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Development of a multi-directional rating test method for bicycle stiffness

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Abstract

The methods for determining the bicycle frame stiffness exist in many forms. Because the measuring method is not standardized, each bicycle magazine or bicycle constructer uses his own test setup. This leads to a wide variety of setups; they differ in many aspects such as applied load, boundary conditions and frame deflection measurement. To clarify some misunderstandings in frame testing, a multi-directional rating test method for bicycle frame stiffness has been developed. Prior to testing the stiffness of different frames it is important to assess the confidence limits of the stiffness result. This includes (i) the contribution of the test bench due to its non-zero compliance, (ii) the influence of mounting the frame in the test bench with a certain preload, (iii) the errors related to the force-and displacement measurement and finally (iv) estimating the influence of experimenter This sensitivity analysis on the test bench already led to a better understanding of frame stiffness testing, and which minor modifications can lead to major differences in stiffness values.

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Bicycle; stiffness; test method; measuring errors

1. Introduction

High bicycle frame stiffness is found to be important for professional cyclists because it allows for maximal propulsion and avoids energy loss due to bicycle frame compliance. In bicycle industry it is accepted to use bracket- and torsion stiffness as quantities to assess the mechanical stiffness of a bicycle frame. To the authors' best knowledge, there is no open scientific literature available on bicycle frame stiffness testing. However, test services are provided by Zedler (2013) or EFBe (2013), individual bicycle designers as Cervélo (2013) and Specialized (2013) have developed test configurations themselves. Due to lack of standardization in bicycle frame stiffness testing, many different bracket- and torsion test configurations have been developed by test centres,

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bicycle manufacturers and bicycle magazines. They differ each in (i) how the load is applied, (ii) how the frame deflection is measured and (iii) how the frame is supported. Each of these test setups results in other stiffness values for the same frame type which makes comparison among bicycles impossible.

Therefore, this paper attempts to meet the question on how a universal stiffness test bench can be designed, taking different aspects into account as (i) the implementation of boundary conditions, (ii) applying a representative force on the frame and (iii) measuring the frame deflection.

2. Proposal of a multi-directional test bench for stiffness testing

In this paper it is chosen to test the frame itself, without using the front fork. The frame is positioned in the test bench such that the head tube angle corresponds with the normal cycling situation. The frame head tube should be able to rotate and is prevented to move in the in-plane translational directions when mounted in the test bench. Depending on the test configuration other boundary conditions apply as well.

Applying a general load on the frame only gives limited information about the stiffness quality of a frame. Subdividing this load in its main components (both force and torque) and measuring the corresponding frame deflection allows for drawing conclusions about the directional stiffness of the frame. As such is information available about (i) the frame's directional stiffness or (ii) the contribution from the front- and rear triangle stiffness can be distinguished from the global frame stiffness. Based on these results, the bicycle constructor can adopt the bicycle design depending on the needs of the cyclist. It can be argued that these individual force components do not represent the real frame loading on the frame and consequently the measured stiffness is not representative. However, with combined loading the frame deforms in multiple directions simultaneously, hence making stiffness analysis not straightforward. Based on these arguments, three different test configurations have been selected to quantify the frame stiffness.

2.1. Bicycle stiffness test configurations

The first measuring configuration is the in-plane frame stiffness, depicted in Fig. 1.a. The frame is fixed at the head tube, preventing any in-plane motion ($U_{x'}$, and $U_{z'} = 0$); the load F_z is applied vertically at the bottom-bracket or at the rear dropouts. The in plane deflection U_x and U_z is measured at the bottom-bracket or the rear-dropouts respectively. Applying the load either at the bottom-bracket or at the rear-dropouts allows assessing the contribution of the front triangle to the total in-plane frame stiffness.

The transversal stiffness measures the frame's resistance against transversal loading (Fig. 1.b) The rear axis is supported preventing transversal translation ($U_y = 0$) and the transversal frame deflection is measured at the bottom bracket. Some frames have an asymmetric rear triangle geometry, but by loading the frame in b0tu directions it is possible to check for stiffness differences at both sides.

The third test configuration is the eccentric stiffness (Fig. 1.c). This test configuration mimics closely to the pedal force, the load is applied off-center, resulting in both a torque and force at the bottom bracket. The resulting deflection is constituted of both a rotation and a vertical displacement. Depending on the loading direction is only the front triangle or both the front- and rear triangle loaded. Aligning the force vertically (cf. F_z in Fig. 1.c) gives the resultant torque T_X, consisting of $T_{X'}$ and $T_{Z'}$ giving respectively the elastic torsional loading $T_{X'}$ around the head tube and the rigid body rotation along the head tube axis z'. The latter requires transversal support at the rear dropouts (U_Y=0). If one is interested in the resistance against torsion of the front triangle only one should align the force with the z'-axis. This introduces an elastic torsional loading $T_{X'}$ around the head tube, without the rigid body rotation, transversal restriction (U_Y=0) is not necessary anymore.

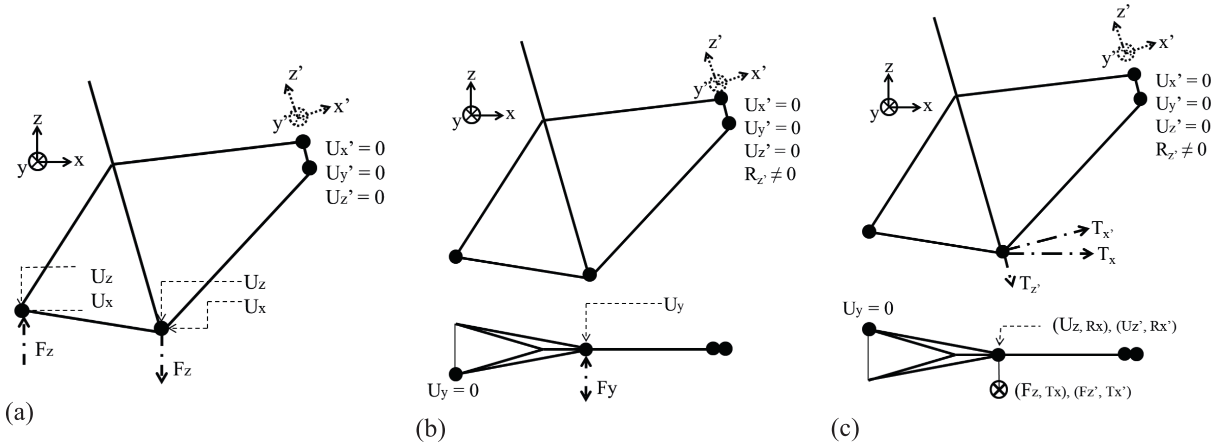


Fig. 1 Stiffness configurations. (a) in-plane bottom-bracket and rear-dropout stiffness; (b) bi-directional transversal stiffness; (c) eccentric stiffness, with vertical (Fz) and head-tube aligned force (Fz')

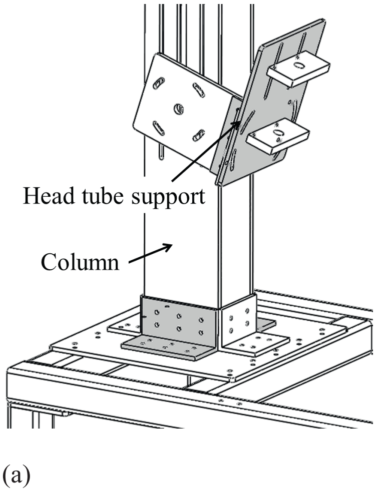
2.2. Materials and methods

The bicycle frame is loaded with pneumatic actuators which are controlled by pressure regulators. The push- and pull force applied by the pneumatic actuators is measured with ±5 kN range force transducers whereas the frame deflection is measured with ±5 mm range spring return linear variable differential transducers (LVDT). The analog input voltages from the force transducer (±10 V) and displacement sensor (±10 V) are acquired with NI hardware and are sampled at the same time base. All tests in this work are assessed on one single frame, a carbon fibre reinforced composite racing bicycle frame from Eddy Merckx Cycles, EMX- 1, size 51, year 2012.

3. Sensitivity analysis of the test setup for frame stiffness testing

3.1. Test bench compliance

Preceding the actual frame stiffness measurements, the compliance of the test bench should be measured. This is necessary to estimate its relative influence on the bicycle frame stiffness. The in-plane bottom-bracket stiffness configuration (Fig. 1.a, force F_Z at bottom bracket) is selected for this analysis. From initial tests it already resulted that the head tube support has a major contribution in the test bench compliance and the column tends to bend over (Fig. 2.a). This information has led to some well-reasoned modifications to the test bench, depicted as the grey areas in Fig. 2.a and Fig. 2.b respectively before and after the reinforcement: (i) additional profiles are welded at the base construction near the column base; (ii) larger L-profiles at each side fix the column to these profiles and (iii) the plate at the head tube support holding the two clamping blocs is thicker and shorter to enlarge the geometric bending stiffness.



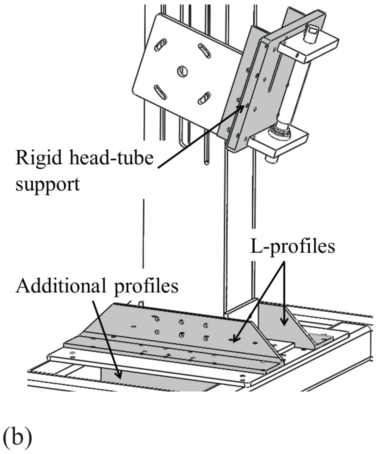


Fig. 2 Test bench modifications for compliance reduction. (a) head-tube support before reinforcement; (b) head tube support after reinforcement.

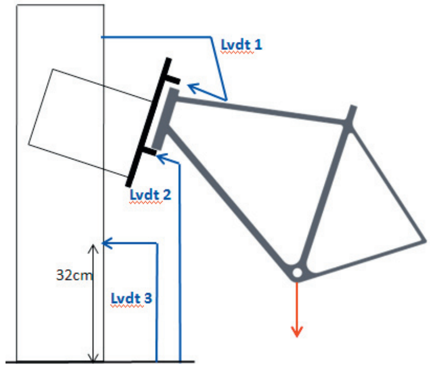


Fig. 3 Loading- and measuring setup for test bench compliance before and after reinforcement

The test bench deflection before and after the reinforcement is measured at three locations (Fig. 3), LVDT 3 is a measure for the column compliance, LVDT 1 and LVDT 2 are located at the head tube fixation part. The results in Table 1 show that reinforcing the test bench had led to a test bench which is on average 20 times stiffer, e.g. the compliance at LVDT 1 has reduced from $51.0 \cdot 10^{-5}$ mm/N to $2.07 \cdot 10^{-5}$ mm/N. The relative influence of the test bench compliance on the frame deflection was estimated at 23 % originally, the influence is expected to be less than 2 % after the reinforcement.

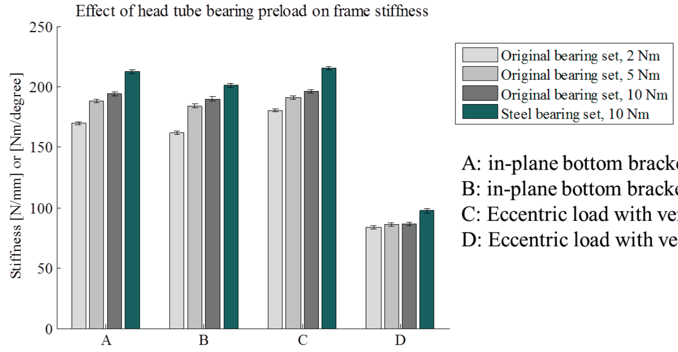
Table 1 Test bench compliance before and after reinforcing the test setup

Test bench compliance (x 10^{-5}) [mm/N]		
	Before reinforcement	After reinforcement
LVDT 1	51.0	2.07
LVDT 2	13.0	1.58
LVDT 3	15.9	0.85

3.2. Head tube bearing set: preload

In analogy with the frame-front fork assembly a steel shaft is positioned through the upper and lower head tube bearing, and then the bearing is preloaded till an appropriate torque with a torque wrench. Two types of bearing sets have been chosen, the first is the original bearing set as delivered with the frame-front fork assembly whereas the second type is a steel replica from the original one. For the original bearing set three preload magnitudes have been selected, namely 2 Nm (this is the prescribed torque), 5 Nm and 10 Nm, the steel replica is tightened with a preload of 10 Nm. Once the shaft and the bearing set are positioned in the head tube, the frame is positioned in the head tube support. Two clamping blocks tighten the head tube shaft with a torque of 100 Nm.

Two test configurations have been selected for this sensitivity analysis, the in-plane bottom bracket stiffness and the eccentric vertically aligned load stiffness. From the four stiffness measurements given in Fig. 4 (A, B, C and D) yields that the stiffness increases with a higher preload torque, and the steel bearing set shows the highest stiffness value. This effect is most pronounced for the vertical and horizontal stiffness component, the torsion stiffness is less sensitive to this effect. It can be concluded that both the preload torque and bearing type have a significant contribution to the frame stiffness. As it is preferred to measure the frame stiffness only, and minimise external influences it is chosen to use the steel bearing set for the in-plane stiffness configuration and the original bearing set for the other test configurations. Test configurations which require frame rotation need a bearing seat anyway, thus it is the best option to use the bearings delivered with the frame-front fork assembly and preload with the prescribed torque of 2 Nm. Using the steel replica is not an option because the increased torsion stiffness (configuration D in Fig. 4) has nothing to do with the bicycle frame but it is related to the friction at the head tube.



A: in-plane bottom bracket, vertical stiffness component.
B: in-plane bottom bracket, horizontal stiffness component.
C: Eccentric load with vertical aligned force F_Z, vertical stiffness component.
D: Eccentric load with vertical aligned force F_Z, torsion stiffness component

Fig. 4 Effect of head-tube bearing preload on frame stiffness.

3.3. Hysteresis: friction in pulley mechanism

Stiffness testing requires measuring both displacement and force. Although a static force is relatively easy to measure, when using pulley mechanisms it is observed that a considerable amount of friction disturbs the force measurement. The transversal stiffness configuration uses a pulley to change the loading direction from the pneumatic actuator, as illustrated in Fig. 5.a. The applied load F_2 causes the structure to deform in the direction U_2, hence the pulley friction force is pointed as F_3. This yields that the measured force F_1 is larger than the applied force at the test structure. Analogue reasoning is valid during unloading; U_2 points in the opposite direction giving that the reaction force F_2 is larger than F_1. This inevitably leads to hysteresis when plotting F_1 versus U_2. Because of this reason it is necessary to measure the force F_2, acting on the bicycle frame.

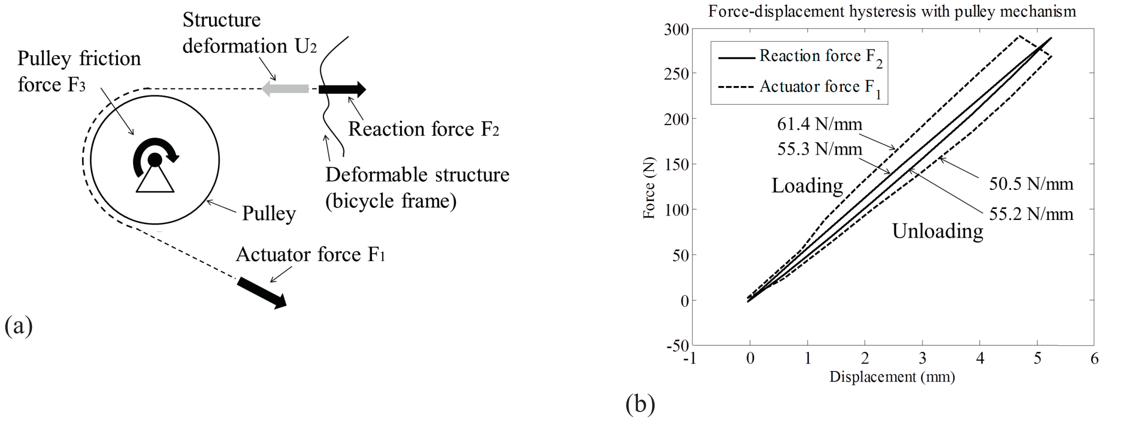


Fig. 5 Pulley mechanism for transversal stiffness configuration.(a) action- and reaction forces; (b) force-displacement hysteresis with pulley mechanism

Fig. 5.b plots the loading and unloading force-displacement curve for both the actuator force F_1 and the reaction force F_2, respectively in dashed and solid line format. The area enclosed by one curve is a measure for the amount of friction in the test configuration. The pulley mechanism adds a significant amount of friction, resulting in a large

stiffness difference between loading and unloading. This is not observed when virtually eliminating the pulley mechanism through using the reaction force at the bicycle frame. The area between the loading and unloading part of the curve is due to friction at the head tube bearing and the transversal support at the rear dropouts (Fig. 1.c).

3.4. Stiffness confidence interval

Drawing conclusions on frame stiffness measurements only is valid if the accuracy of the test setup is known. To include errors related to (i) positioning the frame in the test bench, (ii) preloading the bearings in the head tube and (iii) aligning the pneumatic actuators and displacement sensors, it is chosen to dismount the frame five times and reposition the actuators and transducers. From this data set, the mean value and the 95 % confidence interval (CI) are calculated, the 95 % CI limits are then expressed in percentage deviation from the mean value (Table 2). This percentage value will be used to determine the CI on the mean stiffness value from future measurements; this speeds up the tests without giving in reliability on the executed tests. The 95 % CI is within 2 % of the mean value for all test configurations. This small value is necessary to detect small differences between frames mutually, or between different test configurations.

Table 2 Reliability of the stiffness result from different test configuration, given as the 95 % confidence interval

Test configuration	Stiffness component		95 % CI for mean value	% CI on mean value
In plane stiffness, bottom bracket	Vertical	[N/mm]	(277.1 ; 281.3)	0.76
	Horizontal	[N/mm]	(262.1 ; 266.9)	0.92
In plane stiffness, rear dropouts	Vertical	[N/mm]	(83.6 ; 84.0)	0.24
	Horizontal	[N/mm]	(162.9 ; 165.4)	0.76
Transversal stiffness			(55.5 ; 57.8)	2.09
Eccentric load F_Z, vertical aligned	Torsion	[Nm/degree]	(92.0 ; 94.7)	1.44
	Vertical	[N/mm]	(193.0 ; 196.0)	0.76
Eccentric load $F_{Z'}$, aligned with head tube	Torsion	[Nm/degree]	(84.8 ; 87.9)	1.77
	Vertical	[N/mm]	(118.1 ; 119.8)	0.70

4. Conclusion

This work proposes a multi-directional rating test method for bicycle stiffness testing. But, prior to drawing conclusions on frame stiffness mutually it is important to assess the accuracy limits of the test bench. This includes (i) how the frame is loaded, (ii) which boundary condition is used and (iii) how the deflection is measured. Initial results have shown that the test bench compliance should be orders of magnitude lower than the frame deflection itself. Reinforcing the test bench has led to a frame stiffness increase of 25 %. Besides this it is found that the head tube bearing set preload has a significant influence on the frame stiffness and from comparison with steel replicas of the head tube bearings it results that the original bearings contribute to the frame stiffness as well. Also wrong force measurements when pulley mechanisms are used have been explained and a solution is proposed. The result is a test bench which has an accuracy of less than 2 % on the measured stiffness value.

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