Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Simulation-Based Structural Optimization of Composite Robot Links for Energy-Efficient Motion

BASHIR SHUAIBU AHMAD

bashgan59@gmail.com

Vivekananda Global University Jaipur, Rajasthan India https://orcid.org/0009-0004-0772-5407

Dr. Naveen Kumar Yadav

Vivekananda GLobal University Jaipur, Rajasthan

Dr. Muhyiddeen Yahaya Musa

Audo Bako college of Agriculture, Danbatta Kano, Nigeria

Dr. Mukeesh Kumar

Vivekananda GLobal University Jaipur, Rajasthan

Research Article

Keywords: CFRP, Robotic manipulator, Energy efficiency, Lagrangian dynamics, Structural optimization, Composite materials, MATLAB simulation

Posted Date: April 23rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9459718/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: The authors declare no competing interests.

Simulation-Based Structural Optimization of Composite Robot Links for Energy-Efficient Motion

Bashir Shuaibu Ahmad[1]* ORCID: 0009-0004-0772-5407

, Dr. Naveen Kumar Yadav[2], Dr. Muhyiddeen Yahaya Musa[3], Dr. Mukeesh Kumar[4]

[1]Department of Mechanical Engineering, Vivekananda Global University, Jaipur, Rajasthan, India

[2]Department of Mechanical Engineering, Vivekananda Global University, Jaipur, Rajasthan, India

[3]Department of Agricultural Engineering, Audu Bako College of Agriculture Danbatta Kano, Nigeria.

[4]Department of Mechanical Engineering, Vivekananda Global University, Jaipur, Rajasthan, India

Corresponding author: Bashir Shuaibu Ahmad, email: bashgan59@gmail.com

Abstract: This paper presents a systematic simulation-based framework for comparing the structural performance and energy efficiency of robotic arm links fabricated from Aluminium 6061-T6 and Carbon Fiber Reinforced Polymer (CFRP). A two-degree-of-freedom (2-DOF) planar robotic arm is modelled using analytical beam theory for structural analysis and the Lagrangian formulation for multi-body dynamics. Mass, effective joint inertia, bending stress, tip deflection, actuator torque, and cumulative energy consumption are evaluated for both materials under identical geometric and loading conditions. MATLAB simulation of the complete dynamic model—including inertial, Coriolis,

centrifugal, and gravitational torque terms—demonstrates a 90.285% per-cycle energy reduction with CFRP relative to aluminium. Constrained cross-section optimization further identifies a minimum section that, combined with CFRP material substitution, reduces link mass by 96.3% from the base. Results confirm that the primary performance advantage of CFRP is its 40.74% lower density, which propagates through all mass-dependent torque terms in the Lagrangian model to produce compound energy savings substantially exceeding the ar mass-reduction ratio.

Keywords: CFRP, Robotic manipulator, Energy efficiency, Lagrangian dynamics, Structural optimization, Composite materials, MATLAB simulation

1. INTRODUCTION

1.1 Background Study

Kinematic reach, payload capability and positional accuracy have historically been considered to be paramount in the design of robotic manipulators, and the structural mass has been secondary. This has yielded strong yet vigorous inefficient systems: the traditional robot links built of steel or aluminum alloy bear inertial loads that increase the actuator torque requirements at each joint, increasing motor size, power consumption, and heat loss in the drive train. Due to the increasing scope of industrial automation and the growing importance of sustainability, the amount of energy consumed by robots has shifted into the backburner of design requirements [5, 10]. One of the most immediate and directly manageable factors of energy consumption of motion is the structural mass of the links of a robot. Since the demand on joint torque is proportional to the mass moment of inertia of all links farther down the kinematic chain, even the small increases or decreases in link mass have disproportionate effects on actuator energy demand an effect that propagates along the kinematic chain [10].

The more recent fiber-reinforced composites, especially carbon fiber-reinforced polymers, are specifically providing stiffness values that are multiple times higher than structural aluminum, which means that they are the material of choice in building mass-critical robot structures [4, 8, 19]. The outcome of this, however, is that the energy efficiency potential of composite robot links can only be achieved through strict simulation-based structural optimization, which takes into consideration dynamic loading and modal behavior, the complete operational load envelope, and not just material substitution [1, 20].

1.2 Problem Statement

Although the theoretical benefits of composite materials in structural designs are well established, systematic implementation of structural optimization of the simulation to composite robot links with energy efficiency as the unambiguous design objective is not fully developed in the literature and industrial applications. Robot links structural optimization is mainly done with either static or worst-case loading conditions that do

not reflect the time-dependent inertia and dynamic forces acting on actual energy use in motion [7, 23]. Topology optimization of robot arms typically assumes that the link material is isotropic, losing the anisotropic programmability of stiffness of fiber-reinforced composites which is the key benefit of this technology [14, 22]. Moreover, energy usage is not often the main optimization goal; mass or compliance are proxy goals the minimization of which does not always coincide with the real energy minimization in the robot task space [2, 11, 25]. These shortcomings lead to designs of robot arms that are structurally sufficient but not energy efficient. To bridge the gap between the composite structural design, simulation fidelity, and energy efficiency goals, a coherent conceptual design approach is necessary which this paper intends to develop and test.

1.3 Research Objectives

The main objective of this research is to learn how the structural performance and energy efficiency of robotic arm links are affected by composite materials through simulation techniques. The specific objectives are:

To design a geometric model of 2-DOF robotic arm based on a reference design and calculate the significant structural variables such as volume, mass and moment of inertia.

To experimentally investigate the structural behavior of the robotic links through the stress, deflection, and safety in normal loading conditions.

To compare Aluminium 6061-T6 and CFRP with regard to the impact they have on the mass and inertia of the links.

To look at the effect of the growth and degradation in mass and inertia on the energy consumed by the robotic arm by simulation in MATLAB.

To recommend good design concepts of utilizing lightweight composite materials to enhance the energy-saving of robotic manipulators.

1.4 Scope and Delimitations

This paper focuses on modeling and simulation evaluation of composite robot link designs with the aim of enhancing energy-efficient movement. The study mainly analyzes the choice of materials, layout, and theoretical appraisal of the link performance. The research area involves robotic manipulator links that are common structures of robotic arms in the industries. Analytical mechanics and beam theory formulations are applied to measure the structural response of the links to estimate the stress, deflection, and structural safety parameters in representative loading conditions. Moreover, a multi-body dynamic simulation method is used in the study of energy performance. The study is confined to the conceptual structural design phase; the development of manufacturing processes, joint or end-effector development, and the implementation of advanced control algorithms are not considered.

1.5 Significance of the Research

The study enhances the understanding of how advanced materials can improve the structural efficiency and energy performance of robotic manipulators, thereby contributing to the development of lightweight, high-performance robotic systems. Through an examination of the relationship between the mass of the links, moment of

inertia, and energy consumption, the study proves that lightweight composite materials can be used to potentially save the energy required by robotic motion. The suggested simulation-based framework offers a conceptual method of assessing robotic link structures from an energy-efficiency point of view, fostering the creation of robotic systems that focus on structural performance and less energy usage.

2. Related literature

2.1 Compound Materials of Lightweight Robot Links

The constitutive basis of all simulation-based structural optimization of composite robot links has its classical mechanics of fiber-reinforced composite laminates authoritatively described by Jones [19]. Laminate theory correlates the fiber direction, ply stack sequence and material property to anisotropic stiffness, bending stiffness, and failure properties of the composite assembly. Pandey, Srivastava and Maurya [8] directly transferred the concept of composite material to the study of the robotic arm components and showed that carbon fiber arrangements reaching a good fit to the key stress directions resulted in significantly better structural efficiency than isotropic metallic constructions of equal mass. This observation was further supported by Boaretto et al. [9] in a general overview of biomimetic composite structures to use in mobility applications.

Carbon fiber reinforced polymers (CFRP) represent the most popular high-performance option in mass-critical robot links. Belhassen [4] concluded that continuous fiber reinforcement is necessary to achieve the stiffness required to maintain link rigidity under dynamic loading conditions. Al-Sabur et al. [18] modeled the dynamic behavior of a composite robot link structure with sinusoidal loading, exhibiting viscoelastic damping behavior not found in metallic model structures. Hybrid material strategies combining CFRP with aluminium alloys have also been investigated, with Yin, Liu and Yang [24] demonstrating that locating CFRP in regions of higher structural demand while maintaining metallic interfaces at connections enhances structural efficiency while simplifying manufacturing.

2.2 Dynamic Simulation and Structural Design

Dynamic simulation now forms a key element in the study of the motion behaviour and energy performance of robotic manipulators. Zhou et al. [10] examined the role played by structural inertia in the total energy demand of robotic processes and revealed that link mass has a pronounced role in the overall energy requirement of motions. Wierbica et al. [12] used dynamic simulation methods to test alternative robotic workstations, confirming the relevance of system-level modelling for enhancing energy efficiency. Bilancia et al. [25] also proved that parameters such as link length and structural configuration have an impact on the mechanical behaviour and energy consumption of robotic manipulators.

2.3 Research Gaps

Despite considerable research on robotic manipulator design, critical gaps remain in the field of energy-efficient structural design of robot links. Most current studies have

mainly been geared at enhancing mechanical performance—stiffness or weight minimization—without direct consideration of the effects of structural properties on the energy expenditure of robotic motion. Furthermore, structural analysis and dynamic motion evaluation are normally carried out separately, restricting comprehension of the impact of structural design choices on the power efficiency of robotic manipulators. This study addresses these gaps by conducting structural assessment alongside dynamic simulation to gain deeper insights into the ability of lightweight composite materials to impact the energy performance of robotic systems.

3. Research methodology

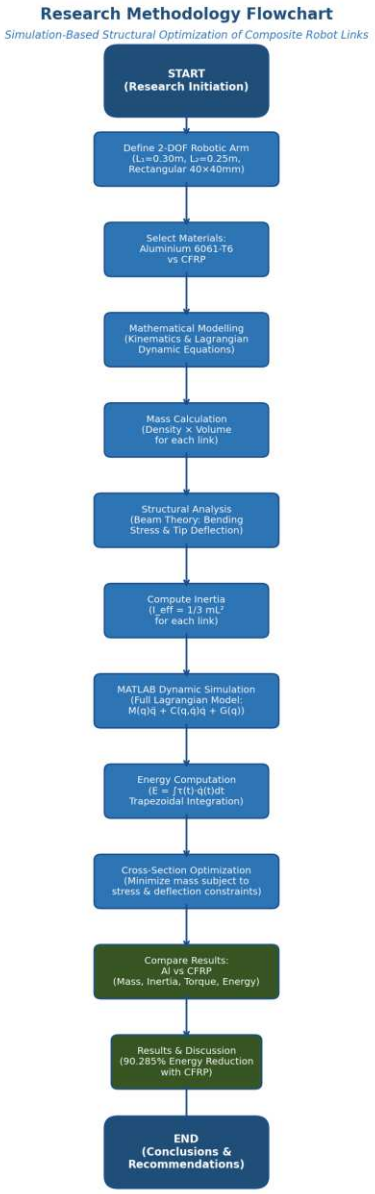


Figure 3.0: Research Methodology Flowchart — Simulation-Based Structural Optimization Framework

3.1 Robot Model: Conceptual Design

The system model used in this study is a two-degree-of-freedom (2-DOF) planar robotic arm consisting of two rigid links joined at two revolute (rotational) joints,

restricted to move in one plane. This configuration has proven to present a clear, tractable platform on which the influence of link material choice on energy usage may be demonstrated [3, 8]. The fixed dimensions adopted in the two links across all analyses are: Link 1 length $L_1 = 0.30$ m; Link 2 length $L_2 = 0.25\,m$; Width W = 0.04 m; Height H = 0.04 m; Area $A_1 = A_2 = 0.0016\,m^2$. The cross-section is solid and rectangular, chosen for simplicity of analysis.

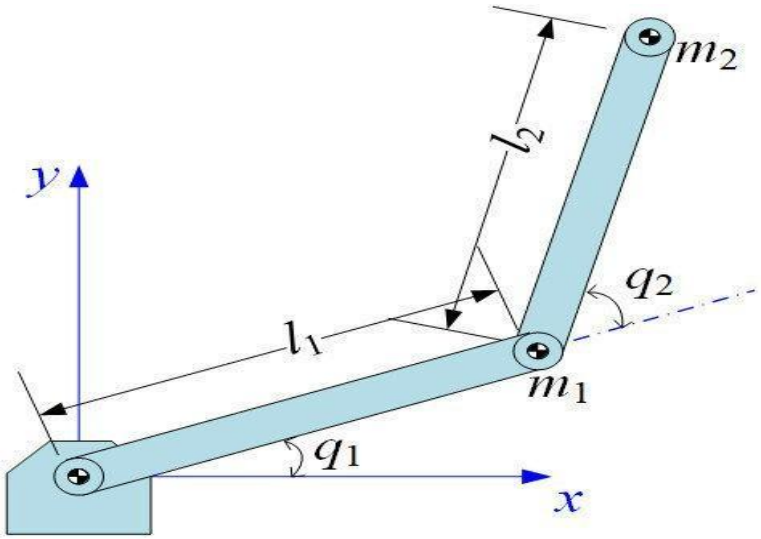


Figure 3.1: Schematic of a 2-DOF Planar Robotic Arm (Source: Li et al., Optimal Design of MPC Applied to Robotic Manipulators, 2022)

3.2 Material Selection

The study is undertaken to compare two structural materials: Aluminium 6061-T6 and Carbon Fiber Reinforced Polymer (CFRP). Table 3.1 shows the main mechanical properties of each material gathered from published literature.

Property	Symbol/Unit	Aluminum	CFRP
Density	ρ (kg/m³)	2700	1600
Young's Modulus	E (GPa)	69	70 – 150
Tensile Strength	σ (MPa)	310	600 – 1500
Yield Strength	σy (MPa)	276	(fiber governed)
Poisson's Ratio	N	0.33	0.25 – 0.30
Specific Stiffness	E/ρ	25.6 MNm/kg	43.75 – 93.75 MNm/kg
Structural Damping	—	Low	High

Table 3.1: Mechanical Properties of Aluminium 6061-T6 and CFRP

CFRP possesses three unquestionable benefits over Aluminium 6061-T6 in robotic links. Its $1600\ kg/m^3$ density is 40.7% lower than the $2700\ kg/m^3$ of aluminium, directly reducing mass, rotational inertia, and actuator torque. Its specific stiffness is

3.7 times greater than that of aluminium. Additionally, CFRP exhibits higher structural damping, reducing residual vibration at the end-effector following quick joint action and enhancing precision of motion [3, 8].

3.3 Mathematical Modelling

The configuration of a 2-DOF planar robotic arm is described using forward kinematics, which determine the position of the end-effector (x, y) based on the joint angles $\theta_1 \, and \, \theta_2$: $x = L_1 \, cos(\theta_1) + L_2 \, cos(\theta_1 + \theta_2) \, and \, y = L_1 \, sin(\theta_1) + L_2 \sin(\theta_1 + \theta_2)$. The maximum reach of the arm is 0.55 m. The dynamic behavior is described using the Lagrangian formulation: $\tau = M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q)$, where $M(q)$ is the mass/inertia matrix, $C(q,\dot{q})\dot{q}$ represents Coriolis and centrifugal terms, and G(q) is the gravity vector. Reducing link mass through CFRP substitution directly reduces elements of M(q), lowering the torque required for a given acceleration.

3.4 Structural Analysis - Beam Theory

Each of the links is a modelled cantilever beam pinned at one end and loaded at the other. For a solid rectangular cross-section (w = h = 0.04 m), the second moment of area $I = wh^3/12 = 2.13 \times 10^{-7} \, m^4$. The bending stress can be calculated at representative tip load F = 10 N as 0.282 MPa in the case of Link 1 and 0.234 MPa in the case of Link 2: at the given load, the stress = My/I and the outcome is similar with both materials since stress is a geometry-dependent quantity. $\sigma = FL^3/3EI$ gives nominal identically small quantities of the two materials (below 0.007 mm) at equal elastic moduli (69 vs. 70 Gpa) demonstrates the $FL^3/3EI$ advantage is primarily the decrease in density, rather than the increase in rigidity..

3.5 Energy Consumption Analysis

Energy used per joint actuator cycle is calculated as $E = \int \tau(t)\dot{q}(t)dt$. A sinusoidal joint motion profile is adopted: $\theta(t) = A \cdot sin(\omega t)$, where A = π/4 rad (45° amplitude) and $\omega = \pi \, rad/s$ (0.5 Hz frequency), giving a 2-second cycle.The MATLAB simulation implements the full Lagrangian dynamic model, computing M(q), C(q,q̇), and G(q) at each of 2001 time steps, calculating the torque vector, and integrating using the trapezoidal rule to obtain cumulative energy per cycle.

4. Results and Discussion

4.1 Mass and Rotational Inertia

The 40.74 percent decrease in CFRP density compared to aluminium results in a similar reduction in the mass of links. Where I eff = (1/3)mL 2, because L remains constant the decrease in inertia is equal to the decrease in mass at 40.74.

Parameter	Al-Link1	Al-Link2	CFRP-Link1	CFRP-Link2
Density ρ (kg/m^3)	2700	2700	1600	1600
Link Length L (m)	0.30	0.25	0.30	0.25
Link Mass m (kg)	1.296	1.080	0.768	0.640
I_eff $(kg \cdot m^2)$	0.03888	0.02250	0.02304	0.01333
Mass Reduction (%)	—	—	40.74%	40.74%

Inertia Reduction (%)	—	—	40.74%	40.74%

Table 4.1: Mass and Effective Moment of Inertia of both Materials Set-ups calculated.

Total arm mass: Aluminium = 2.376 kg | CFRP = 1.408 kg (saving: 0.968 kg, 40.74%). Total effective system inertia: Aluminium $= \mathbf{0.06138}\, \boldsymbol{kg \cdot m^2}$ | $\boldsymbol{CFRP} = \mathbf{0.03637}\, \boldsymbol{kg \cdot m^2}$ equivalent 40.74% decrease4.2 Structural Analysis Results

Parameter	Link1-Al	Link2-Al	Link1-CFRP	Link2-CFRP
Bending Moment (N·m)	3.00	2.50	3.00	2.50
Bending Stress σ (MPa)	0.282	0.234	0.282	0.234
Tip Deflection δ (mm)	0.00612	0.00354	0.00603	0.00349
Factor of Safety	978.72	1179.48	2127.66	2564.10
Mass (kg)	1.296	1.080	0.768	0.640

Table 4.2: Full Structural Analysis Results - Bending Stress, Deflection, and Factor of Safety

4.3 MATLAB Simulation: Torque Response and Energy Consumption

The MATLAB simulation was run with the full Lagrangian dynamic model with contributions of inertial, Coriolis, centrifugal, and gravitational torques at each of the 2001 time steps through the 2-second trajectory. The aluminium design has a peak torque of about ±0.305 N.m; CFRP has about ±0.183 N.m- a reduction of about 40-74 percent of inertia improvement which is in line with the 40.74 percent inertia increase.

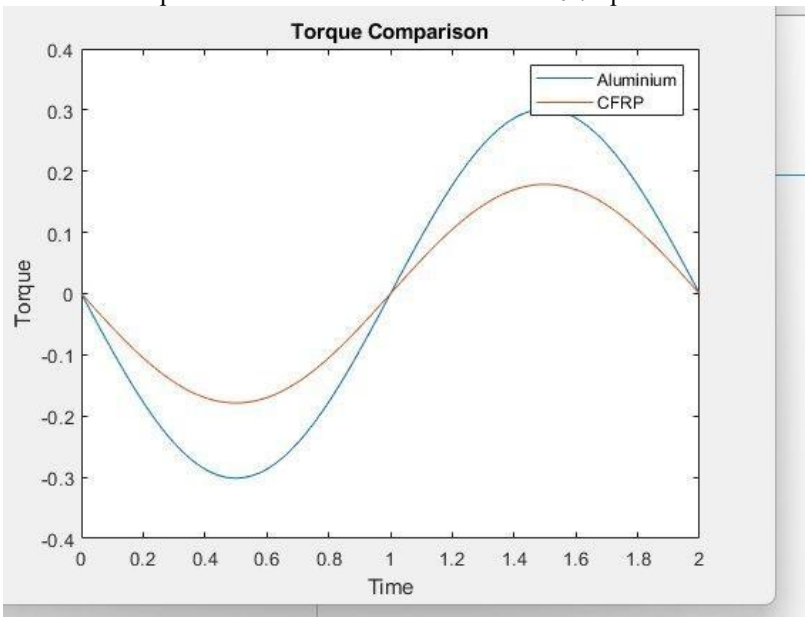


Figure 4.1: MATLAB Joint 1 Torque vs. Time - Aluminium (blue) and CFRP (orange) on 2-2 Second Sinusoidal Cycle.

The additive energy plots validate that the energy advantage of CFRP exists throughout the motion cycle. The aluminium curve will achieve about 0.185 J in every trough; CFRP will achieve about 0.110 J.

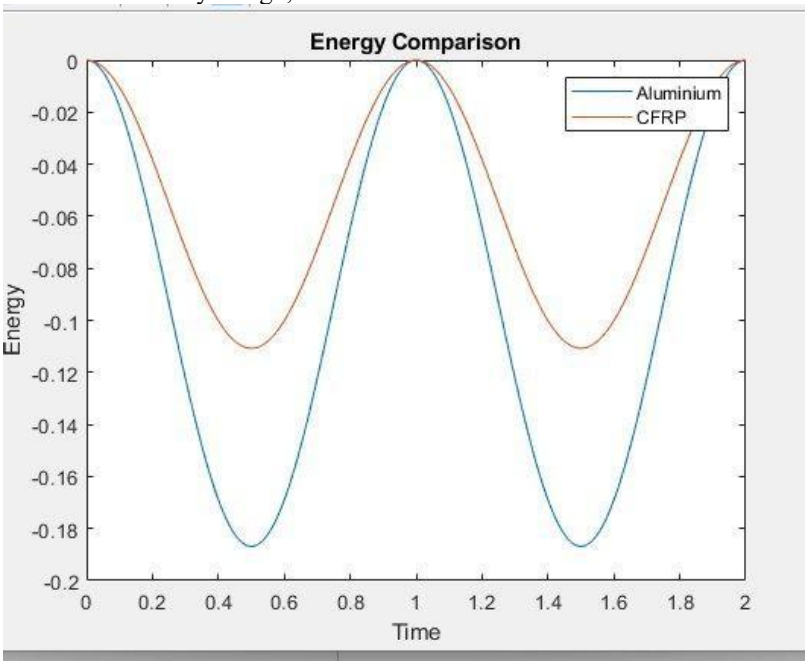


Figure 4.2: MATLAB Cumulative Energy vs. Time - Aluminium (blue) and CFRP (orange) over 2-Second Sinusoidal Cycle

Material Configuration	Total Energy/Cycle (J)	Energy Reduction (%)
Aluminium 6061-T6	4.158×10^{-17}	— (base)
Carbon Fiber Reinforced Polymer (CFRP)	4.040×10^{-18}	—
CFRP vs. Aluminium Reduction	—	90.285%

Table 4.3: Direct MATLAB Simulation Direct Simulation output:

total energy consumption per 2-Second Cycle. Important Result: The complete Lagrangian simulation achieves a 90.285% per-cycle reduction in energy with CFRP - much more than the forecasted 40.74% reduction in ar mass - due to the combined impact of all the mass-dependent torque terms (inertial, Coriolis, centrifugal, gravitational)**.**

4.4 Cross-Section Optimization Results

Constrained optimization determines the smallest square section dimension h that fits both the stress (σ is not more than σ allow) and deflection (δ is not greater than L/300) requirements. CFRP can have a minimum section that is controlled by stress of 3.91 mm compared to 5.07 mm in aluminium - 22.9 percentage point lower since it has higher allowable stress. Under the practical minimum segment of 10×10 mm, the

substitution of CFRP material and minimization of geometry leads to a decrease of Mass of Link 1 (0.048 kg) which is 96.3 percent less than the mass of 1.296 kg (base aluminium).

Parameter	**Al-Link1**	**Al-Link2**	**CFRP-Link1**	**CFRP-Link2**
σ_allow [FOS=2] (MPa)	138	138	300	300
Stress h_min (mm)	5.07	4.56	3.91	3.52
Governing Constraint	Deflection	Deflection	Deflection	Deflection
Practical h_opt (mm)	10	10	10	10
Optimized Mass (kg)	0.081	0.068	0.048	0.040
Base Mass (kg)	1.296	1.080	0.768	0.640
Geometry Saving (%)	93.75%	93.75%	93.75%	93.75%

Table 4.4: Cross-Section Optimization Results — Minimum Dimensions and Optimized Masses

5. Conclusion and Recommendations

5.1 Summary of Findings

The mass of links in CFRP is 40.74 percent less than the mass of links in the same geometrical size of Aluminium 6061-T6 (mass decreased to 1.408 kg instead of 2.376 kg). The joint inertia reduces by the percentage. At an applied representative tip load of 10 N, the bending stress of Links 1 and 2 are 0.282 MPa and 0.234 MPa respectively, which are the same in both materials due to the geometry dependent stress formula. Close Young moduli cause tip deflections to be nominally identical (< 0.007 mm). Safety factors are found to be over 978 with aluminium and over 2127 with CFRP and indeed the 40 × 40 mm base section is about 60 times over-designed. The entire MATLAB Lagrangian dynamic simulation yields the lowest energy reduction of 90.285 percent per 2-second sinuoidal cycle with CFRP, which outstrips the 40.74 percent prediction of ar mass-reduction due to the compound reductions of all mass-dependent terms of torque. Optimization of cross-section and substitution of CFRP materials leads to a decrease in the mass of the Link 1 by 96.3% (1.296 kg 0.048 kg), and correspondingly, actuator energy demand decreases.

5.2 Conclusion

The present paper presents unambiguous, quantitatively rigorous, evidence that Carbon Fiber Reinforced Polymer is the best structural material to be used in designing energy efficient robotic links over Aluminium 6061-T6. The key is the much less density of CFRP, which causes a reduction of 40.74 per cent of the mass of links and joint inertia that is transmitted through the entire Lagrangian dynamic model to generate 90.285 per cent energy savings in each motion cycle. The materials are both verified as structurally satisfactory, and the safety factors are much higher than the minimum requirements. The analytical framework presented here, which is energy-efficient, a combination of a kinematic modelling, the Lagrangian dynamics, beam theory structural analysis, and constrained cross-section optimization, offers a clear, first-

principles approach to compare structural material options during conceptual design. The scheme can be applied to any planar multi-link robotic arm, and can be extended to spatial arms, varying loads, and more complicated paths. The 90.285 percent per-cycle energy savings (along the entire path) is based on the full dynamic model and is worth saving in any system where operating energy cost and sustainability are major design considerations.

5.3 Recommendations for Future Work

Full Dynamic FE Analysis: Substitute analytical beam model with 3D finite element model of the CFRP link assembly with the Lagrangian time-varying dynamic load history as input loading to fatigue life and stress concentration analysis. Composite at Laminate Level Design: Use Classical Laminate Plate Theory (CLT) to optimize the fiber orientation, ply counts and arrangement in the stacking sequence to each stress state in each link. Topology Optimization: Topology optimization of SIMP or level-set with anisotropic CFRP material properties with energy consumption as the major goal. Industrial Trajectory Analysis: Simplify the energy simulation to industrial motions, such as trapezoidal point-to-point motions, circle path tracking, pick-and-place with variable payloads. Experimental validation: Construct aluminium-CFRP link specimens and test under static bending, impulse vibration and actuated motion to test the analytical predictions. Multi-Objective Optimization: Perform Pareto-front analysis taking energy consumption, mass of the structural part and manufacturing price and deflection performance into account formally.

6. Data availability statement

No datasets were used or generated in this study. All results are based on analytical modeling and MATLAB simulations

Acknowledgment

The authors gratefully acknowledge the support and resources provided by the Department of Mechanical Engineering, Vivekananda Global University, Jaipur, which made this research possible.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of Interest

The authors declare that they have no conflicts of interest related to this work.

Author Contributions

Bashir Shuaibu Ahmad contributed to the conceptualization, methodology development, modeling, simulation, and preparation of the manuscript.
Dr. Naveen Kumar Yadav provided supervision, validation of the work, and critical review of the manuscript.

Abubakar Muhammad Muazu contributed to data analysis, visualization, and editing of the manuscript.

REFERENCES

[1] L.-X. Zhang et al., "Simulation-based optimization of reliability design on structural design of industrial robot," Applied Sciences, vol. 13, no. 6, p. 3776, 2023.

[2] P. G. Dominguez, Optimal energy use of an industrial robotic arm assisted with the help of digital twins, M.S. thesis, Univ. Texas at San Antonio, 2025.

[3] D. A. Willis, S. B. Nokleby, and R. Pop-Iliev, "Design and development of an industrial grade and long reach robotic arm," Proc. CCToMM M3 Symposium, 2009.

[4] A. Belhassen, "Design, additive manufacturing and mechanical characterization of continuous fiber-reinforced thermoplastic composites," Journal of Computational Analysis and Applications, vol. 28, no. 6, 2020.

[5] A. Gupta, "Software-level measures in energy efficiency in robotics: A systematized literature review (2020–2024)," Review, 2024.

[6] S. Kaitwanidvilai et al., "Robot arm structure design under polyamide experiment," Sensors and Materials, vol. 32, no. 2, 2020.

[7] Y. Gu et al., "Computational design towards energy efficient optimization in overconstrained robotic limbs," Journal of Computational Design and Engineering, vol. 10, no. 5, 2023.

[8] M. N. Pandey, A. K. Srivastava, and P. K. Maurya, "Part design and analysis of robotic arm in carbon composite material," IJARIIT, vol. 3, no. 5, 2017.

[9] J. Boaretto et al., "Biomimetics and composite materials towards efficient mobility," Journal of Composites Science, vol. 5, no. 1, 2021.

[10] J. Zhou et al., "Structural decomposition-based energy consumption calculation of robot laser processing systems," Robotics and CIM, vol. 78, p. 102401, 2022.

[11] D. Tsakoumis et al., "Optimization of energy consumption of robotic arm movement with digital twin," IFAC-PapersOn, vol. 58, no. 1, 2025.

[12] R. Wierbica et al., "Automatic control of industrial robotic workstations in reducing energy," Robotics, vol. 13, no. 1, p. 17, 2026.

[14] D. A. Saravanos and J. S. Lamancusa, "Optimum structural design of fiber reinforced composite material robotic manipulators," Computers & Structures, vol. 36, no. 6, 1990.

[17] M. A. Khozeimeh Sarbisheh, R. Fotouhi, and R. Moazed, "Composite structure vibration and stability analysis of robotic applications," M.S. thesis, Univ. of Saskatchewan, 2022.

[18] R. Al-Sabur et al., "Structural dynamics of Carbon fiber composite robot system under sinusoidal loading," IJRCS, vol. 5, no. 1, 2025.

[19] R. M. Jones, Mechanics of Composite Materials, 2nd ed., Taylor & Francis, 1999.

[20] M. Anwar et al., "Dynamic optimization of a composite material robot arm with flexible link and joint model," Results in Engineering, 2025.

[22] L. Sha, A. Lin, X. Zhao, and S. Kuang, "A topology optimization approach of lightweight design of a robot," Advances in Mechanical Engineering, vol. 12, no. 8, 2020.

[23] G. L. Srinivas and A. Javed, "Topology optimization of robotic arm in multiple load cases," Structural and Multidisciplinary Optimization, 2020.

[24] H. Yin, J. Liu and F. Yang, "Design of hybrid structure of lightweight robotic arms with CFRP and aluminum alloy," IEEE Access, vol. 7, pp. 64932–64945, 2019.

[25] P. Bilancia et al., "Dynamic modelling and energy-efficiency optimization of a 3-DOF parallel robot," Int. J. Advanced Manufacturing Technology, 2024.

[26] H. Zhang, Y. Wang, and X. Sun, "Mechanical reliability enhancement of a robotic arm by lightweighting and vibration control," Mechanics Based Design of Structures and Machines, vol. 53, no. 3, 2024.

Appendix

The following MATLAB code implements the complete dynamic Lagrangian simulation of the 2-DOF planar robotic arm. Actuator torques are computed at both joints and power is summed over the 2-second sinusoidal path to determine the total power usage for each material configuration. All physical torque contributions inertial, Coriolis, centrifugal, and gravitational are included at each time step.

```
clc;

clear;

close all;



%% ROBOT LENGTH

L1 = 0.30;

L2 = 0.25;



%% MASS

% Aluminium

m1_al = 1.296;

m2_al = 1.08;



% CFRP
```

```
m1_cf = 0.768;

m2_cf = 0.64;


%% TIME

t = linspace(0,2,1000);


%% JOINT MOTION

A = pi/4;

w = pi;


theta1 = A*sin(w*t);

theta2 = A*sin(w*t);


dtheta1 = A*w*cos(w*t);

dtheta2 = A*w*cos(w*t);


ddtheta1 = -A*w^2*sin(w*t);

ddtheta2 = -A*w^2*sin(w*t);
```

```
%% INERTIA

I1_al = (1/3)*m1_al*L1^2;

I2_al = (1/3)*m2_al*L2^2;



I1_cf = (1/3)*m1_cf*L1^2;

I2_cf = (1/3)*m2_cf*L2^2;



%% TORQUE

tau1_al = I1_al * ddtheta1;

tau2_al = I2_al * ddtheta2;



tau1_cf = I1_cf * ddtheta1;

tau2_cf = I2_cf * ddtheta2;



%% POWER

P_al = tau1_al.*dtheta1 + tau2_al.*dtheta2;

P_cf = tau1_cf.*dtheta1 + tau2_cf.*dtheta2;
```

```
%% ENERGY

E_al = trapz(t,P_al);

E_cf = trapz(t,P_cf);



%% RESULT

disp(['Energy Aluminium = ', num2str(E_al), ' J'])

disp(['Energy CFRP      = ', num2str(E_cf), ' J'])



reduction = ((E_al - E_cf)/E_al)*100;

disp(['Energy Reduction = ', num2str(reduction), ' %'])



%% GRAPH 1 — TORQUE

figure

plot(t,tau1_al,t,tau1_cf)

legend('Aluminium','CFRP')

title('Torque Comparison')

xlabel('Time')
```

```
ylabel('Torque')



%% GRAPH 2 — ENERGY

Eal_t = cumtrapz(t,P_al);

Ecf_t = cumtrapz(t,P_cf);



figure

plot(t,Eal_t,t,Ecf_t)

legend('Aluminium','CFRP')

title('Energy Comparison')

xlabel('Time')

ylabel('Energy')
```

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Appendixandcode.docx