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Experimental Verification of Ski Model for Finite Element Analysis

ZBONČÁK Radek[1, a]

[1]Svárovská 619, 46001 Liberec, Czech Republic

[a]radek.zboncak@vuts.cz

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Abstract. The topic of this work is FE analysis as a first step to understanding of mechanical performance of a ski. At the very beginning a real part scanning has to be done because only hand drawings of the design is available. Creating of a CAD model by reverse engineering is obvious following step to prepare input CAD data for later simulation. The carbon fiber composite ski has sandwich structure with a wooden core. Material testing is an inherent part of any analysis so all represented materials are tested according to testing standards with respect to the anisotropy. In this sense there are three types of used materials – an isotropic, an orthotropic and a transversally isotropic material. Two different types of extensometers (mechanical and optical) must be used as material like wood needs special treatment. The FE model of a ski middle part is created in software Siemens NX using Laminate Composites module (NX LC). The behavior of the FE model is compared with experiment based on deflection in three point bending test. If the resultant deflections show deviation optimizing modifications are done to fit the model more precisely. Deviation of 3 % is reached for this model without any special interventions which means good experimental results. Flexural performance as a predominant loading of the ski is simulated in FEA to get the stress distribution in the ski and in each layer of sandwich structure. In this phase of analysis the exact values of stress are not so important as the way of stress distribution which the work is focused on.

Introduction

The composite materials are used in various occasions. Aerospace is an example of one of well-known hi-tech applications. But there are many other areas where high performance parts are needed or weight reduction is important aspect. The sport, where limits are moved every day, is an excellent example of application of composites. High demands on stiffness, strength and weight reduction is the main way how to reach better results.

This paper is focused on skis. First modern skis were designed by Sondre Norheim in 1870. From that time various materials and their combinations were used to get best performance. In these days, sandwich structure with wooden core is used for high performance skis. Modern cores are made of glued oriented wooden stripes and the top and bottom skins are made of laminates. This combination is proven by practice as the best. But trial and error method usually used by manufacturers is a time consuming approach which consequently costs lot of money. Despite of that fact it is still most widespread approach in ski design. That also reflects the fact that every individual skier has subjective perception of movement and ski performance which makes manufacturing of one perfect ski for everyone almost impossible. There are some efforts to use FEA and optimization methods in design process, but it still does not reach the level of required accuracy and sufficient conformity with the experiment [1]. The material properties and some additional negative effects which are inseparably connected together with manufacturing process are the biggest issue. For example, not properly fulfilled material datasheets or thermal expansion of different used materials which can cause creation of inner tension after cooling down during curing. It can be said, that mechanics of ski is very complex problematics based on understanding and creation of material respectively FE model [2] [3].

The manufacturer of the ski has not had any CAD data. The geometry of the ski is defined only by dimensions in several cross sections positioned alongside the ski length. Therefor the first step is to make a scan of the manufactured ski so the computer model can be created. The output of the scan is a cloud of surface points in *.stl* file (Fig. 1). Then the reverse engineering techniques are used to make a CAD model of the ski. Material properties of the individual constituents of the sandwich structure – wooden core, top and bottom laminate, plastic base and steel edges; are determined experimentally by testing according relevant standards.

Fig.28 Scan of the ski

Experimental data are evaluated and mechanical properties of the material such as moduli and Poisson's ratios are determined by analytical calculations to define material in FE analysis. There are three types of anisotropic material used in the model – isotropic (plastic base or coating), orthotropic (laminate skins) and transversally isotropic (wooden core). To declare that wooden core is transversally isotropic material is a sort of simplification. On the other hand, the fact that the core is glued together of several oriented thin wooden stripes increases the effect of transversally isotropic behavior of the core. Setting up of the FE model is tuning of parameters so that model performs in the same way as the real part during the experiment. In our case the calculations of material properties are done mainly based on tensile tests and the flexural test of the middle part of the ski is what is used to match simulation results with experiment. The maximum acceptable deviation of simulation and experiment is about 15 % which is generally stated value of deviation tolerance.

Experiment and Calculations

Constituents' properties of laminate and properties of wooden core are identified by experiment or used from material datasheets. Sometime is needed to verify the data provided by the manufacturer or supplier of the constituents. They can differ from the reality as they are determined in laboratory conditions. In case of experiment following standards for tensile test and flexural test are used: ČSN EN ISO 527-4/1, ČSN EN ISO 527-4/10, ČSN EN ISO 527-4/50 and ČSN EN ISO 6892-1. Laminates and wood are orthotropic and transversally isotropic materials where 9 and 5 elastic constants (Young's and shear moduli, Poisson's ratio) must be determined to fully describe the material. Those which cannot be measured must be calculated or estimated by prediction methods. Different behavior in tension and compression must be taken into account as well. In case of isotropic material just 3 elastic constants must be evaluated.

Steel is used for edges to increase their endurance. Edges do not have any serious influence on the total ski stiffness or strength. The material is isotropic and Young's modulus E, shear modulus G and Poison's ratio ν are used from material datasheet because the dimension and shape of the edge does not allow the test to be performed. The relationship among these three elastic constants for mentioned isotropic material is

$$G = \frac{E}{2\cdot(1+\nu)} \tag{1}$$

In case of plastic base (coating) and wooden core, three methods of elastic constants determination are used – biaxial extensometer (Biaxial), advanced video extensometer (AVE2) and digital image correlation (DIC). Biaxial is mechanical extensometer which is clipped directly on the specimen and one can get Poisson ratio directly as the device measures longitudinal and transverse deformation at the same time. Handling with this could be a problem if the specimens do not have acceptable geometry, for example if they are too thin like the plastic base. It is realized that also soft material such as "*balsa-type*" wood can be a problem because sharp blades of the extensometer can cut in the specimen just by the gripping force. And that can influence the value of resultant deformation. Improvement in accuracy is expected from using of video extensometer (AVE2 and DIC) which is confirmed by the results. However there are still some issues with recording of deformation in transvers direction.

Plastic base is also isotropic material. Young's modulus and Poisson's ratio are determined experimentally according tensile test standard ČSN EN ISO 527-2/1. Then the shear modulus is evaluated from the equation (1).

Wooden core is made of light so called *"balsa-type"* wood, which means good mechanical properties combined with low density. The core consists of glued thin slices of wood. Generally the properties of wood vary a lot thanks to variety of imperfections in the natural structure. The consequence of such a glued structure are more balanced properties. As it is mentioned above, the wood is taken as transversally isotropic material which means that 5 elastic constants are needed to define material properties. Tensile test in longitudinal and transversal direction is performed with biaxial extensometer, which allows to construct Mohr's circle for stress and strain in case that one is able to pair two tensile tests in sense of corresponding stress and strain in longitudinal and transvers direction. Principal stresses and strains have indexes *L* in longitudinal and *T* in transverse direction.

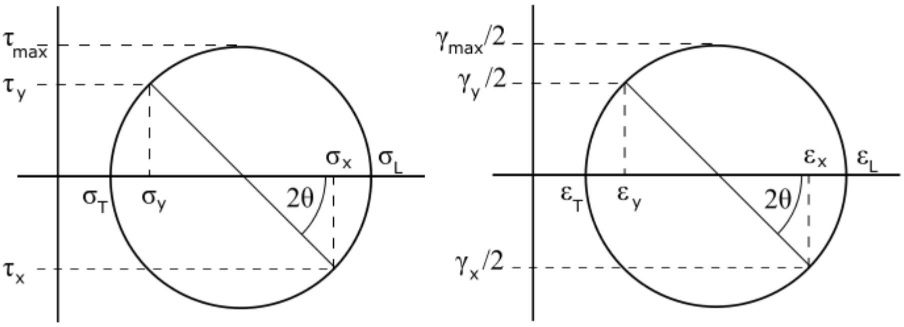

Fig.29 Mohr's stress and strain circle

The relationship between principal stresses and strains in plane is

$$\begin{Bmatrix} \varepsilon_L \\ \varepsilon_T \\ \gamma_{LT} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_L} & \frac{-\nu_{TL}}{E_T} & 0 \\ \frac{-\nu_{LT}}{E_L} & \frac{1}{E_T} & 0 \\ 0 & 0 & \frac{1}{G_{LT}} \end{bmatrix} . \begin{Bmatrix} \sigma_L \\ \sigma_T \\ \tau_{LT} \end{Bmatrix}. \tag{2}$$

One can get E_L, E_T and ν_{LT} from the first two equations and the additional one based on the matrix symmetry

$$\frac{\nu_{LT}}{E_L} = \frac{\nu_{TL}}{E_T}. \tag{3}$$

Shear modulus G_{LT} must be determined from another test. For θ equal to 45° the shear will be maximal. Applying transformation from global (*LT*) to local (*xy*) coordinate system local stresses and strains are obtained.

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_x} & \frac{-\nu_{yx}}{E_y} & \frac{\eta_{xy}}{G_{xy}} \\ \frac{-\nu_{xy}}{E_x} & \frac{1}{E_y} & \frac{\mu_{xy}}{G_{xy}} \\ \frac{\eta_x}{E_x} & \frac{\mu_y}{E_y} & \frac{1}{G_{xy}} \end{bmatrix} \cdot \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}, \tag{4}$$

where η and μ are nonconventional coupling coefficients which show that normal stress induces a distortion. To remind, the matrix in *x*-*y* coordinates is symmetrical. Additionally the tensile test of the coupon with different fiber orientation than 0° is made to get E_x. With knowledge of E_L, E_T and ν_{LT} from the previous tests and measured E_x the G_{LT} can be calculated.

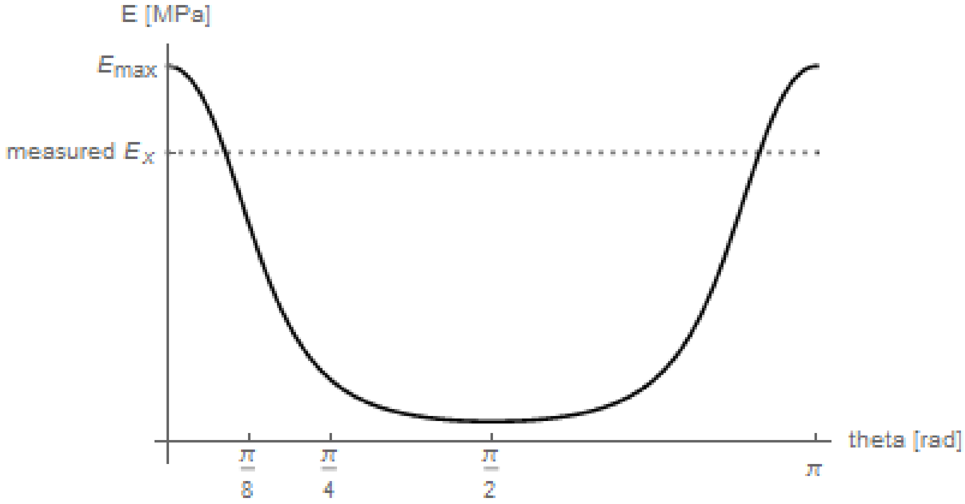

Fig.30 Transformation of modulus E_x where $E_{max} = E_L$

Laminate properties are evaluated from the theoretical values for high strength (HR) carbon fibers and epoxy resin using predictive micromechanical models [4]. This partially idealized approach is selected because of circumstances arising from impossibility to manufacture the specimens with the same hot press molding technology under the same conditions. Laminate is created in SW Siemens NX, where constituents' properties are defined and the software itself computes the laminate properties.

Finite Element Model

As mentioned above, the key is a creation of a precise model of the ski. Because of its complexity, a certain degree of simplification is always needed. And that is what this approaches differ in. Other models are often made as a simple prismatic sandwich beam which seems to be too big simplification where the idealization causes difference of simulation results and experiment. This could lead to inappropriate adjustment of material properties values. The point is to find such approach which will be simple enough to be computed and in the same time complex enough to get the results corresponding the experiment or reality with respect to part geometry.

First of all the scan of the real ski is done and CAD model is created from *.stl* file by reverse engineering techniques. The middle part of the ski is cut out and that as a solid body is used for finite element model.

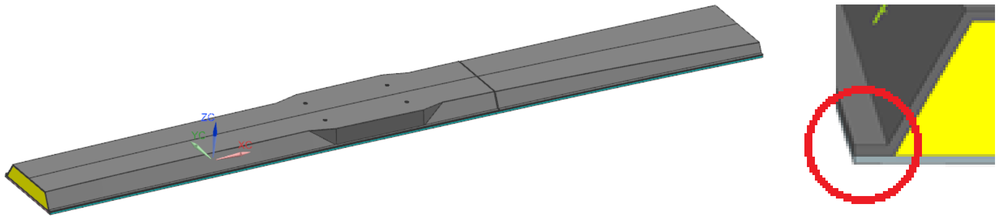

Fig.31 CAD model of the part middle part of the ski (left) and detail of the ski edge (right)

It is split into top, middle and bottom parts which stand for top laminate, core and bottom laminate of the ski. Laminates are extruded on 2D element meshes and core is meshed with 3D elements [1]. All geometrical details are preserved as shown on Fig.31.

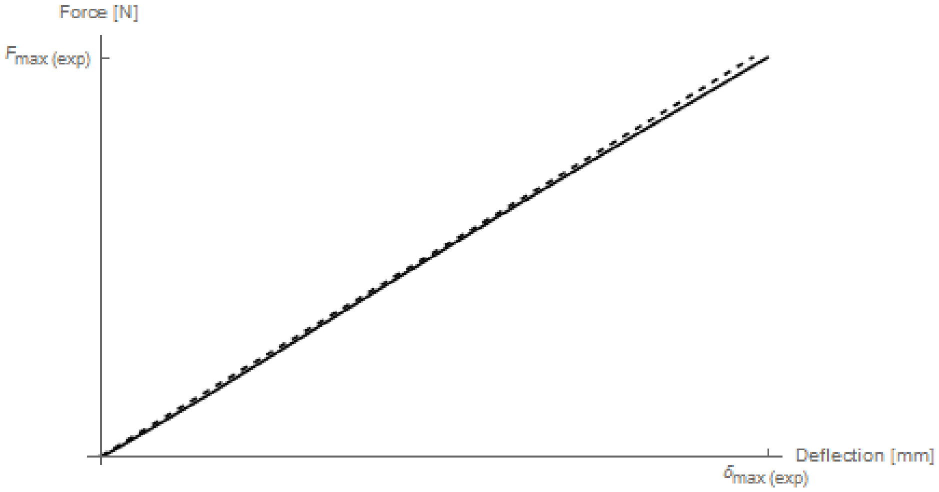

Fig.32 Deflection of the ski from the experiment (thick line) and from FEA (dashed line)

All elastic constants are determined in tensile test. But the bending as a type of major loading is simulated. That fact is taken as an advantage because it should eliminate the potential introducing an error into the result. The actual difference between experiment and FEA result is 2.3 %. The fact that FEA model has lower deflection than the real part is a consequence of geometrical idealization of a model and simplifications made during calculations. The conformity of simulation and experiment is under the acceptable deviation and so defined material can be used for simulation of entire ski.

Finite Element Analysis of Entire Ski

Based on the created model of the ski structure the FEA of the entire ski is done. As the ski is symmetrical along its length, only the half of the ski is simulated. Load and constraints are selected to correspond with typical loading state for ski which is primarily bending. The same three-point bending as for finite element model of the ski middle part is used to have the same conditions for the ski. Constraint supports are moved apart as much as possible to simulate worst loading conditions.

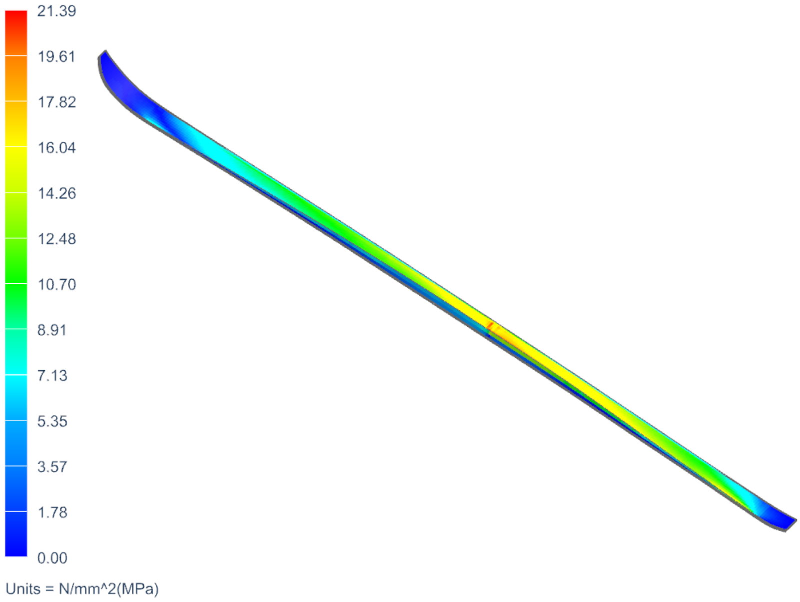

Fig.33 Simulation result

The absolute stress values are not so important in this moment. The attention is focused on the stress distribution in the ski and in each layer of sandwich structure. This information is used as input data in further calculations and FEA with the aim to optimize the structure. Optimization criteria are high stiffness and maximal weight reduction at the same time. These are activities of further work.

Conclusions

Even if the geometrical model is prepared precisely and the simulation constraints are set in an appropriate manner to correspond the real state, the deviation of the result of the complex model is still considerable. The obvious reasons are simplified calculation theories and inevitable idealization of the model. And there are some influences which still cannot be included in the simulation at all, such as some consequences of technological processes. On the other hand, partial results have sufficient precision and can be successfully used in particular steps during design process which definitely reduce labor time and cost. It is possible to design sandwich parts (facesheet and core) with sufficient precision if the model has basic geometry. Then the results can be successfully used for further computations such as optimization of laminate by certain parameters.

The experimental determination of material data is an issue itself. Especially for materials like wood which has scattering of values of its mechanical properties. Such experiments are very sensitive to size of the specimens and test conditions. Also large number of samples must be tested to get a good statistics.

Resultant deflection of the FE model differs about 3 % from the experiment. That is considered as a good result. But this is just first step to further work which is optimization process and one must remember that the results does not include for example influence of binding which causes local stiffening in the middle section of the ski.

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