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Pitfalls and myths when designing from composite materials

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1. Introduction

Designers, computational engineers and technologists of mechanical equipment consider with responsibility many requirements and apply a number of criteria in designing and assessing the loading capacity of particular components of machines. Most machines and equipment designed in the last two centuries were made of metals. Their physical and mechanical properties can be generally considered as isotropic. For centuries design processes were developed and design know-how accumulated. The view, however, remained unchanged – it worked with metals and established itself in the minds of designers - “isotropic thinking“. This view, unfortunately, predominates until now, when we can design parts with a controlled orientation of the load-bearing components, for example fibres or structural elements.

The rapid outset of development and use of composite materials in the last decades of the previous century caught the designers as well as the technologists unprepared to change their way of thinking. However, the designer who uses composite materials (we will here focus on long fibre composites used for primary structures and principal structural elements) is provided with a much broader range of structural options, [1]. Today we already know that the mere substitution of a metallic material with a composite is not enough. Often good application results were not obtained even with optimized designs of composite components which replaced the original one in the remaining all-metallic structure. And this is when then the discussed “myths about composites“ started to appear.

The optimized properties and effectivity of fibre composites and implementation of their “academic advantages“ can be fully applied only in an absolutely new and comprehensive structural design. This paper should help the traditional designer to gain courage to apply new composite materials, to get rid of thinking in the “isotropic dimension“ and not succumb to uninterpretable myths which often accompany composite applications.

2. Can be composite structures so strong and tough as traditional metallic ones?

Indeed, such results in the history of the development and use of composites were arrived at by a number of companies, since by the mere replacement of the metallic material the required equivalents were not reached, e.g. stiffness and strength, [2]. Table 1 gives a comparison of selected physical and mechanical properties and prices of most current classical materials and basic types of fibres (HS – high strength, HM – high modulus, UHM – ultra high modulus fibres) and matrices most frequently used for the construction of long fibre composite structures, [3-5]. This table shows the known fact, that e.g. glass fibres have a potential to equal aluminium alloys in the longitudinal Young modulus E_x and also in strength. Carbon fibres reach in these parameters even much higher values than e.g. high strength steel. A bonus brought by composites is considerably lower specific mass ρ

compared with metals. If for example we should design a beam (here according to Fig. 1 with a rectangular profile *b*×*h*) with a given bending stiffness k and concurrently minimize its mass, we would have to choose a material with the lowest *ρ/E* ratio), as follows from Equation 1.

Table 1. Comparison of selected physical and mechanical properties and material prices

Material	**Density**	**Longitudinal Modulus**	**Transverse Modulus**	**Shear Modulus**	**Ultimate Strength Tension (T) Compresion (C)**	**Relative Price**
	ρ	**E_x**	**E_y**	**G_{xy}**	**R_m**	**P**
	kg.m^{-3}	**GPa**	**GPa**	**GPa**	**MPa**	**€/kg**
Steel	7850	210	210	80	500…2000	0.5
Aluminum alloys	2690	71	71	27	360…470	1.9
Ductile Iron	7100	169	169	66	500…800	1.3
Gray Iron	7100	130	130	51	55 (T) 140 (C)	1.5
Mineral Casting	2400	40	40	15	12 (T) 120 (C)	2...5
Standard Carbon fibre	1760	230	40	60	3550	10
HS Carbon f.	1800	310	15	50	5550	40
HM Graphite f.	2120	350	6	10	3800	50
UHM graphite f.	2170	780	5	20	4200	60
E-Glass	2580	78	78	30	3450	2
S-Glass	2460	87	87	38	4580	15
Aramide Fiber	1440	110	5	12	3600	25
Epoxide matrix	1200	3...4.5	3...4.5	1.6	70 (T) 180 (C)	12

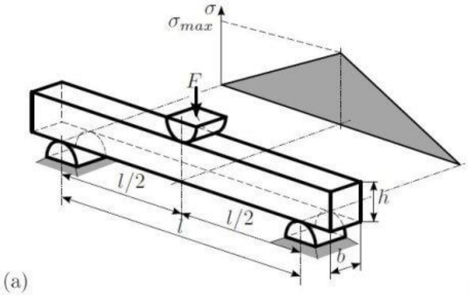

Fig. 1. Configuration of the specimen for the three-point bending test

$$J = \frac{1}{12} b \cdot h^3 = \frac{h^2}{12} A; \quad k = \frac{48\,EJ}{l^3}; \quad m = A \cdot L \cdot \rho = \frac{1}{4} k \cdot l \cdot \frac{\rho}{E} \tag{1}$$

3. Are composite structures expensive in relation to new benefits?

The value of the ratio *ρ/E* can even be by one order more appropriate for a carbon composite than for steel. On the contrary in other quantities given in the table, namely the shear elastic modulus *G* or the relative price, composite fibres seemingly cannot compete with metals. The utility properties and price of a composite component are specified by a more comprehensive combination of factors, namely optimum structure, used semiproducts and technology of their processing, selection of the type and orientation of the fibres in the structure, their part by volume and a number of other parameters. This gives a broad range of application of sophisticated procedures (analytical and numerical methods and optimizations) how to obtain various concepts which differ from one another which can observe the required criteria on a different level. The range of the covered parameters is e.g. in Table 2, which shows the properties of five types of laminates made of various types of carbon fibres with various layer orientations. The table shows a theoretical example how to alternate types of fibres and orientations in a such a way that the resulting stiffness moduli can reach equivalence with those of classical materials (even in shear stiffness), or to reach even considerably higher stiffness parameters (e.g. by applying UHM fibres).

As the comparison of relative prices in Table 2 shows, the use of composites will lead to higher material costs. In a comprehensively conceived, e.g. all-composite concept, or in a specially designed composite structure, the newly gained utility properties must prevail over the purchase costs. For example, the temperature stability of dimensions can be reached by using layers with a zero thermal expansion coefficient or the effect of the thermal source can be eliminated by a structure of layers with low thermal transmittance. Such designs would be difficult to put into practice by application of the classical “metallic design“. We often use the possibility to increase eigenfrequencies, and to increase damping of the composite structure (e.g. machine tool slides). The low masses of structures of e.g. manipulators, makes it possible to increase the dynamics of motions and thus to increase the cycle time on production lines with a consequent rapid returnability of costs. Further by applying sufficiently tough and long composite shafts the structure can be simplified and its cost reduced (less bearings in the supports of long rotating drives and in couplings between individual sections of the long shaft). A lot of other examples of the effective use of composites can be mentioned.

Table 2. Comparison of properties and prices of classical materials and typical carbon laminates

Material	**Density**	**Longitudinal Modulus**	**Transverse Modulus**	**Shear Modulus**	**Thermal expansion**	**Thermal conductivity**	**Relative Price**
	ρ	**E_x**	**E_y**	**G_{xy}**	**α_x**	**λ_y**	**P**
	kg.m^{-3}	**GPa**	**GPa**	**GPa**	**10^{6}.K^{-1}**	**W.m^{-1}.K^{-1}**	**€/kg**
Steel	7850	210	210	80	13	50	0.5
Aluminum alloys	2690	71	71	27	22	205	1.9
Gray-iron	7050	169	169	66	10	55	1.5
HS C/E: Unidirectional	1550	203	8,2	4.3	0.9	0.5	20
HS C/E: 0/90	1550	106	106	4.3	3.1	2.8	20
UHM C/E: Unidirectional	1750	470	4.8	3	-1.1	10	60
UHM C/E: 0/90	1750	237	237	3.6	-0.4	195	60
UHM C/E: 45/-45	1750	13.8	13.8	118			60

4. How can we improve the weakest link in the composite structure – joints?

In complicated equipment there is only a small change that the entire structure could be an all-composite one or in “one piece“. Usually we must count with a composite-metal or composite-composite “interface“ or “join“ the composite component with other elements of the structure. Even in classical metallic structures it holds that most joints (whether screwed, riveted, pressed-on or welded) cause local concentration of deformation and stress and are potential points for the creation of fatigue cracks (e.g. during cyclic loading) or locally weaken the point even for static loads. However even the best optimization of the composite structure can be ineffective, if the designer is not able to tackle with the transfer of load over the composite-metal or composite-composite interface. The development of various types of production technologies was accompanied by the development of various types of joints (mechanical joining – screwing, riveting, gluing and their combinations). The development of new types of glues makes it possible to design sufficiently strong joints. Composites with a thermoplastic matrix can be joined also by welding. Special “composite“ methods of joining are developed, e.g. so-called stitching (multi-pin joining or z-pinning) of a 3D composite fabric, etc. So-called integrated joints can also be included in the assortment of specific joints of wound composite structures. They utilize load bearing longitudinal fibre bundles to create e.g. an assembly eye which embraces another composite or metallic component as shown in Figure 2. Also these joints are characterized by high strength and life.

(a) (b)

Fig. 2. Finite-element model (a); real part of the integrated composite joint at the end of a carbon fibre composite rod (b)

5. Conclusion

The portion of new types of materials including composites in mechanical engineering will even in future surely grow. What is important for their functional application and reliable operation is the profound knowledge of their properties and inventive utilization of their potential in connection with sophisticated designing and production technologies. Also important is a correct balance-sheet of their use from the aspect of the entire life cycle of the structure. Only then will deep-rooted myths begin to disappear, myths which more likely represent the traditional views of designers including the discussed “isotropic thinking“.

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