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Composite Spring – Development of suspension for a composite E-Bike

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MENG MECHANICAL ENGINEERING

Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has lead to the award of a degree.

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Abstract

The purpose of the work done in this project was to create a composite spring, which was to be integrated into the rear triangle of an electric bicycle frame to provide the frame with some degree of suspension to increase the comfort for the rider on the bicycle. The objective was to be achieved by first using a computer model of the frame to perform finite element analysis and optimise the layup of the unidirectional composite material which the frame would be made up of in order to provide the necessary displacement for the suspension system whilst maintaining the necessary strength to be used for its intended purpose. Once the composite layup for the computer model of the frame was optimised to the correct standard, a prototype frame and corresponding physical testing rig was to be produced in order to test the frame and validate the results from the computer analysis of the frame. Ultimately, due to the frame provided by the third party designer not being compatible with the aims of this project, it was not possible to integrate the composite suspension system to this frame. The project did however yield knowledge and the development of a model which could possibly be applied to other bicycle frames or to a frame designed with the purpose of this project in mind in order to integrate suspension to said bicycles.

Introduction

Carbon fibre composites have been used as the principle material in the construction of bicycle frames since the first carbon fibre bicycle was created by Carlton in 1971 and as with the growth of the use of carbon fibre composites across other sectors such as the automotive and aerospace industries, the use of fibre based composites in the production of bicycles has increased rapidly since, mostly due to its high stiffness to weight ratio. The aim of the project covered in this report however is to produce a composite spring, which is to be integrated into the rear end of the frame of an electric bicycle to provide the bicycle with a form of rear suspension to provide additional comfort for the rider. The frame will be primarily composed of a composite monocoque, possibly with some metal or other material for reinforcement however it is the composite section of the frame and in particular the manipulation of the 'rear triangle', comprising the seat tube, chain and seat stays which this project will be focussing on, in order to provide the desired suspension effect for the rear end of the frame. The project is a collaborative piece of work, as the design for the frame which is to have the composite spring suspension integrated to will be provided by a third party external to the work being performed in this project and there is another third party group who are concerned with the manufacture of the frame and so as such the design and manufacturing of the frame itself falls largely outside the remit of this project. The development of the composite spring suspension will be done by analysing the frame using computer analysis tools in order to model and optimise the composite layup on the frame. This is in order to achieve the desired displacement on the correct part of the frame whilst keeping the deformation of the frame within the elastic limit for the composite layup used, such that the frame returns to its original state when no force is applied and there is no composite ply failure. The frame remaining within the composite materials elastic limit is essential as the deformation of the frame dissipates the energy which is otherwise experienced as a shock in the frame, giving the frame the desired suspension element, however if this goes beyond the elastic limit of the frame material, the frame will begin to deform plastically and so therefore the frame will not return to its original shape and the overall structure of the frame will have altered such that its mechanical properties have been altered and the frame will no longer perform as intended. It is also essential that there is no failure in the composite material from which the frame is constructed, due to the fact that delamination of the fibres within the composite structure can compromise the structural integrity of the frame whereas a matrix crack in the composite material can lead to a catastrophic failure of the frame, potentially leading to the user experiencing some form of injury. Once the model meets these criteria, the final piece of computer analysis to be performed on the frame is a fatigue analysis to see how the frame and suspension system will withstand prolonged use as the suspension system is likely to see many cycles of varying magnitude with every use and due to the frame likely being a premium product, it

will be expected to be able to withstand several years of use before requiring to be replaced. Once the computer analysis on the frame provides a composite structure layup which meets the necessary aforementioned criteria, a prototype can then be produced, either of the entire frame or a prototype of just the rear triangle of the frame with which physical testing can be performed in order to verify the results of the computer analysis and ensure that the frame behaves as expected. This verification can be achieved by constraining the front, bottom bracket and seat tube of the frame in a jig and applying a force to the rear end of the frame at the point where the rear wheel would connect into the frame, possibly with the introduction of an axle for the force to be applied to. This force can then be cycled on and off and at different magnitudes in order to simulate the stresses the frame would experience when the bicycle is in use. Performing this test on the frame should work to verify the computer analysis for the fatigue in the frame that was performed and can give some indication as to how long the frame would last in use and when it does fail, what its likely mode of failure will be.

Literature Review

Although from researching the topic area of the work in the project there is no research into this as a composite spring has never been used for the application of providing suspension to the rear end of a bicycle, there is still some research material which was of use to the development of the project.

Fatigue testing of carbon fibre reinforced polymers under VHCF loading by M Gude et al 2013 talks about the testing of carbon fibre reinforced polymers under very high cyclic force loading and the effects that this has on the workpiece being studied. This is mostly focussed on the effects of the loading at a micro scale and the damage that is done to the fibres and the fibre matrix it also talks about setting up the experiment for testing the fibre workpiece and the mechanisms by which the composite material fails. This would have been useful for when the testing of the frame progressed to physical testing of a prototype frame due to its example of setting up a sample for fatigue testing under very high cyclic force loading such as what the prototype frame used in the project would have been subjected to.

Chen Qian's 2017 article in the Composite Structures journal entitled Fatigue reliability design of composite leaf springs based on ply scheme optimization again discusses the effects of fatigue on the composite matrix within the material and how the cracks which cause the material to fail are created in the inner face of the bend and how over time the number and size of the cracks spread, propagating deeper into the matrix of the composite which eventually leads to the failure of the material. The main point of the article however is how the ply orientation and thickness of a composite material can be adjusted in order to maximise the desired properties of the material for a given application. This piece of work is helpful to the development of this project as the focus of the article is composite leaf springs which are a form of automotive suspension composed of composite material and therefore this is the closest thing to the suspension being developed in this project with literature which is readily available. In addition to this, given the shape of the frame which is to have the composite spring suspension integrated to it, the chain stays of the frame will have to bow in order to provide the displacement necessary for the suspension, this is similar to how a leaf spring bends, albeit with the force on the leaf spring being applied approximately in the centre of the leaf, unlike the frame which will be under compression.

The United States' Department of Transportation Federal Aviation Administration 1996 technical report on the 'Comparative Evaluation of Failure Analysis Methods for Composite Laminates' provides a definitive explanation of all of the composite failure criteria, such as; Tsai Wu, Tsai Hill, Hoffman, maximum stress and strain and Hashin, including their equations and applications. This was beneficial to the advancement of this project as it provided a basis on which to decide between all of the

different composite failure criteria to select the failure criteria which was most applicable for the bicycle frame being studied and optimised in this piece of work.

Another piece of literature studied was 'fiber [SIC] direction and stacking sequence design for bicycle frame made of carbon/epoxy composite laminate' written by Thomas Jin Chee Liu in 2010, which discusses how the orientation of the fibres in each ply as well as the total number of plies making up the composite material can be adjusted to affect the stiffness and strength of a bicycle frame. This aided the project by adding to the understanding of how the composite ply orientation and thickness can be applied and varied in order to achieve a desired stiffness within the frame of a bicycle and so in reverse can be manipulated to provide an area with less stiffness which is what is required to provide the suspension to the bicycle frame which is being developed.

Utilization of FEA in the design of composite bicycle frames, 1995, by L B Lessard outlines the benefits of using finite element analysis in creating a composite bicycle frame such as the analysis of the frame used in this piece of work. The article attests to the case that the use of finite element analysis in the development of the frame for a composite bicycle is central to reducing the amount of time and material lost to the process of iterative prototyping, particularly for experimental concepts for frames such as the one being worked on in this project. It also talks about creating a special jig for the experimental testing of the prototype frame once the finite element analysis of the frame has been completed.

A piece of literature which directly influenced the analysis is 'Contributions of rider-induced loads to bicycle frame stress' by M L Hull and F Bolourchi from 1988. This piece explains the loads which are exerted on the frame of a bicycle that are generated by the rider and provides a stress analysis case for them. This article provided the basis for which the rider induced loads on the frame for the analysis and optimisation of the frame created for use in this study, the rider induced loads from pedalling however were largely not taken into account as unlike the bicycle which was studied in the article, the bicycle created in this project was to be an electric bicycle and so as such pedalling forces are unlikely to be fully exerted on the frame.

Suspension Designs

There are many forms of suspension currently available for the damping of the back wheel of a bicycle and choosing the correct suspension format is essential to being able to integrate the suspension to the composite monocoque frame being designed in this project and for the suspension to be correct for the application of the bicycle. Starting with the most basic rear end format for a bicycle, a hardtail is the original and most commonly used rear end on a bicycle, it is simply the standard rear triangle which features on most bicycles, both from the past and those currently produced. A hardtail allows for maximum pedalling efficiency as there is no shock absorption in the frame to lose energy to. This is the standard rear end on commuter and road bikes as they do not generally require much shock absorption and so the loss in pedalling efficiency isn't worth the gains in seated comfort and so the use of the name 'hardtail' originates from mountain bikes. A Single pivot is the simplest form of rear suspension and features the introduction of generally an air or coil spring damped shock absorber into the frame which is actuated through the movement of a swingarm around a frame mounted pivot point. A single pivot suspension system is generally only used on recreational mountain bikes as they benefit more from the additional damping of bumpy trails and a decrease in pedalling efficiency is more acceptable given the increased comfort provided by the suspension. Moving up in complexity from single pivot suspension there are multi-link suspension systems. There are many forms of multi-link suspension, most of which utilise complex geometry of the links in order to focus on changing the motion of the swingarm of the bicycle in order to make the design more efficient for pedalling. One particular system is the Santa Cruz VPP system which uses different sized links, rotating in opposition to one another in order to minimize the energy loss from pedalling. Alternatively, the multi-link designs, are used to make the suspension 'ramp up' more and thus give the feeling of a greater amount of suspension travel whilst retaining the higher degree of pedalling efficiency given by the multi-link suspension layouts. A suspension system which is rarely used in modern bicycles is softtail suspension. A softtail is effectively a hardtail frame with some flex integrated to the chain and seat stays of the frame. This allows for some of the impact to be taken out of the system for the user, but doesn't absorb much of the lower end bumps, this means that it is inherently quite an efficient system as the pedalling forces of the bicycle rider are unlikely to be sufficient to cause the frame to flex noticeably. This means that a softtail should have almost the pedalling efficiency of a hardtail whilst damping some of the larger bumps, adding comfort. These are very rarely used in contemporary bicycle frames due to them being more complex to design and having more fatigue in the frame than conventional suspension layouts despite often having minimal or no weight and efficiency advantage over particularly multi-link suspension systems. In order to minimise the fatigue on the frame itself and to avoid permanent of the frame, which would cause the suspension to be ineffective, the suspension

travel in soft tail bicycles tend to be of a smaller magnitude than those of other suspension systems. Despite this, a modern example of a softtail frame is the BMC Micro Travel Technology (MTT) system which introduces elastomers to the composite frame in order to provide the suspension effect. For a commuter or road electric bike such as the one being worked on in this project, a softtail is ideal as it allows for high pedalling or motor efficiency and for the frame to remain a carbon fibre monocoque whilst integrating some suspension to the rear end.

Market

Before releasing any new product, it is important to understand the market for such a product to be released into in order to have an idea as to how the product will fit into the market and therefore how it is likely to sell. At present, according to the government's Department for Transport, 7.2 million adults, approximately 15% of the population in the UK cycle at least once a week, for the purposes of either leisure, exercise or travel – most often commuting which has been bolstered by the government's 'cycle to work' scheme. The cycle to work scheme was introduced by the government in 1999 as part of the 1999 Finance Act, in order to assist in reversing the general trend of declining bicycle use in the UK which had been occurring since the 1950's, largely due to the rising popularity and availability of the motor car. The cycle to work scheme was intended to promote people cycling both to their place of work and recreationally by offering a hire to buy scheme for bicycle, either a conventional pedal or electrically assisted bicycle and related equipment such as helmets and lights ownership at a reduced rate. The objectives for offering people this scheme for bicycle ownership was to increase the use of bicycles and reduce peoples use of cars, which the government felt would benefit the economy, help to reduce pollution in major cities and improve general public health, both through the reduced pollution but also through the increased exercise undertaken by those participating in the scheme. Although there are no exact figures for the duration of the scheme, in the 2014 financial year 183000 people took part in the scheme, which is an 11% increase in the number of people using the scheme in the previous financial year and using London as a city with a strong commuting population, the number of people entering the city using a bicycle during the morning peak has increased by almost a factor of 4 since 1999, with a bump in 1999 when the cycle to work scheme was launched.

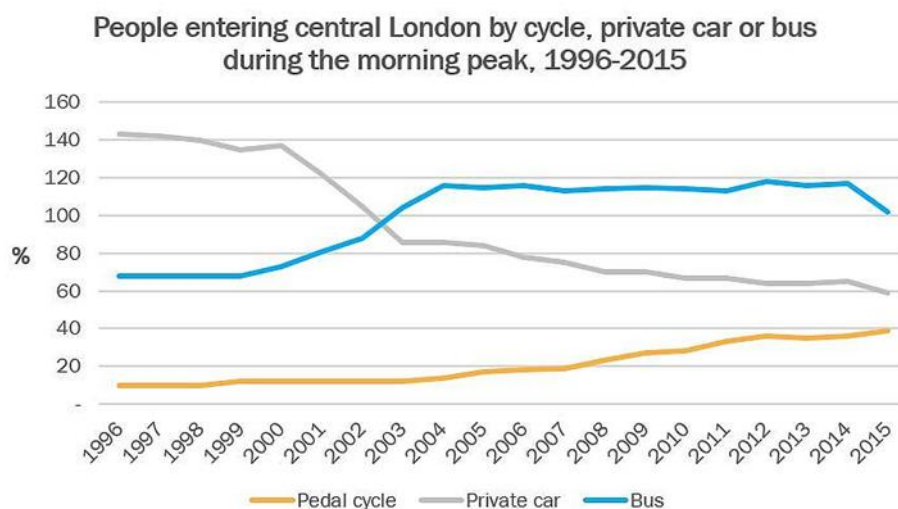


Figure 1 – Graph showing methods of entry to London during rush hour 1996-2015

Unfortunately, since 2015, the sales of bicycles in the UK in general has been declining and with the UK being the largest purchaser of bicycles in Europe aside from Germany, which has a vastly larger population and also has declining bicycle sales, it is safe to say that the sales of bicycles across Europe is declining. The decline in bicycle sales in the UK has been blamed on the effects of Great Britain leaving the European Union such as increased import costs due to the decline in the value of the pound as well as previous overstocking by UK distributors. Electric bicycles on the other hand are the only form of bicycle which has rapidly rising sales and if the electric bike sales trends in other countries are followed in the UK in the same way as the otherwise declining sales, this growth could be as much as 12%, with the sales of electric bikes in Germany increasing by 19% in the 2017 financial year, which is largely advantageous to the bicycle which to be produced from this project. With public awareness of electric bikes and appreciation for their positive aspects on the rise and the cost of purchasing an electric bike largely declining due to increased innovation and mass production, it is very likely that the increase in sales currently being experienced by the electric bike market will only continue to rise.

Composite Failure

Modelling composites is more complex than modelling materials such as metals, due to metals and metal alloys being a uniform material as opposed to the nature of composite materials which are made up of multiple plies of unidirectional fibres to build up the material. As such, predicting the failure composite materials under loading is also more complex, due to the possibility of failures of individual fibres, delamination of layers and failure of the matrix within the material, most of which are unique to the failure of composite materials. As such there have been several different models for composite failure created, several of these are incorporated into the composite optimisation software used in the creation of the composite spring suspension system, these are; Tsai Wu, Tsai Hill, maximum stress and maximum strain.

The Tsai Wu failure criterion considers the total strain energy which is made up of both distortion energy and dilatation energy for predicting failure. It is more general than the Tsai Hill failure criterion because it distinguishes between the compressive and tensile failure strengths of the material. The Tsai Wu criterion can also be used for the calculation of the factor of safety in a composite structure as the criterion gives its value for the probability of a composite failure as a fraction or decimal with 1 being a failure of the composite material, the factor of safety is calculated as the denominator of a fraction or the value given by the reciprocal of the decimal failure index given.

The Tsai Hill criterion considers the distortion energy portion of the total strain energy that is stored due to loading. The distortion energy is the portion of strain energy that causes shape change, the other portion of strain energy is the dilatation energy that causes volume change or causes area change in a two dimensional format, such as a change in cross sectional area in a material being drawn out, due to loading. The biggest limitation of the Tsai Hill failure criterion is that it cannot predict several different failure modes including fibre failure and matrix failure. Calculating the factor of safety from composite failure as the reciprocal of the square root of the failure index calculated. The factor of safety is the coefficient by which all stress values in the frame can be multiplied by in order to reach laminate failure. A factor of safety value greater than one indicates that the laminate is safe from failure.

The maximum stress criterion is broadly speaking the simplest of the composite failure methods and occurs when the stress in one of the principal material directions exceeds the maximum stress in that direction. The factor of safety is again calculated as the reciprocal of the failure index, with a factor of safety value greater than one indicating that the laminate should not fail for the application used. The maximum strain failure criterion is essentially the same as the maximum stress criterion however with strain values taking the place of the stress values.

For the application of the analysis of the bicycle frame for the development of the composite spring suspension system, Tsai Wu is the most effective criterion to use for the composite failure prediction. This is because when the suspension system compresses, there is definitely going to be distortion in the structure as this distortion is what will bring the suspension damping effect, however there could be dilation in the cross sectional area of the frame and so the use of the Tsai Wu criterion should allow for this.

Analysis Set Up

Computer finite element analysis tools mean that the composite layup for the frame can be optimised to provide the desired effects and have an idea of its longevity before prototyping the frame which saves time and material. This also has the advantage of the prototype or prototypes serving mostly to verify the results obtained using computer finite element analysis, meaning that far less prototypes will need to be produced before the frame can be produced.

The first step in the computer analysis of the frame is to use Solidworks and launch a static study of the frame, a static study of an object is generally used for studying the effects of applying a force such as stresses and displacements in the structure of the model which is being analysed. The first step in analysing the frame in this case is the generation of a mesh to divide the frame up into elements through which the analysis can be performed, for the analysis of the frame, the model of the frame is divided up into 10mm elements over the whole body, to a tolerance of 0.5mm. For some applications this mesh would be too coarse, however given that the frame as a whole is a body of considerable size, 10mm elements are of an appropriate size, due to mesh density always being a compromise of computing power against accuracy as the higher the density of the mesh, the more time and computing power that will be required in order to analyse the mesh. The next step is to constrain the frame to create stationary geometry which the frame can flex relative to. Given the simplified model of the frame being used for the composite analysis, it is necessary to create fixed geometry on the frame around the top tube where the seat post would be situated and where the bottom bracket would be, this is to simulate the steel or aluminium joining member between these two points which is omitted from the simplified frame due to it not being made from composite. The final piece of fixed geometry is the head of the frame which is fixed due to it having the forks to provide it with stability. At this point the load case for the simulation can be added to the model, the first part of the load case is a 1000 Newton force acting in the negative Z direction, at the point at which the seatpost would be passing through the frame. This is to simulate the force that would be exerted on the frame by the bicycle having a rider and due to the bicycle being designed being designed for use by commuters, the figure for the force on the frame is higher than simply having a person on it to account for the person on the bicycle quite possibly carrying a bag containing things such as a computer, or alternatively to account for a heavier user. This force should act in the vicinity as the seatpost, however it should not act in the same place as is constrained for the joining member as applying a load to an area of fixed geometry causes errors within the analysis software. The second component of the load case is a 10,000 Newton force on the inside face where the dropouts or axle would be situated on the frame. This is to act in the positive Z direction this is to simulate the bicycle hitting a big bump and this amount of force is the value for which the maximum displacement in the frame should be achieved. Due to

the simplified model for the frame being a shell, it is required to define the thickness of the material, in order to save time setting up the material later in the analysis set up, the value for the thickness is set as 5mm, the material selected is not important at this point. At this point the model can be imported into Vanderplaats Design Studio, which is the software which is to be used for the actual analysis and optimisation of the composite layup. The first objective in Design Studio is to define the unidirectional composite fibre material which is to be used, the values for which are:

Young's Modulus in the longitudinal direction (E_1): 132 GPa

Young's Modulus in the lateral direction (E_2): 10.8 GPa

Poissons Ratio (ν_{12}): 0.24

In plane Shear Modulus (G_{12}): 5.65 GPa

Transverse Shear Modulus (1-Z plane) (G_{1z}): 5.65 GPa

Transverse Shear Modulus (2-Z plane) (G_{2z}): 5.65 GPa

Mass Density (ρ): 1540 kg/m³

Allowable longitudinal stress in tension (X_t): 1513 MPa

Allowable longitudinal stress in compression (X_c): 1000 MPa

Allowable transverse stress in tension (Y_t): 43.4 MPa

Allowable transverse stress in compression (Y_c): 43.4 MPa

Allowable in plane shear stress (S): 43.4 MPa

The second part of the setup within Design Studio is to align the theta vectors for the elements which make up the frame. The theta vectors provide the relative 0 degrees for the local area, meaning that for the material layup the direction of the theta vector of the elements gives 0 degrees for the direction of the fibres in the material to be aligned to. In order to more accurately model the layup of the composite material for the frame, multiple coordinate systems are required around the curvature of the frame both at the top of the frame and in the area of where the axle or dropouts would be situated on the frame.

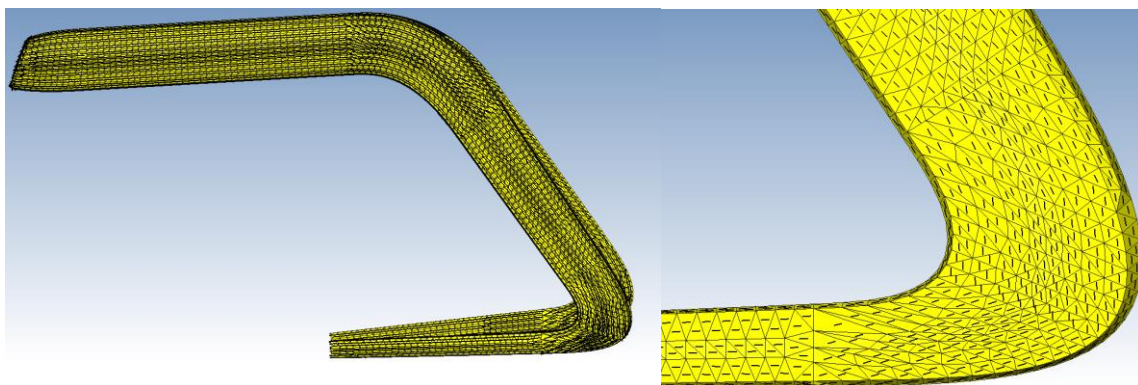


Figure 2 – Left: Mesh applied to the simplified frame, Right: Theta vectors around the lower curvature of the frame

Once the theta vectors are defined and aligned, the next part of the setup is to create a group property for the composite material layup. The group type for the analysis is 'PCOMP/PCOMPG' which is the group type for layered composites within Design Studio and the composite failure theory to be used is Tsai Wu.

Global Ply ID : Material : Thickness : Angle : Output					
Layer 1					
	2 Composite	0.001	-90.0	Yes	+ -
Layer 2					
	2 Composite	0.001	-45.0	Yes	+ -
Layer 3					
	2 Composite	0.001	0.0	Yes	+ -
Layer 4					
	2 Composite	0.001	45.0	Yes	+ -
Layer 5					
	2 Composite	0.001	90.0	Yes	+ -

Figure 3 – Basic setup of the composite material

The layup for the composite material is how it is shown in the figure above, with 5 layers of the unidirectional composite material defined earlier in the Design Studio setup process. Each of the layers in the material layup is 1mm thick and the angles vary from -90 to +90 degrees, increasing in 45 degree increments, this angle is relative to the theta vectors which were defined for each area of the frame. Once the group properties are correctly defined, all of the elements which make up the frame can be changed such that they are made up of the multi layer composite group that was created using the unidirectional composite material.

Using the Genesis solver in Design Studio, a single analysis of the frame should show whether the frame is behaving in the manner expected. Given the loadcase which is acting on the frame, the rear end of the frame should have displace in the positive Z direction, however this displacement should be of a very small magnitude, a maximum displacement of 0.000041 metres was achieved in the analysis performed.

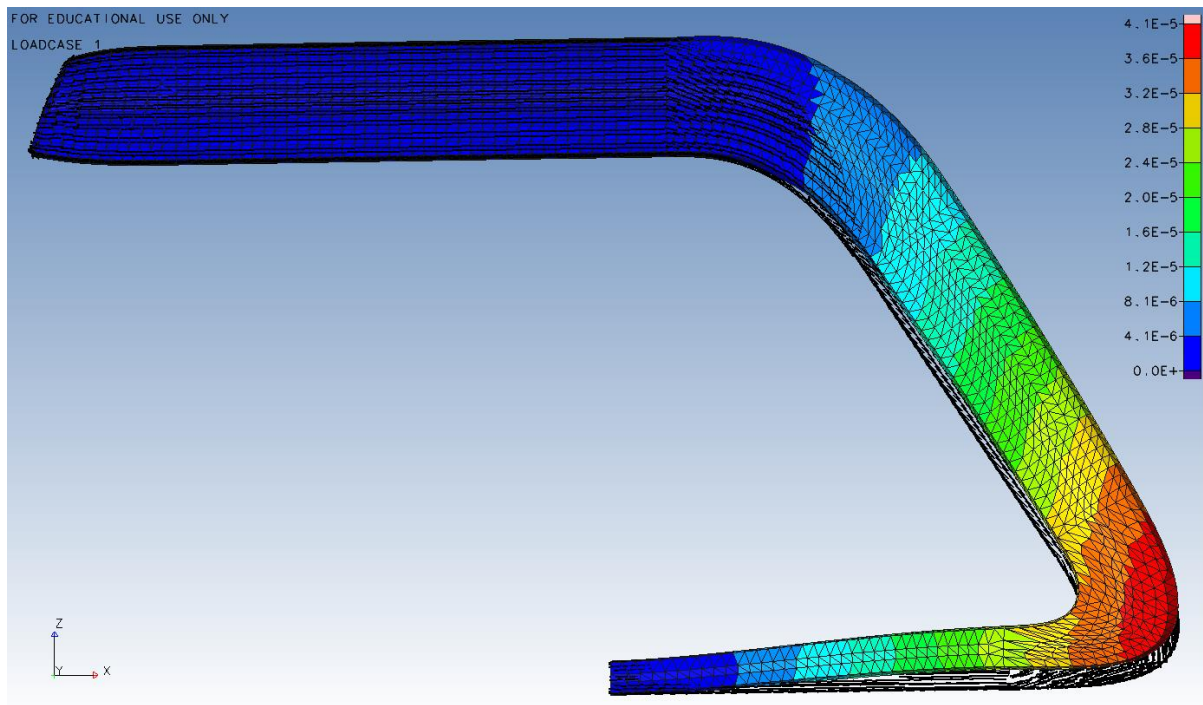


Figure 4 – Post processing diagram showing the displacement in the frame following the single analysis using Genesis

Once the model is behaving as expected, the focus moves to optimising the layup of the composite material in the frame in order to achieve the desired displacement. The desired displacement for the frame when acted on by a 10,000 Newton load is 10mm and so the displacement is set as a design constraint, with 7.5 millimetres as a lower bound and 12.5 millimetres as an upper bound. This is done so that the optimisation software will view the displacement of the frame between the upper and lower bounds as a prerequisite requirement for the frame to meet these criteria before moving onto fulfilling the objectives of the optimisation. The allowable fail probability is in this case set as 0.25, this is due to the allowed fail probability being the composite failure index. A composite failure index of 1 is a failure of the composite material and therefore an allowed fail probability of 0.25 allows a factor of safety of 4, which is a very safe margin given that the 10,000 Newtons acting on the frame in this load case is supposed to be the maximum amount of stress exerted on the frame when it is in use. Minimising mass across the entire model is set as the objective of the optimisation, this means that the optimisation software will remove all of the unnecessary material that it can from the frame in order to minimise the mass of the overall structure, provided that it does not violate the constraint criteria that are defined. In the case of the bicycle frame, the objective of minimising mass will mean that it will remove all unnecessary material from the frame provided that the displacement of the frame is within the bounds and maintains the factor of safety. The design variables which the optimisation software can use to achieve the target displacements whilst removing unnecessary weight are the thicknesses of each of the layers of composite material. These are discrete design

variables as the thickness of each layer must be a whole number, due to the thickness of the layers being made up of multiple plies of composite fibre. The thickness of each of the five layers which make up the composite can be from 0.25 millimetres, which is one single ply of the unidirectional composite fibre up to 3 millimetres or any multiple of 0.25 millimetres in between the bounding values.

Once the optimisation of the composite layup in the frame meets the criteria required for the displacement in order to provide the suspension for the bicycle, it is necessary to perform a computer fatigue analysis on the resulting design to see how well the composite layup in the frame stands up to being used over a longer period of time than the single cycle used in the optimisation of the composite layup. To do this a fatigue simulation in Solidworks is used, with the frame for the study being the frame which was optimised using Design Studio, imported into the fatigue simulation. The loading for the simulation is to act on the same area of the frame as was used for the load case for the optimisation of the composite in Design Studio, however for fatigue analysis the frame is subjected to cyclic loading of varying magnitude, as directed as 'events'. For the 'events', the frame is to be subjected to 10,000 cycles of the same 10,000 Newton maximum designed load as well as 50,000 cycles of load of varying magnitude, up to a maximum 5,000 Newton load.

Results

When the setup for the computer analysis was completed, the analysis and optimisation of the frame could take place. The load case on the frame was checked by performing a single analysis using the Genesis analysis within Design Studio, this showed that the frame was displacing in the correct fashion, with a displacement of 0.041 millimetres.

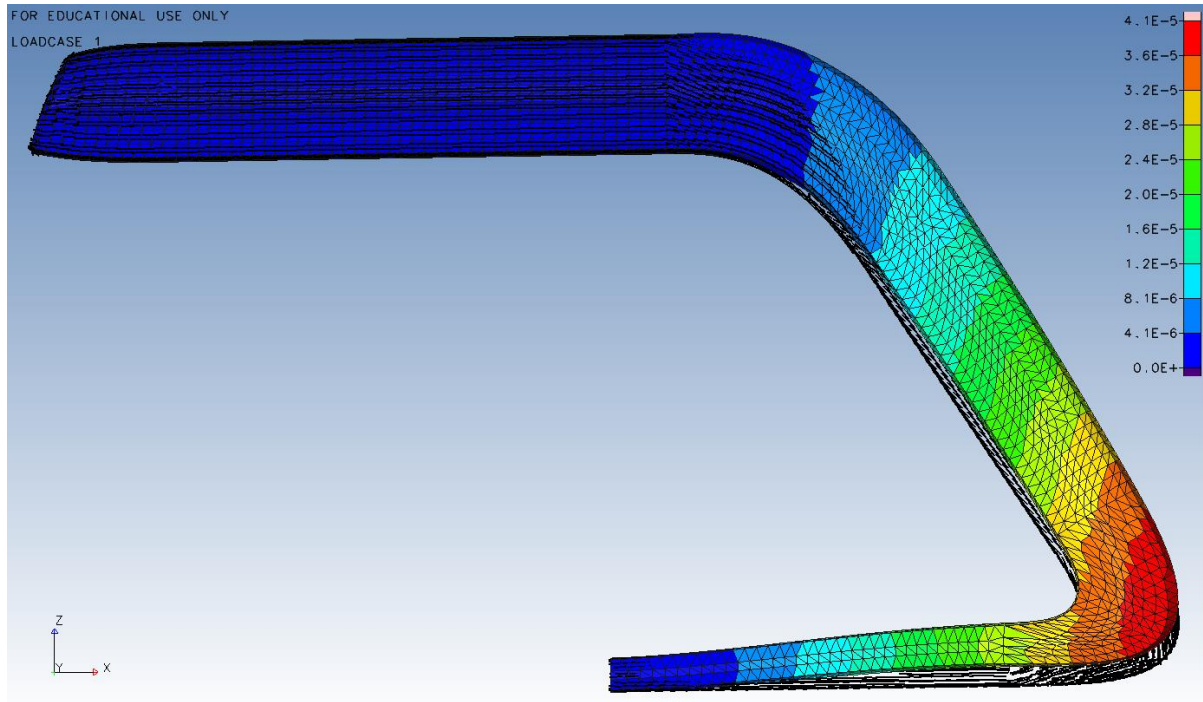


Figure 5 - Post processing diagram showing the displacement in the frame following the single analysis using Genesis

With the load case and behaviour of the frame under load being correct, the optimisation to achieve the desired displacement could take place. When the first round of optimisation took place, the results for the displacement within the frame yielded strange dome like displacements around the areas where the drop outs or axle would meet the frame.

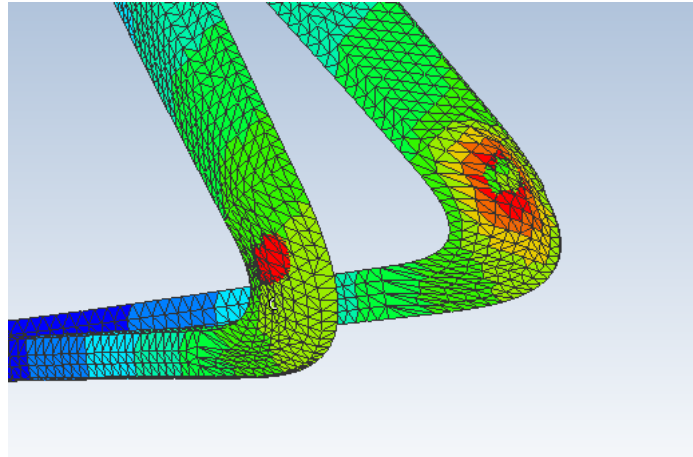


Figure 6 – Post processing diagram showing dome shaped displacements

This was possibly due to the translation of the magnitude for the displacement when it was set as a design constraint, due to it being set as total magnitude of displacement, this was changed to the translation magnitude in the Z axis, which is the vertical axis and the axis which is correct for use as suspension travel, however changing the translation magnitude for the displacement didn't change the output as the optimised frame still had the domed displacements around the axle locations. The next thing to be adjusted in an attempt to rectify the model was the elements around the curvature in the lower end of the frame as the elements, particularly the ones around the edge were very skewed.

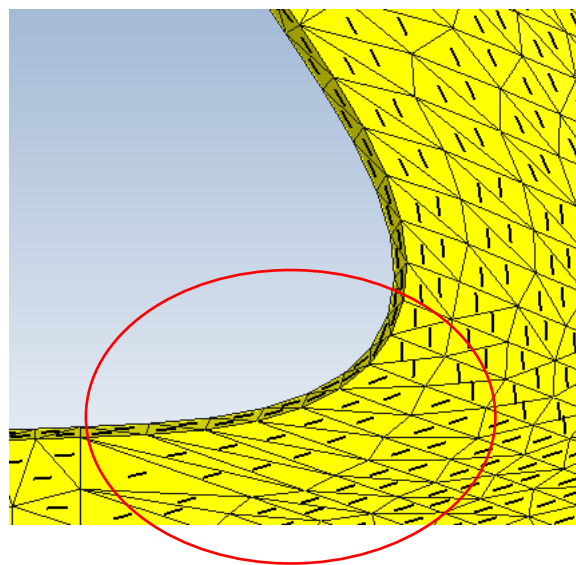


Figure 7 – Skewed elements in the frames lower curvature

In order to try counteracting the skewness of the elements, the ones spread around the lower curvature of the frame, such as the ones circled in the figure above, were divided into multiple smaller

elements in an attempt to make them less skewed in their shape and work properly for the optimisation of the frame. As with changing the direction of the displacement magnitude however, the dividing of the elements had little to no effect on the outcome of optimising the frame, with the domed areas of displacement still being present on the optimised frame model.

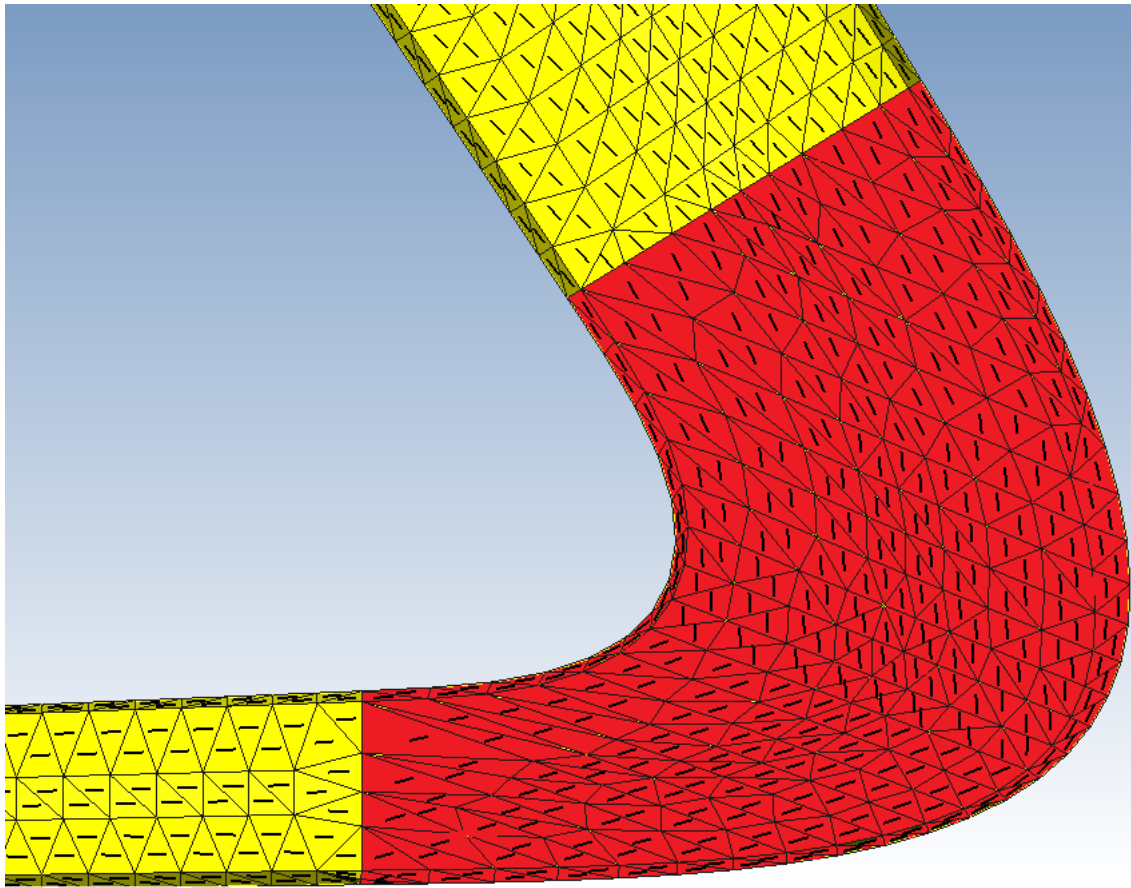


Figure 8 – Elements removed from the lower curvature of the frame to be replaced with RBEs

Due to dividing the highly skewed elements around the lower curvature of the frame being ineffective in addressing the problem with the strange displacement developing from the optimisation of the frame, the elements selected – the ones highlighted in red in the previous figure, were replaced by a rigid body element. A rigid body element replaces all of the elements highlighted in red with one single element on each side, situated in the location where the axle would be on the frame, these rigid body elements are infinitely rigid and they transfer the load to the elements that they are connected to. With the load case acting on the model having been transferred to acting solely upon the two rigid body elements which replaced the areas of lower curvature but remaining acting in the vertical axis, the load is transferred to each of the elements which were adjacent to the elements that were removed to create the rigid body elements which replaced them. The use of rigid body elements is allowable in this case as the area of elements which were replaced by the rigid body elements are the area around the axle or dropouts and therefore will actually be made of either steel or aluminium in

the final design of the frame and so as such this area of the frame would not be made from composite material, meaning that the replacement of the elements around the lower curvature in effect makes the model more accurate to the final design of the frame. Despite the replacement of the highly skewed elements with the rigid body elements, the model didn't optimise properly. The model seemed to be optimising well with the weight of the model generally decreasing whilst not violating the design constraints for the first few iterations however when the Genesis solver began to use the discrete numbers for the thickness of the plies, the solver stopped working properly. It stopped working properly in that it began to default to exclusively using the minimum material thickness despite this violating the design constraints set and the types of displacements which were displayed in the optimised versions of the frame were extremely strange, with some being completely unfeasible.

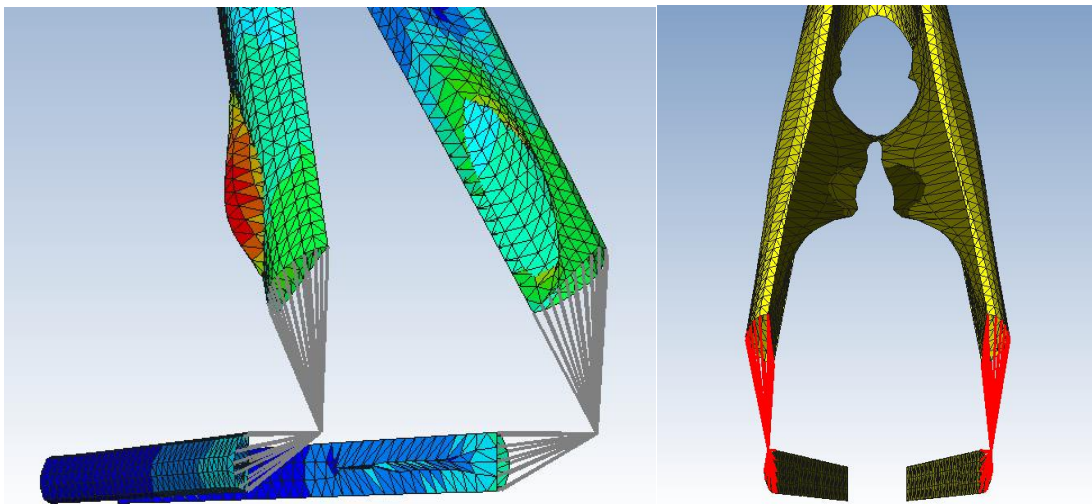


Figure 9 – Post processing diagrams showing the strange displacements achieved following the implementation of RBEs

It is unclear as to why the optimisation of the frame has not worked in the manner desired despite the objectives of the optimisation being clear and the model for the optimisation being set up correctly in order to create a scenario for the creation of a suspension model. The only explanation, given the last set of displacements and particularly the strange inner displacement, is that the design of the frame itself is in some way inherently opposed to the implementation of the composite spring suspension within the frame.

Further Work

With regard to further work which could be done with this project, it is felt that despite the process not being able to produce the composite spring suspension system which was the primary objective of the project, this was most likely down to inherent problems with the design or model of the frame which the study was done upon and so as such the knowledge gained over the course of the project could with the right frame be used to create a fully functioning suspension system for said frame. This would however mean starting from the bottom, with the frame being designed from the initial stages to have this form of composite suspension integrated into it such that it does not cause the same sorts of problems that were experienced when optimisation of the frame used in this project was attempted. Due to the nature of when the details for the design of the frame in this project were received, the scope of the research into the implementation of the suspension wasn't solely focussed on the commuter bicycle sector and so as such any further use of the knowledge could easily be applied to any form of bicycle within reason for example it could be used for cross country or trail mountain bicycles, to improve the comfort of touring bicycles or as in the case used in this project to combat larger impacts on an urban or commuter bicycle.

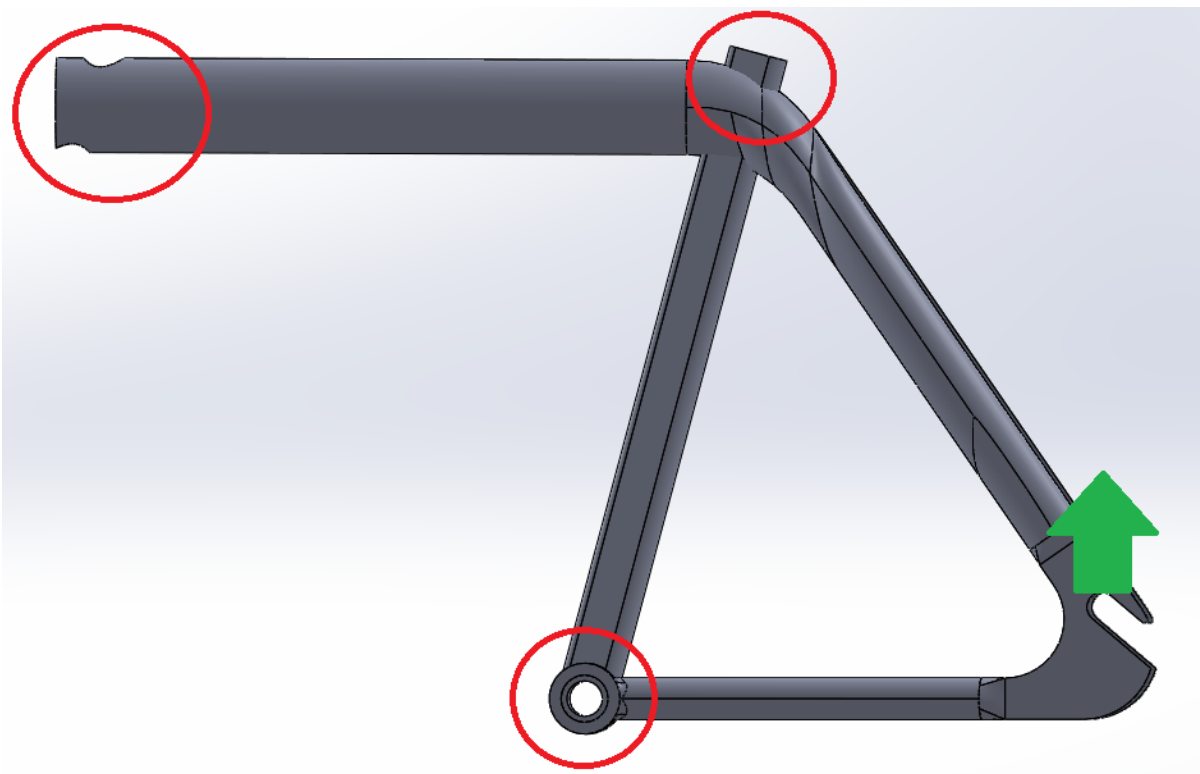


Figure 10 – For the testing of the prototype; Red: areas to be constrained, Green: Direction and area of force from piston

In addition to this, once the computer analysis on the frame has been completed to the correct outcome and the prototype has been built, the prototype would need to be tested to verify the findings of the computer analysis. This would involve having to produce a test rig for this purpose

which is capable of holding most of the frame of the bicycle stationary relative to the rear of the frame which will be acted upon by a vertical force to simulate the rear wheel of the bicycle hitting a bump. This force could be generated using a hydraulic piston connected to the axle between the chain stays of the frame, the use of a hydraulic piston would allow for the magnitude of the force exerted on the frame to be varied, allowing the frames behaviour under various levels of stress to be examined and recorded. The use of the rig also allows for the lifespan of the frame to be examined as the number of cycles of force on the frame before failure can be determined and from that a life cycle assessment can be performed on the frame. The recording of the frame could be performed using a camera with a scale positioned behind the frame relative to the camera and provided the time period for one cycle of force to be exerted by the piston remains constant across all values for load, the total number of cycles on the frame can be determined.

Conclusion

Despite the project failing in its intended purpose of integrating the composite spring suspension to the bicycle frame provided by the third party designer, which was largely attributed to the limitations caused by the frame, as mentioned in the future work section of the report it did however yield a model which could be used to develop a composite frame with integrated suspension provided the frame was designed for this purpose and therefore the project should not be looked upon as a complete failure.

References

Gude, M. (2013). Fatigue testing of carbon fibre reinforced polymers under VHCF loading, *Procedia Materials Science*, Volume: 2, Page: 18-24

Qian, C. Shi, W. Chen, Z. Yang, S. Song, Q. (2017). Fatigue reliability design of composite leaf springs based on ply scheme optimization, *Composite Structures*, Volume: 168, Page 40-46

U.S. Department of Transportation Federal Aviation Administration. (1996). Comparative Evaluation of Failure Analysis Methods for Composite Laminates.

Jin-Chee Liu, T. (2010). Fiber direction and stacking sequence design for bicycle frame made of carbon/epoxy composite laminate, *Materials & Design*, Volume: 31, Issue: 4, Page: 1971-1980

Lessard, LB. Nemes, JA. Lizotte, PL. (1995) Utilization of FEA in the design of composite bicycle frames, *The International Journal of the Science and Technology of Reinforced Materials*, Volume: 26, Issue: 1, Page: 72-74

Hull, ML. & Bolourchi, F. (1988). Contributions of rider-induced loads to bicycle frame stress, *The Journal of Strain Analysis for Engineering Design*, Volume: 23, Issue: 3, Page: 105-114

Santa Cruz Bicycles, (2017). Virtual Pivot Point (VPP) Suspension Design. [Online] Available at: <https://www.santacruz bicycles.com/en-GB/virtual-pivot-point-vpp-suspension-design> [Accessed 4/12/17]

BMC Switzerland, (2017). MTT - Micro Travel Technology. [Online] Available at: <https://www.bmc-switzerland.com/int-en/innovation/mtt-micro-travel-technology/> [Accessed 4/12/17]

Beale, L. Earle, D. (2008). Rear suspension system for bicycles. US RE39159.

Clarke et al (2014), Cycle to work scheme – weekend warriors or daily commuters?, *Scottish Transport Applications & Research Conference 2014*.

Department for Transport, (2017). Table TSGB 0106. [Online] Available at: <https://www.gov.uk/government/statistical-data-sets/tsgb01-modal-comparisons> [Accessed 30/12/17]

Sutton, M. (2017). Bicycle sales in Germany decline again, e-Bikes add 12% growth. *Cycle Industry*, [Online] Available at: <https://cyclingindustry.news/bicycle-sales-in-germany-decline-again-e-bikes-ad-12-growth/> [Accessed 30/12/17]

Reid, C. (2017). UK cycle industry predicted to sell 1 million fewer bikes this year. *bikebiz*, [Online] Available at: <https://www.bikebiz.com/retail/uk-cycle-industry-predicted-to-sell-1-million-fewer-bikes-this-year> [Accessed 31/12/17]

Laker, L. (2017). Rise of the ebike: how going electric could revolutionise your ride. *The Guardian*, [Online] Available at: <https://www.theguardian.com/lifeandstyle/2017/sep/16/rise-of-the-ebike-how-going-electric-could-revolutionise-your-ride> [Accessed 2/1/18]

Cotterell, S. (2018). UK Cycling Statistics. *Cycling UK*, [Online] Available at: <https://www.cyclinguk.org/resources/cycling-uk-cycling-statistics#How%20many%20people%20cycle%20commute> [Accessed 15/3/18]

Oortwijn, J. (2018). German E-Bike Market Sees Record Growth in 2017. *Bike Europe*, [Online] Available at: <http://www.bike-eu.com/sales-trends/nieuws/2018/3/german-e-bike-market-sees-record-growth-in-2017-10133185> [Accessed 15/3/18]

UK Government, (2017). Walking and cycling statistics. [Online] Available at:
<https://www.gov.uk/government/collections/walking-and-cycling-statistics> [Accessed 30/12/17]