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OPTIMISATION IN THE DESIGN PROCESS - Carbon Fibre Reinforced Plastic Bicycle Frame

M7X01380 – Simulation and Modelling

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The objective of the work carried out in this assignment is to investigate the benefits of the structural optimisation of a component. The component chosen to be optimised for this piece of work is a bicycle frame manufactured from carbon fibre reinforced plastic.

This component is highly suited to structural optimisation both due to the variety of shapes which can be used in the design of a bicycle frame but also due to the nature of carbon fibre reinforced plastic material which it is manufactured from being a composite laminate. The composite material in particular lends itself to optimisation because according to Altair Engineering:

“The design of composite structures involves the definition of the ply angles, numbers of plies, and stacking sequence for the given laminate. Given the large number of potential variables, designs are usually limited to standard sets of design configurations based on experience and available test data. There is potential for laminated composite structures that have increased performance and reduced weight by utilizing optimization methods to find the best combination of variables for a given application.”

In the case of a carbon fibre reinforced plastic bicycle frame, what this means is that the composite laminate material which the frame is manufactured from can also be optimised to produce a higher performance product with reduced weight and material use. Naturally, a higher performance product is a desirable feature for any application, however with the application of this piece of work being a bicycle frame, the reduction of the overall weight of the component is also a highly desirable quality and with many customers seeking the lightest product available, many manufacturers of bicycle frames are constantly competing to produce the lightest product possible in order to appeal to these customers. Carbon fibre reinforced plastic is ideal for this application as when the fibres within the composite material are properly laid up, the material can be stronger than steel but at a fraction of the weight, making it a popular choice for the manufacturing of lightweight bicycle frames. A smaller yet not inconsiderable advantage to the optimisation of the composite material is the reduction in the overall amount of material which is required. This has the advantage of the reduction in material costs but is also advantageous environmentally due to the nature of some composite materials. Most carbon fibre reinforced plastic bicycle frames are manufactured using a thermoset matrix, meaning that once it has set it is very difficult to recycle, with most carbon fibre reinforced plastic components being ground down for use as filler at the end of its usable life due to the complex and expensive chemical processes required to separate the carbon fibres from the thermoset matrix.

One of the largest advantages of the optimisation of the carbon fibre reinforced plastic bicycle frame would be the reduction in the development costs of the frame with an optimisation led approach when compared to a traditional development process or a CAD led approach. This is due to more traditional and CAD led approaches producing detailed designs for the final product before then testing or simulating the design produced to verify whether it works as desired. This approach isn't ideal and is often expensive due to the design then being subject to iterative redesign and improvement, requiring large amounts of time and money over the process of the development. An optimisation led approach however means that once a rough geometric model of the desired component has been produced, this can then be optimised, and the model can be developed for the sole purpose of meeting the desired criteria. This means that once the optimised geometry meets the desired criteria, then the detailed CAD model can then be produced from the optimised geometry, removing the iterative process of redesign and testing required in a more traditional or CAD led approach to design and therefore cutting down the required time and cost of the overall process.

The reduction of cost is an important factor for all manufacturers, however many bicycle manufacturers are considered to be small-medium sized enterprises and so as such the reduction in development costs and time is a critical factor due to smaller financial reserves and therefore a desire to get the product to market as fast as possible, meaning that an optimisation led approach is highly beneficial to the manufacturer themselves.

Due to the component being optimised being subjected to multiple loading scenarios, the first form of optimisation which could be carried out would be a topological optimisation, to assess and optimise the overall shape of the bicycle frame to minimise stress concentrations and unnecessary structures. The advantages of performing topological optimisation of bicycle frames has been documented previously, with Empire bicycles and Renishaw Engineering using topological optimisation to lighten areas of low stress and reduce or reinforce areas of higher stress in order to produce an entirely 3D printed bicycle frame in 2015. Once the shape of the frame has been topologically optimised, the carbon fibre reinforced plastic material which the frame is made can be optimised. As the passage from Altair Engineering stated, there are many variables which can be adjusted within the composite material itself once the frame has been optimised topologically such as; ply angle, stacking order – the order of the plies relative to each other, and the overall number of plies within the material – this can be adjusted both globally (throughout the component) or locally (in specific locations within the component).

The overall objective of the optimisation would in this case be to 'minimise weight'. Giving the optimisation software the objective of minimising the overall weight of the component means that the software will remove as much material as possible from areas of low stress without creating other areas of high stress concentration and without violating any of the constraints which have also been set within the optimisation software.

There would be several constraints specified within the optimisation software in order to ensure that the frame performs appropriately and does not fail in use once optimised. These constraints are the parameters which the optimisation software cannot violate when adjusting other parameters within the component in order to achieve the specified objectives of the optimisation, in this case to minimise weight. Given that the given application of the component being optimised is a bicycle frame, the first constraint would be geometric, to ensure that all necessary clearances are maintained. For example, there must be space between the chain stays on the frame for the back wheel and areas such as the head tube, seat tube and bottom bracket housing must be of the correct size to be able to fit the forks, seat post and bottom bracket respectively. The next constraint to be applied would be displacement within the frame. The desired displacement within the frame would be dependent on what type of bicycle frame was being developed, for example the frame for a bicycle designed for road racing would look to have the smallest amount of displacement possible for a given load case in order to maximise the stiffness of the frame, making it as efficient as possible for pedalling at the expense of comfort. Whereas the frame of a bicycle designed for mountain biking, recreational road biking or commuting may want to have more of an allowance for some displacement built into the frame in order to allow the frame to absorb some of the bumps from the rougher surfaces encountered to provide a suspension effect and a bit more comfort for the rider. The magnitude of this displacement would however be subject to the elastic limit of the composite material used for the frame and would also introduce more fatigue into the frame than would otherwise be experienced by a bicycle frame with minimal displacement. The next constraint which should be used would be the failure index. The failure index is a numerical quantity calculated using the materials strength and the calculation of the internal stresses within the material when it is loaded according to the given load case.

$$F_I = \frac{\sigma}{F}$$

F_I = Failure Index, σ = Internal Stresses, F = Material strength

The value for the failure index is generally a decimal as a failure index of 1 equates to a material failure and so any value higher than that is also a failure. The value assigned to a failure index constraint would depend on what factor of safety the manufacturer would like to have built into the component, which would also likely depend on the given application for the frame. Using the same examples as previously, a road racing bicycle frame could likely have a higher failure index of 0.5, giving a factor of safety of 2, than a bicycle frame designed for mountain biking or commuting for which it would be necessary to have a lower failure index, for example 0.25. This gives a factor of safety of 4 and means that the frame could withstand four times more loading than the given loadcase before immediate failure, which is a desirable quality for particularly a mountain bike frame which is likely to be subject to high forces and repeated impacts. Another constraint which would be necessary to specify within the optimisation software would be the material thickness due to the frame being manufactured from carbon fibre reinforced plastic. This is necessary because the material is a composite laminate, built up of multiple individual layers of material which are cured together using heat and pressure. This means that the material thickness can only be increased or decreased in finite steps due to the fact that the number of plies must be a whole number and each ply has an associated thickness, this is contrasting to the optimisation of conventional plastics or metals which due to their nature as homogeneous materials can reduce the thickness of the material to any degree.

In order for the optimisation software to work and for the optimisation of the bicycle frame to be an effective process there must be defined boundary conditions. In the case of the optimisation for a bicycle frame, these would fall into two distinct categories of boundary condition; a load case defining the forces which are expected to be exerted on the component and modelling constraints which hold the model in place. In order for the optimisation of the frame to be effective it is important that these boundary conditions replicate the conditions that the frame would experience when in use as closely as possible

The load case defines the loading of the component, specifying the location, magnitude and direction of the loads on the component. Being a bicycle frame there are three distinct areas of the frame which are subjected to direct loading when the bicycle is in use and so as such these three areas of the frame are the areas which the loads would act upon to make up the loadcase for the optimisation study:

Head tube – the part of the frame where the forks attaching the front wheel of the bicycle meet the frame:

- Force in the negative Y direction to the magnitude of half of the simulated rider's weight
- Force in the positive Y direction to the magnitude which it is desired for the frame to be tested to, simulating an impact on the front wheel

Rear dropout – the part of the frame where the rear axle of the bicycle attaches the back wheel of the bicycle to the frame

- Force in the negative Y direction to the magnitude of half of the simulated rider's weight
- Force in the positive Y direction to the magnitude which it is desired for the frame to be tested to, simulating an impact on the rear wheel

- Rotational force acting counter clockwise (assuming the bicycle frame is left side on) of a suitable magnitude for a pedalling force, to simulate the force exerted on the bicycle frame when the rider is pedalling.

Seat tube – the part of the frame where the seat post supporting the saddle meets the frame

- Force in the negative Y direction to the magnitude of the simulated rider's weight, simulating the rider being sat on the saddle

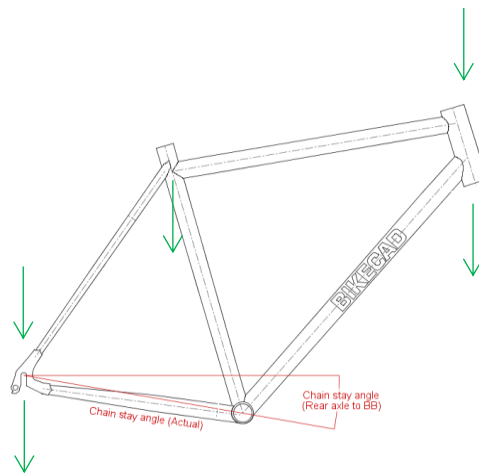


Figure 1 – Diagram showing location and direction of loads on frame (size not indicative of magnitude)

The second part of the boundary conditions necessary for the optimisation software are the modelling constraints, these are the areas which remain stationary relative to the rest of the frame over the course of the simulations which are used in the optimisation software in order to provide fixed geometry. In the case of a bicycle frame such as the one being studied here, there are two areas which should be constrained; the top of the seat tube and the bottom bracket housing. This is because the seat tube which connects them is an important structural member, but one which is unlikely to experience any form of deformation, due to the force on it acting in line with the tube, whereas the tubes connecting to the interfaces with the wheels, the head tube and the rear dropout, are much more likely to experience displacement due to the load case which has been applied to them and this means that the optimisation can be focussed on the areas which are more likely to experience higher amounts of stress and displacement.

Once the optimisation software has converged on what it considers to be a suitable design solution for the component there are still several things which must be considered before the component can be thought to be completed. First, it should be checked that the geometric constraints were properly adhered to such that the necessary clearances for the fitting of wheels and other components was maintained over the course of the optimisation as this is critical to the component being usable. Due to the frame being subjected to repeated cyclic stress from impacts over the course of its useable lifetime, it would also be necessary to perform a computer fatigue analysis on the optimised design in order to assess how well the frame would perform as it may be necessary to reinforce other areas of the frame due to the effects of fatigue causing failures or reduced performance over the expected life of the frame. This fatigue analysis would simulate the cyclic loading experienced by the frame in use, using many cycles over a range of magnitudes of

loading. This is especially important because of the frame being manufactured from carbon fibre reinforced plastic which has had its lay up optimised as it is possible for there to be instances where the loading in localised areas of the lay up exceeds the interlaminar shear strength of the composite material, causing delamination between the layers, creating a point of weakness which over time could result in a catastrophic failure of the component. It should also be considered that the optimisation of composites is not as fully developed as other forms of optimisation and due to the vast number of different factors which can affect the performance of a composite material, the optimised model may not be fully representative of the physical component which is produced.

In conclusion, the optimisation of a carbon fibre reinforced plastic bicycle frame holds many benefits, from a higher performance product which is more desirable to the customer, to being a more economical and faster method of the development of the frame for the manufacturer when compared to more traditional product development methodologies, to even being slightly beneficial to the environment due to reduced material use. When all of these advantages are considered, they make a strong case for why the carbon fibre reinforced plastic bicycle frame should be subjected to computer optimisation. This is however subject to the accuracy of the data which is inputted to the optimisation software and the limitations of the software to predict the behaviours of composite materials which must be considered before the final design solutions are implemented.

References

Altair Engineering, Online (<https://www.altair.com/>), Accessed 31/5/19

Altair University, Practical Aspects of Structural Optimisation, 2018

El Hami, A, Radi, B, Uncertainty and Optimization in Structural Mechanics, 2013

Macquarta, T, Maes, V, Bordogna, M.T, Pirrera, A, Weaver, P.M, Optimisation of composite structures - Enforcing the feasibility of lamination parameter constraints with computationally-efficient maps, 2018

Rothwell, A, Optimisation methods in structural design, 2017

Schumacher, A, Vietor, T, Fiebig, S, Bletzinger, K-U, Maute, K, Advances in Structural and Multi-disciplinary Optimization, 2018

Souza de Cursi, E, Reliability based optimization, 2015