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MATERIAL SELECTION STRATEGIES FOR ENVIRONMENTAL-BASED FATIGUE DESIGN

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ABSTRACT

Environmental imperatives require that the environmental consequence of material selection be minimized. This can be achieved by assessing the relative environmental impact of the candidate materials. However, limitations of traditional material selection tools may result in non-optimal outcomes for fatigue-limited applications. The novel material selection tools discussed in this paper seek to improve design decision-making through increased quantitative certainty.

Fatigue-limited material selection procedures presented in the literature to evaluate the environmental impact for infinite-life design are not directly suited to finite-life design. In response to this deficiency, a novel design tool has been developed to systematically assess material performance for finite-life design. The novel design tool allows the relative environmental performance of candidate materials to be presented graphically as a function of the associated fatigue life. This outcome enables environmental impact to be minimized for fatigue-limited scenarios by:

- assisting the application of the finite-life design philosophy, which can enable significant mass reduction over infinite-life design
- allowing the relative environmental impact of the candidate materials to be evaluated early in the design life cycle

The outcomes of this work are especially important for non-stationary applications, as component overdesign results in additional mass that does not contribute to functional performance, but does contribute to fuel consumption and emissions during the use-phase. The design tools developed in this work may be integrated with standard techniques for evaluation of the environmental impact of the use-phase.

Keywords: Material selection, finite life, design for fatigue, design for environment, light alloys.

1 MATERIAL SELECTION

A structural component may be fully defined by its functional requirements, *F*, geometry, *G*, and material properties, *M*. When these measures are independent, the performance, *P*, may be expressed as [1]:

$$P = f_1(F)f_2(G)f_3(M^*) \tag{1}$$

For a given function and geometry, $f_1(F)f_2(G)$, the performance is fully defined by a specific combination of material properties, defined as the *material index*, M^* [2]. Minimizing the material index results in optimal material selection. Design objectives lead to ratios of material properties, known as material selection indices, that rank the performance of a material for a given objective. Material selection indices provide a powerful design tool for guiding material selection for a given design scenario, allowing:

- identification of the material properties of relevance to performance
- definition of the relative importance of these material properties
- comparison of the performance of specific materials

For relevant material properties, α and β, the general form of the material indices of interest to this work is (Table 1):

$$M^* = \left(\frac{\alpha}{\beta^{1/k}} \right) = C = k \quad (2)$$

Each value of the material index, C, defines a locus of constant performance. When plotted on a log-log chart of the relevant material properties, the locus of constant performance forms a linear *selection guideline* [1, 2], with gradient, k (Equation 2). The selection guideline is a powerful tool for systematic material selection as (Figure 1):

- performance is constant at any point along a selection guideline, for example, the performance at point A is equal to that of point A'
- for a family of selection guidelines, performance is proportional to C, e.g. the performance of point A (or A') is greater than the performance at point B (or B')

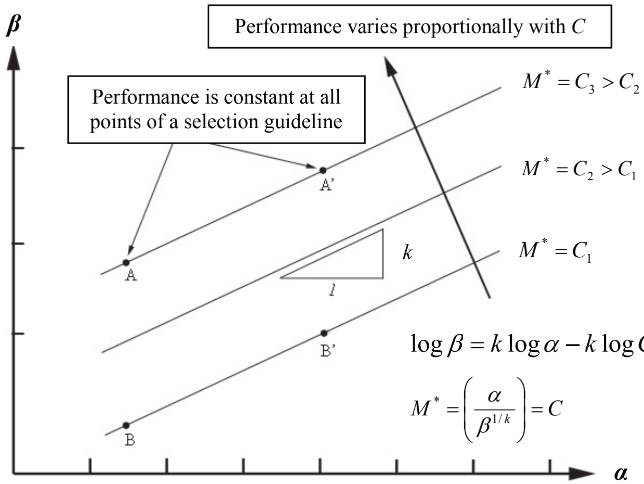

Figure 1. A generic material property chart, indicating a family of selection guidelines for unspecified material properties, α and β.

1.1 Structural elements

The selection guideline is a function of the geometry of the structural element under consideration, including ties, beams and plates (Figure 2). To simplify initial analysis, the pertinent geometry of each structural element can be represented by an associated free variable, resulting in material selection indices for the objectives of minimal mass and minimal cost (Table 1). Each combination of structural element and associated free variable has a specific guideline gradient, k. The guideline gradient defines the contribution of the relevant material properties to performance:

- For $k \to \infty$, the selection guidelines tend towards vertical, and performance scales linearly with α. For minimal mass design, α represents the material density ρ. Mass reduction scenarios with $k \to \infty$ benefit from a low density in preference to a high fatigue strength.
- For $k \to 0$, the selection guidelines tend towards horizontal, and performance scales linearly with β. For fatigue-limited design, β represents material strength (Table 1) and mass reduction scenarios with $k \to 0$ benefit from a high material strength in preference to low density.
- For $k \in (0, \infty)$, performance is a compromise between these limiting scenarios.

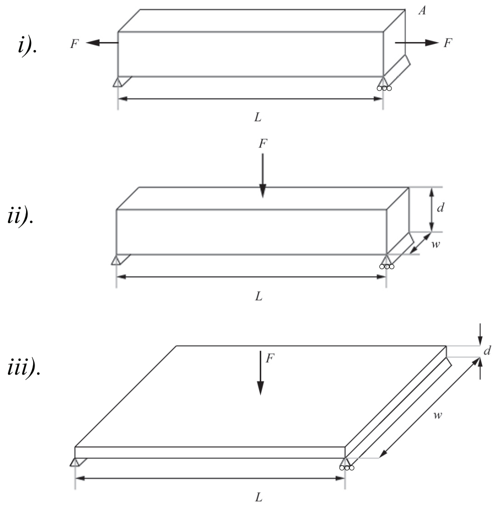

Figure 2. Simplified structural elements of relevance: tie (i), beam (ii) and plate (iii). Nomenclature: Force (F), Area (A), Length (L), width (w), depth (d).

Table 1. Material selection indices for minimal mass, including the free variable and guideline gradient, for fatigue-limited design of beam, tie and plate elements for minimal mass and minimal cost. Nomenclature: material density (ρ), material cost per unit mass (C_m), fatigue strength (S_N), Area (A), width (w), depth (d), material index (M^*_{kn}). The first suffix of a material index is the guideline gradient (k), the second suffix refers to the design objective of minimal mass (m).

Structural element		Free variable	*k*	Minimal mass
	Tie	A	1	$M^*_{1m} = \left(\frac{\rho}{S}\right)$
	Beam	w		
		$A\ (w = d)$	3/2	$M^*_{3/2m} = \left(\frac{\rho}{S^{2/3}}\right)$
		d	2	$M^*_{2m} = \left(\frac{\rho}{S^{1/2}}\right)$
	Plate	d		

1.2 Fatigue limited design

The Infinite-Life Design (ILD) criterion provides a logical starting point to assess the optimal materials for fatigue-limited design, as the fatigue limit is the most extensively available measure of the material fatigue response. Although the ILD criterion is not strictly compatible with materials that do not display a fatigue limit, such as magnesium and aluminium, the associated endurance limit provides a basis for an initial estimate of the mass reduction opportunities associated with material substitution.

Fatigue-limited safety-critical automotive component design has been traditionally based on ILD, due to the inherent safety factor, for example [3]. However, demand for mass optimisation has led to an increased application of the Finite-Life Design (FLD) criteria for the design of fatigue-limited automotive components, for example [4]. FLD requires that a component safely withstand the design-life, including an appropriate design safety factor, and may fail if the associated design-life is exceeded. For complex and uncertain loading conditions, FLD requires significantly higher design effort to safely implement than ILD, but has the potential to provide mass reduction:

- by reducing the modelling uncertainties that occur when the design-life is less than the fatigue limit, or associated endurance limit of the material under consideration
- by allowing application of materials that do not have a well defined fatigue limit, such as many light alloys

1.2.1. Material selection curves

The traditional approach to material selection for fatigue-limited design is to identify the relative material performance at a specific design-life, for example the fatigue limit or endurance limit [5]. This approach does not engage with the unique requirements of FLD, particularly the dependence of material performance on the required design-life. In response to this deficiency, novel design tools have been developed to systematically assess material performance for FLD [6-8]. By systematically evaluating the material indices at a range of design-lives, a novel *material selection curve* may be generated to assist material selection for FLD [8]. Given that material indices tend to zero as performance increases, the lowest material selection curve for a given design-life is optimal. The material selection curve provides:

- guide material selection of for finite-life design applications
- provide a basis for assessing the relative performance of candidate materials
- define the envelope of conditions for which light alloys are optimal for finite-life applications

A systematic approach has been employed to compare the performance of candidate metals for fatigue-limited applications and structural elements of interest (Section 2). Material performance will be compared for a range of design-life requirements and environmental design objectives (Section 1.3), resulting in a family of material selection curves for each combination of structural element and design objective.

1.3 Environmental applications

This paper will extend the material selection curves of Section 1.2 to allow the environmental impact of material selection decisions to be made for finite-life design. Of the many metrics available to assess for environmental impact, for example [9-11], the embodied energy and CO2 footprint will be assessed in this paper. However, the novel material selection tools developed are compatible with other metrics of interest.

The product life-cycle results in energy use and undesirable emissions during the manufacture, use and retirement phases [12, 13]. The system boundary applied in this work will not include the retirement phase as it is considered to have a negligibly small contribution to the holistic life-cycle costs [14]. The following procedures will identify the environmental impact for the manufacturing phase. Methods for use-phase evaluation are discussed in Section 3.

Embodied energy

The total embodied energy associated with the production of a material is defined as the energy required to produce one unit-mass of the primary material under consideration from the original feedstock, E_e. The embodied energy estimate includes: mining of raw materials, transportation of the raw material to the production plant, primary processing, and an estimate of the energy associated with use and maintenance associated with the processing plant (Equation 3).

$$E_e = \frac{\sum \text{Estimated energy required for primary production}}{\text{Mass of primary material production}} \tag{3}$$

CO2 emissions

Of the undesirable outputs associated with the product life-cycle, CO2 emissions are of significant importance due to their contribution to climate change. The CO2 emission estimate applied in this work is based on the emissions associated with primary production, transport and feedstock manufacture (Equation 4).

$$E_c = \frac{\sum \text{Mass of CO2 arising from production}}{\text{Mass of material produced}} \tag{4}$$

The values for environmental impact include uncertainties due to the imprecise nature of the available data and associated estimates, for example [15]:

- emissions associated with manufacture vary due to differences in the associated manufacturing methods and transport distances
- the definition of an appropriate system boundary is complex and may result in uncertainties

Despite the associated uncertainties, estimates are provided from industry-average estimates obtained from a commercially available materials selection system [16] (Table 4). To acknowledge the identified uncertainties, the reported environmental metrics include a tolerance bound. This data is of use in the absence of resources available to complete a customized life-cycle analysis, or as a preliminary analysis of the environmental impact of material selection.

1.3.1. Environmental material selection curves

A novel extension to the traditional approach to material selection, material selection curves, has been developed to assist material selection for fatigue limited applications [8]. This work extends this design tool to accommodate environmental objectives such as minimal embodied energy and minimal CO2 emission. Based on the identified material selection indices for minimal mass (Table1), environmental material selection indices have been developed for the environmental objectives of minimal embodied energy and minimal CO2 emissions (Table 2). Based on these material selection indices a series of material selection curves can be plotted for candidate materials of interest, thereby increasing the quantitative certainty of the environmental consequence of material selection.

A case study outlines the application of this strategy when applied to candidate materials in a finite-life fatigue loading application (Section 2).

Table 2. Environmental material selection indices, including the free variable and guideline gradient, for strength-limited design of beam, tie and plate. Nomenclature: material density (ρ), fatigue strength (S), Area (A), width (w), depth (d), material index (M^*_{kn}), Embodied energy (H_e), CO2 emissions (C). The first suffix of a material index is the guideline gradient (k), the second suffix refers to the design objective, either minimal embodied energy (e) or minimal CO2 emissions (c).

Structural element		Free variable	k	Environmental objective: Minimal embodied energy	Environmental objective: Minimal CO2 emissions
	Tie	A	1	$M^*_{1e} = \left(\frac{E_e \rho}{S}\right) = E_e M^*_{1m}$	$M^*_{1c} = \left(\frac{E_c \rho}{S}\right) = E_c M^*_{1m}$
	Beam	w			
	Beam	$A\ (w = d)$	3/2	$M^*_{3/2e} = \left(\frac{E_e \rho}{S^{2/3}}\right) = E_e M^*_{1m}$	$M^*_{3/2c} = \left(\frac{E_c \rho}{S^{2/3}}\right) = E_c M^*_{3/2m}$
	Beam	d	2	$M^*_{2e} = \left(\frac{E_e \rho}{S^{1/2}}\right) = E_e M^*_{1m}$	$M^*_{2c} = \left(\frac{E_c \rho}{S^{1/2}}\right) = E_c M^*_{2m}$
	Plate	d			

2 CASE STUDY DISCUSSION

A series of candidate metals were proposed by a collaborative supplier of forged automotive components as being within their manufacturing expertise, including grades of aluminium, magnesium and titanium (Table 3 and Figure 1). A ferrous metal with a precedent for application in fatigue-limited safety-critical applications (i.e. AISI 1040 steel) provides a performance baseline for assessing the relative performance of the light alloy alternatives. These materials provide a basis for reporting the environmental materials selection curves proposed in this work. Environmental material selection curves have been generated for the material selection indices of interest (Tables 3 and 4):

- tie, or beam with width as the free variable, i.e. $k = 1$
- beam with width and depth equal and area as the free variable, i.e. k = 3/2
- beam or plate with depth as the free variable, i.e. $k = 2$

Material selection curves have been generated for design objectives of minimal: mass, M_m, embodied energy, M_e, and CO2 emissions, M_c (Figures 3 to 6). Fatigue properties have been identified from publicly available data (Table 3, Figure 3). The embodied energy and CO2 emissions were based on the mean value reported by a commercially available material selection system [16] (Table 4).

Table 3. Fatigue strength of candidate materials [17-19].

	Fatigue strength, SN (MPa)						
Fatigue life, N	**AISI 1040**	**2024-T4**	**6061-T6**	**7075-T6**	**ZK60A-T5**	**AZ31B-F**	**Ti-6Al-4V**
1E+04	497	342	221	354			655
1E+05	328	265	175	274	160	180	552
1E+06	299	206	138	215	140	160	483
1E+07	296	160	109	171	125	145	483
1E+08	296	124	87	139	125	130	483

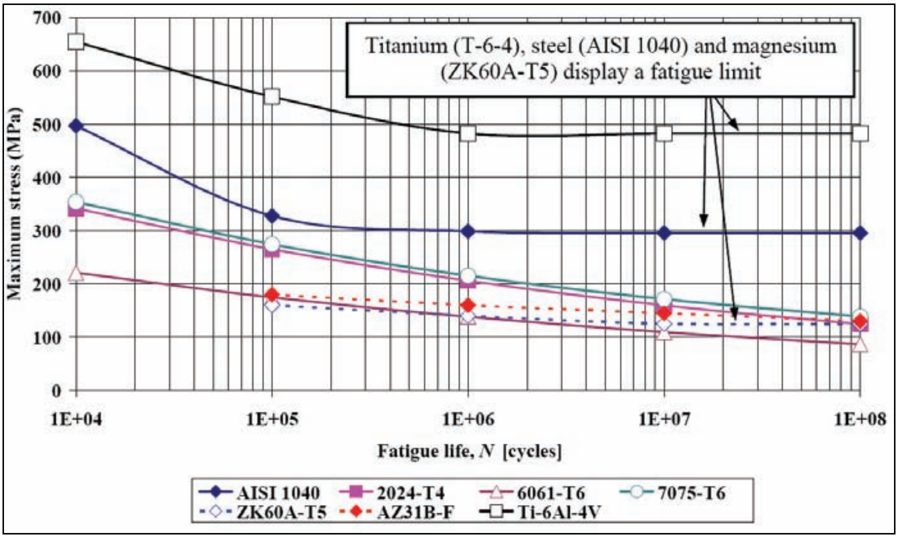

Figure 3. S-N curves of materials of candidate materials.

Table 4. Candidate materials and associated properties.

Material	Type	Common applications	Density, ρ, (kg/m^3)	Embodied energy, E_e (MJ/kg)	CO2 emissions, E_c (kg/kg)
2024-T6	Aluminum	Aerospace, transport [17]	2770	184 – 203	11.6 – 12.8
6061-T6	Aluminum	Architectural, transport [17]	2710	184 – 203	11.6 – 12.8
7075-T6	Aluminum	Weight critical applications [17]	2800	184 – 203	11.6 – 12.8
AZ31B-F	Magnesium	Aerospace, racing vehicles [19]	1770	356 – 394	22.4 – 24.8
ZK60A-T5	Magnesium	Aerospace, transport [19]	1824	356 – 394	22.4 – 24.8
Ti-6-4	Titanium	Weight critical applications [19]	4430	855 – 945	53.8 – 59.5
AISI 1040	Steel	Automotive suspension [18]	7845	22.4 – 24.8	1.9 – 2.1

3 CASE-STUDY DISCUSSION

The novel material selection tools were applied to the candidate metals to provide an objective estimate of environmental impact for a range of design scenarios. Pertinent outcomes of the environmental material selection curves are:

- With the exception of very large N and $k = 1$, the reference steel provides higher mass than the candidate light alloys.
- For $k = 1$, titanium (Ti-6-4) minimises component mass. As k increases the performance of lighter candidate alloys increases. For $k = 2$, magnesium minimizes mass for all N.
- The performance indices correlate more closely with material density as k increases. Subsequently the component mass, and environmental consequence of light alloy application is reduced for scenarios with large values of k, such as a beam or plate with depth as the free variable.
- As N increases, the disparity between materials with a fatigue limit (i.e. AISI 1040, Ti-6-4 and ZK60A-T5) and materials that do not display a fatigue limit (i.e. 2024-T4, 6061-T6, 7075-T6 and AZ31B-F) increases monotonically, and the performance of materials that do not display a fatigue limit continuously decreases.
- Although light alloys provide a significant mass reduction opportunity for FLD, the associated environmental consequences of production are very high (Table 4). Consequently the reference steel provides lower embodied energy and CO2 emissions for all k and all N.
- As k increases, the relative mass of the light alloys decreases, but the associated E_e and E_c remain constant. Consequently the environmental consequence of light alloy application is minimised for scenarios with large k, for example plates and beams with depth as the free variable.

Light alloys are not optimal for the environmental material selection scenarios presented in this paper. However, it is apparent that light alloys provide lower mass than the reference ferrous metal for many design scenarios (Figure 3). If these scenarios are associated with non-stationary applications, such as aerospace, automotive and transport applications, the environmental impact associated with use-phase emissions must be considered. For such applications, the environmental benefit of reduced mass, and therefore reduced use-phase emissions, may offset the increased environmental impact associated with light alloys. The design tools developed in this work may be integrated with standard techniques for evaluation of use-phase environmental impact, for example [20].

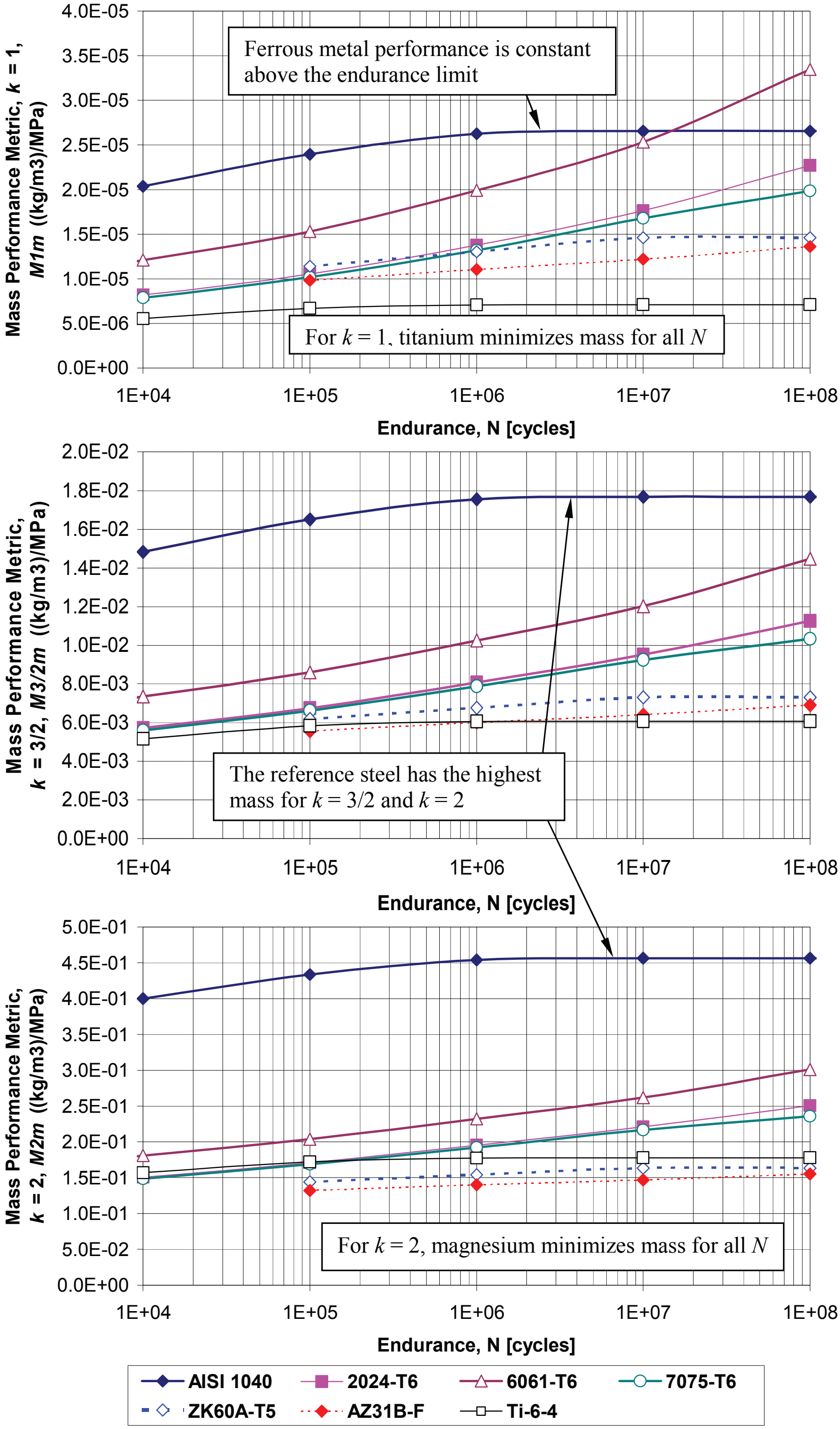

Figure 4. Relative mass for: tie (upper), beam (middle) and plate (lower) structural elements.

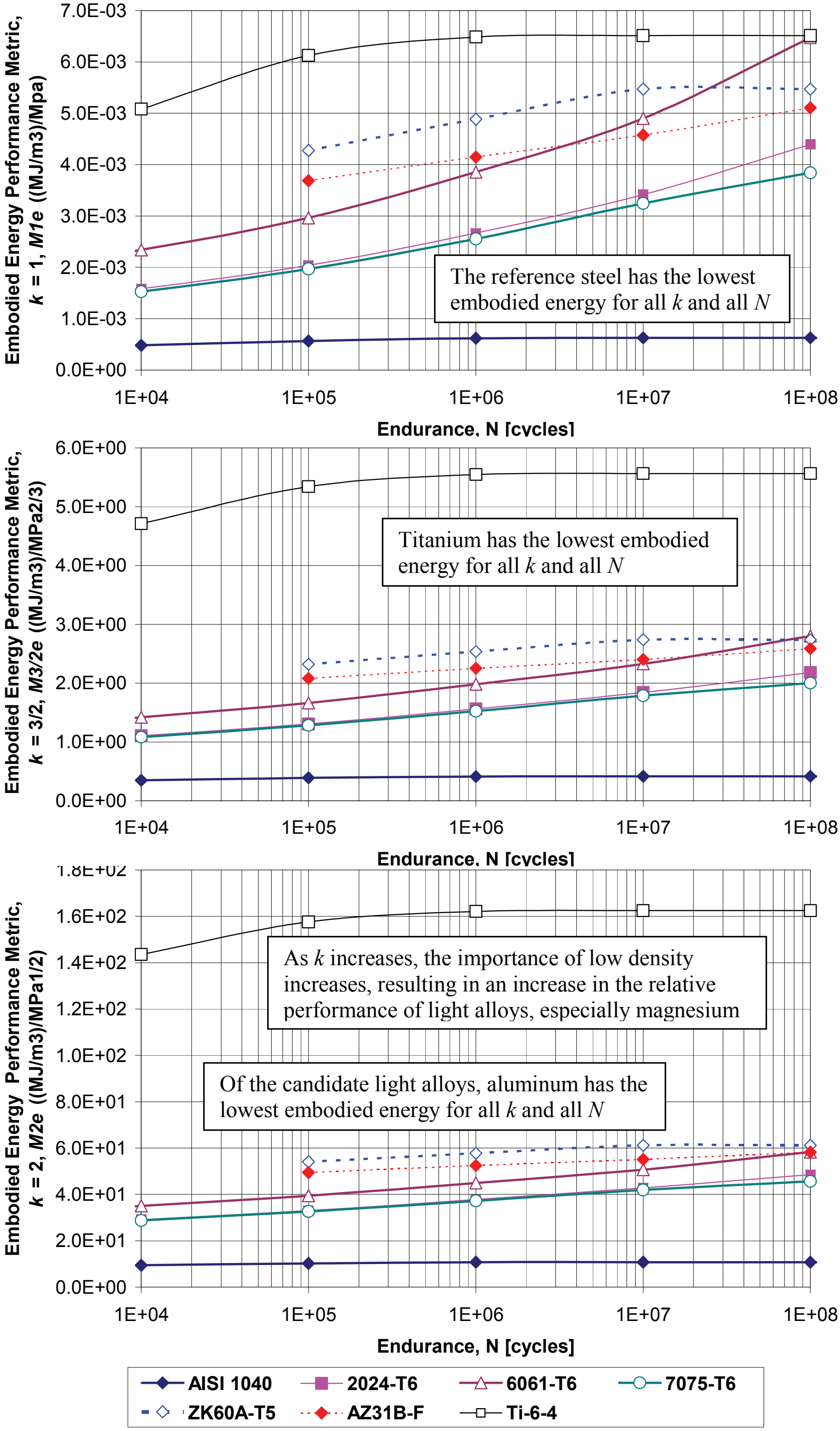

Figure 5. Embodied energy for: tie (upper), beam (middle) and plate (lower) structural elements.

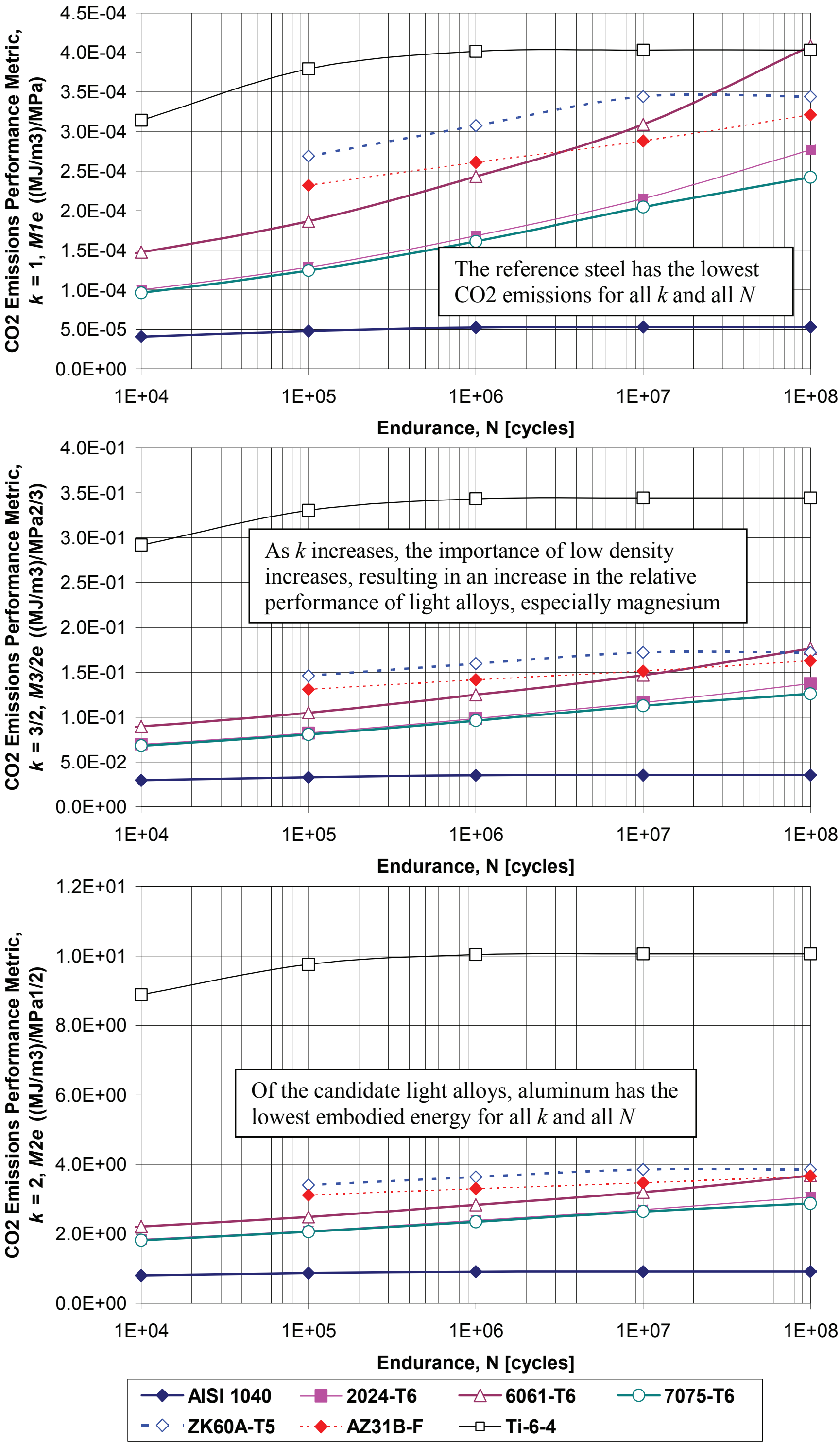

Figure 6. CO2 emissions for: tie (upper), beam (middle) and plate (lower) structural elements.

4 CONCLUSION

Environmental imperatives require that the environmental consequence of material selection be minimized. This can be achieved by assessing the relative environmental impact of the candidate materials. However, limitations of traditional material selection tools may result in non-optimal outcomes for fatigue-limited applications. A novel extension to the Ashby approach to material selection has been introduced to accommodate the environmental objectives of minimal embodied energy and minimal CO2 emission for finite-life fatigue-limited design.

The novel material selection tool introduced in this paper seeks to improve design decision-making through increased quantitative certainty. The tool allows the relative environmental performance of candidate materials to be presented graphically as a function of the associated fatigue life. This outcome enables environmental impact to be minimized for fatigue-limited scenarios by assisting the application of the finite-life design philosophy, and allowing the relative environmental impact of the candidate materials to be evaluated early in the design life cycle.

A case study outlines the application of this approach when applied to candidate materials of interest to a collaborative supplier to the automotive industry. The outcomes of this case study suggest that although light alloys provide minimal mass, the reference ferrous metal provides optimal environmental performance for the scenarios of interest to this work.

Although outside the scope of this paper, the approach could provide the basis of an expert system to, for example, identify preferred candidate materials for multi-objective applications that include environmental performance and fatigue-loading scenarios. Of course, material cost must also be recognised as light alloys are typically more expensive (per kilogram) than traditional ferrous metals [21].

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