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COMPUTATIONAL METHODS FOR WIDER APPLICATION OF SHORT-FIBER COMPOSITE

Zuzana MURČINKOVÁ [1]

Abstract: *The paper dealt with influence of development of computational methods to designing the structures in near history and present period. Moreover, paper dealt with increasing of utilization of composite materials in last decades and with possibilities of wider application regarding to specialized computational methods for different kinds of composites. In case of short-fibre composites it provides the potential strategy for designing the components with fibre orientation according to load.*

Key words: *computational method, material, composite, fibre reinforcement, fibre orientation.*

1. INTRODUCTION

Composite materials are not new material in mankind history. Among the firstly used composites there were unburnt clay bricks consist of clay (matrix) and straw, reed or grass stalks (oriented fibres). The ancient composites were generated without computational methods but based on experiences and knowledge obtained during longer periods.

Even, the titles of single historical periods are defined according to used material for tools or weapons – stone age, bronze age and iron age. One can see that in historical periods the man is returning to already known things that serve as resource of knowledge. The man makes some re-discovering but every time it creates also the new added value.

Presently, we are re-discovering the composite materials and the added value is creation of new and superior and more sophisticated materials, but also computational methods, manufacturing technologies and applications (Fig. 1). Sophisticated and progressive materials are developed thanks to new computational methods used in designing process of either material or composite component and furthermore thanks to new manufacturing technologies of materials.

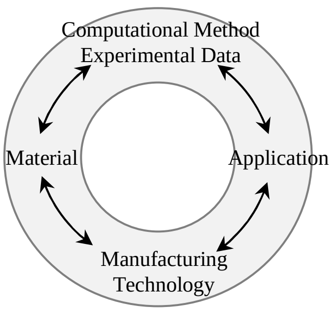

Fig.1. System.

[1] PhD, Eng., Lecturer, Faculty of Manufacturing Technologies in Prešov, Technical university Košice, Department of Technological Devices Design, Štúrova 31, 080 01 Prešov, Slovak Republic, E-mail: *zuzana.murcinkova@tuke.sk*

The four mentioned elements, it means material – computational method – manufacturing technology – application, create system that is schematically shown in the Figure 1. Finally, the outcome of interaction among the first three elements is application; it means the sophisticated product based on composite materials.

2. ANALOGY

The analogy can be made with steel (iron) that was not the completely new material in the middle of 19th century. The steel became the re-discovered material regarding to new technologies of steel production in 19th century that allowed the wide industry applications and also the low price of steel. The possibility of usage the steel as engineering material the new methods had to be developed. Many scientists contributed to development of mechanics and its computational methods in 19th century such as L. Navier and his theory of beam bending and computing of suspension bridges, G. Moseley and his first theory of steel bridges computing, L. Schwedler and his theory of space arched roofs, S. Poisson, B. Saint Venant, G. Lamé, B. Clapeyron, D. Maxwell, L. Cremon, K. Coulman and others who concern to graphical and graphic-analytical methods of structure estimation.

We can declare the influence of computational method and new material to structure by bridges built in New York between 19th and 20th centuries. The firstly built Brooklyn Bridge was the bridge connecting the single parts of New York. However, Brooklyn Bridge involved new material in form of steel ropes (the first suspension bridge using the steel ropes), it has robust construction (stone bridge towers), and it was being built for 13 years (finished in 1883). The new computation methods (Moisseiff's deflection theory) applied to material and used for other bridges in New York changed bridges to lighter-weight, all-steel and longer constructions that were built in much shorter time.

Moisseiff's deflection theory was used to design Manhattan Bridge with steel towers. L. Moisseiff had become a leading suspension bridges engineer in USA in the 1920s and 1930s. He made such saving modifications in construction of Tacoma Bridge (the third longest sus-

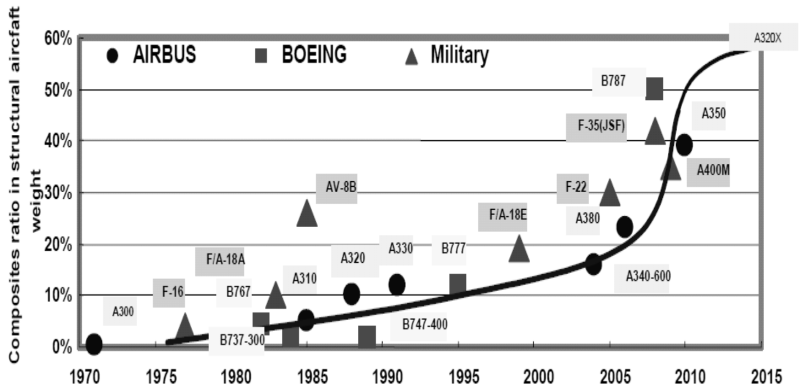

Fig. 2. Structural weigh of carbon fibre composite [4].

pension bridge span in the world in its period) based on his theory that resulting the collapse in four months. The failure confirmed the limitation of hid theory.

Naturally, the usage of steel definitely changed the arms and weapons of that time armed forces. Since 1900 the all battle ships as the guns and cannons were made of steel. Many new weapons as the machine guns, submarines and tanks (the first in 1915) could not be made of other material than steel.

The similar situation in field of composites is in aircraft and armament industry. It was the first that starts to use composite materials and it still moves the usage possibilities of composites. Presently, the composite materials are in use of all industries. However this field can present the case of engineering work failure (except the Tacoma Bridge). It was the Challenger Space Shuttle accident in 1986. The designers inclined in design of failed component to experimental data without specific theory [2].

The mentioned two cases of engineering fail (Tacoma Bridge and Challenger accident) in 20th century serve as examples of two anti-poles: computational method and experimental data. It is needful to realize that there are two sides of the same coin.

3. COMPOSITES

While in 1970s the share of carbon fibre composites used in Airbus aircraft was only 5%, at the beginning of 1990s it was 10% and at the beginning of 21st century 15%. The share was 22% in Airbus 380 in 2005 and the new Boeing 787 (the first fly in December 2009) involves 60% of carbon fibre composites [4]. The composite usage increment is evident in Fig. 2.

The term composite material (shortened to composite) includes the large range of designing materials because the definition of composite material allows it. Composites are engineered materials consist of one or more discontinuous phases embedded in a continuous phase. The discontinuous phase is usually harder and stronger then continuous phase and is called the reinforcement (reinforcing material), whereas the continuous phase is termed matrix [1]. The classification of certain materials as composites often is based on cases where significant property changes occur as result of the combination of constituents; and these property changes generally will be most obvious when one of phase is in platelet or fibrous form, when the volume fraction is greater

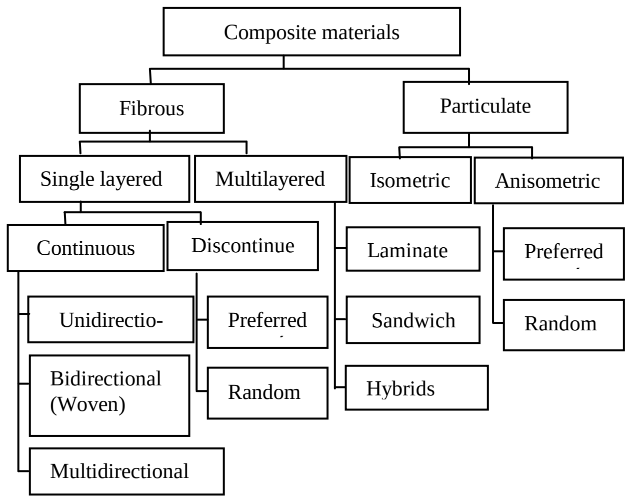

Fig. 3. Classification.

than 10% (some authors show 5%) and when the property of one constituent is much greater (≥5 times) than the other [1]. The composites are classified usually on the basis of the geometry of reinforcement (Fig. 3).

The steel alloys are not considered as composites. The modulus of elasticity of steel alloys is insensitive to the amount of the carbide present. The common metals contain impurities or alloying elements, also plastics contain fillers. Such materials are not composites regarding either small volume fraction or the properties of constituent phase are nearly identical. In terms of structure metal alloys and plastics are good examples of composite material.

4. DESIGNING OF FIBRE COMPOSITE STRUCTURES

The designing either of structure or material are two connected fields influencing one another. The classical designing approach supposes the homogeneous and isotropic material.

Dimensioning the components on base of the most stressed place provides the over dimensioning in other parts of components. The failure criterion is fulfilled in the most stressed place and other parts of component are over-dimensioned regarding the lower stresses. Considering the oriented material structure, the most stressed locations can be reinforced and moved to other parts of component.

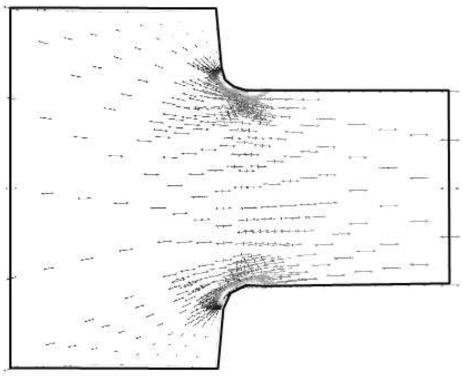

Fig. 4. Principal stresses-fibre orientation.

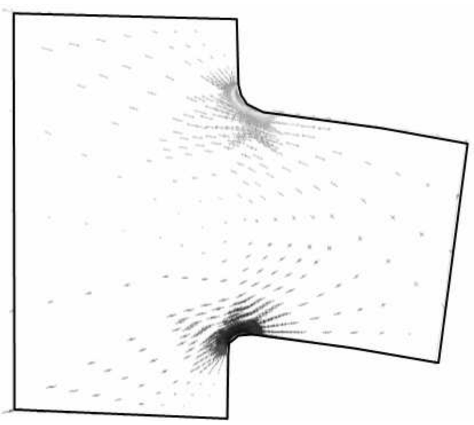

Fig. 5. Fibre orientation in bending.

Such approach is changed by use of non-homogeneous materials – composites – employing of the anisotropic unconventional material properties. In case of short-fibrous composites is possible to change mechanical (thermal and others) properties by fibre orientation. Moreover, the higher concentration of fibres in critical locations allows the effective use of material.

The higher effectiveness can be achieved by fibre orientation in direction of principal stresses. The finding out the directions of principal stresses is not problem by use even the commercial software.

Fig. 4 shows the component of plane stress loaded by tensile force distributed along the right-side curve. The opposite side is fixed. The distribution of principal stresses of deformed component is visible.

Fig. 5 shows the principal stresses in case of bending the same component as in Fig. 4. If the component would be made of short-fibre composite, the fibres should be oriented as the Figs. 4 and 5 show. The direction of fibres is the same as direction of maximum/minimum principal stress.

Fig. 6 presents the detail of principal stresses in case of torsion of component in Figs. 4 and 5. What would the fibre orientation be? The principal stresses are almost the same in two directions. The bidirectional fibre composite would be appropriate for torsion loading or randomly oriented fibres.

Figs. 4, 5 and 6 show component of plane stress but another figure shows the application of short-fibre composite to three-dimensional stress.

Fig. 7 illustrates the con rod loaded by space oriented force resulting three-dimensional stress. The stress state is documented by stress state at the point on the right side of figure. The maximal principal stress should be transmitted by oriented fibre and other two stresses by matrix or the randomly discontinuous fibre composite should be used.

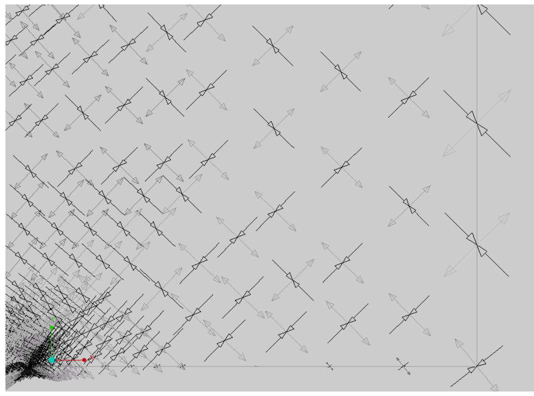

Fig. 6. Detail of principal stresses-torsion.

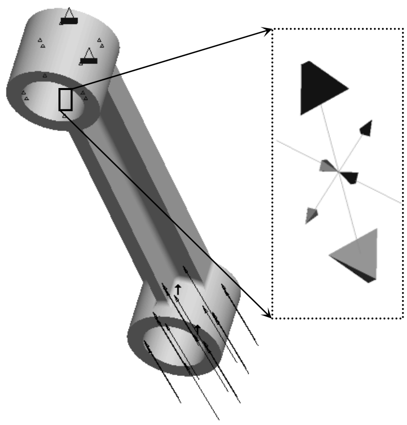

Fig. 7. Three-dimensional stress state.

Further, the shape of component can be non-convenient. As it was mentioned, not only shape and mechanical properties can be changed by fibre orientation but also weight and others.

5. COMPUTATIONAL METHODS

The main problem for simulation of composite behaviour is the determining of material properties. That can be estimate experimentally but also computationally.

The most available computational method is Finite Element Method (FEM) implemented in many programs. FEM is intended for wide range of standard engineer problems but specific problems as composite structure response are not suitable for FEM [5]. The reasons are the large number of elements and thereafter the high computational effort. Moreover, it is indicated that finite elements smooth out the interaction of fibres.

In the simulations domain-type, boundary-type, mesh-free methodologies, or some combinations of different type methodologies can be used. In generally, the most effective method is the method which enables to obtain good accuracy with smallest computational effort. The present methods mostly used to simulate the fields in solids are mentioned FEM and other volume discretization methods, Boundary Element Method (BEM), Meshless and Mesh-Reducing methods.

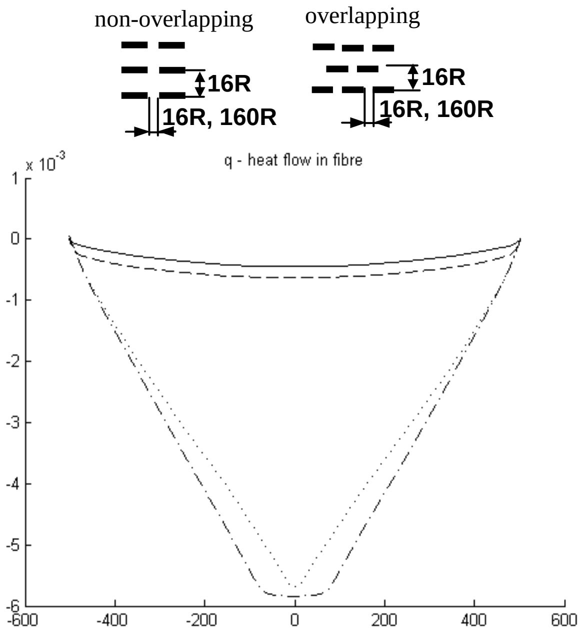

Fig. 8. Heat flow in non-overlapped fibres (L = 1000 R) - continuous and dashed lines - and overlapped fibres - dotted and dot-and-dashed lines.

The main FEM and BEM disadvantage is very fine meshing to keep gradient and aspect ratio either in volume or in surface. BEM defines the problem by corresponding fundamental solution and leads to singular integral equations and full matrix after discretization. Because of large gradients and large aspect ratio of fibre surface, many boundary elements are necessary to solve the problem by required accuracy. Similar properties have also present formulations using meshless and mesh-reducing methods.

There are many computational methods that are attempting to obtain reliable results with the lowest computational effort. Such effective method for short-fibre composites is Continuous Source Functions Method (CSFM) [3]. This method determines the field distributions in short-fibrous composite. The CSFM is a boundary meshless method reducing the problem considerably.

The basic equation is derived from the boundary integral equation approach introducing a source function. In case of structural analysis, the source function is a unit force, in case of thermal analysis it is a unit heat source. The source functions produce fields of displacement, stress, temperature, heat flow in the elastic body (matrix). The derivative of source function in corresponding direction is called a dipole and is composed of two collinear forces acting in the opposite directions or a heat sink and a heat source acting at the same point.

Example of computational simulation for regularly unidirectional distributed fibres with and without overlapping in a matrix is presented in Fig. 8. It is case of micro-thermal analysis of short-fibre composite. In case of mechanical load, there is analogy between heat flow and stress in fibre direction and between temperature and displacement.

The patches of fibres in the presented example (Fig. 8) consist of overlapping and non-overlapping rows of fibres. One can see the strong interaction between fibres in case of overlapping fibres. This is very different from the case of non-overlapping rows of fibres. Fig. 8 illustrates heat flow in fibre with and without overlap. The aspect ratio of fibres is 1:500 (fibre diameter:fibre length, R is radius, L – length). The continuous and dashed lines are for non-overlapping fibres with smaller (16 R) and larger (160 R) gap in fibre direction.

The overlapped fibres show the different contribution to heat transmission. The dotted line presents smaller gap (16 R) and dot-and-dashed curve larger one (160 R). One can see that the fibres without overlap transmit more heat in the case of larger gap between the rows of fibres. It is because of larger difference of temperatures in the points connecting the ends of fibres. Similar behaviour introduces also the patches with overlap.

Comparing the cases with or without overlap, the fibres with overlap transmit much more heat and the ends of fibres interact very strongly with the nearest fibres.

6. CONCLUSIONS

The design-material approach in designing process puts together the component designing and inner material structure that is not homogeneous but anisotropic (orthotropic).

Designing of structures regarding composite material structure is connected with components manufacturability. Finding the appropriate production technologies is the work for material engineer technologists.

There are other tasks: what would be strength and stiffness of designed composite material of component; what are the material properties of designed composite material; where is the dangerous location of component, etc.

Finding the answers is impossible without appropriate computational methods that are able to reliably simulate the material structure including the reinforcement or provides some idealisation – homogenisation. Furthermore the experiments are necessary to do to verify the computational models.

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