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## An Assessment of Bicycle Frame Behaviour under Various Load Conditions Using Numerical Simulations

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### Abstract

This paper outlines the use of a finite element model to simulate the behaviour for a standard steel bicycle frames under a range of measured load cases. These load cases include those measured both in the laboratory setting and also in the field, and include loads transmitted at key areas such as the dropouts and hub, the bottom bracket and drive, the headset and handlebars, and the seat post and saddle. The load cases analysed include static representations of dynamic bump situations which occur sporadically and also those which occur constantly or regularly such as those generated at the drive and handlebars during climbing or cruising. The resulting stresses within the bicycle are analysed in the context of frame performance relating to static and fatigue strengths and are also compared to similar load cases presented in the literature. Further research is required to understand the influence of tube profiles on frame strength, and to analyse the modes of failure for various bicycle designs and materials used under typical and extreme usage in order to understand the implications of design on safety.

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### 1. Introduction

Bicycles are subject to a wide range of loads at various locations around the frame. The first published measurement of loads applied to a bicycle occurred in 1968 with Hoes et al [1] measuring pedalling loads using strain gauges mounted on the pedal and crank of a bicycle ergometer. Since then, loads have been measured around the bicycle at the pedals/cranks [2-19], handlebars [3,5,10,11,14,20,21], saddle/seatpost [3,5,11,15,21,22] and hubs [14,23] in the lab environment as well as outdoors (including both on and off-road conditions). Most commonly, these loads have been measured indirectly using strain gauges, with other techniques used including cinefilm analysis [3], piezo-electric force sensors [8], force platforms [17] and Hall effect force transducers [18].

Since as far back as 1986, finite element models have been used to simulate and in some cases improve the physical behaviour of bicycle frames and components [24]. A range of academic [25-33] and non-academic [34-37] literature exists outlining the use of this simulation tool to compare the performance of framesets for steel [24,28,30,31], aluminium [24,29,32], carbon fibre [25-27] and even bamboo frames [33] for static [24-31,33] and dynamic [31,32] scenarios. While some of these articles shed light onto behaviour of specific or generic frame designs, few are linked explicitly with bicycle manufacturers or provide insight into current practice in the industry and some are rather limited in their usefulness for bicycle designers.

While this provides a useful backdrop to the current practice of bicycle designers and engineers, there is clearly a considerable body of work that goes unpublished by manufacturers as a result of commercial sensitivity. Direct insights into current industrial

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practice are piecemeal and often described only loosely. In those cases where work is published or as is more common - referred to in the media, and where insufficient detail is provided for input data in models used [24,36-38] (e.g load cases designed for, boundary conditions or material properties used), or sources for input data [26] or experimental work [36-38] (including the test setup and equipment used, description of methods or actual results obtained) this makes replication of such experiments and models difficult. In 2004 it was concluded that bicycle structural analysis was in its infancy, referring specifically to the work by Peterson and Londry [24] as an example of good practice in this area [34]. While clearly there have been a handful of isolated publications on this topic that have been useful or insightful for bicycle designers since 1986, it is our opinion that the potential for rigorous, open and wide ranging studies in this area has not yet been realised in the public domain.

This article attempts to begin to piece together those articles relating to the measurement of bicycle loads and apply them to a finite element simulation of a standard road bicycle frame in order to provide some context for frame performance relating to stress distribution and quasi-static and fatigue strengths. While we have focused our attention here on a single road bicycle frame, the intention is for the application of this work to be extended to a wider range of road frames as well as other common bicycle types, e.g. mountain bikes, commuter bicycles, and folding bicycles.

## 2. Methods

A 3D linear elastic finite element model was constructed using 812,481 solid 8-node curvilinear tetrahedral elements (element between 0.5- 2 mm) to represent a standard road bicycle frame as shown in Fig. 1 below. This figure presents details of the frame and tube geometries (centre-to-centre tube lengths, angles, outside diameters, wall thicknesses) and the zones which were used for the analysis in this study, with fillets at all joints assumed to have a radius of 4 mm, and all tubes are plain gauge with no butted sections.

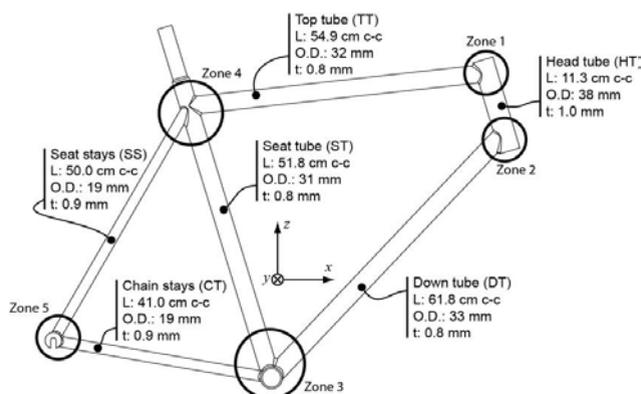


Fig. 1. Details of the frame/tube geometries for the road bicycle frame analysed in this study (head tube angle  $XX^\circ$ , seat tube angle  $YY^\circ$ ).

The types of loads were categorized into four load cases and these were: a road bump at the front wheel (LC1 – based on [23]), a road bump at the rear wheel (LC2 - based in LC1 to allow for a direct comparison with the front wheel bump case), climbing whilst seated in the saddle (LC3 – based on [11-12]), and climbing whilst not seated in the saddle (LC4 – based on [10,12,14,20,23]). The free body diagram for these load cases are depicted in Fig. 2. These loads applied in the model were based on measurements presented in the literature for a rider of 75 kg or similar, since the loads measured between publications varied widely depending on the mass of the rider. Boundary conditions in the form of loads and restraints were applied to the various locations around the bicycle (bottom bracket, steering tube, seat post, front/rear axles as shown in Fig. 2) using a rigid link which eliminated the need to include superfluous components such as the saddle, handlebars, wheels, cranks and bearings. Furthermore, the bottom bracket, steering tube and seat post were simulated here as 2 mm thick tubes with solid front/rear axles and bearings all with fixed contact to the frame/fork apart from the dummy crank which was free to rotate within the bottom bracket, to provide a simple yet repeatable means for load transfer to the respective areas of the frame. Material properties assigned to all components were those of steel ( $E=205$  GPa,  $\nu=0.29$ ).

## 3. Results

The regions of high stress on the bicycle under various load cases can be seen in Fig. 3. Below, with the corresponding stress (and relative stress) values shown in Table 1. The front wheel load (LC1) induces a maximum Von Mises stress of 228 MPa in the welded joint area at the top of the top tube/head tube junction, and also in the welded joint area underneath the down tube/head tube junction (224 MPa). The rear wheel load (LC2), induces a maximum stress of 268 MPa on the underside of the top tube near the down tube, and also above this in the welded joint at the top of the top tube/seat tube junction (260 MPa), with a high stress (253 MPa) also recorded in the welded joint area at the top of the top tube/head tube junction as in the case of LC1.

These are the highest stresses recorded in any of the load cases simulated for this study and are also the least common loads that the bicycle would be subjected to. Perhaps the most common loading scenario (LC3) induces the lowest stresses of all the load cases simulated with a maximum of only 84 MPa located on the outside of the chain stays near the bottom bracket. Much higher stresses are noted for the out of saddle climbing load case (LC4), with 227 MPa located again on the outside of the chain stays near the bottom bracket.

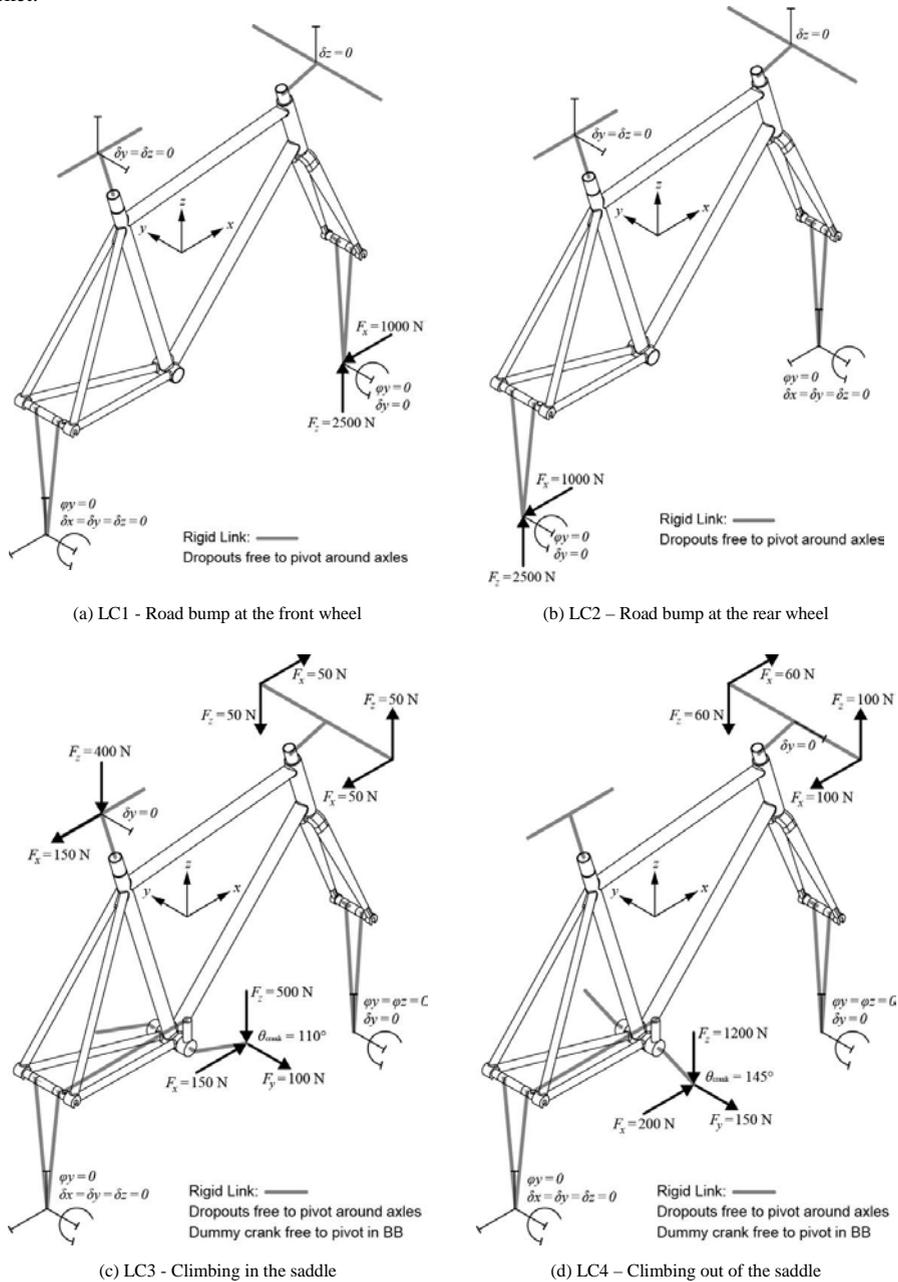


Fig. 2. Free body diagrams for the four load cases simulated in this study, based on measurements presented in the literature. Note  $\theta_{crank}$  is measured anti-clockwise from the vertical z-axis.

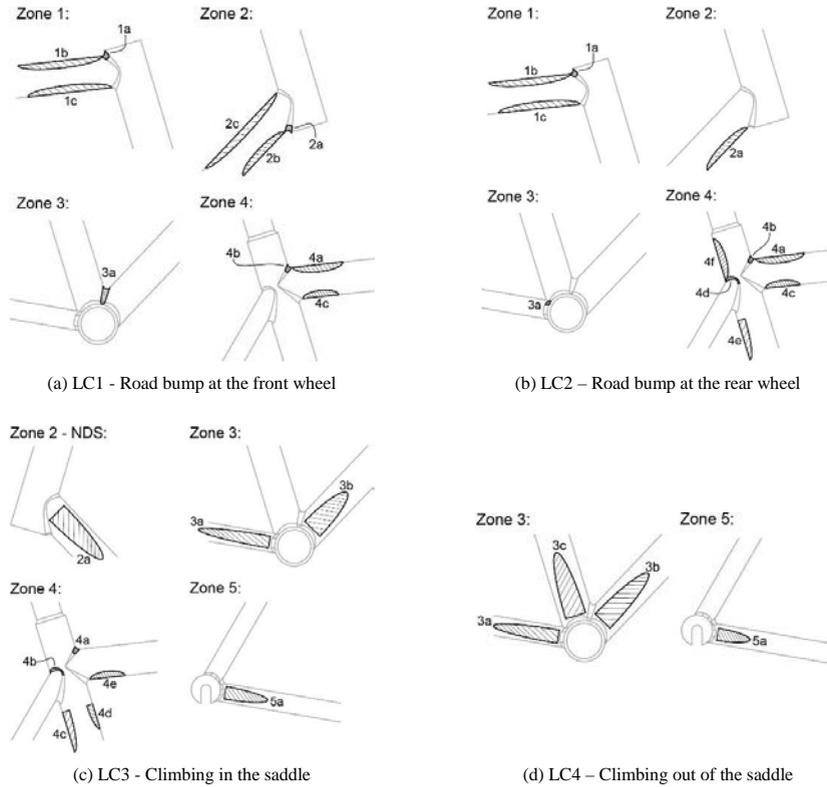


Fig. 3. High stress regions zones around the bicycle with relative stresses above 0.4 for each load case.

Table 1. A full breakdown of absolute and relative stresses for four out of the five zones showing only regions with relative stresses above 0.2 with respect to the maximum stress for that load case. Note that NDS is the Non Drive Side.

LC1			LC2			LC3			LC4		
Zone	VM Stress (MPa)	Relative Stress Level	Zone	VM Stress (MPa)	Relative Stress Level	Zone	VM Stress (MPa)	Relative Stress Level	Zone	VM Stress (MPa)	Relative Stress Level
1a	228	1.0	1a	253	0.9	2a	37	0.4	3a - RO	227	1.0
1b	168	0.7	1b	200	0.7	3a - RO	84	1.0	3a - RI	103	0.5
1c	200	0.9	1c	205	0.8	3a - RI	43	0.5	3a - LO	163	0.7
2a	224	1.0	2a	159	0.6	3a - LO	68	0.8	3a - LI	139	0.6
2b	179	0.8	3a - R&L	150	0.6	3a - LI	57	0.7	3b - DS	123	0.5
2c	122	0.5	4a	180	0.7	3b - DS	53	0.6	3b - NDS	83	0.4
3a	124	0.5	4b	260	1.0	3b - NDS	46	0.5	3c	106	0.5
4a	87	0.4	4c	268	1.0	4a	50	0.6	5a - RI	180	0.8
4b	117	0.5	4d	178	0.7	4b	50	0.6	5a - LI	101	0.4
4c	126	0.6	4e	146	0.5	4c	43	0.5			
			4f	130	0.5	4d	51	0.6			
						4e	51	0.6			
						5a - RI	68	0.8			
						5a - LI	43	0.5			

#### 4. Discussion

An interesting finding for LC3 and LC4 (both out of plane load cases) was that the chain stays have relatively higher stresses on the side rather than on the top or bottom (at both the bottom bracket and rear dropout ends). Since the sections used in this study were circular, a logical design improvement for this would be to increase the lateral width of the chain stays at both ends, whilst reducing their vertical depth. Since the design space in this area on the drive side is particularly limited, clearly widening the chain

stays in this area is not feasible (due to tyre clearance and the rotational motion of the crank). However, reducing the vertical depth of the chain stays is feasible, yet current trends in frame design indicate a move towards increased vertical depths for chain stay profiles in both metallic and composite material options which may be a means to compensate for the reduced strength effects of having laterally thinner chain stays at the expense of vertical frame compliance. Further analysis is required to understand such effects based on existing profiles for chain stay tubes.

In comparing stresses for similar simulated load cases presented in the literature, the highest stresses for the out of saddle climbing load condition in [24] were located in the lower section of the seat tube (352 MPa), and in [3] were located in the down tube and chain stays (300-400 MPa) while in this study they were somewhat lower and located on the outside of the chain stays at the bottom bracket end (227 MPa). While generally the areas of high stress for this load case both simulations are similar, it does highlight the differences that result from variations in load case (e.g. crank angle, gear ratio, force magnitude) and frame design (tube sizes and frame angles) and in some cases there is insufficient details available to replicate load cases used in the literature.

Relatively, the zones with highest stresses existed at the various joints around the bicycle in all load cases apart from LC4 (climbing out of the saddle). Since the actual strength of the welded joint may be variable between manufacturers and frame builders this may have significant effects on performance governed by design criteria and specifications for bicycles with high strength materials. Furthermore, if one considers the fatigue strength of such materials then for cyclic loading which is most prevalent for LC3 and LC4 the fatigue strength after 10 million cycles is unlikely to exceed 900 MPa [39]. For comparison, 500 million cycles is typically used for aluminium bicycles [24], while some standards require testing for cyclic loading to be conducted through only 100,000 cycles [40]. This is the limit for an example high strength maraging steel [39] which is comparable in terms of strength properties to those published by the manufacturers (i.e. UTS approx. 2 GPa [41]) and is considered to be an extreme upper limit for materials used in bicycle applications where in practice the value will be somewhat below this value. Furthermore, fatigue strength would be expected to be in the region of 325 MPa or lower for a chromoly or low alloy steel tube which has a tensile strength of 650 MPa [39], and lower still for aluminium alloys which are typically limited to 165 MPa [24,39]. While not discussed as part of this paper, it is interesting to note for comparative purposes the maximum tensile strength for ultra-high modulus carbon fibre is 2.4 GPa, with a fatigue strength of 1.92 GPa [39], while the maximum tensile strength of titanium 1.63 GPa which has a maximum fatigue strength 600 MPa [39].

It was interesting to note that high stress zones in some cases existed in the transition area for the butted tubes, highlighting their importance in distributing the loads within the tubes, but also indicating that high stress zones are not restricted solely to the joint itself. Conversely, particularly low stresses are noted in the seat stays, indicating that it may be possible for the distribution of loads to be further improved not just within tubes, but between adjacent tubes. In LC2 and LC3 relatively high stresses were noted in the seat tube corresponding with the end of the seat post which provides additional stiffness in the top section of the seat tube. With tube walls reducing down to 0.3 mm in some tubes (e.g. Reynolds 953), this increases the potential for a buckling failure mode to be introduced to longer tubes in addition to the ductile fracture due to high stresses and fatigue failure modes. Further research is required to analyse the modes of failure of various bicycle designs during typical and extreme usage in order to understand the implications of design on safety. In the first instance for metallic bicycles, the influence of the material strength, stiffness and joining methods such as TIG welding, fillet brazing, lugged construction methods, and even the use of adhesives that are available for the variety of steel, aluminium and titanium tube sets can be analysed for their influence on design behaviour related to safety. This type of analysis would be most powerful when coupled with experimental results to investigate the statistical variability associated with the properties of such techniques across various materials, equipment setting, and manufacturers.

There are a number of limitations for the present study, including the fact that the model does not include the presence of realistic bearing conditions, and it represents dynamic peak forces (LC1 and LC2) as static loads and as such does not take into account the propagation and damping of vibrations through the frame as would be expected in such real world situations. This paper presents the findings of our first preliminary effort to systematically analyse various key design parameters on the strength performance of bicycles. While the simulations in this study accounted for only plain gauge tubing, the model has been developed to accommodate butted profiles as standard parametric options for a variety of manufacturers' tube sets that are available on the market, with standard geometric frame inputs (e.g. tube lengths, angles), and a variety of key load cases also applied in this manner.

#### 4. Conclusions

A finite element model was created to simulate the behaviour of a standard steel bicycle frame under a range of measured load cases from both in the laboratory setting and also in the field as presented in the literature. Highly stressed areas correlate reasonably well in terms of being similarly located with those simulations presented in the literature for similar load cases, although our values tend to be somewhat lower than the maximum presented elsewhere, and precise details of load cases is in some publications not complete. Further research is required to understand how tube profiles, selection and load distribution between tubes can be used to influence frame strength, and to analyse the modes of failure for various bicycle designs under typical and extreme usage in order to understand the implications of design on safety.

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