sustainability

MDPI

Article

Comparative Study of Life-Cycle Environmental and Cost Performance of Aluminium Alloy–Concrete Composite Columns

Shafayat Bin Ali [1,*], George S. Kamaris [2], Michaela Gkantou [2,*] and Yue Huang [3]

[1] Institute of Earthquake Engineering Research, Chittagong University of Engineering & Technology, Chattogram 4349, Bangladesh
[2] School of Civil Engineering and Built Environment, Liverpool John Moores University, Liverpool L3 3AF, UK; gekamaris@gmail.com
[3] Institute for Transport Studies, University of Leeds, 34-40 University Road, Leeds LS2 9JT, UK; y.huang1@leeds.ac.uk
* Correspondence: shafayat@cuet.ac.bd (S.B.A.); m.gkantou@ljmu.ac.uk (M.G.)

Abstract: As is widely known, the construction industry is one of the sectors with a large contribution to global carbon emissions. Despite numerous efforts in the construction industry to develop low-carbon materials, there is a limited number of studies quantifying and presenting the overall environmental impact when these materials are applied in a construction project as structural members. To address this gap, this study focuses on assessing the life-cycle performance of novel structural aluminium alloy–concrete composite columns. In this paper, the environmental impacts and economic aspects of a concrete-filled aluminium alloy tubular (CFAT) column and a concrete-filled double-skin aluminium alloy tubular (CFDSAT) column were assessed using life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) approaches, respectively. The cradle-to-grave system boundary is considered for these analyses to cover the entire life-cycle. A concrete-filled steel tubular (CFST) column is also assessed for reference. All columns are designed to have the same load-carrying capacity and, thus, are compared on a level-playing basis. A comparison is also made of the self-weight of these columns. In particular, the self-weight of the CFST column is reduced by around 17% when the steel tube is replaced by an aluminium alloy tube, and decreased by 47% when the double-skin technique is adopted in CFDSAT columns. The LCA results indicate that the CO_2 emission of CFST and CFAT is almost the same, which is 21% less than the CFDSAT columns due to the use of high aluminium in the latter. The LCCA results show that the total life-cycle cost of CFAT and CFDSAT columns is around 29% and 14% lower, respectively, than that of the CFST column. Finally, a sensitivity analysis was carried out to evaluate the effects of data and assumptions on the life-cycle performance of the examined columns.

Keywords: aluminium alloy; concrete-filled section; life-cycle assessment; CO_2 emission; life-cycle cost; sensitivity analysis

check for updates

Citation: Ali, S.B.; Kamaris, G.S.; Gkantou, M.; Huang, Y. Comparative Study of Life-Cycle Environmental and Cost Performance of Aluminium Alloy–Concrete Composite Columns. *Sustainability* **2024**, *16*, 9252. https://doi.org/10.3390/su16219252

Academic Editors: Maged A. Youssef and Constantin Chalioris

Received: 4 July 2024
Revised: 11 October 2024
Accepted: 22 October 2024
Published: 24 October 2024

1. Introduction

Concrete-filled steel tubular (CFST) structural members are increasingly used in the construction sector due to their advantages over reinforced concrete or bare steel members. The advantages include higher load-bearing capacity with the same cross-sectional area, good ductility, elimination of temporary formwork for concrete casting and high-speed construction [1–4]. The self-weight of CFST members can be reduced by using aluminium instead of steel tubes, forming concrete-filled aluminium alloy tubular (CFAT) members. By leaving empty the inner concrete core, the self-weight of CFAT structural members can be further decreased. This is the case of concrete-filled double-skin aluminium alloy tubular (CFDSAT) structural members that consist of two aluminium alloy hollow tubes, where the space between two tubes is filled with concrete. By using CFAT and CFDSAT members, the dead load of structures can be reduced remarkably, which can also result in lower section sizes of the structural members and thus savings in materials, labour costs and construction time. Hence, despite the low modulus of elasticity of aluminium, aluminium–concrete composite members could enable the utilisation of the exceptional properties of structural aluminium alloys (i.e., corrosion resistance, strength-to-weight ratio, and recyclability) along with the compressive strength of concrete in a synergistic manner. Therefore, these composite members could result in an efficient solution for structures situated in harsh environments, such as bridge piers, oil platforms, wind turbines and other structures in offshore areas, containment buildings of nuclear power plants and bridges and tall buildings in seismic-prone regions.

To achieve a balance between environment and cost, it is important to focus on the sustainable design of structures [5]. For this, it is essential to have information on the long-term environmental impacts and economic aspects of a structural member. Several studies were conducted to assess the environmental performance and cost at different stages of the life-cycle of CFST structural members. Hastak and Halpin [6] assessed the life-cycle benefit–cost of composite members. They developed a life-cycle benefit–cost model and used this model to evaluate the cost of CFST columns. Rossi et al. [7] conducted a life-cycle assessment of steel, steel–concrete, reinforced concrete and wooden columns. The cradle-to-gate system boundary was used to assess different environmental impacts, such as global warming potential, acidification potential and energy consumption of these columns. This study concluded that the steel column provides the lowest environmental impacts compared to the other column options. Hou and Han [8] studied the life-cycle performance of deteriorated CFST columns under lateral impact. A finite-element (FE) model was developed to investigate the structural behaviour of deteriorated CFST columns. Different factors, including chloride corrosion, residual stress, geometric imperfection and loading conditions such as axial load and lateral impact load, were considered in the numerical analysis. It was shown that the current design methods overestimate the residual capacity of the CFST columns to these loading and environmental conditions. Duarte et al. [9] presented a comparative assessment of the sustainability of CFST columns filled with rubberised concrete. The sustainability of these columns was evaluated in terms of cost, thermal performance and embodied energy, and compared with that of conventional CFST and reinforced concrete columns. The results demonstrated that the cost and embodied energy of rubberised CFST are slightly higher (1%) compared to those of CFST column. Zhao et al. [10] conducted a life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) of composite structural members incorporating uncertainty. Three composite columns, including a CFST column, a concrete-filled fibre-reinforced polymer (FRP) tubular (CFFT) column, and a hybrid FRP–concrete–steel double-skin tubular (DSTC) column, were considered in this study. The deterministic LCA results concluded that the CFST column emits 50% and 60% less CO_2 compared with the DSTC and CFFT columns, respectively. The LCCA study indicated that the DSTC column is 15% less costly compared to the other design alternatives.

Research Significance

Research on CFAT and CFDSAT structural members is mainly focused on investigating their structural performance under different loading conditions [11–20]. However, no effort has been devoted so far to study the life-cycle performance of these novel structural members, which can be applied in medium-to-high-rise buildings. To bridge this knowledge gap, this study aims to assess the life-cycle economic and environmental performance of CFAT and CFDSAT columns, using LCA and LCCA methods, and compare them with those of a conventional CFST column. The cradle-to-grave system boundary is considered for these analyses to cover the entire life-cycle. The findings of this study will be beneficial to engineers who are looking for sustainable and cost-effective design solutions. It should also act as a guide for the engineering research community, who is investigating the LCA and LCCA and optimising the performance of different structural components of a construction project.

2. Investigated Composite Columns

In this study, the life-cycle environmental performance and the cost of three different forms of composite columns, i.e., CFST, CFAT and CFDSAT columns, are assessed. All columns are designed to have the same load-carrying capacity and, thus, are compared on a level-playing basis. The design life of these columns is considered 50 years [21]. The columns are designed in a one-storey building configuration. The slab of the building was considered a composite panel consisting of a profiled steel sheet filled with concrete. The dimensions of the panel are 10 m × 20 m, and the composite column is responsible for carrying the loads of this panel. The appropriate dead and live loads for the panel are defined according to Eurocode 1 [22]. The calculated compressive load on a column is evaluated as equal to 1065 kN. All columns are considered to have a height (*L*) equal to 3 m, whilst the cross-sectional shapes of the three columns are shown in Figure 1. Key dimensions are provided in Table 1.

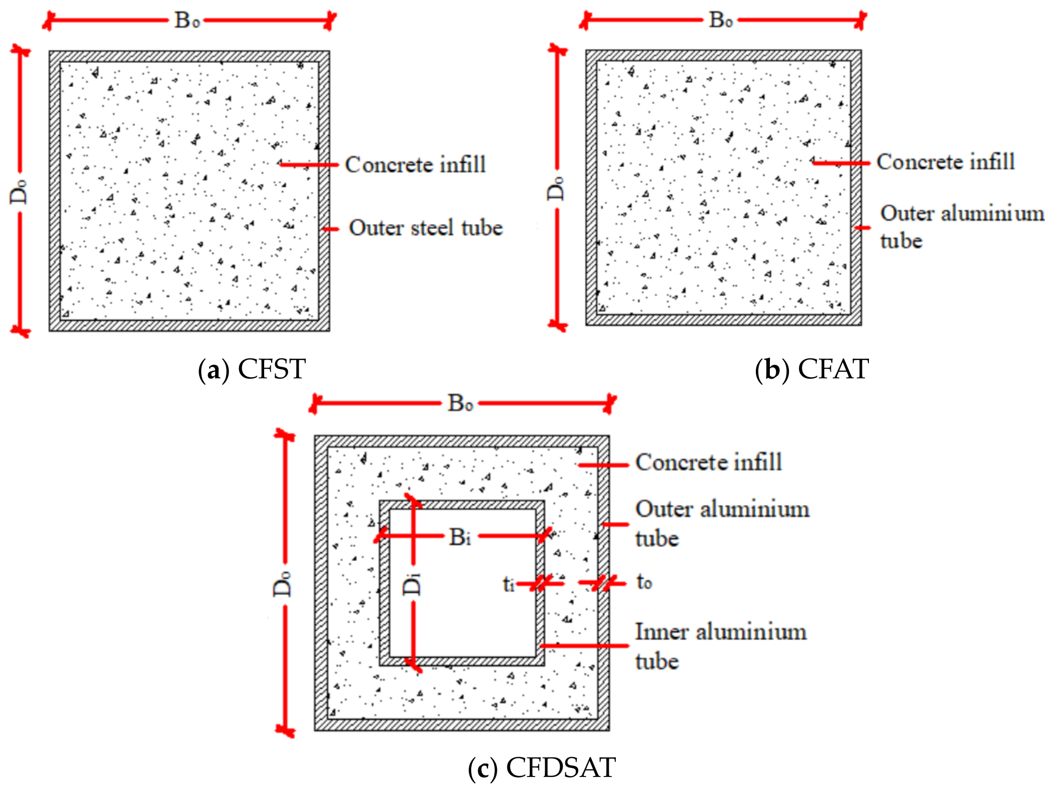

Figure 1. Cross-sections of the three different columns used in this study.

Table 1. Dimensions of the composite columns.

Column	D_o (mm)	B_o (mm)	t_o (mm)	D_i (mm)	B_i (mm)	t_i (mm)	L (mm)
CFST	150	150	4	-	-	-	3000
CFAT	150	150	6.75	-	-	-	3000
CFDSAT	150	150	6.75	100	100	3.61	3000

2.1. Material Properties

In order to design the columns and specify the required cross-sectional dimensions to achieve an axial compressive load of 1065 kN, it is necessary to know the strength properties of the constituent materials. Here, the material properties of the components of the composite columns are taken from the literature, as listed in Table 2. In particular, the material properties of aluminium hollow sections are taken from the coupon test results by Georgantzia et al. [19]. It should be noted that for a fair comparison, the yield stress of the steel tube is selected to be equal to the yield stress of aluminium tube (i.e., 276 MPa). The yield strength of steel is reported by Tao et al. [23]. With regard to the concrete, its nominal cylinder compressive strength is considered equal to 30 MPa, which can be achieved via the concrete mix design as in the study conducted by Georgantzia et al. [19]. In Table 2, E is the modulus of elasticity, $f_{0.1}$ is the 0.1% proof stress, $f_{0.2}$ is the 0.2% proof stress and f_c is the nominal cylinder compressive strength of concrete.

Table 2. Material properties of the components of composite columns.

Column	Component	Reference	Material Properties			
			E (GPa)	$f_{0.1}$ (MPa)	$f_{0.2}$ (MPa)	f_c (MPa)
CFST	Steel tube	[23]	200	276	Not available	-
	Concrete	[19]	32,837	-	-	30
CFAT	Aluminium tube	[19]	69	276	315	-
	Concrete	[19]	32,837	-	-	30
CFDSAT	Outer aluminium tube	[19]	69	276	315	-
	Inner aluminium tube	[19]	69	276	315	-
	Concrete	[19]	32,837	-	-	30

2.2. Structural Design and Dimensions of Composite Columns

Using the material properties of steel and concrete from Table 2, the CFST column is designed based on Eurocode 4 [24]. However, due to the absence of design guidelines for the aluminium alloy–concrete composite members, the design methodologies proposed by Georgantzia et al. [19] and Ali et al. [20] are applied to design the CFAT and CFDSAT columns, respectively. Based on Eurocode 4 [24], the cross-sectional resistance of CFST, CFAT and CFDSAT columns is determined by summing the plastic resistance of the hollow tube/tubes and concrete infill (see Equation (1)).

$$N_{pl} = \begin{cases} A_o f_{0.2,o} + \alpha A_c f_c & \text{for CFST and CFAT columns} \\ A_o f_{0.2,o} + \alpha A_c f_c + A_i f_{0.2,i} & \text{for CFDSAT column} \end{cases} \quad (1)$$

where A_c, A_i, and A_o represent the cross-sectional areas of the concrete infill, inner and outer sections, respectively. $f_{0.2,i}$ and $f_{0.2,o}$ denote the 0.2% proof stresses of the inner and the outer sections, respectively. f_c is the compressive strength of concrete cylinder.

According to Eurocode 4 [24], the ultimate capacity of these composite columns is calculated by multiplying a buckling reduction factor χ with their plastic cross-sectional resistance (see Equation (2)). χ is estimated as a function of the slenderness $\overline{\lambda}$ and a parameter φ, according to Equation (3).

$$N_u = \chi N_{pl} \quad (2)$$

$$\chi = \left[\varphi + \sqrt{\phi^2 - \overline{\lambda}^2}\right]^{-1} \leq 1.0 \quad (3)$$

Column slenderness is calculated by Equation (4).

$$\overline{\lambda} = \sqrt{N_{pl}/N_{cr}} \quad (4)$$

where N_{cr} is the critical buckling load, which is obtained from Equation (5).

$$N_{cr} = \begin{cases} \pi^2 (E_o I_o + k_e E_c I_c)/L_{cr}{}^2 & \text{for CFST and CFAT columns} \\ \pi^2 (E_o I_o + k_e E_c I_c + E_i I_i)/L_{cr}{}^2 & \text{for CFDSAT column} \end{cases} \quad (5)$$

in which E_c, E_i, and E_o indicate the modulus of elasticity and I_c, I_i, and I_o represent the moment of inertia of concrete infill, inner and outer sections, respectively. L_{cr} is the buckling length of the columns and k_e is the concrete factor. The value of k_e is taken as equal to 0.6 [24].

Parameter φ is calculated by Equation (6).

$$\varphi = 0.5\left[1 + \alpha_1\left(\overline{\lambda} - \overline{\lambda_0}\right) + \overline{\lambda}^2\right] \tag{6}$$

where $\overline{\lambda_0}$ and α_1 are the horizontal plateau limit and imperfection parameter, respectively. The values of these parameters suggested by Eurocode 4 [24] for CFST and Eurocode 9 [25], Georgantzia et al. [19] and Ali et al. [20] for aluminium–concrete composite columns are considered in this study.

The composite columns are designed to carry an axial compressive load of 1065 kN, whilst it is expected for all three columns to have the same outer dimensions. To achieve this, an iteration process was used to obtain the cross-sectional dimensions of the columns. During this process, the depth and width of the outer tube of the columns are kept the same, while the thickness of the outer tube is varied to achieve the targeted ultimate capacity. The cross-sectional dimensions of the composite columns obtained from the iteration process are listed in Table 1, where the geometric symbols refer to the notation presented in Figure 1. The calculated ultimate capacity of CFST, CFAT and CFDSAT columns are 1065.9, 1065.5 and 1065.6 kN, respectively. They are considered to fulfil the same function in the life-cycle model (see Section 4).

3. Comparison of Self-Weight of Columns

Initially, a comparison of the self-weight of the composite columns is made to define the lighter design alternatives. For this purpose, the volume of the components of the columns is calculated and then multiplied by their density. Finally, the self-weight of the columns is determined by summing up the self-weight of their components. Table 3 reports the self-weight of the composite columns, along with their density (in kg/m^3), volume (in m^3) and mass (in kg) of their components.

Table 3. Material quantities of the composite columns.

Material	Density (kg/m^3)	CFST		CFAT		CFDSAT	
		Volume (m^3)	Mass (kg)	Volume (m^3)	Mass (kg)	Volume (m^3)	Mass (kg)
Concrete	2400	0.06	145.18	0.06	134.13	0.026	62.13
Steel tube	7850	0.01	55.01	-	-	-	-
Outer aluminium tube	2700	-	-	0.01	31.35	0.012	31.35
Inner aluminium tube	2700	-	-	-	-	0.004	11.26
		Sum (kg)	200.19		165.48		104.75
		Reduction (%)	0%		−17%		−47%

It can be observed that the self-weight of the CFST, CFAT and CFDSAT columns is 200.19, 165.48 and 104.75 kg, respectively. These results indicate that the self-weight of the CFST column is reduced by around 17% when the steel tube is replaced by an aluminium alloy tube, while it has the same outer depth and width for cross-sectional dimensions and resists the same compressive load. Moreover, the self-weight of the CFST column decreases by 47% when the double-skin technique is adopted using aluminium alloy tubes in the CFDSAT column. Compared to the CFAT column, the self-weight of the CFDSAT column is around 36% lower due to the absence of inner concrete. Therefore, it can be concluded that the weight of the CFST column can be reduced significantly by using an aluminium alloy tube instead of steel and further weight reduction is possible when the double-skin technique is adopted. Hence, by using these lighter structural members, the size of the foundation of the structures can be reduced, which can result in savings of construction materials, costs and time.

4. Life-Cycle Model

In this section, a life-cycle model is developed for the three composite columns. The material quantities of each composite column presented in the previous section are used to evaluate the long-term environmental impacts and costs of the composite columns. The goal and scope of this study are defined by specifying the functional unit (axial compressive load of 1065 kN) and system boundary (cradle-to-grave). A deterioration model is used for the columns to define a maintenance schedule during their working life.

4.1. Goal and Scope Definition

The comparison made in this study is between three different composite columns, i.e., CFST, CFAT and CFDSAT. As mentioned earlier, the columns are designed to carry the same axial load of 1065 kN, whilst the height of each column is considered 3 m, which is the typical column height for a residential building. In this study, the cradle-to-grave system boundary is chosen, which covers all aspects of the life span ranging from raw material extrusion to disposal (or recycling process) at the end of life. According to this approach, the life-cycle of the composite columns is split into five main stages, including (i) the production of structural components, (ii) transportation, (iii) column construction, (iv) maintenance and (v) end-of-life stages. The first stage considers the production of the structural components, which includes the extrusion of sand and stone chips and the production of cement, steel and aluminium hollow sections. In the second stage, the transportation of structural components from the production plants to the construction site is taken into account. In the third stage, on-site construction of the composite columns is considered. In the fourth stage, a maintenance plan is taken into account for a certain loss of mechanical performance during the life span of the columns. At the end-of-life stage, demolishment of the product and waste disposal or recycling are considered. Figure 2 presents the schematic framework of the cradle-to-grave system boundary considered in this study.

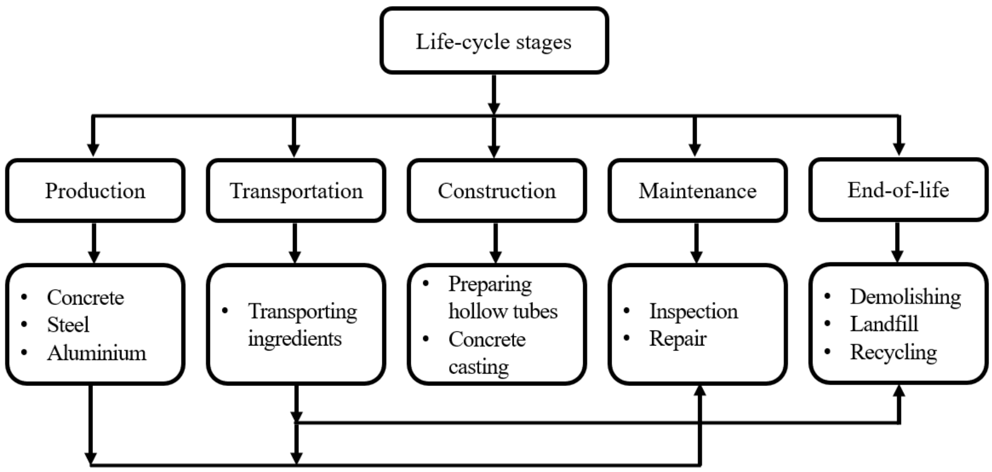

Figure 2. Schematic diagram of the studied life-cycle stages.

4.2. Life-Cycle Stages

This section presents the main assumptions considered for the life-cycle stages. The concrete and hollow metal tubes are purchased from local suppliers and transported to the construction site. The environmental impact and unit price of these structural ingredients are collected from previous studies, reports, literature and contacts with local suppliers, and specified for each of the materials in the following section. During the construction stage, an electric concrete mixer and a vibrating table are used to cast the composite columns. The production, transportation and construction stages (cradle-to-site) are collectively considered the initial stage.

Maintenance work is essential when a structural member loses a certain level of mechanical performance during its lifetime. This study adopts an established deterioration model for the CFST column to develop a maintenance plan. Based on the time-dependent corrosion model suggested by Wang et al. [26], a CFST column can lose 10% performance in around 10 years under axial compression and harsh environment. Zhao et al. [10] concluded that for the CFST column, maintenance is required every 10 years and, each time, 10% of the original materials need to be replaced or repaired. This maintenance plan is applied in this study. As the aluminium alloy has excellent corrosion resistance, no expense related to the maintenance of CFAT and CFDSAT columns is considered in this study. This approach agrees with the same assumption made in the past by Gardner et al. [27]. For the LCA and LCCA studies, it is considered that maintenance work is required to replace or repair a certain percentage of material used in the initial stage and is represented as the maintenance-to-initial ratio. For the CFST column, the baseline maintenance-to-initial ratio is considered 0.1, which means that 10% material of initial stage needs to be replaced or repaired, whereas this ratio is taken as 0 for the CFAT and CDSAT columns. The effect of maintenance stage on the life-cycle environmental performance and economic aspects is evaluated in the sensitivity analysis section by considering different percentages of replacement or repair of original materials in these composite columns.

At the end-of-life stage, it is considered that the structural elements will be demolished and the waste will be disposed. Several waste management options, such as landfill, recycling and incineration are commonly used in the construction sector. In this study, it is assumed that 100% steel and aluminium alloy will be recycled at the end-of-life stage. Concrete can be disposed by landfilling or recycling. Recycled concrete is a good source of aggregates and can be used for new concrete [28]. However, due to quality requirements, the use of these aggregates in high-value applications is limited [29]. Therefore, it is assumed that after demolition, concrete wastes will be transported to the nearest landfill plant [10]. The environmental impact and economic aspects associated with all these stages are determined in terms of CO_2 emission and cost, respectively.

5. Life-Cycle Assessment (LCA)

5.1. LCA Inventory Data

The environmental impact of composite columns is evaluated for their CO_2 emissions during their life-cycle. The unit CO_2 emissions during the production of cement, fine/coarse aggregates, steel and aluminium alloy hollow sections are taken as 0.951 kg CO_2/kg [30], 1.06×10^{-3} kg CO_2/kg [30], 1.910 kg CO_2/kg [31] and 6.70 kg CO_2/kg [32], respectively. It is assumed that the ingredients of concrete, steel and aluminium hollow sections are transported by a medium-sized diesel truck from local suppliers to the construction site. A medium-sized diesel truck usually generates 0.166 kg CO_2 to carry one-tonne material for one kilometre [33]. The driving distances between local suppliers and the construction site are taken from a Google map and presented in Table 4. Carbon emissions in the construction stage are related to the energy consumption of different equipment, such as concrete mixture, compacting equipment, crane, and so on. In this study, the value of CO_2 emission is taken as 0.016 kg for casting 1 kg concrete [34]. According to [10], steel installation time was considered half of the time required for concrete casting. Therefore, it is assumed that half the amount of CO_2 is emitted during steel installation, i.e., 0.008 kg CO_2 per kg of steel, compared to during concrete casting. A similar assumption is made for CFAT and CFDSAT columns' construction. The CO_2 emission for concrete landfilling is taken as 0.007 kg CO_2/kg, according to Cho and Chae [35]. The recycling process of aluminium and steel needs around 95% [36] and 74% [37] less energy, respectively, than the primary production. During the recycling process, 0.390 kg [36] and 0.880 kg [38] CO_2 are emitted for 1 kg aluminium alloy scrap and 1 kg steel scrap, respectively. Here, it is assumed that 100% steel and aluminium will be recycled at the end-of-life stage. Table 4 lists the weights of the components of the three different forms of composite columns along with their environmental impact in terms of CO_2

emission during different stages of the life-cycle. The amount of CO_2 emission for each type of column is calculated by Equation (7).

$$E_{Total} = E_P + E_T + E_C + E_M + E_E \quad (7)$$

where E_{Total} is the total CO_2 emitted during the life-cycle, E_p, E_T, E_c, E_M and E_E are CO_2 generated at production, transportation, construction, maintenance and end-of-life stages, respectively.

Table 4. Life-cycle environmental impact assessment.

Column	Life-Cycle Stage	Consumed Material	Amount	Unit	GWP Coefficient	Unit	Reference	GWP ($kgCO_2$)
CFST	Production	Cement	26.62	kg	0.951	$kgCO_2/kg$	[30]	25.31
		Fine aggregate	38.71	kg	0.001	$kgCO_2/kg$	[30]	0.04
		Coarse aggregate	65.63	kg	0.001	$kgCO_2/kg$	[30]	0.07
		Steel tube	55.01	kg	1.910	$kgCO_2/kg$	[31]	105.07
		Sum						130.50
	Transportation	Materials for concrete (5.7 km)	0.75	t.km	0.166	$kgCO_2/t.km$	[33]	0.12
		Steel tube (32.9 km)	1.81	t.km	0.166	$kgCO_2/t.km$	[33]	0.30
		Sum						0.43
	Construction	Concrete	145.18	kg	0.016	$kgCO_2/kg$	[34]	2.32
		Steel tube	55.01	kg	0.008	$kgCO_2/kg$	[10]	0.44
		Sum						2.76
	Maintenance	(Maintenance-to-initial ratio = 0.1)					[10]	66.84
	End-of-life	Concrete-landfill	145.18	kg	0.007	$kgCO_2/kg$	[35]	1.02
		Steel tube (100% recycled)	55.01	kg	0.880	$kgCO_2/kg$	[31]	48.41
		Sum						49.43
	Total							249.96
CFAT	Production	Cement	24.59	kg	0.951	$kgCO_2/kg$	[30]	23.39
		Fine aggregate	35.77	kg	0.001	$kgCO_2/kg$	[30]	0.04
		Coarse aggregate	60.65	kg	0.001	$kgCO_2/kg$	[30]	0.06
		Aluminium tube	31.33	kg	6.70	$kgCO_2/kg$	[32]	209.9
		Sum						233.39
	Transportation	Materials concrete (5.7 km)	0.69	t.km	0.166	$kgCO_2/t.km$	[33]	0.11
		Aluminium tube (32.9 km)	1.03	t.km	0.166	$kgCO_2/t.km$	[33]	0.17
		Sum						0.29
	Construction	Concrete	134.15	kg	0.016	$kgCO_2/kg$	[34]	2.15
		Aluminium tube	31.33	kg	0.008	$kgCO_2/kg$		0.25
		Sum						2.40
	Maintenance		(Maintenance-to-initial ratio = 0)					0.00
	End-of-life	Concrete-landfill	134.13	kg	0.007	$kgCO_2/kg$	[35]	0.94
		Aluminium tube (100% recycled)	31.33	kg	0.390	$kgCO_2/kg$	[36]	12.22
		Sum						13.16
	Total							249.23
CFDSAT	Production	Cement	11.39	kg	0.951	$kgCO_2/kg$	[30]	10.83
		Fine aggregate	16.57	kg	0.001	$kgCO_2/kg$	[30]	0.02
		Coarse aggregate	28.10	kg	0.001	$kgCO_2/kg$	[30]	0.03
		Aluminium outer tube	31.33	kg	2.68	$kgCO_2/kg$	[32]	209.9
		Aluminium inner tube	11.26	kg	2.68	$kgCO_2/kg$	[32]	75.47
		Sum						296.25
	Transportation	Materials concrete (5.7 km)	0.32	t.km	0.166	$kgCO_2/t.km$	[33]	0.05
		Aluminium tube (32.9 km)	1.40	t.km	0.166	$kgCO_2/t.km$	[33]	0.23
		Sum						0.29
	Construction	Concrete	62.13	kg	0.016	$kgCO_2/kg$	[34]	0.99
		Aluminium tube	42.59	kg	0.008	$kgCO_2/kg$		0.34
		Sum						1.33
	Maintenance	(Maintenance-to-initial ratio = 0)						0.00
	End-of-life	Concrete-landfill	62.13	kg	0.007	$kgCO_2/kg$	[35]	0.43
		Aluminium tube (100% recycled)	42.59	kg	0.390	$kgCO_2/kg$	[36]	16.61
		Sum						17.05
	Total							314.92

5.2. LCA Results and Discussions

Figure 3 presents the CO_2 emissions during the life-cycle of three different composite columns. It can be observed from Table 4 and Figure 3 that the carbon footprint of CFST and CFAT columns is almost the same, which is 21% lower than the CFDSAT columns.

At the initial stage, the CFAT and CFDSAT columns lead to around 43% and 55% more environmental impact than the CFST column; the main reason for this is that the CO_2 emissions during the production of aluminium alloy are much higher compared to steel production. Due to the excellent corrosion resistance of aluminium alloy, no maintenance work is considered for the CFAT and CFDSAT columns, whereas for the CFST column, CO_2 emitted at the maintenance stage accounted for 10% of CO_2 emitted at the initial stage every 10 years. At the end-of-life, the emission of CO_2 of the CFAT and CFDSAT columns is around 73% and 65% lower, respectively, compared to the carbon emission of the CFST column. Therefore, it can be concluded that, overall, the CFST and CFAT columns provide the lowest environmental impact, which is around 249 $kgCO_2$, compared to the CFDSAT composite column, which emits 315 $kgCO_2$.

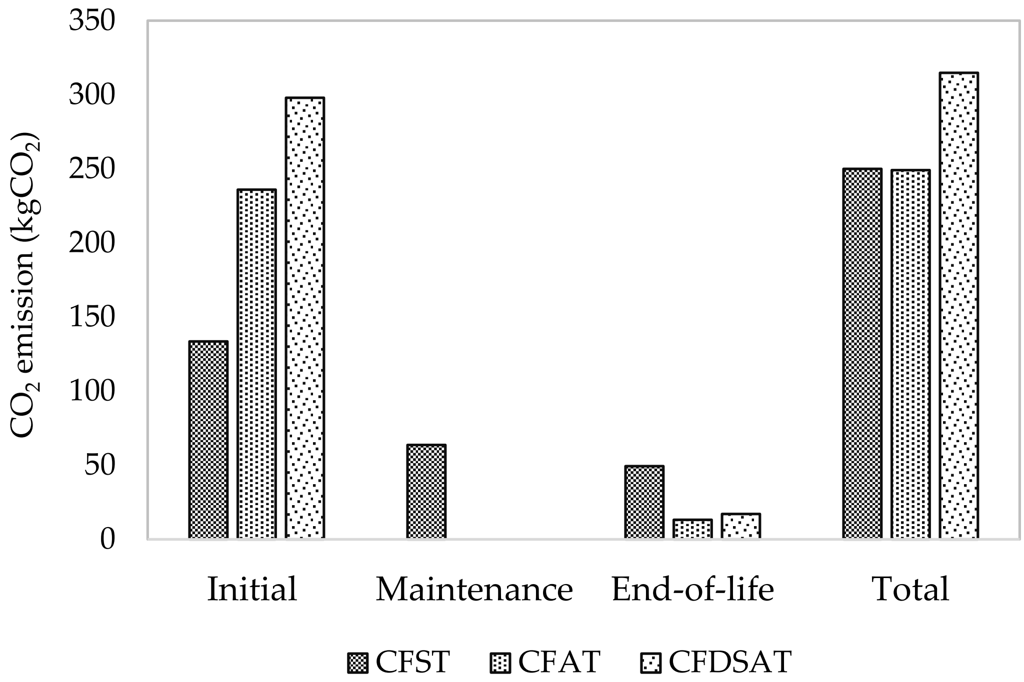

Figure 3. Comparison of CO_2 emissions at different stages of the composite columns.

6. Life-Cycle Cost Analysis (LCCA)

6.1. LCCA Model and Data

The total cost associated with the entire life of composite columns is determined in this section. The individual cost of different components of composite columns is presented in Table 5. The unit prices of cement, coarse aggregates and fine aggregates are 0.30 GBP/kg [39], 0.59 GBP/kg [40] and 0.07 GBP/kg [41], respectively. The price of metal hollow tubes varies depending on the dimensions of the cross-section. The unit price of 150 mm × 150 mm × 4 mm steel hollow section is 6.95 GBP/kg [42]. The cost of 150 mm × 150 mm × 6.75 mm and 100 mm × 100 mm × 3.61 mm aluminium hollow sections is 8.62 GBP/kg and 9.51 GBP/kg, respectively [43]. The transportation cost is considered by adding the delivery charge required to transport the raw materials from the local supplier to the construction site. In the construction stage, the cost is related to labour used for erection, concrete casting, installation, etc. For determining the construction cost, the labour constant is introduced by considering the amount of work a labourer can do per unit of time. Based on a previous study [44], labour constants for concrete and steel are taken as equal to 5 m^3/hour and 0.02 tones/hour, respectively. The same labour constant for steel is assumed for aluminium alloy hollow sections. In the UK, the average labour rate is GBP 12.88 per hour [45]. The maintenance cost of the column forms is calculated according to the maintenance plan determined in Section 4. At the end-of-life stage, money needs to be spent on demolition and disposal of the materials. The unit costs of demolition and landfill of concrete are taken from the work of Zhao et al. [10]. However, money can be earned by selling scrap steel and aluminium alloy to recyclers, and thus the disposal of steel and aluminium represents negative costs. This amount is deducted from the total cost of the end-of-life stage. The local scrap metal selling rate is considered for both steel and aluminium alloy [46]. The unit cost associated with maintenance and end-of-life stage are discounted to the present value. The total life-cycle cost of the three different composite columns is determined and converted to the present value using Equation (8) [47].

$$LCC = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \tag{8}$$

where t is the time in years of incurred cost, T is the total studied period equal to 50 years herein, C_t is the cost incurred at time t and r is the discount rate. C_t is calculated by Equation (9).

$$C_t = C_P + C_T + C_C + C_M + C_E \tag{9}$$

where C_P is the production cost, C_T is the transportation cost, C_C is the construction cost, C_M is the maintenance cost and C_E is the end-of-life cost at time t. The discount rate refers to the time value of money. It is applied to determine the future value by accounting for the nominal interest rate and inflation rate. In this study, the discount rate is considered equal to 3.51% [48]. The discount rate is not taken into account at the initial stage, i.e., the production, transportation and construction stages. However, the discount rate is applied for the cost associated with the maintenance and end-of-life stages.

Table 5. LCCA of composite columns.

Column	Life-Cycle Stage	Consumed Material	Amount/Hour	Unit	Unit Cost	Unit	Reference	Cost (GBP)
CFST	Production	Cement	26.62	kg	0.30	GBP/kg	[39]	7.98
		Fine aggregate	38.71	kg	0.59	GBP/kg	[41]	22.84
		Coarse aggregate	65.63	kg	0.07	GBP/kg	[40]	4.59
		Steel tube	55.01	kg	6.95	GBP/kg	[42]	382.34
		Sum						417.76
	Transportation	Materials for concrete (5.7 km)						30.00
		Steel tube (32.9 km)						21.50
		Sum						51.50
	Construction	Concrete	1.00	h	12.88	GBP/h	[45]	12.88
		Steel tube	2.50	h	12.88	GBP/h	[45]	32.20
		Sum						45.08
	Maintenance	(Maintenance-to-initial ratio = 0.1)					[10]	257.17
	End-of-life	Concrete—demolition	0.06	m^3	98.00	GBP/m^3	[10]	5.93
		Concrete—landfill	145.18	kg	0.07	GBP/kg	[10]	10.31
		Steel tube—100% recycled	55.01	kg	0.06	GBP/kg	[46]	−3.30
		Sum						12.94
	Total	Interest rate			3.51	%	[10]	562.47
CFAT	Production	Cement	24.59	kg	0.30	GBP/kg	[39]	7.38
		Fine aggregate	35.77	kg	0.59	GBP/kg	[41]	21.10
		Coarse aggregate	60.65	kg	0.07	GBP/kg	[40]	4.25
		Aluminium tube	31.33	kg	8.62	GBP/kg	[43]	270.05
		Sum						302.78
	Transportation	Materials concrete (5.7 km)						30.00
		Aluminium tube (32.9 km)						21.50
		Sum						51.50
	Construction	Concrete	1.00	h	12.88	GBP/h	[45]	12.88
		Aluminium tube	2.50	h	12.88	GBP/h	[45]	32.20
		Sum						45.08
	Maintenance	(Maintenance-to-initial ratio = 0)						0.00
	End-of-life	Concrete—demolition	0.06	m^3	98.00	GBP/m^3	[10]	5.48
		Concrete—landfill	134.15	kg	0.07	GBP/kg	[10]	9.52
		Aluminium tube—100% recycled	31.33	kg	0.60	GBP/kg	[46]	−18.80
		Sum						−3.80
	Total	Interest rate			3.51	%	[10]	398.68

Table 5. *Cont.*

Column	Life-Cycle Stage	Consumed Material	Amount/Hour	Unit	Unit Cost	Unit	Reference	Cost (GBP)
CFDSAT	Production	Cement	11.39	kg	0.30	GBP/kg	[39]	3.42
		Fine aggregate	16.57	kg	0.59	GBP/kg	[41]	9.78
		Coarse aggregate	28.10	kg	0.07	GBP/kg	[40]	1.97
		Aluminium outer tube	31.33	kg	8.62	GBP/kg	[43]	270.05
		Aluminium inner tube	11.26	kg	9.51	GBP/kg	[43]	107.12
		Sum						392.33
	Transportation	Materials concrete (5.7 km)						30.00
		Aluminium tube (32.9 km)						21.50
		Sum						51.50
	Construction	Concrete	1.00	h	12.88	GBP/h	[45]	12.88
		Aluminium tube	2.50	h	12.88	GBP/h	[45]	32.20
		Sum						45.08
	Maintenance	(Maintenance-to-initial ratio = 0)						0.00
	End-of-life	Concrete—demolition	0.03	m^3	98.00	GBP/m^3	[10]	2.54
		Concrete—landfill	62.15	kg	0.07	GBP/kg	[10]	4.41
		Aluminium tube—100% recycled	42.59	kg	0.60	GBP/kg	[46]	−25.56
		Sum						−18.61
	Total	Interest rate			3.51	%	[10]	485.60

6.2. LCCA Results and Discussions

Figure 4 shows the life-cycle costs of the composite columns. It can be observed from Table 5 and Figure 4 that compared to the CFST column, the CFAT and CFDSAT columns cost 29% and 14% less, respectively. The initial cost of CFAT and CFDSAT columns is around 22% and 5% lower than that of the CFST column. According to the maintenance plan devised in Section 4, each maintenance activity for CFST column requires 10% of the cost of the initial stage, whereas this amount is zero for the CFAT and CFDSAT columns. Although the price of aluminium and steel fluctuates with time for many reasons, in general, aluminium is more expensive than the steel. The main reason of this high price is because of the higher cost of raw materials associated with aluminium compared with steel. Hence, the scrap value of aluminium alloy is also higher than the steel. Therefore, the total cost at the end-of-life stage of CFAT and CFDSAT columns can be offset compared to that of the CFST column. However, the initial costs of CFAT and CFDSAT are lower than CFST. This is because aluminium is used in smaller quantities. In summary, the CFAT column is estimated to be the most cost-effective solution among the three composite columns. However, due to the application of double-hollow tube, the total cost of CFDSAT column increased by around 22% compared to the CFAT section.

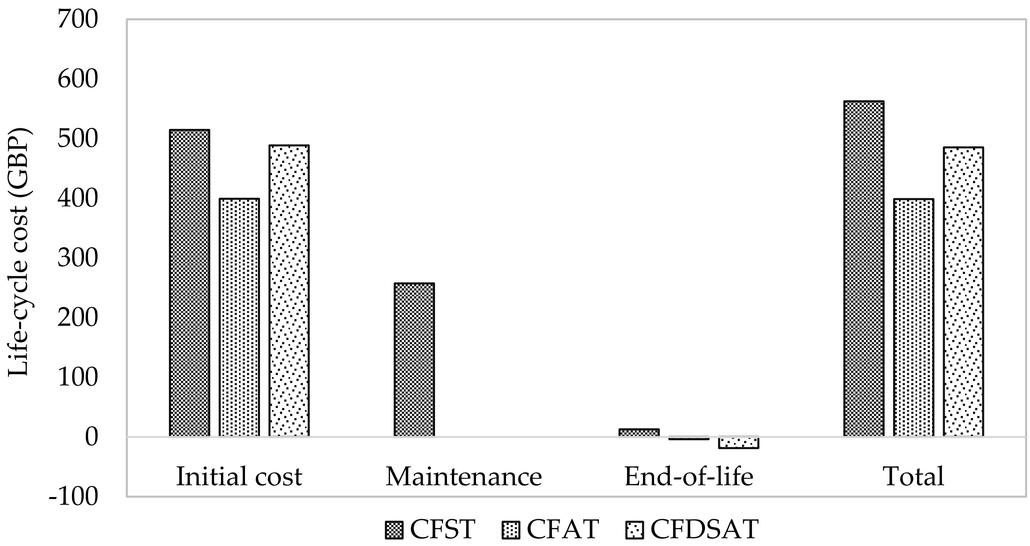

Figure 4. Comparison of life-cycle costs of the composite columns.

7. Sensitivity Analysis

A sensitivity analysis is a study that determines the effect of variation in input parameters on the output of analysis. In this paper, a sensitivity analysis was carried out to identify the impact of variation in data and assumptions, such as (a) the CO_2 emissions of steel and aluminium during production stage, (b) the maintenance-to-initial ratio and (c) the discount rate, on the life-cycle environmental performance and economic aspects of the three composite column forms.

7.1. Renewable Energy Use

Aluminium production requires a very large amount of electricity. According to the International Aluminium Institute [49], 60% of CO_2 from aluminium production is emitted due to the consumption of electricity during the smelting process. Therefore, the amount of CO_2 emission can be reduced significantly by using renewable energy. The steel industry is also responsible for about 7% of man-made CO_2 emissions worldwide because of the massive use of coal in the blast furnace process. Using hydrogen produced with renewable energy instead of coal can largely decarbonise the production of steel [50]. Hence, a sensitivity analysis was conducted by considering reduction in CO_2 emissions by the use of decarbonised electricity for aluminium and decarbonised hydrogen for steel production. The results of this sensitivity analysis are presented in Figure 5. It can be seen that by decreasing the CO_2 emissions of steel and aluminium production, the total environmental impacts of CFST, CFAT and CFDSAT columns decrease significantly. The maximum decrease is around 31%, 42% and 45% for the CFST, CFAT and CFDSAT columns, respectively, at 50% CO_2 emissions reduction in steel and aluminium production. The higher decrement in total environmental impacts of CFAT and CFDSAT columns is observed compared to the CFST one because of the low carbon emission at the maintenance and end-of-life stages of those columns.

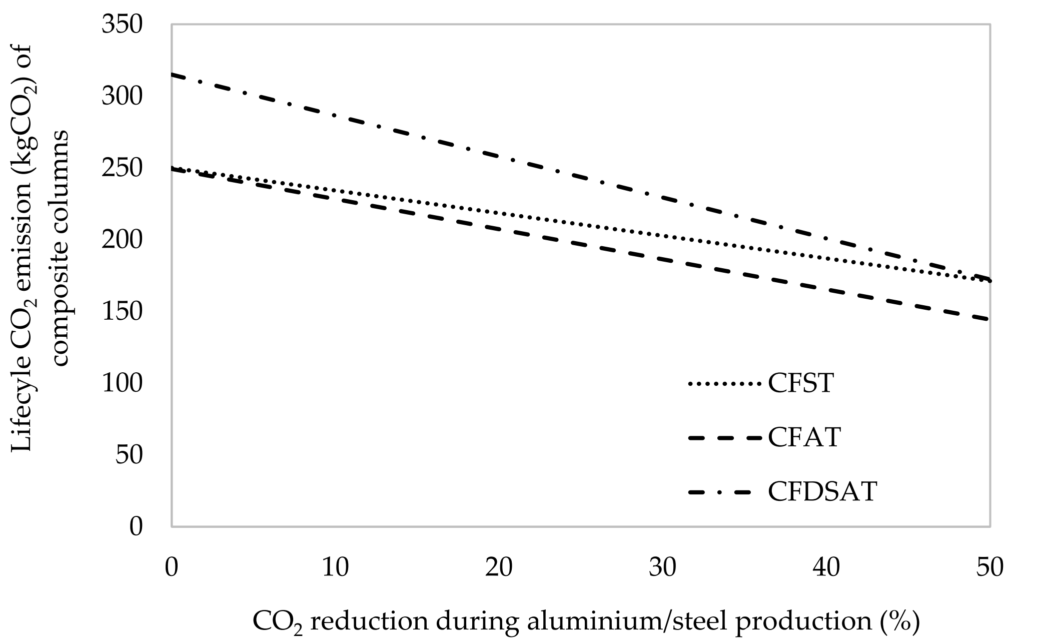

Figure 5. Life-cycle environmental impacts using decarbonised electricity for aluminium and decarbonised hydrogen for steel production.

7.2. Maintenance-to-Initial Ratio

The effect of maintenance-to-initial ratio on the environmental impacts and economic aspects of three composite column forms is investigated and presented in Figures 6 and 7, respectively. In this sensitivity analysis, the baseline maintenance-to-initial ratio is varied from 0 to 0.4. Figures 6 and 7 illustrate that the life-cycle environmental impact and the cost increase with the increase in maintenance-to-initial ratio as expected. Note that for the results presented in Sections 5 and 6, zero maintenance was assumed for the CFAT and CFDSAT columns. In this study, it is considered that the maintenance plan is related to the production stage; hence, high CO_2 emissions of the CFAT and CFDSAT columns during the production of primary aluminium lead to a larger carbon footprint at the maintenance stage with an increasing maintenance-to-initial ratio. However, the CFST column remains the costliest alternative for different maintenance-to-initial ratios, and the difference in cost compared with the aluminium alloy composite columns largely remains the same with an increase in the maintenance-to-initial ratio. It is also obvious from both figures that due to double-aluminium tubes, CO_2 emissions and cost are higher for CFDSAT compared to CFAT. In particular, the differences are 26% and 22%, respectively, for the maintenance-to-initial ratio of 0.4 considered in this study.

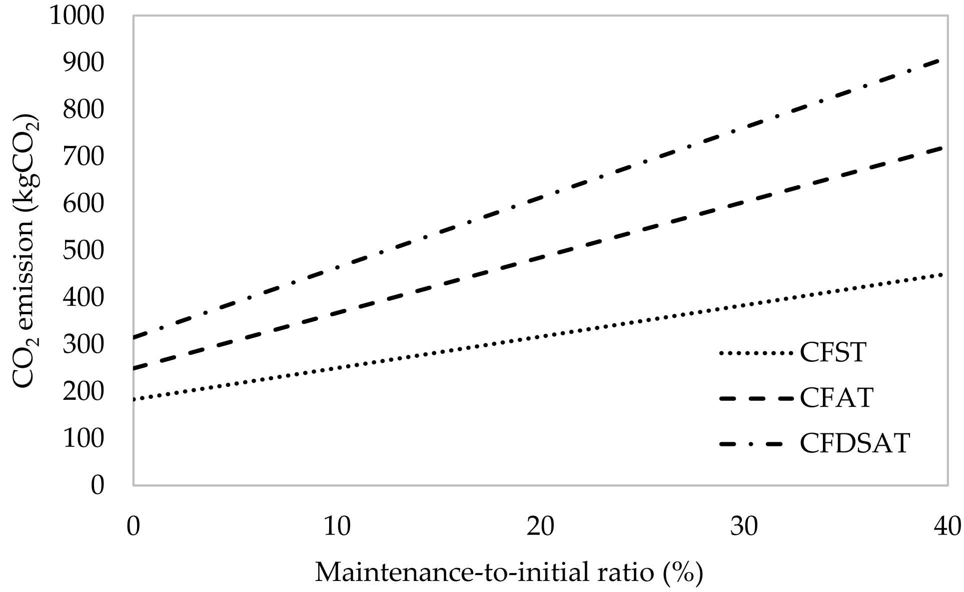

Figure 6. Life-cycle environmental impact for varying maintenance-to-initial ratios.

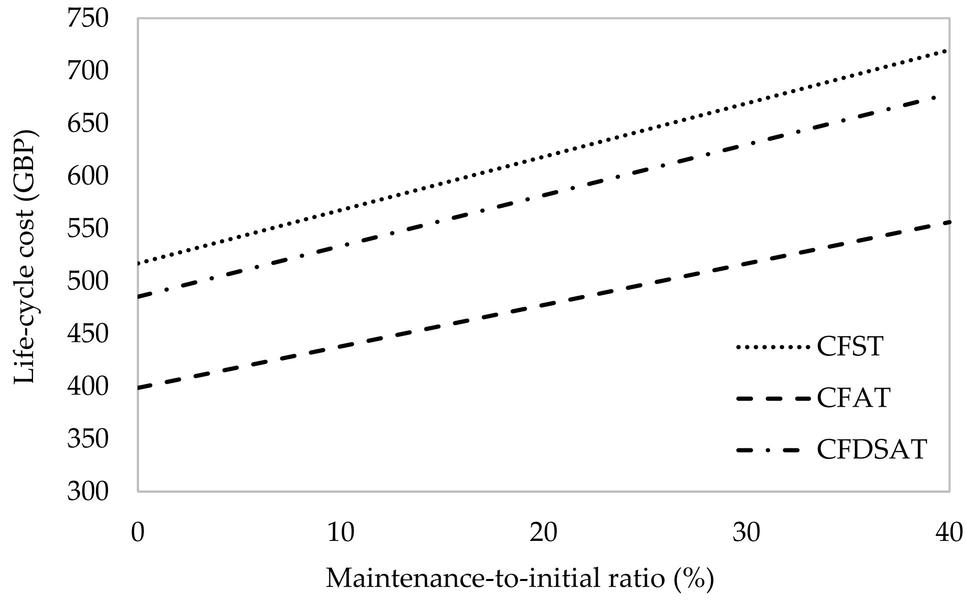

Figure 7. Life-cycle cost for varying maintenance-to-initial ratios.

7.3. Simultaneous Variation in Renewable Energy Use and Maintenance-to-Initial Ratio

A global sensitivity analysis is performed to see the effect of variation in renewable energy use and maintenance-to-initial ratio simultaneously on the long-term environmental performance of composite columns. Figure 8 shows the average CO_2 emissions along with their standard deviation (SD) value at different life-cycle stages of these columns. As expected at the initial stage, the average carbon footprint of CFAT and CFDSAT is 41% and 52% higher, respectively, than that of CFST due to the carbon-intensive manufacturing process of primary aluminium. At the maintenance stage, an anticipated upward trend is noticed for aluminium–concrete composite columns. At this stage, the average CO_2 emission of CFAT and CFDSAT is 39% and 49% larger, respectively, compared to that of CFST, as the considered maintenance plan in this study related to the production phase; hence, a big maintenance-to-initial ratio results in a high carbon footprint of the aluminium alloy. No variation is considered at the end-of-life stage. As a result of low environmental impact at the initial and maintenance stages, the total average CO_2 emission of CFST column is 38.2% and 68.3% lower than that of CFAT and CFDSAT. The SD value of the total average CO_2 emission of CFST is the lowest, which is 31.1, where the value for CFAT and CFDSAT is 42.9 and 46.3, respectively.

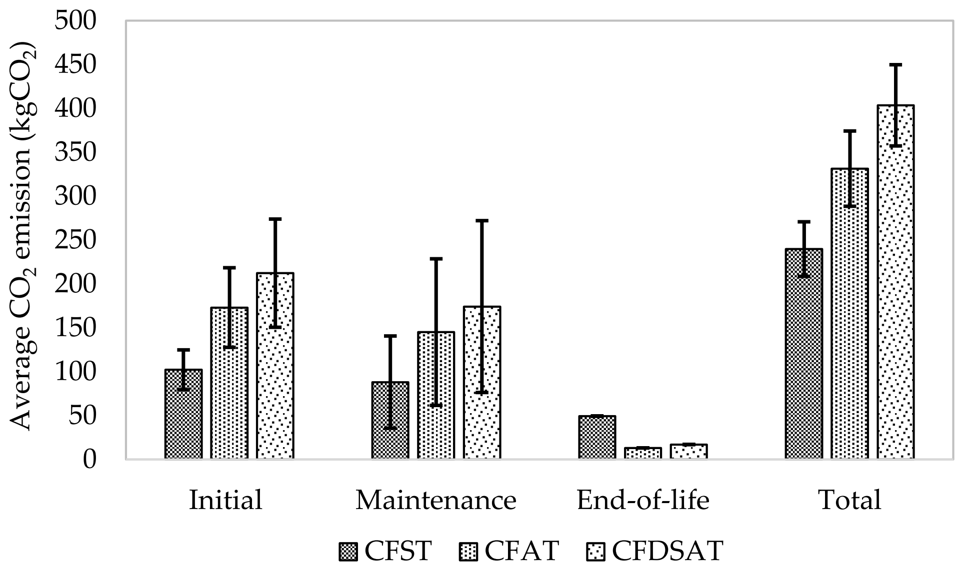

Figure 8. Life-cycle environmental impact for variation in renewable energy use and maintenance-to-initial ratio simultaneously.

7.4. Discount Rate

The effect of discount rates on the economic aspects of the three design alternatives is also studied. Figure 9 presents the results of LCCA with varying discount rates varying from 0 to 0.4. It can be seen that the discount rate has a noticeable effect on the total cost of CFST column. For this column, a decreasing trend of life-cycle cost is noticed with increasing discount rates; this is because the present value of future cost becomes smaller with higher discount rates. The total cost of CFST column is reduced by 4.4% when the discount rate is increased to 5% from the baseline value of 3.5%. However, variation in discount rate has a negligible effect on the economic characteristic of CFAT and CFDSAT columns. The discount rate is applied only for future costs related to maintenance and demolition/recycling actions of structural members. In this study, the cost associated with the maintenance of the CFAT and CFDSAT columns is assumed zero because of the excellent corrosion resistance of the aluminium alloy. In addition, the end-of-life cost of these columns is offset by the high scrap value of aluminium alloy. So, the future cost is almost zero for these structural members. Hence, the discount rate is a less sensitive parameter for calculating the life-cycle cost of CFAT and CFDSAT columns.

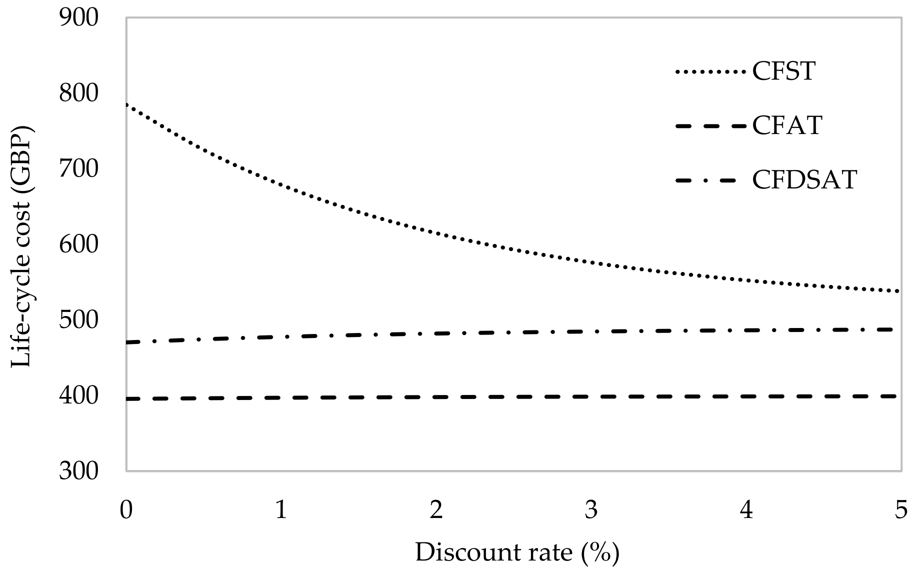

Figure 9. Life-cycle cost for varying discount rates.

8. Conclusions

In this study, the life-cycle performance of CFAT and CFDSAT columns was assessed for their environmental impact and cost using LCA and LCCA, respectively. The LCA and LCCA results of the composite columns were compared with those of a CFST column with the same load-carrying capacity and outer cross-sectional dimensions. To calculate the inventory, the self-weight of these columns was calculated before being multiplied by unit inventory. The holistic approach with long analysis period in LCA and LCCA creates uncertainty and requires assumptions to be made in order to proceed. Finally, a sensitivity analysis was conducted to study the effect of data and assumptions on the life-cycle performance of these composite columns. Based on the findings, the following points can be summarised:

- It was found that the self-weight of the studied CFAT and CFDSAT columns is around 17% and 47% lower than that of the CFST column. Therefore, it can be concluded that the self-weight of CFST column can be reduced by replacing steel with aluminium alloy and it becomes significantly lighter when the double-skin form is applied using aluminium alloy hollow sections.
- It was observed from the LCA that the carbon footprint of CFST and CFAT is almost the same, which is 21% lower than that of the CFDSAT columns because of the high aluminium usage in the latter. Therefore, it can be concluded that the high embodied carbon in CFAT columns can be offset by fewer maintenance needs, owing to its superior corrosion resistance compared with CFST. However, excessive use of aluminium such as in the CFDSAT composite column will result in an increase in carbon emissions.
- The LCCA results show that the total life-cycle cost of CFAT and CFDSAT columns is around 29% and 14% lower, respectively, than that of the CFST column, largely due to assuming no expense related to the maintenance because of the excellent corrosion resistance of aluminium. It suggests that the CFAT column is the most cost-effective design solution compared to the other two composite columns.
- From the sensitivity analysis, it was found that by using decarbonised electricity in the production of steel and aluminium, the total environmental impacts of the CFST, CFAT and CFDSAT columns can be reduced significantly. A reduction of 31%, 42% and 45% for the CFST, CFAT and CFDSAT columns, respectively, can be achieved when a 50% CO_2 reduction in the production of steel and aluminium is considered. A higher reduction in carbon emissions by CFAT and CFDSAT columns is observed at the maintenance and end-of-life stages compared to the CFST column.

- With the increase in the maintenance-to-initial ratio, the CO_2 emissions of CFAT and CFDSAT increase noticeably compared to the CFST column, whereas the CFST column remains the costliest alternative in all maintenance-to-initial ratios. Future studies could include a sensitivity analysis of the corrosion resistance of aluminium columns as well as of the residual value of scrap metals when data become available.
- From a global sensitivity analysis, it was observed that the average life-cycle CO_2 emission of CFST column is 38.2% and 68.3% lower than that of CFAT and CFDSAT due to low environmental impact at the initial and maintenance stages of steel.
- Finally, the life-cycle cost of CFAT and CFDSAT columns is less sensitive to the variation in the discount rate, which is mainly due to the durability of aluminium assumed in the analysis period, i.e., 50 years.

9. Future Research

Further research is recommended to broaden the LCA study beyond just CO_2 emissions. It is essential to incorporate additional sustainability indicators, such as energy use, resource depletion, and water consumption, to obtain a more comprehensive understanding of the environmental impact. Furthermore, investigating various composite aluminium–concrete structural members and different types of aluminium alloys will be crucial in identifying the most efficient and sustainable configurations. This approach will not only enhance the overall sustainability of structural materials but also contribute to the development of innovative designs that minimise the environmental impact while maximising performance.

Author Contributions: Conceptualisation, S.B.A., G.S.K. and M.G.; methodology, S.B.A., G.S.K., M.G. and Y.H.; formal analysis, S.B.A., G.S.K., M.G. and Y.H.; investigation, S.B.A.; writing—original draft preparation, S.B.A.; writing—review and editing, G.S.K., M.G. and Y.H.; supervision, G.S.K. and M.G.; funding acquisition, G.S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within this article.

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

References

1. Morino, S.; Uchikoshi, M.; Yamaguchi, I. Concrete-filled steel tube column system-its advantages. *Int. J. Steel Struct.* **2001**, *1*, 33–44.
2. Morino, S.; Tsuda, K. Design and construction of concrete-filled steel tube column system in Japan. *Earthq. Eng. Eng. Seismol.* **2002**, *4*, 51–73.
3. Lam, D.; Wong, K. Axial capacity of concrete filled stainless steel columns. In Proceedings of the Structures Congress, New York, NY, USA, 20–24 April 2005. [CrossRef]
4. Starossek, U.; Falah, N.; Lohning, T. Numerical analyses of the force transfer in concrete-filled steel tube columns. *Struct. Eng. Mech.* **2010**, *35*, 241–256. [CrossRef]
5. McLennan, J.F. *The Philosophy of Sustainable Design: The Future of Architecture*; Ecotone Publishing Company: Washington, DC, USA, 2004; p. 4.
6. Hastak, M.; Halpin, D.W. Assessment of life-cycle benefit-cost of composites in construction. *J. Compos. Constr.* **2000**, *4*, 103–111. [CrossRef]
7. Rossi, B.; Lukic, I.; Iqbal, N.; Du, G.L.; Cregg, D.; Borg, R.P.; Haller, P. Life cycle impacts assessment of steel, composite, concrete and wooden columns. In Proceedings of the International Conference on Sustainability of Constructions—Towards a Better Built Environment, Innsbruck, Austria, 3–5 February 2011.
8. Hou, C.C.; Han, L.H. Life-cycle performance of deteriorated concrete-filled steel tubular (CFST) structures subject to lateral impact. *Thin-Walled Struct.* **2018**, *132*, 362–374. [CrossRef]
9. Duarte, A.P.C.; Silvestre, N.; Brito, J.D.; Júlio, E.; Silvestre, J.D. On the sustainability of rubberized concrete filled square steel tubular columns. *J. Clean. Prod.* **2018**, *170*, 510–521. [CrossRef]
10. Zhao, M.; Dong, Y.; Guo, H. Comparative life cycle assessment of composite structures incorporating uncertainty and global sensitivity analysis. *Eng. Struct.* **2021**, *242*, 112394. [CrossRef]
11. Zhou, F.; Young, B. Tests of concrete-filled aluminum stub columns. *Thin-Walled Struct.* **2008**, *46*, 573–583. [CrossRef]

12. Zhou, F.; Young, B. Concrete-filled double-skin aluminum circular hollow section stub columns. *Thin-Walled Struct.* **2018**, *133*, 141–152. [CrossRef]
13. Zhou, F.; Young, B. Compressive strengths of concrete-filled double-skin (circular hollow section outer and square hollow section inner) aluminium tubular sections. *Advances Struct. Eng.* **2019**, *22*, 1–17. [CrossRef]
14. Wang, F.; Zhao, H.; Han, L. Analytical behavior of concrete-filled aluminum tubular stub columns under axial compression. *Thin-Walled Struct.* **2019**, *140*, 21–30. [CrossRef]
15. Feng, R.; Chen, Y.; Gong, W. Flexural behaviour of concrete-filled aluminium alloy thin-walled SHS and RHS tubes. *Eng Struct.* **2017**, *137*, 33–49. [CrossRef]
16. Chen, Y.; Feng, R.; Gong, W. Flexural behavior of concrete-filled aluminum alloy circular hollow section tubes. *Constr. Build. Mater.* **2018**, *165*, 295–319. [CrossRef]
17. Ali, S.B.; Kamaris, G.S.; Gkantou, M.; Kansara, K.D. Concrete-filled and bare 6082-T6 aluminium alloy tubes under in-plane bending: Experiments, finite element analysis and design recommendations. *Thin-Walled Struct.* **2022**, *172*, 108907. [CrossRef]
18. Ali, S.B.; Kamaris, G.S.; Gkantou, M. Flexural behaviour of concrete-filled double skin aluminium alloy tubes. *Eng. Struct.* **2022**, *272*, 114972. [CrossRef]
19. Georgantzia, E.; Ali, S.B.; Gkantou, M.; Kamaris, G.S.; Kansara, K.D.; Atherton, W. Flexural buckling performance of concrete-filled aluminium alloy tubular columns. *Eng. Struct.* **2020**, *242*, 112546. [CrossRef]
20. Ali, S.B.; Kamaris, G.S.; Gkantou, M. Flexural buckling behaviour of concrete-filled double skin aluminium alloy columns. *Eng. Struct.* **2023**, *275*, 115316. [CrossRef]
21. *EN 1990:2002*; Eurocode: Basis of Structural Design. European Committee for Standardisation (CEN): Brussels, Belgium, 2002.
22. *EN 1991-1-1:2002*; Eurocode 1: Actions on Structures—Part 1-1: General Actions—Densities, Self-Weight, Imposed Loads for Buildings. European Committee for Standardisation (CEN): Brussels, Belgium, 2002.
23. Tao, Z.; Han, L.H.; Zhao, X.L. Behaviour of concrete-filled double skin (CHS inner and CHS outer) steel tubular stub columns and beam-columns. *J. Compos. Constr.* **2004**, *60*, 1129–1158. [CrossRef]
24. *EN 1994-1-1:2004*; Eurocode 4: Design of Composite Steel and Concrete Structures. Part 1-1. General Rules and Rules for Buildings. European Committee for Standardisation (CEN): Brussels, Belgium, 2004.
25. *EN 1999-1-1:2007*; Eurocode 9: Design of Aluminium Structures. Part 1-1. General Structural Rules—General Structural Rules and Rules for Buildings. European Committee for Standardisation (CEN): Brussels, Belgium, 2007.
26. Wang, Y.; Cao, M.M.; Sun, H. Time-dependent reliability analysis of circular CFST stub columns under environment corrosion. *Pac. Sci. Rev.* **2014**, *16*, 201–206. [CrossRef]
27. Gardner, L.; Cruise, R.B.; Sok, C.P.; Krishnan, K.; Ministro, J. Life cycle costing of metallic structures. *Proc. Inst. Civ. Eng. Eng. Sustain.* **2007**, *160*, 167–177. [CrossRef]
28. Aslani, F.; Ma, G.; Wan, D.L.Y.; Muselin, G. Development of high-performance selfcompacting concrete using waste recycled concrete aggregates and rubber granules. *J. Clean. Prod.* **2018**, *182*, 553–566. [CrossRef]
29. Silva, R.V.; De Brito, J.; Dhir, R.K. Availability and processing of recycled aggregates within the construction and demolition supply chain: A review. *J. Clean. Prod.* **2017**, *143*, 598–614. [CrossRef]
30. Müller, H.S.; Breiner, R.; Moffatt, J.S.; Haist, M. Design and properties of sustainable concrete. *Procedia Eng.* **2014**, *95*, 290–304. [CrossRef]
31. Worldsteel Association. *Sustainability Performance of the Steel Industry 2004–2022*; Sustainability Indicators 2023 Report; Worldsteel Association: Brussels, Belgium, 2023.
32. European Aluminium. *Environmental Profile Report: Life-Cycle Inventory Data for Aluminium Production and Transformation Processes in Europe*; European Aluminium: Brussels, Belgium, 2018.
33. Xu, K.; Kang, H.; Wang, W.; Jiang, P.; Li, N. Carbon emission estimation of assembled composite concrete beams during construction. *Energies* **2021**, *14*, 1810. [CrossRef]
34. Ceb-Fip. *Ceb-Fip Model Code 1990*; Thomas Telford Ltd.: London, UK, 1993.
35. Cho, S.H.; Chae, C.U. A Study on Life Cycle CO2 Emissions of Low-Carbon Building in South Korea. *Sustainability* **2016**, *8*, 579. [CrossRef]
36. European Aluminium. *Environmental Profile Report: For the Aluminium Refining Industry*; European Aluminium: Brussels, Belgium, 2021.
37. Bureau of International Recycling, Ferrous Metals: Extract Bir Annual Report 2022. Available online: https://www.bir.org/the-industry/ferrous-metals (accessed on 11 December 2023).
38. 8billiontrees, Carbon Footprint of Steel per kg & lb (Calculator & Full List of Steel Items). Available online: https://8billiontrees.com/carbon-offsets-credits/carbon-footprint-of-steel (accessed on 12 December 2023).
39. Blue Circle Multipurpose Cement, 25 kg Bag. Available online: https://www.diy.com/departments/blue-circle-multipurpose-cement-25kg-bag/35715_BQ.prd (accessed on 11 December 2023).
40. Resapol, Stone 10 mm, 25 kg. Available online: https://www.resapol.com/product/limestone-10mm-25kg/ (accessed on 11 December 2023).
41. Wickes, Building Sand. Available online: https://www.wickes.co.uk/Tarmac-Building-Sand---Jumbo-Bag/p/131889 (accessed on 11 December 2023).
42. Metalsupermarkets, Mild Steel. Available online: https://www.metalsupermarkets.co.uk/metals/mild-steel/ (accessed on 11 December 2023).
43. Simmal, Aluminium Tube. Available online: https://www.simmal.com/product-category/aluminium-tube/ (accessed on 11 December 2023).

44. Chan, T.K.; Aibinu, A.A. A comparison of construction cost and technology choice. In Proceedings of the Management of Construction: Research to Practice Conference, Montreal, QC, Canada, 26–29 June 2012.
45. Linear Recruitment, Highest Paying Construction Jobs in the UK. Available online: https://www.linearrecruitment.co.uk/news/highest-paying-construction-jobs-uk (accessed on 11 December 2023).
46. Scrapmetalpricesuk, Scrap Metal Prices UK. Available online: http://www.scrapmetalpricesuk.co.uk (accessed on 11 December 2023).
47. Younis, A.; Ebead, U.; Judd, S. Life cycle cost analysis of structural concrete using seawater, recycled concrete aggregate, and GFRP reinforcement. *Constr. Build. Mater.* **2018**, *175*, 152–160. [CrossRef]
48. GOV.UK, DHSC Group Accounting Manual 2022 to 2023: Additional Guidance, Version 3. Available online: https://www.gov.uk/government/publications/dhsc-group-accounting-manual-2022-to-2023/dhsc-group-accounting-manual-2022-to-2023-additional-guidance-version-1 (accessed on 11 December 2023).
49. International Aluminium Institute. Aluminium, Shaping a Better Tomorrow. Available online: https://international-aluminium.org/new-test-article/ (accessed on 11 December 2023).
50. Ledari, M.B.; Khajehpour, H.; Akbarnavasi, H.; Edalati, S. Greening steel industry by hydrogen: Lessons learned for the developing world. *Int. J. Hydrogen Energy* **2023**, *48*, 36623–36649. [CrossRef]