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Parametric finite element analysis of bicycle frame geometries

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Abstract

This paper has outlined a FE model using beam elements to represent a standard road bicycle frame. The model simulates two standard loading conditions to understand the vertical compliance and lateral stiffness characteristics of 82 existing bicycle frames from the bicycle geometry project and compares these characteristics to an optimised solution in these conditions. Perhaps unsurprisingly smaller frames (490mm seat tube) behave the most favourably in terms of both vertical compliance and lateral stiffness, while the shorter top tube length (525mm) and larger head tube angle (74.5°) results in a laterally stiffer frame which corresponds with findings from literature. The optimised values show a considerable improvement over the best of the existing frames, with a 13% increase in vertical displacement and 15% decrease in lateral displacement when compared to the best of the analysed frames. The model has been developed to allow for further develop to include more detailed tube geometry, further analysis of more frame geometries, alternative materials, and analysis of other structural characteristics.

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Keywords: bicycle; frame; geometry; finite element analysis; stiffness; compliance; parametric.

1. Introduction

There is evidence of increasing participation and interest in cycling (Grous, 2011), and a large body of literature exists relating to bicycle technology. Mostly these relate to the common diamond “safety” framed road or mountain bicycles, and wide range of specialist tools are now available to support bicycle development through analysis and iterative improvement. Performing Finite Element Analysis (FEA) on bicycle frames has become a

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common activity for bicycle designers and engineers in the hope of improving the performance of frames. This is typically achieved by balancing priorities for key requirements, including minimising the mass of the frame (possibly using competition rules to constrain this), maximising lateral stiffness in the load transfer from the hands and feet to the drive, maximising the strength capabilities of the frame to allow for a higher load capacity or better load distribution, and adjusting the vertical compliance of the frame to tune the softness of the ride. FEA has been used to analyse composite, aluminium and steel bicycle frames (Peterson and Londry, 1986; Lessard et al, 1995; Maestrelli and Falsini, 2008; Liu and Wu, 2010; Reynolds Technology Ltd, 2011a) with the aim of understanding physical behaviour and improving performance relating, however a comprehensive study on the influence of key geometric parameters on the stiffness of frames has not been conducted. The aim of this study was to evaluate the influence of key geometric parameters on frame stiffness using a wide range of bicycle frame designs from historical data and to compare these to an optimised solution.

2. Literature review

As far back as 1986, Peterson and Londry (1986) used FEA to fine-tube the design of the Trek 2000 aluminium frame using two other existing designs (one steel, one aluminium) as performance benchmarks for mass, strength and stiffness characteristics. Their model used beam elements to represent the tubular frame structure (excluding forks) with restraints at the rear axle and head tube, and loads applied in a range of load cases at the seat tube, head tube, brake bridge, and bottom bracket (BB). While this study did not include an analysis of varied geometry, the analysis of varied load cases provided a rich insight into various generic performance characteristics, for example that energy losses in the vertical direction could be increased with little negative effect on hill climbing performance (i.e. an out of saddle load case) and that the down tube was always the greatest strain energy absorber, storing between 38-49% of the total (followed by the seat tube, storing between 19-25%). While this study did not consider variations in geometric parameters, it has laid down important groundwork for the use of FEA to support the design and development of frames. Reynolds Technology Ltd (2011a) as producers of tubes for bicycles (and other industries) have produced a similar beam element FE model called eReynolds that they have made available to bicycle designers and frame builders. While eReynolds is capable of modelling more complex tube geometries than the model created by Peterson and Londry (including tube diameters, oval and round butt profiles, wall thicknesses), frame geometries and standard Reynolds materials (Reynolds, 2011b), it limits the load case to that specified in BS EN 14766 (British Standards, 2005b).

Early FE models using shell elements to model composite frames were developed by Lessard et al (1995), who also modelled tubular frames using beam elements. This study included comparison of frame types and included some experimental validation of these models with load cases analysing vertical compliance and lateral stiffness. Maestrelli and Falsini, (2008) developed a parametric model to optimise a composite frame geometry using varied frame shapes to reduce vertical stiffness and increase lateral stiffness. These authors used six load cases based on experimental loads measured in the field (Soden and Adeyefa, 1979) and the model was bounded by constraints on frame geometry imposed by professional bodies, with potential limitations to such design solutions including difficultly in manufacturing and potentially unappealing aesthetic outcomes. Other optimisation algorithms have been applied to bicycle frame geometries, bearing in mind simple load cases and evolutionary optimisation (Xie, 1994) and as part of a process to fit the frame and key components to rider biomechanics (Xiang *et al*, 2011). Liu and Wu (2010) investigated the influence of fibre stacking sequence and orientation on the stress distributions on a carbon-epoxy composite frame using shell elements to simulate torsional, frontal and vertical load cases. While this study focuses on the details of the layup with the intent of identification and elimination of highly stressed regions, like all the above papers no consideration was given to the influence of key frame geometry, i.e. tube lengths and angles.

3. Finite element model description

For this study a FE model was created using 317 beam elements to represent a standard road bicycle frame (including road, audax and touring options), including key tube lengths and angles and an idealised stem/handlebar and BB geometry as shown in Fig1. Material properties for all elements were based on those supplied by Reynolds (Reynolds, 2011b), and included Young's modulus (E=207GPa), Poisson's ratio (ν=0.34), density (ρ=7800kg/m^3). Load cases that were analysed include a) a vertical load through the seat post of 2400N (sitting rider) and a simulated scenario of a rider out of the saddle pushing on the right pedal such that loads are applied to the left and right ends of the handlebar and on the right side of the BB and a BB extension as shown in Fig.1 below.

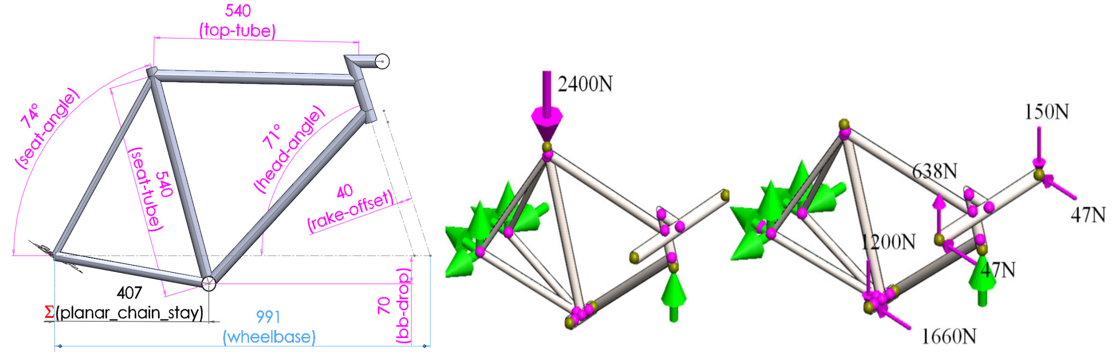

Fig. 1. Beam element model with key frame geometries (left). Rear dropout and head tube restraints for seat tube (middle) and BB/handlebar (right) load cases from Maestrelli and Falsini (2008).

These load cases are based on two extremes as modeled by Maestrelli and Falsini (2008) which are based on experimental loads measured by Soden and Adefeye (1979). Fig. 1 also shows the three translational restraints at the rear dropouts, and the vertical restraint on the bottom of the head tube as modeled by Peterson and Londry (1986) and Maestrelli and Falsini (2008). For the first load case (vertical seat tube load) the vertical displacement of the top of the seat tube was used to indicate the vertical compliance of the frame (i.e. a large vertical displacement corresponds with a high vertical compliance -since compliance is the inverse of stiffness). For the second load case (out of saddle handlebar/BB loads) the lateral displacement of the BB in the axial direction of the BB was used as an indicator for lateral stiffness (i.e. a large lateral displacement corresponds with a low lateral stiffness). As such, by dividing the vertical displacement in the first load case by the lateral displacement of the second case a lateral compliance/vertical stiffness ratio was used as a means to directly compare frame geometries under consistent loading conditions.

Each load case was analysed on a single frame geometry and then a design sensitivity study implemented to analyse a further 81 frame geometries. These were based on data from the bike geometry project (Mann, 2010), which provides a historical catalogue of frame geometries. While the list is limited in that some key geometry is omitted (i.e. head tube length and down tube length) and in some cases there are missing data (i.e. BB drop and wheelbase are often missing), it provides a useful dataset to map and compare theoretical stiffness behaviour of many real frames in a sensitivity study. All measurements for tube lengths have been assumed to be center to center and top tube measurements are assumed to be actual tube lengths rather than effective top tube length. For this initial study, a sampling technique was used to reduce the number of frames, from the original 1141 frames, to 503 datasets with complete data. This was then further sampled using a systematic approach (sampling 1 in 5 from an ordered list from small to large frames based on seat tube length), leaving 99 frames which was further reduced to 82 when duplicates were removed. The range for all input frame parameters and tube sizes (which were held constant for all studies) is shown in Table. 1. Once all 82 frame geometries were analysed in both the vertical and lateral load cases, an optimisation study was run using a Box-Behnken algorithm to find an optimum solution for the vertical load case, the lateral load case, and both load cases (equal weighting) using the objectives of maximising vertical displacement (seat tube load) and minimising lateral displacement (out of saddle loads). From this, a theoretical optimum stiffness-compliance ratio could be established, allowing all frame geometries to be compared to and normalised against.

Table 1. Model input parameter ranges for the frame (left) and tubes (right).

Frame parameter	Range	Tube	Tube size (ø, thickness)
Seat tube length (mm)	490-640	Seat tube	Ø28.6, 0.5
Head angle (deg)	71-74.25	Top tube	Ø28.6, 0.5
Rake offset (mm)	38-80	Down tube	Ø28.6, 0.5
Seat angle (deg)	72-74.3	Head tube	Ø31.75, 1.5
Chain stay length (mm)	405-470	BB	Ø38.1, 1.5
Wheelbase (mm)	972-1100	Seat stay	Ø17, 0.5
Top tube length (mm)	525-610	Chain stay	Ø24, 0.5
BB drop height (mm)	45-80		

4. Results and discussion

Fig. 2 shows example displacement plots for a frame in both load cases. Table 2 shows the displacement values from the range of frames analysed and the optimised results also, and Table 3 shows the optimised geometry for both load cases and the combined model. The smaller frames (490mm seat tube) behave the most favourably in terms of both vertical compliance and lateral stiffness, while the shorter top tube length (525mm) and larger head tube angle (74.5°) results in a laterally stiffer frame which generally corresponds with Peterson and Londry (1986), since this combination will result in the shortest down tube which is mostly responsible for supporting lateral loads. The optimised values show a considerable improvement over the best of the existing frames, with a 13% increase in vertical displacement (from 0.342 to 0.387) and 15% decrease in lateral displacement (from 1.708 to 1.453) when compared to the best of the analysed frames.

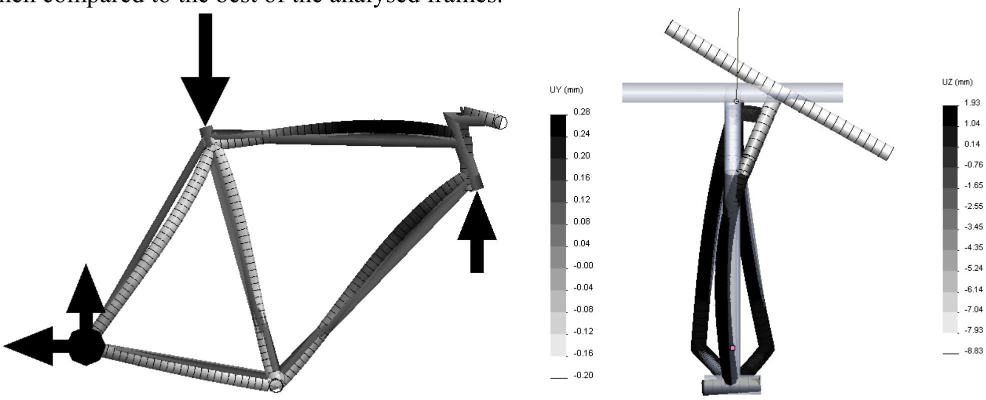

Fig. 2. Example displacement plots for a frame under a vertical load at the top of the seat tube (left) and loads applied to the BB/handlebars (right). Schematic displacements are scaled for visual purposes.

Table 2. Vertical and lateral displacement results for the range of frames analysed and optimised values.

	Best value from range of existing designs (vertical seat tube load)	Optimisation to maximise vertical displacement (vertical seat tube load)	Best value from range of existing designs (lateral BB/handlebar load)	Optimisation to minimise lateral displacement (lateral BB/handlebar load)	Optimising both vertical and lateral displacement conditions
Vertical displacement at seat tube (mm)	0.342	0.387	-	-	0.311
Lateral displacement at BB	-	-	1.708	1.453	1.453

Table 3. Optimised geometry for vertical compliance (maximising displacement), lateral stiffness (minimising displacement) and both.

	Maximising vertical displacement (vertical seat tube load)	Minimising lateral displacement (lateral BB/handlebar load)	Optimising both
Seat tube length (mm)	490	490	490
Head tube angle (deg)	71.50°	74.25°	74.25°
Rake offset (mm)	76	38	80
Seat tube angle (deg)	74 °	72°	72°
Chain stay length (mm)	468	405	405
Wheel base (mm)	981	1100	972
Top tube length (mm)	608	525	525
BB drop (mm)	80	45	45

Fig. 3 shows the plots of normalised stiffness-compliance ratio when compared to the seat tube length and top tube length for all frames analysed, since these two parameters have the highest co-efficients of determination. This figure also shows the vertical and lateral displacements plotted against the seat tube and top tube lengths for all frames analysed. The seat tube and top tube lengths explain most of the variance in the displacement data and as such contribute the most to the overall stiffness-compliance ratio, but it can be seen that of all the frames tested those smaller frames are still some way short of the theoretical optimum stiffness-compliance ratio of 1.00 for the range of frame geometries analysed.

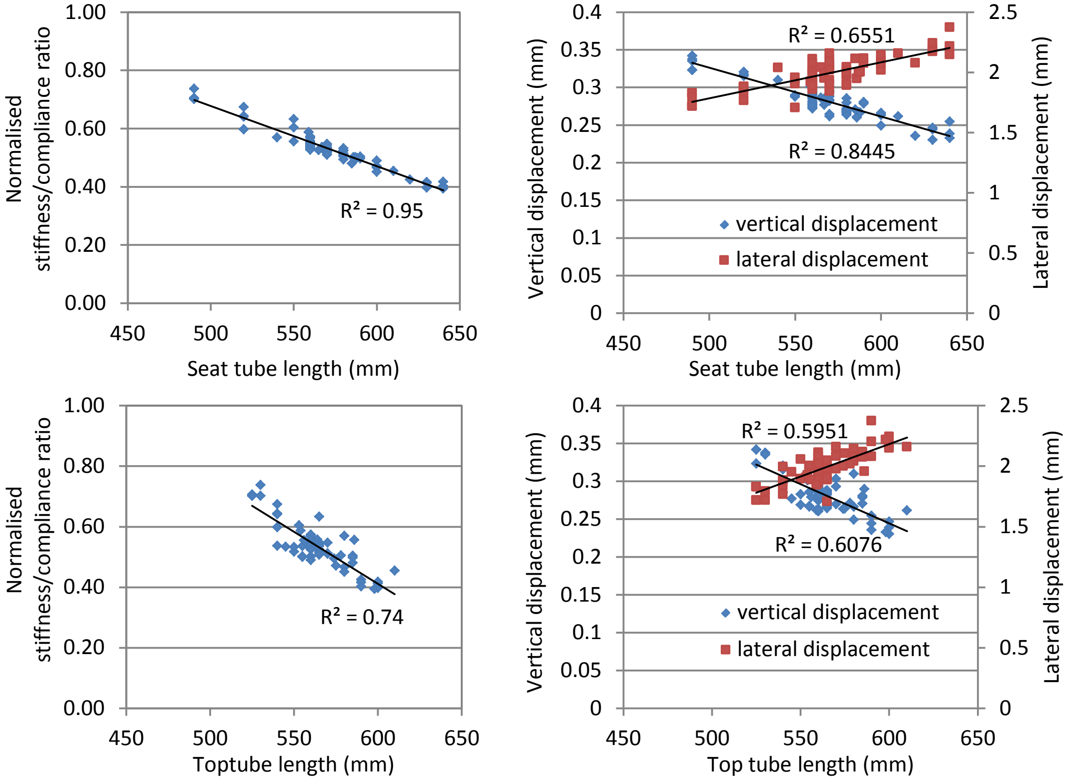

Fig. 3. Analysis of normalised stiffness-compliance ratio against seat tube length (top left) and top tube length (bottom left) and corresponding vertical and lateral displacements for the seat tube (top right) and top tube (bottom right).

There are a number of key limitations to this model. When considering the overall riding experience other components will also contribute to the vertical compliance and lateral stiffness of the bicycle (e.g. tyres, wheels, saddle, handlebars, grips). The model does not consider the anthropometric requirements of the rider which would pose constraints on the frame geometry. It does not include other frame types and does not include an evaluation of handling performance. Only two load cases were analysed and these were simplifications which didn't include varied out of plane loading conditions, or changes to the pedaling leverage during the loading cycle. Regarding the tubes, these have been simply represented using beam elements as plain gauge tubes and don't include tube butting, profile changes, changing curvature along the length, or joining methods (i.e. fillet brazed, TIG welded or lugged construction).

Regarding the materials, no consideration has been given to the strength requirements of the frames, and other common frame materials such as aluminium, titanium and carbon fibre have not been considered. The sampling techniques could be used to further develop stochastic approaches, as detailed in Jalalpour et al (2013) for other structural frame designs. This study has however focused on carrying out a comprehensive analysis specifically on the frame geometry, in order to understand the contribution of key frame parameters to the overall stiffness and compliance behaviour of the frame. The model could now be adapted to include many of the above limitations as parametric inputs to develop a fuller understanding of the physical behavior of bicycle frames.

Conclusions

This paper has outlined a FE model using beam elements to represent a standard road bicycle frame. The model simulates two standard loading conditions to quantify the vertical compliance and lateral stiffness characteristics of 82 existing bicycle frames from the bicycle geometry project and compares these characteristics to an optimised solution in these conditions. Perhaps unsurprisingly smaller frames (490mm seat tube) behave the most favourably in terms of both vertical compliance and lateral stiffness, while the shorter top tube length (525mm) and larger head tube angle (74.5°) results in a laterally stiffer frame which corresponds with findings from literature. The optimised values show a considerable improvement over the best of the existing frames, with a 13% increase in vertical displacement and 15% decrease in lateral displacement when compared to the best of the analysed frames. The model has been developed to allow for further develop to include more detailed tube geometry, further analysis of more frame geometries, alternative materials, and analysis of other structural characteristics.

References

British Standards. 2005. Mountain bicycles -Safety requirements and test methods. BS EN: 14766- 2005.

Grous, A. 2011, The British cycling economy. Retrieved 20/9/2013, from: http://corporate.sky.com/documents/pdf/publications/the_british_cycling_economy

Jalalpour, M., Guest, J., Igusa, T. 2013. Reliability-based topology optimization of trusses with stochastic stiffness. Structural Safety 43, 41–49.

Kolin, M., De la Rosa, D. 1979. The custom bicycle: buying, setting up and riding the quality bicycle. Rodale Press, Emmaus, USA.

Lessard, L., Nemes, J., Lizotte, P. 1995. Utilization of FEA in the design of composite bicycle. Composites, 26(1), 72-74.

Liu, T., Wu, H. 2010. Fiber direction and stacking sequence design for bicycle frame made of carbon/epoxy composite laminate. Materials and Design, 31(4), 1971 – 1980.

Maestrelli, L., Falsini, A., Bicycle frame optimization by means of an advanced gradient method algorithm. 2nd European HTC Strasbourg, September 31-October 1 2008.

Mann, D. 2010. Bicycle geometry project. Last accessed 20/9/13 from: http://home.comcast.net/~pinnah/dirtbag-bikes/geometry-project.html

Peterson, L., Londry, K., 1986. Finite-Element Structural Analysis: A New Tool for Bicycle Frame Design: The Strain Energy Design Method. Bike Tech: Bicycling Magazine's Newsletter for the Technical Enthusiast, Summer 1986, 5(2).

Reynolds Technology Ltd. 2011a. Steel tube materials and processes. Provided by Reynolds Technology through correspondence.

Reynolds Technology Ltd. 2011b. eReynolds Manual for eReynolds software. Provided by Reynolds Technology through correspondence.

Soden, P., Adeyefa, B. 1979. Forces applied to a bicycle during normal cycling. Journal of Biomechanics 12, 527-541.

Xiang, Z., Xu, R., Bu, Y., Wu, X., 2011. Optimal Design of Bicycle Frame Parameters Considering Biomechanics. Chinese Journal of Mechanical Engineering, vol 24, 1-5.

Xie, Y., Steven, G., 1994. Optimal design of multiple load case structures using an evolutionary procedure. Engineering Computations 11(4), 295 - 302.