PLASTIC BICYCLE FRAME DESIGN AND CONSTRUCTION

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Abstract: There is a great amount of plastic material, of different types, available worldwide that end up discharged in nature causing great polution. This material could be used in several applications. Construction of bike frames is one of them. This ideia is pursued here in the design of a plastic frame for a road bicycle. In an iterative procedure, the drawing of frame elements is considered first with the assemblage of the frame ensuing next. Finite element modeling and analysis is used afterwards to evaluate the design. Failure modes are investigated. Once considered adequate, connector parts produced in a 3D printer are to be assembled with tubular elements in a very simple and cheap manner. The solution has promissing advantages over similar designs.

Keywords: frame concept, drawings, finite element model, 3D printing, assemblage

1. INTRODUCTION

The history of two wheel vehicles is already 200 years long and is marked by continuous development. It starts in 1817 with Baron von Drais (Icebike 2022), in Germany. His bike, called draisine, had a wood frame and wheels, with iron rims covered with leather. The vehicle was well received by society worldwide. Fifty years later, mass production of bikes was already a reality, with some industries using even steam propulsion. By 1869, solid rubber was in use. Variations, like the unicycle appeared on those days, by 1870, high wheels appeared in England in 1872, with chain-drives included in 1884. Inflatable tubes were adopted after the Dunlop's vulcanization process invention in 1888. By 1890, Daimler added an internal combustion engine to bikes, creating the first motorcycles. Battery equipped bikes appeared soon after. Braking systems, pedaling wheels and other developments appeared next. Much of the developments were brought by cyclists, that among other conquests, had already cycled around the world, competed in long races, and cycling entered the Olympic games. Velocipedes, velocars and recumbent bicycles were common in the first part of last century. Shimano transmissions were in development on those days but suspension systems where introduced only many years later (Wikipedia, 2022).

Diversification was intensified in the second half of last century: Motocross bikes, BMX, appeared in 1956, mountain bikes, MBs, in the 70's as well as other concepts, like the all-terrain, ATB, for example. With diversification the bike market increased fast, mostly due to pollution and traffic problems in the cities. No matter theses facts, bicycle frames were metallic, with use of steel, aluminum and even titanium, Use of plastics and composite materials – glass and carbon fibers – are very recent. The plastic bicycle was introduced in the US in 1970, with polycarbonates, but the project was not successful. Years later, a Swedish project, the Itera, created a bike using injection molding. The project had many problems, with many plastic parts broken after early use. In 2011, EADS put in the market the Airbike, made of nylon. Fiber reinforcements are now present in several projects. Even recycled plastics have shown lately very promising results, In Brazil, the Muzzi Cycles (Olhar Digital, 2021) designed by a Uruguayan living in Brazil, made of recycled PET is already in the on sell. It is constructed by plastic molding process.

The Dutch start-up Dutchfiets – country with higher number of bicycles per capita - is one of them, with a recyclable plastic, PE, used for almost the whole body of the bicycle. Nowadays there are more than a billion bikes in the world, being the most important means of locomotion in many places. Many advantages are claimed by plastic bike developers: recycled plastic could save 980 tons of oil and reduce greenhouse gas emissions by about 6,000 tons of CO_2 per year, Plastic is shock absorbing, eliminating the need for separate shock absorbers and ensuring a smooth ride. Composite plastic bikes are very light, because composite materials are light, with easy of repair, but low impact resistance, having as disadvantage the fact that damages in carbon fibers are invisible, and not so easily predictable. Fabrication is another part of the newness, with solutions showing a different trend, with 3D printing for example, present in the bike produced in China (Printed Bike, 2021), with components made of plastics, of different types, Figure 1. The 3D plastic printing included wheels, tires, transmission, pedaling and braking components. Multi-body assemblage is used.

Figure 1. Plastic bike made with 3D print technology produced in China

2. ONE DIMENSIONAL MODEL

Bike frames have different sizes, according to usage, driver weight, size and performance. An example of framing, dimensions and terminology of a normal bike are shown in the Fig. 2. There are variations on the number of elements, forms and sizes. Tubular form is common, even though exotic forms appear as wells, mostly shell forms. For beam elements, and elastic material behavior, the design is made easier with the matrix stiffness approach, for the initial design phase, at least. From there on, standard sizes for the elements of framing are in general selected, avoiding special tooling, mounting devices and processes.

2.1 Geometry, Material and Loading

The frame shape in most bikes is the diamond one, and for it there are charts with geometric information. Different designs and manufacturers have different sizes and proportions (Rideblue, 2020). They may very a lot with the type of material employed in the construction. In the case investigated in this work the large size LG geometry was considered. Nylon was used in the design procedure, a part its high flexibility. It shows good results for most list of material performance. PET and Teflon have also been analyzed after 3D printing showed the superior quality of the last one for frames. The required mechanical properties of nylon are presented in Table 1.

Table 1: Mechanical properties of nylon

PROPERTY	VALUE
Young;s Modulus: E Pa	2.70 e+09
Poisson's ratio: ν	0.28
Yield Strength: S_y Pa	70.e+06
Ultimate Strength: S_u Pa	72. e+06
Density: ρ kg/m3	1.17e+03

Loading considered a continuous pedaling situation, with a cyclist producing a maximum force $P = 400$ N at 90 º position, with torque of $T = 112$ Nm, which is a superior limit for an athlete. Weight of the athlete was taken to be $W = 980$ N, with an upset $\delta = 10\%$ from seat tube, applied at the seat as a point force. The *guidon* force G was assumed to be of the order 20% of the weight of the cyclist – arm resting condition - with the same order of deviation from the tube center. Steering and braking forces were not considered. Reaction forces were applied at the center of rear and front wheels. The design scenario is quasi-static, with pedaling torque being used in the transmission for motion only.

Figure 2. Dimensions and terminology used in bicycle frames
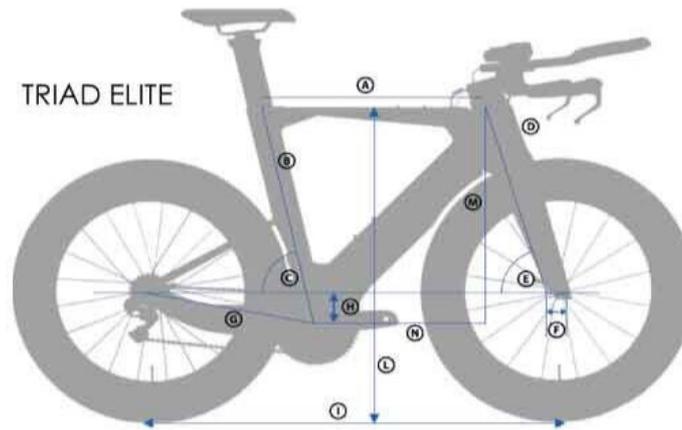
TRIAD ELITE	XS	SM	MD	ML	LG
A Top Tube Length C–C (cm)	48.9	49.8	52.2	54.3	56.2
B Seat Tube Length C–T (cm)	52.3	53.5	55.5	57.5	59.4
C Seat Tube Angle	77	77	77	77	77
D Head Tube Length (cm)	8.5	9.5	11.5	13.5	15.5
E Head Tube Angle	71.5	72.5	72.5	72.5	72.5
F Fork Rake (cm)	4.5	4.5	4.5	4.5	4.5
G Chain Stay Length (cm)	40.8	40.8	40.8	40.8	40.8
H Bottom Bracket Drop (cm)	7.5	7.5	7.5	7.5	7.5
I Wheelbase (cm)	96.5	96.5	98.9	101.4	103.5
J Seat Tube Diameter (mm)					
K Seat Post Diameter (mm)			·		
L Stand Over Height (cm)	77.7	79	80.9	82.8	84.7
M Stack (cm)	49.4	50.7	52.6	54.5	56.4
N Reach (cm)	37.5	38.1	40.1	41.7	43.2

The external loading, transferred to the joints of the frame, requires reaction loads from the wheels be computed. They include a pair of efforts acting in the axis of each wheel in the <X, Y> directions, being the front wheel reactions transferred to the fork tube, with a bending moment included because of the presence of a rake angle. They depend on the conditions of pavement, and are obtained solving the motion problem, that give the inertia forces, Fig. 3.
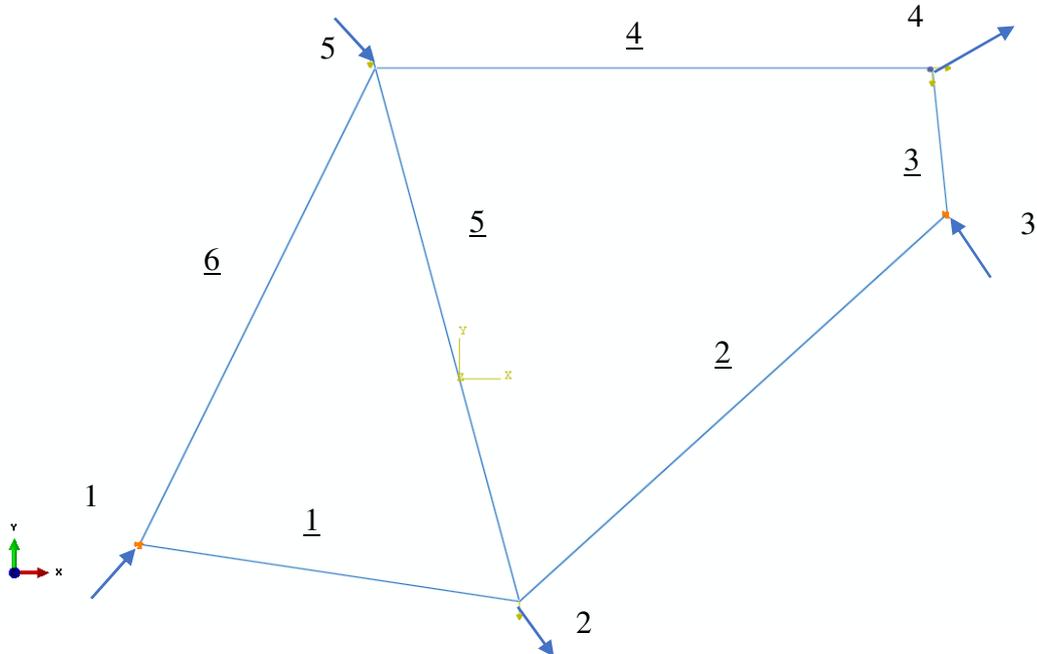

Figure 3 Plastic bike frame loading and reactions

2.2 Stiffness Matrix Design Method

The bike frame above has six tubular elements, numbered with underlined numbers. Connecting junctions, known as nodes, are numbered as {1,2,3,4,5}. They are five with numbering starting at the center of the rear wheel, where the reaction forces from the pavement act, node 1. The chain stay tubes connect this point to the position where the transmission system is fixed, node 2. These tubulars constitute a double parallel beam. Pedaling forces occur at the pedal arm. At node 3, spring forces resulting from front fork act. The tubular connected to this fork works in a sliding contact form inside the head tube. The same that fits also the *guidon,* where guiding forces are applied. They converge at node 4, where the top tube connects to the seat tube and extension, node 5. The seat is fixed in an adjustable form. Closing the frame, a pair of elements connect to the rear wheel center, another double parallel curved beam.

Local coordinates $< x_k, y_k >$ are used for each element k, using the central line connecting nodal points as abscissae. The geometry of these elements may have different profiles, materials and sections. For straight prismatic parts, however, beam element idealization may be used. For kth-beam element, with end nodes identified as i and j. the generalized internal efforts vectors e_i and e_j, on these nodes, are related to the displacements vector d_i and d_j, respectively, by means of the stiffness matrix (Hibbeler, 2009):

$$e^k = k^k d^k; k = 1,2,..6 \tag{1}$$

where $e^{kT} = \lfloor e_i \quad e_j \rfloor^k$ is the internal efforts vector which comprises the internal efforts sets $\lfloor n \quad s \quad m \rfloor$ for nodes i and j, standing n for normal, s for shear, and m for bending moment of element k. The vector of generalized displacements $d^{kT} = \lfloor d_i \quad d_j \rfloor^k$, comprising the nodal displacements $\lfloor u \quad v \quad \theta \rfloor$, containing the axial u, lateral v displacements and rotations $\theta = v_{,xx}$. The stiffness matrix depends on the kind of material used, elastic in this case, its sectional properties and length:

$$k^k = \begin{bmatrix} k_{ii} & k_{ij} \\ k_{ji} & k_{jj} \end{bmatrix}^k ; k^k{}_{ii} = \overset{k}{k}^{\sim} \quad k^k{}_{ij} = \overset{k}{k}^{\bullet} \quad \overset{k}{k}{}_{ji} = \overset{k}{k}^{\bullet} ; \quad \overset{k}{k}{}_{jj} = \overset{k}{k}^{*} \tag{2}$$

Each of the internal matrices depend on axial $p^k = \dfrac{EA^k}{l^k}$, lateral $q^k = \dfrac{12EI^k}{l^{3^k}}$ and $r^k = \dfrac{6EI^k}{l^{2^k}}$ plus rotational $t^k = 4\dfrac{EI^k}{l^k}$ generalized stiffness elements, with sign variation of these between matrices. The element matrices are written in local coordinates, and therefore need to be transformed into global coordinates, valid for all elements. Being T the transformation matrix between local, $< x_k, y_k >$, and global $< X, Y >$, coordinate systems, for plane cases with Z perpendicular to the frame plane:

$$E^k = K^k D^k; \quad E^K = \overset{k}{T} e^k; \quad D^k = \overset{k}{T}{}^{T} d^k \tag{3}$$

Once each element matrix is transformed into its global form, assemblage of the whole structure needs to be done. In the process, element connections as well as boundary conditions are considered. Using this matrix, equilibrium based on nodes, comprises the set:

$$\begin{aligned}
AD_1 + BD_2 + CD_5 &= F_1 \\
BD_1 + DD_2 + ED_3 + FD_5 &= F_2 \\
ED_2 + GD_3 + HD_4 &= F_3 \\
HD_3 + ID_4 + JD_5 &= F_4 \\
CD_1 + FD_2 + JD_4 + LD_5 &= F_5
\end{aligned} \tag{4}$$

where $A = 2(\overset{1}{K}{}^{\sim} + \overset{6}{K}{}^{*})$, $B = 2\overset{1}{K}{}^{*}$, $C = 2\overset{6}{K}{}^{\bullet}$, $D = 2\overset{1}{K}{}^{*} + \overset{2}{K}{}^{\sim} + \overset{5}{K}{}^{\sim}$, $E = \overset{2}{K}{}^{\bullet}$ and $F = \overset{5}{K}{}^{\bullet}$. Also $G = \overset{2}{K}{}^{*} + \overset{3}{K}{}^{\sim}$, $H = \overset{3}{K}{}^{\bullet}$, $I = \overset{3}{K}{}^{*} + \overset{4}{K}{}^{\sim}$, $J = \overset{4}{K}{}^{\bullet}$ and $L = \overset{4}{K}{}^{*} + \overset{5}{K}{}^{*} + 2\overset{6}{K}{}^{\sim}$. The vectors F_1 and F_3 are reaction vectors, unknown. The others, F_2, F_4 and F_5 are known applied load vectors.

Some remarks may be made at this point, as the *guidon,* for example, may be designed using a similar, independent procedure, with load transfer. Or it may be incorporated to the frame to increase of the matrix system. Use of curved

beams, may be solved with multi-element discretization, or use of special interpolation functions. Front fork may, as well, be solved as an independent system, to handle the displacement D_3 and hence F_3.

Equilibrium of the frame requires the set of external loads, body and contact as well, equilibrate the internal efforts at every node, so that $KD = F$, being K a 15x15 matrix, the assemblage frame global matrix. The vector of external forces F, 15x1 column vector equilibrates the internal loads applied by the elements to the nodal joints, KD, being the global displacement vector D a column vector 15x1. One of the external forces is displacement dependent, $F_3 = SD_3$ being S the stiffness matrix of the suspension element supposed to hold the front part of the frame to the fork.

Analytically matrix inversion with, boundary conditions imposed, may formally be written as $D = K^{-1}F$ what involves a 15x15 matrix inversion. It is not usable for design. Instead, solving the system with back substitution, allows using 3x3 matrices. The solution is very long, but fit to computational solution. In particular, when the fork stiffness is very large, $D_3 \rightarrow 0$, being $D_1 = 0$ it turns out that:

$$D_2 = F^{-1}(F_5 - JI^{-1}F_4) + F^{-1}(JI^{-1}J + L)S^{-1}R$$
$$D_4 = I^{-1}(F_4 - JS^{-1}R)$$

(5)

where $S = DF^{-1}(JI^{-1}J + L) + D$ and $R = F_2 - DF^{-1}(F_5 - JI^{-1}F_4)$ defining $D_5 = S^{-1}R$ which is dependent only on known applied forces. With nodal displacements known, reaction force F_1 is found from first, while F_3 comes from third of Eqs. (4). With them, internal efforts may be found next at the ends of each element, once the displacements are set back to local coordinates. Internal efforts diagrams, for normal, shear and bending moments derive thereafter. With them, critical sections in every beam of the frame may be found with the results plotted into a failure locus to choose the required sectional dimension.

The procedure was programmed into a systematic solution in a numerical script. For tubular elements, material properties and profile mean diameters served as input variables. Beam lengths and internal angles were required as well as loading. Setting an elastic domain for the solution, allows finding a desirable thickness for each frame tubular. Possibly a set of six independent profile moduli may be gathered. If desired an optimization procedure may be nested to the numerical scheme also. Set a figure of merit, like minimum frame weight, new values for the geometric parameters may then be chosen and iteratively searched a better solution.

3. RESULTS

3.1 Finite Element Verification
The matrix design procedure is a restricted form of the finite element method, with no discretization, for beam and bar elements. It was a departure point for the finite element method of 1D parts. It is a rather robust method with several resources, but not specific for bike frames. It is only practical for iterative design. In that sense the matrix solution presented above may be used to find the main moduli in a simple and rapid form. From there on, the finite element method may be used, inclusive with shell elements, as required moduli are already known.

Matrix solution was used to generate the frame sections of the plastic frame presented in figures 3 and 4 in deformed form to show flexibility also. Results have been analyzed using the finite element method of the processor of program (Abaqus™, 2015) Obtained values were quite close with differences ranging in the mark of 10 %. A reason for that are the large deformations occurring with soft plastics like nylon, which induce nonlinear effects.

Figure 3 shows the results for the shear forces, which are higher in the lower tubulars, chain stay mostly. However, it is worth remembering that this part of the frame has parallel beams, which have additional stiffness, not considered in the model. A 3D model would show that. Axial efforts appear but they are not large.

In the following, Fig. 4, the bending moments distribution is shown, Regions around the seat have larger values of moment, and consequently of bending stresses Results show that in this region higher thickness of tubing is required, even though the yield strength has not been reached, in the static simulation. However, in impact and under different loading cycles it could be reached easily.

Because of the excessive flexibility of nylon, ABS, carbon and glass fibers, polycarbonate and PET materials were tried for the same geometry and loading. The fiber composites have shown much higher stiffness, while polycarbonates and PET show comparable performance to the one of nylon.

3.2 Fabrication

After some verifications, and still in the learning process, it became clear that complete frame printing may not be the best solution for plastic bikes. Instead joint printing coupled to mold injection of the tubulars may render better results. This is in test now, with the alternative of using out-of-shelf tubular elements glued to the joints. PET material framing is still to be tested.
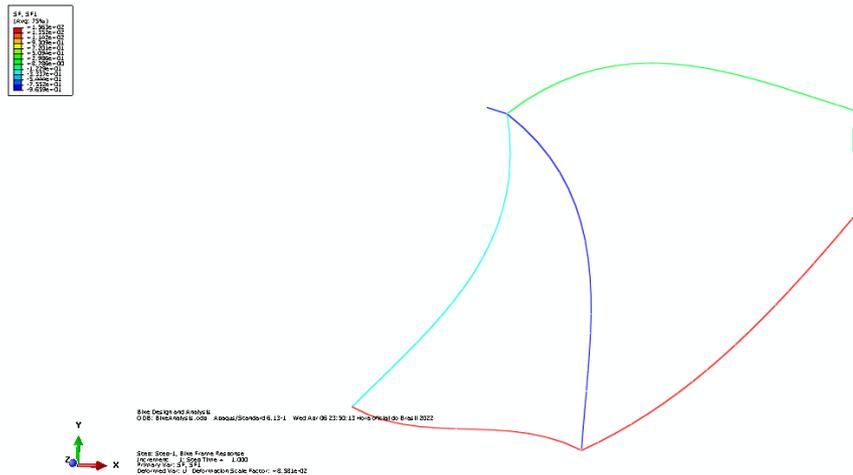
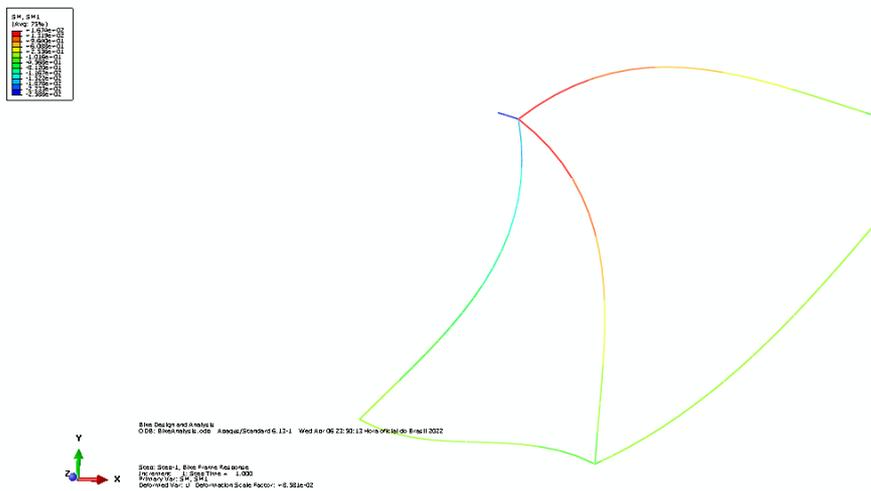Figure 3. Shear force distribution on the frame – aumengted deformation field

Figure 4. Bending moment distribution on the frame – augmented displacement field

4. CONCLUSIONS

The design procedure, using the matrix stiffness method, formulated and solved for bike frames, once coded has proved be a fast and reliable approach for initial sizing. It may accommodate distribute loading and pseudo dynamic cases for impact. In the verification application with finite elements of same discretization, it showed consistent elastic internal efforts all over, as predicted.

5. REFERENCES

Icebike, 2022 in https://www.icebike.org/58-milestones-from-bicycle-history-you-must-know/
Wikipedia, 2022 in https://en.wikipedia.org/wiki/History_of_the_bicycle
Olhardigital, 2021 in https://olhardigital.com.br/2021/06/22/videos/bike-ecologica-inventor-mostra-como-e-a-bicicleta-feita-com-plastico-reciclado/
Printed Bike, 2021 in https://3dprint.com/54601/chinese-3d-printed-bike/
Rideblue, 2020, in https://rideblue.com/triad-frame-geometry
Hibbeler, R.C., 2009, "Structural Analysis", Pearson-Prentice Hall, 7th Edition, New York, USA, 667 p.
Abaqus^TM, 2015, *FEA: Finite Element Analysis*, 13th edition, Dassault, France

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