CHAPTER 8
Linear elastic calculation of composite materials

8.1 Introduction

In this Chapter we will focus on the problems that are encountered whenever it is necessary to deal with the modeling and calculation of a structure made of composite materials, indicating with this term those materials that, not being homogeneous and isotropic, present some more complications, both with regard to the construction of the model and with regard to the interpretation of the results. We will not dwell even for a moment on the theory at the base of the behavior of a composite material. For that we refer to the specific texts reported in the references.

Here we will limit ourselves to saying that the use of composite materials is becoming part of everyday life and is now used even where previously other materials were used and the sophistication of the former was relegated to highly technological and very specific fields: military (especially in the aeronautical area), motor and naval competition, sports (tennis rackets, golf bats, skis, fishing rods, bicycles).

The attempt, in part successful, to industrialize the realization of an object in composite material (while before it was a handcrafted procedure and in some cases still today to get the maximum performance from a certain element a manual operation is necessary) has lowered the costs of the product and extended the use of such advanced materials also in areas less "advanced" than those just mentioned. Above all, pieces obtained by plastic injection molding have seen the insertion of short, non-oriented fiber reinforcements (mainly glass) in the resin.

The use of sheets (pre-impregnated with resin) where the fibers (glass, Kevlar, carbon, etc.) are organized and oriented all in a desired direction is difficult to industrialize and still requires the work of highly specialized technicians for the realization of high performance and at the same time reliable components. Computerized 3D drawing systems (CAD) certainly facilitate the determination of the shape that the various sheets must have in order to be placed in the mold without too many difficulties and have led to the creation of machines that allow the cutting of the sheets according to the desired shape. The operator must therefore use his skill only to arrange the sheets with the greatest possible care, without having to worry about "trimming" them with a cutter and scissors or making dangerous joints during the production phase.

In parallel with the use of composite materials, the need to know, before testing the first prototypes, whether the part will be able to resist the loads that stress it or where it must be reinforced to reach the target has grown. So the automatic calculation of structures, especially those based on the Finite Element Method, finds a new terrain on which to measure itself. Nothing particularly complicated for the end user (if adequately prepared); the real complication lies in the programming of the code because the construction of the stiffness matrix of the single elements made of composite material is no longer based on the simple constitutive equations that link deformations to stresses in a homogeneous and isotropic material, but must take into account the anisotropy of the laminate (i.e. how the various pre-impregnated sheets are superimposed one on the other, how they are mutually oriented, the elastic characteristics of each of them). It may happen, for example, that a simple rod made of carbon fibers and subjected to a perfect axial load is also subjected to bending, even in the absence of a bending moment. All these effects are explained by the Classical Lamination Theory (see for example [7]), on which, as already said, we will spend very few words, referring the reader to other specialized texts. Here we will limit ourselves to the practical aspect of modeling a composite structure.

8.1.1 Historical background

At the beginning of the commercial era of Finite Element computation software (we are talking about the end of the '60s of the last century), codes were exclusively linear and had in their library an extremely reduced number of element types. Beam and truss models were the common practice, and shell models were used when strictly necessary. Solid models were therefore a dream, not only for the computational effort required to computers that were far less powerful than the least powerful smartphone on sale today, but also because the construction of a three-dimensional model with brick elements (the tetrahedron in fact would come only later) was not at all a simple thing: it should not be forgotten, in fact, that the models were first drawn to scale on a sheet of graph paper and then entered into the computer by typing the numbers of each node, its coordinates, the number of each element and its connections with the nodes.

It seems like prehistory and yet only a little more than fifty years have gone by.

The materials that could be used were only homogeneous and isotropic, also because at that time the aerospace industry (do not forget that NASTRAN, the first finite element code to be marketed, is the acronym of NAsa STRucture ANalysis) used only this kind of materials (steel, titanium, aluminum alloys).

More recent times have seen the development of long and oriented fiber composite materials, and the need to automatically analyze structures made of these materials has required the adaptation of codes, at least to a certain extent: for shell elements it was at one point possible to assign different materials according to the stress-strain state, i.e., for example, a Young's modulus for membrane behavior and a different one for the flexural behavior. And this just to adapt to the characteristics of composite panels, where flexural and membranal stiffness, in general different from each other, are a function of the materials used, of their orientation and of their stacking along the thickness of the panel. This was a step forward, but it was still necessary to compute the equivalent flexural and membrane Young's moduli by hand and then feed them to the code; thus, every time the materials, their orientation or their stacking sequence were changed, it was necessary to recalculate the equivalent properties. But the difficulties didn't end there; once the solution was obtained it was necessary to calculate the stresses in the various layers of material because, since the panel is not homogeneous, the discontinuity of the stresses between the various layers can be very marked.

Therefore, the last evolutionary step was to automate also the calculation of equivalent properties: today it is possible to "simply" indicate which material is assigned to a particular layer, which is the orientation of its fibers and which is its thickness to have, at the output of the calculation, also the stresses and failure indexes of each layer. All this, we remember, is done for shell elements, i.e. for elements designed to model structures in which two dimensions are much greater than the thickness: thin plates and shells, in essence.

However, today, given the increasing use of composite materials and the development of production technologies unimaginable only a few years ago, we often see composite structures that to define "thin" seems at least hazardous and their structural analysis undoubtedly poses some perplexity. Extending the capabilities of the shell element beyond its intrinsic limits seems to be the only way forward, but even with all due caution and the awareness that the results can lead largely off track, the risks associated with it are high. The exploration of alternative paths then becomes almost a must and in the following we will see an example taken from industrial practice where it was necessary to resort to a sophisticated approach because the classical one produced wrong results that led to the failure of a component.

8.2 Element types to be used

For objects made of plastic material and reinforced with short, non-oriented fibers, it is the geometry of the component itself that guides the choice of the type of element to be used. Stubby structures will be modeled with solid elements (bricks or tetrahedrons) while organs with thin walls will be realized with shell elements. In fact, as we will see later, generally this type of composite material is still treated as homogeneous and isotropic.

Structures realized with long and oriented fiber plies, on the other hand, will generally be "thin", with some exceptions, and hence of exclusive domain of shell elements; this happens because the plies have small thicknesses (of the order of 0.1÷0.5 mm) and therefore, in order to obtain a laminate with high thickness, it would be necessary to stack many plies, thus facing some technological problems. In some cases, when it is necessary to have stubby structures made with long and oriented fiber composites, this approach is still followed and overall thicknesses of 20÷22 mm can be reached (and if we consider to have an average thickness of the single ply of 0.2 mm it is necessary to stack 100÷110 plies). But even without arriving at a product that in this hypothesis would be solid carbon, it is sufficient to think of "sandwich" panels, where between two outer skins of fiber (more or less thick depending on the case) there is a "core" of a completely different nature: aluminum honeycomb or cardboard (the so-called Nomex), foam filler, balsa wood, etc.. Also in this case, even if the skins are thin (maybe made of 4÷5 sheets) the final product can still be thick because of a core that can reach 30 mm in thickness (see figure 8.1 for an example of a sandwich panel). And this can start to create modeling problems when using shell elements, especially along surfaces that perhaps have a radius of curvature of the same order of magnitude as the thickness. In geometric situations of this nature and having a homogeneous and isotropic material, solid elements would be used. But with composite materials the matter changes.

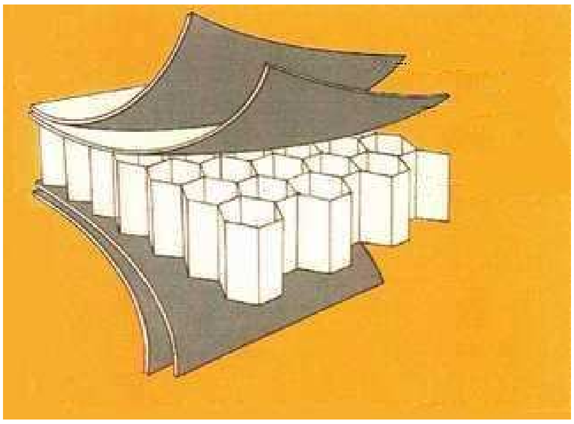

Figure 8.1. Example of sandwich panel. The core generally consists of a honeycomb structure, made of aluminum, cardboard or plastic material (sometimes even reinforced with fiber). The outer skins can be fiber laminates or sheets of metal material (e.g. aluminum).

In addition, materials commonly referred to as "3D composites" have recently been appearing, especially in high-tech fields where the economic aspect is of secondary importance. They involve the presence of fibers not only on a surface but also along its normal to facilitate the packing of the various layers of fiber and to avoid the so-called delamination. Beyond the technological problems and production aspects related to such a material, our interest is related to the way such a structure is discretized for a finite element calculation.

Precisely for these reasons, nowadays many commercial calculation programs have introduced, alongside the classic 2D element to model a laminate, 3D elements called "structural layered elements", i.e. 3D structural elements in which it is possible to define layers, each with its own elastic and mechanical characteristics and its own orientation with respect to a predefined direction. Basically, with these elements the characterization of their constitution occurs in the same way as shell elements, but the fundamental difference lies in the fact that the geometry of the structure is respected. However, this approach presents some difficulties and problems, both in defining the elastic and mechanical properties, and especially in being able to establish a failure assessment criterion.

In the following paragraphs we will address FEM modeling issues for both element types, 2D and 3D.

However, it is first necessary to give some information about the materials used in the manufacture of composite objects.

8.3 Short and non-oriented fiber composites

Let's get this topic out of the way right away because, as mentioned earlier, a piece made from this type of material is usually stubby and is modeled with solid elements. Since the fibers are randomly oriented, the material can be considered homogeneous and isotropic. Typically, the reinforcing "filler" is obtained by mixing the fibers into the resin just before the material is injected into the mold. The reinforcement usually makes the plastic material in which it is embedded more resistant and rigid, but it embrittles it because the fibers have a notching effect in the material (a bit like what hap-