Multi-Criteria Material Selection of Monolithic and Multi-Materials in Engineering Design**

By Pasu Sirisalee,* Michael F. Ashby, Geoffrey T. Parks and P. John Clarkson

The benefits of combining different homogeneous materials to give heterogeneous materials have been recognized since our early history; straw-reinforced brick and goat hair-reinforced pottery are examples.[1] Such combinations are known as multi-materials[2] or hybrid materials.[3] A useful working definition[4] is “a combination of two or more materials in a pre-determined configuration and scale, optimally serving a specific engineering purpose”. Established examples are particular and fiber-reinforced composites[5] like CFRP and GFRP, and sandwich structures. Barbero classifies multi-materials – composites as he terms them – into three classes: reinforced composites, laminated composites and hybrid composites.[6] Ashby includes lattice materials and segment materials in addition to reinforced composites and sandwich structures.[7] Four classes of multi-materials, following Ashby,[7] are presented in Figure 1. This article describes a tool to support designers in comparing the performances of multi-materials with those of other materials and to guide their selection for a given application. One particular type, sandwich panels, is chosen as a focus to implement and illustrate the methodology.

Approaches to multi-material selection: Designers should ideally explore the widest possible range of conceptual solutions before selecting one. Thus, the material search space should be as broad as possible at the conceptual design stage, as shown in Figure 2. As the design proceeds this space is narrowed, culminating in a single choice.

Multi-material selection is more complicated than that of monolithic materials for two reasons: first, because the configuration in which the constituents are to be combined must be chosen, and, second, because, in optimizing the combination, the number of free variables is greater – it now includes the relative volumes of the two constituents, their configuration and their scale. What is needed is a way of exploring and optimizing these. Designers can then bring multi-materials into consideration in either of two broad approaches, as mentioned by Phillips[8] and Quinn.[9]

Catalogue approach: Particulate and fibrous composites – the best known hybrids – can be included in a materials database in the same way as monolithic materials, allowing direct comparison and selection by established material-selection methodologies.[7] An example is the Cambridge Engineering Selector (CES) database,[10] which includes some 200 composites and foams. Work on developing a knowledge-based system to assist composites selection has also been undertaken.[11] This allows selection from among existing, commercially available composites, but it does not allow for optimization; to do that requires ways of exploring all feasible combinations of material, configuration, and, where relevant, scale.

The proposed approach: The alternative is to think of multi-materials as the combination of several constituents. This approach might well lead to a better solution since the multi-materials can be tailored to meet the particular design requirements. A common design strategy for multi-materials is to tailor them to fulfill the design requirements as closely as possible by varying either constituents, configuration or scale. This strategy works well with single objective problems in which a single optimal solution can be found without the need to reach a compromise between conflicting objectives and constraints. However, engineering components are increasingly required to be multi-functional, simultaneously meeting a number of requirements.

In multi-criteria selection, the optimal solution depends on the designer’s preferences. Presenting to designers a Pareto-optimal front, showing the best achievable trade-offs between the competing objectives, can help them make a better decision. Therefore, the strategy proposed is to generate a representative range of multi-materials and to include these in the materials database to facilitate comparison of their performances with other candidates, either monolithic or multi-material.

At the highest level, the basis for the selection of materials in forming multi-materials is to use the desirable attributes of...
one monolithic material to compensate for the inadequate attributes of another or others. As a general rule, while the individual material properties of a multi-material will not usually exceed the best values from among its constituents, the performance metrics, which combine various material properties, can do so.

The established approach to material selection is presented in Figure 3. The starting point is that all materials are potential candidates until shown to be otherwise. The number of candidates is reduced in a systematic way by applying constraints set by the requirements of the design and by ranking candidates according to the criteria that represent better performance for the application in question.

To include multi-materials in this procedure, the optimal structure of each multi-material is required. The optimization method used does not have to be very sophisticated since, at the conceptual design stage, design information is still fluid and imprecise. Only an approximate estimate of sizing and configuration is needed in order to rank multi-materials. Accurate sizing and rigorous engineering analysis will be undertaken later when design information is more precisely known.

We propose a selection approach for multi-materials as presented in Figure 4. In principle, including as many configurations of multi-materials as possible is desirable, but time-consuming because the range of multi-materials is large.

The first stage of the process is configuration (as in Fig. 1) selection. Once the designer selects a configuration for the multi-material (a sandwich, a composite laminate and so forth), the configuration determines the main form of the components. If the configuration is “fibre-reinforced composite”, the components will be fibre and matrix; if “sandwich”, the components will be core and face sheets. The material search space is thus divided into groups according to the desired attributes of each component. For instance, if the objective is to design stiff and lightweight sandwich structures, at least two kinds of materials will be required: low density materials for the core and stiff, strong materials for the faces.

Each possible material combination can then be optimized subject to the specified objectives and constraints, enabling the most promising material systems to be found. However, the procedure in Figure 4 should allow for iteration, reflecting the uncertainties inherent in conceptual design. Once the candidate multi-materials have been short-listed, more precise calculation refines the optimization.

To implement this approach, a computational tool is required. Each configuration of multi-material requires its own set of predictive models for optimization, and these are

**Fig. 1. Four classes of multi-materials.**

**Fig. 2. Material search space in the design process.**
generally known. To illustrate this approach, one class of multi-materials, sandwich panels, is used as a focus in the remainder of this paper.

Multi-criteria sandwich panel selection: Typically, a sandwich panel consists of two stiff, strong face sheets bonded to a lightweight core, as shown in Figure 5.

To implement the high-level multi-material selection approach proposed in Section 2.2, for sandwich panels, we follow the procedure outlined in Figure 6.

First, materials from the materials database are divided into a face materials group and a core materials group. This pre-selection can be based on either a quantitative or a qualitative approach. In the quantitative approach, material indices are used to identify promising face and core materials, which can reveal innovative solutions although these may not always be feasible from a manufacturing standpoint. Alternatively, and more conservatively, face and core materials can be selected from lists of those already in established use.

Once lists of potential face and core materials have been obtained, they are then paired up subject to their compatibility. This list of sandwich materials is included in the materials database. Here the concept of an exchange constant chart is helpful, offering guidance in selecting materials when two or more conflicting objectives are to be met.[13] Such charts are illustrated in Section 3.3. A shortlist of promising material combinations can be retrieved and compared with catalogue materials – the materials available in the database.

For the regions on the exchange constant chart where sandwich materials appear promising, an optimization, as shown in Sirisalee et al.[14] can be carried out to confirm the ranking of the results and their sensitivity to the design parameters. Using the exchange constant values suggested from the exchange constant chart, multiple design objectives can be combined into a single “merit” function, allowing the optimization routine for single criterion problems to be used. The penalties of materials calculated from the exchange constant chart, multiple design objectives can be combined into a single “merit” function, allowing the optimization routine for single criterion problems to be used. The penalties of materials calculated from the exchange constant chart, multiple design objectives can be combined into a single “merit” function, allowing the optimization routine for single criterion problems to be used. The penalties of materials calculated from the exchange constant chart, multiple design objectives can be combined into a single “merit” function, allowing the optimization routine for single criterion problems to be used. The penalties of materials calculated from the exchange constant chart, multiple design objectives can be combined into a single “merit” function, allowing the optimization routine for single criterion problems to be used. The penalties of materials calculated from the exchange constant chart, multiple design objectives can be combined into a single “merit” function, allowing the optimization routine for single criterion problems to be used. The penalties of materials calculated from the exchange constant chart, multiple design objectives can be combined into a single “merit” function, allowing the optimization routine for single criterion problems to be used.
must be included in order to compare the objective values limited by different design constraints. The active constraint is the one for which the face thickness is greatest.

The design constraints for sandwich panels are inevitably more complicated than those for catalogue materials since there are interactions between their constituents. The six design constraints for sandwich panels included in calculating the objective function are stiffness, face yielding, face wrinkling, core shearing, local indentation and maximum panel thickness. For catalogue materials, only stiffness, strength and maximum thickness (sizing) constraints are needed. The design constraint functions for both sandwich panels and catalogue material panels are summarised in Table 1.

Generate the Pareto front of each pair of sandwich materials: In multi-criteria problems, each pair of materials, when made into sandwich panels, will have its own Pareto-optimal front since a different volume ratio of sandwich materials yields different sandwich material properties, as illustrated in Figure 7.

In the exchange constant chart construction procedure presented in Sirisalee et al.\textsuperscript{[13]} discrete data are required. We can generate a set of data to represent the Pareto-optimal front of each sandwich material pair by stepping through representative volume ratio values. However, only some parts of Pareto-optimal front are likely to be feasible due to the design constraints. Thus, a series of volume ratios are calculated by dividing the range of feasible core thicknesses into a set of points and calculating the corresponding face thickness, which depends on the active constraints, at each point. With this approach, most of the existing procedures for exchange constant chart construction are still applicable. A discrete distribution using a stepwise sequence of volume ratios is adequate to define the Pareto-optimal front of each sandwich material, simplifying the procedure.

Combine the regions of the same sandwich material: Once calculated, the objective values of each sandwich material pair are then compared with those of other sandwich materials, as well as other catalogue materials, to find the non-dominated solutions. The dominance-finding scheme is the same as the one used in Sirisalee et al.\textsuperscript{[13]}

The exchange constant chart construction procedure is almost the same as that for catalogue materials. The concept underlying the exchange constant chart is that the non-dominated solutions on convex portions of the Pareto front will be optimal for a certain range of values of exchange constants, as illustrated in Figure 8 for a two-objective problem, in which the penalty function is defined by:

\[
Z = C + aP
\]

When three objectives are involved, the exchange constant band shown on the right of the two-objective plot in Figure 8 becomes an exchange constant chart, as shown in Figure 9.

\begin{table}[h]
\centering
\begin{tabular}{|l|l|}
\hline
\textbf{Design parameters} & \textbf{Values} \\
\hline
Applied load per unit area (N/m\textsuperscript{2}) & \(1.4 \times 10^5\) \\
Maximum allowed deflection (m) & 1% of span length \\
Sandwich panel manufacturing cost (£/m\textsuperscript{2}) & 10 \\
Span length (m) & 1.4 \\
Minimum contact dimension (m) & 0.079 \\
Concentrated load per unit area (N/m\textsuperscript{2}) & \(1.18 \times 10^6\) \\
Maximum panel thickness (m) & 5% of span length \\
\hline
\end{tabular}
\caption{Design parameters for refrigerated truck floor panels.}
\end{table}
An adaptation to the exchange constant chart method of construction when including sandwich panels is made in order that contiguous regions occupied by sandwich panels of different geometrical designs but using the same face and core materials are shown as a single region in the chart. The boundaries between regions occupied by different solutions are found by determining the exchange constant values for which the penalties for pairs of non-dominated solutions are the same. This procedure is simply omitted if the two solutions are different sandwich panels made from the same materials.

To illustrate the approach described above, a case study is now presented.

Case study: Floor panels of refrigerated trucks: The problem: The floor panel of a refrigerated truck presents an interesting case study because it has to meet several design objectives. First, minimizing mass is crucial for transportation applications. A lighter floor panel could either allow more payload on the truck or reduce fuel consumption. Second, trucks are utilisation vehicles: minimizing cost is important. Finally, the floor panel must have adequate thermal insulation to keep goods refrigerated: minimizing heat loss is also an objective. A traditional configuration of the floor panels of refrigerated trucks is shown in Figure 10. The panel is a sandwich reinforced by wooden stiffeners, supported on the chassis beams. The sandwich panel in the traditional configuration of a refrigerated truck floor is not load-bearing since the key load-bearing components are the wooden stiffeners. However, a load-bearing sandwich panel is obviously a possibility and one that might allow substantial weight saving.

The refrigerated truck floor can be modelled as a simply supported panel subjected to a uniform load, as shown in Figure 11.

The load cases for the panels are taken from Rasmussen and Staelens. The truck floor is 2.5 m wide and 13.5 m long. The distance between chassis beams is 1.4 m. The normal applied load case is derived from a 24-ton payload uniformly distributed over a truck floor panel. The concentrated load case has been derived from the localised force of a forklift truck wheel applied on the truck floor panel. The width of a forklift wheel is 79 mm. Following Rasmussen and Staelens, a safety factor of 2 has been applied to account for the dynamic effects of driving. All the design parameters are summarised in Table 2.

Materials: For catalogue materials, some “protective” screening constraints are applied to eliminate materials that are totally unsuitable. These screening constraints are summarised in Table 3. The constraint on density is applied in order to eliminate very high-density metals, while the constraint on shear modulus eliminates elastomers and other flexible materials. The minimum acceptable value of the shear modulus is set to be equal to that of fluorinated ethylene propylene (FEP) or Teflon. Finally, the constraint on toughness is also necessary in order to eliminate brittle materials. 1,760 of 2,945 catalogue materials from the CES 4.0 database pass these screening constraints.

For sandwich panels, the face and core materials are predetermined using a qualitative approach. The most commonly used face and core materials are included. There are 12 face materials and 12 core materials, as listed in Table 4.
The model: The design objectives for the refrigerated truck floor panel are to minimize mass, cost and heat transfer through the panel. The mass objective can be defined by

\[ m = \rho d \quad \text{(Units: kg/m}^2\text{)} \quad (2) \]

Similarly, the cost objective can be defined by

\[ \bar{C} = C_m \rho d + C_{\text{manu}} \quad \text{(Units: £/m}^2\text{)} \quad (3) \]

For all catalogue materials, \( C_{\text{manu}} \) is assumed to be zero since the material cost \( C_m \) obtained from the CES 4.0 database\(^{[10]}\) is the cost of intermediate forms of materials, such as beams, panels, columns and so on. For sandwich panels, \( C_{\text{manu}} \) has to be included to reflect the additional face and core bonding process.

Finally, the heat transfer objective can be defined by

\[ \dot{Q} = \frac{\dot{\lambda}}{d} \quad \text{(Units: W/(m}^2\text{K))} \quad (4) \]

It is worth noting that for sandwich panels \( \rho, C_m \) and \( \lambda \) are replaced by \( \bar{\rho}_{\text{L,U}}, \bar{C}_{\text{L,U}} \) and \( \bar{\lambda}_{\text{L,U}} \) calculated using the formulae in Table 5.

We consider three types of design constraint: constraints on stiffness, strength and sizing. For catalogue materials there is just a single constraint of each type. For sandwich panels, there are four strength constraints, one stiffness and one sizing constraint.

These design requirements limit the panel thickness \( d \). For the mass and cost objectives, the panel thickness should be minimized, limited by either the stiffness, strength or sizing constraint. However, for the heat transfer objective, the panel thickness should be maximized, limited only by the sizing constraint. Therefore, the thickness that is optimal for the heat transfer objective. Nonetheless, the range of viable values for monolithic materials is rather narrow; just upper and lower limits on the panel thickness should provide a good approximation of the range for these materials.

The three conflicting objectives above can be combined into a single merit function, a penalty, in order to find the optimal solution at particular exchange constant values. The penalty function is defined as

\[ Z = \bar{C} + a_1 m + a_2 Q \quad \text{(Units: £/m}^2\text{)} \quad (5) \]

Material selection: Figure 12 shows the exchange constant chart constructed by using the procedure described in Section 3.

<table>
<thead>
<tr>
<th>Screening constraints</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toughness (kJ/m(^2))</td>
<td>( \geq 1 )</td>
</tr>
<tr>
<td>Density (kg/m(^3))</td>
<td>( \leq 10,000 )</td>
</tr>
<tr>
<td>Shear modulus (GPa)</td>
<td>( \geq 0.11 )</td>
</tr>
</tbody>
</table>
In the bottom left of the chart (dot Number 1) where minimizing cost is more important than minimizing mass or heat loss, woods are seen to be appropriate for this application. The cheapest solution is wood chipboard.

At the bottom right of the chart (dot Number 2), sandwich panels become the optimal solutions since low mass is paramount. The best performing combination is PEEK/Carbon faces with an aluminium honeycomb core.

For applications where thermal insulation is important, the most promising solutions in the relevant area (at the top of the chart) are sandwich panels (dot Number 3). PEEK/Carbon faces with a PVC foam core sandwich is the best solution.

For refrigerated truck applications, the exchange constant between mass and cost should be 5–10 per kg according to Ashby.\[7\] However, the exchange constant between heat transfer and cost is not clearly defined. Aluminium faces with a PS foam core seem an appropriate choice for a refrigerated truck application since it lies in the correct range for the exchange constant between mass and cost with a moderate preference towards minimizing heat transfer (dot Number 4).

In the real world, the materials most commonly used for refrigerated truck floors are carbon steel faces with foam core, aluminium faces with foam core and GFRP faces with foam core. Reassuringly, the latter two appear on the exchange constant chart in the area expected; while the chart suggests that carbon steel/foam sandwich panels are not an optimal choice for this application.

An application map for floor panel applications in general can be presented as shown in Figure 13. For house flooring applications, cost seems to be the most important criterion. Wood panels become appropriate here. For aircraft flooring applications, minimizing mass becomes paramount. CFRP faces with either aluminium honeycomb, aramid honeycomb or PMI foam core sandwich panels are suitable. These sandwich materials are indeed commonly used for aircraft floors. For the heat transfer objective, the results suggest that any face material with PVC or PMI foam is appropriate when thermal insulation is paramount. However, in real-world applications, if thermal insulation is the key design objective, the approach taken is usually to separate the function by using a dedicated thermal insulator attached to the panels. This tends to provide better thermal insulation.

**Conclusions:** A methodology to compare the performance of multi-materials with other materials in multi-criteria design was proposed. The design tool we used was the exchange constant chart.

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**Table 4. Lists of face and core materials.**

<table>
<thead>
<tr>
<th>Face materials</th>
<th>Core materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al6061</td>
<td>Paper honeycomb</td>
</tr>
<tr>
<td>Al7075</td>
<td>Al honeycomb, low density</td>
</tr>
<tr>
<td>Plywood</td>
<td>Al honeycomb, medium density</td>
</tr>
<tr>
<td>Epoxy/Aramid</td>
<td>Aramid (or Nomex(^\text{®})) honeycomb, low density</td>
</tr>
<tr>
<td>Epoxy/E-glass</td>
<td>Aramid (or Nomex(^\text{®})) honeycomb, medium density</td>
</tr>
<tr>
<td>Epoxy/Carbon</td>
<td>PMI foam, low density</td>
</tr>
<tr>
<td>Epoxy/S-glass</td>
<td>PS foam, low density</td>
</tr>
<tr>
<td>PEEK/Carbon</td>
<td>PVC foam, low density</td>
</tr>
<tr>
<td>Polyester SMC (glass)</td>
<td>Phenolic, medium density</td>
</tr>
<tr>
<td>Low carbon steel</td>
<td>PMI foam, medium density</td>
</tr>
<tr>
<td>Stainless steel 316</td>
<td>PVC foam, medium density</td>
</tr>
<tr>
<td>Titanium alloys</td>
<td>Balsa wood</td>
</tr>
</tbody>
</table>

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**Table 5. Predictive models for sandwich panels.**\[12\]

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Upper bound formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>( \rho_{LU} = \rho_f (1 - \rho_c) )</td>
</tr>
<tr>
<td>Cost</td>
<td>( C_{LU} = \rho_f C_f (1 - \rho_c C_C) )</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>( \lambda_{LU} = \frac{1}{\lambda_f + \lambda_c} )</td>
</tr>
</tbody>
</table>

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Fig. 12. Exchange constant chart for refrigerated truck floor panels.
change constant chart. The exchange constant chart is used to identify the exchange constant values for which different choices are optimal. Sandwich panels, which are one of the commonly used multi-materials, provided a focus for this paper. A procedure to include sandwich panels in designers’ consideration was developed. This procedure was then illustrated through a case study.

The case study of refrigerated truck floor panels has successfully suggested some panel designs commonly used in real applications. Floor panels for other applications can be mapped onto the chart as well.

The concept of the exchange constant chart represents a step forward in multi-criteria material selection. The chart provides complete information to designers before they make a decision. The preferences of designers can be clearly mapped to the materials on the chart. This allows designers to instantly assess the sensitivity of their preferences. Moreover, as shown in this paper, this approach allows the simultaneous consideration of multi-materials alongside monolithic materials, offering a wider range of potential candidate solutions to the designer. Through the exchange constant chart, the benefits of different multi-materials can be clearly compared with other materials.

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Nomenclature

<table>
<thead>
<tr>
<th>Subscript</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>Core material</td>
</tr>
<tr>
<td>f</td>
<td>Face material</td>
</tr>
<tr>
<td>a</td>
<td>Exchange constant</td>
</tr>
<tr>
<td>( \delta^b )</td>
<td>Maximum allowed deflection (m)</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Thermal conductivity (W/mK)</td>
</tr>
<tr>
<td>( \lambda_{L,LI} )</td>
<td>Thermal conductivity of multi-material (W/mK)</td>
</tr>
<tr>
<td>p</td>
<td>Density (kg/m³)</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Yield strength (MPa)</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Shear yield strength (MPa)</td>
</tr>
<tr>
<td>b</td>
<td>Panel width (m)</td>
</tr>
<tr>
<td>( B_i )</td>
<td>Structural constant, ( i = 1, \ldots, 4 )</td>
</tr>
<tr>
<td>C</td>
<td>Cost per unit mass (£/kg)</td>
</tr>
<tr>
<td>( C_{L,LI} )</td>
<td>Cost per unit mass of multi-material (£/kg)</td>
</tr>
<tr>
<td>( C_m )</td>
<td>Material cost (£/kg)</td>
</tr>
<tr>
<td>( C_{manu} )</td>
<td>Manufacturing cost per unit area of sandwich panel (£/m²)</td>
</tr>
<tr>
<td>( \hat{C} )</td>
<td>Cost index (£/m³)</td>
</tr>
<tr>
<td>c</td>
<td>Core thickness (m)</td>
</tr>
<tr>
<td>d</td>
<td>Panel thickness (m)</td>
</tr>
<tr>
<td>( d^+ )</td>
<td>Maximum allowed panel thickness (m)</td>
</tr>
<tr>
<td>E</td>
<td>Young’s modulus (GPa)</td>
</tr>
<tr>
<td>G</td>
<td>Shear modulus (GPa)</td>
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Particulate reinforced metal matrix composites (PRMMCs) containing a high volume fraction of ceramic particles (> 50 vol.%) display an elastic stiffness that far exceeds that of aluminium and its alloys, at only a small cost in terms of density. If their microstructure is adequately designed and optimized, these materials can be made to exhibit strength/toughness combinations that match those of unreinforced high-strength engineering aluminium alloys.\textsuperscript{[1–2]} The potential of these composites in energy-intensive structural applications is thus clearly high.

The elevated toughness of these composites is achieved by meeting certain critical microstructural conditions, defined and explained in\textsuperscript{[1–4]} To summarize, these include: (i) the initial (high) quality of the stiff ceramic particles used, which must be free of stress concentration sites and internal defects, (ii) the presence of a ductile matrix free of brittle second phases, (iii) a capacity for composite bulk plastic deformation, made possible in spite of the high ceramic loadings by the fact that only the metal is continuous in their microstructure. These characteristics combined produce, in the composite, a

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