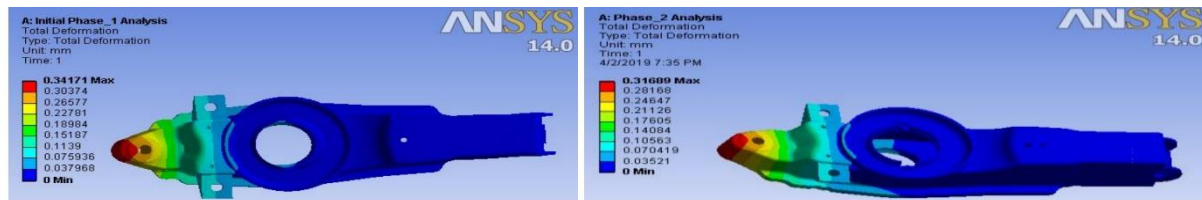


Figure 18 – Total Deformation Of The Wishbone, Mild Steel (Left), EDDS (Right) (Varpe, 2019)

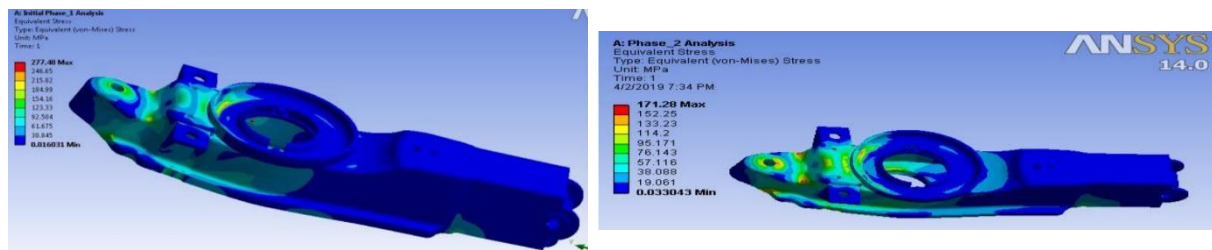


Figure 19 – Equivalent Stress On The Wishbone, Mild Steel (Left), EDDS (Right) (Varpe, 2019)

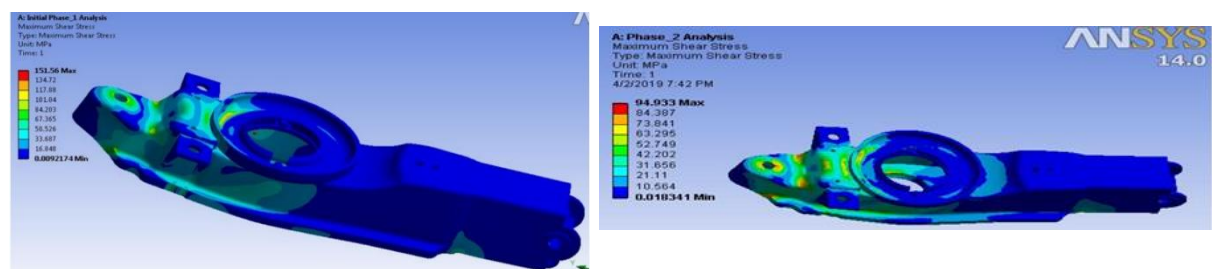


Figure 20 – Maximum Shear Stress On The Wishbone, Mild Steel (Left), EDDS (Right) (Varpe, 2019)

The picture quality isn't fantastic, but it is clear to see that although there is a reduction in both deformation, Figure 18, & stress magnitude, Table 2, there is an increase in the spread of the stresses within the EDDS component, with a higher percentage towards the maximum recorded values, as compared to its mild steel counterpart, Figure 19 & Figure 20.

Varpe concluded that due to the reduced deformation and stress values that noticed throughout the experiment, they will pursue the use of EDDS as a potential wishbone material in greater detail.

Sr. No	parameters	Before	After
1	Total Deformation	0.34 mm	0.31mm
2	Equivalent Stress Plot	277.48Mpa	171.28Mpa
3	Max Shear Stress	151.56MPa	94.93MPa

Table 2 – Comparison of Recorded values using FEA, Mild Steel (Before), EDDS (After) (Varpe, 2019)

The software can calculate where within the rigid body it determines as wasted material by analysing both the design of the component and the forces applied through it, by means of topology. “Topology optimization is performed on a model to create a new topology for the structure, removing any unnecessary material. The resulting structure is lighter and satisfies all design constraints.” (Swapnil S. Khode, 2017)

Properties	Yield Stress (MPa)	Ultimate Tensile Stress (MPa)	Density (kg/m ³)	Modulus of Elasticity (GPa)	Poisson's Ratio
Material					
A7075-T6	450	530	2800	70e3	0,33

Table 3 – Material Properties Of A7075-T6 Aluminium (Javad Marzbanrad, 2015)

Javad Marzbanrad and Abolfazl Hoseinpour researched the potential to reduce the weight of an A7075-T6 aluminium alloy wishbone through topological optimisation. (Table 3) By reducing the mass of the component without compromising structural integrity, it would, reduce the unsprung mass on the vehicle in succession. Hence, providing a cost effective and fuel-efficient solution. (Javad Marzbanrad, 2015)

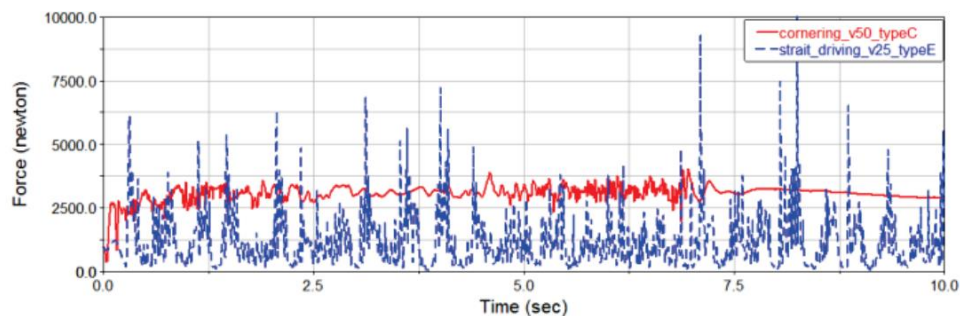


Figure 21 – Forces Applied To The Wishbone Throughout The 10 Second Simulation (Javad Marzbanrad, 2015)

By examining the dynamic forces acting upon the wishbone throughout the simulation (Figure 21), it is possible to draw a basic desired 3D shape and display the distribution of fatigue damage to the wishbone, when driving in a straight line and undertaking a corner, given the correct constraints, Figure 22.

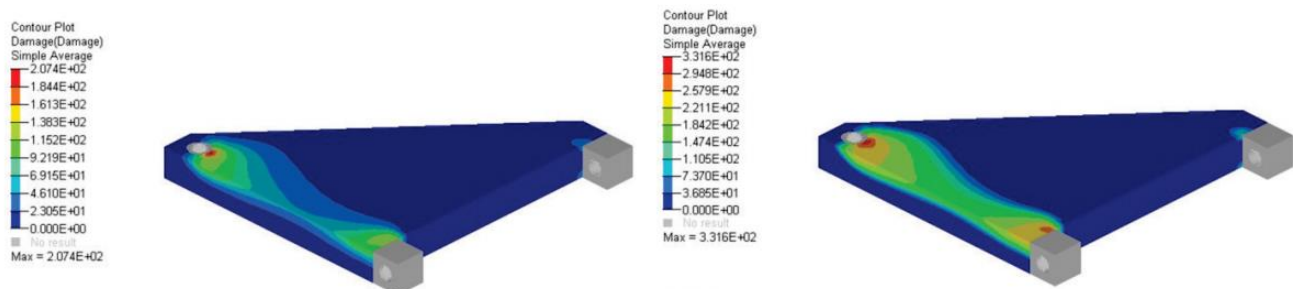


Figure 22 – Distribution Of Fatigue Damage In Wishbone, Straight Line (Left), Cornering (Right) (Javad Marzbanrad, 2015)

The software then removes elements within the mesh of component until compliance reduction is less than 1% of that from the previous iteration, leaving the optimum design, Figure 23 – Left, then smoothing the CAD model to remove any sharp edges, Figure 23 – Right.

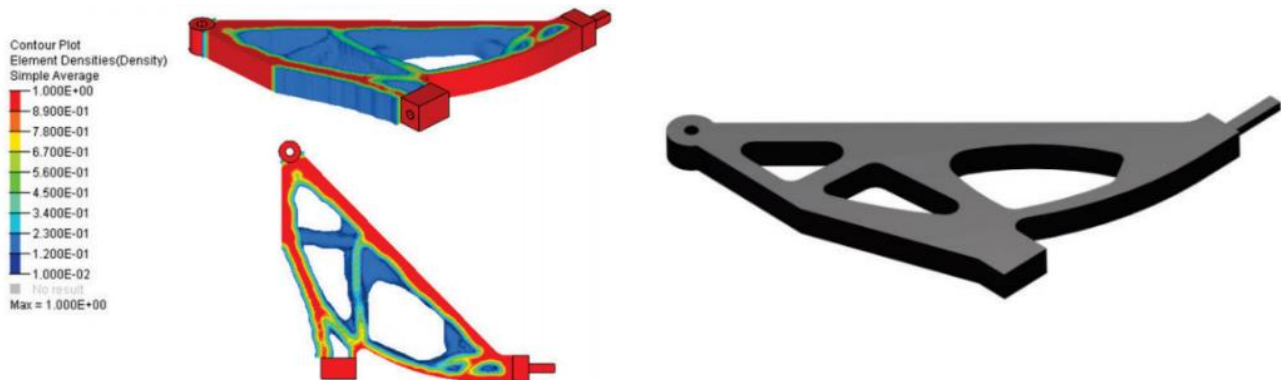


Figure 23 – Topology Optimised Model (Left), CAD Model After Smoothing Geometry (Right) (Javad Marzbanrad, 2015)

The modified design satisfies the constraints of the design criteria with both equivalent stress (70.8MPa) and fatigue life (1.46 mil. cycles) below their respectable limitations, Figure 24.

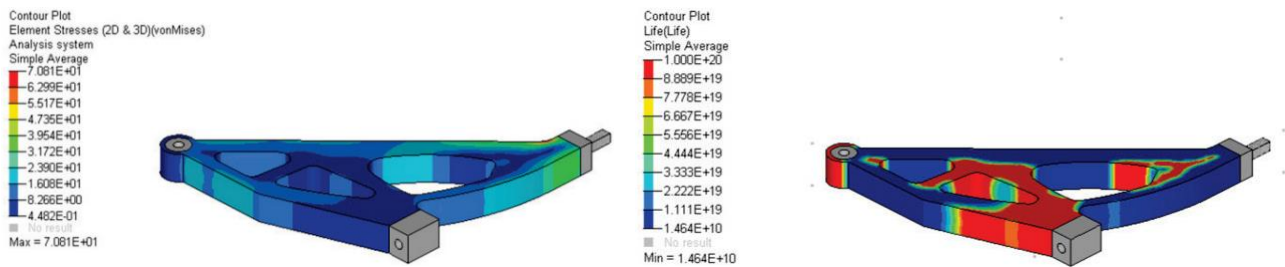


Figure 24 – Smoothed Geometry Model, Equivalent Stress (Von Mises) (Left), Fatigue Life (Right) (Javad Marzbanrad, 2015)

The shape was then optimised respectively to the radius of arcs and the thickness of linkages within the structure to reduce stress concentrations, Figure 25 – Left.

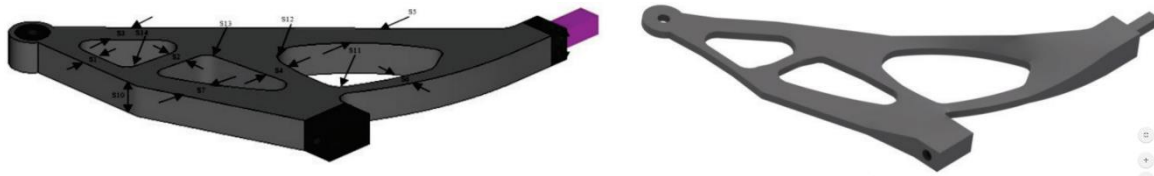


Figure 25 – Shape Optimisation of the Wishbone (Left), Resultant Topologically Optimum Shape (Right) (Javad Marzbanrad, 2015)

The optimised design satisfies the constraints of the design criteria with equivalent stress (157.6MPa) and a more even spread of fatigue life (1.33 mil. cycles), both below their respectable limitations, and a Safety Factor of 2.85, Figure 26.

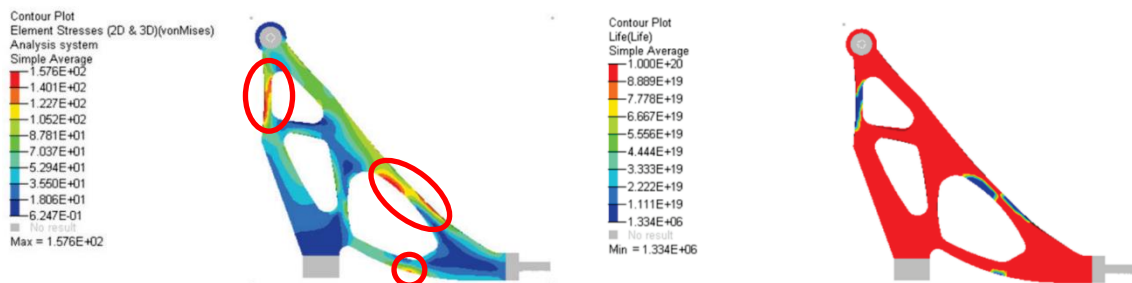


Figure 26 – Geometry Model, Equivalent Stress (Von Mises) (Left), Fatigue Life (Right) (Javad Marzbanrad, 2015)

Marzbanrad and Hoseinpour concluded that with a reduction in mass of 25% to the model currently used and fulfilled their requirement within fatigue life and strength. They stated that although they improved the design, in terms of weight, it reduced the cycle life of the wishbone by $0.57 * 10^6 \text{ cycles}$ and more than doubled the maximum stress exerted, Table 4. (Javad Marzbanrad, 2015)

	Mass (kg)	Minimum Fatigue Life (10^6 cycles)	Maximum Von Mises stress (MPa)
Primary model	3,6	1,9	70,6
Optimal topology	1,8	-	-
Modified CAD	2,2	1,46	70,8
Final model	0,75	1,33	157,6

Table 4 – Comparison Of Each Step Within The Topological Optimisation Process (Javad Marzbanrad, 2015)

The full topologically optimised model (Figure 25 – Right) is aimed to be manufactured in one piece via die casting. If this was to be machined by CNC, a block of metal to the same dimensions as the original design (Figure 22) will have to be machined into the desired shape. Thus, the sections regards as “wasted material” and hence removed, may not be recyclable and ends up being wasted either way, in a cost perspective. (Swapnil S. Khode, 2017)

On the other hand, with the new topographic design, there may be new induced stress concentrations by design or by the machining method applied, which may not be discovered until physical failure occurs due to corrosion, fatigue or fracture. (S. Karimi, 2019) The finalised design displays this exactly, showing a significant increase in the maximum equivalent stress value in 4 localised points. (Figure 26 – Left – Circled) Otherwise the values would be similar to those seen within the original and modified designs, Table 4.

Edgar Farquharson-Laver identified the OEM wishbone of the K11 Nissan Micra (FIGURE) as a weak component and prone to structural failure when used in off-road applications which it was not designed for, (SECTION). For his undergraduate project, he investigated the potential avenue of manufacturing aftermarket replacements through a small online business. (Farquharson-Laver, 2014) Figure 27 shows the typical failure observed within the front wishbones and identified a potential niche market if an affordable replacement was provided.

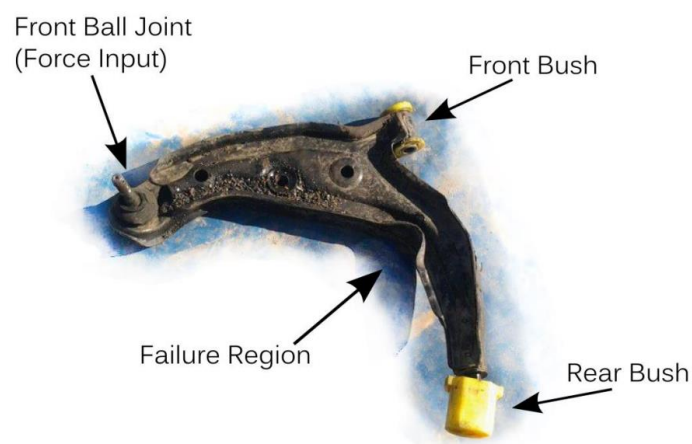


Figure 27 – Nissan Micra Wishbone Showing Typical Failure Mechanism

A proof load displacement test was carried out to replicate the conditions in which the wishbone deforms. The wishbone was displaced up to 50mm using a jig to replicate the chassis, while a tensile test machine and 500kN load cell applied the deformation at a rate of 2mm/min. This test was performed on three identical wishbones in the interest of result repeatability.



Figure 28 – Forced Displacement Of The Wishbone At 0mm (Top), 50mm (Bottom) (Farquharson-Laver, 2014)

The load-displacement, Figure 29 – Left, alongside the strain-displacement, Figure 29 – Right values were plotted using the measurements recorded throughout the test procedure by means of six single axis strain gauges placed along three positions on both sides of the wishbone.

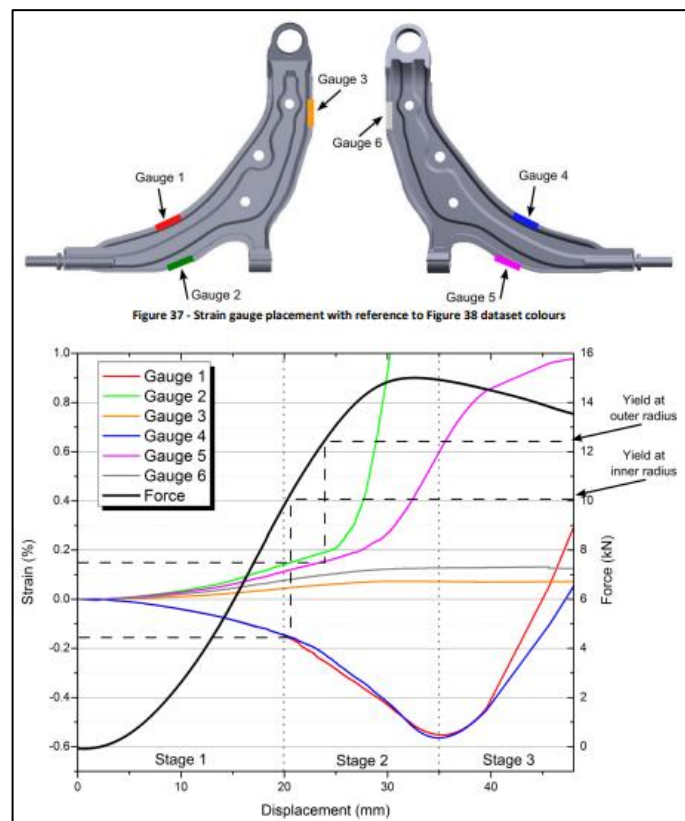
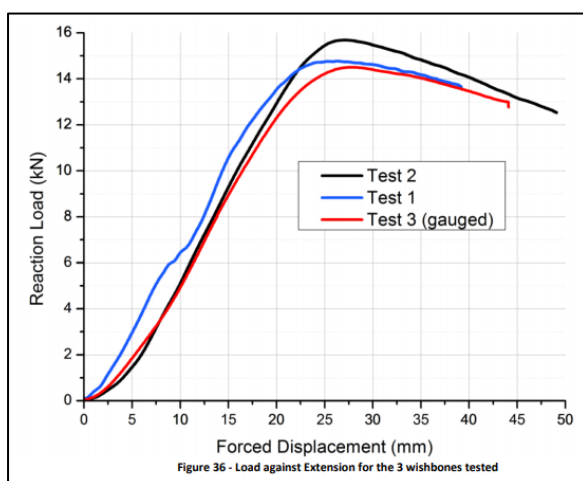


Figure 29 – Load Against Extension For The Three Wishbones Tested (Left), Placement & Strain Measurements Of The 6 Strain Gauges (Farquharson-Laver, 2014)

The stress distributions were then analysed using FEA to corroborate the results for the physical procedure, Figure 30.

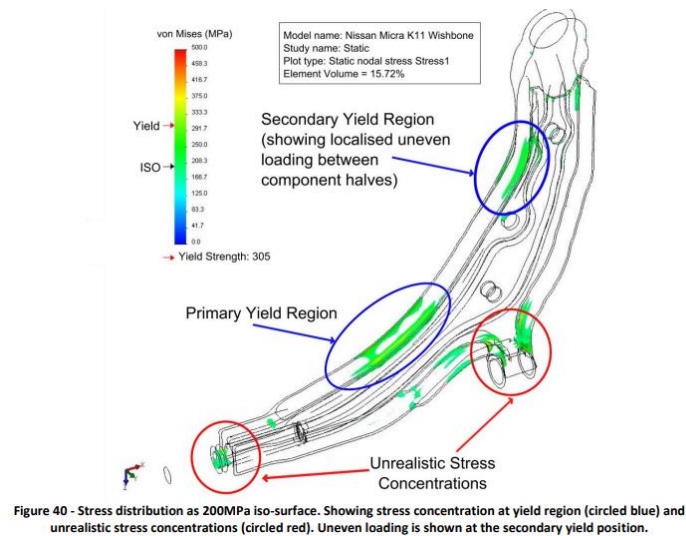


Figure 30 – FEA Displaying Stress Concentrations Through The Structure Of The Wishbone (Farquharson-Laver, 2014)

Upon examining the results, various design concepts could be examined to fulfil the design specification. These comprised of; a sheet metal clamshell design, a tubular construction as well as reinforcement of the OEM wishbone. (Farquharson-Laver, 2014)

Positives:

- Highly customisable design
- Possibility of geometrical adjustment for suspension setup

Negatives:

- High cost
- Lengthy design process, dependant on material choice

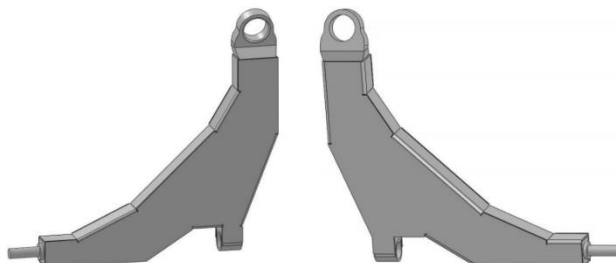


Figure 46 - Clamshell concept design - front (left) and rear (right) view

Positives:

- Limited to materials currently available in tubular form.
- Possibility of geometrical adjustment for suspension setup

Negatives:

- High cost of materials used
- Extensive tooling required
- Thick tube results in large mass



Figure 49 - Tubular concept design - front view (left) and rear view (right)

Positives:

- Low cost
- No need for extensive tooling manufacture

Negatives:

- Design is driven by the size and shape of the OEM item
- High deformation in the OEM bushes
- Lack of geometrical adjustment
- High mass



Figure 53 - OEM Reinforcement concept design - exploded views showing OEM wishbone with bend steel reinforcement at inner and outer radius

Figure 31 – Various Concepts For Improving structure Integrity Of The Wishbone, Clamshell (Top Left), Tubular (Top Right), OEM Reinforcement (Bottom) (Farquharson-Laver, 2014)

To adequately select the appropriate design, items were weighted within a selection matrix and their scores displayed within (Figure 32) for easy comparison.

	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>	<u>E</u>	<u>F</u>	<u>G</u>	<u>H</u>	<u>Weight</u>
A- Cost		1	1	1	1	1	1	0	21.43 %
B- Mass	0		1	1	1	1	1	0	17.86 %
C - Durability	0	0		0	0	0	1	0	3.57 %
D - Adjustability	0	0	1		0	1	1	0	10.71 %
E - Ease of Installation	0	0	1	1		1	1	0	14.29 %
F - Aesthetics	0	0	1	0	0		1	0	7.14 %
G - End of life	0	0	0	0	0	0		0	0.00 %
H - Safety	1	1	1	1	1	1	1		25.00 %

Table 7 - Concept selection criteria weighting digital matrix

	<u>Weight</u>	<u>Clamshell</u>		<u>Tubular</u>		<u>Reinforced Wishbone</u>	
	<u>Factor/ %</u>	Score/10	Weighted	Score/10	Weighted	Score/10	Weighted
Cost	21.43%	2	0.43	3	0.64	10	2.14
Mass	17.86%	9	1.61	4	0.71	8	1.43
Durability	3.57%	8	0.29	6	0.21	8	0.29
Adjustability	10.71%	5	0.54	8	0.86	0	0.00
Ease of Installation	14.29%	10	1.43	7	1.00	10	1.43
Aesthetics	7.14%	6	0.43	9	0.64	3	0.21
End of Life	0.00%	8	0.00	6	0.00	8	0.00
Safety	25.00%	10	2.50	10	2.50	10	2.50
<u>Final Score / 10</u>			<u>7.21</u>		<u>6.57</u>		<u>8.00</u>

Table 8 - Concept selection matrix

Figure 32 – Selection Matrix Weighing Items Based On Their Compatibility To The Design Specification (Farquharson-Laver, 2014)

Considering the cost requirement for the clamshell and tubular designs, the option to reinforce the OEM wishbone was selected. The design could now undergo further development to reduce mass whilst maintaining the required strength using SAE 1010 steel, Figure 33.

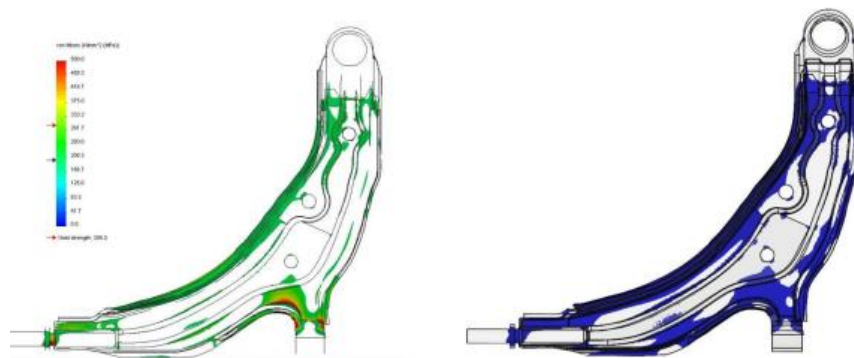


Figure 59 - New design - 200MPa stress iso-surface plot (left) and SolidWorks 'design insight' topology study (right)

<u>NEW DESIGN</u>	
Mass (kg)	3.85
% of elements over 200MPa vonMises Stress	25.09
Cost (vehicle set with polyurethane bushes)	£224.50

Figure 33 – FEA Analysis Of New Wishbone Design (Top), Cost Analysis Of New Design (Bottom) (Farquharson-Laver, 2014)

This new design underwent the same forced displacement test procedure to monitor its behaviour. The test revealed three weak points within the structure that had failed, Figure 34.

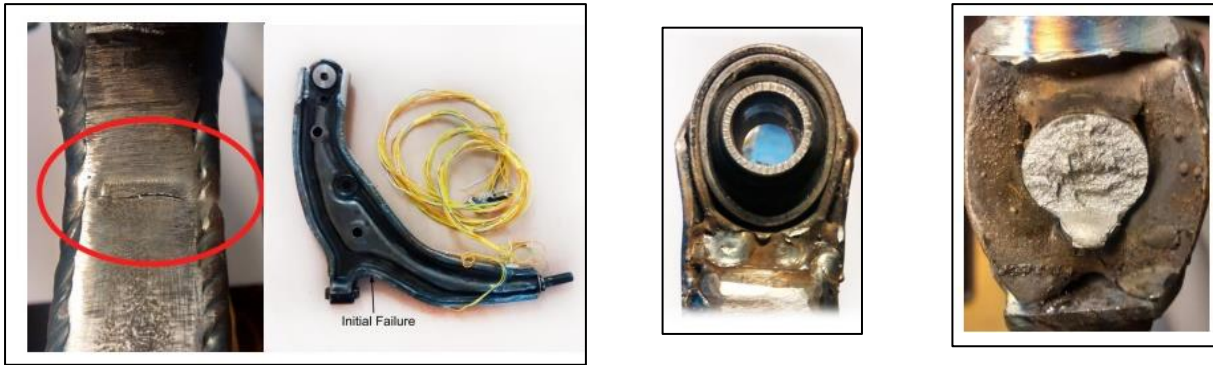


Figure 34 – Failures within the wishbone structure, Initial Crack (Left), Deformation Of Front Bush Housing (Middle), Rear Bush Pin Fracture (Right) (Farquharson-Laver, 2014)

Farquharson-Laver concluded that although improved design met the concept criteria by yield strength and manufacturing cost, it does so at the cost of a reduced safety factor, implying further development is required. Also uncovering the further investigation due to a noticed welding defect to determine the individual cause and effect of such.

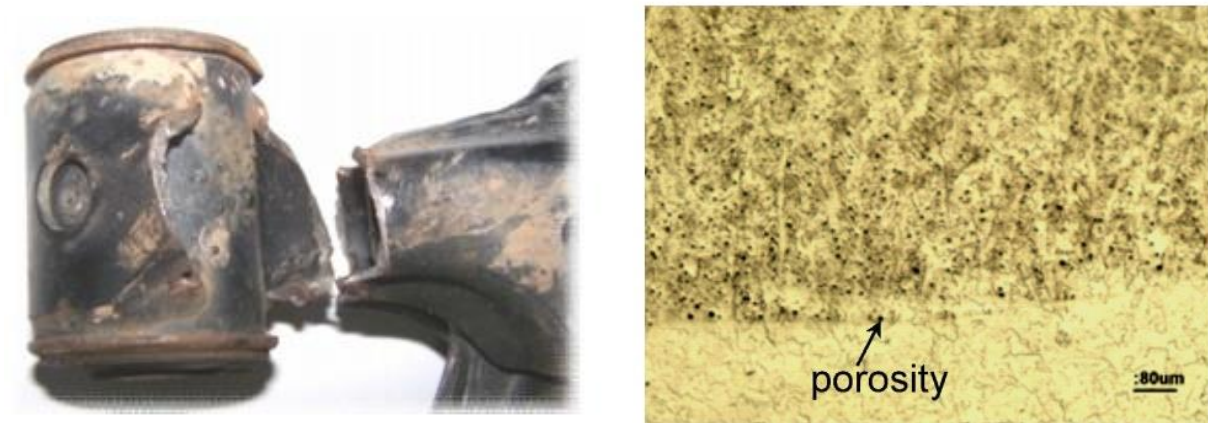


Figure 35 – Fatigue Failure Of A Wishbone Around Front Bushing Housing (Left), Porosity Within Weld Junction (Right) (Rutci, 2015)

Further fatigue failure analysis on the parent body and connection region of a lower wishbone (control arm) in a light commercial vehicle was pursued by Alimurtaza Rutci. This has been left out of the report for word count concerns but makes for interesting reading for the metallographic observations such as the presence of porosity and hardness distributions of both the sheet metal and weld junction microstructures were analysed after performing a fatigue test.

5. Conclusion

The design of a wishbone must incorporate numerous factors and be examined under a worst-case scenario for an accurate reflection of their true performance under load. The use and subjective environment must be strictly analysed and tested to prove the components durability. By considering every element to each design, a singular solution can be identified as the best within its intended application.

For word count concerns the corrosive effect of dissimilar metals joined together was not investigated. This was a huge concern for the Land Rover Defender (Figure 9 – Left) notorious for bolting aluminium body panels to a steel chassis, leaving the aluminium to be eaten away. (Glen Coyne, 2021) The chassis was infamous for corrosion itself due to inadequate protection from road salt and mud, but the wishbones can withstand the test of time.



Figure 36 – Corrosion Display On The Chassis Of A Land Rover Defender (Left) (Glen Coyne, 2021), Tesla Model S Wishbone Failure (Right) (Wivaneff, 2016)

The failure of a wishbone due to poor design can have significant consequences. Tesla Model S & X vehicles manufactured between 2013 and 2018 contained wishbones that were prone to premature fatigue and fracturing. The company allegedly concealed the known issues from drivers to also hide the high repair costs incurred, even when under warranty, stating the issue was down to driver abuse. (Wood, 2020)

A scandal like this would do nothing but damage the reputation and public image of a company and shatter any trust that had been previously built in regard to occupant safety. This shows how important it is to sufficiently test a components capability before manufacture and adequately recall faulty components to satisfy consumer and investor faith within the company.

For as much virtual testing and experimentation can be executed, there are numerous limitations and without validation, these results cannot be assumed to be 100% accurate. Small variations throughout the manufacturing process can have a significant impact on the end product between batches.

Should the chemical composition of the selected alloy alter minutely, or the temperature fluctuates slightly during the smelting process, the end product would see an adverse impact upon its material embrittlement, or tensile & yield strengths. (Rutci, 2015) This is also apparent should the component required welding e.g. A-shape with a brace bar, where a weld of poor quality could result in failure, due to impurities or poor penetration causing weaknesses within the system. (WebCorr Corrosions Consulting Services, 2021) (L.B.Godefroida, 2014)

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