International Journal of Mechanical and Materials Engineering (IJMME), Vol. 5 (2010), No. 1, 95-100.

MATERIALS SELECTION OF A BICYCLE FRAME USING COST PER UNIT PROPERTY AND DIGITAL LOGIC METHODS

M.A. Maleque and S. Dyuti
Department of Manufacturing and Materials Engineering,
International Islamic University Malaysia, Kuala Lumpur, Malaysia
Email: maleque@iiu.edu.my

ABSTRACT

The aim of this paper is to develop the material selection method and select the optimum material for the application of folding bicycle frame. Two methods are introduced for the selection of materials, such as cost per unit property and digital logic methods. In cost per unit property, only one property (strength) is considered whereas in digital logic method, multiple properties such as tensile strength, yield strength, young's modulus, toughness and density were considered for the optimum selection of the materials. The Ashby's material selection chart was used for the initial screening of the candidate materials. The results are presented both in tabular and graphical forms.
The materials selection method showed that AISI 1020 steel, Ti-alloy, carbon fiber reinforced polymer (CFRP), kevlar fiber reinforced polymer (KFRP) and glass fiber reinforced polymer (GFRP) are the candidate materials for the design of bicycle frame. From the cost per unit property method it is found that the KFRP shows the least cost material followed by AISI 1020 steel material. The digital logic method also showed the highest figure of merit value for KFRP material followed by AISI steel and Ti-alloy. Based on the developed materials selection method and analysis of the few candidate materials it can be concluded that the KFRP is the suitable material for the design and application of bicycle frame.

Keywords: Material Selection Charts; Performance Indices; Bicycle frame.

1. INTRODUCTION

Among the human powered vehicles, bicycles are the most common and widely used means of transport around the world. Cycling is nowadays considered not only an efficient and healthy means of transportation but also a popular recreational and sport activity (Laios and Giannatsis, 2009). A bicycle frame is the main component of a bicycle, onto which wheel and other components are fitted. The modern and most common frame design for an upright bicycle is based on the safety bicycle (http://en.wikipedia.org). Since frames are a crucial component from safety point of view, the material used for frame in bicycle should have very stable and reliable mechanical properties under varying conditions of load (Emily et al., 2009). The proper material selection and design are important before manufacturing the component. Therefore, the recognition of the importance of materials selection in design has increased in recent years. The adoption of concurrent engineering method in design and manufacturing has reinforced the fact that materials and manufacturing are closely linked in determining final product performance (George, 2000).

The bicycle frame is consists of two triangles, a main triangle and a paired rear triangle as shown in Fig. 1. The main triangle consists of the head tube, top tube and seat tube. The head tube contains the headset which primarily interfaces with the fork. The top tube connects the head tube to the seat tube at the top, and the down tube connects the head tube to the bottom bracket shell.

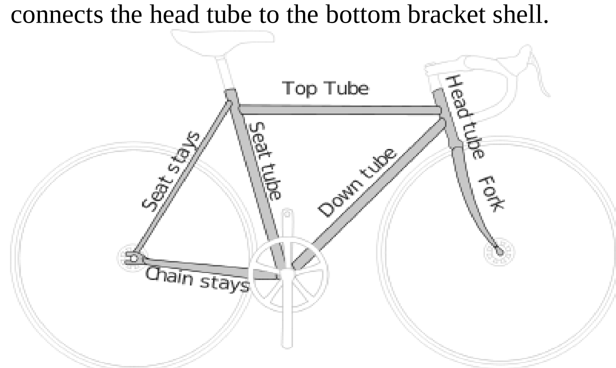

Figure 1 Schematic view of a bicycle frame.

The rear triangle connects the rear dropout which consists of seat tube, paired chain stays and seat stays. The chain stays run parallel to the chain, connecting the bottom bracket to the rear dropouts. The seat stays connect the top of the seat tube (often at or near the same point as the top tube) to the rear dropouts.

The materials selection chart is very useful in comparing a large number of materials at the concept design phase which could be reflected the fundamental relationships among particular material properties and be used to find out a range of materials suitable for a particular application (Ashby, 2005). In generally, the material selection process is performed based on performance indices in chart [Shanian et al., 2008]. As an alternative approach, digital logic methods have been occasionally used in material selection for certain engineering application (Jahazi and Hossein-Nejad, 2004). In order to select an appropriate material for a particular application the designer can use materials handbook, or international standard sources. However, knowledge-based system for selecting and ranking the materials for a particular application are also available in some literature (Sapuan et al., 2002; Zhu et al., 2008; Jahan, et al., 2010). The information on the development and application of the materials selection method for the design of bicycle frame is scare in literature. Therefore, the main purpose of the present work is to develop possible material selection methods and apply that for the selection of best candidate material for bicycle frame application using Ashby's chart and finally rank the materials according to the performance indices using digital logic method. Current study is quite new for the materials selection method and it is hoped that it will provide a high value to the design and materials researchers for the application of any material for any application.

2. STAGES OF MATERIAL SELECTION

For material selection there are small numbers of methods that have evolved to a position of prominence (George, 2000). Material selection process is an open-ended and normally lead to several possible solutions to the same problem. This can be illustrated by the fact that similar component performing similar function, but produced by different manufacturers, are often made from different materials and even by different manufacturing processes (Mahmoud, 2008). However, selecting the optimum combination of material and process is not a simple task rather gradually evolved processes during the different stages of material selection. In this investigation, the stages of material selection method are shown using a flow chart in Fig. 2.

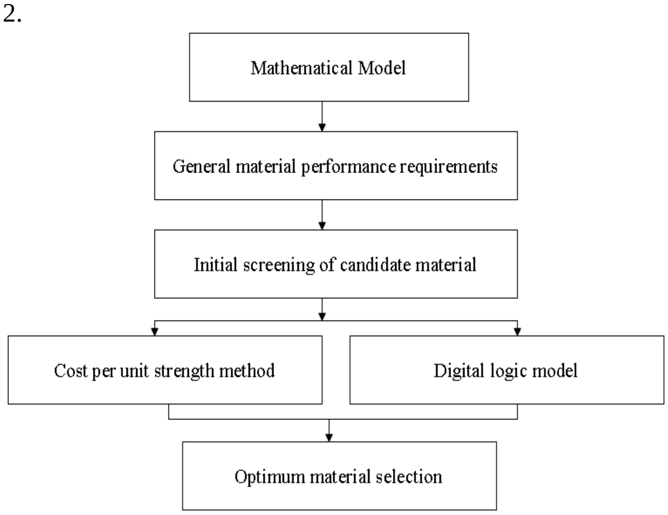

Figure 2 Flow chart of material selection.

3. MATHEMATICAL MODEL

During riding of a bicycle, the stresses those act on the bicycle frame system are shown by a free body stress diagram in Fig. 3. The types of stress mainly are compressive and bending stress from braking or crashing point of view.

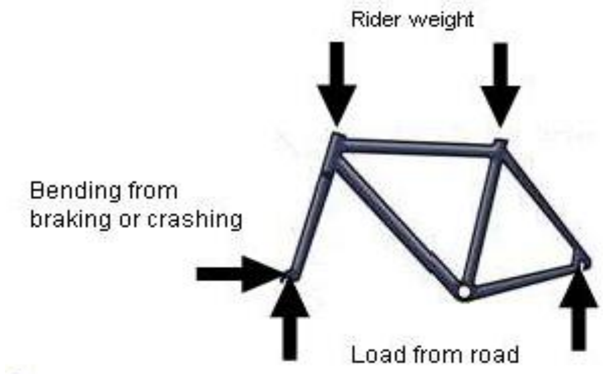

Figure 3 A free body stress diagram of a bicycle frame.

In order to develop a mathematical model for the calculation of cost on unit strength of a bicycle frame the following parameters are considered are taken into consideration: length of cylindrical bicycle frame, ***l;*** a compressive force, **F** and cross-sectional area, **A**. It is also considered that the frame is light and strong of fixed diameter. The cross-sectional area **A**, of the frame can be expressed as:

$$A = \frac{F}{S} \tag{1}$$

where, S is the working stress of the material which is related to its yield strength divided by an appropriate factor of safety. Then mass m of the cylindrical frame is,

$$m = \pi r^2 l \rho \tag{2}$$

where, r is the radius of the cylindrical frame and ρ is the density of the material from which the frame is made of.
Area of the frame can be written as:

$$A = \pi r^2 \tag{3}$$

From equation (2) and (3)

$$A = \frac{m}{l\rho} \tag{4}$$

From equation (1) and (4)

$$m = \frac{\rho F l}{S} \tag{5}$$

Finally, the cost of the frame C' is given by

$$C' = \frac{C\rho F l}{S} \tag{6}$$

where, C is the cost of the material per unit mass.

4. GENERAL MATERIAL PERFORMANCE REQUIREMENTS

Functional requirements are directly related to the required characteristics of the component, subassembly, or product. An important requirement for materials used in bicycle frame is its strength.

Compressive strength is the basic measurement of strength of a material. It is specifically a measurement of the force required to push apart a material. In frame design, the higher the strength betters the performance of the frame. More strength allows less material to be used resulting less weight of the component and hence AISI 1020 steel could be a potential candidate based on its strength.

Yield strength (YS) measures how much force it takes to permanently bend a material. As with compressive and fatigue strength, higher YS is expected from the candidate materials for the use of frame. The higher strength level of titanium (typically 800-1080 MPa) allows material to be used which in tern reduces the weight of the structure.

Toughness is the property that defines exactly how much a material can stretch before failing. Titanium is an incredibly tough material whereas aluminum has good toughness as a raw material. However, some extra care needs to be taken during manufacturing of the aluminum frame to make sure not let the tube wall get too thin. Carbon/epoxy composite laminate is also used for bicycle frame (Liu and Wu, 2010). Toughness is the Achilles heel of carbon fiber composites. If carbon composite receives an indentation, fibers will be most likely severed, strength will be reduced, and the possibility of further fracture will be seriously increased.

Density is simply the weight of a material for a given volume such as grams per cubic centimeter. The density of the carbon fiber composite showed lower density (hence lighter weight) with the approximate value of 1.8 g/cm^3 followed by aluminum (2.71 g/cm^3) (ASM Handbook, 1997). However, titanium showed higher density (4.43 g/cm^3). The density of a material certainly is an important factor in materials evaluation especially it is more important consideration for bicycle application compared to its strength and durability.

5. INITIAL SCREENING OF CANDIDATE MATERIAL

Having specified the material requirements, the rest of the selection process involves searching the materials that would best meet those requirements. The starting point is the entire range of engineering materials. At this stage, creativity is essential to open up channels in different directions and not let traditional thinking but exploration of ideas.
Ashby's material selection chart is used in order to choose the preliminary candidate materials for bicycle frame. Based on the chart given in Fig. 4, the materials that fulfill the properties of a bicycle frame are:

- Metals and alloys
- Ceramics
- Composites

Fig. 4 shows easy visualisation of properties and ideal for a first 'rough cut' selection. From the above mentioned materials list, ceramics are eliminated because of their brittleness, which is not appropriate for mechanical application of a bicycle frame. Thus only metal alloys and composites are left to be considered for the detail analysis.

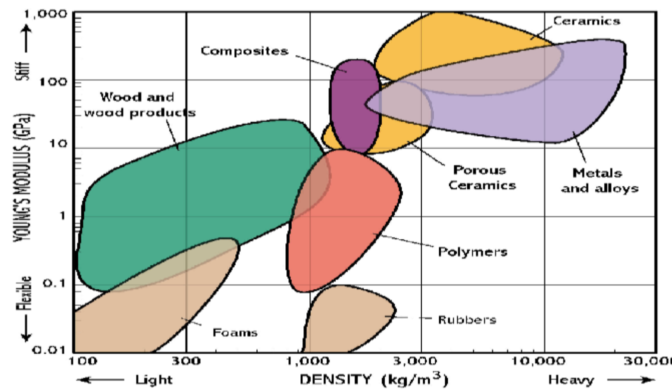

Figure 4 Ashby materials selection chart: Young's modulus vs. density (Mahmoud, 2008)

Fig. 5 shows the elastic modulus of polymers, metals, ceramics, and composites against density to show how the classes of materials group into common regions (Ashby, 1992). Lines of constant slope are drawn on the diagram for different properties of material. For simple axial loading the relationship is $E/\rho= C$, for buckling of a slender column, $E^{1/2}/\rho=C$, and for the bending of a plate it is $E^{1/3}/\rho=C$. For example, to determine materials suitable for a column in compression, the slope would be $E^{1/2}/\rho=C$ [Ashby, 1989]. In order to use this chart, it is essential to start at the lower right-hand corner and move it toward the upper left-hand corner. All the materials which lie on the line will perform equally well when loaded as a column in compression. Those materials which lie above the line are better, and those farthest from the line are the best [Ashby, 1989]. It can be said that the only materials that could meet this condition would be a fiber reinforced composite material, such as a graphite fiber-reinforced polymer (GFRP), a kevlar fiber-reinforced polymer (KFRP), and a carbon fiber-reinforced polymer (CFRP).

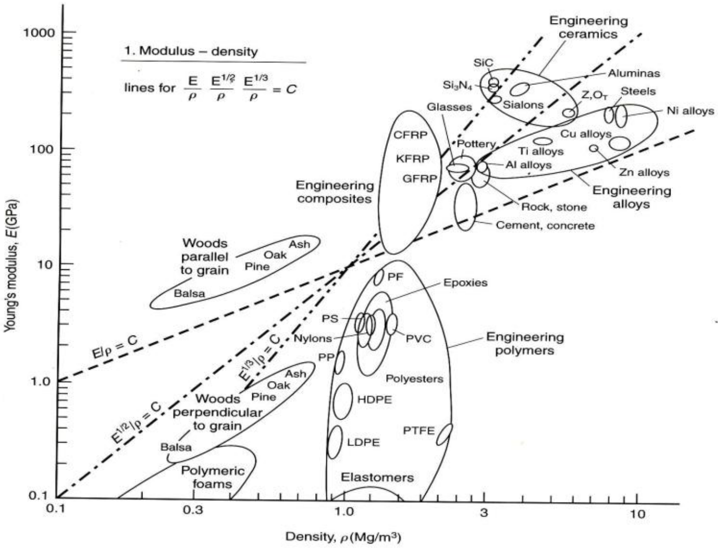

Figure 5 Ashby materials selection chart: Young's modulus vs. density (Liu and Wu, 2010).

From this aspect the following materials are considered for the bicycle frame application:

- AISI 1020 Steel
- Ti alloys
- CFRP
- KFRP
- GFRP

6. MATERIAL SELECTION METHODS

6.1 Cost per Unit Property (CUP) Method

Quantitative methods can be used to narrow down the choices to a manageable number for subsequent detailed evaluations. The cost per property method is suitable for initial screening in applications where one property stands out as the most critical service requirement (Mahmoud, 2008).
Materials with lower cost per unit property are preferable for any application. Using the mathematical model expressed in equation (6), cost of unit strength of the specified materials are calculated and given in Table 1.

Table 1 Characteristics and cost per unit strength value for the candidate materials for bicycle frame

Material	Yield Strength (MPa)	Working Stress [a] (MPa)	Specific Gravity (Kg/m^3)	Relative Cost [b]	Cost of Unit Strength
Steel 1020	296	98.67	7.8	1	0.08
Ti-alloy	965	321.67	4.3	10	0.134
CFRP	544	181.33	2.0	22.5	0.25
KFRP	621	207	2.3	3.75	0.042
GFRP	102	34	1.5	3.25	0.143

[a] The working stress is computed from yield strength using a factor of safety 3.
[b] The relative cost per unit weight is based on AISI 1020 steel as unity. Material and processing costs are included in the relative cost.

Based on Table 1 and the appropriate formula in equation (6), the cost of unit strength for the different material is calculated and the results are shown in the last column of the same Table. The results show that the KFRP is a better candidate material followed by AISI 1020 steel. However, the other materials such as CFRP, Ti-alloy and GFRP could be candidate materials though are more expensive.

6.2 Digital Logic Method

The digital logic method also can be employed for the material selection using with ranking. As a first step, the property requirements for a bicycle frame were determined based on the Ashby's material selection chart as shown in Figs. 4 and 5. The properties and the total number of decisions, i.e. $N\ (N-1)/2 = 10$ are given in Table 2. The weighting factor for each property, which is indicative of the importance of one property as compared to others, was obtained by dividing the numbers of positive decisions given to each property by the total number of decisions. The resulting weighting factors are given in Table 3, yield strength and toughness has the highest weight followed by young's modulus, whereas the least important properties are hardness and density.

Table 2 Application of digital logic method to material selection for bicycle frame

	Decision Numbers									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Tensile Strength	0	0	0	1						
Yield Strength	1				1	0	1			
Young's Modulus		1			0			0	1	
Toughness			1			1		1		0
Density				0			0		0	1

Table 3 Weighting factors for bicycle frame

Property	Positive Decisions	Weighting Factor(α)
Tensile Strength	1	0.1
Yield Strength	3	0.3
Young's Modulus	2	0.2
Toughness	3	0.3
Density	1	0.1
Total	10	1.0

The properties of the candidate materials are listed in Table 4 (http://ocw.mit.edu/NR/rdonlyres). The next step in the weighted properties method is to scale the properties given in Table 4. For the present application, materials with higher mechanical properties are more desirable and highest values in tensile strength, yield strength, young's modulus and toughness is considered as 100. Other values in Table 4 are rated in proportion. However, a lower value of density is more desirable for this application. The scaled values and performance index (γ) are given in Table 5 which was calculated using equations (7) and (8) respectively (Mahmoud, 2008).

$$\text{Scaled property} = \frac{\text{Numerical value of property} \times 100}{\text{Maximum value in the list}} \quad (7)$$

$$\text{Material performance index, } \gamma = \sum_{i=1}^{n} \beta\, i \alpha\, i \quad (8)$$

where β is the scaled property, α is the weighting factor and i is summed over all the n relevant properties.

Table 4 Properties of candidate materials for bicycle frame for calculation and ranking of the candidate materials (ASM Handbook, 1997)

Material	1 Tensile Strength (MPa)	2 Yield Strength (MPa)	3 Young's Modulus (Gpa)	4 Toughness MN $m^{-3/2}$	5 Density (Mg/m^3)
Steel 1020	380	200	210	140	7.8
Ti-alloy	950	910	100	85	4.5
CFRP	550	200	56	38	1.5
KFRP	1380	621	76	39	1.4
GFRP	530	125	26	40	1.8

Table 5 Scaled values of properties and performance index

Scaled Properties						
	1	2	3	4	5	Performance Index (γ)
Steel 1020	28	22	100	100	18	61.2
Ti-alloy	69	100	48	61	31	67.9
CFRP	40	22	27	27	93	33.4
KFRP	100	68	36	28	100	56.0
GFRP	38	14	12	29	78	26.9

The performance index showed that the technical capability of the material without regard to the cost. It is also important to consider the cost of material before making any final design or ranking. Therefore, in this study, the figure of merit (FOM) M is calculated using the equation (9):

$$M = \frac{\gamma}{C\rho} \quad (9)$$

where,C=Total cost of the material per unit strength
ρ = Density of the material

The values of the relative cost, cost of unit strength, performance index, and figure of merits of the different materials are shown in Table 6. The plot of figure of merits against all the candidate materials is shown in Fig. 6. From Fig. 6 it can be seen that kevlar fiber reinforced polymer (KFRP) showed higher figure of merit (FOM) followed by AISI 1020 steel. From the both cost per unit strength (CUP) and digital logic methods it is shown that Kevlar fiber reinforced polymer (KFRP) is the optimum material for bicycle frame followed by AISI 1020 steel.

Table 6 Cost and figure of merit of candidate materials

Material	Relative Cost	Cost of Unit Strengthx100	Performance Index	Figure of Merit
Steel 1020	1	8.0	61.2	7.65
Ti-alloy	10	13.4	67.9	5.07
CFRP	22.5	25.0	33.4	1.34
KFRP	3.75	4.2	56.0	13.33
GFRP	3.25	14.3	26.9	1.88

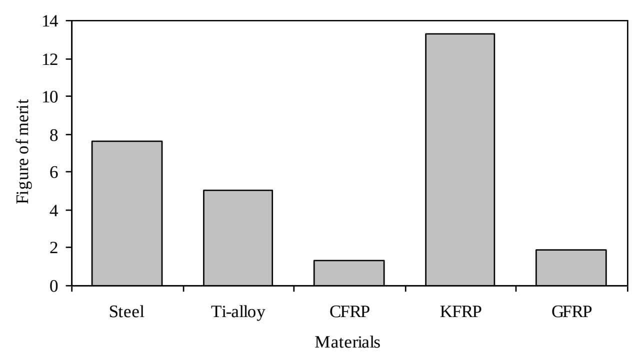

Figure 6 Plot of figure of merits (FOM) against all materials.

7. CONCLUSIONS

The material selection methods for the design and application of bicycle frame are developed. The Ashby's material selection chart was used for the initial screening of the candidate materials. The cost per unit property (CUP) method showed that KFRP material is a better selection followed by AISI 1020 steel material. The digital logic method also showed the highest figure of merit for KFRP material and identified as an optimum material among the candidate materials for bicycle frame. In the digital logic method, the strength and density were considered twice for determining the performance index and the cost of unit strength. This procedure may have overemphasized their effect on the final selection. This could be justifiable in this case as higher strength and lower density are advantageous from the technical and economical point of view for this type of application.

Acknowledgement

Authors are grateful to the Research Management Centre, International Islamic University Malaysia (IIUM) for financial support to conduct this research work under project EDW A 09-472.

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