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FAILURE ANALYSIS OF BICYCLE FRAME COMPOSITE STRUCTURE BASED ON STACKING VARIANT OF LAMINATE LAYERS

ANALIZA OTKAZA KOMPOZITNE KONSTRUKCIJE RAMA BICIKLA U ZAVISNOSTI OD VARIJANTE SLAGANJA SLOJEVA LAMINATA

Originalni naučni rad / Original scientific paper
UDK /UDC:

Rad primljen / Paper received: 1.02.2020

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Keywords
- bicycle frame
- composite materials
- fiber orientations
- fracture criterion

Ključne reči
- ram bicikla
- kompozitni materijali
- orijentacija vlakana
- kriterijum loma

Abstract

No matter what kind of bike the parts belong to (according to the requirements they need to meet), these parts are almost identical. The most complex bicycle part in the structural optimization for manufacture is a bicycle frame that can be made of steel, aluminium, titanium or composite material. All the parts on the bicycle are customized to the frame. Functional dimensions and angles should be taken into account when selecting the frame geometry. Manufacturers present them in the form of tables with a sketch of the frame itself. The process of development and identification of stress-strain distributions must provide unique insight into the behaviour of composite structures. This paper presents the results of structural analysis of a composite bicycle frame with clearly defined fiber orientations at the level of complex geometry, according to relevant load cases. Emphasis is placed on identifying critical zones on the frame when pedalling and crossing holes in the road. The modern ANSYS software package (module dealing with composites: ANSYS Composite Prep Post) is used for modelling and numerical analysis.

Izvod

Bez obzira kojoj vrsti bicikla pripadaju (u skladu sa potrebama koje treba da zadovolje), delovi na njima su gotovo istovetni. Najkompleksniji deo za izradu i optimizaciju jeste ram bicikla koji može da bude napravljen od čelika, aluminijama, titanijuma ili kompozitnog materijala. Svi delovi koji se nalaze na biciklu su prilagođeni ramu. Prilikom izbora geometrije rama, treba voditi računa o dimenzijama i uglovima. Njih proizvođači predstavljaju u obliku tabela sa skicom samog rama. Proces proračuna i identifikacije naponsko-deformacijske slike pruža jedinstven uvid u ponašanje kompozitnih konstrukcija. Ovaj rad predstavlja rezultate strukturalne analize kompozitnog rama bicikla sa jasno definisanim orijentacijama vlakana na nivou kompleksne geometrije. Naglasak je stavljen na utvrđivanje kritičnih zona na ramu prilikom pedaliranja i prelaska preko rupa na putu. Za modeliranje i numeričku analizu korišćen je savremeni softverski paket ANSYS (modul koji se bavi kompozitima: ANSYS Composite PrepPost).

INTRODUCTION

Although all bikes are visually similar, there are significant differences in requirements that need to be satisfied. Specifically, several types of bicycles are intended for riding on relatively flat terrain and longer sections, while the rest are intended for shorter distances and rough terrain. No matter what type of bike the parts belong to, they are almost identical /2/.

The bicycle part most complex for designing and optimizing is the bike frame. The frame can be made of steel, aluminium, titanium, or composite material, /11/. All the parts on the bike are customized to the frame. Functional dimensions and angles should be taken into account when selecting the frame geometry. Manufacturers present them in the form of tables with a sketch of the frame itself. For the same frame model, it can be observed that individual dimensions differ, depending on the frame size. Different authors in various papers and other references have provided many explanations for how particular dimensions affect performance.

A DK Publishing book /3/ deals with the history of bicycle development. Bicycles are shown, significant for specific periods of time, from the beginning to the present. The information on bike models themselves is purely informative and is a good start for further research. The book by Lopez and McCormack /5/ is a kind of guide for beginner cyclists, and provides detailed explanation on how to buy and maintain a mountain bike without going into too much technical detail.

To understand the mechanics of composite materials, the reader has possibilities to study basic textbooks and papers, authored by Daniel /6/, Guy /7/, Jones /8/, Gibson /9/, and Hayer /10/. They outline in more detail the properties of composites, the methods and ways in which they are obtained, and the constructions made from them. Basically, stress-strain distributions are calculated for the laminae and laminates, and are shown in relevant figures of this paper. The textbook /7/, e.g. abounds with real-world case studies of composite structural calculations and provides unique insights into the process of composite design, structural analysis and manufacture of structures.

The engineering design process itself covers all stages of realisation, from the creation of a product idea to the final product. Today, engineers in the design process have at their disposal powerful tools that they use to identify critical zones. Therefore, where the structure is weakest, a good structural design and rationalisation of weight and price of a bicycle in whole are a key factor. There are also detailed instructions on how to model structures in CATIA© and then test them virtually in ANSYS© software package. In addition, a reversible engineering procedure can be found, as well as a guide for 3D printing of assemblies, /2/.

The process of developing a complete mountain bicycle is time consuming and expensive. A modest number of scientific papers have been published dealing with bicycle frames. Papers /16, 19, 20/ deal with the analysis of a carbon/epoxy composite frame. The goal is to reach the optimal number of layers in the laminate for each pipe individually, so that it meets all three cases according to the ISO standard /2/, with appropriate testing /16/.

This paper differs from others in that it gives a clearly defined laminate configuration with fiber orientations at a complex geometry level. The emphasis in this paper is on identifying critical zones on the frame when pedalling and crossing holes on the road. A common feature of all significant papers on this subject is that they use modern modelling software with numerical tools (ANSYS© or ABAQUS©).

FAILURE CRITERIA OF COMPOSITE LAMINAE

For isotropic materials, a necessary and sufficient condition is to know at least one critical stress value at which fracture occurs, whereas this is not the case for composite materials. In today's engineering practice, there is a number of criteria that have been set up for analysis in most available commercial software, in accordance with the hypotheses: maximal deformations, maximal normal stresses, maximal shear stresses and Von Mises concept. The criteria used to determine the fracture of a composite laminate are based on classical fracture theories for homogeneous isotropic material. In the broadest sense, failure criteria of laminae can be divided into three groups /6/:

- non-interactive (criterion of maximal stress and maximal deformation);
- interactive (Tsai-Hil and Tsai-Wu);
- partially interactive (Hashin-Rotem and Puck's theory).

Tsai-Wu applied the failure theory to a lamina in plane stress. A laminate is considered as failed if it is damaged. This failure theory is more general than the Tsai–Hill failure theory because it distinguishes between compressive and tensile strengths of a laminate. The components F_1 - F_66 of the failure theory are found using the five strength parameters of a unidirectional laminate. More details on the failure criterion of the composite laminate are given in /8/, and a direct selection of relationships, regarding the results of analyses in this paper, are given in /2/.

BASIC INFORMATION ON THE STRUCTURE

The part that connects the seat support and the sprocket is the most complex part of the bike, so it must be carefully modelled at the frame level. The final design implies that all elements are connected into one system assembly (option: 'Join'). When completed, the model looks like in Fig. 1. This model is imported into ANSYS and does not initially need to be simplified to be virtually tested.

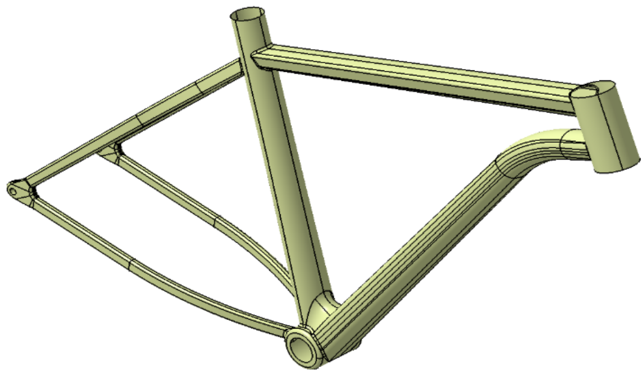

Figure 1. Appearance of the final bike frame.

A composite module (ANSYS Composite PrepPost) is used for purposes in this paper. Pre-processing consists of four steps. The first step is to define the material to be used. In this step, it is possible to select additional material from the library itself, or to create a new material with certain characteristics. The next step is to import the model from CATIA. Step three is to create a model with the definition of a finite element network. The program itself offers the ability to generate a network by some of its parameters. Here, an initial network of 62222 nodes and 63226 elements is generated /2/. Selecting the option: 'Model', it brings up additional options, of which the option: 'Named selection', allows multiple model surfaces to be grouped together into one whole. Figure 2 shows the top tube surface, consisting of six surfaces.

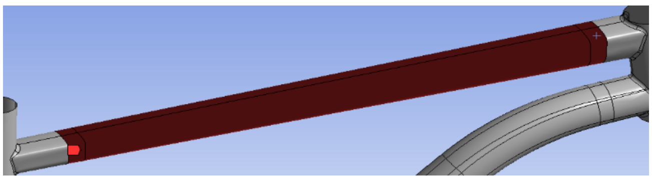

Figure 2. Upper tube of grouped surfaces

Other areas are similarly grouped. Each colour represents grouped surfaces, that is, one element of the bicycle frame, Figure 3. The edges, that will serve in defining the fiber orientations, are selected in the same way (the next step).

The last, fifth field, is reserved to define all the necessary parameters to obtain a composite model. Within the analysis option, it is possible to conduct analysis of entire laminates. Depending on the selected options, clicking 'Apply results', the data is graphically depicted in Fig. 4. From the CLT analysis drop-down menu, data on engineering constants and data on stiffness matrix of laminae (or laminates) can be obtained, /8/. The elements set parameters and edges are automatically linked using the ‘Named selection’ option from the previous step (Model). A parameter named ‘Rosettes’ represents a sort of coordinate system for fibers on a particular element. Right-click the ‘Rosette > Create Rosette’ option to create the desired rosette. Double-clicking on it opens the window shown in Fig. 5.

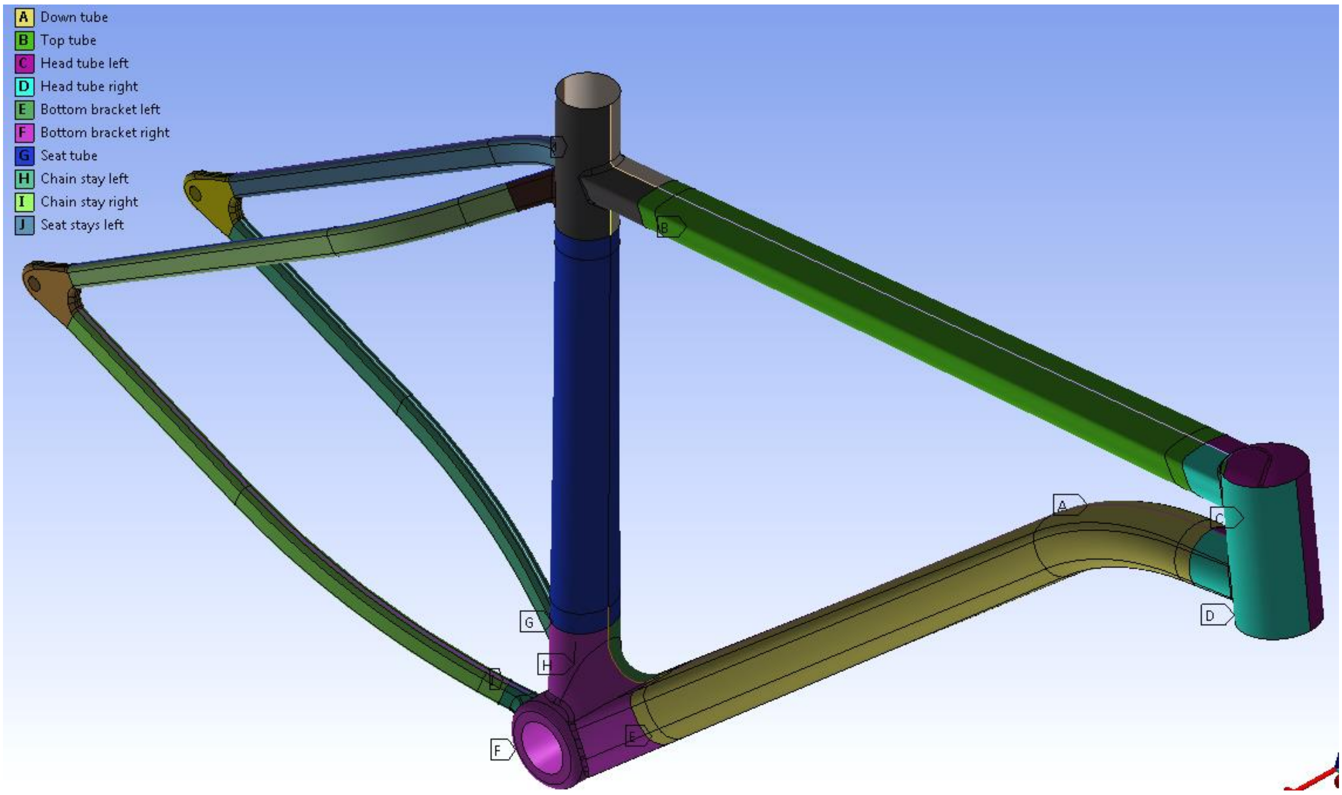

Figure 3. Grouped frame elements.

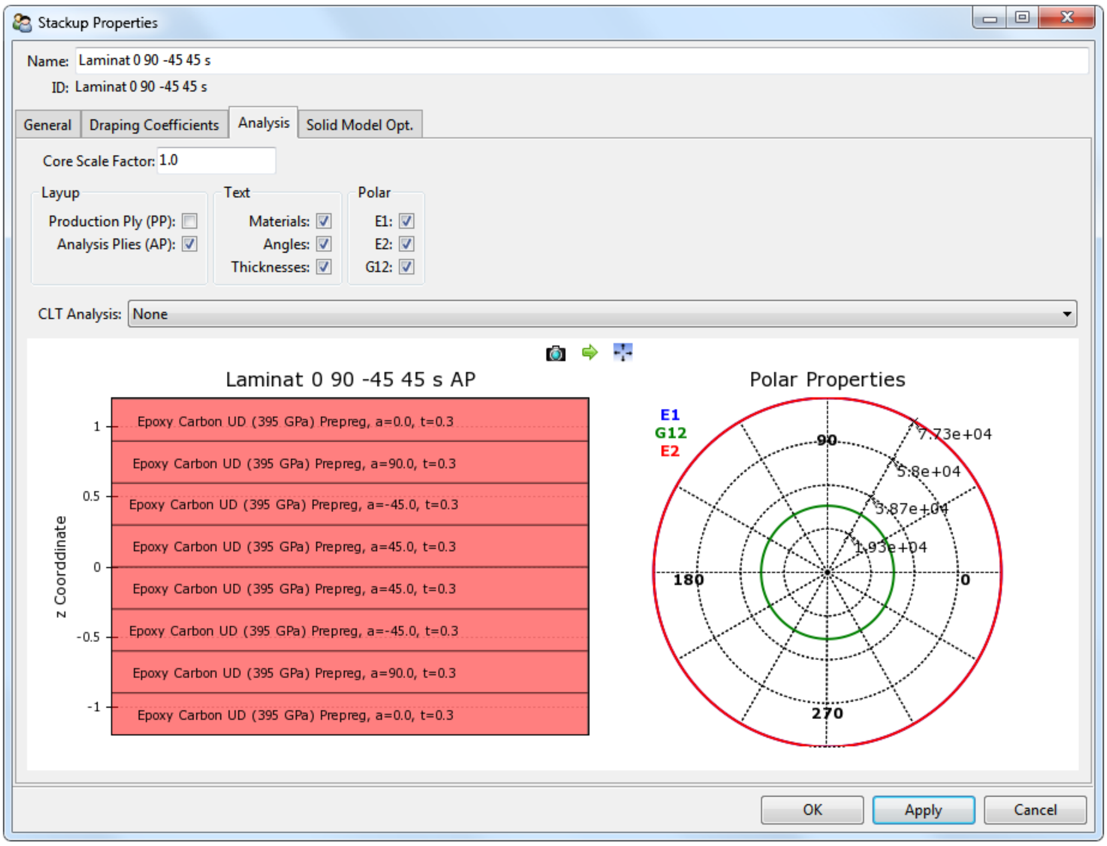

Figure 4. Analysis of laminate.

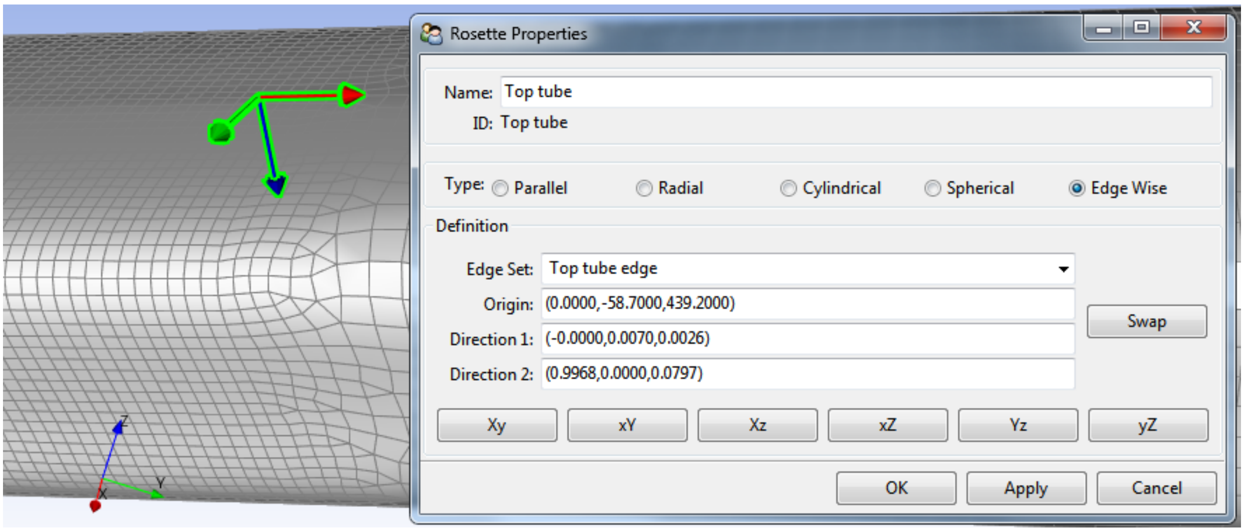

Figure 5. Defining the 'Rosette'.

The type of rosette is selected first. Each type of rosette has its own specific characteristic. 'Edge wise' means that the fiber reference direction will follow the edge, while 'Parallel' follows the direction exactly as the rosette coordinate system is set, /12/. The first option allows to select the line to follow, and the line itself is selected from the drop-down menu. The second option allows the coordinate system to be defined, while the third and fourth options serve to define lines 1 and 2, longitudinal direction of the fiber and the transversal direction, respectively. Lines 1, 2 and 3 are visually represented in this software package, i.e. that each colour corresponds to one direction (directions are indicated as: red - 1, green - 2, blue - 3).

This visual rule applies to every rosette that is made, allowing the user to easily and quickly check that everything is correct without including additional options. It is desirable to define as few such coordinate systems as possible to facilitate manipulation of the fibers. In some cases, multiple rosettes need to be combined to obtain the desired fiber orientation. When all the necessary rosettes are set, several parameters need to be combined into one unit and added to another feature (parameter: 'Oriented Selection Set').

The last option defines a zero degree and it is possible to select multiple rosettes in it to configure the direction correctly. It is necessary to choose one of the applied methods to know which rosette has primacy on a particular set of elements, /12/. Clicking OK completes the definition of this parameter.

STATIC STRUCTURAL ANALYSIS AND ANSYS© POSTPROCESSING

In this paper, virtual testing is performed based on the content of papers /16, 18, 19, 20/ and ISO standards /17/. The results of these analyses are presented in detail in tables, and the boundary conditions, reactions and forces are presented individually for each case, /2/. The network used for all tests finally contains 99812 nodes and 102839 elements. A drastic increase in the number of elements and nodes relative to the initial network is due to the need to obtain more accurate values at bar (pipe) joint locations.

Tests are performed for the following cases:

- testing when the driver is pedalling with a force of 1200 N;
- vertical testing to determine how the frame behaves when a person weighing 120 kg is seated on the frame;
- horizontal testing with a force of 600 N (when driving on rough terrain, the driver encounters obstacles in the form of tree roots, stones, holes, etc.);
- horizontal test with force of 1200 N (the test mode differs from the previous test only in the direction of force action).

In order to confirm the assumption in the first virtual test (the exerted force by the driver on the pedal), as the next case is generated, the fifth case is subsequently made, representing the most realistic case. The force is transmitted over the surface of the seat bar (tube) while the support is placed on the upper and lower edge of the steering tube. Boundary conditions defined in this way represent substitutions for components that would also need to be modelled. In Fig. 6, the deformation values are shown, while the red lines represent boundary conditions for case 5.

Figure 7 shows the support per line for case 4. In cases 1 and 4, the largest deformations occur in the lower tube (Fig. 8), and in cases 2 and 3 on seat supports (Fig. 9). Table 1 shows all IRF (inverse reserve factors), MOS (margin of safety), deformation and stress values for each case.

Table 1. Cases of horizontal tests during impact with an obstacle.

case	IRF	MOS	strain (mm)	stress (N/mm^2)
1	0.6162	0.62278	2.6432	283.33
2	0.2954	2.3853	0.7504	155.11
3	0.2890	2.4598	0.7341	152.17
4	1.0557	-0.0545	3.8973	659.91

From Table 1 it can be seen that frame failure appears only in case 4.

The critical part is shown in Fig. 10. The two (2) mark indicates that the failure in the laminate occurs in the second layer according to the Tsai-Wu criterion. If 'Ply-wise' is selected in the 'Failure' option, it will be possible to go and see layer by layer through the laminate. Turning on this option gives a visual representation of where the critical point is in the layer, and the corresponding IRF value, Table 2.

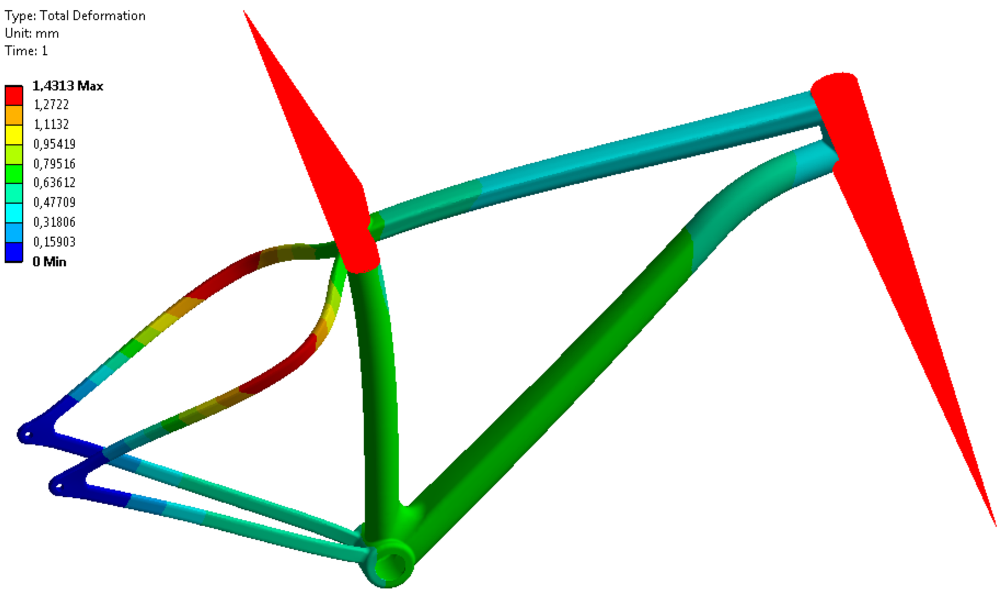

Figure 6. Visual representation of deformations and boundary conditions in case 5.

Figure 7. Front boundary conditions for case 4.

Figure 8. Horizontal force of 600 N (case 1).

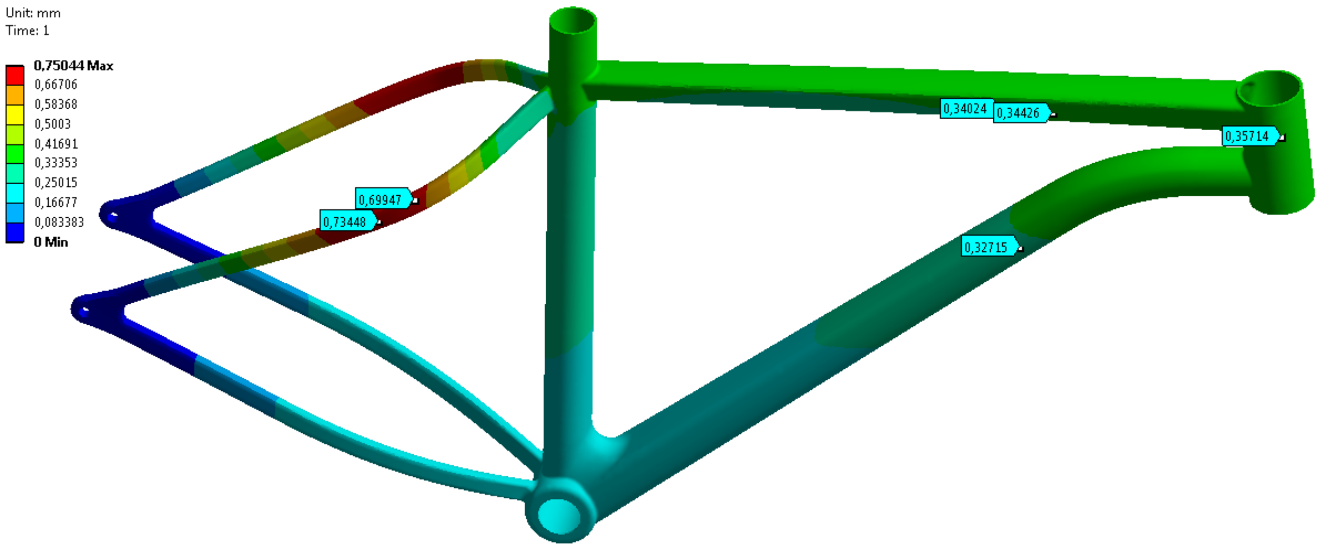

Figure 9. Horizontal force of 600 N (case 2).

Table 2. IRF values for individual layers, case 4.

	IRF 1	IRF 2	IRF 3	IRF 4	IRF 5	IRF 6	IRF 7	IRF 8
Case 4	0.81	1.06	0.76	0.35	0.31	0.49	0.55	0.61

Figure 11 shows the critical area where the frame is fractured. Since no fracture has occurred in the other regimes for adopted cases, it is now necessary to make changes to the frame dimensions (or configuration) at critical points.

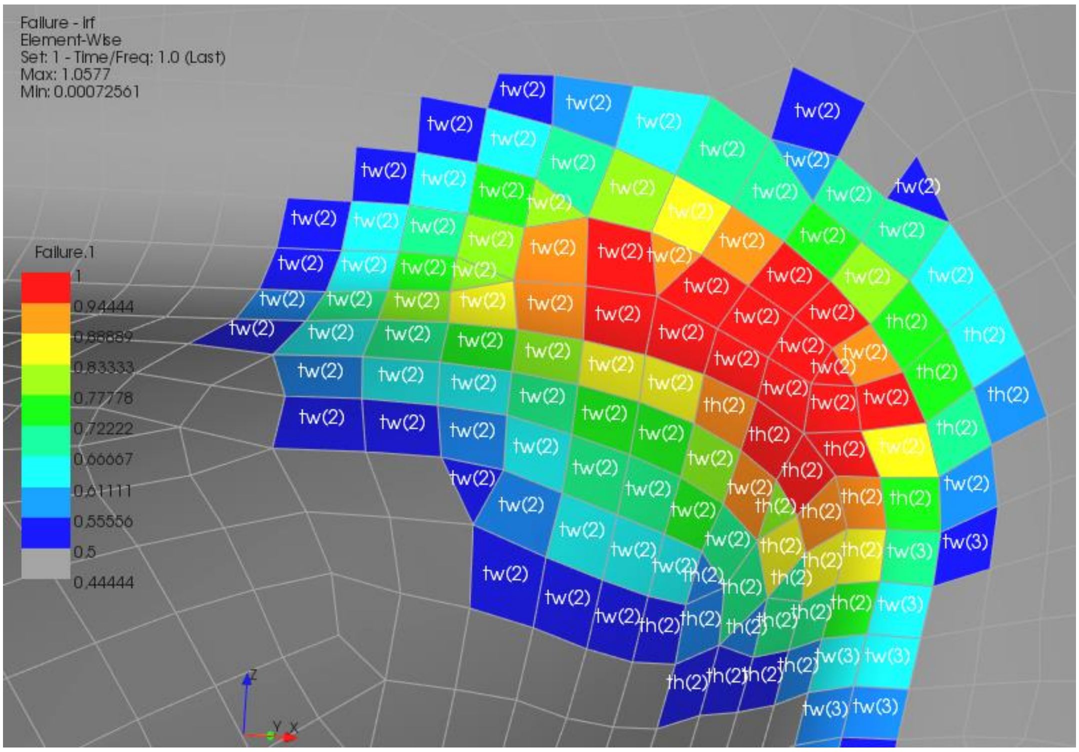

Figure 10. Case 4, IRF around the transition from the steering tube to the upper tube.

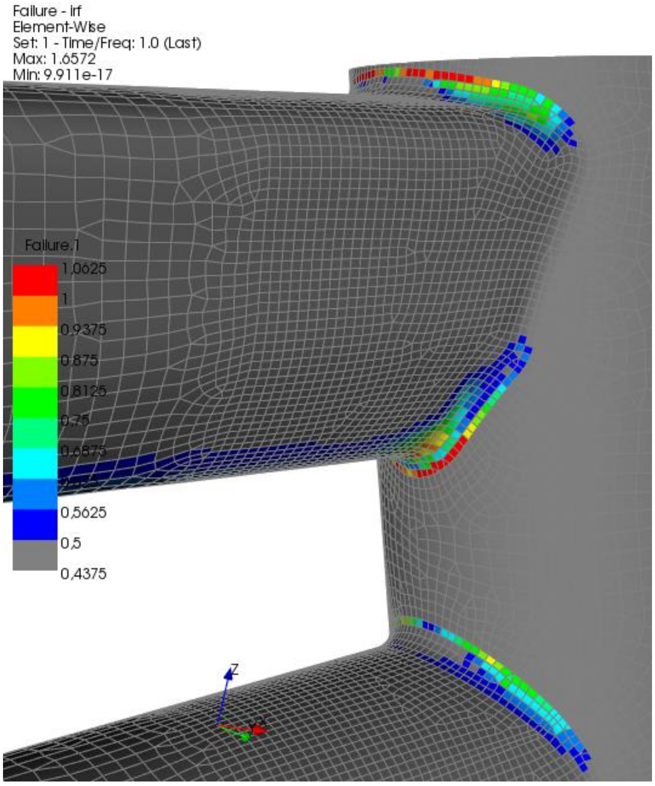

Figure 11. Case 1, IRF factor around the transition from the steering tube to the upper tube.

FRAME MODIFICATION

The results obtained for each regime (and specific load case) indicate that the critical areas in which frame fracture occurs (or there is a possibility of frame fracture) are precisely transitions from one level to another of structures themselves. There are two variants that can be used to solve this complex problem. The first option is to modify the frame geometry at critical points (zones), and the second is to include additional layers at critical points.

Case 1 of the previous test regime is adopted, and the simplest modification of the steering tube and certain parts of the lower and upper pipes is used, which is to add another layer of already predefined laminate [0/-45/+45/90]s. With this intervention and new analysis, it is determined that no fracture will occur, /2/. After that, the remaining problem is how to connect parts of different diameters, because an unrealistic picture of stresses, deformations and other parameters is obtained (jumps occur at places of different pipe thicknesses). Because of that, it is necessary to define the transition areas between the upper and lower pipe sections that connect to the steering pipe. Defining the solution is extremely easy and takes a few steps. The first step is to define the transition areas, i.e. the overlap of the upper and lower pipe on one side and the steering tube on the other ('Named selection' is used) in order to define overlapping surfaces and boundaries where they end. The 'Setup' and 'Update' options are then used to keep all parameters updated. For desired pipe modification it is necessary to open 'Modeling Ply' and in the 'Thickness' option to define all parameters within the 'Taper Edges' option, /12/.

This process is repeated until all transitions are satisfactorily achieved (realistic model with low level stress concentration). Figure 12 shows the cross-section of the steering tube and the upper tube. From the image itself, it can be observed that the thickness of the laminate from the steering tube to the upper tube is gradually reduced in order to provide proper geometry. The final step is to release a new simulation to check for fracture and to determine if there are any unwished effects at the crossing. Table 3 shows the values of both cases (before and after modification).

From the data provided, it can be concluded that the stress values have decreased significantly, and deformation values have also decreased. Figure 12 shows the deformation state of the frame, the most critical parts being the lower and upper tubes and partly tube of the seats.

Table 3. Comparison of case 1 and its modified version.

	IRF	MOS	strain (mm)	stress (N/mm^2)
Case 1	1.657	-0.3966	5.2864	566.65
Case 1 mod.	0.799	0.25015	4.9865	378.01

Comparing Figs. 11 to 13, it can be observed that the critical zone is now at the point of intersection of the upper tube. This solution is not ideal, but it is certainly better than in case 1.

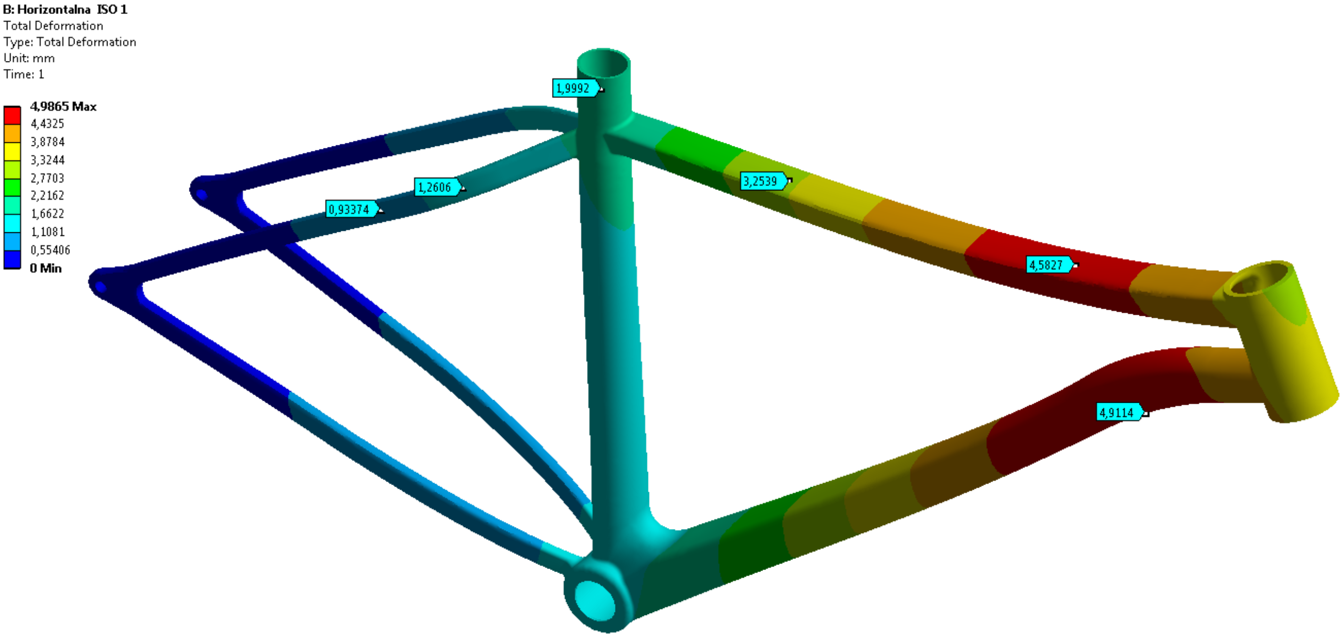

Figure 12. Modified frame deformations (case 1).

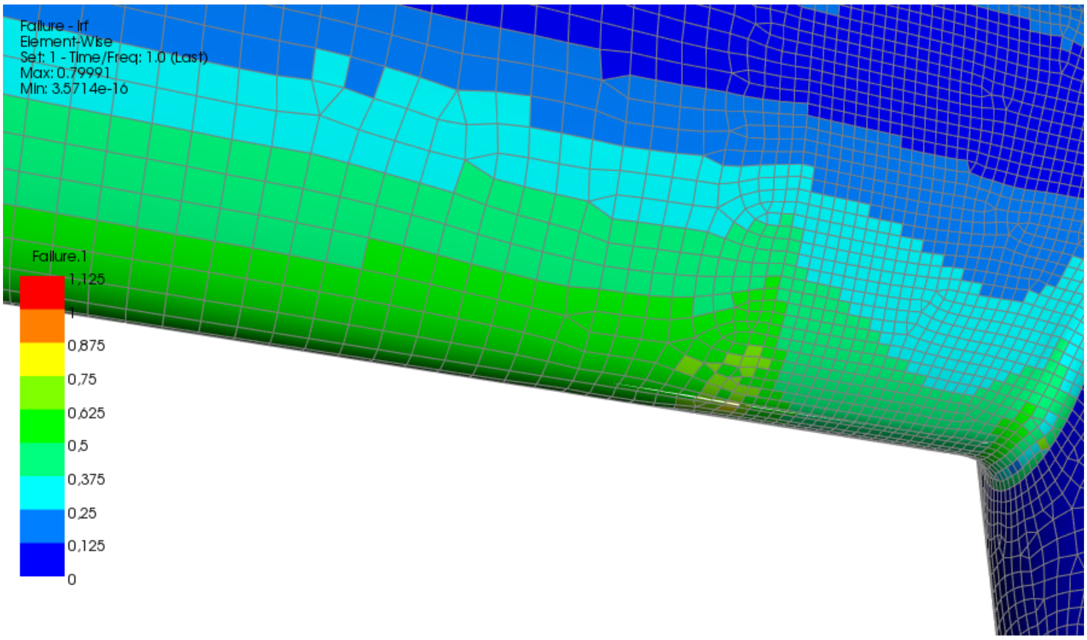

Figure 13. Modified frame (case 1) - IRF around the transition from the steering tube to the upper tube.

CONCLUSION

It is evident that it is crucial to make correctly the definition and construct the frame, which will allow the cyclist to ride reliably and safely, and to enjoy the ride. The cyclist must be safe that during the ride, there will be no frame failure (if he/she encounters an unforeseen situation). Since this is a vital part of the bicycle, whose failure can endanger the safety of the cyclist, the proper construction of that part is made for every possible situation.

The paper deals with a part of the process of constructing a bicycle frame (definition of basic geometry, profile of pipes and supports), including the final model and virtual testing in different situations. The configuration of the frame, the profiles of tubes and supports, are made as a functional assembly that at the same time gives an aesthetically acceptable solution. The advanced CATIA software option is used in the frame modelling process. After defining the model, calculations and virtual testing is performed using the finite element method in the ANSYS software package, /2/.

It is found that the bicycle frame has failed in only one of the relevant cases (case 1 at horizontal force of 1200 N). In the next step, because of the right modification made in the critical part, the newly obtained results show that the failure of the structure will not occur. Thus, for the modified frame, the tests are repeated in other relevant cases (1 and 2), where obtained results show that absolute values of stresses are lower than absolute corresponding values indicated in relevant tables, /2/. Other cases (3 and 4) for different situations are not taken into account, because the probability of them happening in reality is very small (practically, it is impossible for fracture to occur).

For the latter situation only, a virtual examination of case 4 is conducted and the values obtained are such that an error can be referred (i.e. IRF values are slightly above 1). Otherwise, had all the cases been taken into account, the frame itself would have been oversized, and thus, heavier and more expensive.

It is evident that there are some situations where modelling of additional components is still necessary to create a more accurate picture of the stress-strain state of the frame. The values of the parameters obtained in this paper should be taken with reserve, that is, they should be interpreted as a good approximation. The concrete values need to be confirmed by detailed experimental testing of the manufactured prototype (and serial product) under real conditions.

Future research directions in the subject area could include optimization of the structure, above all the frame itself, with respect to laminate configurations and thicknesses of pipes and supports, as well as research and testing the behaviour of the supporting structure of the frame, if falling from the bicycle at a certain height. Everything is subject to controlled modifications, from the selection of the base material to the achievement of suitable geometry of the structure (pipes, zones around the steering pipe, as well as seat supports), and reliable satisfactory solutions regarding all interfaces of structural parts.

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