Micromechanics challenges in composite design

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Abstract

Composite materials are increasingly used in different industries to develop new innovative products. This trend is supported by the tailoring flexibility of composite materials thatcanleadtodesired system-scale performances. The challenge is, therefore, to set up a design framework that relates micro-scale proprieties to structural components behaviors. An important building block passage of this framework is the bridge between micro-scale and meso-scale through micromechanical models, especially in the case of a realistic nonlinearbehavior. Thus, this work is devoted to shedding light on composite design strategies and recently developed software in this field. In light of this overview, micromechanical models in the nonlinear case are discussed and routes for their improvement are stressed out.

Keywords: Micromechanical models, nonlinearity, design approach, composite materials.

Introduction

Performing a multitude of experimental tests to validate system parts in respectof their material constituents and manufacturing has shown inefficiency with regard to the time and cost it takes and most importantly to the drastic limitation of parts concept-possibilities that can be explored. Thus, the focus shifted towards a composite design process to obtainoptimized structures achieving better innovative performance,by using the endless possibilities of composites arrangements with respect to manufacturing constraints. The core motor of this process is the efficiency of micromechanical models that enable to relate microstructure to meso-scale in a realistic environment.

Thus, the improvement of the micromechanical models adopted to evaluate the effective properties of composite materials exhibiting nonlinearity is a critical issue. It is worth highlighting that though the foundations for meeting the challenge to deal with nonlinearity have been laid [1,2], it is rarely brought to the forefront of their using in material design framework.On the other hand, the manufacturing inhomogeneities in composite materials limittheir competitive advantages. As a result, to accommodate heterogeneous parts of complex shape, manufacturing process has to be taken into account to consider the influence of the local microstructure,through micromechanical models,in the design framework.In this regard, the concept that form the basis of composite design optimization, the integration of the interdisciplinary materials engineering, i.e. tools for modeling, design, as well as concurrent design for manufacturing, is required to simulate the behavior of the composite material before facing the expensive production of the structural product.

In this paper, the goal is to highlight the difficulties encountered in the nonlinear homogenization of composites, to address the opportunities for improving micromechanical models from composite design framework point of view.

Composite Design Framework:

The design of materials with desired properties is consideredas one of the most critical engineering issues today. We cannot afford to continue to limit the requirements of system level only to the available materials. By contrast totraditional materials, composite materials provide a great flexibility to develop innovative materials, thanks to their modular character that allows tailoring in according with the final desired uses.Moreover, to take advantages of its capabilities, composites are usually designed simultaneously with their respective parts.

The boundary between the product and the material is therefore less blurred than with traditional materials, which implies profound changes in the design of industrial products.

The acceleration of the development of composite materials is ofmajorinterest for many industrial sectors and their use is becoming widespread.However, to optimize production cost and time, the empirical trial-error practicehas to become rational, organized and systematicthrough the design process to offer the potential for tailoring composite materials with respect to all the specifications.

As mentioned by [3], an ideal design process to achieve performance requirements is mainly based on a top-down and bottom-up process (Figure 1), because the fundamental parameter in tailoring composites is to discern the relation of process journey to microstructure, structure to properties, and properties to performance (bottom-up). Such deductive approach is necessary but not sufficient for designing a composite material since the vital objective in a design process is to transform the functions, which incorporate the expectations requirements of the resulting product, into design description (top down process)[4]. It is worth noting here that the importance of composite design process lies in the fact that it is a multi-scale approach since the tailoring of materials is carried out with respect to the structure at each level.

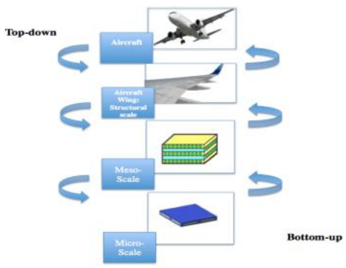

Figure 2: Hierarchy of structural scales ranging from micro scale to system level

In dealing with composite materials, it is worth noting that it is a three-phase process of design, analysis and manufacturing.If the manufacturing limitations are not taken into account at the stage of the design process, the outcome may be a non-manufacturable design. In addition, due to the significant influence of the microstructure on the structural part, composite materialshave to be considered extensively with regard to the microstructure. It should be highlighted at this level that multi-scale simulations are needed to accommodate the huge number of variables that is difficult to directly control via experiments.

In short, on exploring the design process engineers can close the loop between manufacturing, design, and analysis. Hence, the question is no longer about building the material but about optimizing it.

Challenges in integrating micromechanical models in composite design:

Inexpensive approaches to design composite material characteristics are essential to obtain specific properties for given applications. Thus, micromechanics models provide exciting opportunities to achieve this aim, by predicting the effective properties based on the definition of their constituents' characteristics.

Mostpopular approaches enabling the micro-macro transition gravitate around the self-consistent estimates (SC)[5]. Despite the pertinence of these schemes, they remain incomplete as far as the composite materials with matrix phase areconcerned. Many extensions have been developed to overcome these limitations [6]. A well-know extension is the modified Double Inclusion (MDI) model proposed by Aboutajeddine and Neal [7], to enhance the original model stems from Hori and Nemat-Nasser[8]. The strength of the MDI estimate arises in the ability to provide good estimation for materials with rigid particle and for material containing voids.

The most common materials in a variety of industries including aerospace, automotive and wind energy exhibit an inelastic behavior (e.g Elastoplasticity). Therefore, themain challenge in designing a composite material is the nonlinearity of the response because unlike the field of linear behavior, which has obtained a relatively well established and stabilized modelling framework, the field of nonlinear behaviors is still subject to active research.

The inherent difficulty with nonlinear problems is the non-uniform stress and strain fields in each phase. For this reason the eshelby tensor cannot be generalized and the mean field homogenization based in the assumption of a linear elastic material behavior cannot be directly applied. However, in an approximate manner, two separate steps need to be followed in order to extend linearmean field homogenization schemesto nonlinear regime: The first step consists ofapproximating the nonlinear constitutive equations of the individual constituents of the composite onto linear elastic or thermoelastic form, through a specific linearization procedure, so as to define a fictitious elastic or thermoelastic composite, designed to possess uniform instantaneous stiffness operators in each phase , usually referred to as the linear comparison composites ''LCC'' [9].The secondstep consists ofdefining theappropriate linear homogenization model for the LCC microstructure and approximating the overall as well as the local responses of this fictitious LCC.

Different linearization methods for predicting the elastoplastic response of the composite material have been proposed. Nonetheless, the most popular in the available literature includeSecant approach[1], incremental estimate [1]and affine method. However, the incremental method possesses an acceptable accuracy to capture in a good manner the elastoplastic behavior of heterogeneous materials. It is well known that the incremental method in its original form lead to an overall response, which is too stiff [1]. With regard to that limitation, many extensions have been attempted in order to improve its predictivecapabilities [2]and has shown that very acceptable estimates of the macroscopic response are obtained using an isotropic form of the tangent operator to compute Eshelby's Tensor (Figure 2).

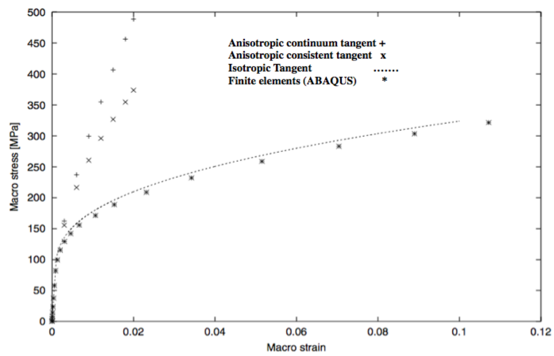

Figure 2: *The nonlinearMori-Tanaka predictions [2].*

Several extensions were performed in order to target nonlinear performance of the homogenization models as well as different type of material microstructure. Despitethe accurate predictions obtained, the modelsdeveloped are still limited. In further work, the double inclusion model of Aboutajeddine and Neal [7]will be extended to nonlinear problem using the most robust incremental method existing in the available literature.

New routes for research

To meet the demands of the market, Composite material innovation is considered the driving force in various industries. Such industries need to unify the design, analysis and manufacturing into one integrated process. In this respect, thanks to the numerous microstructural behaviors of particle reinforcement orientation, and the huge number of variables ranging from the right amount of material to the right configuration, an analytical model relating the basic characteristics of a composite material to its in-service performance is quite difficult to obtain. However, engineers can now explore the design process using software tools to create an integrated environment for the modelling and optimization of the overall behavior of a heterogeneous material based on the behavior of its different phases and itsmicrostructure morphology under specific operation conditions, to allow for new materials manufacturing that can be used in the design of composite structure.

It should be noted that as the desired properties depend on the phenomena that operate at different length scale, we need to define the length scale at which the properties of interest are directly relevant. Multi-scale modelling is the core of composite design and micromechanical models ensure the bridging between the two most important scales (meso to macro scale).Furthermore, the micromechanical models must capture the microstructure morphology, generated by the process simulation.

As the material properties of the composite material depend on the fibers directions, one of the most appropriate sequence processes in composite product making began with a draping process, which enables us to assess and control fiber shear when dealing with complex surfaces, to predict the flat pattern, check its producibility, maintain good performance and reduce the effort put in the work, it should be noted that the 3D composite structures are manufactured by placing 2D sheets of fabric onto 3D surface. It follows from here that a manufacturing ecosystem is needed to control the deformed shape of the final part. The study carried out by the German Aerospace Centre, DLR (Deutsches Zentrum für Luft- und Raumfahrt)[10], emphasizes the superiority of the structural analysis software Fibersim[11] regarding its capability of supporting simultaneously: complex parts geometries and manufacturing methodologies when the criteria of fiber simulation, design functionality, and interfacing are taken into account jointly. Fibersim is applied only to the long fibers. Lately, however, many industries shifted their interest to composite reinforced by short fibers; mainly, to their ability to provide both higher Stiffness to mass ratio and flexibility from the processability point of view. One of the most important computational modelling tools is the Digimat software [11,12] due to its ability to simulate almost all kind of material microstructures, including short and long fibers. In this software engineers are able to identify the link between part geometry, material flow during fabrication, microstructure and the effect of all this on the ultimate mechanical behavior of the part by integrating a virtual world, i.e. virtual design, virtual testing, virtual manufacturing (Figure 3).

Figure 3: *Composite Design process.*

In order to meet the challenge of the performance in the industrial environment, engineers are more and more called upon to extend the above-mentioned micromechanical models to nonlinear structures. Accordingly, the improvement of the nonlinear micromechanical models from the composite design perspective is a promising avenue that has to be explored for the ultimate goal of obtaining innovative material performances.

Conclusion

Thiswork addressed the micro-mechanical models from the perspective of design process. It highlighted the limitations of such models, especially when the problem is nonlinear, and set the guidelines to follow in order to solve the problem of nonlinearity. Besides,this paper highlights the necessity of integrating the manufacturing process as it governs the microstructure, and suggests a unification of the design analysis and manufacturing into one integrated process, which can be handled in software tools.

References

[1] H.Teng, A new incremental formulation of elastic-plastic deformation of two-phase particulate composite materials.J.Appl.Mesh 81(6) (2014).

[2] I.Doghri, A.Ouaar, Homogenization of two-phase elasto-plastic composite materials and structures: study of tangent operators, cyclicplasticity and numerical algorithms. Int. J. Solids Struct. 40 (2003) 1681–1712.

[3] N. F. O.Evbuomwan, S.Sivaloganathan, A.Jebb, “A survey of design philosophies, models,methods and systems,” Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 210 (1996) pp. 301-320.

[4] J. H.Panchal,S. R. Kalidindi, D. L McDowell,Key computational modeling issues in integrated computational materials engineering. Computer-Aided Design, 45 (2013) 4-25.

[5] R.Hill, *Aself-consistent mechanics of composite materials*. J MechPhys Solids 13 (1965) 213–222.

[6] M.Bennoura, & A. Aboutajeddine, (2016). Predictive Capabilities of Micromechanical Models for Composite Materials. Journal of Reinforced Plastics and Composites, Vol. 35.No.14.pp. 1115–1125.

[7] A. Aboutajeddine and KW.Neale, The double-inclusion model: a new formulation and new estimates. Mech Mater 37 (2005) 331–341.

[8] M.Hori and S.Nemat-Nasser,*Double-inclusion model and overall moduli of multi-phase composites*. Mech Mater 1993; 14: 189–206.

[9] P.Ponte Castaneda, The effective mechanical properties of nonlinear isotropic composites. J. Mech. Phys. Solids 39 (1) (1991) 45–71.

[10] K. Andreas, Draping simulation–the key to low cost high performance net shape parts? , 2011.

[11] http://www.compositesworld.com/articles/software-update-simulation-saves, Karen Wood, Software Update: Simulation saves, 2014,2016.

[12] DIGIMAT software documentation, e-Xstream engineering, 2016.