International Journal of Mechanical Engineering and Technology (IJMET)
Volume 9, Issue 3, March 2018, pp. 204–213 Article ID: IJMET_09_03_022
Available online at http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=9&IType=3
ISSN Print: 0976-6340 and ISSN Online: 0976-6359

CONCEPTUAL DESIGN AND STRESS ANALYSIS OF THE COMPOSITE FRAME OF DIRT JUMP MOUNTAIN BIKE

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ABSTRACT

The subject of this paper is conceptual design and stress analyses of the composite frame for a special mauntain bike. The existing solutions for frames of this type were analyzed, and the design was conceptualized, which was thoroughly analyzed for extreme loads occurring on the Dirt Jump Mountain Bike Frames. By using the methodology of conceptual design, we have obtained a conceptual solution of the frame, which has been evaluated as optimal one based on a set of criteria. We later confirmed this hypothesis by the stress and other analyzes we carried out to validate the frame, and found that the chosen conceptual solution really meets all the criteria.

Keywords: Frame, Composite material, Conceptual design, Stress analysis.

Cite this Article: Isad Saric, Nedim Pervan, Mirsad Colic and Adil Muminovic, Conceptual design and stress analysis of the composite frame of Dirt Jump Mountain Bike, International Journal of Mechanical Engineering and Technology 9(3), 2018. pp. 204–213.
http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=9&IType=3

1. INTRODUCTION

Bicycles are subject to a wide range of loads at various locations around the frame. Since 1968, loads have been measured around the bicycle at the pedals [1-4], handlebars [5, 6], saddle/seatpost [5-7] and hubs [8] in the lab environment as well as outdoors (including both on and off-road conditions).

A bicycle frame is the main component of a bicycle that has a function of connecting the wheels and other components together to constitute a functional unit. Frames also have a bearing function, and they are expected to overcome all the loads that occur during bicycle exploitation. Frames take bending and torsion loads that occur during the ride, as well as the vibrational loads that arise by crossing uneven surfaces.

Due to the dynamic character of the loads, there is a possibility of fatigue failure, so that this must be anticipated and prevented. There are different versions of frame construction, and today the most widely used is the construction of the frame in the form of diamond, as shown in Figure 1.

Figure 1 Frame construction of mountain bike in the form of diamond

Due to the high loads and the possibility of fatigue failures, there is a need for using composite materials for this type of construction. Composite materials have good mechanical properties and are highly resistant to fatigue failure [9].

The construction of the bicycle also requires as little weight as possible, because it facilitates the ride of a cyclist, reducing his tiredness and ultimately, we enable him to perform better.

From the aforementioned, we can conclude that frame is one of the most responsible components of a bicycle construction. Possible frame failures undermine the integrity of the entire construction of a bicycle, and it becomes dysfunctional. Therefore, the design issues are being approached very meticulously and carefully to ensure the greatest possible safety against failure. Because of its bearing role, high strength and stiffness of a frame are required features and due to reduction of losses during cycling and reduced tiredness of a cyclist, as lighter bicycle weight as possible is required.

2. CONCEPTUAL DESIGN OF THE COMPOSITE FRAME

This work seeks to offer a solution to the problem of failure occurrence due to fatigue that happens because of the nature of dynamic loads. As far as it concerns the material of frames, we will consider only the composites, which showed good resistance to fatigue failure. They are characterized by a better strength-to-weight ratio compared to metallic materials. It is known that for bicycles one of the most important demands is a smaller weight, which also justifies the use of this material.

In the branch of industrial design there are today a significant number of companies and researchers who deal with the problem of establishing the best methodology for product development, as well as all its individual phases. In this paper, one of the newer approaches has been selected.

2.1. Identification of customer needs and product specifications

Customer needs should be identified, because the development of a successful product is based on good knowledge of them, analysis, and the introduction of engineering and technical improvements in relation to competition. This leads to the satisfaction of customers' needs and in the same way to the financial success of the manufacturer. Identification of needs is done by interviewing cyclists, both professional and recreational ones. [10]

In addition to direct product users, it is also necessary to interview the producers/ distributors of this product, i.e. the people who know the market of this product and the advantages/disadvantages of competition's solutions. The competition's solutions provide the best insight into customers' needs, since the disadvantages of these solutions represent the area in which we want to operate and improve the product. A detailed analysis of the existing solutions is one of the most important steps in the development of conceptual design.

The engineering specifications we want to define need to be a reflection of customers' needs and desires, and as such should not be specifically related to a single need. Some specifications may at the same time influence the satisfaction of more customer needs. Table 1 shows the interdependence of customer needs and specifications.

Table 1 Matrix of customer needs – specifications

Description of the Specification **Customer need**	**Total weight of frame**	**Angle of the front tube**	**Lateral stiffness of frame (front part)**	**Frame stiffness (front part)**	**DIN EN 14764 – strength test**	**Product price**	**Insensitivity to water and dirt**	**Length of assembly/disassembly**	**List of tools for assembly/disassembly**
Sufficient stiffness and strength			●	●					
Increase the lifetimes of products					●				
Stability when riding a bicycle		●							
Minimum weight	●		●	●					
Affordable price						●			
Compatibility with a variety of bicycle		●							
Non-contamination by the environment							●		
Simple disassembly								●	●
Cyclist safety in case of failure			●	●					

After defining the customers' needs, and based on them we described the product specifications that we consider to be the key ones. The next step would be to collect data about competition's product solutions. This step is one of the most important in the development of a new product.

2.2. Establishing target specifications

In major companies involved in the development of new products, significant resources are available for a detailed analysis of competition's solutions. In the present case, this would mean that we need to examine a significant number of frames that are currently in the market. The examination of the frames would be carried out according to the defined specifications. This process takes a lot of time and money. The competitors do not provide this information, so that we, with a team of people, should buy all the frames, which we deem to be relevant, and examine them thoroughly according to defined specifications. On the basis of those data, the most appropriate target specifications should be sought, which would position the product above the competitors' ones, and enable it to succeed on the market. The competition's solutions have not been thoroughly analyzed in the work process, but the data used are available on the Internet, based on which we will get good assumptions about the extent to which the values of the target specifications should be. Therefore, due to the aforementioned inability to carry out larger and more extensive analyzes, the target specifications, as shown in Table 2, have been reached in another way (which is equally in use).

Table 2 Target specifications

No.	Description of the specification	Importance	Target specification	Unit
1	Total weight of frame	5	< 850	g
2	Angle of the front tube	4	73	°
3	Lateral stiffness of frame (front part)	5	(18÷30)	N/mm
4	Frame stiffness (front part)	5	< 111.3	N/mm
5	DIN EN 14764 – strength test	3	satisfy	binary
6	Product price	3	~ 750	€
7	Insensitivity to water and dirt	2	satisfy	binary
8	Length of assembly/disassembly	3	< 420	s
9	List of tools necessary for assembly/disassembly	3	- hex wrench - ring spanner - fork spaner	list

2.3. Generating the concept

The conceptual solution of the product represents an approximation of the final product. This implies the definition of the technology of production, the principles of work and the final product form. Previously, conceptual solutions used to emerge as the fruit of an individual's imagination, and their generation was linked to the individual and his own way of conceiving solutions.

Because of market development and the establishment of high standards for product quality and time of a new product development, this approach has encountered great problems, what has led to the development of new methodologies for solving the problem of generating the concept. Generating the concept can be broken down into five basic steps shown in Figure 2.

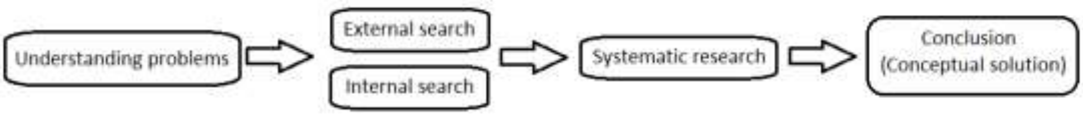


Figure 2 The methodological approach of generating concept

These steps aim at generating a higher number of conceptual solutions. Of course, during the development of conceptual solutions, all solutions that are found not to be able to achieve good market success are eliminated. This implies rejecting the conceptual solutions that are too complicated, too expensive, dysfunctional, and the like. Thus, with the process of generating the concept we have come up with twelve conceptual solutions that are approximately equal in quality, and then the selection of the optimal concept is made.

2.4. Selection of the concept

Choosing the optimal concept can be a very tough job. The product can have a very large number of variants of the concept, and the evaluation itself is burdensome because it is very difficult to quantify the quality of the concept. Due to this fact, the methodology of selection of the concept has been developed, and it consists of two steps. The first step is triage of the concept, and the second step is evaluation of the concept. In the first step, the goal is to efficiently and quickly determine better variants, and exclude all other variants that do not promise success of the product. In the triage, each concept is not analyzed in detail. All variants are quickly ran through, leaving at the end only the best ones, which are further analyzed in the next step, i.e. in the evaluation of the concept.

The evaluation is done by selecting a reference variant and we rate the remaining variants according to the criterion by the following method: if the variant we are considering has no particular advantages or disadvantages compared to the reference one according to the criterion we evaluate, we put the rating „0”, if the variant is better than the reference one we put „+”, and if it is worse than the reference one we put „-”. As a reference variant, we will take the variant L, which we assume, does not fall within the best or the worst solutions in accordance with the ranking.

After we evaluate the variants by the above method, we perform the aggregation and the evaluation of the final rating. Each „+” brings one point to the given variant, „0” does not change the rating, while „-” reduces the score for one point. In the end, according to the rating i.e. the number of points, the ranking of all variants is done, (Table 3).

Table 3 Matrix of conceptual solutions

	Variant											
Selection criteria	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
Product price	+	+	+	+	+	+	+	-	+	+	-	0
Technologicality of make	+	-	0	+	0	-	0	0	0	0	0	0
Safety of construction	0	0	0	+	-	-	-	-	-	-	0	0
Possibility of disassembly	+	0	0	0	+	0	0	0	+	0	+	0
Mass of construction	+	+	+	+	+	+	+	+	0	0	-	0
Sum +	4	2	2	4	3	2	2	1	2	1	1	0
Sum 0	1	2	3	1	1	1	1	2	2	3	2	5
Sum -	0	1	0	0	1	2	1	2	1	1	2	0
Rating	4	1	2	4	2	0	1	-1	1	0	-1	0
Rang	1.	5.	3.	1.	3.	8.	5.	11.	5.	8.	11.	8.
Continue?	🟩	🟥	🟩	🟩	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟨

The variants that are in the last row of Table 3 colored green will be further considered, and continue to the next step of selecting the optimal variants. The variants colored red are those that will be rejected and certainly not go into production. Yellow colored are those solutions whose possible combination may improve the existing solutions.

The variants A, C and D go directly to the phase of evaluation of the concept. The variants I and L had certain advantages and possible combinations of these variants into the IL variant could make significant improvements in comparison with the variants from which the new variant emerged.

The step of concept rating contains the same activities as triage. The important difference in this step of the selection of the concept is in the rating method. The variants are rated on the basis of the same criteria. However, a reference solution is not selected here, but each one is rated by 1 to 5, where 5 is the best score. Each criterion gets a weight factor, because not all criteria are equally important for the construction of the frame.

The final sum of percentual weight factors of all criteria must be 100%. The ratings given for each criteria are multiplied by the weight factor, and thus summarized give the final rating of the variant. (Table 4)

Table 4 Matrix with ratings of conceptual solutions

		Variant							
Selection criteria	**Factor (%)**	**A**		**C**		**D**		**IL**	
		Rating	**Factor**	**Rating**	**Factor**	**Rating**	**Factor**	**Rating**	**Factor**
Product price	20	5	1	5	1	4	0.8	4	0.8
Technologicality of make	15	4	0.6	4	0.6	4	0.6	3	0.45
Safety of construction	25	4	1	4	1	5	1.25	3	0.75
Possibility of disassembly	10	4	0.4	1	0.1	1	0.1	5	0.5
Mass of construction	30	4	1.2	4	1.2	5	1.5	3	0.9
Weight rating		4.2		3.9		4.25		3.4	
Continue?		🟥		🟥		🟩		🟥	

The best rating gets the concept D. Thus, we will use the composite material made of carbon fibers for the frame, the structure of the frame will be a monocoque, and the frame will be made out of one piece. With this decision we move on to the next step in the product development, which is its geometric development. The geometric representation will be done in the CATIA software system [11].

2.5. Geometric model of the selected concept

For specific dimensions of the geometry of the frame, we will use the information available for making mountain bikes. In doing so we will made modifications that are usually performed on special bicycles, and we will use already previously adopted geometric characteristics (Figure 3).

Figure 3 3D model of composite frame

The thickness of all the tubes of the frame is 1.56 mm. This is because the frame will be composed of twelve layers of laminates of individual thickness of 0.13 mm. For the composite material, we selected carbon T-500 15k/976 in the form of a one-dimensional strip [12]. This fiber material uses the union carbide T-500 15k and the matrix is fiberit 976. The process in which this composite is formed is that it is autoclaved at a temperature of 175 °C with a pressure of 0.68 MPa and a duration of 45 min.

3. STRESS ANALYSIS OF THE COMPOSITE FRAME

The stress analysis of the selected conceptual solution was done in the software Abaqus.

From the 3D model of the frame that we created in the CATIA software system, it is necessary to make a geometric representation. Based on the surface model we will generate a mesh of finite shell elements. As a type of element we will select a quadruple quad (the term denotes the number of sides) element (Figure 4a). The most important thing is that the mesh correctly defines the geometry of the very structure we are modeling. This means that the elements should be of the appropriate size in order to be able to follow the contours of the structure itself.

In order for a model to be a realistic representation of a part made of composite material, it is necessary to properly define the material. Using the data read out from a military standard, the carbon material T-500 15k/976 is adopted, in the series of software dialogs we defined the mechanical properties of the selected composite.

The mechanical properties of the laminate do not depend only on the mechanical properties of the fibers and the matrix used, but also on the orientation of laminates [13].

We will analyze different load cases by performing three tests, as follows:

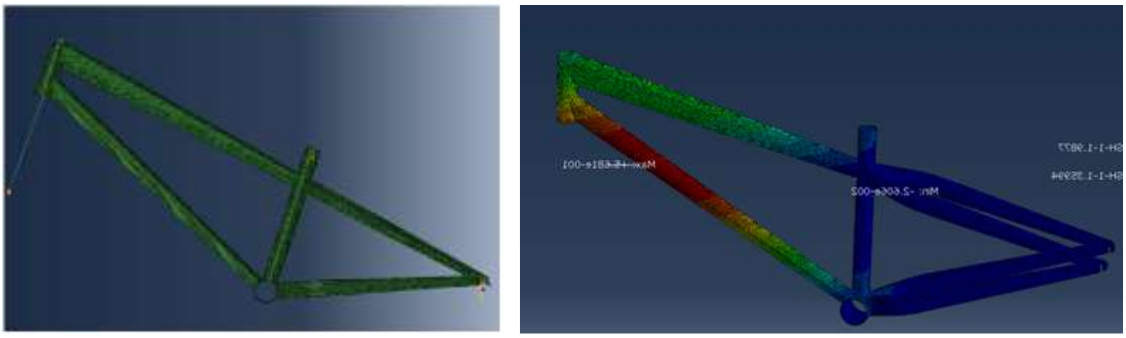
- Rinard test,
- frame stiffness test,
- DIN EN 14764 – strength test.

Rinard test is a static test of lateral stiffness of frame. This test checks how the frame behaves due to torsional loads to which it will be exposed during exploitation.

This test will serve us to validate the target specifications, and it is important for us to read out the displacements that arise from the application of load. In addition to the displacements we will also analyze the stresses that occur and the values obtained by the FEM analysis compare with the allowed ones for the laminate with our specifications.

The stiffness test of a frame is a static test that gives us an idea of how the frame will be deformed due to the driver's landing. A test similar to this checks for fatigue by the specification of DIN EN 14764 standard.

One of the most important tests for frame construction is this static strength test. It is especially important for the frames used in „free” style cycling, because the test is intended to simulate critical load conditions of a frame. (Figure 4)



a) b)

Figure 4 Test model within FEM software: a) preprocessing, b) postprocessing

The 1200 N force is applied at the top of the seat tube. The frame structure limitations are made in accordance with Figure 4a. Since this is a strength test, we will only analyze the stresses occurring after applying the load (Figure 4b). Then we will check if the stresses are inside the permissible limits, and we will use the Hill-Tsai criterion for failures of individual layers. The test shall be deemed to be satisfied if no failure occurs in any layer of laminate.

4. RESULTS AND VALIDATION OF THE CONCEPTUAL SOLUTION

The results obtained by performing the FEM analysis by carring out the above three tests, are shown in Table 5, where:

σ (MPa) – Von Mises stress,

σ_l(MPa) – stress in the longitudinal direction of laminate,

σ_t(MPa) – stress in the transversal direction of laminate,

τ_{lt}(MPa) – shear stress of laminate,

u(mm) – total displacement of structure,

u_x(mm) – displacement in the direction of x axis of the global coordinate system,

u_y(mm) – displacement in the direction of y axis of the global coordinate system,

u_z(mm) – displacement in the direction of z axis of the global coordinate system.

Table 5 Results of FEM analysis

Location	Test	σ	σ_l	σ_t	τ_{lt}	u	u_x	u_y	u_z
Top tube	R	467.1	405.3	-	-	-	-	-	-
Front tube	R	-	-	-	-	11.4	-11.4	-0.9	-0.27
	SF	173.7	-175.3	-	-	-	-	-	-
	EN	656.2	-398.8	-	-	-	-	-	-
Down tube	SF	-	-	-	-	0.73	-	0.56	-0.47
Seatstays	R	-	-462.5	64.86	-68.05	-	-	-	-
	SF	-	106.5	-15.82	23.25	-	-	-	-
	EN	-	231.9	-47.7	-89.31	-	-	-	-
Chainstays	R	-	-	-	-	-	-1.29	-	0.26
	SF	-	-	-	-	-	0.07	-0.02	-

Based on the results obtained by Abaqus software using the finite element method, an analysis was carried out to verify whether the frame structure has sufficient strength and stiffness to meet the target specifications in Table 2.

Based on the results of the displacement of Rinard test and the force applied in the test, the lateral stiffness of the frame is:

$$c_{lat} = \frac{F}{u} = 18.52\left(\frac{\mathrm{N}}{\mathrm{mm}}\right) \quad (1)$$

Based on the results of the displacement of frame stiffness test and the force applied in the test, the frame stiffness is:

$$c_{frame} = \frac{F}{u} = 290.26\ (\frac{\mathrm{N}}{\mathrm{mm}}) \quad (2)$$

The most commonly used as the criterion of failure for composite materials is Hill -Tsai criterion, which considers individual layers of laminates, expression (3). [14-16]

$$\alpha^2 = \left(\frac{\sigma_l}{\sigma_{lz}}\right)^2 + \left(\frac{\sigma_t}{\sigma_{tz}}\right)^2 - \frac{\sigma_l\sigma_t}{\sigma_l^2} + \left(\frac{\tau_{lt}}{\tau_{lts}}\right)^2 = 0.506 \quad (3)$$

By solving the expression (3) i.e. based on the Hill-Tsai number $\alpha = 0.71 < 1$ we can conclude that in the laminate there will be no failure of any layer.

Another way of validating conceptual solutions is reflected in checking whether the selected conceptual solution truly meets the defined target specifications. By comparing the obtained results with the given target specifications from Table 2, we can conclude that the chosen conceptual solution has met all the given specifications.

5. CONCLUSION

In the present case, the paper deals with the development of a composite frame for a special mountain bicycle. The paper presents the methodology for the development of a new product. In doing so, we pass through different stages. The initial considerations are based on the customer needs of buyers or the market itself, and then on the basis of these requirements the product specifications are defined. By defining the product specifications, we give a description of the more important characteristics that the product is expected to possess. The next step is to define the exact values of the previously defined specifications. Specifically, for the construction of the frame, this required a studious research of the frame data obtained from manufacturers, distributors and users. This part of the work, i.e. conceptual design, represents a larger part of the integral process of the product development. The second part of the integral process is an analysis of the conceptual solution itself. The product analysis requires the setting of mathematical models for the product, based on which we can evaluate the conceptual solution. When talking about mechanical constructions, the stress analysis has the primacy among all analyzes. However, in general, the analysis includes various geometric, dynamic and economic analyzes. Given that this is a frame made of composite materials, it is necessary to get familiar with the mechanics of composites. Using FEM software Abaqus, we have created three different tests that we need to justify the target specification. The two tests are related to the stiffness, which we find as relevant by the manufacturers of frames, and the third one is the strength test defined by the standard DIN EN 14764. The obtained results were processed, and we determined the frame dimensions that are in function of the specification. The last step for a conceptual solution is validation. Here, we considered all the target specifications that were required from the frame at the very beginning, and we checked these parameters by different methods and in the end determined that the conceptual solution really meets all the target specifications. In this way we have confirmed that the considered conceptual solution is really optimal for the needs of customers, and the specifications arising from these needs. Taking into consideration a very large number of input variables in the construction of composite materials, it has been found that the conceptual solution can even be improved. This refers primarily to mass. It is possible to reduce the number of layers of laminate, but increase the percentage share of layers that have orientation in the directions of 0° and 90°. We concluded this on the basis of the stress state that prevails within the frame structure.

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