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Structural Materials and Processes in Transportation

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Structural Materials and Processes in Transportation

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Foreword

From Mechanics and Materials Science to Engineering

Transportation has at all times given engineers, craftsmen, and builders a challenge: making it easier to move. This means: make it lighter, stronger, more reliable, more comfortable, easier to build, less expensive . . . all with available materials.

Although means of transportation have been designed and built over millennia, truly engineered products have arisen recently. The first engineering book, *La Science des Ingénieurs*, by Belidor, was published in 1729. A. Wöhler developed the theory of mechanical fatigue and used it to improve the rolling stock of Northern German Railways in the mid-nineteenth century. A.N. Krylov applied modern stress analysis methods to ship design, based on his initial publication in 1906. A.A. Griffith published his theory of the strength of glass fiber, underlying structural composite performance, in 1920. The commercial production of glass fibers, by Owens Corning, dates back to no further than 1935 Ref. [1]. Also the field of polymer chemistry for technical plastics – the molecular design of new materials – emerged in the second half of the twentieth century. This paved the way for the widespread replacement of natural, renewable materials for strong lightweight structures.

Challenges of the Past Century and the Breakthroughs They Have Provoked

We are only a century away from the major roots of our current design and materials science for transportation! But the new scientific tools developed since then have allowed engineers to tackle some big challenges during the twentieth century.

Big strides were made, for example, in protecting metal structures from corrosion using organic coatings, and where relevant, using noncorroding materials such as stainless steel (patented in 1912) and plastics.

Sometimes problems with fabrication processes led to improved design rules. During World War II, the massive failure of a number of Liberty Ships practically gave birth to the discipline of fracture mechanics. More than 2700 Liberty Ships were built between 1941 and 1945 at unprecedented war-time rates. ‘‘One shipyard built a Liberty ship in five days. The massive increase in production was possible in large part because of a change from riveted to electric-arc welded construction . . . saving a thousand tons of weight in the hull'' Ref. [2]. The better understanding of crack propagation led to durable progress in ship – and other – production thereafter.

Air transport, with its literally sky-high requirements, stimulated a race for energy efficiency and mass reduction, and thus prompted great strides in the development of new grades of aluminum, titanium, and carbon-fiber composites. A significant step in modern aircraft design was the De Havilland Mosquito, whose airframe largely consisted of sandwich structures built up of thin skins of laminated plywood over a balsa core. Its lightweight and aerodynamics gave it a speed superior to any other airplane of the day. Sandwich panels are now widespread in all kinds of vehicles, including trains.

The emergence of powerful and affordable computers quickened the pace of development by providing a means to create and ''test'' designs numerically. It thus provided a new way to meet the challenge of improving the robustness of material models and predictive simulation. This led to significant progress in reliability and safety. A second effect was the capacity to imagine and realize structures with much more complex geometries. Ensuring, in particular, the safety of ever more sophisticated structural systems became intimately linked to finding the compromise between strength and formability in new-generation materials, be they steel alloys, nonferrous alloys, or structural plastics.

Airplanes, boats, trains, trucks, and cars today are thus built of very different materials than they were even 50 years ago.

Challenges of the New Century and the Breakthroughs They Will Require

In this twenty-first century, armed as we are with numerical tools and a rich knowledge of materials and process science – to which this book is contributing – the new challenge is applying our technological base to make our prosperity last and share it more widely. We have become obsessed with finding the optimal materials to push the performance envelope, improve safety, reduce costs, and preserve our resources – in a competitive global market environment.

From the point of view of materials and mechanical engineering, a number of standards have gained preeminence for various transportation applications such as plastic bumpers, magnesium steering wheels, composite train cabins, aluminum bus frames, titanium ship propeller shafts, and carbon-fiber composite structural components for aircraft. We have mastered the most pressing trade-offs so far, but the uncomfortable realization remains, that our best solutions are local, rather than global optima, increasingly subject to extrinsic factors.

Mass reduction for the improvement of energy consumption and emissions has become one of the principal drivers in material selection for transportation. The debate has evolved from the primitive level of asking which material – polymer composites or metals – future vehicles will be made of, to an understanding that significant progress can only be made by thinking in terms of pragmatic, fully optimized multimaterial designs used in appropriate vehicle architectures.

In the automotive sector, performance improvement has finally become synonymous with downsizing, for higher efficiency in use. The newest generations of internal combustion engines, with outputs upward of 90 kW l^{-1} and 200 Nm l^{-1}, rely on increasingly sophisticated materials with high temperature and dynamic wear resistance. A typical engine consists of more than 60 grades of metallic alloys and 20 types of organic materials, plus a variety of coatings and surface treatments. Electric vehicle (EV) motors, running at 20 000 rpm, will require yet different structural materials with improved creep and magnetic resistances.

Although very promising, however, advanced materials such as carbon-fiber composites are not suited for some of the applications with the strongest projected growth. For both individual and shared means of transportation, the access to mobility in new markets is opened under different economic constraints. Here the conditions for success are low initial and operation costs, local availability of materials, damage tolerance under loads that are more severe than in countries with mature infrastructures, good repairability, and adaptability to a widely varying, sometimes minimal industrial system.

Durable development requires not only robustness and durability of the means of transportation itself but also a design that favors repair, reuse, and recycling. The recycling pathways for many material classes are not yet reliable or even inexistent in many regions. Designs that favor easy separation for maximal recovery rates will become an essential element of a durable mobility for all.

Finally, for a global economy that is growing well above 3% per year according to the World Bank, using recycled materials will not suffice to cover our industries' needs – no matter how intensely we recycle. At such growth rates, we will have to continue injecting primary materials into the production streams. That means that we must pay increased attention to our resources, with the aim of reducing the footprints in minerals and metals, energy, and water. Given the expected long-term upward trend in energy costs, getting a grip on our material consumption will soon be synonymous with protecting ourselves against cost impacts, and thus finding a better path toward durable business.

Toward a Society Working by the Principles of Durability and Material Efficiency

Several trends are outlining the way ahead for structural materials:

- mass reduction, with, for example, a goal of −20% in production cars within 10 years;
- a pronounced bifurcation toward more/less ‘‘technicality,’’ with high tech for a growing premium segment, and ultralow cost, frugally engineered low tech (but high appeal!) for the booming new markets;
- the integration of functions such as decoration, optical effects, and information (sensors) in structural parts;

- design-for-*x*, where ''*x*'' stands for drivers such as cost, global production, logistics, disassembly, recycling, and the environment;
- more focus on process to require less raw materials and energy.

We are indeed shifting our paradigm from one of pure technical efficiency to one of a broader sustainable material management (SMM). As a recent European report remarked, ''the EU is the world region that outsources the biggest part of resource extraction required to produce goods for final demand'' Ref. [3]. SMM is thus not just a catchphrase for durability – be it environmental or business – but in fact one of raw material security. In several ways, beyond the pure technical challenge, mass reduction is becoming a strategic society issue.

The general term of ecodesign is gaining a strong, concrete footing as a credible practice to make ''green'' good for business. Michael Ashby has dedicated a recent book to the issue, extending his popular material selection charts to cover environmental criteria for broad classes of materials and applications. Ref. [4]. A metric of particular relevance, in relation with the mainstream considerations of CO_2 emissions, is the energy trade-off between manufacturing and in-use consumption. Life cycle analysis (LCA) is thus finally becoming established as an economic tool, with strong bearing on not only corporate social responsibility, but also on mid-to-long-term competitiveness. It helps us understand where, in the supply chain, we can reduce our energy impacts, and therefore costs. Such approaches aim at guiding economical material selection in a broader perspective. Beyond the traditional steel versus aluminum versus composite choices, they allow us to construct optimized material–process–localization combinations or aim for the right pace of introduction of recycled materials.

The conditions of success are multiple. Starting with reliable and comparable data, we need to define new value equations that integrate extended design drivers such as sustainability, and allow arbitration between them. In some cases, we will need to make hard choices between adapting the requirements to available technologies that may be more economical or durable and developing new technologies when more sophisticated materials are considered readily accessible over the longer term. Third, management needs to provoke and actively support more interdisciplinary research and improved cross-functional interactions within and between companies. Underlying all this is an integrated approach that gives appropriate simultaneous consideration to design, materials, and process: a truly production- and life-cycle-oriented engineering. And finally, we may simply need to have more courage and willingness to make decisions that could pay off only in the midterm – to truly build a vision.

Outlook on Structural Materials for Transportation

The future of structural materials lies in optimized hybrid structural systems that conform to a larger set of requirements and constraints. A commonly heard expression is ''the right material at the right place, at the right time.'' In order to develop durable solutions to the technical challenges of safe and efficient transportation, we will need to solve equations that integrate macro-economic and policy factors, trade considerations and externalities, and customer appeal and reassurance.

To do this successfully, the necessary starting point is a comprehensive knowledge of the options, of the potentials, and limitations of the different classes of structural materials. This is precisely what this book aims to give you. Beyond the basic yet extensive design and process reference data, it aims to bring you new insights based on recent, first-hand information from some of the top research centers in the EU.

As we look toward the future, we will want to keep our scope wide: state-of-the-art research is continuously extending the horizon for novel, sometimes surprising applications of classical materials. This is the spirit behind concrete canoes, carbon-fiber-reinforced bridges, plastic engines, and cars made of castor-oil-based polymers. Having ready access to comparable data will, it is hoped, promote synergies between fields of application.

We are confident that this book will be useful to you to orient your current material selection and also as a starting point to imagine the means of transportation of tomorrow.

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Preface

This book is meant to provide an introduction to current developments in the field of structural materials for the transportation industry. This includes rail, maritime, automotive, and aerospace industries, with a focus on the last two. Deliberately excluded from the scope are purely functional materials.

Quite literally, structural characteristics of materials are the backbone of any engineering design. They provide self-supporting capabilities to components where mechanical stability is a secondary concern. Whenever the bearing of mechanical loads becomes the primary role, and materials are optimized in view of this demand, we speak of structural materials. Solutions that address this challenge are what this book revolves around. The perspective chosen to deal with the topic is that of materials science and engineering. We have structured our work accordingly by dedicating the central parts to the main material classes.

However, any structural material we see in a specific application is in fact a combination of material and process. Its properties are defined by both, and thus, treating one aspect while neglecting the other is not a viable option. Besides, it is development tools which are built on similarly advanced modeling and simulation techniques that finally enable usage of emerging materials by allowing their evaluation in diverse application environments. With this in mind, we have included these aspects in our book. In all of them, the perspective is forward-facing: We do not intend to comprehensively cover the fundamentals of the various fields. Instead, we have attempted to identify major trends and highlight those that we see at the threshold to practical application.

Materials are evolving. So are the processes associated with them, as well as the tools and methodologies that allow their development and application. The rate of change in material development is dictated by external pressure. We have defined the major periods in the development of early mankind by the structural materials that dominated them. When bronze technology evolved, stone had to yield. The same occurred to bronze once iron became available on a larger scale. In transportation, we have seen change from wood and other natural materials to metal, and nowadays to composites. The rate of change steps up once pressure rises. The period of time that one material prevails appears to become shorter and shorter. On the other hand, since the shift from natural to technical materials, we mostly observe additions to the spectrum of materials rather than complete replacement. This may not be true for individual exponents of a material class, but definitely so for the classes themselves. Transportation, in all its width, is currently under considerable pressure to increase resource efficiency. One major handle to achieve this is lightweight design. This affords either new structural concepts or new materials offering improved performance. Very often, both go hand in hand. While such general pressure strengthens the motivation to search for entirely new approaches, it will also fuel inter-area competition. The past has shown that this may significantly speed up developmental processes within one class of materials. A good example in this respect is the recent evolution of high-strength steels, which took place at least partly in response to aluminum-centered automotive body designs entering volume production. A comparable situation can be observed in the commercial aircraft industry, where large-scale introduction of carbon-fiber-reinforced composites challenges the established status of aluminum alloys. New production processes support such tendencies are enablers of cross-fertilization between modes of transport: considering their properties, automotive design could profit greatly from application of carbon-fiber-based composites, too, but the sheer cost of state-of-the-art aerospace materials and processes forbids immediate takeover. Adaptation of processes to match another industry's needs, like transition from single part to large-scale series production, can help diminish such barriers. As a result, we currently see an extremely high rate of change in the range of available materials for load-bearing structures in the transport industry. With this in mind, it is the conviction of editors and authors of this book that a work is needed that familiarizes materials scientists, design engineers, and innovation managers in industry with developments in structural materials science and engineering that are likely to find their way into high-technology products within the next 5–10 years. We do give some background on the various materials and technologies, but the major focus is on what is currently on the verge of application.

Besides our primary target audience, we are confident that students and graduates in mechanical engineering, as well as academic researchers in the field, will find this compilation helpful to first get and then adjust their bearings through a highly dynamic field of research. In this sense, we intend our book to serve as a guideline for both groups. As such, it is meant to give them the first idea of the respective material class as well as a clear vision of where the present focus of developmental work will lead it within the near to mid-term future. This knowledge base shall allow them to decide which material classes and subclasses to study in more detail in view of their specific interest. Suggestions on where to search for in-depth fundamental information and keep track of future advances shall complete the picture.

The book is structured along the major material classes relevant for transport industry structural applications. All of these are treated in separate parts, starting with metals (Part I) and proceeding via polymers (Part II) and composites (Part III) to cellular materials (Part IV). Each part covers associated processes on the level of its individual chapters, that is, for the exemplary case of metals separately for iron-, aluminum-, magnesium-, and titanium-based materials (Chapters 1–4). In a further section (Part V), selected aspects of modeling and simulation techniques are being treated. Highlights have been set here in terms of modeling approaches covering multiple scales of material description (Chapter 13) and adaptation of artificial intelligence (AI) techniques to material modeling (Chapter 14). The use of fundamental ab initio techniques in designing new metallic material compositions and states is treated in yet another subsection (Chapter 15). Finally, specific trends that go beyond an individual class of materials are discussed in Part VI. An example are hybrid design approaches, which attempt to locate the optimum material for a purpose at the place where best use can be made of its properties, thus leading to complex, multimaterial structures (Chapter 16). In extrapolating trends already discussed in terms of structural health monitoring for composite materials (Chapter 8), material-integrated sensing and intelligence, summarized under the descriptive term of sensorial materials, are covered in Chapter 17. Additive manufacturing as an approach with promise for highly versatile production and structural complexity that in some respects cannot be reached by other processes is presented in the final chapter (Chapter 18).

We have attempted to organize each of the main chapters in Parts I–IV and Part VI in a similar way. In these predominantly material-related chapters, we start with some fundamentals and go on to detail new developments. In this, we do not separate material and process because of the close link between both. However, we do subdivide the chapters according to distinctions that are already established for the respective class of materials. An example is the distinction between wrought and cast alloys realized in the chapters on aluminum and magnesium. A similar approach, though adapted to the specifics of such composites, is reflected in the separation between processes involving thermoplastic versus those employing thermoset matrices in the chapter on polymer matrix composites. The major chapters are concluded with a section on further reading for intensified study and a hint at major organizations, conferences, or other events dedicated to the respective topic.

We are extremely grateful to the many authors who have shouldered the task of providing the content to this work. We are indebted to Dr. Martin Preuss (Wiley-VCH) who encouraged us to venture this endeavor, which was originally based on two symposia organized in the course of the Euromat 2009 Conference held in Glasgow (UK) from 7 September 2009 to 10 September 2009 (www.euromat2009.fems.eu). Finally, our thanks go to Lesley Belfit, again of Wiley-VCH, who helped us steer our course through all the hindrances of the editorial process with grace and patience.

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