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## Parametric finite element analysis of steel bicycle frames: the influence of tube selection on frame stiffness

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### Abstract

This paper presents a parametric Finite Element model of road bicycle frames using beam elements with varying tube profiles. A range of existing frame geometries were subject to various in plane and out of plane loading conditions to examine the influence of tube profiles (as published by the Reynolds, Columbus and Tange manufacturers) on the lateral stiffness and vertical compliance of the frames. This was an extension of previous work which characterised the influence of overall frame geometries (tube lengths and angles) on the stiffness characteristics of frames. For a subset range of frame sizes (with seat tube lengths varying from 490-630mm), parameters were used to define dimensions for circular tube profile shapes, varying wall thicknesses associated with butted tubes. In this paper only steel tubing was considered in order to isolate and focus in detail on the influence of the tube profile geometries on the stiffness characteristics of the frames for a single material. Further work is required to validate this model using a frame stiffness jig and to characterise the influence of material choice on the stiffness and strength characteristics for steel, aluminium and titanium frames using commercially available tubesets and their published stiffness and strength values.

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## 1. Introduction

From a sports engineering perspective, the literature relating to bicycles varies widely and includes the biomechanics and physiology of cycling (Burke, 1994 [4]; Burke 2003 [5]), design requirements and manufacturing technology of bicycles (Ballantine, 2000 [1]; Burrows, 2008 [6]; Reynolds Technology Ltd., 2011a [20]), injury prevention and safety of cyclists (British Standards. 2005a [2]; British Standards. 2005b [3]) development of specialist measuring equipment for bicycles (Soden and Adeyefa, 1979 [22]; McKenna et al, 2002 [15]; Oertel et al, 2010 [17]; Petrone et al, 2012 [19]; Vanwalleghem et al, 2012 [25]; Vanwalleghem et al, 2014 [26]) simulation of bicycles and bicycle components (Peterson and Londry, 1986 [18]; Xie, 1994 [28]; Lessard et al, 1995 [11]; Maestrelli and Falsini, 2008 [13]; Liu and Wu, 2010 [12]; Tak et al, 2010 [24]; Xiang et al, 2011 [27]; Covill et al 2014 [7]; Kingsley et al 2015 [9]), and the ergonomic and anthropometric requirements of cyclists (Kolin and De la Rosa, 1979 [10]; Burke, 1994 [4]; Stevens, 2006 [23]; Mann, 2010 [14]; Moore et al 2010 [16]; Hsaio and Ko, 2013 [8]). Performing Finite Element (FE) analysis on bicycle frames has become a common activity for bicycle designers and engineers in the hope of improving the performance of the frames. This is typically achieved by balancing priorities for key idealistic 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.
- Adjusting the vertical compliance of the frame to tune the softness of the ride.
- Maximising the strength capabilities of the frame to allow for a higher load capacity or better load distribution.

This paper presents a parametric FE model of road bicycle frames using beam elements with varying tube profiles. A range of existing frame geometries were subject to various in plane and out of plane loading conditions to examine the influence of tube profiles (as published by the Reynolds, Columbus and Tange manufacturers) on the lateral stiffness and vertical compliance of steel frames. Previous work in this area focused on characterising the influence of overall frame geometries (tube lengths and angles) on the stiffness characteristics of frames, and as such this paper focuses on extending this work to analyse the influence of the steel tube sets available on the market to commercial frame builders and designers. The intention here is to develop a parametric model that can be driven using a single spreadsheet to control parametric changes to the frame geometry and individual tubes based on commercially available options to understand how changes to these parameters influence stiffness, compliance and ultimately strength characteristics of a frame.

## 2. Finite element model description

The FE model presented in this paper comprises 317 beam elements to represent a steel road bicycle frame (including road, audax and touring options), including key tube lengths and angles and an idealised geometry for stem/handlebars, bottom bracket and forks. The load and boundary conditions for two load cases (a vertical saddle load condition and lateral out of saddle load condition) were taken from Maestrelli and Falsini (2008) [13] and Covill et al (2014) [7]. Beam element sectional properties for top tube, down tube, seat tube, seat stays, and chain stays were taken from the tube profiles published by the manufacturers Reynolds (953, 853, 725, 631, 525 tubes), Columbus (XCR, Spirit, Life, Zona tubes) and Tange (Superlight, Ultra Strong, Infinity tubes). The model accounts for single, double and triple butting of the tubes (where the inner section of the tube varies along the length to allow for thicker sections at the joint) by separating the tubes into three separate beams with discrete sectional properties.

The FE model was firstly used to analyse the influence of the 12 different tube profiles (as they vary in their individual sectional properties) for a single 56cm road frame geometry on the lateral stiffness and vertical compliance characteristics of the frame using the displacement of the bottom bracket as an indicator for both using the standard load cases described above (i.e. a small lateral displacement corresponds with a high lateral stiffness and a large vertical displacement corresponds with a high vertical compliance). The sensitivity of the stiffness and compliance behaviour was assessed by using a benchmark tube set (Columbus Spirit) then isolating individual tubes which were then varied across the 12 options from the various manufacturers.

Secondly, the model was used to analyse the influence of the 12 tube sets on the lateral stiffness and vertical compliance behaviour across a range of frame sizes from 48-64cm for a single Trek road frame model. These would also be compared to an optimum steel frame solution whereby the best performing individual tubes from any of the manufacturers could be combined into a single, high performing frame.

### 3. Results and discussion

#### 3.1. Effects of tube profile properties on vertical compliance and lateral stiffness

The effects of the various individual tube profiles for the 12 tube types on the lateral stiffness and vertical compliance can be seen below in Figure 1. These graphs show the lateral displacement (for the out of saddle lateral load case) and vertical displacement (for the vertical seat load case) plotted against the second moment of area for each of the tubes, noting that the tubes have been considered as circular so the second moment of area for in plane and out of plane load cases are equivalent and if the tubes were butted the largest of the second moment of area values was used here. Clearly for the out of plane load case, the dominant tube is the down tube whereby the lateral displacement can vary by up to 71% simply by changing the down tube from Reynolds 853 (lowest stiffness) to Columbus Life (highest stiffness), while in the vertical load case the seat stays can have a significant effect on the vertical compliance of the frame with only a relatively small change in sectional profile compared with other tubes.

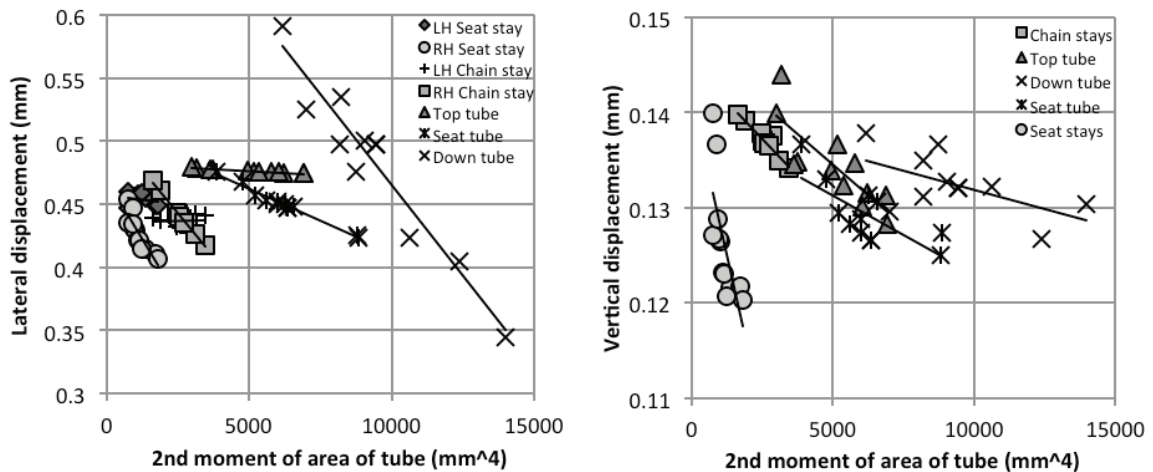


Fig. 1. Lateral stiffness (left) and vertical compliance (right) behaviour for various tube profiles when plotted against their sectional 2<sup>nd</sup> moment of area values.

Figure 2 below shows the stiffness-compliance ratios (i.e. lateral displacement in out of plane load case divided by vertical displacement in in-plane load case) that have been normalized against the optimum steel frame solution which included the best performing individual tubes from any of the manufacturers combined into a single, high performing frame. Here the largest contributors to this particular performance measure are the down tube, right hand seat stay and top tube with stiffness-compliance ratios varying by 62%, 19% and 11% respectively (when comparing lowest to highest values for these particular tubes). This is consistent with the findings of Peterson and Londry (1986) [18] which highlighted that for vertical impact load cases the seat stays absorb the largest proportion of total strain energy, while in the out of plane (hill climb) load case the down tube is the main contributor.

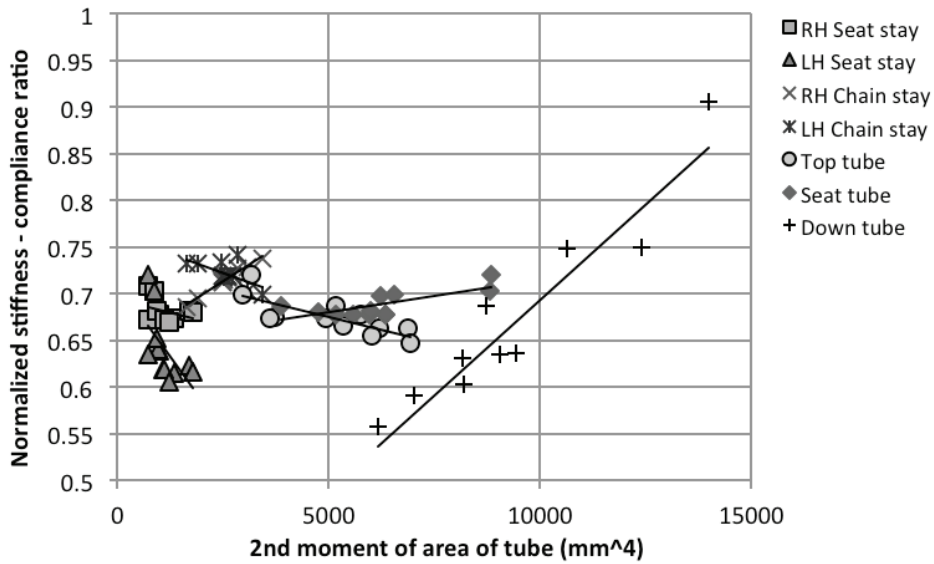


Fig. 2. Normalised stiffness – compliance ratios for various tube profiles vs with their sectional 2<sup>nd</sup> moment of areas when compared with the highest performing combination of tube options from the various manufacturers.

Table 1 below shows the highest performing individual tubes for a single 56cm frame geometry. This is the combination of tubes that has been used as the benchmark against which the other data in Figure 2 above has been normalised since it performs considerably better than any single tube set option.

Table 1. Highest performing individual tubes for the stiffness-compliance ratio for a single 56cm frame geometry.

Top tube	Down tube	Seat tube	LH Seat stay	RH seat stay	LH chain stay	RH chain stay
Reynolds 953	Columbus Life	Columbus Life	Columbus XCR	Columbus XCR	Columbus XCR	Tange Ultra Strong

### 3.2. Effects of tube set on frame stiffness and compliance

Figure 3 shows that the highest performing tube sets were the Columbus Life for the smaller frame sizes, while for the larger frame sizes it was the Columbus XCR range. This graph also highlights the trend that the smaller frames have a higher performance measure than larger frames, since the smaller frames are inherently more stiff laterally and also more compliant vertically than larger frames which was also found in other studies such as Covill et al (2014) [7].

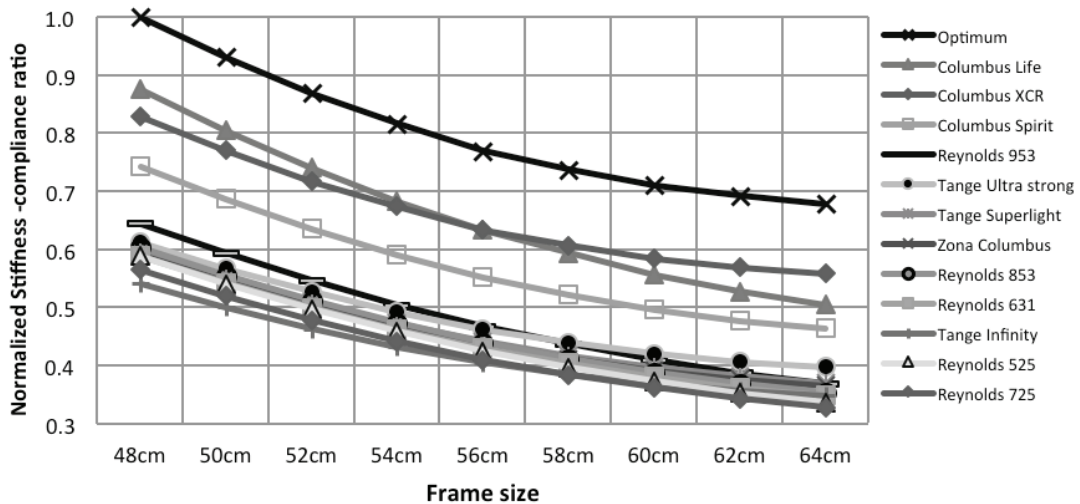


Fig. 3. Stiffness-compliance ratios for a range of frame sizes using the 12 different tube sets when normalized against the highest performing set of tubes.

The FE model presented here has been developed to allow for parameters to be driven using a single spreadsheet, including parameters for all key frame tube lengths and angles, using drop down menus for the commercially available tube sets as outlined above. Currently the model includes only the two load cases outlined above, but the intention is to also include further load cases as standard parametric inputs as outlined by Soden and Adeyefa (1979) [22], Peterson and Londry (1986) [18], Lessard et al (1995) [11], Maestrelli and Falsini (2008) [13], and Vanwalleghem et al (2014) [26] as well as customisable load cases at all frame joints. Validation of this model is also required, and the next steps for this project are to use jigs such as those developed by Vanwalleghem et al (2014) [14] to evaluate the models against measured frame stiffness values in various load cases as outlined above. The overall intention is for this model (and the open access publication of validated simulation results) to be a useful tool for frame builders and bicycle designers to understand the role of tubeset and material choices on overall frame performance.

#### 4. Conclusions

This paper has included an analysis of commercially available steel tube sets on the stiffness characteristics of bicycle frames. This parametric model can be driven using a single spreadsheet to control parametric changes to the frame geometry and individual tubes based on commercially available options to understand how changes to these parameters influence stiffness, compliance and ultimately strength characteristics of a frame.

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