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Life Cycle Sustainability Assessments of an Innovative FRP Composite Footbridge

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Abstract: Sustainable construction and the design of low-carbon structures is a major concern for the UK construction industry. FRP composite materials are seen as a suitable alternative to traditional construction materials due to their high strength and light weight. Network Rail has developed a prototype for a new innovative footbridge made entirely from FRP with the aim of replacing the current steel design for footbridges. This study conducted a life cycle analysis of this novel composite footbridge design to quantify the cost and environmental benefits. An LCA and LCC analysis framework was used to analyse the environmental impacts and cost savings of the bridge throughout its lifespan from raw material extraction to its end of life. From the results of the LCA and LCC, the FRP footbridge sustainability was reviewed and compared to a standard steel footbridge. Due to the uncertainty of the fibre-reinforced plastic (FRP) structure's lifespan, multiple scenarios for longevity at the assets-use stage were studied. The study revealed that the FRP bridge offered substantial economic savings whilst presenting potentially worse environmental impacts, mainly caused by the impact of the production of FRP materials. However, our study also demonstrated the influences of uncertainties related to the glass-fibre-reinforced plastic (GFRP) material design life and end-of-life disposal on the whole life cycle analyses. The results show that if the FRP footbridge surpasses its original estimation for lifespan, the economic savings can be increased and the environmental impacts can be reduced substantially.

Keywords: life cycle assessment; life cycle costing; FRP footbridge; sustainability; composite

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1. Introduction

The adoption of sustainable construction methods has been a growing trend in the construction industry in recent years. Climate change is a major concern; in Europe, the construction industry is estimated to be responsible for 36% of carbon emissions [1], and it is estimated that construction-related waste in the UK accounted for 62% of the total UK waste in 2016 [2]. The UK government put forward the Climate Change Act in 2008, later updated in 2019, as a legally binding target to reduce the UK's greenhouse gas emissions by 2050 to 100% lower than the 1990 baseline [3]. To meet this target, the industry is looking to move away from conventional construction and be accountable for its impact [4–8]. Sustainable development is generally defined as "development which meets the need of the present without compromising the ability of the future generations to meet their own needs" [9,10]. Since this initial definition was put forward, the term has come to encompass three interdependent aspects: social development, economic development and environmental protection [11]. Thus, in the interest of sustainability, it is important for new construction projects to consider these aspects and assess their impact. Life cycle assessments (LCAs) are a commonly used industry tool that is used to evaluate the environmental impacts of a product, system or asset during its whole life cycle. The framework for an LCA is given by ISO 14040 [12]. Similarly, life cycle costing

(LCC) analysis is an economic assessment tool that can be used for a number of purposes including design optimization, building efficiency or financial benefits.

Fibre-reinforced plastics (FRPs) are composite materials consisting of fibre strands providing stiffness and strength in a resin matrix that transfers stresses. The use of FRP materials in construction has grown due to their desirable and structural durability properties [13,14]. Primarily, FRP offers a high strength to low weight ratio making them desirable structural materials. Second to the light weight of FRP materials, their other main advantage is durability; their resistance to environmental issues such as electrochemical corrosion makes them more favourable to steel. These properties are beneficial to bridge structures as an alternative to concrete and steel [15]. The sustainability of FRP composite materials is debatable; for example, the most common method of FRP waste disposal in the UK is landfill, and there is little consideration for deconstruction, re-use and recycling at the design stage. However, it has also been shown that the materials can meet structural needs with a reduced environmental impact [16]. However, the lack of design codes for FRP materials and brittle behaviour of FRP present problems for their anticipated lifespan [17].

In the past, there have been several attempts to produce bridges made entirely from FRP composites, but a lack of design codes and debate over the materials' sustainability have limited the materials' adoption in the industry [18,19]. Network Rail is currently developing a prototype for a new footbridge with a substructure and superstructure constructed entirely from FRP materials to replace the current standard steel footbridges. The new bridge design intends to reduce the impact of current infrastructure issues and offers a more economically sustainable alternative. By selecting a lighter material than standard steel, the bridge can be constructed faster than the standard design and does not have the same construction requirements, such as temporary works and heavy plants. A proposed application of the FRP design is for rural areas to provide a cheaper, safer crossing for live tracks. As this bridge is in the research and development phase, currently there has been no in-depth analysis of its economic and environmental sustainability [20,21].

This study aimed to assess the sustainability of infrastructure constructed from FRP composite materials through the case study of the innovative FRP footbridge being developed by Network Rail as shown in Figure 1. The FRP footbridge asset was assessed as part of a life cycle analysis and compared to a standard steel footbridge design currently in use. The environmental aspects of the footbridges were assessed using the framework of a life cycle assessment (LCA), and the economic aspects were assessed through a life cycle costing (LCC) analysis. The study assessed and compared the two assets' environmental impacts and costs throughout their respective lifespans. Once an LCA and LCC were completed, the sustainability and feasibility of the FRP footbridge were evaluated and compared to the standard steel footbridge. In order to meet these aims, the critical tasks included: (i) collecting necessary asset information, material quantities and construction processes; (ii) collecting environmental data for raw material production processes and material extraction; (iii) determining the maintenance strategies and categories of repair for each asset; (iv) determining the options for the end-of-life processes for each asset; (v) calculating the assets' environmental impacts and economic costings; and (vi) reviewing the sustainability and feasibility of the FRP footbridge and making recommendations.

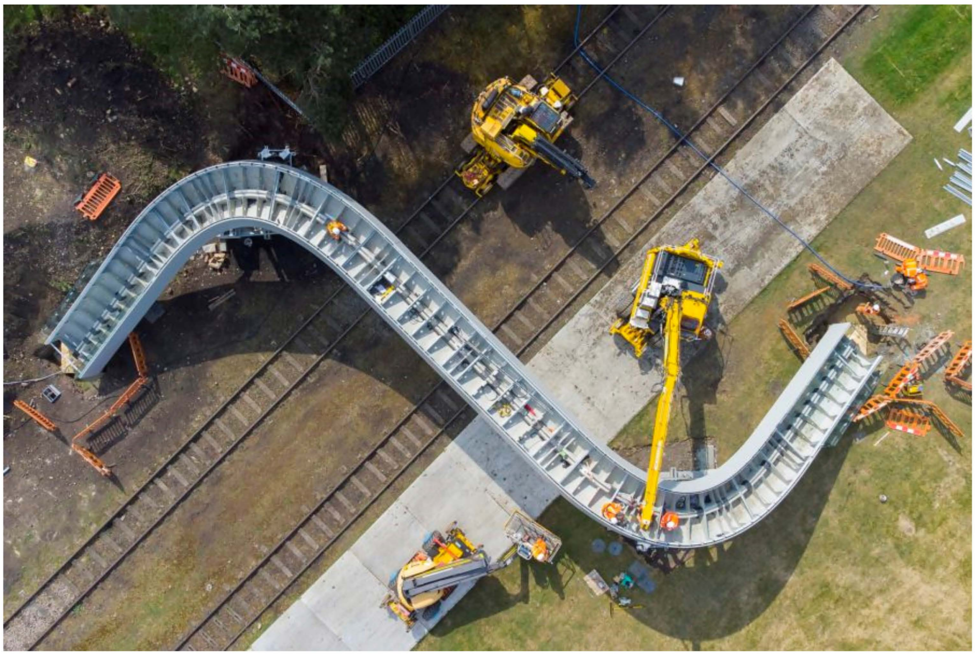

Figure 1. An innovative composite footbridge. Courtesy: Network Rail.

2. Literature Review

2.1. FRP Composites for Civil Engineering Applications

Research undertaken by Daniel [22] used an ecological material analysis to compare the environmental impact of a new pedestrian bridge in the Netherlands. Interestingly, Daniel [22] rejected the LCA model framework for environmental impact assessment on the grounds that not enough input data are known at the early design stages. Instead, the author focused on the environmental impact of the materials considered, the embodied energies and the air and water pollution that results from material extraction. Daniel's research concluded that a composite material would be the most ecological option. Further research undertaken in [23] focusing on the application to road bridges suggested that composite bridge projects require half of the energy input of conventional materials. It was noted that savings are highly dependent on the project's individual requirements and local conditions. Both studies focused on wholly FRP composite structures and their environmental impact; however, as they did not follow an LCA model, they failed to recognise the end-of-life stage of FRP assets. Daniel [23] highlighted the uncertainties in performing speculative LCA analysis and the importance of accurate and extensive input data.

A similar study undertaken by Zhang, Amaduddin and Canning [24] and later Mara et al. [25] aimed to examine the sustainability of FRP structural solutions in comparison with traditional steel and concrete bridge designs. The paper focused on the application of FRP materials to highway bridges considering the total replacement of an entire bridge and the replacement of the concrete deck. Mara et al. [25] used LCC analysis in addition to an LCA to conclude that the use of FRP bridge decks provided reduced costs and environmental impacts; however, they also noted uncertainty in the values of embodied material carbon emissions. The authors' findings also suggest that substantial cost savings of FRP are achieved through bridge refurbishment over the complete FRP deck replacement. Even though both studies [24,25] analysed the project for the whole life, they only considered the transport costs at the end of life and not the actual deconstruction/waste disposal impacts.

Research undertaken by Zhang [17] critically evaluated the LCA framework in the context of FRP construction materials and previous studies conducted by Daniel [22] and Zhang et al. [24]. Zhang [17] warned caution must be taken in generalising findings and commented that LCA analysis studies tend to be case-specific without a standard result presentation, and hence, it is difficult to compare findings. Additionally, Zhang [17] remarked the recycling of FRP composites is not widely considered, and due to the durability properties of FRP composites, they are difficult to sustainably dispose of.

Żyjewski et al. [26] wrote a sustainability review with an emphasis on FRP solutions in bridge structures. The report compared the advantages of FRP with traditional materials using case studies for bridge replacement and renovation. Additionally, the report briefly presented an FRP footbridge prototype being developed by the Gdansk University of Technology; interestingly, the paper suggested a 60% reclamation of materials at the end-of-life stage. However, the research presented in this paper was not extensive, and its generalised findings fit with the existing general trend of FRPs' sustainable potential.

A recent, more comprehensive study on the application of FRP materials in bridge structures internationally was undertaken by Ali et al. [18]. The report studied the developments of FRP material usage in bridge structures and reviewed the suitability of the structures. As with previous research, the advantages of FRP materials for structural purposes are clear, and their adoption in several aspects of the industry is growing. The authors identified that, in terms of feasibility, FRPs have higher production costs than steel and concrete but lower repair costs. However, Ali et al. [18] also underscored the future challenges of FRP bridges, chiefly, the lack of design codes for FRP and the lack of comprehensive studies on the long-term performance of FRP materials. The authors acknowledged that these challenges are holding back the capabilities of FRP structural applications. However, one aspect that was critically overlooked by the study was the end-of-life stage of FRP structures, which was too easily dismissed by the study.

An early life cycle feasibility study of FRP bridges conducted by Ehlen [27] and later Nystrom et al. [28] noted the uncertainty in the cost-effectiveness of the material; both studies concluded that FRP bridges would only be cost-effective in specific scenarios. A study by Nystrom et al. [28] went further and looked at future financial viability, concluding that the use of FRP technology in bridges would be limited to bridge deck construction and repair due to the material's high costs. The result shows that short-span bridges (a span less than 10 m) are financially unviable.

2.2. Life Cycle Assessments

There have been many critical review papers published on the use of life cycle analysis in the construction industry. Singh et al. [29] reviewed the applications of LCA in building construction and attempted to address the reasons for fragmentation in the LCA reports previously published. The literature built on research previously conducted by Kohler and Moffatt [30] identified problems related to LCA methodologies. Problems raised included issues with assessing site-specific local impacts, differing model complexities, the uncertainty of long-term models and, in relation to buildings, the indoor environment design. To overcome these problems, the authors suggested the development of methods and databases as well as decision support tools.

A review conducted by Buyle et al. [31] gave an overview of LCA analysis in the construction industry outlining the standards and frameworks in place at the time. The review found the main limitations of the tool for analysis to be the difficulty of comparison between studies, the estimation of the buildings' service life and uncertainties in environmental databases. Additionally, the report noted that a statistical approach to the lifespan of a building would improve the reliability of future LCA studies and that, even with its limitations, LCA is a powerful scientific tool for assessing sustainability in construction. A similar study undertaken by Abd Rashid and Yusoff [32] found similar results regarding the need for accuracy in data inputs.

A critical review of LCA frameworks undertaken by Dossche et al. [33] focused on the problem of the lack of specificity in LCA procedures. The report criticised the open interpretation of the ISO 14044 standard and the lack of guidance specific to the calculation of environmental impacts leading to difficulties in LCA comparison. Another interesting issue with LCA analysis raised is the incorrect interpretation of analysis due to the lack of clear and transparent research information. A recent study by Sauer and Calmon [34] aimed to identify the current knowledge gaps in LCA analysis. The lack of standardisation was found to be the main cause of knowledge gaps. They argued, after a systematic review of literature, that LCA is a simplified version of reality that is filled with uncertainties.

Regarding LCC analysis, a study undertaken by Durairaj [35] evaluated the approaches to the LCC analysis methodology regarding any product. Upon reviewing existing life cycle cost models, the author concluded that, while it is not feasible to develop a unique LCC analysis model, it is, however, beneficial to merge relevant features of existing models for a more descriptive LCC. However, most of the methods reviewed in the paper lacked application to construction. In a review of published LCC case studies, research undertaken by Korpi and Ala-Risku [36] found that the majority of LCC applications were not accurate and lacked credibility. The research detailed that many of the case studies did not cover the whole life cycle, lacked detail in cost estimations and did not use sensitivity analysis to determine life cycle costs. The research recommended a multi-case study approach for specific contexts and scenarios. Additionally, the authors noted the disparities in life cycle phase coverage, with only 26% of reviewed studies assessing the retirement and disposal (end-of-life) stage. Islam et al. [37] put forward a building-orientated LCA and LCC comprehensive review that discussed the issues related to the two methods of life cycle analysis. The authors concluded that the two analysis tools depended on the studies' assumptions and system boundaries. It was noted that LCC analysis was sensitive to the changes of the discount rate as it affected the assumptions for anticipated costs in the use and end-of-life stages. The paper recommended that it is important to make correct assumptions and be careful in setting system boundaries when it comes to a robust model outcome.

The pitfalls of the previous studies on LCA and LCC methods and their relevancy to this study were expressed by a framework study conducted by Ho [38]. This study is highly relevant to this report as the author primarily focused on the life cycle management and LCC of footbridges. The report was critical of the lack of frameworks for small/medium-scale projects, as in the case of footbridges, due to the growing number of infrastructures at this level, an efficient tool is required. The report proposed a management and costing framework applicable to Hong Kong, where there is a growing trend of building footbridges to link properties. Finally, the author acknowledged that, due to the lack of available literature concerning management, it is difficult to develop a practical management framework for footbridges. A comprehensive guide to LCA by Gibbons and Orr [39] and published by the Institute of Structural Engineers proposed a standardized LCA methodology that conforms to the ISO standards [40] as well as building upon the guidance recommendations from the RICS [41]. Not only does the guide give recommendations for methods but also covers data selection, reviews several material bases and heavily references the ICE database [42]. However, for accuracy, sourcing data directly from designers and suppliers is recommended. Additionally, it should be noted that the framework is created for building developments and lacks the specificity required for a detailed study of a medium-scale footbridge.

3. Materials and Methods

3.1. Data Collection

Additional sources of material LCA and LCC information had to be reviewed as it was unlikely that all of the required information would be made available from primary sources (i.e., Network Rail) and data may be unknown at this point in the footbridge's development phase. The use of LCA and LCC tools and external material databases is common for life cycle analysis, and there is a variety of databases and tools available, in addition to industry guides. As glass-fibre-reinforced plastics (GFRPs) are not a widely used construction material, many existing databases and LCA tools do not provide the necessary information for FRP materials. The source of the material data is crucial for accuracy, and Gibbons and Orr [39] recommended sourcing data from material databases and suppliers located in the same region as the site. Thus, a review of databases and material information sources and their credibility was undertaken to ensure the accuracy and reliability of additional inputs for the LCA analysis, as summarised below in Table 1.

Table 1. Material stock–flow databases.

Resource	Type	Application Region	FRP Material Information	Reference
BRE Impact Database	Material database	UK	Not included	[43]
ECO Impact Calculator	Material LCA tool	EU	Included	[44]
Ecoinvent	Material database	Global	Not included	[45]
EC3	LCA tool	USA	Not included	[46]
GRANTA Edupack	Material database	Global	Included	[47]
Hawkins\Brown Emission Reduction Toolkit (H\BERT)	LCA tool (REVIT-based)	UK	Not included	[48]
The ICE database, version 3.0	Material database	UK	Not included	[42]
OneClick LCA	Planetary LCA tool	UK	Not included	[49]
RICS Whole life carbon assessment for the built environment	LCA guide	UK	Not included	[41]
RSSB Rail Carbon Tool	LCA tool and project database	UK	Not included	[50]

As expected, most material databases and LCA tools did not include FRP composite materials. Two that did include detailed material specification regarding composites were ECO Impact Calculator [44] and GRANTA Edupack [47]. EuCIA [44] is a free online tool that estimates carbon emissions of composite products based upon the FRP's composition and manufacturing process. The tool is specific for composite materials and requires specific information and data regarding the material's "recipe". GRANTA Edupack material database is an extensive database containing information and properties of a wide range of materials. Unlike the other databases, Edupack is a more general database and is not normally used for construction purposes. For FRP materials, the data are less detailed than EuCIA [44] but still include important environmental impact information. For the purpose of this study, where FRP material information was not available, GRANTA Edupack was used as, although the data are less specific for FRP material, EuCIA [44] does not cover the autoclave process, and without the exact composition of the material, a carbon emission factor cannot be established.

For the steel bridge, the RSSB tool [50] and the ICE database [42] were used where information was missing. As steel is a commonly used construction material, carbon impact data are widely available; all the databases in Table 1 contained information for steel. The ICE database was chosen due to recommendations from Gibbons and Orr [39] and data source transparency. Additionally, for steel, the database includes carbon factors for product stage for multiple steel elements and factors for recycling carbon emissions. The RSSB tool contains a database of historic rail LCA assessments, providing a breakdown of the carbon emissions of infrastructure projects. In the cases where inputs could only be calculated from estimations and assumptions due to a lack of available information, the RICS [41] guidance was used.

Unlike the LCA, data for costing information required for the LCC are less widely available from external sources. Some LCC tools do exist and are recommended by RICS [51,52], namely, RICS Building Cost Information Service (BCIS), HAPM Component Life Manuals [53] and the SCQS Whole Life Cost Service [54].

3.2. Method

A methodology combining the general frameworks of an LCA and LCC accordingly was proposed. The framework for an LCA given in ISO 14040 [40] was adapted to incorporate an LCC analysis with the addition of Step 4, costings analysis, and a joint interpretation of results in Step 5. In addition, the LCA methodology was based off of methods given by Gibbons and Orr [39]; this methodology was developed to closely follow the existing industry framework. By adopting existing methods recommended by UK industry, the results should be more comparable; this is an issue highlighted by previous studies. The LCC methodology as illustrated in Figure 2 is based upon the LCC approach presented by Islam et al. [37] and guidelines set out by RICS [41].

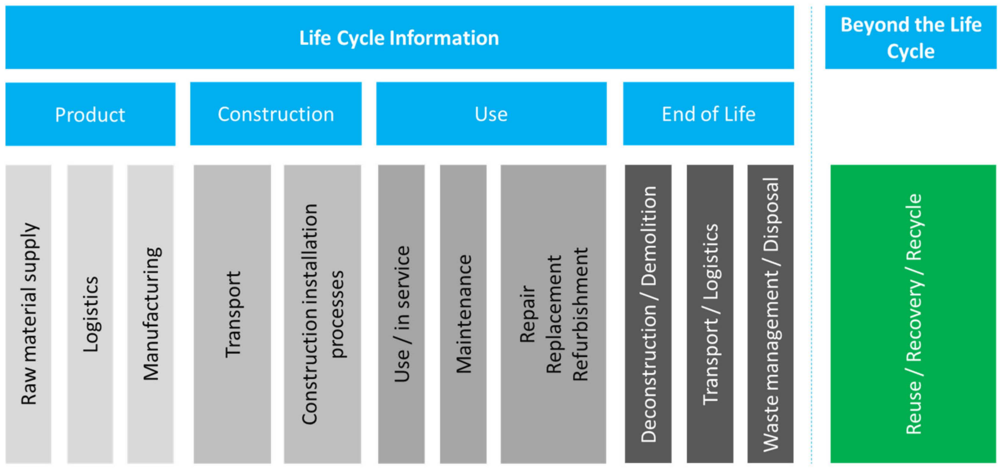

Figure 2. Building life cycle stage framework.

Step 1: Goal definition. The purpose of this stage is to identify the system boundaries and identify the purpose of the assessment and a specification of the object of assessment. The necessary environmental impact categories and project scope.

Step 2: Data collection and inventory analysis. This step consists of two parts: firstly, quantification of all the materials based upon the design drawings for the assets and, secondly, the quantification of the environmental impacts and financial costs. Input information is collected for the asset life cycle stages as outlined in BS EN 15978: 2011 [12]. The breakdown of each stage is detailed in Figure 2. Data and asset information is gathered through continued correspondence with the FRP footbridge project team at Network Rail. Where material data are unavailable, information is sourced from material databases. The embodied carbon factors are collected from manufacturers' specifications. Where information is unavailable, existing material databases are used, as recommended by Takano et al. [55] and Gibbons and Orr [39]. As the FRP footbridge is a newly built prototype, there are no operational data available for the maintenance scenarios during the asset-use stage. The anticipated maintenance is based upon information supplied by the bridge design team [20] and Ciria [19] guidelines for FRP footbridges. Different end-of-life (EoL) options for the FRP footbridge are identified using recommendations from Ciria [19] for a comparative analysis in Step 5. For the standard steel footbridge, anticipated maintenance requirements and end of life are based upon Network Rail recommendations [20].

Step 3: Environmental impact assessment. Using embodied carbon factors and material quantities gathered in Step 2, embodied carbon of the assets is calculated. The calculation is undertaken separately for life cycle stages. Carbon emissions are calculated using the general equation (Equation (1)) [39]:

$$\textit{material quantity}\ (\text{kg}) \times \textit{carbon factor}\ (\text{kgCO}_2\text{e}/\text{kg}) = \textit{embodied carbon}\ (\text{kgCO}_2\text{e}) \quad (1)$$

Step 4: Costing analysis. For the LCC analysis, costing information is obtained for the life cycle stages supplied by the project team and, where information is missing, RICS recommendations [51,52]. For the anticipated costs of the use stage and EoL stage, an estimation and prediction of these costs are gathered through information provided by the project design team [20] and recommendations from Ciria [19]. For future life cycle costs, the costs are adjusted to account for inflation (Equation (2)) [37], and net present value (*NPV*) is determined using Equation (3) [51].

$$FC = PV\ (1 + f)^n \quad (2)$$

$$NPV = FC/(1 + d)^n \quad (3)$$

where FC = future cost; PV = present value; f = inflation rate; n = number of years; NPV = net present value; and d = discount rate.

This step is undertaken for both assets, and discount rate is to be taken as the discount rate stipulated by HM Treasury [56], as recommended for public-sector projects [51]. Treasury discount values are presented below in Table 2.

Table 2. Treasury discount rate (STPR) values [56].

Year	0–30	31–75	76–125
STRP (standard)	3.50%	3.00%	2.50%
STRP (reduced rate)	3.00%	2.57%	2.14%

Sensitivity analysis is used to estimate the anticipated maintenance costs using a variable value for inflation rate. A range of 0–4.5% is used for inflation.

Step 5: Life cycle analysis interpretation. Results from the environmental impact assessment (Step 3) are evaluated and discussed as part of the LCA findings. The LCA results from the two assets are compared against each other, and the environmental impact of each is discussed, considering the individual life stages. The LCC is assessed from the costing analysis (Step 4), and the feasibility of the two assets is compared and evaluated. The results from the LCA and LCC are then compared to findings in literature, and the sustainability of the FRP footbridge structure is discussed. The limitations of the study are identified and factored into the study's discussion and conclusion.

4. Case Study

4.1. Scope of Work

For the LCA, this study focused on assessing the CO_2 emissions of each asset. The unit base that was used throughout the project was $kgCO_2e/kg$ of material, or carbon dioxide equivalent emissions. For the LCA and LCC, the study considered the four life cycle stages—product, construction, use and end of life—as detailed in Figure 2 due to the multiple options and scenarios for the future life cycle stages.

4.2. Data Input

At the time of this investigation, in May 2021, the FRP footbridge had been in research and development for the past 12 months, and the first prototype of the bridge was constructed in a rail depot at Long Marston, Warwickshire, in April 2021. The FRP footbridge has a deck that spans approximately 23.2 m (see Figure 1 for images of the bridge). Currently, the bridge has a simplistic design, consisting of two stair towers and a deck, with no inclusion of ramps or lifts. The substructure of the bridge consists of a structural spine made of prepreg GFRP processed by autoclave; this section is custom made and consists of eight main parts. The deck and superstructure of the bridge are similarly constructed from prepreg GFRP, with a flax FRP layer addition. The parapets consist of toughened glass stretching the length of the bridge. The design life of the FRP bridge is 40 years; this estimation was given by the project structural design team [20]. The steel and FRP footbridge data were gathered through a number of sources; due to difficulties obtaining data directly from Network Rail and suppliers, some data and material information were supplemented through material databases. Table 3 summarises the nature of the input data collected for LCA and LCC analysis.

Table 3. Case study's life cycle information sources.

Component	Product Stage	Construction Stage	Usage Stage	End-of-Life Stage
FRP LCA	NR	BA	BA	BA
FRP LCC	NR	NR	NR	BA
Steel LCA	DB	BA	BA	DB
Steel LCC	NR	NR	NR	DB

Key: NR—Network Rail, information/data supplied directly from the bridge project team [20]; DB—database, relevant data taken from historic material/report databases, RSSB [50], Circular Ecology [42]; BA—basic assumptions, used when no reliable data were made available, basic assumptions taken using appropriate recommendations given by either British Standards Institution [40], Ciria [19], Gibbons and Orr [39] or RICS [41,51,52].

4.2.1. Product Stage

The FRP bridge components were produced from KS composites, with a modular design produced offsite reducing onsite activity. The component masses were supplied by a structural engineer working on the project [57]; however, approximately 36% of the structure's masses were not accounted for at the time of writing, and thus estimations based on component proportions were made (these estimations are listed in Appendix A). For the GFRP carbon factors, expressed in $kgCO_2e/kg$ units, values including processing embodied carbon were taken from GRANTA Edupack [47]. However, Edupack only provides a range of values for the materials' carbon data; an average of this range was taken to provide an estimate. For the toughened glass, carbon factors were taken from the ICE database [42]. The production stage data for the standard steel bridge were sourced from a case study of a steel footbridge spanning 19.8 m detailed in the RSSB carbon tool [50]. However, the data are only available in final product-stage $kgCO_2e/kg$ values. A key piece of material information missing from both assets is the foundations, and due to the inability to make an accurate assumption regarding the carbon emissions, the foundations were not accounted for in this study. LCC costing/cashflow data were kindly supplied directly [20]. For the FRP bridge, the costs were also split into recurring and non-recurring costs due to the production of moulds and patterns. No cost breakdown was provided for the steel bridge's components, and an average for the cost from three separate suppliers was taken.

4.2.2. Construction Stage

The analysis of the construction-phase carbon emissions was limited; most existing carbon tools do not cover construction emissions, and without a detailed construction methodology from both bridges, a reliable estimation could not be undertaken. Instead, a basic approach, recommended by the RICS [39,41], was adopted, where the equivalent carbon value due to construction was approximated based upon the construction costs, using the following equation (Equation (4)):

$$EC_{A5} = CAEF\ (PC/100{,}000) \tag{4}$$

where EC_{A5} is the embodied carbon from construction activities, $CAEF$ is construction activities emission factor, and PC is project cost. Note that all costs are in GBP. As stipulated by the RICS [41], factor $CAEF$ was taken as 700 $kgCO_2e$/GBP 100,000 for each asset. Equivalent embodied carbon due to construction wastage could not be estimated as the wastage rates for each construction process were not made available. For the LCC analysis, the costs of both the FRP bridge and the steel bridge were broken down; due to the bridge being in development, some costs were not accounted for as they were not directly comparable. Regarding transport distance, even though for the FRP bridge site at Long Marston the transport distances are considered local (less than 50 km), a national transport distance carbon factor of 0.032 $kgCO_2e/kg$ [39] was used for all transport calculations. Identical transport distances were used as the study's focus was the materials comparison, not the locality of suppliers. As the bridges can be built in multiple locations where distances from suppliers will vary, for a fair comparison, the same transport factors were used. Additionally, it was assumed that the transport mode would be via road. Information regarding the onsite wastage was not available as the FRP bridge construction was ongoing at the time of investigation.

4.2.3. Usage Stage

Due to the uncertainty in the FRP footbridge's design life [19], the methodology was adapted to account for multiple life cycle scenarios. To compare the use stage of the two bridges, over a projected period of 120 years, the FRP bridge was analysed using a number of anticipated life cycle scenarios:

- Scenario (i): 40-year life;
- Scenario (ii): 60-year life;
- Scenario (iii): 80-year life;
- Scenario (iv): 100-year life;
- Scenario (v): 120-year life.

Once the FRP bridge has reached its anticipated lifespan, it will be presumably replaced with a newly constructed identical bridge; this cycle will take place over a period of 120 years to allow comparison with the steel bridge. The anticipated maintenance and repair recommendations were supplied by Network Rail [20] (see Table 4). Due to the monitoring system installed in the FRP bridge, it is expected that the bridge will not need to undergo the same maintenance inspections as standard infrastructure. Pressure washing and steam cleaning processes are proposed for cosmetic cleaning [19,20]. Significant repairs are repairs necessary to the structure, extending its serviceability life, and they are anticipated to involve the replacement of landings/access and damage to the FRP components. It should be noted that the method of repair is highly dependent on the cause of damage, and therefore, the actual cost and carbon emissions due to significant repairs for both bridges may vary. Currently, most existing LCA tools and databases do not cover the use stage, and there is a lack of guidance for the maintenance stages, as noted by De Wolf et al. [58], as current LCA guides are designed for building maintenance requirements. Hence, due to the lack of guidance given regarding the nature of significant repairs, reasonable assumptions were made. It was assumed that the footbridge's access components (the external landing and steps) will be replaced due to wear from usage. For repainting and cosmetic cleaning, without an accurate value for the bridges' surface areas, a reliable analysis cannot be undertaken. Hence the calculations are limited to significant repair and bridge replacement only. For the LCC, the estimated cost of each repair task was provided by Network Rail [20].

Table 4. Footbridges' maintenance strategies.

FRP Composite Footbridge	Steel Footbridge
Cosmetic cleaning, every 25 years	Visual inspection, every year
Significant repairs, every 40 years	Detailed examination, every 6 years
	Structural assessment, every 18 years
	Repainting, every 25 years
	Significant repairs, every 40 years

4.2.4. End-of-Life Stage

Similar to the use stage, different scenarios for the end-of-life (EoL) stage were analysed for the FRP footbridge. GFRP is a highly durable material making it difficult to dispose of sustainably; hence, landfill is the generally accepted route for disposal. However, in recent years, other disposal options have become available [19]. This approach is supported by the guidance given by [39]. The possible EoL options are as follows: (a) landfill, (b) downcycle, (c) combustion recovery and (d) re-use.

Currently, in the UK, the landfill tax rate is GBP 94.14/T for standard waste; however, this value has risen by 196% in the last 10 years [59]. The change in tax rate is due to an increase in the retail price index and government targets to reduce landfill waste. As noted by Ciria [19], the UK government's plan to reduce non-hazardous landfill waste may rapidly increase this tax and possibly ban disposal of materials such as FRP. In the absence of environmental product declaration (EPD) data from the FRP material supplier, recommendations from Gibbons and Orr [39] were used to determine landfill carbon data, using the carbon factor of 0.013 kgCO_2e/kg waste. The downcycle of GFRP involves recycling the material into a fine filler material; however, this process is costly, requiring a large amount of energy. This method is not yet widely practiced, and its financial sustainability is debatable [19]; the decision was taken not to analyse this option due to the lack of available data regarding costs and carbon emissions. Combustion recovery involves the incineration of FRP materials to recover energy; data for energy values and CO_2 emissions were taken from GRANTA Edupack [47]. For the re-use of materials, it can be assumed that carbon emissions of re-using components will be equivalent to the saving of the initial production carbon emissions as recommended by the RICS [41]. For the EoL process of the steel bridge, it was assumed that the majority of the steel will be recycled. Steel has a high rate of recycling in the industry for structural sections and plates with 92% of material being recycled, 7% being re-used and 1% disposed of in landfills [39]. However, the data for the steel bridge are given in kgCO_2e, not masses, and thus the mass of the steel was back-calculated. As the RSSB tool uses the ICE database, the mass of steel components was calculated using the steel carbon factors given in the ICE database [42]. Using the ICE database, the EoL carbon cost was determined using specified recycled steel carbon factors. For the LCC, it was decided that no analysis was to be undertaken for the EoL stage due to the lack of available information regarding EoL options and the unlikelihood of Network Rail allowing the asset to be disposed of via landfill [60].

4.3. Assumptions

For the FRP production stage, due to the lack of material supplier information, it was assumed that 100% of the FRP material is GFRP when, in reality, there is a surface layer of flax FRP. Additionally, it was assumed that the bridge's GFRP material has the same values as the one selected from GRANTA Edupack, polymer code EP-GF50 [47], and that the estimations used for missing FRP component masses are accurate.

For the construction stage, the costs for the FRP bridge were estimations made before the construction of the bridge; therefore, it was assumed the bridge had been constructed as planned and there were no additional costs. It was assumed that the FRP bridge and the steel bridge are of the same size for a balanced comparison; however, the steel bridge's span is 3.4 m shorter (due to physical restraints in actual construction). For calculations of the carbon emissions due to transport, the assumption was made that the mode of transport is an average rigid heavy goods vehicle (HGV) with an average laden load. The method put forward by the RICS [41] assumes emissions are directly related to material mass, but it does not consider the transport of temporary works or heavy plants to site. Additionally, although the FRP bridge is lighter, the modular design means the components are transported to the site partially assembled and would not have the same transport requirements as bulk steel materials. Calculation of carbon emissions due to construction is dependent on construction costs and does not account for the methods and processes used.

The uncertain nature of the use and EoL stages means that the accuracy of the LCA and LCC for this stage is questionable. For both bridges, the maintenance strategies were assumptions; the true maintenance requirements for the bridges would depend on multiple external factors, such as location and usage, and thus are unlikely to follow rigid schedules. For the FRP bridge, the uncertainty in lifespan was accounted for by the analysis of multiple lifespans. There was an assumption in the maintenance stage that the cost of repairs would only change due to inflation and NPV discount savings; however, this model did not account for changes in the maintenance strategy. As mentioned earlier, the nature of significant repairs made on the footbridges was assumed, affecting the accuracy of the results as it may not reflect the reality of actual repairs. The cost of repairs was a fixed assumption, something that, again, is highly unlikely for the future of both case studies.

An additional assumption made was that the production of the FRP components using the specific design will continue for the 120-year period and it will not be phased out by a newer design. The calculations for bridge replacement did not include the impacts due to the deconstruction and disposal of the previous bridge.

A key EoL stage assumption was that the options for disposal will still be available in 120 years' time. As previously mentioned, the option for landfill will most likely be unavailable. The carbon factor used for waste and disposal uses a fixed factor value and does not account for the nature of the material being processed; this is an oversimplification of the actual waste processing impacts. For the FRP options, it was assumed that the entirety of the structure was being disposed of in that method; as shown by Gibbons and Orr [39], for the example of steel, this is unlikely. For the option of re-use, it is highly unlikely the entirety of the bridge is being re-used and there are no additional costs for reconditioning. Finally, there was the critical assumption that the FRP bridge information supplied by Network Rail at the time of investigation would remain the same for the final design of the bridge. In reality, the information used in this study was based off the research and development of the bridge and could deviate slightly once the bridge is completed.

5. Results and Discussion

5.1. Life Cycle Assessment (LCA)

The breakdown of the carbon data due to the materials and construction stage is represented in Figure 3. For the FRP footbridge, the superstructure has the highest proportion (44%) of the total carbon emissions; however, for the steel footbridge, the access components, which include the stairs and landing, have the largest carbon emissions. Comparing the total carbon emissions for the access components, the standard steel bridge has produced 320% more carbon. These differences in carbon emissions are likely due to the difference in design between the two bridges, the FRP bridge's modular design means the superstructure has more built-in components. This result suggests the leaner and lightweight design of the FRP bridge does not counteract the high material carbon emissions of the GFRP material, making steel a lower-carbon option. The carbon emissions due to the construction stage are negligible in comparison to the production stage; still, the steel bridge has emissions 209% greater than the FRP material.

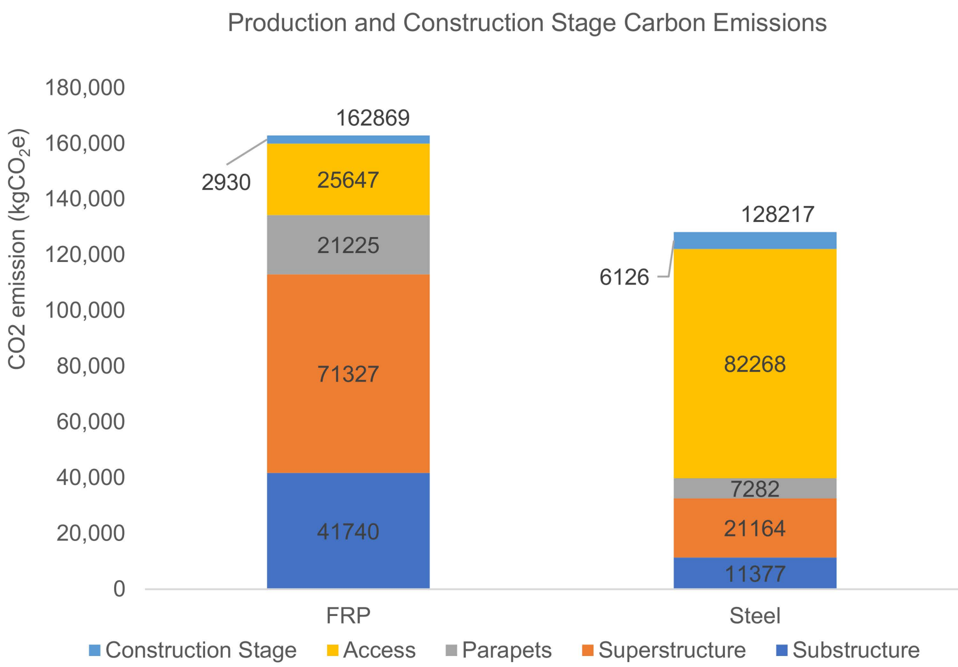

Figure 3. Production stage carbon emissions.

The environmental impact of having a shorter design life is clear in the use stage, as represented in Figure 4. The carbon impact at the start of this stage is taken as zero, and the impact of the construction and production is not held over. Due to the high carbon emissions of the production of the FRP components, only scenario (v) has smaller emissions than steel as the bridge is not reconstructed. Scenario (i), where the bridge is replaced twice, has the highest impact with a 181% increase for steel. Interestingly, scenarios where the bridge is replaced once (ii, iii, iv) have similar carbon emissions, which are comparable to steel. Those of scenario (iv) are higher than those of scenario (iii) due to a bridge renewal activity incurred near the end of the economic service life.

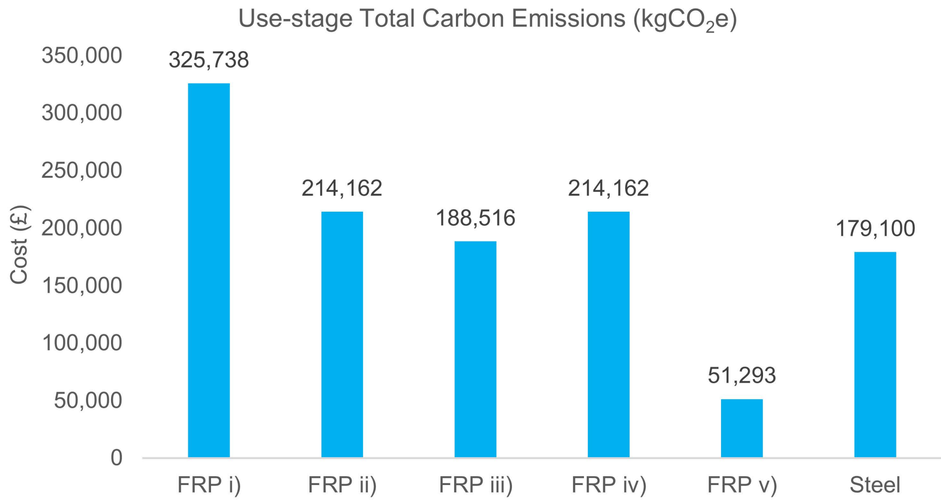

Figure 4. Total use-stage carbon emissions.

Figure 5 presents estimations of carbon emissions of the steel bridge and the possible FRP options for the EoL stage. The most sustainable option is being able to re-use the FRP bridge in its entirety for another construction scenario. It should be noted that although the option for combustion has the highest carbon emissions, 26,054.2 kgCO_2e, this option produces 308,637.8 MJ.

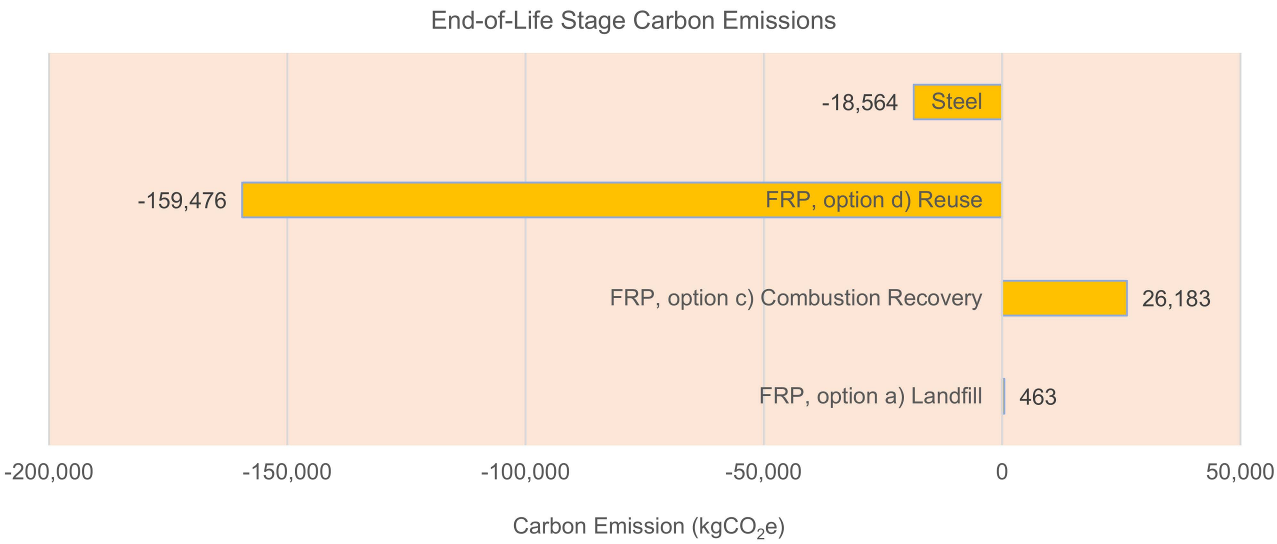

Figure 5. EoL stage carbon emission.

The whole life cycle costs for the two bridge designs are compared in Figure 6. The main difference between the FRP scenarios is the use stage, and therefore FRP (iii) and (iv) were not included due to similarities in this stage to FRP (ii). As expected, the use stage has the largest impact on the whole life cycle carbon cost.

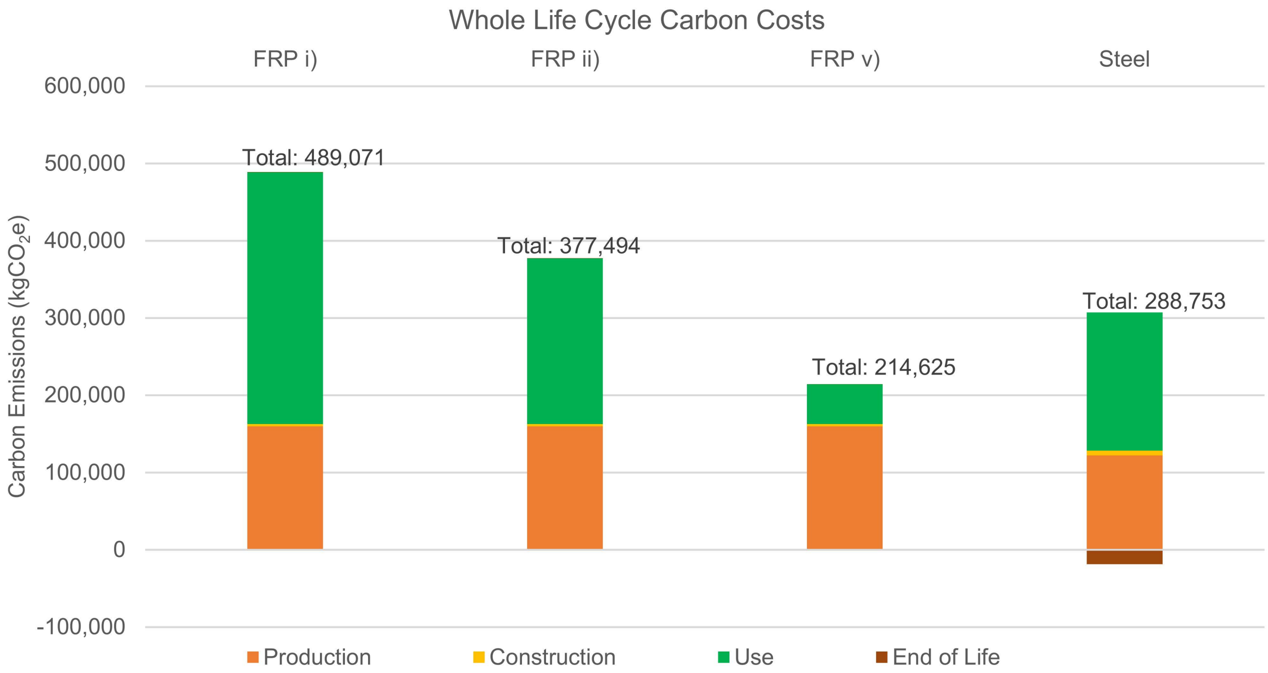

Figure 6. Whole life cycle carbon emissions.

5.2. Life Cycle Costing (LCC)

For the LCC, production and construction costs were combined. As previously mentioned, the FRP bridge has a high preliminary cost due to the development of moulds and patterns, and this cost is reflected in Figure 7 with the additional development costs at the product stage being 199% greater. The cost at the product stage is GBP 193,608 higher for the FRP bridge than that of steel for the product stage; however, significant cost savings are achieved in the FRP bridge at the construction stage. The construction of the FRP bridge costs 31% of the cost of the steel bridge's construction; this FRP cost saving outweighs the material and production costs, as shown by an overall reduction in the combined costs. The saving is less for the initial FRP bridge but still significant: GBP 66,044. However, as noted by Ciria [19], a problem with FRP materials is that they are specialist, and if the bridge needed to be replaced in 40 years' time, the moulds and patterns may need replacing.

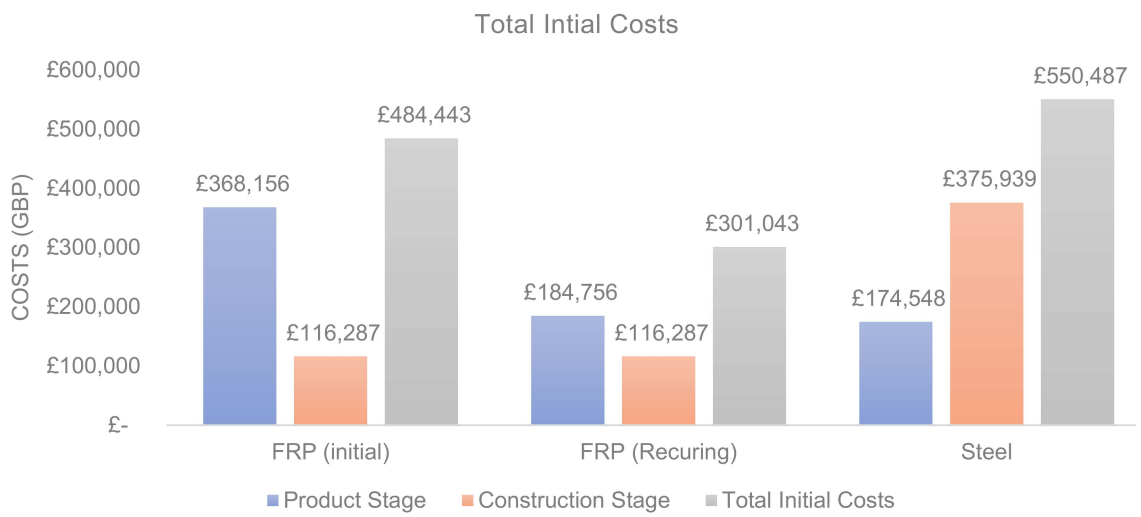

Figure 7. Total initial cost results.

To establish the general trend for the expected maintenance, the cumulative maintenance costs for each scenario at a fixed present cost (no inflation) are compared in Figure 8. As expected, for the 40-year FRP bridge, scenario (i), the total maintenance costs are significantly high due to the costly multiple reconstructions of the bridge. Interestingly, due to the similarities in the construction cost for the FRP bridge and the cost of significant repairs for the steel bridge, scenario (i) and steel have similar cost patterns. As expected, scenario (v) where the bridge lasts the full 120 years has the smallest projected costs.

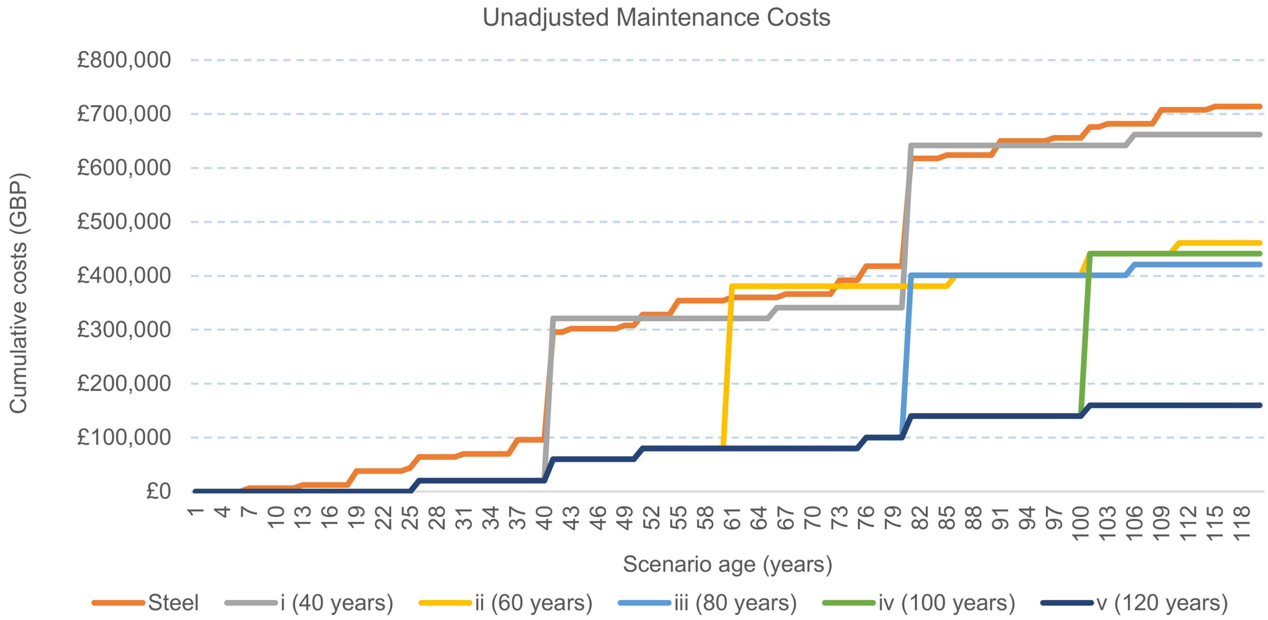

Figure 8. Unadjusted use-stage costs.

Applying sensitivity analysis using a varying value for the rate of inflation and a fixed value for the discount rate, the following total cost projections were established, as shown in Figure 9. Mostly, the results follow the same general trend for each scenario, with the total cost increasing with rising inflation rates due to the low recurring maintenance costs of FRP scenario (v), which remain the lowest and are not greatly affected by inflation. FRP scenario (i) and steel show a similar trend, experiencing a steady rise due to rising inflation; this is due to the gradual increase in maintenance costs. FRP (iv) (replacement after 100 years) is the most sensitive to rising inflation. After 1.5% inflation, the total cost rises rapidly with inflation increase, having a similar cost to steel at 4.5% inflation; this rapid increase is due to the high adjusted cost of bridge replacement late in the given time period. Scenario (iii) does not experience the same rapid price increase and, unlike (iv), retains economic savings when compared to steel.

Based on the use-stage NPV costs with varying inflation rates applied as demonstrated in the results from the previous section, it is clear that the FRP composite material bridge presents significant economic savings for the product, construction and use stages whilst having a potentially worse environmental impact than the standard steel footbridge. The cost savings experienced by the FRP bridge are expected, as reduced costs were the driver of the bridge's development. Uncertainty in the longevity of FRP structures means that the sustainability of the bridge remains questionable. A design life beyond 40 years would provide substantial cost savings and lesser environmental impacts; the results show that if the bridge surpassed or matched the lifespan of the steel bridge, it would be a more sustainable option. The high embodied carbon of GFRP limits the environmental sustainability of the bridge. The reduction of embodied carbon in the FRP bridge's product stage would be a possible way of reducing the overall environmental impact of the whole life cycle of the structure. Similarly, the re-use of moulds and patterns would substantially reduce the costs of the bridge.

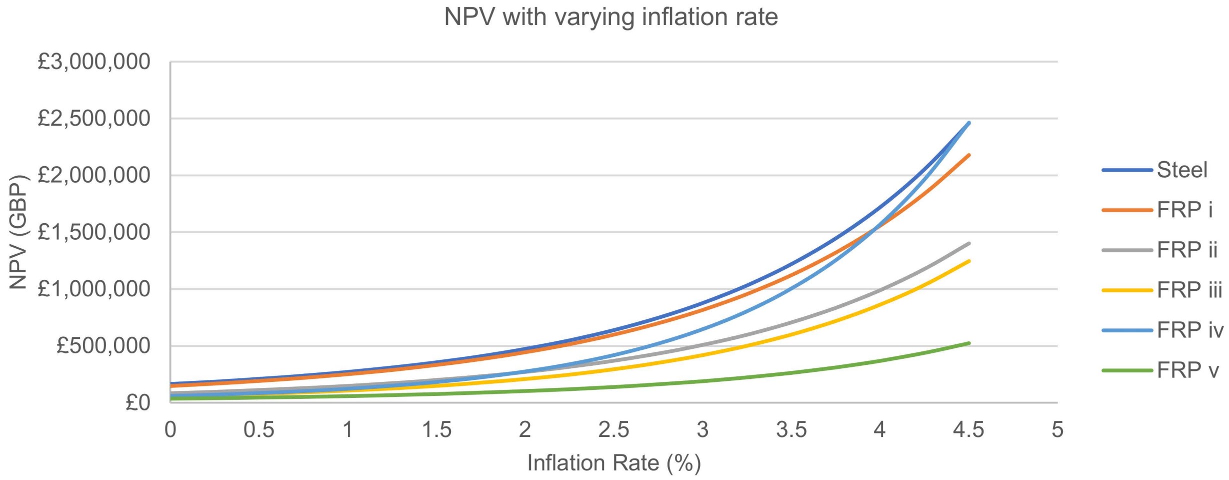

Figure 9. Use-stage NPV costs with varying inflation rates applied.

The inclusion of the EoL stage in this study affected the study's accuracy as a cradle-to-grave, whole-life analysis. The uncertainty of GFRP material disposal limited the analysis and produced a speculative result that lacks the same credibility as the previous stages' results. However, in recent years, the growth of a small industry surrounding the recycling of FRP materials as detailed by Ciria [19] and papers in the literature means a more reliable study of this end of life could be conducted in the future. The method adapted from Gibbons and Orr [39] did present reliable results for the product stages, enabling good comparison. Analysis for the LCA construction stage was weak due to the use of recommendations from the RICS [41]; the methods assumed standard carbon factors that were unrelated to the actual construction method. From the results of the use-stage LCA and LCC analysis, it is clear that the maintenance strategy and lifespan of the bridge are responsible for a significant proportion of the asset impacts. By approaching the analysis speculatively and looking at multiple scenarios of the lifespan, the importance of effective maintenance and repair is clear. This aspect of the study could potentially be improved by viewing the steel bridge through different design life scenarios. For example, this study did not consider the location of the bridge, for a coastal area, as the effects of increased steel degradation due to the high salinity and aggressive atmosphere would be substantial and GFRP is highly resistant.

The input data used in this study could be another source of uncertainty that could be improved upon in future studies, as shown in Table 3; for the LCA, most of the inputs were estimated. Alternative, independent sources of carbon emission data were relied upon. The inclusion of FRP materials in LCA tools and databases is recommended. This study was also limited in assessing environmental sustainability, as only embodied carbon was considered. Even though CO_2 emissions have a significant environmental impact, the impact of other pollutants due to the production of GFRP materials should be considered as in the study by Daniel [22]. Additionally, the study assumed that the bridge can be in service for 120 years' time, of which its purpose may be changed in the future.

6. Conclusions

From the methods used and results of this study, the following conclusions concerning the sustainability of FRP bridge structures were made:

- Compared to a standard steel bridge, the FRP footbridge presented economic savings in the product and construction stages, even with a high initial production cost. This was achieved due to the significantly reduced construction costs. All use-stage scenarios presented economic savings, with the 120-year lifespan scenario being the greatest.

- The environmental sustainability of the FRP bridge is less certain; the only category where the bridge presented savings was in the event of a 120-year lifespan scenario.
- The uncertainty of the EoL disposal of GFRP and the lack of widely available information regarding recycling of the material prevented reliable analysis of this stage.

Overall, the study demonstrates that the sustainability of GFRP materials can be debatable in a short term of service. However, it is noteworthy that ensuring a longer structure lifespan can be substantially environmentally beneficial.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Material quantities of composite footbridge.

Component	Section	Description	Material	Mass/Unit (kg)	Units	Total Mass (kg)
External landing	Straight Stair (1)	Straight stair landing	*GFRP Deck*	85.20	12.00	1022.40
	Curved stairs (1)	Lower curved stair landing	*GFRP Deck*	346.60	2.00	693.20
	Curved stairs (2)	Mid curved stair landing	*GFRP Deck*	367.97	2.00	735.94
	Straight Stair (2)	Upper curved stair landing	*GFRP Deck*	351.09	2.00	702.18
	Deck span	top deck landing	*GFRP Deck*	70.00	10.00	700.00
					Total	**3853.72**
Parapet	Mark L0 through L6	Glass Parapet, straight stair, left	Toughened Glass		14.00	1756.90
	Mark R0 through R6	Glass paraper, straight stair, right	Toughened Glass		14.00	0.00
	Mark OC 20 through 29	Glass parpet, lower curve ouside	Toughened Glass		20.00	1179.80
	Mark IC 9 through 23	glass parapet, lower curve, inside	Toughened Glass		16.00	0.00
	Mark OC 10 through 19	glass parapet, mid curve outside	Toughened Glass		20.00	1252.60
	Mark IC 8 through 15	glass parapet mid curve, inside	Toughened Glass		16.00	0.00

Table A1. *Cont.*

Component	Section	Description	Material	Mass/Unit (kg)	Units	Total Mass (kg)
	Mark OC 0 through 9	glass parapet, upper curve outside	Toughened Glass		20.00	1195.10
	Mark IC 0 through 7	glass parapet, upper curve inside	Toughened Glass		16.00	0.00
	Mark MS 1	glass parapete top deck	Toughened Glass	60.75	24.00	1458.00
					Total	**6842.40**
Superstructure	Ramp 1 and 2	Straight stair deck	GFRP (deck)	1376.00	2.00	2752.00
	Curve 1A and 1B	Lower curved stair deck	GFRP (deck)	924.00	2.00	1848.00
	Curve 2A and 2B	Mid curved stair deck	GFRP (deck)	981.00	2.00	1962.00
	Curve 3A and 3B	Upper curved stair deck	GFRP (deck)	936.00	2.00	1872.00
	Horizontal 1 and 2	Top deck section	GFRP (deck)	1141.90	2.00	2283.80
					Total	**10,717.80**
Substructure	SP-NRB-002-000	stair stair spine	GFRP (spine)	656.00	2.00	1312.00
	SP-NRB-003-000	Lower curved stair spine	GFRP (spine)	302.50	2.00	605.00
	SP-NRB-005-000	Mid curved stair spine	GFRP (spine)	224.00	2.00	448.00
	SP-NRB-004-000	Upper curved stair spine	GFRP (spine)	338.00	2.00	676.00
	SP-NRB-001-000	Straight deck spine	GFRP (spine)	501.25	2.00	1002.50
	SP-NRB-007-000	Spine foot	GFRP (spine)	65.60	2.00	131.20
	SP-NRB-006-000	Spine connector	CFRP	65.60	2.00	131.20
					Total	**4305.90**
Foundations	Rapidfoot cruciform		Galvanised		4	0
					Total	0
					Total Mass	**25,719.82**

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