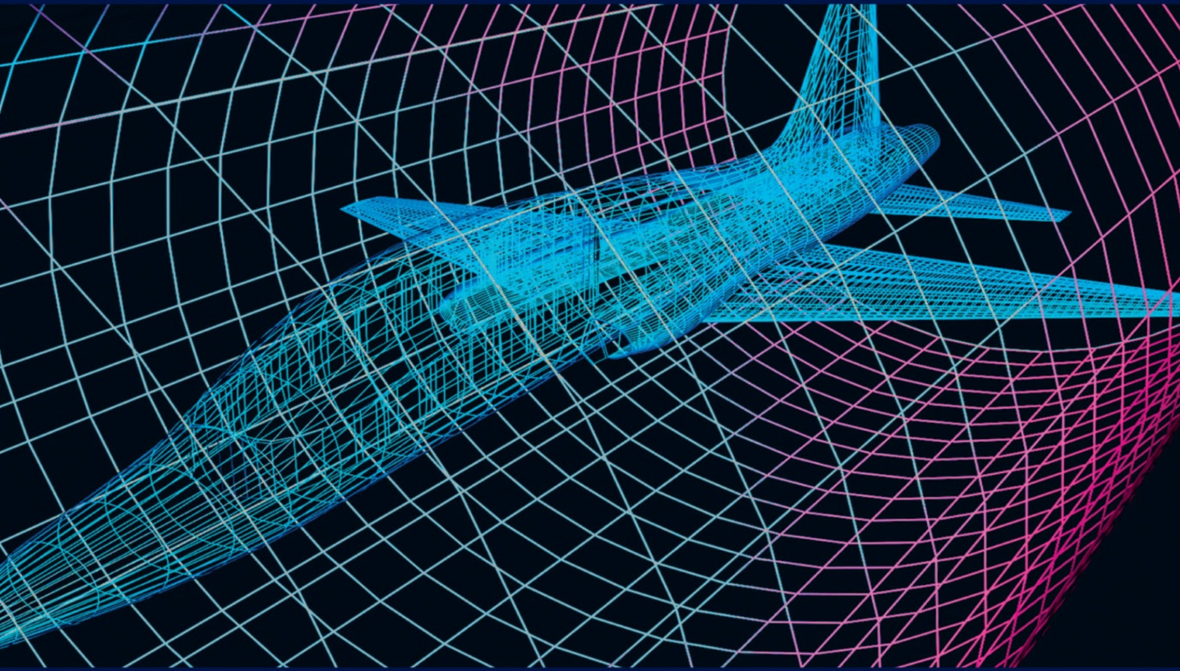
MECHANICAL ENGINEERING AND SOLID MECHANICS SERIES

Mechanics of Aeronautical Composite Materials

Christophe Bouvet



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Foreword

When my young colleague gave me his manuscript to proofread and asked me to write a few words for a foreword, it is with great pleasure that I accepted, even though the preamble and title were quite sufficient to present this book.

Many books have been written on composite materials. The originality of this one comes in part from the objective, which is targeted towards aircraft structures made of composite materials. To this end, the calculation of holed structures, and their subsequent multi-bolt joints, and the theme of damage tolerance are presented alongside the problems that they carry with them, as well as the calculation methods that are currently in use. These two axes are rarely presented in the literature, yet they are essential to perform an accurate and realistic sizing since they often govern the resistance of a given structure and thus its sizing.

This book covers all classic notions surrounding composite structures. Theoretical formulae are presented concisely and without unnecessary developments allowing the focus to remain on the essentials. When studying criteria, another crucial point, the differences between first damage and final fracture are made abundantly clear, something that is essential for achieving optimal structures and performing realistic calculations. This is another essential aspect of composite calculations that is nonetheless quite absent from the literature.

Lastly, a number of exercises surrounding all studied themes are proposed with complete and detailed corrections. They will allow the readers to assimilate the presented themes more easily. This is without doubt one of this book's strongest assets as there are few other titles that carry quite this many examples.

I recommend reading this book as it uses concision and precision to provide essential bases for designing and sizing composite structures.

Jean-Jacques BARRAU
Former Professor at the University Paul Sabatier
Toulouse, France

Preface

The objective of this lesson on composite structure sizing is to present the principles that allow the sizing of composite laminates widely used in composite structures. After a brief presentation of the primary material used in aircraft structures, the basic theory of laminated plates under membrane and bending loading as well as their associated fracture criteria is touched on. The fracture of a UD ply is then explained in detail, in order to demonstrate its inherent complexity and the limits of the criteria in use. Next, these criteria of the base ply are used to size a complete composite laminate. Lastly, two fundamental cases of structure calculations are presented: sizing holes and multi-bolt joints, as well as the study of buckling.

The criteria that are specific to aviation, in particular the notion of limit loads and ultimate loads, are addressed. The notion of damage tolerance specific to aviation is then presented, and in particular the notion of impact damage tolerance. These notions are fundamental to understanding the specificities of sizing aircraft composite structures.

Corrected exercises then allow curious readers to test their understanding of the different subjects. These corrected exercises are typical for sizing aircraft composite structures. Engineers will also find exercises that resemble their case studies. Lastly, an Excel spreadsheet allows the presentation of the calculations in the book in detail for review (available to download at www.iste.co.uk/bouvet/aeronautical2.zip).

The originality of this particular title is that it places itself very clearly in the field of aviation, where the sizing criteria are very specific. Take the calculation of holed plates and multi-bolt joints that are typical for composite aircraft structures and yet are not often touched on in the literature. Nonetheless, the notions in this book remain valid for most industrial purposes.

Another originality of this book is that it shows a number of typical calculations for aeronautics. These examples illustrate the many complexities of sizing for composite laminates. Readers can also easily perform these calculations using the Excel spreadsheet provided.

Lastly, this book groups many of the notions required to understand sizing for aircraft composite structures, and it should interest engineers who work in that field.

We will also note that the field of aeronautics is not the only one interested in using composite structures, and other areas, such as automotive, railway or civil engineering (bridges, etc.) increasingly use composite structures. While the field of aviation has precedence when it comes to composite structure sizing, it should be noted that these methods will be widely used in other fields in the years to come.

Christophe BOUVET
June 2017

Introduction

Composite materials are increasingly used within industry, thanks to their high performance to mass ratio. This is, of course, particularly true in aviation and airspace due to the crucial importance of the mass of such structures (Figure I.1). This high performance to mass ratio is due to the use of materials with specific mechanical characteristics such as carbon, glass or Kevlar. This type of material nonetheless presents the major drawback of being brittle, and therefore needs to be used in combination with a less brittle material such as resin. This is the basic concept of composites, which join a brittle resistant material (typically fibers of varying length depending on the application) with a less effective but more resistant matrix (typically resin). Don't forget that there is then an interface that appears between the two materials which also plays an important role in the behavior of the composite.

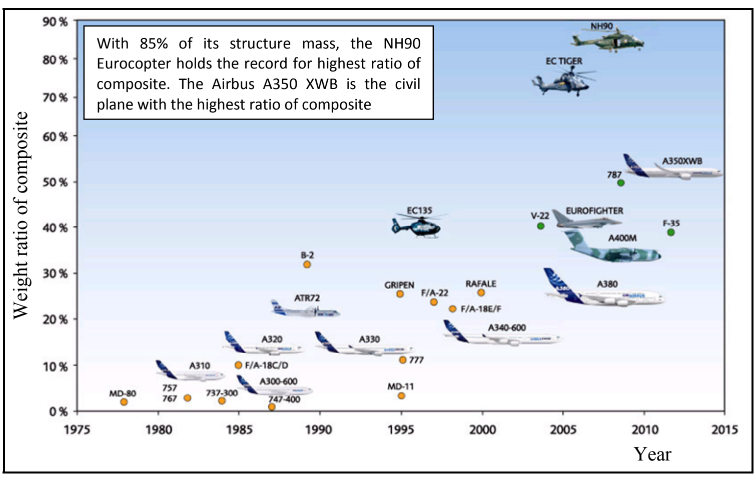

Figure I.1. *Weight ratio of composite material in aircraft structures from the Airbus group and a few others (http://www.airbus.com/)*

The structure of the composite is therefore more complex than a standard homogeneous material such as metal, and requires an entirely new way of designing parts. Composite structure design means designing the structure at the same time as the material; this is the fundamental difference between designing a metallic structure and a composite structure. This composite design also requires classic design iterations on the geometry as well as design iterations on the material itself; these two types of iterations are, of course, inherently linked. In practice, on top of deciding geometry for the structure, the choice of stacking sequence and manufacturing process will have to be taken into account.

The majority of composite materials also present an important anisotropy (meaning its characteristics depend on the direction considered); they are presented in the form of unidirectional fibers, i.e. all facing the same direction. The performance of the composite is, of course, much better in the direction of the fibers, and since in reality a structure is generally under different loadings depending on the direction, a good choice of fiber orientation will make for a bespoke material adapted to real situations. This optimization of the direction of the fibers then allows a mass benefit and therefore a high performance to mass ratio. This benefit will nonetheless require an optimization process in the direction of the fibers to external loadings, which will also depend on the geometry of the structure, which is why the material and structure must be designed together.

Another important point for composite structures is the possibility of obtaining complex forms in one shot, for example, using layer-by-layer production processes along with molds and counter-molds or dry pre-forms. The advantage is that it decreases the mass and complexity of the assembly of the structure by reducing the number of screws or rivets. We can, for instance, cite the tail fin of the Tristar plane (Lockheed-USA) that was composed of 175 elements and 40,000 rivets with a classic construction, and 18 elements and 5,000 rivets with a composite construction [GAY 97]. Once again, this allows mass reductions while decreasing the number of parts and assembly elements, but requires a more complex design process and forces us to integrate the design of the structure and the material.

However, despite the advantages of composites, one of their main drawbacks is the price of the manufacturing process. Examples include the shelf life of the epoxy resins, the prices of laminate ovens (autoclaves), the resin injection devices, shaping using molds and counter-molds, and even the necessity for non-destructive control and assessment to guarantee that the material is healthy. All of these things make the production process more complex and thus increase the price.

Their brittleness under impact is also a negative factor as it leads to structures being oversized thus counteracting the potential mass benefit in order to guarantee their residual strength after impact. This brittleness is also associated with complexity in repairing these impact damages. These repairs can be complex and repair methods are still ill-suited and need to be refined for large-scale structures subject to impact, such as the fuselages of planes like the Boeing 787 or the Airbus A350.

The objective of this lesson is to present the primary sizing principles of composite structures, in particular the ones used in the field of aviation. The objective is to show the sizing of simple composite structures such as plates, and also to provide engineers with the elements required to perform and interpret composite structure calculations made using a finite element code. The complexity of real structures makes it impossible to size these structures by hand, as is presented in this book, but understanding case studies is necessary for the interpretation of results as complex as those obtained by finite elements or even simply from experimental results.

Before beginning this book, it is recommended that readers have prior knowledge of different existing composite materials, of their reinforcements and resins, and of the semi-products used such as pre-pregs and their primary advantages and drawbacks. Indeed, only a few unidirectional composites will be presented in the first chapter, but there are plenty of books out there that have more in-depth presentations in this area [GAY 97, BAT 13, BER 99, CAS 13, DAN 94, DEC 00, SES 04].

1

Presentation of an Aeronautical Unidirectional Composite

1.1. Introduction

As it stands, the two main materials in use in aircraft structures are aluminum and a carbon fiber-based material. These two materials make up approximately 70% of the mass of the structure of a typical commercial plane such as the Boeing 787 (Figure 1.1).

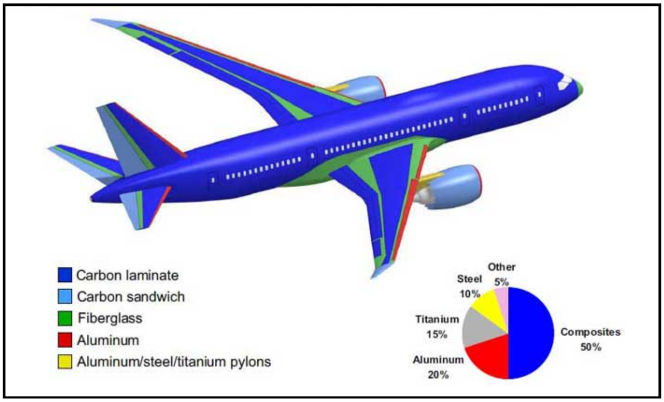

Figure 1.1. *Material breakdown of the Boeing 787 (according to http://www.boeing.fr). For a color version of this figure, see www.iste.co.uk/bouvet/aeronautical2.zip*

The remaining structural materials are glass fiber-based composites, sandwich structures (a honeycomb core covered with two composite sheets), titanium, steel, etc.

Mechanics of Aeronautical Composite Materials, First Edition. Christophe Bouvet.

Keep in mind that the weight ratio of composite materials is of over 50% of the overall mass for the Boeing 787 or the Airbus A350, but more standard commercial aircrafts such as the Airbus A320 or A380 are primarily composed of aluminum alloy, which makes up over 60% of its mass.

1.2. Carbon/epoxy composite T300/914

We will now look at a carbon/epoxy composite that is widely used in aircraft structures, called T300/914. The T300 portion of the name refers to a carbon fiber produced by Toray® [TOR 16], while 914 is a reference to an epoxy resin produced by Hexcel® [HEX 16]. T300/914 is a first generation carbon/epoxy composite that is 50% (in volume) carbon fiber and 50% epoxy resin. It takes the form of a thin fabric (less than a millimeter thick) that can subsequently be cut and draped to obtain a desired thickness (Figures 1.2 and 1.3).

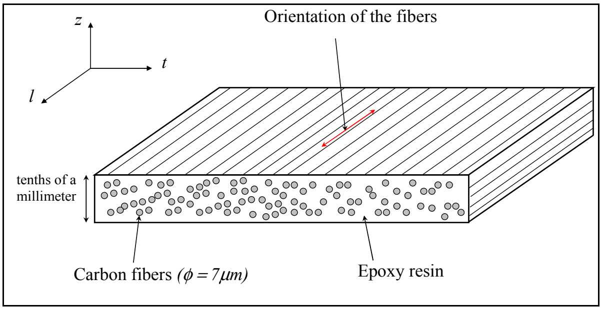

Figure 1.2. *Unidirectional carbon/epoxy laminate*

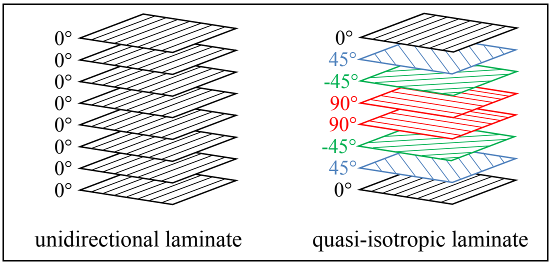

Figure 1.3. *Unidirectional and quasi-isotropic laminate*

Performing a test along the direction of the fibers, also called the longitudinal direction, we can observe a brittle elastic behavior comparable to the fibers. The elastic limit is obviously lower than that of the fibers, since approximately 50% of the resin has been added, which has a relatively low elastic limit (Figure 1.4). This resin is necessary in order to obtain a less brittle material and to shape it. The carbon fibers are indeed thoroughly interesting elements from the aspect of their mechanical characteristics but cannot be used to adopt a desired geometry. Furthermore, when a crack appears in the material and propagates perpendicularly to the fibers, it will cause a lot of fiber failures and fiber debonding, thus requiring an elevated dissipation of energy; the material will therefore be less brittle (Figure 1.5). In practice, a crack would travel parallel to the fibers if it could, which is why there are plies in other directions, so as to reinforce the material in different orientations of loading (in practice, we can demonstrate that four directions 0°, +45°, –45° and 90° are enough). It is then a case of a composite laminate, as opposed to a composite with fibers facing only one direction, which is called a unidirectional composite (Figure 1.3).

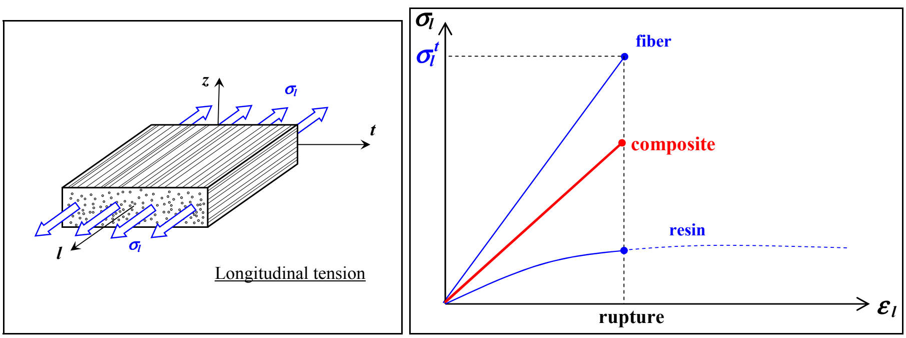

Figure 1.4. *Tension along the longitudinal direction of a composite: behavior of fiber, resin and composite. For a color version of this figure, see www.iste.co.uk/bouvet/aeronautical2.zip*

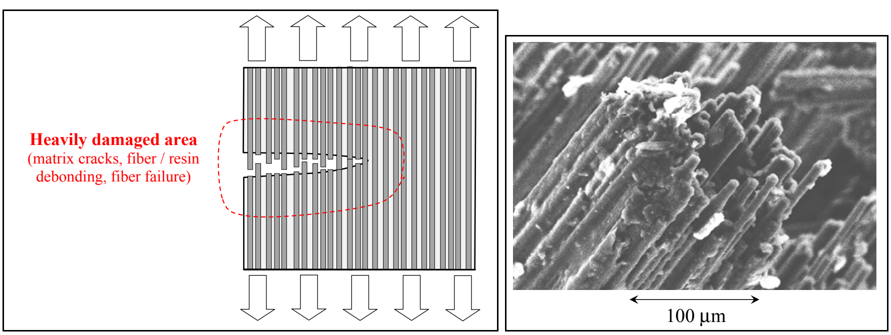

Figure 1.5. *Tension along the longitudinal direction: damaged area*

Comparing Young's modulus and the strength of the main structural materials according to density, we note that composite materials are very well positioned compared to the metals (Figures 1.6 and 1.7). Ceramic materials are also very interesting but often too brittle for any structural use.

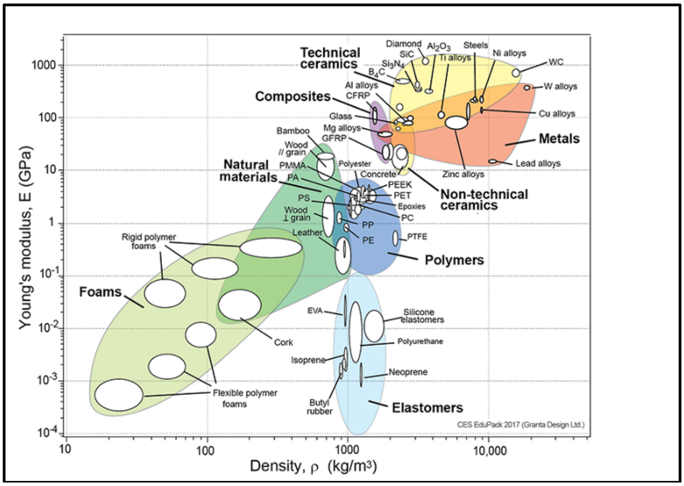

Figure 1.6. *Young's modulus according to density [ASH 00a] CFRP: carbon fiber reinforced plastic; GFRP: glass fiber reinforced plastic. For a color version of this figure, see www.iste.co.uk/bouvet/aeronautical2.zip*

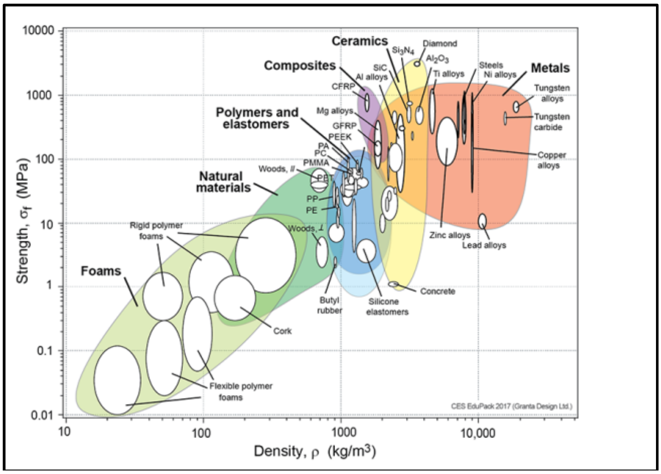

Figure 1.7. *Strength according to density [ASH 00a] CFRP: carbon fiber reinforced plastic; GFRP: glass fiber reinforced plastic. For a color version of this figure, see www.iste.co.uk/bouvet/aeronautical2.zip*

The way to better understand a composite material is to take a close look at its composition and microstructure, in particular for epoxy resin.

1.3. Polymers

The epoxy matrix is part of the polymer family commonly referred to as plastics. The word plastic comes from the mechanical behavior of polymers that present plastic strains, i.e. the deformation does not return to its original point when loading is released.

Polymers are composed, as indicated by the name, of chains of monomers linked together with covalent bonds. In this particular work, we will limit ourselves to organic polymers. Keep in mind that organic matter is created by living creatures (plants, mushrooms, animals, microorganisms), particularly by their decomposition. In contrast, inorganic or mineral matter is composed of metals, glass, ceramics, rocks, etc.

Organic polymers are therefore based on chains of monomers linked together by carbon atoms. The carbon–carbon covalent bond is strong and will provide elevated mechanical properties. These carbon–carbon bonds serve as a basis for macromolecules that make up the skeleton of the polymer material. On top of these strong bonds, these macromolecules are linked together via the intermediary of weak bonds (hydrogen bonds, Van der Waals bonds, etc.). It is the deformation of these weak bonds which will induce important plastic strain on behalf of the polymers.

Take for instance, the case of polyethylene, one of the simplest and cheapest polymers. It is made up of the polymerization of ethylene monomers (CH_2=CH_2) which leads to the creation of long chains. These chains are simply linked together via weak bonds. The mechanical characteristics obtained are therefore relatively weak and depend on temperature.

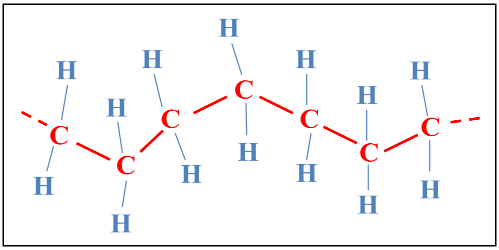

Figure 1.8. *Structure of polyethylene*

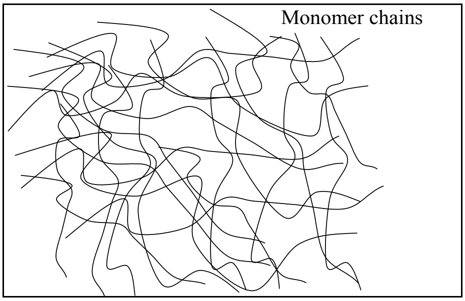

Figure 1.9. *Structure of polymer in monomer chains*

If we trace, for example, the Young's modulus according to temperature, we then obtain a characteristic three-part curve that demonstrates the existence of two distinct temperatures points within the studied material; its glass transition temperature T_g (*g* for glass; this glass appellation will be refined further on) and its melting temperature T_m. Below T_g, the behavior of a material is typical of a solid material; beyond T_m, it takes on a practically fluid (more or less viscous) behavior and in between the two, we observe a rubbery behavior characterized by very low rigidity and a high capacity for deformation. Typically, polymers cannot be used as structure materials, in particular as a resin for a composite material, for a temperature beyond T_g (there are, nonetheless, exceptions which we will see further along).

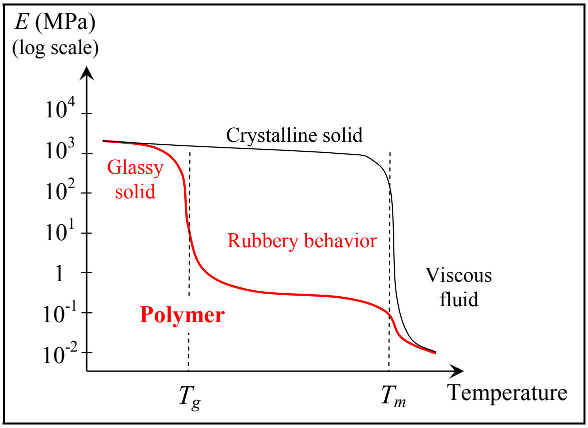

Figure 1.10. *Rigidity of a polymer depending on temperature. For a color version of this figure, see www.iste.co.uk/bouvet/aeronautical2.zip*

This rubber-like behavior is made possible because the molecular chains present only weak bonds (hydrogen bonds, Van der Waals bonds, etc.) linking them. They can therefore reorient and align when loaded. This type of polymer is called thermoplastic, because its plastic behavior depends on temperature.

If we want to increase the mechanical characteristics of a polymer, we need to lock the relative movement of molecules by creating covalent bonds between molecule chains; this phenomenon is called cross-linking. We can then describe the polymer as thermoset if the level of cross-linking is significant, while it is referred to as thermoplastic in the absence of these cross-links. We note that the term thermoset stems from the fact that the chemical reaction that allows this cross-linking is activated by temperature; in other words, the material hardens with temperature. This is true during manufacturing, but is no longer the case once the polymer is already cross-linked.

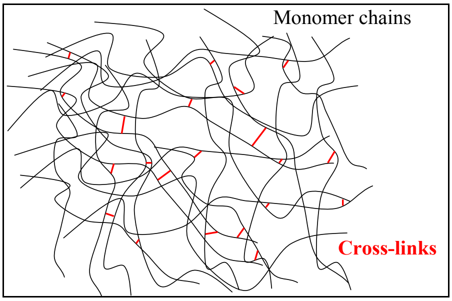

Figure 1.11. *Secondary links between monomer chains: cross-linking. For a color version of this figure, see www.iste.co.uk/bouvet/aeronautical2.zip*

There is a third class of polymers, elastomers, that present an intermediary behavior somewhere between thermoset and thermoplastic. Elastomers generally present a low level of cross-linking and these cross-links are realized from sulfur-based covalent bonds (a process referred to as vulcanization). These sulfur-based secondary bonds grant the material a high level of elasticity (nonlinear in general).

Going back to Young's modulus depending on temperature, we distinguish a thermosetting polymer from a thermoplastic polymer via a less pronounced – if not non-existent – glass transition, and the absence of a melting temperature. The glass transition is a result of the dissociation of weak bonds by thermal agitation. Nonetheless, because thermosetting materials present high levels of cross-linking, this network of cross-links will last beyond T_g and grant the thermosetting material a decent mechanical behavior after T_g. Increasing the temperature further, we reach the material's decomposition pyrolysis, i.e. decomposition into different forms of gas and residue (CO, CO_2, H_2, etc.).

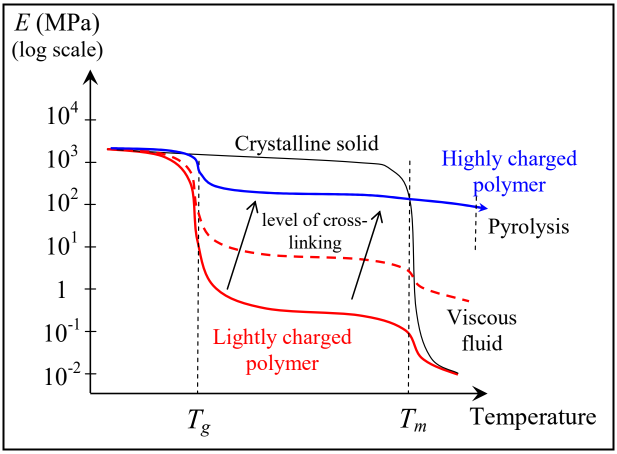

Figure 1.12. *Rigidity of a polymer depending on temperature and cross-linking. For a color version of this figure, see www.iste.co.uk/bouvet/aeronautical2.zip*

From a chemical standpoint, this thermoset/thermoplastic difference is due (upon first approximation) to the type of chemical reaction used to synthesize the polymer. Thermoplastics are obtained using a simple reaction of addition or polyaddition (making it difficult to create cross-links), while thermosetting polymers are obtained using a condensation or polycondensation reaction (that induces many cross-links). We can also talk about polymerization reactions, which cover both of these types of reactions.

The presence (or lack thereof) of cross-links in the network of a polymer modifies its mechanical behavior entirely, and also changes the processes for manufacturing and recycling it. Thermosetting materials are obtained once and only once during the polycondensation reaction. It therefore needs to be shaped before this reaction and cannot be reshaped afterwards. Going back to the carbon/epoxy T300/914 composite discussed previously (the epoxy is a thermosetting polymer), it is currently sold in the form of a thin film, 0.125 or 0.25 mm thick, made up of approximately 50% epoxy matrix and 50% carbon fiber (with diameter measuring approximately 7 µm), called pre-impregnated or pre-preg. This designation comes from the fact that the fibers are impregnated with resin beforehand. This resin is composed of monomers and a hardener, which improves the polymerization reaction. In order to avoid polymerizing the pre-preg, it is conserved at a low temperature (typically in the freezer at –20 °C) and it has a short shelf life (generally no more than 2 years). It is then a matter of assembling the pre-pregs into the desired

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