Gardner, L., Cruise, R. B., Sok, C. P., Krishnan, K. and Ministro, J. (2007). Life cycle costing of metallic structures. Proceedings of the Institution of Civil Engineers - Engineering Sustainability. **160(4)**, 167-177.

Life cycle costing of metallic structures

Leroy Gardner*
BEng MSc DIC PhD CEng MICE MIStructE
Senior Lecturer in Structural Engineering, Imperial College London, UK

Rachel Bethan Cruise
BSc DipArch DIC PhD
Lecturer in Structural Engineering, University of Bath, UK

Cui Ping Sok
MEng ACGI
Engineer, Building and Construction Authority, Singapore

Krishanth Krishnan
BEng, MSc, CEng, MIMarEST
Senior Engineer, DNV Energy, UK

Jose Ministro Dos Santos
BEng MSc DIC
Technical Adviser, Mott MacDonald, UK

*Lead author contact details:

Dept of Civil and Environmental Engineering
Imperial College London
South Kensington Campus
London, SW7 2AZ, UK
Tel: 0207 594 6058 Fax: 0207 594 5934
Email: Leroy.gardner@imperial.ac.uk

No. of words: 6260

No. of figures: 11

No. of tables: 4

Keywords

Aluminium alloy, carbon steel, life cycle costing, material properties, metallic structures, stainless steel, whole life costing

Notation

A - Initial corrosion and fire protection costs (£)

A_o – Strain at fracture (%)

E - End of life costs (£)

E - Young's modulus (N/mm^2)

I – Material costs (£)

M -Maintenance costs (£)

R - Residual value of the structure (£)

r - Discount rate (%)

t_i - Period from the start of construction to the time that the maintenance is anticipated (years)

t_n - Total design life (years)

α - Thermal expansion coefficient (K^{-1})

k - Thermal conductivity (W/mK)

ρ - Density (kg/m^3)

σ_y - Material yield strength (N/mm^2)

$\sigma_{0.2}$ – Material 0.2% proof stress (N/mm^2)

Abstract

Structural material selection has traditionally been based on initial material cost. However, growing pressure on the construction industry to consider the longer term financial and environmental implications of projects is encouraging a more holistic view. Thus, materials with higher initial costs, but which offer cost savings over the life cycle of a structure, are gaining increasing recognition. The life cycle costs of structures of two such metallic materials, namely aluminium alloy and stainless steel, are compared to those of ordinary structural carbon steel in the present study. Two structural applications – a typical office building and a bridge – are analysed, whilst offshore applications are briefly discussed. The ratio of initial material cost per tonne was assumed to be 1.0: 2.5: 4.0 (carbon steel: aluminium alloy: stainless steel). Following a preliminary structural design to current European design standards taking due account of the material densities and structural properties (principally strength and stiffness), it was found that on an initial cost basis, carbon steel offers the most competitive solution for both the building and the bridge. However, considering the additional life cycle costs including maintenance costs, end of life costs and the residual value of the structure (appropriately discounted to present values), the results indicate that carbon steel offers the most competitive life cycle solution for the office building, but delivers the most expensive life cycle solution for the bridge. Overall, it is concluded that on a whole-life basis aluminium alloy and stainless steel may offer more competitive solutions than carbon steel for bridges and exposed areas of building structures.

1. Introduction

1.1 Background

The elegance and functionality of metallic structures have long been a feature of the construction industry. Historically, the overriding factor in the selection of structural materials has been initial cost, leading to the dominance of structural carbon steel over other metallic materials. Familiarity and ease of design and construction using carbon steel, together with a comprehensive range of structural products, have also contributed. However, growing pressure on the construction industry to consider the longer term environmental and financial implications of projects is encouraging a more holistic approach. Previous research to quantify the environmental impact of carbon steel and other alloys has been carried out by Norgate et al.[1], Fujii et al.[2] and Seppälä et al.[3]. The corrosion resistance, durability and therefore low maintenance demand of two potential alternatives to carbon steel, namely aluminium alloy and stainless steel, are well known and have been acknowledged and utilised in other industries for products such as cutlery, storage tanks and reaction vessels in the case of stainless steel[4], and in the automotive, aerospace and shipping industries in the case of aluminium[5]. The longevity of performance of these alternative materials can, in some applications, compensate both economically and environmentally for the initial outlay of resources. However due to their higher initial costs the construction market has been slow to exploit this opportunity. Overviews of the structural use of aluminium alloys and stainless steel have been prepared by Mazzolani[5] and Gardner[6], respectively. A further alternative, weathering steel, has been described by Miki et al.[7] in the context of bridges, but has not been included in the present investigation.

In this study, life cycle cost analyses have been performed to establish areas of financial viability for these alternative metals in structures and as an incentive to exploit the environmental benefits associated with their durability. The study focuses on the costs directly associated with the three considered structural metallic materials. The costs utilised in the study have been taken from the most up to date sources available; this includes using quotes from producers and values given in research documents which will be detailed for each particular structure considered. In order to show how the results of the analysis might change due to variations in the adopted values, sensitivity studies have been carried out. In the present study LCC is performed for two different structural applications: a typical office building and a bridge. A third application, an offshore structure, is discussed. These applications differ in scale, life time expectancy, environmental corrosivity, maintenance requirements, cost of disrupted use and in the manner in which they are funded.

1.2 Life Cycle Costing

Life cycle costing (LCC), first defined in 1977 in its basic form, is an analytical tool to assess the long-term cost implications of a project, where future expenditures are converted to their present values through a discount rate. LCC is formally defined in the draft International Standard, ISO 15686 Part 1[8]. The application of life cycle costing to construction projects has been advocated in ‘Rethinking Construction’[9]. A number of different models and techniques have been developed[10] and the history of the development of LCC has been documented by Gluch and Baumann[11]. Since calculations are based on predicting future material and labour costs, the risk associated with making the predictions is often included in the analysis as well as cost equivalents of the environmental impact. A number of LCC studies have been previously carried out on concrete[12] and steel structures[13], and comparisons have been made between the two materials[14]. For any built scheme the actual lifetime of a structure relies on social and environmental factors beyond the scope of a standard life cycle costing calculation. Two such factors are flexibility (generally defined as capacity for low cost alterations due to change of use) and adaptability (generally defined as capacity for higher cost structural changes or extensions), both of which determine the ability of a structure to fulfil its purpose despite changing demands[15]. The importance of considering these aspects can be seen in numerous studies, such as those provided by Davis Landgon & Everest et al.[16] where the cost of structural grids of varying spans was presented. The study showed that although costs increase with larger spans, the greater flexibility that results is attractive to stakeholders and prospective tenants, leading to a constructed property of higher value. A building with larger structural spans can also accommodate more internal change before it is regarded as obsolete or before it requires an expensive outfit or conversion. Steel structures are generally considered to be relatively easy to modify or to add to[17, 18].

Owing to the complexity of some of the issues introduced above, disparities have been observed between the analyses performed by industry and those conducted as academic studies[11]. This research employs a simple form of the life cycle costing but includes a sensitivity analysis to determine how variations in the assumed parameters will influence the results of the study. The method employed in this study has the advantage that it focuses purely on cost issues and therefore forms a persuasive argument for industry to consider alternative metallic structures.

The life cycle costing calculations carried out in the present study, together with the specific issues and costs considered, are summarised in Figure 1. As shown in Figure 1, initial material costs (I) and the costs (A) associated with initial corrosion and fire protection are taken at their capital costs, whilst maintenance costs (M), end of life costs (E) and the residual value of the structure (R) are future costs that are discounted to their present values by means of the discount rate r. Whilst maintenance costs are discounted at the year t_i in which the maintenance is anticipated, end of life costs and the residual value of the structure are discounted over the total design life t_n (in years).

For this study, the discount rate has been taken as 3.5%, as recommended in the Green Book[19]. The origin of this value is derived in Appendix 6 of the Green Book. This discount rate has been proposed by the government to assess costs in all Public Finance Initiatives and is used by the Highways Agency in assessing bridges over time periods of 30 years or less. Reduced discount rates may be applied for longer time scales, e.g. for 31 – 75 years a 3.0% discount rate is proposed). However, for consistency the 3.5% discount rate is maintained for all life cycle costing studies presented herein and a sensitivity analysis conducted as part of the study shows the effect of choosing a different discount rate.

1.3 Linking life cycle costing with sustainability

With growing environmental concerns, sustainability is becoming an increasingly important issue in the construction industry. Sustainability is now viewed not just as the conservation of the environment but it is acknowledged that sustainable development is dependent on three factors[18]: environmental, social and economic. Direct links between sustainability and economic growth have been found by financial markets which now monitor the sustainable performance of companies. The London stock exchange has correlated the sustainability performance of the largest companies in the UK in the FTSE4Good Index, showing that the 50 most sustainable companies have out performed the FTSE 100 Index by 15% for five consecutive years up to 2004[20].

LCC analysis does not directly consider environmental impact; this is considered in a life cycle assessment (LCA) and by independent tools such as BREEAM (BRE environmental assessment methods) and CEEQUAL (the civil engineering environmental quality and assessment scheme). However, the process that is initiated by performing an LCC encourages discussions and the recording of information associated with the durability, performance and end of life use of proposed schemes and their components. This includes consideration of the required level of maintenance and the residual value of components. Minimising the need for maintenance and replacement of components and utilising the potential residual value of components clearly supports the reduction of environmental impact and encourages the economic development of the construction industry.

Considerable energy is required to produce metal alloys. Based on extraction of metal ores to produce the metal alloys, carbon steel has a lower embodied energy and lower global warming potential than both aluminium and stainless steel[1]. However, there is increasing pressure for the construction industry to consider the long term effects of building materials, taking due account of their durability and maintenance requirements and the level of reuse and recycling. In an automotive application, for example, life cycle assessment (LCA) has been used to demonstrate that, over its design life, aluminium can more than compensate environmentally for the initial high outlay of resources compared to carbon steel[21].

2. Material selection

2.1 Introduction

The life cycle performance of three metallic materials, namely carbon steel, aluminium alloy and stainless steel, employed in two structural applications – an office building and a bridge – has been analysed. Typical grades for structural use of each material have been selected (see Table 1). A range of contributory factors have been included in the analyses; these are introduced in the following subsections. A summary of the key material properties of carbon steel, aluminium and stainless steel is given in Table 1.

2.2 Material cost

Structural material selection has traditionally been based on initial material cost, leading to the dominance of carbon steel over other metallic materials. The cost per tonne of aluminium alloy is approximately 1.5 times that of carbon steel[22], whilst the cost per tonne of stainless steel is around four to six times that of carbon steel[23]. These higher costs are partly due to the low volume of production of aluminium alloys and stainless steel in comparison to carbon steel, but are primarily linked to the cost of the base material and of the constituent alloying elements that give the different grades their particular properties. Stainless steel, production of which has increased at a rate of approximately 6% per year since 1960[24], comprises at least 10.5% chromium and varying levels of nickel and molybdenum. The cost of these alloying elements can be highly variable, for example the world wide cost of nickel was seen to triple between 2001 and 2004[25]. This fluctuation in cost is dependant on a number of complex factors including the availability and ease of extraction of metal ores and reclamation of scrap metal, together with the demand for the material[26].

Clearly the cost of a structure is not only dependant upon the cost per tonne of the structural material, but also on the material density, strength, stiffness, efficiency of use and so on. Whilst stainless steel and carbon steel are of similar density, aluminium has a significantly lower density, approximately one third of their values. However, as explained in the following sub-section, aluminium also has a stiffness (Young's modulus) of only one third of that of carbon steel, generally necessitating the use of larger sections. Weight savings, where they can be achieved, may also lead to reduced transportation, erection and foundation costs, though these have not been considered in this study. Structural efficiency is partly due to the choice of structural form, to which similar principles apply for all three metallic materials, and partly due to the sophistication of the design codes. Again although similar principles apply in design, structural carbon steel codes are more developed than those for either aluminium or stainless steel because of the greater pool of available structural performance data and more expansive research capacity. A new design approach offering greater efficiency for non-linear structural metallic materials (including aluminium and stainless steel) has been developed[27].

Based on quotations obtained in 2005[28,29], the initial material costs per tonne (including manufacturing and fabrication costs) for this study have been taken as £720 for carbon steel (grade S275), £1750 for aluminium alloy (EN AW 6061 T4) and £3060 for stainless steel (austenitic grade EN 1.4401). This gives an initial material cost ratio per tonne (carbon steel: aluminium alloy: stainless steel) of approximately 1.0: 2.5: 4.0. All subsequent cost ratios will be given in the order - carbon steel: aluminium alloy: stainless steel.

2.3 Strength, stiffness, ductility and fatigue resistance

Strength, stiffness, ductility and fatigue resistance are crucial properties for structural materials. In general, strength and stiffness are required to provide load carrying capacity and to control deflections, whilst ductility is important for avoiding brittle failures, allowing redistribution of stresses and for energy absorption. Fatigue resistance is important in applications where the structural material is subjected to cyclic loading, such as that due to traffic on a road bridge.

A wide range of strengths can be achieved for each of the considered metallic materials through variation in alloy content, level of cold-work and heat treatment. For the present study, typical structural grades have been selected, the material strengths (yield strength, σ_y

for carbon steel and 0.2% proof strength, $\sigma_{0.2}$ for aluminium and stainless steel) of which are compared in Table 1. Unlike strength, the stiffness of a metal cannot be significantly altered. The stiffness (Young's modulus) of carbon steel and stainless steel are similar (see Table 1), though stainless steel does exhibit a rounded stress-strain curve which results in increased deflections. Aluminium, in contrast, has a much lower Young's modulus, approximately one third of that of carbon steel and stainless steel. Ductility, generally defined as strain at fracture varies considerably between the materials; as shown in Table 1, for the grades considered, carbon steel (S275) has a strain at fracture of about 24%, aluminium about 12% and stainless steel about 45%. The fatigue resistance of carbon steel and stainless steel is similar[6], whereas the fatigue resistance of aluminium is about one-third that of carbon steel[30]. The fatigue performance of aluminium also deteriorates rapidly at elevated temperatures and in corrosive environments. The inferior fatigue performance of aluminium may be partly offset by the lower stress ranges that are likely to result from the use of larger aluminium sections (which will generally be required to account for the lower strength and stiffness).

2.4 Production and fabrication

The prevalence of carbon steel in the construction industry has led to the development of efficient production processes, a comprehensive range of structural products in standard section sizes and familiarity and efficiency in structural design, fabrication and construction. For both aluminium and stainless steel, there is generally less familiarity amongst structural engineers and fabricators, and reduced product availability and standardisation. With increasingly widespread usage, these shortcomings are being overcome.

Schedin[31] describes particular aspects of fabrication of stainless steel that require specialist knowledge. More attention, for example, is required to control local distortions during welding since the coefficient of thermal expansion of stainless steel is between 30% and 50% greater than that of carbon steel[23]. Welding aluminium on the other hand, encounters the possibility of localised deterioration of material properties, though specific aluminium alloys have been developed that retain their properties after welding[32].

2.5 Corrosion resistance

Both aluminium and stainless steel react with oxygen to form a protective oxide layer (aluminium oxide and chromium oxide, respectively). This oxide layer adheres to the surface of the material and prevents the occurrence of further oxidation or corrosion. When damaged, provided oxygen is present, this oxide layer very rapidly reforms. Carbon steel also oxidises to form iron oxide. However, unlike aluminium and chromium oxide, iron oxide does not adhere to the material, but rather occupies a larger volume and becomes detached from the surface, exposing un-corroded material to further oxidation.

In certain conditions, both aluminium and stainless steel can be susceptible to corrosion. One such instance is where insufficient oxygen is present to regenerate the oxide layer (anaerobic corrosion). This occurs where the metallic surface is immersed in water. Other aggressive environments, where particular care needs to be taken to select appropriate material grades to avoid severe corrosion, include strongly acidic or alkaline conditions; sea water, for example, is a weak chloride solution. General guidance on the corrosion of aluminium has been presented by Davis and Associates[33], whilst information relating to the corrosion of stainless steel is also available[34].

In this study it has been assumed that no corrosion protection is required for either aluminium or stainless steel, whilst for carbon steel allowance for the initial cost of corrosion protection and subsequent maintenance thereof has been made. For the building, an allowance of £3.60/m^2 of surface area of structural steelwork has been made[35]. For bridges, corrosion protection requirements are more onerous due to the more aggressive environment. For this study an allowance for a four-coat epoxy and polyurethane corrosion protection system of £25.00/m^2 of surface area of structural steelwork has been made, and a maintenance period of fifteen years has been assumed, based on the Highways Agency's minimum requirements for coating systems. Additional costs associated with maintenance of the corrosion protection, including access, surface preparation, worker health and waste disposal have also been included[36]. Maintenance may also lead to traffic disruption, and an allowance of ten days of disruption for the steel bridge, five days for the aluminium bridge and 2.5 days for the stainless steel bridge has been made. The cost of disruption for a single carriageway was assumed to be £8000 per day[37]; 10% of this cost accounts for traffic management schemes and 90% is to account for the cost of traffic disruption.

2.6 Fire resistance

At elevated temperatures, all metals lose strength and stiffness. A comparison of the strength and stiffness retention of carbon steel, aluminium and stainless steel at elevated temperatures is shown in Figures 2 and 3. In Figure 2, the strength reduction factor is defined as the elevated temperature yield strength normalised by the room temperature yield. In the case of stainless steel the strength reduction factor is initially greater than unity due to the strain hardening nature of the material and an allowance for higher deformation (and strain limits) in fire. In Figure 3, the stiffness reduction factor is defined as the elevated temperature Young's modulus normalised by the Young's modulus at room temperature. From Figures 2 and 3, it may be observed that generally stainless steel offers superior retention of strength and stiffness at elevated temperature than carbon steel, whilst aluminium alloys are considerably inferior. A number of comparative studies of the structural behaviour of stainless steel and carbon steel in fire have been reported[38,39,40,41].

In order to comply with building regulations[42], which generally require 60 minutes of fire resistance to allow occupants to evacuate and fire fighters to operate, an allowance of £10.50/m^2 of surface area[35] has been made for the carbon steel building. To reflect the respective material performance at elevated temperature, the cost of fire protection for the aluminium building has been estimated as 1.5 times that for carbon steel, whilst for stainless steel the cost of fire protection has been estimated as half that for carbon steel. No allowance for fire protection has been made for the bridge scenario. General guidance on the fire protection of structures of a range of materials is given by Buchanen[43].

2.7 End of life costs and residual value

The residual value of a structure depends upon whether it is demolished, where the material can be recycled, or more carefully deconstructed to allow structural components to be reused. All three metals can be reused or recycled without any degradation of mechanical properties allowing 100% of the material to be recovered, provided it can be retrieved from construction sites. Table 1 sets out the overall percentage of each metal that is thought to be reclaimed from all industries and subsequently recycled[44]. The price of recycled scrap metal, as with the material cost, varies with its availability and with the market demand. The values adopted herein are average values taken from European metal recycling[45], the London metal exchange[46], and quotes obtained from Metal world[47] in 2004.

In the analysis of the building structure the cost of demolition and, as an alternative end of life scenario, deconstruction has been considered. Only the demolition scenario has been considered for the bridge structure. In a study reported by Geyer et al.[48] it was stated that if a structure is demolished, 99% of the material from structural steel sections can be recovered at a cost of £50 per tonne. In the current study, a conservative estimate of 80% recovery was taken. Deconstruction (or dismantling) of a structure is a much more labour intensive operation and therefore incurs higher costs, taken as £100 per tonne[48]. Birat et al.[49] suggest that 90% of material can be recovered by deconstruction. The advantage of deconstruction is that damage of components is less likely and they may therefore be sold for reuse within the construction market rather than being recycled. The choice between recycling and reusing structural products is often made on the basis of practical and economic issues such as the ease of reclamation and the additional associated costs. Despite the economics of these two alternative end of life scenarios, Lazarus[50] reports that the current level of recycling for carbon steel reduces the embodied energy of a structural section by approximately 50%, whereas the embodied energy for reused carbon steel sections is reduced by 85%-95% from that required to produce a section from primary carbon steel resources. Reuse is clearly therefore the more environmentally favourable scenario.

3. Life cycle costing

In this section, the life cycle costs of two structures (a typical office building and a bridge) of the three considered structural metallic materials are presented. The studies are based on current costs of the three structural materials (carbon steel, aluminium alloy and stainless steel) giving an initial ratio of the material cost per tonne of 1.0: 2.5: 4.0. The sources of costs used in the analysis have been detailed in the previous section. Based on the material costs per tonne, the material densities and an initial design of the primary members of the structures (to the current European structural design standards[51,52,53] given in Table 2), ratios of the initial estimated costs of structural material for the building and the for the bridge were obtained. A brief description of the structures and discussion of the results of the life cycle costings are given in the following sub-sections.

3.1 Office building

A typical, flat-roofed four-storey office building was chosen as the basis for the life cycle costing study. The overall dimensions of the structure were 48 m by 13.5 m on plan, and the inter-storey height was 2.7 m. The span of the primary beams was 6 m and the span of the secondary beams was 13.5 m. A design life of 50 years was assumed. Although it is likely that no significant maintenance would be required on protected internal steelwork, four scenarios (two of which make an allowance for inspection and maintenance of the corrosion protection at ten yearly intervals, assuming an external or exposed structure) were considered:

- Maintenance costs incurred every ten years and end of life demolition.
- No maintenance costs incurred and end of life demolition.
- Maintenance costs incurred every ten years and end of life deconstruction.
- No maintenance costs incurred and end of life deconstruction.

Results of the building study are presented in Table 3 with the costs shown as a ratio of the total material costs for the carbon steel structure. The initial material cost of the structures, taking due account of the material cost per tonne, the material densities and the structural properties, normalised to that of the carbon steel structure were found to be 1.00: 1.82: 4.87. Inclusion of the additional initial costs (corrosion protection and fire protection) gives initial cost ratios of 1.37: 2.36: 5.02. These ratios confirm that, on an initial cost basis, carbon steel represents the most economic solution. Assessing the maintenance and end of life costs of the building, it may be observed that the durability and residual value of both aluminium and stainless steel offer cost savings, but once discounted to their present values these savings are small, and on a life cycle costing basis, the carbon steel building remains the most economic solution for all four scenarios considered. Accumulation of normalised life cycle costs (including maintenance) with time for the three structural materials for the more likely scenario of demolition of the building is shown in Figure 4(a).

The results of the study on the building indicate that the higher initial material costs of the aluminium alloy and stainless steel are not offset by the lower corrosion protection costs, maintenance costs and decommissioning costs over the life cycle of the structure. This is likely to be true in all low maintenance applications. However, it may be appropriate to consider these materials in exposed areas of a building structure, particularly in aggressive environments, where maintenance requirements will be greater and aesthetics may be enhanced. An example of where stainless steel has been employed in such a situation is the external bracing system on the Sanomatalo building in Helsinki (Figure 5).

3.2 Bridge

Modern bridges are designed with an envisaged life span of 120 years, which, coupled with the more exposed nature of the structural elements, means that maintenance costs are generally a far more significant portion of the total life cycle costs than for the case of buildings. It has been estimated, for example, that the total annual cost of highway bridge maintenance (to prevent corrosion) in the US is between £3.67 billion and £5.79 billion[36]. The same study also highlighted that the ensuing traffic disruption is thought to cost ten times that of the corrosion protection in loss of productivity.

A typical plate girder highway bridge of 57.5 m span has been taken as the basis for the second life cycle costing study. Initial sizing of the primary members has been performed to current European design standards, but no consideration has been given to fatigue due to traffic loading. Two scenarios have been considered – one including maintenance and the other excluding maintenance. Results of the life cycling costing study are shown in Table 4. The initial material cost ratio for the bridge structure was found to be 1.00: 1.73: 5.47 and the ratio of the material weight for each structure was 1.00: 0.71: 1.29. In research carried out by Moss and Saetre[54] on offshore trusses, aluminium alloy structures were found to be 60-65% of the weight of those of carbon steel, whilst in a separate study carried out by Shuttleworth[55] the weight for stainless steel structures was found to be 125 % of carbon steel structures. These values broadly support those found in this study. Accumulation of normalised life cycle costs (including maintenance) with time for the three structural materials for the bridge application is shown in Figure 4(b).

Considering the first scenario (which included maintenance), the life cycle cost ratio was found to be 7.32: 2.14: 5.66, with the aluminium alloy providing the most competitive solution, and carbon steel being the least competitive. Stainless steel offers the lowest maintenance costs and highest residual value, resulting in a more competitive life cycle solution than carbon steel, but its high initial cost makes it less competitive than aluminium. If all maintenance costs are ignored, the life cycle cost ratio becomes 1.15: 1.72: 5.45, but clearly the performance and life expectancy of the carbon steel structure will be comprised, and the no-maintenance scenario is unsustainable.

Examples of the use of aluminium and stainless steel in bridge applications are shown in Figures 6 and 7, respectively. Figure 6 shows an aluminium alloy arch bridge at Bourke's Luck in South Africa, whilst Figure 7 shows a stainless steel bridge in St. Saviours Dock in London.

3.3 Potential use in offshore structures

The use of aluminium alloys and stainless steel in offshore structures such as the common topside and jacket structure of offshore oilrigs is a third potential application. Offshore applications for aluminium alloys have been previously discussed by Moss and Saetre[54], and for stainless steel by Shuttleworth[55].

In offshore applications, the corrosive environment is severe. A number of methods are employed to protect offshore carbon steel structures from corrosion, including protective coatings and cathodic protection. Over-sizing of structural members is also commonly carried out to allow for loss of material. The inherent corrosion resistance of aluminium and stainless steel would clearly be of benefit in offshore applications. However, given the harshness of the environment, higher performance grades, (at greater expense) will generally be required. Stainless steel offers the additional advantages of superior fire resistance and impact resistance. Savings in maintenance costs may also be augmented by savings related to shorter periods of down time and minimising loss of production.

4. Sensitivity studies

Representative values for all contributory components of the described life cycle costing analyses have been obtained from a range of sources, as summarised in Table 2. However, there is clearly a degree of uncertainty, variability and fluctuation with market conditions associated with many of these values. A set of sensitivity studies has therefore been performed to assess the influence of the following variables on the calculated life cycle costs: material cost, design life, discount rate and duration of traffic disruption (in the case of the bridge). Throughout the sensitivity studies, all life cycle costs have been presented relative to the life cycle cost of the original corresponding carbon steel structure.

4.1 Influence of initial material costs

Initial material costs were varied between 0.5 and 2.0 times their assumed values of Table 2. As outlined previously in this paper, variation in the cost of metals occurs as a result of fluctuation in levels of demand and resources. Figure 8 shows the resulting change in the life cycle costs for the building and bridge, given relative to the life cycle cost of the original corresponding carbon steel structure. The influence of variation in initial material costs is most significant for the stainless steel structures since compared to the other metals considered, the initial material cost of stainless steel is a larger proportion of the LCC. For the bridge structure (Figure 8(b)), variation of the initial material costs was found to have less impact on the total life cycle costs than seen in the building structure (Figure 8(a)). This was due to the high maintenance costs associated with the bridge, which represented a large portion of the life cycle costs.

4.2 Influence of design life

This study considered a range of design lives from 0.4 to 1.6 times the originally considered values given in Table 2. This corresponds to design lives of 20-80 years for the building and 48-192 years for the bridge structure. These ranges are considered appropriate since despite the intended design lives of structures, events often conspire whereby these must be shortened or extended. For example, buildings may be demolished well before their intended design life has elapsed due to pressure on land density or due to an incompatibility with the desired function, and it is common for bridges to be repaired or upgraded to extend their design lives. The sensitivity of the results of the study to variation in design life was found to be less than the sensitivity to variation in initial material costs. For the case of the both the building (Figure 9(a)) and the bridge (Figure 9(b)), although variation in design life influences life cycle costs, the relative competitiveness of the three materials is essentially unaffected. The lower maintenance requirements associated with shorter design lives are most beneficial in the case of the carbon steel bridge, where the life cycle costs may be seen to reduce rapidly (Figure 9(b)).

4.3 Influence of discount rate

The discount rate controls the present value of costs over the life cycle of the structure. Variation of the discount rate changes the impact of costs associated with maintenance and end of life costs on the LCC. Discount rates considered in LCC studies generally vary from around 1.0% up to 8%; a corresponding range is therefore considered in this study. With the initial costs making up a large portion of the life cycle costs, the building is relatively insensitive to variation in discount rate (see Figure 10(a)). The reduction in life cycle cost that may be observed in Figure 10(a) for the aluminium and stainless steel building for low discount rates is due to the increased influence of the residual value of the structure. The aluminium and stainless steel bridge structures show little sensitivity to variation in discount rate, due to the low maintenance costs. Conversely, the carbon steel bridge shows a high level of sensitivity to discount rate (Figure 10(b)).

4.4 Influence of duration of traffic disruption

Variation in the duration of assumed traffic disruption resulting from maintenance of the bridge structure does not greatly affect the economic outcome of the study. Figure 11 shows, as anticipated, that the carbon steel option is more sensitive to this variation due to the initially assumed longer maintenance periods.

5. Conclusions

All structural metallic materials, provided they can be salvaged at the end of a structure's life, can be recycled without degradation of material properties. To date, carbon steel has dominated the metallic construction market owing to its relatively low initial material cost, good structural properties, a comprehensive product range and familiarity within the industry. This dominance is therefore set to continue, but the construction industry has acknowledged that cost savings can be made over the longer term by specifying alternative materials perhaps with higher initial costs, but which offer cost savings over the life span of a structure. The methodology of life cycle costing encourages the industry to consider the long term effects of material specification in terms of maintenance and end of life scenarios, though performing a life cycle costing analysis may not generate the most sustainable design solution. Whilst minimising maintenance requirements may reduce the need for additional materials and energy to be expended during a structure's life, it is less clear whether life cycle costing directly encourages end of life scenarios with the lowest environmental impact (such as deconstruction and section reuse). Clearly, regardless of the cost of doing so, reuse and recycling is increasingly imperative to meet the rising demand for metallic materials.

On the basis of material produced by extraction and processing of raw materials, aluminium and stainless steel have a higher embodied energy than carbon steel. However, non-structural life cycle assessment studies have indicated that, as for life cycle costing, an initial high outlay of resources in comparison to carbon steel can be more than compensated for over the life time of a product. In the context of structural applications, the high durability, low maintenance requirements and extended design lives offered by aluminium and stainless steel may substantially decrease the longer term environmental impact. In these ways, the more durable metallic structural materials (such as aluminium and stainless steel) may decrease the environmental impact of construction whilst also maintaining the ease of construction, flexibility and adaptability associated with carbon steel which contributes to longer life spans and therefore fewer new build structures.

In this study, the life cycle performance of aluminium and stainless steel, employed in two structural applications – an office building and a bridge – has been analysed, and compared to that of carbon steel. The ratio of initial material cost per tonne was assumed to be 1.0: 2.5: 4.0 (carbon steel: aluminium alloy: stainless steel). Following a preliminary structural design to current European design standards taking due account of the material densities and structural properties (principally strength and stiffness), initial material cost ratios of 1.00: 1.82: 4.87 for the building and 1.00: 1.73: 5.47 for the bridge were obtained. Additional initial costs (corrosion protection and fire protection) altered these ratios to 1.37: 2.36: 5.02 for the building and 1.15: 1.73: 5.47 for the bridge (where ratios are relative to the initial material costs of the corresponding carbon steel structure). On an initial cost basis, carbon steel offers the most competitive solution for both the building and the bridge. However, considering the additional life cycle costs including maintenance costs, end of life costs and the residual value of the structure (appropriately discounted to present values), the situation changes. For the building, with only modest maintenance requirements, the life cycle cost ratio was found to be 1.58: 2.33: 4.92, but for the bridge, where maintenance requirements are significant, the life cycle cost ratio was found to be 7.32: 2.14: 5.66. Although there is clearly a degree of uncertainty and variability associated with the component costs of the life cycle analyses, the results indicate that carbon steel offers the most competitive life cycle solution for the office building, but delivers the most expensive life cycle solution for the bridge. Overall, it is concluded that on a whole-life basis aluminium alloy and stainless steel may offer more competitive solutions than carbon steel for bridges and exposed areas of building structures.

References

[1] Norgate T. E. Jahanshahi S. and Rankin W. J., *Assessing the environmental impact of metal production processes*. Journal of Cleaner Production, 2007, **15**, No. 8-9, 838-848.

[2] Fujii H., Nagaiwa T., Kusuno H. and Malm S. *How to quantify the environmental profile of stainless steel*, SETAC North America 26th Annual Meeting, 2005.

[3] Seppälä J., Koskela S., Melanen M. and Palperi M., *The Finnish metals industry and the environment*, Resources, Conservation and Recycling, 2002, **35**, No. 1-2, 61-76.

[4] Truman J. The initiation and growth of high alloy (stainless) steel production. *Journal of the Metallurgy Society,* 1985, 116-125.

[5] Mazzolani F. M., Competing issues for aluminium alloys in structural engineering. *Progress in Structural Engineering and Materials*, 2004, **6**, No. 4, 185-196.

[6] Gardner, L., The use of stainless steel in structures, *Progress in Structural Engineering and Materials*, 2005, **7**, No. 2, 45-55.

[7] Miki C., Homma K. and Tominaga T., *High strength and high performance steels and their use in bridge structures*. Journal of Constructional Steel Research, 2002, **58**, No. 1, 3-10.

[8] ISO 15686-1:2000, *Buildings and constructed assets, Service life planning Part 1: General principles*, BSI, 2000.

[9] DTLR, Department of Transport Local Government and the Regions, (Formerly Department of the Environment, Transport and the Regions), *Rethinking Construction (Egan report),* Office of the Deputy Prime Minister, 1998.

[10] Boussabaine, A. and Kirkham, R. *Whole Life-cycle costing; Risk and Risk Responses*, Blackwell publishing, Oxford, 2004.

[11] Gluch P. and Baumann H. The life cycle costing (LCC) approach; a conceptual discussion of its usefulness for environmental decision-making. *Building and Environment*, 2004, **39**, No. 5, 571-580.

[12] Val D. V., Stewart M.G. Life-cycle cost analysis of reinforced concrete structures in marine environments. *Structural Safety*, 2003, **25**, No. 4, 343-362.

[13] Lee K-M., Cho H-N. and Cha C-J., Life-cycle cost-effective optimum design of steel bridges considering environmental stressors. *Engineering Structures*, 2006, **28**, No. 9, 1252-1265.

[14] Corus Commercial & Industrial, *Supporting the Commercial Decision - Comparing the cost of steel and concrete framing options for commercial buildings*, Corus, Scunthorpe, 2004.

[15] Kincaid, D. *Adapting buildings for changing uses: guidelines for change of use refurbishment,* Spon press, London, 2002.

[16] Davis Landgon and Everest, Davis Landgon and Mott Green and Wall, *Office design – cost model,* Building Magazine, 10th December, 2004.

[17] Sansom M. Sustainable steel construction: building a better future, *Proceedings of the Institution of Civil Engineers: Engineering sustainability*, 2003, **156**, No. 2, 81-82.

[18] Burgan, B. A. and Sansom, M. R. Sustainable steel construction, *Journal of Constructional Steel Research*, 2006, **62**, No. 11, 1178-1183.

[19] HM Treasury, *The Green Book - Appraisal and Evaluation in the Central Government,* TSO, London, 2003.

[20] BSSA (British Stainless Steel Association), *Stainless steel and sustainable construction,* Special BSSA report, BSSA, 2004.

[21] Norgate T. E., Rajakumar, V. Trang, S., Titanium and other light metals - technology pathways to sustainable development. *Green processing*, Fremantle, AusIMM, 2004, 105-112.

[22] Dwight J. *Aluminium design and construction*, E&FN Spon, New York, 1999.

[23] Baddoo N., Burgan R. and Ogden R. *Architects' guide to stainless steel.* The Steel Construction Institute, Ascot, 1997.

[24] Jonsson J. *Stainless steel in a sustainable society- what we know and what we need to investigate,* AvestaPolarit AB, R&D, Avesta, 2000.

[25] ASSDA (Australian Stainless Steel Development Association). See http://www.assda.asn.au.

[26] Norgate T. E. Metal Recycling: An assessment using life cycle energy consumption as a sustainability indicator. CSIRO Minerals, Report DMR-2616, 2004.

[27] Gardner, L. and Ashraf, M. Structural design for non-linear metallic materials. *Engineering Structures*, 2006, **28**, No. 6, 926-934.

[28] Corus Construction & Industrial, *Price list 5; Structural sections*, Corus, Scunthorpe, 2005, 22nd edition.

[29] AEi Corporation Ltd. See http://www.aei.com.sg.

[30] Kissell J. R. and Ferry, R. L., *Aluminium Structures: A guide to their specifications and design*, Wiley, New York, Chichester, 1995.

[31] Schedin E. Forming Properties of Stainless Steel Sheet, *International Conference on the Application of Stainless Steel, Kista Stockholm, Sweden,* 1992, 137-146.

[32] Mazzolani F. M., *Aluminium Alloy structures*, E &F N Spon, London, 1995.

[33] Davis J. R. and Associates (Ed.), Corrosion of aluminium and aluminium alloys, ASM International, Materials Park, OH, 1999.

[34] Sedriks A. J., *Corrosion of stainless steels*, John Wiley & Sons, Inc, 1996, 2nd edn.

[35] Corus Construction Centre, *Corrosion Protection of Steel Bridges,* Corus, Scunthorpe, 2002.

[36] Koch G. H., Broongers M. P. O., Thompson N. G., Virmani Y. P. and Payer J. H., *Corrosion cost and preventative strategies in the United States*, Federal Highway Administration, McLean, JA, 2002, FHWA-RD-01-156.

[37] Wong S. M. *Element and system risk considerations in bridge management*. Imperial College London, PhD Thesis, 2004.

[38] Gardner, L. and Baddoo, N. R. Fire testing and design of stainless steel structures. *Journal of Constructional Steel Research*, 2006, **62**, No. 6, 532-543.

[39] Gardner, L. and Ng, K. T. Temperature development in structural stainless steel sections exposed to fire. *Fire Safety Journal*, 2006, **41**, No. 3, 185-203.

[40] Ng, K. T. and Gardner, L. Buckling of stainless steel columns and beams in fire. *Engineering Structures*, 2007, **29**, No. 5, 717-730.

[41] Gardner, L. Stainless steel structures in fire. *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, 2007, **160**, No. 3, 129-138.

[42] ODPM Building Regulations, *Approved Document B*. Office of the Deputy Prime Minister, 2000.

[43] Buchanen A. H., *Structural Design for Fire Safety*, John Wiley & Sons Ltd., Chichester, 2001.

[44] Department of Trade and Industry. See http:// www.dti.gov.co.uk.

[45] European metal recycling website. See http:// www.emrltd.com.

[46] London metal exchange. See http:// www.lme.co.uk.

[47] Metalworld. See http://www.metalworld.com/specs.

[48] Geyer R., Jackson T. and Clift R., *Economic and environmental comparison between recycling and reuse of structural steel section.* 10th LCA Studies Symposium and 2002 European meeting of International Society for Industrial Ecology, 2002.

[49] Birat J. P., Dalsheimer J., Gros B. and Phelouzat J. L. *Waste recycling in the construction sector*. International Iron and Steel Institute, 2002.

[50] Lazurus N., Potential for reducing the environmental impact of construction materials, Bioregional Report, 2005.

[51] EN 1993-1-1, *Eurocode 3: Design of steel structures-Part 1-1: General rules and rules for buildings. European Standard,* CEN, 2005.

[52] ENV 1999-1-1, *Eurocode 9: Design of aluminium structures–Part 1-1: General rules and rules for buildings. European standard.* CEN, 1998.

[53] EN 1993-1-4, *Eurocode 3: Design of steel structures-Part 1.4: General rules. Supplementary Rules for Stainless steels. European standard.* CEN, 2006.

[54] Moss P. K. and Saetre I., Use of aluminium in offshore trussed structures. *Proceedings of 10th International Conference on Offshore Mechanics and Arctic Engineering,* American Society of Mechanical Engineering, 1991, Volume III Part A.

[55] Shuttleworth E. P. *Structural applications to stainless steel offshore - Report to Nickel Development Institute*, The Steel Construction Institute, Ascot, 1989, SCI-RT-030.

$$LCC = I + A + \sum_{0}^{t_n}\left(\frac{M}{(1+r)^{t_i}}\right) + \left(\frac{E}{(1+r)^{t_n}}\right) + \left(\frac{R}{(1+r)^{t_n}}\right)$$

where:

I - Initial material costs, including:
- Raw materials (alloying elements)
- Production of alloy (alloying elements)
- Fabrication of members

A - Additional initial costs, including:
- Corrosion protection
- Fire protection

M - Maintenance and inspection, including:
- Material cost of repairs to corrosion and fire protection
- Disrupted use of structure

E - End of life costs, including:
- Demolition/ Deconstruction

R - Residual value of materials, including:
- Recycling

r - Discount value (%)

t_i - Intervening time (years)
t_n - Design life (years)

Figure 1 LCC calculation showing the factors considered

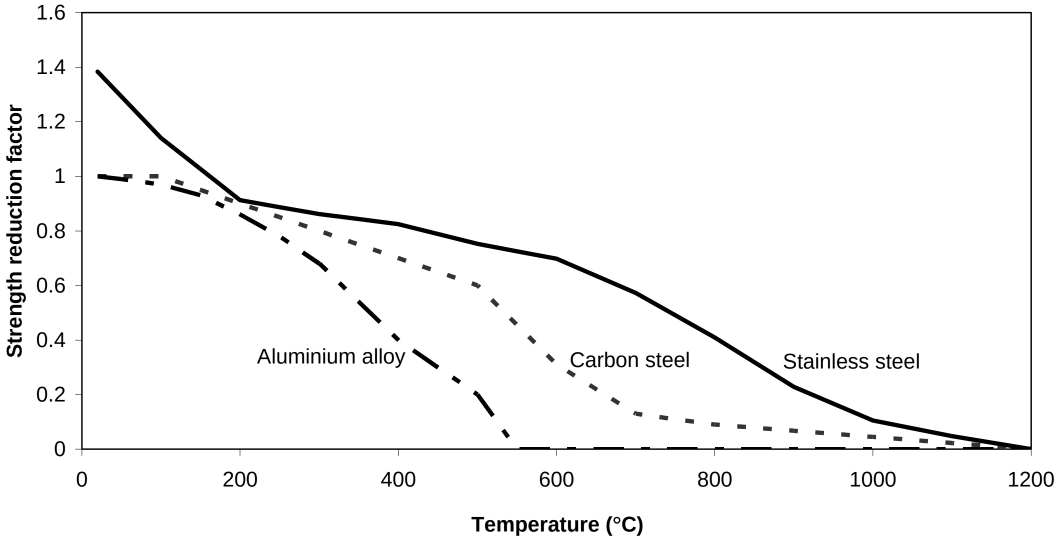


Figure 2 Comparison of strength reduction factors at elevated temperature for carbon steel, aluminium alloy and stainless steel

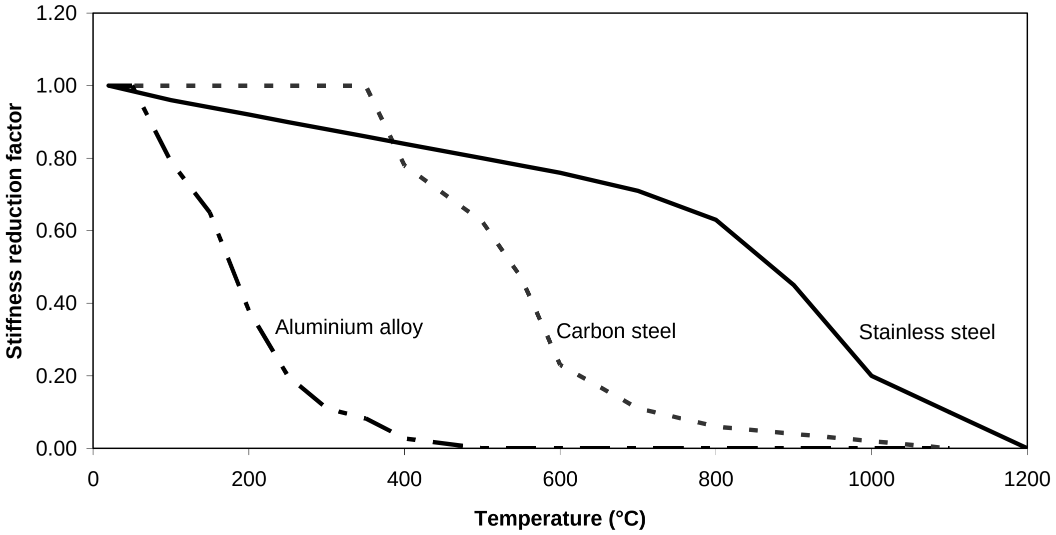
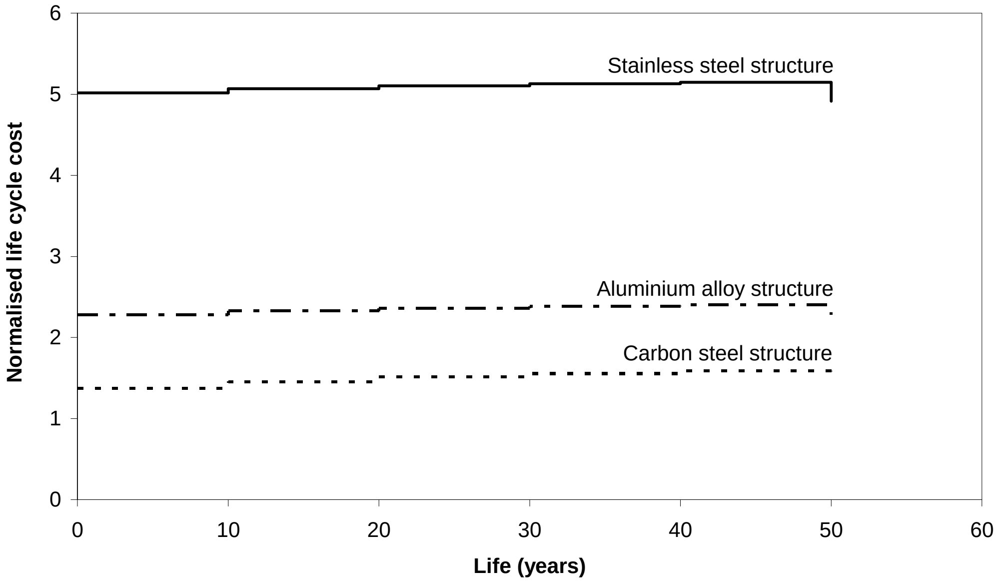
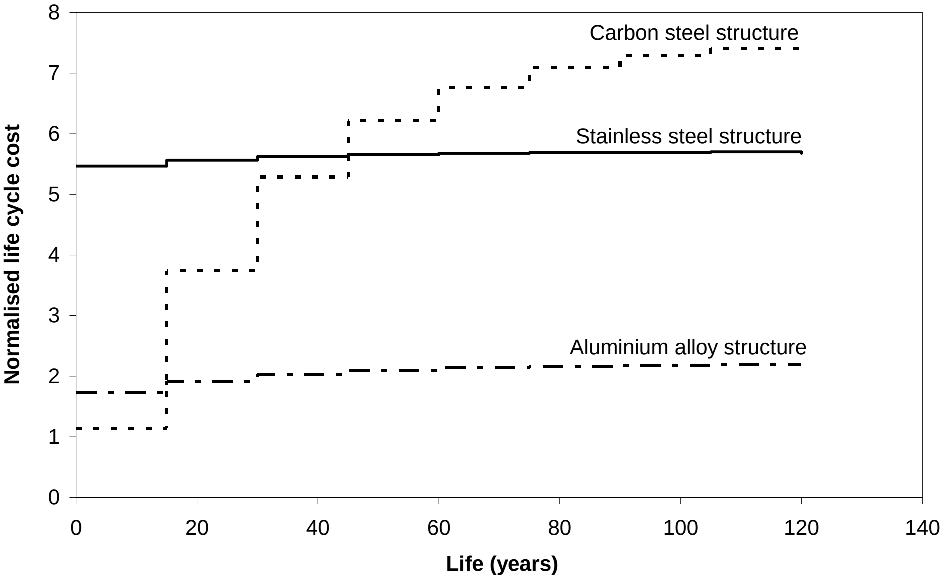


Figure 3 Comparison of stiffness reduction factors at elevated temperature for carbon steel, aluminium alloy and stainless steel



(a) Building structure



(b) Bridge structure

Figure 4 Accumulation of costs over the life cycle of the structures

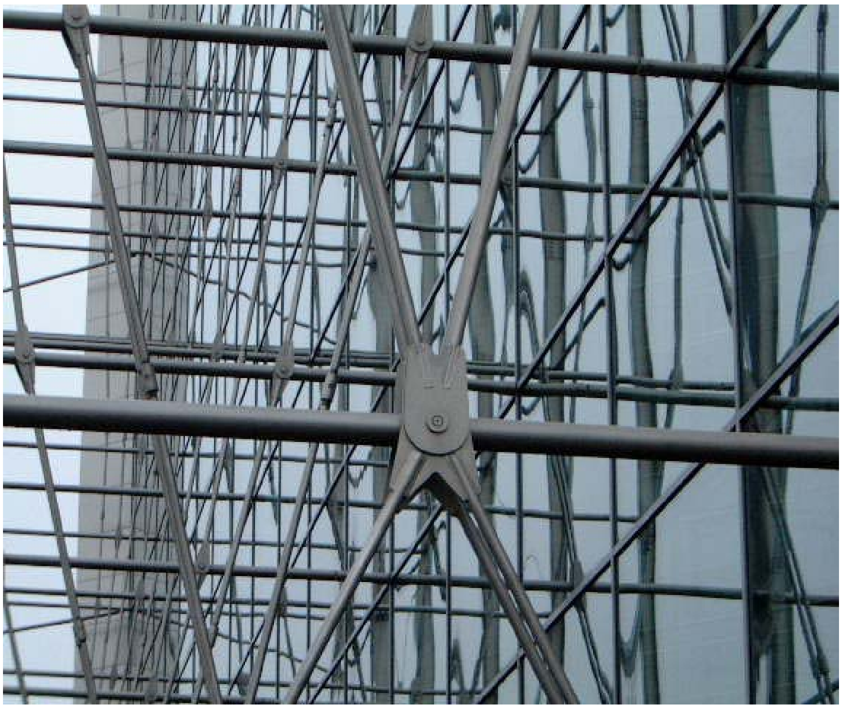
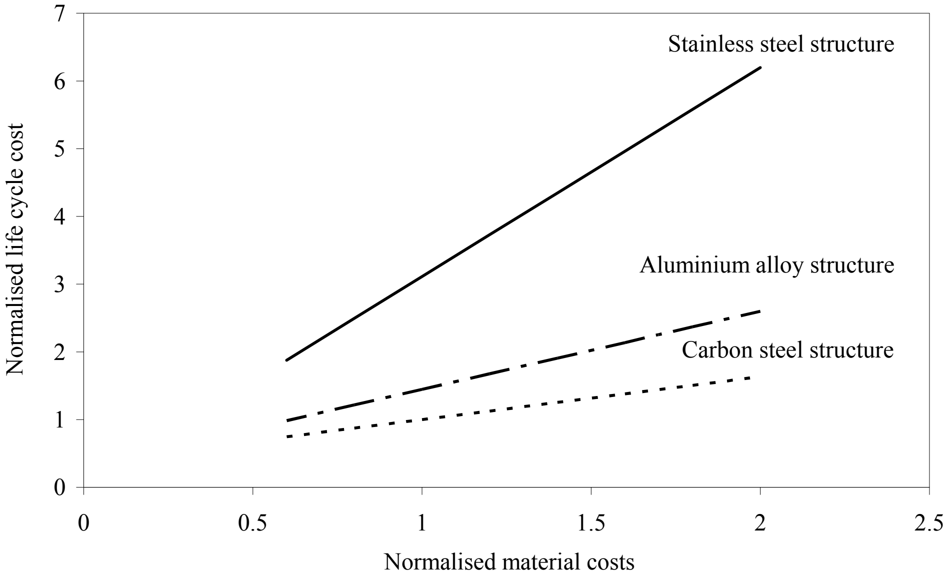


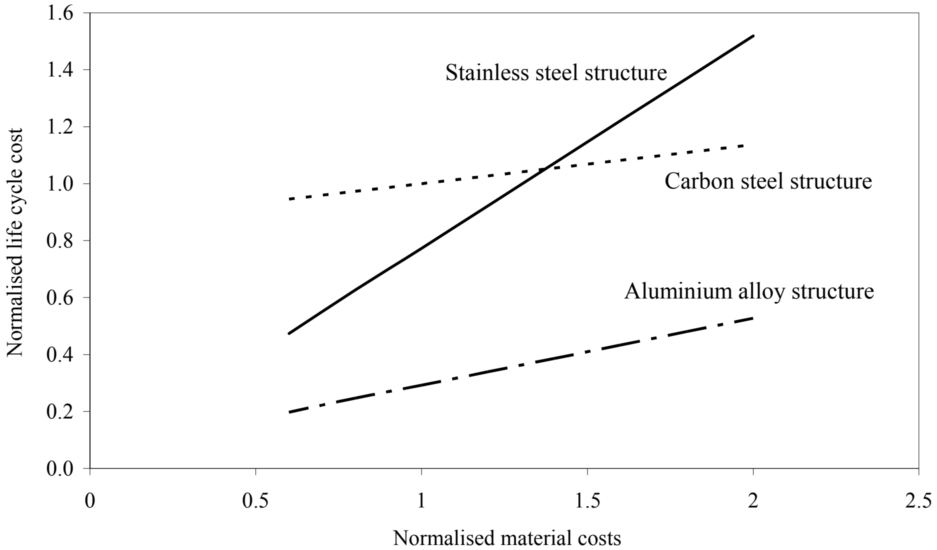
Figure 5 External stainless steel bracing system, Sanomatalo Building in Helsinki

Figure 6 Aluminium alloy bridge, Bourke’s Luck, South Africa

Figure 7 Stainless steel bridge, St. Saviours Dock, Shad Thames, London

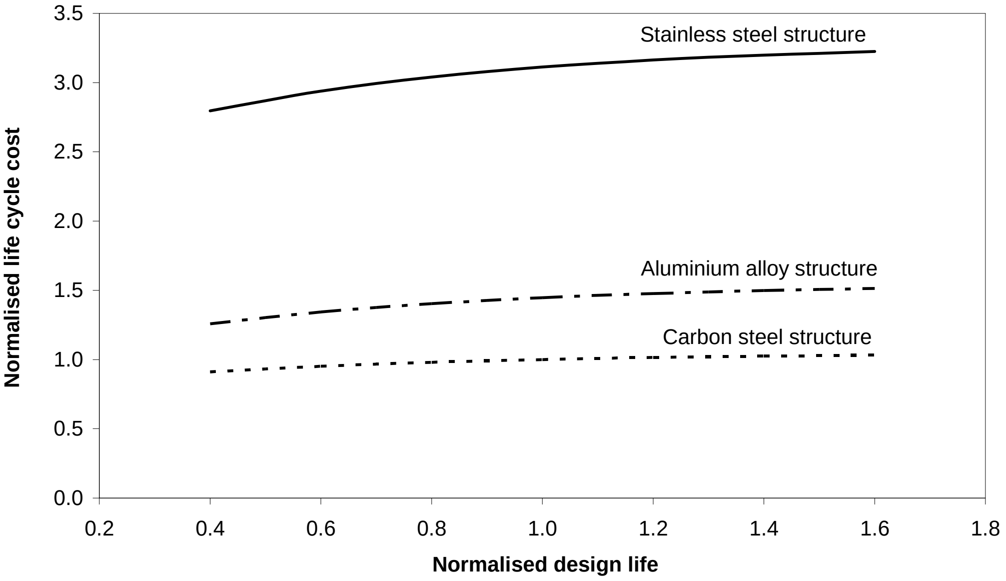


(a) Building structure

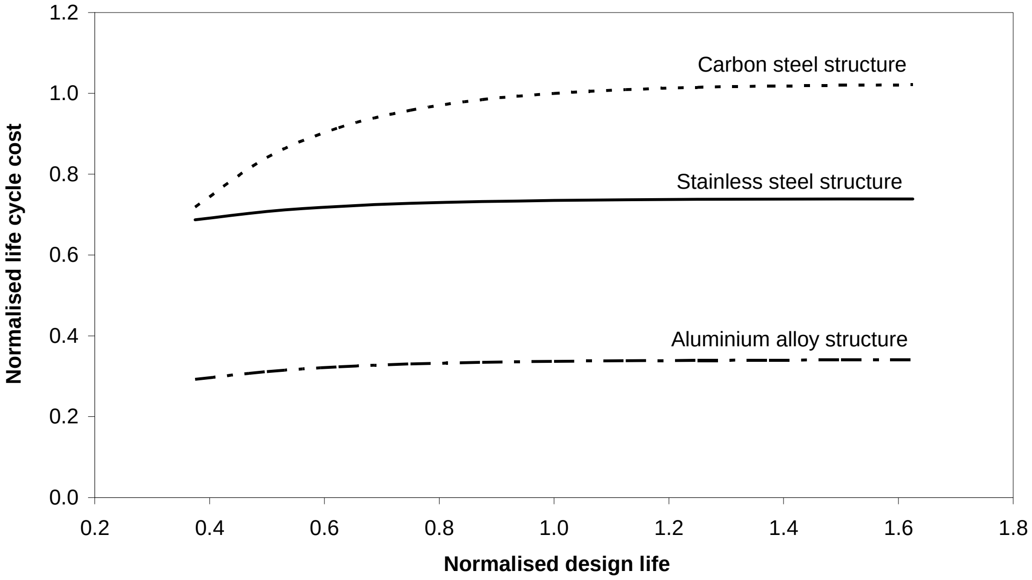


(b) Bridge structure

Figure 8 Sensitivity of LCC to variation in initial material costs

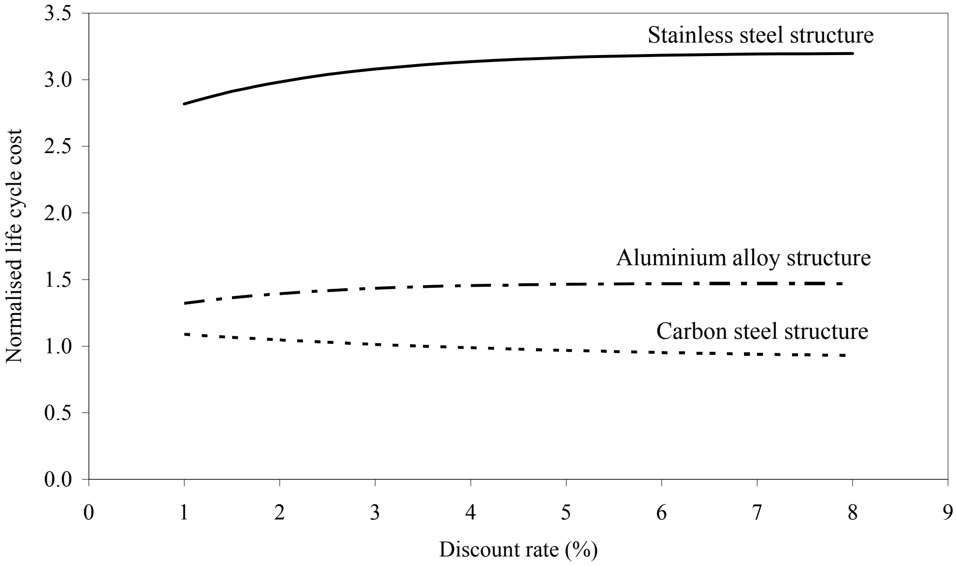


(a) Building structure

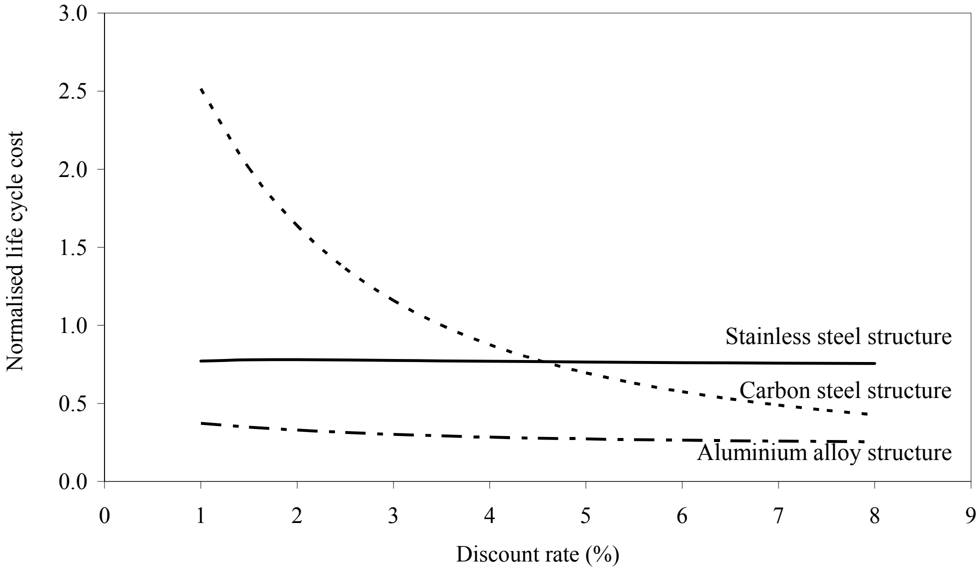


(b) Bridge structure

Figure 9 Sensitivity of LCC to variation in design life



(a) Building structure



(b) Bridge structure

Figure 10 Sensitivity of LCC to variation in discount rate

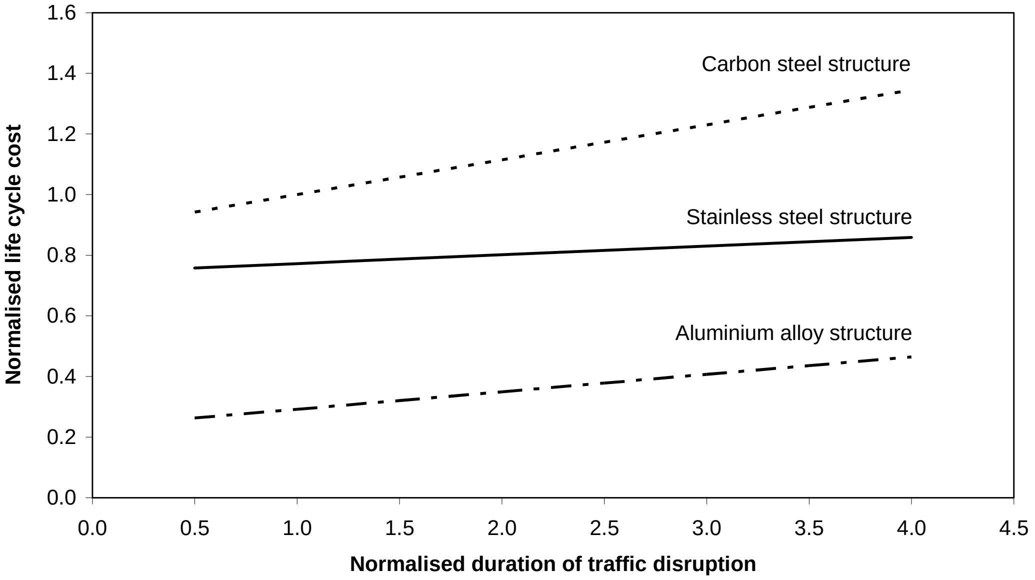


Figure 11 Sensitivity of LCC to variation in duration of traffic disruption

Table 1 Material properties of carbon steel, aluminium and stainless steel

	Carbon steel	Aluminium alloy	Stainless steel
Grade	S275	EN AW 6061 T4	EN 1.4401(316)
Material yield strength σ_y or $\sigma_{0.2}$ (N/mm^2)	275	110	220
Young's modulus E (N/mm^2)	210000	70000	200000
Strain at fracture A_o (%)	24	12	45
Density ρ (kg/m^3)	7850	2700	8000
Thermal expansion coefficient α (K^{-1})	12×10^{-6}	23.2×10^{-6}	16×10^{-6}
Thermal conductivity k (W/mK)	54	250	16
Total amount of material recycled (%)	60[a]	70[a]	70[a]

[a] Department of trade and industry, 2005

Table 2 Data used for LCC study for three types of structures

	Carbon steel	Aluminium alloy	Stainless steel
Structural code	EN 1993-1-1 (2005)	ENV 1999-1-1 (2000)	EN 1993-1-4 (2006)
Office building			
Design life in years	50	50	50
Initial cost (£/tonne)	720	1750	3060
Corrosion protection (£/m^2)	3.60	-	-
Time interval for maintenance (years)	10	10	10
Fire protection (£/m^2)	10.50	15.75	5.25
Material recovery - Demolition (%)	80	80	80
Cost of Demolition (£/tonne)	50	50	50
Material recovery - Deconstruction (%)	90	90	90
Cost of Deconstruction (£/tonne)	100	100	100
Recovered value of scrap (£/tonne)	93	875	1080
Bridge			
Design life (years)	120	120	120
Initial cost (£/tonne)	720	1750	3060
Corrosion protection (£/m^2)	625	-	-
Time interval for maintenance (years)	15	15	15
Down time for maintenance (days)	10	2.5	5
Cost of traffic management system and disruption (£/day)	8000	8000	8000
Cost of maintenance (£/day)	7200	7200	7200
Decommissioning (£/tonne)	100	100	100
Recovered value of scrap (£/tonne)	93	875	1080

Table 3 LCC results for the office building (costs normalised to initial material costs of carbon steel structure)

Office building	Carbon steel	Aluminium alloy	Stainless steel
Normalised weight of structure	1.00	0.75	1.15
Initial costs			
Material cost	1.00	1.82	4.87
Corrosion protection cost	0.10	-	-
Fire protection cost	0.28	0.50	0.14
Total initial costs	1.37	2.32	5.02
Maintenance costs (discounted)			
Maintenance	0.22	0.13	0.13
Decommissioning cost (discounted)			
Demolition	0.01	0.01	0.01
Deconstruction	0.03	0.02	0.03
Residual value (discounted)			
Value recovered (Demolition)	0.02	0.13	0.25
Value recovered (Deconstruction)	0.02	0.15	0.28
Life cycle costs			
Total cost including maintenance (Demolition)	1.58	2.33	4.92
Total cost excluding maintenance (Demolition)	1.36	2.20	4.79
Total cost including maintenance (Deconstruction)	1.59	2.32	4.90
Total cost excluding maintenance (Deconstruction)	1.38	2.19	4.77

Table 4 LCC results for the bridge structure (costs normalised to initial material costs of carbon steel structure)

Bridge structure	Carbon steel	Aluminium alloy	Stainless steel
Normalised weight of structure	1.00	0.71	1.29
Initial costs			
Material cost	1.00	1.73	5.47
Corrosion protection cost	0.15	-	-
Total initial costs	1.15	1.73	5.47
Maintenance costs (discounted)			
Corrosion protection	5.33	-	-
Traffic management and disruption	0.84	0.42	0.21
Total maintenance costs	6.17	0.42	0.21
Decommissioning cost (discounted)			
Demolition	0.00	0.00	0.00
Residual value (discounted)			
Value recovered	0.00	0.01	0.03
Life cycle costs			
Total cost including maintenance	7.32	2.14	5.66
Total cost excluding maintenance	1.15	1.72	5.45