relinea®
Reliable, Resourceful.

SUSTAINABILITY OF GRP

This report highlights the environmental benefits of using GRP in the construction industry.

02

INTRODUCTION

Relinea is committed to using manufacturing and innovation to make the shift towards a more sustainable business. Integrating sustainability into our business model and ways of working creates value for all. At every stage of our process, we reduce our environmental impact through innovation, R&D, and waste minimisation. Early engagement through planning and design combined with robust advanced product solutions ensures a reliable and sustainable future.

MISSION

Our mission is to work together as a team to lead the future of composites by putting innovation and our customers at the heart of everything we do.

VISION

We are committed to developing a distinctive value-creation culture that has a long-term positive impact for all our stakeholders. This culture and associated practices are embedded in our company with sound decision-making, regular investment, and world-class capabilities.

04

SUSTAINABLE GRP SOLUTIONS

“The construction industry consumes more of the earth’s resources (up to 50%) than any other industry”

Composites UK, 2016

The construction, operation & subsequent demolition of all built facilities account for 40 – 45% of global energy use. The concept of sustainability imposes ‘a new way of thinking,’ in which environmental impact is considered at every stage of a product’s lifecycle. It is imperative that we all work towards reducing our impact on the environment to ensure a sustainable future.

Global construction companies. Water treatment facilities. International technology firms. Worldwide energy and transportation providers. Our customers in industries worldwide are moving towards an eco-friendlier future. They need alternatives to traditional materials such as steel, concrete, and wood. We are committed to providing the solutions to help our customers achieve their environmental objectives while meeting their requirements for performance, strength, and economic value.

Relinea is known for providing GRP products and services that continually improve the quality of life and the environment by fulfilling society’s need for infrastructure including, clean water, construction, transportation, and reliable energy – in a sustainable way.

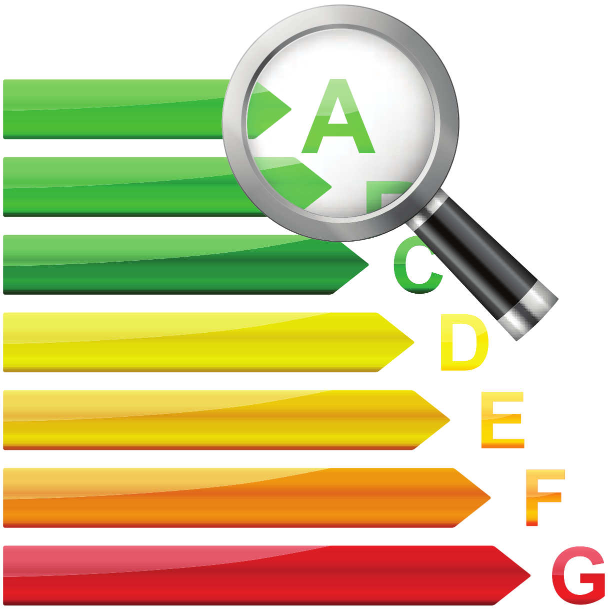
HOW CAN GRP HELP TO REDUCE ENVIRONMENTAL IMPACT?

05

Products made from GRP can offer significant environmental benefits because of their characteristically low weight, good mechanical properties, and excellent resistance to corrosion.

GRP can be effectively used in the development of new structures to achieve a superior service life without the need for regular, costly maintenance. As we work towards sustainability goals and extending the life of products, glass-reinforced plastic can also be incorporated into existing structures to extend existing service life.

With an exceptional strength-to-weight ratio, GRP will reduce the overall carbon footprint of a project. Using a revolutionary approach that focuses on intelligent GRP design combined with innovative manufacturing processes, Relinea can develop solutions that have a much lower carbon footprint in comparison to traditional building materials such as concrete & steel. Built to last, GRP is the material of the future for those seeking energy-efficient, green, sustainable solutions.



Recyclable

GRP waste is often shredded and processed to create a high-grade alternative for the cement industry, where it is used as a fuel and mineral raw material. GRP products are also commonly upcycled for use in a wide range of non-standard applications.

Long Lifespan

The thermosetting resins used in GRP are far stronger and more durable than other plastics, giving most GRP products a lifespan of more than 50 years.

Low Carbon Footprint

GRP's CO2 equivalent is less than half that of a concrete bridge and approximately a third of the CO2 equivalent for a steel bridge. As a result, GRP's carbon footprint is also very favourable.

Energy Efficient

75% less energy is needed to produce glass-reinforced plastic (GRP) than steel.

Lightweight

GRP structures are 75% lighter than steel which means 50% less energy is needed for transport and assembly.

Eco Friendly

GRP produces fewer greenhouse gasses and consumes less energy at the production stage than both steel and aluminum. The production of base resins and fibre rovings doesn't have the same impact on the environment as the production of metals. Pultrusion takes place in a fully-closed process, which minimises the evaporation of volatile compounds, and no smoke clouds or toxic air pollutants are created.

07

LIFE CYCLE ASSESSMENT:

A life cycle assessment is a tool used to evaluate the environmental impacts of a structure over its entire lifecycle from extraction of raw materials through to end-of-life product disposal. The following in-depth study was carried out to review the material options for a new pedestrian bridge located in the ‘Noorland inner harbour, province of Zeeland, an existing steel bridge had functioned for 35 years but had largely deteriorated due to corrosion.

A Composite Bridge is Favoured by Quantifying Ecological Impact

Ryszard A. Daniel, PhD, Eng., Ministry of Transport, Public Works and Water Management, Division of Infrastructure, Utrecht, The Netherlands. Contact: richard.daniel@rws.nl

Abstract

Carrying traffic loads is not the only objective of bridge designers nowadays. Other demands include constructing a bridge in a sustainable way, which reduces pollution and other harm to the environment. In The Netherlands, the government responds to such demands by promoting technologies and materials that decrease the environmental impact of construction projects.

An assessment of that impact is, however, quite complex for bridge projects. The existing analytical methods, such as life-cycle analysis (LCA), require an extensive data input. Moreover, their results are more reliable for relatively simple products of short life cycles, for example, door or window frames, than for complex construction projects. In construction projects, the life cycles cannot be determined with the same precision and the materials are usually chosen in the very early stage of design. As a result, the data required by the LCA are often incomplete or even disputable. Therefore, there is a demand for ecological analysis methods that enable quick scanning of several material options, require less-extensive data input and are hardly, or not, vulnerable to arbitrariness.

Keywords: FRP structures; eco-analysis, material choice; sustainable material; sustainable bridge; energy input; exergy; emissions; pollution data.

Introduction

This paper answers the above-mentioned demand by presenting a method for ecological material selection for a bridge. It shows a way to quantify the environmental impacts of possible material choices in comparable terms and to assess those choices with respect to their impact. The method was first developed and applied for the quay footbridges in the Noordland inner harbour, province of Zeeland, The Netherlands. Five material options were considered: structural steel, stainless steel, composites (fibre-reinforced polymers, FRPs), aluminium and reinforced concrete. The analysis allowed evaluating these options in terms of three crucial ecological indicators: energy consumption, pollution to air and pollution to water.

The ecological analysis was performed along with the costs and service-life assessment. The computed performances of all the material options considered resulted in an advice to construct a bridge of pultruded FRP profiles (*Fig. 1*). The customer followed that advice. It was the first bridge constructed using this technology in The Netherlands. The bridge was assembled and brought into service in 2001. It has been performing remarkably well since then, validating the computed ecological and other indicators. Its good performance suggests the possible construction of more similar footbridges in that area in future. This paper presents a comparison of those indicators for the material options considered, and discusses these and some selected problems of the ecological analyses.

The applied ecological analysis has been presented on various occasions since the bridge construction.[1–3] Yet, it still evokes much interest because of the importance of environmental engineering in relation to, for example, climatic processes. This paper aims to respond to that interest, giving more details of both the applied ecological analysis and the constructed FRP bridge.

Project Objectives and Scope

The Dutch province of Zeeland is a costal area in the south-western delta of the rivers Rhine, Meuse and Scheldt. High exposure to sea water, wind loads and chloride corrosion form part of the usual design specifications. At the end of 1999, the Regional

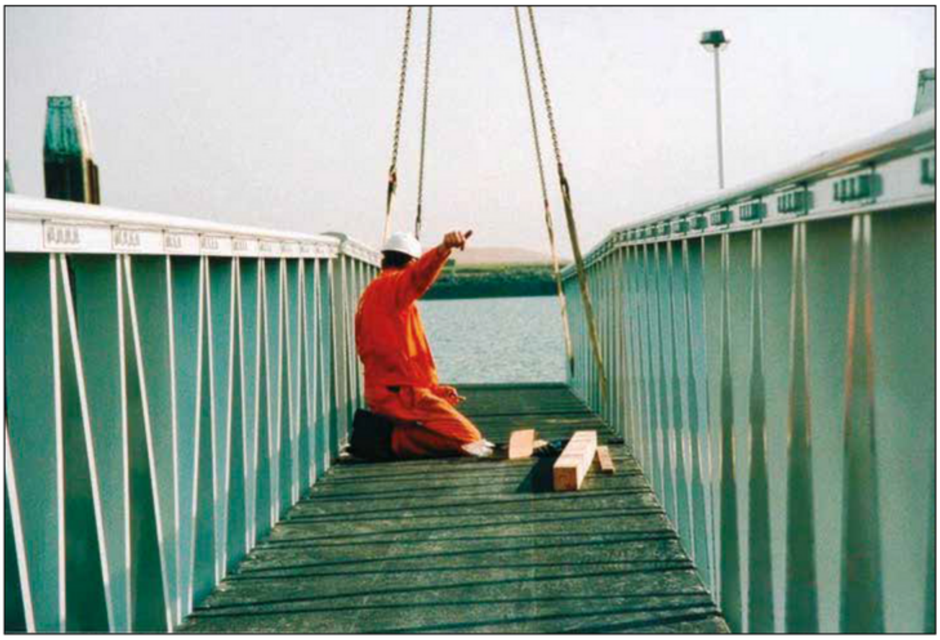


Fig. 1: Installation of the Noordland inner harbour footbridge

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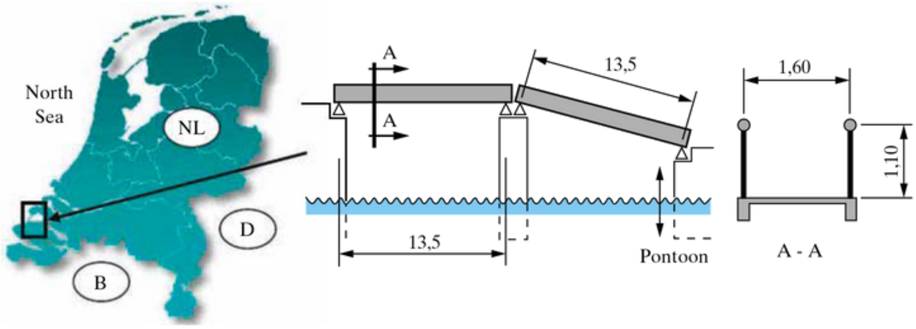

Fig. 2: Bridge location and dimensions (Units: m)

Authority for Public Works and Water Management ordered an investigation on construction materials for a footbridge in the Noordland inner harbour that forms part of the Eastern Scheldt Storm Surge Barrier complex. The bridge provides a double span access to a mooring pontoon (*Fig. 2*). The new bridge was to replace the old steel bridge that was largely deteriorated by corrosion after only 35 years of service. This was not surprising, considering the extreme conditions at that location.

The service load of the bridge is 400 kN/m^2. Other loads are wind, snow, glitter ice, and so on. There is no navigation under the bridge. The support level to pontoon varies because of the tides. The allowable span deflection is limited to 1/250. The customer was interested in comparing the performances of the first four bridge materials from the following list:

- structural steel (with coating);
- stainless steel;
- synthetic material (composite);
- aluminium;
- concrete.

The fifth material was investigated later for the sake of completeness. The weight of a concrete bridge made it unfit for a pontoon support. Timber was also not an interesting option because of its maintenance requirements, combustibility and short service life at this particular location. Nonetheless, it certainly can be considered—also with respect to the environment—in other bridge projects. In this paper, timber is not included, because the considerations that determine its environmental performances are of a different nature. An important criterion is, for example, sustainable forest management.[4] It is difficult to quantify such criteria in a manner that allows for a comparison with other materials.

The performances of each option had to be quantified in terms of the following four criteria: construction costs, maintenance costs, service life and environmental impact. Aesthetics was not a prior concern at this desolate location. Maintenance and service life appeared to show a strong correlation. It was, therefore, agreed to impose a uniform service life of 50 years on all material options. This period reflects the current design views in The Netherlands. In this way, the number of assessment criteria was reduced to three, which simplified the analysis.

Construction and maintenance costs are quite common criteria in engineering; therefore, only the final results are presented. To quantify the environmental impact, however, an investigation method had to be set up first. As already discussed, the existing methods like the LCA[5] were not very helpful. The footbridge appeared to be too complex and too vaguely determined at this stage. Making detailed bridge designs and life-cycle inventories for all material options was, obviously, not the intention. Therefore, a simplified, but workable, two-way evaluation was chosen:

- energy consumption analysis—taking also account of the energy "stored" in materials and products (the so-called "exergy" method[6]);
- analysis of loads (pollutions) to water and air as a result of material winning, processing, fabrication of the final product and its maintenance.

In current views, the first approach can be seen as a measure of not only energy consumption as such (i.e. decrease of global energy resources) but also the processes resulting from fossil fuel combustion, like the greenhouse effect, rise in ocean level, global climatic changes, and so on. The second approach (loads to air and water apart) produced global pollution data of the bridge options under consideration. Loads to soil appeared to be insignificant, but they can be analysed in the same way, whenever relevant.

Conceptual Designs

As the materials in question represented in fact five groups of materials, the material grades had to be chosen. In accordance with the existing practice, the following grades were selected:

- structural steel: S235J0 or S355J0, according to the European norm EN 10025. An arc-sprayed aluminium coating was considered as an alternative to the conventional paint system.
- stainless steel: X2CrNi18-11 or X2CrNiMo18-14-3 according to the European norms (AISI 304L or 316L according to the US standards).
- composite: fibreglass-reinforced polyester resin (FGRP) in pultruded sections.
- aluminium: AlMgSi1,0 F31 according to the DIN 1748 code (or 6061 and 6063 alloys according to the ASTM B221).
- concrete: B35 according to the European norm EN 1992-1, 150 kg of reinforcement per 1 m^3; 100 kg of other steel accessories (e.g. handrails) per 1 m^3.

The next step was to complete five rough conceptual bridge designs, one in each optional material. It soon became clear that each option required a different form, system, manufacturing approach, and so on. In structural steel and concrete, for example, conventional girders with separate handrails were an evident choice, whereas in the other, more expensive materials the handrails were integrated in truss or truss-like girders. Major differences appeared also in section shapes, deck systems, and so on. In *Fig. 3*, one span of the bridge in each of the five materials is shown. The structural analysis was very brief in all cases. Nevertheless, it is fair to say that the bridge spans shown in *Fig. 3* are representative for the considered materials, and comparable with each other in terms of strength and durability.

The material mass estimations are based on a brief analysis and data from similar projects. These masses form the data for estimating both total costs and environmental impact. Remarkably large mass differences are seen between the material options. This requires a few comments. The mass of structural steel span would have been lower (2200–2500 kg) if truss girders

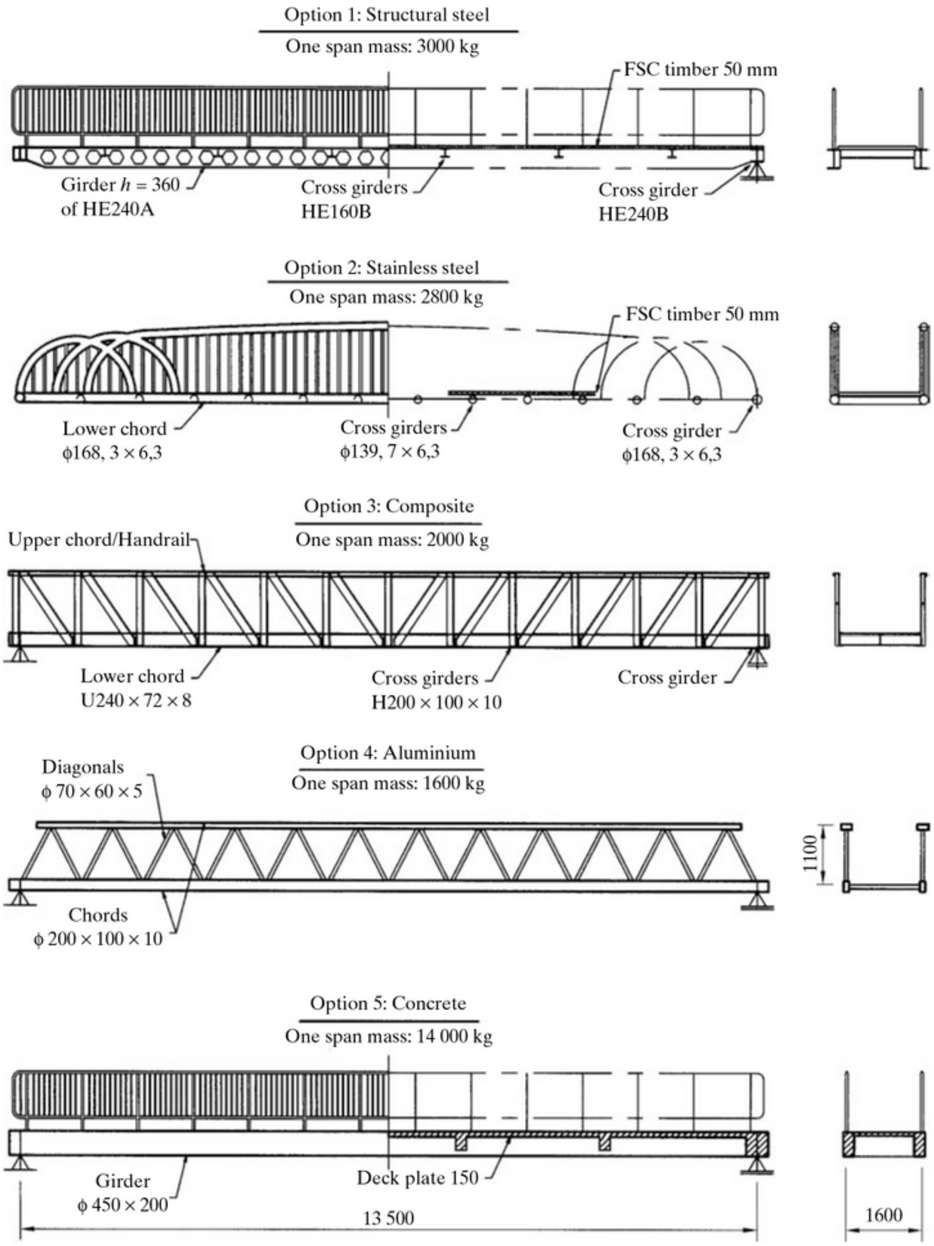

Fig. 3: Bridge span in five material options (length units: mm)

integrated with handrails were chosen instead of beams. This has deliberately not been done to justify neglecting the impact of steel coating. In any case, however, the composite and aluminium bridges appear to be the lightest. The concrete bridge is 5–10 times heavier than the other bridges. The dead weight was of minor importance here, as long as it did not cause pontoon overloading. A smaller weight is, however, desirable in large bridges. It allows for higher traffic loads, lighter foundations, pillars, transport and assembly equipment.

Global Assessment

The bridge conceptual designs were employed to collect more data for the evaluation—not only the total material masses. The drawings in the form of outlines prompted specific questions and enabled collection of relevant data on the market. The desired data covered, in general, the following subjects:

- quantities and unit prices of the materials involved;
- available manufacturing technologies, their costs, conditions, quality assurances and risks;
- transport and assembly requirements, like access, time, heavy equipment, specific provisions;
- inspection and maintenance frequencies during the service life;
- environmental impact of all processes involved.

The accuracy of these data was not always high because of the preliminary nature of bridge design. In some cases, rough estimations had to be made. The concerned specialists agreed, nonetheless, that a sufficient, well balanced base was provided to evaluate the bridge options. The concise results of this evaluation are shown in *Table 1*. The general conclusions are as follows:

- In terms of construction costs, the structural steel and the concrete bridges are favourable. The stainless steel bridge is too expensive; the composite and aluminium bridges score in the middle.
- In terms of maintenance costs, the scores are opposite. The stainless steel bridge is the cheapest, followed by the concrete bridge. The structural steel bridge (conventionally painted) is the most expensive. The scores of the composite and aluminium bridges lie in between.
- Adding construction and maintenance costs (whether or not capitalized) puts the concrete bridge in the first place and the structural steel bridge in the second. The composite bridge takes a good third place, closely followed by aluminium. The stainless steel bridge is evidently the most expensive.
- Analysis of the energy consumption makes the composite bridge a winner. Every other option results in energy consumption that is more than two times as high. Energy consumption is seen as an important indicator of the contribution to the global warming effect.
- The composite bridge is also the best in terms of the resulting water and air pollution levels. The structural steel bridge is the second, concrete bridge is the third and aluminium bridge is the fourth.

The customer was advised as follows: if construction cost was the primary concern, the choice of a structural steel bridge was the best. But if a little extra cost was acceptable in the interest of the environment, the composite bridge of pultruded profiles was the best choice. An additional argument in support of the composite bridge was the innovative character of such a project. It was to be the first composite bridge of pultruded profiles in The Netherlands. The customer was indeed in a position, and willing, to choose the second, pro-environmental option. The composite bridge was constructed in October 2001. It has been closely monitored since then, confirming the results of the analysis.

Bridge material	Criterion			
	Construction costs (EUR)	**Maintenance costs (EUR)**	**Environment: Energy consumption (MJ)**	**Environment: Critical volume of polluted air and water**
Structural steel	Painted: 40 000 Aluminium coated: 50 000	Painted: 30 000 Aluminium coated: 6 000	"Exergy" method: 294 000	Water: 697,4 m^3 Air: 7,09 × 10^6 m^3
Stainless steel	Steel AISI 316L: 110 000 Steel AISI 304L: 96 000	Steel AISI 316L: 6000 AISI 304L more, life cycle shorter	"Exergy" method: 329 600	Not investigated but certainly more pollution than for structural steel
Composite	Pultruded sections of FGRP: 70 000	Rough estimation: 17 000	"Exergy" method: 120 000	Water: 85,8 m^3 Air: 7,92 × 10^6 m^3
Aluminium	Quality AlMgSi1 acc. to DIN 1748: 77 000	Rough estimation: 19 000	"Exergy" method: 268 700	Water: 565,3 m^3 Air: 41,10 × 10^6 m^3
Concrete	Reinforced concrete B35, handrails etc: 30 000	Rough estimation: 10 000	"Exergy" method: 277 200	Water: 341,9 m^3 Air: 31,04 × 10^6 m^3

Table 1: Performances of the five material options for the bridge

Eco-Analysis in Terms of Energy Consumption

Ecological performances of a particular material option cannot be expressed in a single indicator, although it is advisable to keep the number of indicators small. Energy consumption, therefore, does not reveal everything about the ecological performances, but it is an important indicator in this field. It requires no argument today that energy consumption is a global environmental issue in both direct and indirect senses. In the first sense, it decreases the global energy resources which are—for the biggest part—not renewable. In the second sense, it harms the environment in many ways, including its contribution to the emission of CO_2, other "greenhouse gases" and the resulting climatic changes. However, if the latter is seen as the main or only issue of eco-analysis (which is not the author's view), a direct analysis of greenhouse gas emission,[7] will be more appropriate.

The required data is that of the energy use for the processing and manufacturing—from obtaining the raw materials to the final product—of one mass unit of the product in question (in MJ/kg). These data vary because the same materials and products can be obtained using different technologies. As eco-analyses are quite new, there is still much arbitrariness in defining the data. Therefore, it is always advisable to check which processes are covered by the received data. During this study, for example, the following energy consumption rates for structural steel products were found in various sources:

- Source 1 (The Netherlands):[6] 46 MJ/kg;
- Source 2 (The Netherlands):[8] 31 MJ/kg;
- Source 3 (The Netherlands):[9] 18 MJ/kg;
- Source 4 (USA):[10] 6 MJ/kg.

Such differences may be surprising to engineers who are used to approved specifications, standard codes and reliable and well tested data. However, the databases held by various institutes appear to be usable. When high figures, for example, for structural steel are quoted, they usually include energy input for rolling, surface treatment, transport, welding, fabrication, delivery and assembly of the structure. Low figures comprise smaller numbers of those processes. Data on other materials are collected in a similar way so that every database is usually consistent. It is, therefore, recommended to use data from the same source throughout the entire analysis. The lack of standards should temporarily be accepted. In the interest of the environment, one should rather critically apply the existing data than wait until they become better.

The so-called "exergy" method was used to quantify the energy use for the five bridge options. In this method, the total energy consumption is a sum of energy value decreases for the materials in the processes involved. The analysis was limited to basic materials; wooden bridge decks in both structural and stainless steel bridges, stainless steel connectors in aluminium and FRP bridges and so on were ignored. The energy consumption rates per material unit were collected from the first[6] database except for composites (second[8] data base). Although both companies were involved in the official "Eco-indicator" project,[11] no uniform energy database for all materials was available at that time. The review resulted in some adjustments to the data for the purpose of this analysis (*Table 2*). According to recent views, the data for composites might still require a minor increase. These data should, however, not be confused with the much higher energy rates for plastics. Polyester resin usually makes up less than 50% in volume (about 30% in weight) of pultruded profiles. The rest is fibreglass.

In the following example, energy consumption is estimated for a structural steel bridge:

Total mass of two spans: 6000 kg. Assumed: 80% of the primary and 20% of the secondary (recycled) material. Energy consumption on delivery:

$$Ex_0 = 6000 \times [0{,}8 \times (46–7) + 0{,}2 \times (36–7)] = 222\ 000 \text{ MJ} \quad (1)$$

The energy used during maintenance (2 × blast cleaning and painting) was approximated by subtracting the figure for unpainted structure (31 MJ/kg) obtained from another database.[9] To take account of the time delay (about 20 and 35 years), a factor of 0,75 was introduced:

$$\text{E}x_1 = 6000 \times 2 \times 0{,}75 \times (46 - 7 - 31) = 72\ 000 \text{ MJ} \quad (2)$$

This gives the total energy consumption:

$$Ex = Ex_0 + Ex_1 = 222\ 000 + 72\ 000 = 294\ 000 \text{ MJ} \quad (3)$$

The energy consumptions for the other material options were estimated in a similar manner. This gave the energy impact graph for all the five bridge options (*Fig. 4*).

Material	Condition	Energy consumption value (MJ/kg)	Remaining "stored" energy (MJ/kg)
Structural steel (e.g. S235J0)	Primary Secondary	46 36	7 7
Stainless steel (e.g. AISI 316L)	Primary Secondary	69 54	11 11
Composites (FGRP)	Primary Secondary	33 —	9 —
Aluminium (e.g. AlMgSi1)	Primary Secondary	137 45	33 33
Reinforced concrete (B35, handrails)	Primary Secondary	11 —	2 —

Table 2: Energy consumption data for the five material options for the bridge

These results are not as "hard" as, for example, those from structural analyses. One may wonder why the delay factor of 0,75 is used for the maintenance of the structural steel bridge—and if so, then why it is not applied to deck replacements in other bridge options. In this case, the engineers felt that spare decks of "unusual" materials (composite, aluminium) should be secured, that is, delivered together with the bridges. This assumption is, however, arbitrary. Another simplification is that the energy for dismantling after the service life has been neglected. Including it would probably point to the concrete bridge as the most energy-consuming option. Concrete demolition and utilization requires much energy. As mentioned, there are also differences in energy rating between various institutions and countries, especially in regard to composites. German data,[12] often result in higher energy rates and American data[10] in lower energy rates. However, it is undisputable that the composite bridge had the lowest energy consumption.

Loads to the Environment

Energy analyses do not indicate how "clean" or "dirty" the considered options are, that is, they provide no comparison in terms of environmental pollution. The problem with such a comparison is that each material option gives a spectrum of qualitatively different pollutions, which cannot simply be added up. The solution is found by taking account of the so-called "legal thresholds" of the particular pollutants. This was, to the author's best knowledge, the first time that this approach was used in an infrastructure project. The applied method is derived from the so-called critical load method,[10] and is based on the following two data records:

- $B_{m,i}$ (kg/m^3), emitted masses of the pollutants i due to production and processing of 1 m^3 of the material m. Such emissions are usually recorded as loads to air, water and (exceptionally) soil.
- $B_{0,i}$ (kg/m^3), legal thresholds of the pollutants i in 1 m^3 of air, water and (exceptionally) soil.

When these two data records are known along with the total mass G_m and density γ_m of the material m, the total critical volume of polluted air $V^a{}_m$ or water $V^w{}_m$ (m^3) can be computed as follows:

$$V_m = \frac{G_m}{\gamma_m} \times \sum_i \frac{B_{m,i}}{B_{0,i}} \tag{4}$$

Tables 3 and 4 present the emissions $B_{m,i}$ and their legal thresholds $B_{0,i}$ for the four final material options: structural steel, composite, aluminium and concrete. The stainless steel option was not given up at that stage. The data for structural steel and aluminium bridges were collected from Refs. [10, 13]. The emission data for polyester resin were provided by the world market leader in this branch, and combined with the data for glass to give the aggregated emissions for FRP. The data for reinforced concrete (including steel accessories like handrails) were obtained by combining the records for concrete and steel.

Apart from the global results (see *Table 1*), it is interesting to compare the pollutions to water and air qualitatively. For example, for the composite bridge, Eq. (4) and the data in *Tables 3 and 4* give the following critical volumes of polluted air, $V^a{}_{cp}$ and water $V^w{}_{cp}$:

$$\begin{aligned} V^a_{cp} &= \frac{G_{cp}}{\gamma_{cp}} \times \sum_i \frac{B_{cp,i}}{B_{0,i}} = \\ &= \frac{4000}{1700} \times \left(\frac{1{,}03 \times 10^3}{9{,}0 \times 10^{-3}} + \cdots + \frac{1{,}2 \times 10^{-1}}{8{,}0 \times 10^{-7}} \right) \\ &= 2{,}35 \times 3{,}37 \times 10^6 = 7{,}92 \times 10^6 \text{ m}^3 \end{aligned} \tag{5}$$

$$\begin{aligned} V^w_{cp} &= \frac{G_{cp}}{\gamma_{cp}} \times \sum_i \frac{B_{cp,i}}{B_{0,i}} = \\ &= \frac{4000}{1700} \times \left(\frac{2{,}0 \times 10^{-6}}{5{,}0 \times 10^{-5}} + \cdots + \frac{3{,}0 \times 10^{-2}}{1{,}0 \times 10^{-3}} \right) \\ &= 2{,}35 \times 36{,}5 = 85{,}8 \text{ m}^3 \end{aligned} \tag{6}$$

The components of these sums, multiplied by the ratio G_{cp}/γ_{cp}, are represented in diagrams (left) in *Fig. 5*, along with the results for the other material options. The total critical volumes of polluted air and water are compared in pie charts (right) in *Fig. 5*. Also, the composite bridge appears to be more favourable than the other considered options.

The analysis in this paper was deliberately kept simple. The bridge options were approached as single-material cases. Although there usually exists a single dominant material in all bridge projects, it may be advisable to consider other component materials as well. Examples are concrete

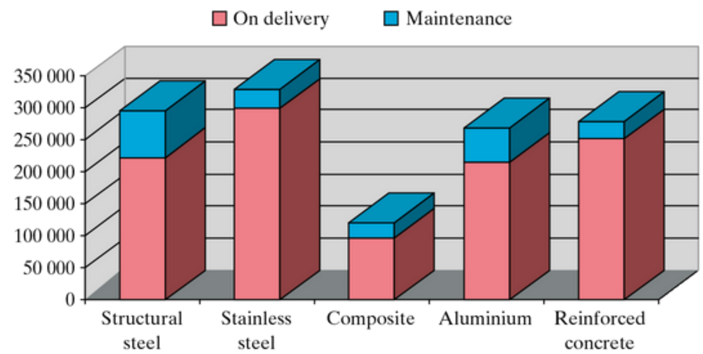

Fig. 4: Energy impact of the bridge for the five material options

Polluter	Structural steel $B_{st,i}$	Composite $B_{cp,i}$	Aluminium $B_{al,i}$	Concrete $B_{cr,i}$	Threshold $B_{0,i}$
CO_2	$2{,}56 \times 10^{+3}$	$1{,}03 \times 10^{+3}$	$2{,}1 \times 10^{+4}$	$4{,}95 \times 10^{+2}$	9×10^{-3}
CO	$9{,}58 \times 10^{+1}$	1,32	$5{,}15 \times 10^{+1}$	3,48	4×10^{-5}
CH_4	5,95	1,21	$5{,}39 \times 10^{+1}$	$9{,}89 \times 10^{-1}$	$6{,}7 \times 10^{-3}$
N_2O	$3{,}7 \times 10^{-2}$	$4{,}8 \times 10^{-3}$	$2{,}94 \times 10^{-1}$	$1{,}51 \times 10^{-2}$	1×10^{-7}
PM Fe/Al-oxi.*	$2{,}2 \times 10^{-1}$	$1{,}05 \times 10^{-1}$	1,65	6×10^{-2}	1×10^{-7}
PM Si/Ca-oxi.*	$4{,}2 \times 10^{-2}$	$5{,}05 \times 10^{-1}$	$2{,}7 \times 10^{-1}$	$4{,}7 \times 10^{-1}$	3×10^{-7}
SO_2	3,28	$2{,}51 \times 10^{-3}$	$1{,}27 \times 10^{+1}$	$2{,}8 \times 10^{-1}$	$1{,}2 \times 10^{-6}$
NO_x	3,08	2,83	$2{,}45 \times 10^{+1}$	1,27	1×10^{-5}
Styrene	—	$1{,}2 \times 10^{-1}$	—	—	8×10^{-7}

*PM = particulate matter (dust), here predominately Fe/Al or Si/Ca oxides.

Table 3: Emissions to air for structural steel, composite, aluminium and reinforced concrete

Polluter	Structural steel $B_{st,i}$	Composite $B_{cp,i}$	Aluminium $B_{al,i}$	Concrete $B_{cr,i}$	Threshold $B_{0,i}$
Aluminium	$3{,}33 \times 10^{-6}$	2×10^{-6}	$3{,}09 \times 10^{-5}$	$1{,}65 \times 10^{-7}$	5×10^{-5}
Ammonia	$4{,}58 \times 10^{-3}$	$1{,}1 \times 10^{-3}$	$4{,}23 \times 10^{-2}$	$2{,}38 \times 10^{-4}$	$2{,}2 \times 10^{-3}$
Cadmium	$4{,}57 \times 10^{-5}$	$2{,}1 \times 10^{-6}$	$4{,}28 \times 10^{-4}$	$2{,}18 \times 10^{-6}$	$3{,}5 \times 10^{-6}$
Copper	$1{,}96 \times 10^{-8}$	$7{,}9 \times 10^{-4}$	$1{,}82 \times 10^{-7}$	$0{,}99 \times 10^{-9}$	2×10^{-4}
Cyanide	$3{,}08 \times 10^{-4}$	$7{,}4 \times 10^{-5}$	$2{,}85 \times 10^{-3}$	$1{,}6 \times 10^{-5}$	1×10^{-4}
Fluoride	$1{,}03 \times 10^{-1}$	2×10^{-4}	$6{,}49 \times 10^{-3}$	$3{,}51 \times 10^{-3}$	$1{,}5 \times 10^{-3}$
Manganese	$6{,}07 \times 10^{-6}$	$3{,}6 \times 10^{-6}$	$5{,}64 \times 10^{-5}$	$3{,}03 \times 10^{-7}$	5×10^{-5}
Mercury	$1{,}57 \times 10^{-4}$	7×10^{-7}	$1{,}45 \times 10^{-3}$	$7{,}53 \times 10^{-6}$	5×10^{-6}
Zinc	3,97	$1{,}4 \times 10^{-3}$	$5{,}44 \times 10^{-2}$	$1{,}35 \times 10^{-1}$	5×10^{-3}
Cobalt	—	3×10^{-2}	—	—	1×10^{-3}

Table 4: Emissions to water for structural steel, composite, aluminium and reinforced concrete

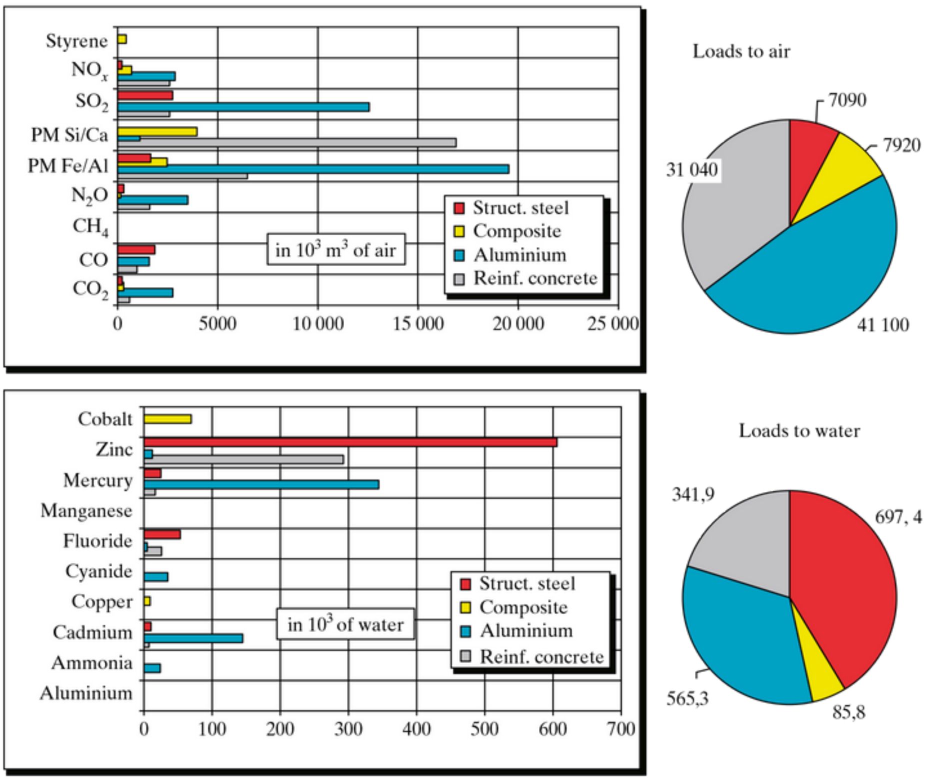

Fig. 5: Polluted air and water as a result of bridge construction with four material options

and steel in cable-stayed bridges or steel and composite in steel bridges with composite decks. The discussed method can be applied in such cases too. Equation (4) then takes the following form:

$$V_{complex} = \sum_j \left(\frac{G_j}{\gamma_j} \times \sum_i \frac{B_{j,i}}{B_{0,i}} \right) \tag{7}$$

where $V_{complex}$ is the critical volume of air or water polluted up to the respective legal threshold (m^3); G_j is the total mass of material j in the considered complex material bridge option (kg); γ_j is the specific mass of material j (kg/m^3); $B_{j,i}$ is the mass of pollutant i emitted by production + processing of 1 m^3 of material j (kg/m^3); $B_{0,i}$ is the respective legal threshold of pollutant i in air or water (kg/m^3).

This may look complex here, but once we have the databases $\boldsymbol{B_{j,i}}$ and $\boldsymbol{B_{0,i}}$ in a PC, this sum presents no problem. In fact, it can easily be generated in a simple spread sheet, along with proper graphs.

Conclusion and Future Outlook

The considered case proves that synthetic composites (FRPs) constitute a very interesting material option for bridges in terms of environmental impact. A composite bridge project

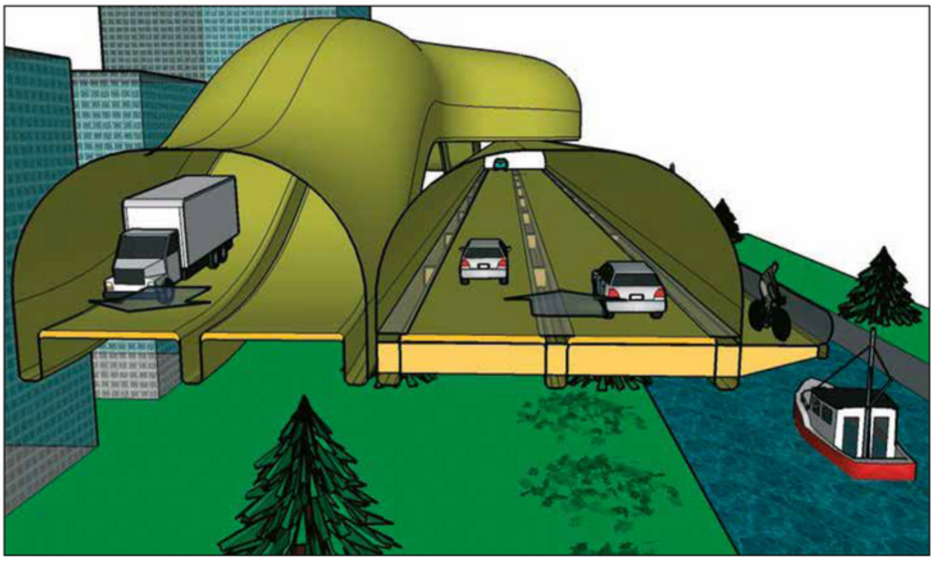

Fig. 6: Closed 'traffic ducts' concept

requires less than half of the energy input that is required for an equivalent project constructed using steel, stainless steel, aluminium or concrete. In terms of loads to air, the composite bridge is the second "cleanest" option after the steel bridge. In terms of loads to water, the composite bridge is the undisputable winner. This makes composites an advantageous material for bridges, despite the slightly higher construction costs.

The main reasons for the good performance of FRP are:

– good mechanical properties, particularly the tensile strength, resulting in small quantities required;
– very good chemical stability, resulting in low maintenance and long service life;
– well-controlled processes, resulting in small error margins and low environment impact.

The presented case should be seen as an indication, but not necessarily as evidence, for other bridge projects. Individual requirements and local conditions often play a decisive role in material selection. In the considered Noordland Bridge, for example, high corrosion resistance was particularly valued because of the surrounding environment (sea water). For road bridges, the relatively low elasticity modulus of composites may limit their applications or require other forms and structural systems, for example, "ribbon bridge",[14] membrane deck,[15] high truss girders or closed traffic ducts.[16] The latter also (*Fig. 6*) offer other advantages for the environment. Yet, as the significance of environmental performances steadily grows, the synthetic composites will likely gain a stronger position in the construction market in the future.

It is also predictable that the methods of environmental analyses will develop fast and that their results will enjoy a growing significance. It is important to develop objective, soundly based and well balanced tools enabling us to comparatively assess the environmental impacts on engineering choices. Only such tools can replace emotions, manipulations and free lobbying, which very often control these choices at present. Such tools should be rooted in official regulations, rather than in individual judgements. This is the main reason why the presented assessment method makes use of "legal thresholds". Even if those thresholds are not perfect yet, they must be endorsed. The idea behind it is the same as for referring to the existing databases: it is better to use them and complain about their shortcomings than wait until they improve.

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