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Optimal selection of composite materials in mechanical engineering design

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ABSTRACT

A method is described for the optimal selection of composite materials based on: *performance indices* to define material performance, *materials selection charts* on to which the material properties and performance indices can be plotted and the use of *bounds* to define the envelope of properties accessible to a particular material. *Weighting factors* are also introduced as a means of compensating for the relative effect and importance of performance index groups. The method makes use of a computer implementation. To demonstrate the method, a case study is described that investigates the feasibility of using composite materials for commercial printing-press cylinders.

INTRODUCTION

Selecting appropriate materials is an important part of the design process for mechanical engineering products, particularly for load bearing components and structures. For a given loading system, the performance of an engineering structure is limited by the properties of the material of which it is made, and by the shapes to which this material can be formed. However, compared to conventional engineering materials, the use of composites complicates the situation because these materials are actually a combination of different materials, comprising of reinforcement, matrix, and possibly fillers and additives. Composites are also expensive and can be difficult to fabricate, but provide an enhanced shaping capability and an ability to tailor the reinforcement, thus leading to efficient material utilisation and high performance structures.

SELECTION METHODOLOGY

For the mechanical engineering design process, materials are considered at all stages. At the concept stage, all materials are considered but at a low level of precision. At the embodiment stage, sub-sets of materials are compared at a higher precision level to determine the size, layout, performance and cost of the design. Finally, at the detailed stage, normally one material is chosen with the best available precision. Designing with a single material at the detail stage is more straight forward with data available from many sources, including in-house testing. The difficulty, particularly if the application is novel, is deciding which material to use.

The performance of a structural component such as minimising energy per unit mass (index) is a function of the functional requirements, geometry and material properties. These three groups of parameters can be separated and therefore the optimum choice of material becomes independent of the details of design; it is the same for all geometries and all values of functional requirements. The performance can therefore be maximised by maximising a group of material parameters.

Performance usually depends on two or more material properties which can be presented by plotting one material property (or combination of properties) on each axis of a Materials Selection Chart [1]. Superimposing the performance index on the chart (a sloping line plotted on log scales) allows an optimum choice of material to be made. Section shape can also be taken into consideration by including a dimensionless shape factor in the selection procedure. If after several selection stages, the sub-set of selected materials is still too large, it may be possible to apply weighting factors to reduce the sub-set even further [2]. Performance indices cannot deal with weighting the relative effects in importance of each index in a quantitative way because each has

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different units. However, this can be dealt with by expressing each index as proportions of the largest value. The performance index values can therefore be converted to relative values (values relative to the largest quantity) and combined empirically. The weightings are decided by intuition based on the relative importance of each performance index.

When the selection procedure results in a composite material, the next step is to determine the proportions of the constituent components. For composite materials, *bounds* (e.g. for modulus) or *limits* (e.g. for strength) defining upper and lower values between which the properties lie, can be used to bracket, or envelope, the properties of all arrangements of matrix and reinforcement [3]. For instance, the modulus of a composite is bracketed by the well-known Voigt [4] and Reuss [5] bounds. The upper bound is obtained by postulating that, on loading, the two constituent components suffer the same strain; the stress is then the volume average of the local stresses. The lower bound is found by postulating that instead that the two components carry the same stress; the strain is the volume average of the local strains. Similar envelopes can be defined for other material properties using other analytical solutions and approximations. The method gives the designer freedom in considering trade-offs pertaining to the potential increase in performance index for a given increase in volume fraction of a constituent.

COMPUTER IMPLEMENTATION

This work has made use of the *Cambridge Materials Selector* (CMS), a computer based implementation of the method described above [6]. This package comprises of a hierarchy of several databases of materials properties (including composites), a management system which recovers and manipulates the data, and a graphical user interface which presents the data on material selection charts. The use of such a package facilitates rapid assessment of selection criteria.

CASE STUDY

A case study was carried out in collaboration with Rockwell PMC in Peterborough to investigate the feasibility of using composite materials to improve the design of commercial printing-press cylinders [7].

A commercial heatset web-offset printing-press comprises of a near vertical stack of large horizontal-axis cylinders (approx. 150-300mm diameter, 2000mm long) as shown in Figure 1. These cylinders are solid and made from steel (medium-carbon). At high speeds, the cylinders tend to vibrate, leading to poor quality printing. The main source of vibration is a longitudinal slot in the surface of each cylinder. A new design of cylinder was required that would delay the onset of vibration, thus allowing higher speeds or reduced diameter cylinders to be used. Another requirement was that the new cylinder must be capable of being retrofitted so that design changes to the rest of the printing-press are not required.

In the case of a printing-press cylinder, the sectional shape and mode of loading is determined by the configuration of the printing-press and cannot be easily changed. The choice of material is therefore the only parameter that can be changed to significantly affect the structural performance of the cylinder. The cylinders operate under high transverse loads (closing force up to 150 kN) and speeds (up to 13 m/s) in an ink/water environment at temperatures slightly above ambient. Mild solvents are also used regularly for cleaning purposes.

To impartially choose a material from the full range of engineering materials, the CMS form of graphical selection procedure, described previously, was used with a database of generic material properties. Sectional shape was not included because it cannot be changed due to the configuration of the printing-press and a constant radius cylinder has a shape factor of unity. A functional analysis of the printing-press cylinder revealed the most appropriate properties, or performance indices, for maximising mechanical performance. These include elastic modulus, damping coefficient, resonant frequency, strength and cost. The selection criterion were superimposed on material selection charts and the intersection of several selection stages produced a sub-set of 21 candidate materials. Figure 2 illustrates one of these selection stages for choosing materials with high resonant frequency. To reduce the sub-set further, the performance index values were converted to relative values and combined empirically using weighting factors. This led to a sub-set of 7 candidate materials.

Taking into account the significance of other important properties such as qualitative data on manufacturing constraints, environmental effects and application suitability, the optimum choice was a composite material consisting of carbon fibre reinforced plastic (CFRP). In general, CFRP possesses high stiffness and strength, good damping capacity and high resonant frequency properties, but have high raw material costs compared to steel. Using the detailed composites database, Figure 3 illustrates the selection of the most appropriate CFRP system. A high modulus carbon fibre embedded in a thermoset epoxy resin matrix was considered to be the most appropriate system. There are a large range of commercially available polymer matrix resin systems. A thermoset resin was chosen instead of a thermoplastic resin because it has better creep resistance. Specifically, epoxy resin was chosen because of its superior physical and mechanical properties, lower cost, availability and ease of processing. Carbon fibre typically ranges from ultra-high strength to ultra-high modulus grades. For similar reasons of economy, availability and ease of handling, high modulus carbon fibre was chosen, even though this did not give the highest modulus value.

The composites selection methodology identified the optimum proportions of fibre and matrix, specified as a fibre volume fraction. Figure 3 shows the use of bounds to define upper and lower property values which correspond to the parallel and perpendicular directions to the fibres respectively. The effect of fibre volume fraction on properties can be determined, thus allowing an optimum choice to be made. Several processing methods were investigated, including hand-layup, compression moulding, resin transfer moulding, pultrusion, and filament winding. To maximise the flexural properties of the cylinder, a high proportion of axial fibre was required. This could be provided by pultrusion or filament winding. The pultrusion process is suited to constant cross-section shapes with high proportions of axial fibre, but the section size exceeds the practical limits of the process. Filament winding was therefore chosen with a practical limit of 60% fibre volume fraction. A special purpose machine was envisaged to wind axial fibres.

The scope of this paper has not permitted a detailed description of the cylinder design. Essentially, the final design comprised of a steel core with a thick-walled filament wound composite sleeve. This construction positioned the composite material furthest away from the neutral axis, thereby maximising its stiffening effect. The steel core was extended beyond the length of the sleeve to provide spigots for locating bearings and gears, as well as acting as a mandrel during the winding process. The new design allows the use of either higher speeds, or smaller diameter cylinders, but the full potential will not be realisable with the retention of the slot. The slot was also investigated as part of the study, but changes in the slot have major effects on the design of the rest of the printing-press and compromise the retrofitting requirement. The final decision is a business one and will depend on whether the increased performance provides sufficient competitive advantage for the company.

CONCLUSIONS

A rational material selection methodology, facilitated by a computer implementation, has been demonstrated through a case study investigating the feasibility of using composite materials for printing-press cylinders. The combined use of performance indices, weighting factors and bounds has enabled the optimal selection of a composite material. The method depends on an unique synergy of theory and practical experience. The result of the case study is a new cylinder design with increased stiffness and damping performance, thus permitting higher operating speeds.

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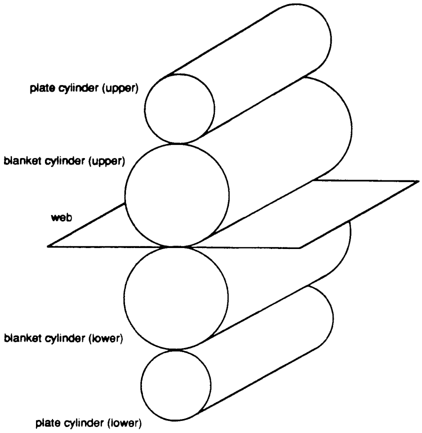

Figure 1: Schematic of printing-press cylinder stack

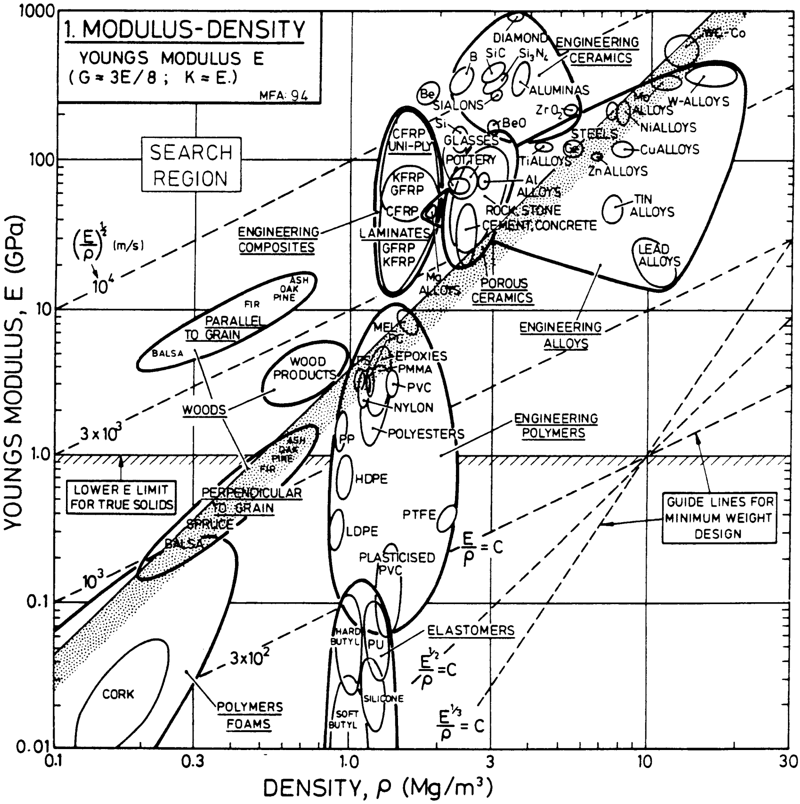

Figure 2: A design chart of generic materials properties showing resonant frequency selection.

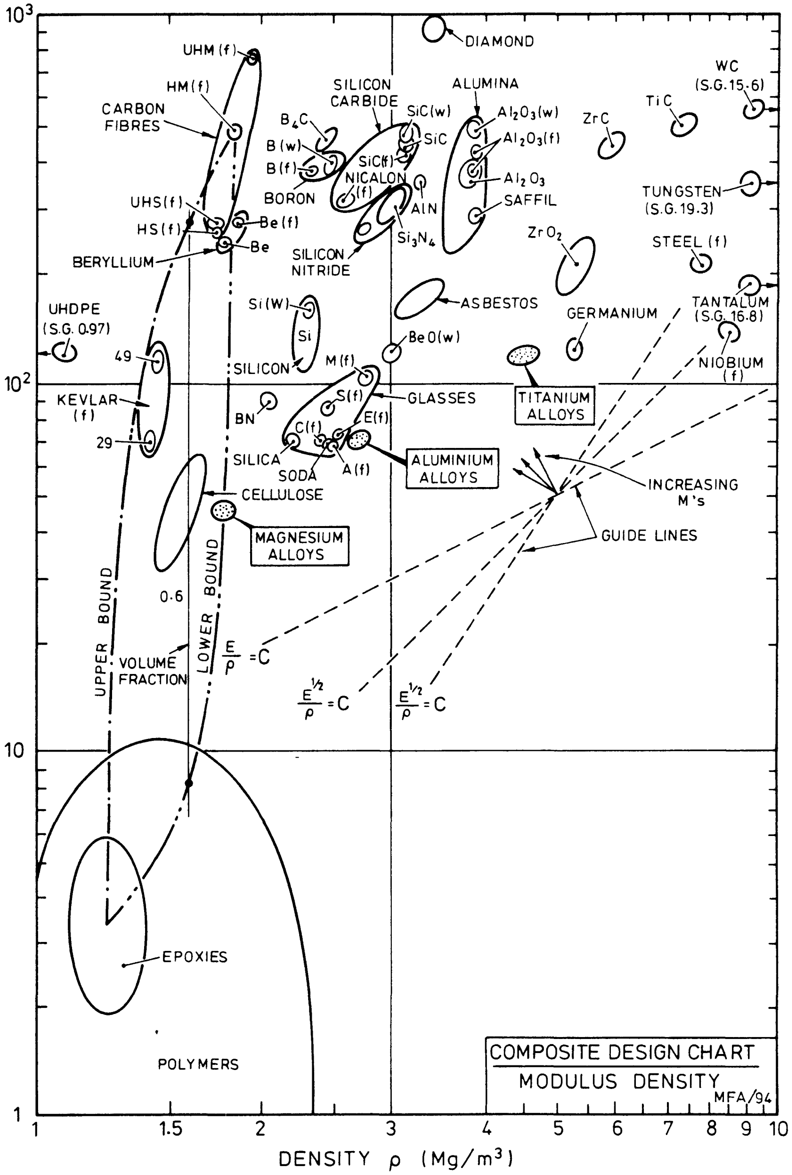

Figure 3: Design chart of composite materials properties showing bounds for unidirectional carbon-epoxy composite