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Adaptive Structural Design of River Monitoring Systems: Enhancing Environmental Monitoring Capabilities and Sustainability

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ABSTRACT

The accelerating degradation of river ecosystems due to pollution necessitates the innovation of River Monitoring Systems (RMS) to protect these critical waterways. This research presents a novel design for adaptive RMS camera structures, aimed at enhancing monitoring capabilities and addressing the limitations of current systems. Highlighting the essential role rivers play in sustaining biodiversity, our study underscores the severe consequences of pollution, as exemplified by the deteriorating condition of Malaysia’s Klang River. We identify the need for a flexible RMS structure to overcome challenges such as excessive weight, corrosion susceptibility, and maintenance difficulties. Our methodology integrates advanced 3D Drawing Software for structural design, Fusion 360 for weight analysis, and a combination of manual calculations and simulations for vibration analysis. The findings reveal that Carbon Fiber Reinforced Polymers (CFRP) are the optimal material choice, offering an excellent balance of performance and cost-efficiency. This research successfully develops a structurally sound, user-friendly, and dynamically stable RMS camera structure, significantly advancing environmental monitoring practices. The study's contributions provide a foundation for future innovations in adaptive structural design, with broad implications for safeguarding river ecosystems worldwide.

1. Introduction

Rivers are not merely conduits of water; they are essential lifelines that support intricate ecosystems, sustaining biodiversity and providing crucial resources for human communities worldwide [1]. These waterways serve as habitats for a diverse array of flora and fauna, contributing to the rich tapestry of biodiversity that sustains life on our planet [2]. They play a pivotal role in regulating natural processes such as nutrient cycling and sediment transport, which are vital for

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maintaining the health of aquatic ecosystems [3-5]. Furthermore, rivers provide essential resources such as drinking water, irrigation for agriculture, and opportunities for recreation and tourism, making them indispensable to human societies. The cultural and economic significance of rivers cannot be overstated, as they have historically been centres of civilization and continue to support the livelihoods of millions of people around the world [6].

However, rivers are increasingly polluted with debris resulting from human activities such asimproper waste disposal, urban runoff, and inadequate waste management practices [7,8]. The accumulation of plastics, metals, and organic matter in these waterways poses significant environmental challenges, affecting aquatic life and disrupting ecosystem functions [9-12]. The persistence of these pollutants degrades water quality and jeopardizes the health of the ecosystems that depend on these rivers for survival. This growing threat underscores the urgent need for effective measures to mitigate debris pollution and protect the vital ecological and societal functions that rivers provide. Addressing these issues is critical for ensuring the sustainability and resilience of river ecosystems in the face of ongoing environmental pressures [13-15].

Current river debris monitoring methods vary widely, from labour-intensive manual sampling and visual inspections to sophisticated automated sensor networks and remote sensing technologies that offer real-time data on debris characteristics and distribution [16-19]. While these advanced methods enhance accuracy, challenges such as high costs and technical limitations hinder their widespread application for continuous monitoring [20,21]. In contrast, attaching cameras to bridges stands out as a practical, cost-effective solution that enables ongoing monitoring without significant infrastructure investments. This approach leverages existing structures to provide continuous surveillance of debris accumulation and movement, facilitating timely intervention and informed decision-making to mitigate environmental impacts.

Bridge-mounted cameras are specialized surveillance systems installed on bridge structures to monitor river environments effectively. These cameras capture high-resolution images and videos in real time, providing crucial insights into debris accumulation, pollution sources, and ecosystem dynamics. Compared to labour-intensive manual methods and expensive automated sensor networks, bridge-mounted cameras offer significant advantages in terms of cost-effectiveness and operational simplicity. Their strategic placement on bridges allows for continuous monitoring without the need for extensive setup or other overhead costs associated with alternative monitoring methods. This approach not only streamlines monitoring efforts but also facilitates prompt responses to environmental changes, ensuring proactive management of river debris and contributing to sustainable environmental practices. However, the regular requirement for maintenance is essential due to factors such as weather exposure and the wear and tear of equipment over time.

Typically, bridge-mounted cameras are installed on bridge railings using specialized mounting systems designed to ensure stability and provide optimal monitoring coverage. These installations are integrated into the bridge structure, requiring careful consideration of load-bearing capacities and the structural integrity of the railing. While these systems significantly enhance monitoring capabilities, maintaining these cameras presents inherent challenges due to their elevated positioning and the intricacies involved in accessing and servicing securely attached equipment. Tasks such as component inspection and replacement demand the use of specialized equipment and skilled personnel, often leading to temporary closures of lanes or pathways to guarantee safe maintenance operations. Furthermore, managing the excessive weight of camera systems and addressing their susceptibility to corrosion due to environmental exposure are critical considerations. These factors highlight the necessity for adaptive and extendable structures that not only streamline maintenance efforts but also ensure efficient upkeep, thereby minimizing disruptions to ongoing monitoring operations while maximizing the longevity and reliability of monitoring infrastructure [22].

In response to the challenges encountered by current RMS, this research proposes a novel approach focused on developing an adaptive structure for river debris monitoring cameras [23]. The study integrates vibration analysis techniques, employing both manual calculations and modern software tools, to ensure structural stability specifically in bridge environments. Emphasizing extendable design features, the approach aims to enhance monitoring capabilities while simplifying maintenance procedures [24]. These innovations are anticipated to significantly bolster the adaptive and sustainable capacity of river monitoring solutions, thereby promoting more effective environmental stewardship and enhanced management of aquatic ecosystems.

2. Materials and Methods

2.1 Data Collection

The data collection section is pivotal for gathering essential information to support the design of adaptive structures for a river monitoring system in Klang, Malaysia. This phase encompasses critical activities such as site selection and detailed measurements of existing structures, ensuring comprehensive data acquisition to inform the adaptive structure design.

2.1.1 Site selection

In Klang, Malaysia, there are two interceptors, Interceptor 002 (Figure 1) and Interceptor 005 (Figure 2), which are vessels designed to collect debris from rivers. These interceptor locations were chosen based on their high debris accumulation rates, making them ideal for addressing the significant issue of river pollution. Near these interceptors, RMS structures are installed to enhance the efficiency and effectiveness of debris collection and management. The RMS structures serve multiple purposes: they provide real-time data on debris accumulation, monitor the performance of the interceptors, and enable prompt maintenance and intervention when necessary. Additionally, they help in assessing the environmental impact of debris on the river ecosystem. To the best of our knowledge, these are the only two RMS structures currently installed in Malaysia, representing a pioneering effort in the country's river debris management strategy.

(a) (b)

Fig. 1. (a) Interceptor 002 (b) Google map location of Interceptor 002 in Klang River, Malaysia (https://maps.app.goo.gl/EvRpSbqVJ7AmTeDu7)

(a) (b)

Fig. 2. (a) Interceptor 005 (b) Google map location of Interceptor 002 in Klang River, Malaysia (https://maps.app.goo.gl/khxAHrmUxj1dWDEE8)

2.1.2 Existing structure measurement

To obtain detailed measurements of the existing structures and bridge railings, we conducted site surveys at Kota Bridge and Parang Bridge (Figure 3). Using high-precision tools, we ensured the accuracy and reliability of our data. These measurements are crucial for evaluating the current state of the RMS and bridge railings, allowing informed recommendations for improvements and future system implementations elsewhere. They provide foundational data essential for designing new structures tailored to meet environmental and operational demands at each location. Meticulous documentation and analysis enable precise design adjustments, optimizing structural integrity and functional efficiency of new RMS installations. Understanding site-specific nuances ensures effective contributions to ongoing debris management and environmental conservation efforts in Klang, Malaysia.

(a) (b)

Fig. 3. RMS Camera's structure at (a) Parang Bridge, Klang (b) Kota Bridge, Klang

2.1.3 Structural integration and adaptability inspection

To comprehensively assess the integration of the existing structures with the bridges and evaluate their adaptability, we conducted thorough visual inspections. These inspections involved detailed observations of how the structures are securely integrated (red circle in Figure 3) into the bridge infrastructure, including methods of anchoring and reinforcement. We documented the materials used and their resilience to environmental factors, particularly corrosion resistance, which is crucial for ensuring long-term durability [25]. Additionally, we studied the strategic placement of these structures relative to the river environment to understand their role in maintaining continuous operational reliability under varying river conditions. These findings were meticulously documented to gain valuable insights into the structural integrity and functional adaptability of bridge-integrated systems.

2.2 Design and Optimization of the Adaptive Structure

In order to design an adaptive structure that aligns with the assessment conducted, several factors are crucially considered for the design stage of the new adaptive structure. These factors are integral to the design process, ensuring that the new adaptive structure meets functional requirements, environmental considerations, and regulatory standards identified during the site assessment.

2.2.1 Length

Ideally, determining the optimal length of the structure is site-specific, depending on factors such as the span over water bodies and integration into existing infrastructure. However, the length of the structure significantly influences its vibrational characteristics. A shorter length results in a higher natural frequency, which helps mitigate resonance with vibrations from the bridge where the adaptive structure is to be attached.

Typically, heavy vehicle-induced vibrations fall within the range of 1 Hz to 15 Hz, influenced by factors such as vehicle speed, weight, and the bridge's characteristics. This range should be avoided when constructing an adaptive structure for a river monitoring system. Ensuring that the natural frequencies of the monitoring structure do not overlap with these induced vibrations is crucial to prevent resonance, which can amplify the vibrations and lead to structural fatigue, instability, and blurred images in captured data.

To ensure the structure's length falls outside the critical natural frequency ranges of 1 Hz to 15 Hz, we employed Beam Theory (Eqn. 1) to calculate the natural frequency of the adaptive structure and cross-check it with these ranges. Beam Theory is a method used in structural engineering to analyze the behavior of beams under various loads, predicting deflections, stresses, and natural frequencies. According to Beam Theory, the natural frequency is inversely proportional to the square root of the length (L), as described by the formula:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad (1)$$

where f_n is the natural frequency, k is the stiffness, and m is the mass. By using this approach, we can ensure that the structure avoids resonance with the bridge's vibrations, thereby enhancing the stability and performance of the adaptive structure.

2.2.2 Thickness

Specifying the appropriate thickness of structural components to meet safety standards, load-bearing requirements, and longevity expectations. Thickness considerations may vary based on material properties and anticipated environmental stresses. In Malaysia, the common available thicknesses for various materials used in construction and manufacturing include High-Density Polyethylene (HDPE) with thicknesses typically ranging from 1 mm to 50 mm, Acrylonitrile Butadiene Styrene (ABS) from 1 mm to 6 mm, Stainless Steel AISI 304 from 0.4 mm to 20 mm, CFRP from 0.2 mm to 5 mm, Aluminum 6061 from 0.5 mm to 150 mm, and Mild Steel from 0.5 mm to 25 mm. These materials serve a wide array of applications, from lightweight and corrosion-resistant uses to high-strength and structural purposes [26]. The thickness selection for these materials will be based on collaborator requests and market availability, ensuring that the specific needs of each project are met while also considering the supply constraints and industry standards [27].

2.2.3 Material

For our study, we employed Fusion 360, a cloud-based 3D modeling software, to conduct a comprehensive material analysis for the RMS camera project. Fusion 360's detailed material library includes properties such as density, yield strength, and thermal conductivity, which are crucial for evaluating materials like HDPE, ABS, Stainless Steel AISI 304, CFRP, Aluminum 6061, and Mild Steel [28]. Each material was selected based on specific performance criteria essential for riverine environments as presented in Table 1.

Table 1
Material properties and structural advantage

Material	Key Property	Description
HDPE (High-Density Polyethylene)	Strength with low weight	Offers good strength while being lightweight.
ABS (Acrylonitrile Butadiene Styrene)	Impact resistance	Provides high impact resistance, making it durable.
Stainless Steel AISI 304	Corrosion resistance and strength	Ensures excellent corrosion resistance along with high strength
CFRP (Carbon Fiber Reinforced Polymer)	Strength-to-weight ratio	Excels in having a high strength-to-weight ratio, making it very strong and lightweight.
Aluminum 6061	Versatility with weight reduction	Combines versatility and good mechanical properties with reduced weight.
Mild Steel	Reliability and compliance	Provides a balance of reliability, ductility, and ease of fabrication.

Within Fusion 360, we simulated each material's response to environmental stresses to ensure the RMS camera's adaptive structure meets rigorous design specifications for stability and reliability [29]. This methodology ensures the optimal integration of materials to enhance durability, efficiency, and performance, which are crucial for effective debris detection in dynamic riverine settings. This approach allows us to precisely tailor the adaptive structure to meet the specific demands of its operational environment.

2.2.4 Weight

Weight is a crucial factor in the design of the adaptive structure due to its impact on structural stability, transportation, installation, and maintenance requirements. Excessive weight can lead to overloading, structural failure, complicated transportation and installation, and increased maintenance needs. To ensure compatibility with existing supports and minimize additional load, we precisely calculated the structural weight using Fusion 360. This calculation helps prevent overloading and allows us to select materials that offer an optimal balance between strength and weight, thereby enhancing the performance and resilience of the RMS camera system. By leveraging Fusion 360, we can create detailed simulations and optimizations to achieve the best possible design for our application.

2.2.5 Vibration Analysis

Vibrations can significantly impact a camera attached to a bridge, resulting in blurred images, jittery video, and reduced data accuracy due to sensor misalignment. Additionally, they contribute to structural fatigue, loosening of fasteners, and accelerated wear on mechanical and electrical components, ultimately reducing the system's lifespan. To mitigate these effects, we conduct vibration analysis to assess dynamic response and structural integrity under operational conditions, focusing on calculating induced displacement. This analysis aids in optimizing design parameters to mitigate vibrations that could affect the system's performance or durability.

Firstly, we calculate the moment of inertia, I using Eq. (2):

Moment of Inertia, $I = \frac{1}{12} \times b \times t^3$ (2)

where
b - width of the beam
t - thickness of the beam

Next, we calculate stiffness of the structure, k using Eq: (3)

Stiffness, $k = \frac{E \times I}{L}$ (3)

where
E - Young’s modulus of the material
I - moment of inertia of the cross-sectional area
L - length of the structure

Subsequently, the damping coefficient, c are calculated using the following equation

Damping coefficient, $c = 2\sqrt{k \times m}$ (4)

where
k - stiffness of the structure
m - mass of the structure

Finally, we calculate displacement x when $t = 1s$ using Eq. (5)

$$m\ddot{x} + c\dot{x} + kx = F(t) \tag{5}$$

where
m - mass of the structure
c - damping coefficient
k - stiffness of the structure
x - displacement
$F(t)$ - external force by the passing vehicle

2.2.6 Cost

To ensure cost-effective fabrication, we conduct a comprehensive cost analysis of the adaptive structure designed for the RMS Camera, we conduct a thorough cost analysis of the adaptive structure designed for the RMS Camera which includes:

i. **Volume Calculation**: Precisely determines component volumes to estimate material costs based on current market prices and quality standards.
ii. **Conversion and Cost Calculation**: Evaluates raw material conversion, waste generation, and associated labour and energy costs to optimize material efficiency.
iii. **Fabrication Cost Assessment**: Accounts for direct labor, machine time, facility overheads, and equipment depreciation during manufacturing.

3. Results
3.1 Site Assessment Findings

Table 2 presents a comprehensive summary of the measurements conducted at Kota Bridge and Parang Bridge. Despite its smaller dimensions, the Kota Bridge structure is essential to the RMS's overarching objective of ensuring continuous debris detection and effective monitoring. The differences in size between the structures at Parang Bridge and Kota Bridge underscore specific considerations tailored to each site. These include variations in railing clamp design, overall structure weight, length, thickness, and the specific requirements for support bars.

Table 2
Specifications of existing mounting structure

Bridge	Thickness	Length of bar	Weight	Type of clamp	Mounting platform	Material
Kota	60mm	1000mm	27.2kg	Rectangular	Bridge fence	Mild Steel
Parang	60mm	2000mm	46.45kg	Round	Bridge railling	Mild Steel

During our field assessments, we noted significant differences in weight between the bridge-mounted structures. The bar at Parang Bridge, weighing 46.45 kg, stands out as particularly heavy compared to the 27.2 kg bar at Kota Bridge. This weight disparity is crucial, especially when considering maintenance tasks such as the retrieval of RMS cameras. The heavier structure at Parang Bridge presents challenges in terms of manoeuvrability and logistical efficiency during maintenance operations. This observation underscores the importance of adaptive structures designed to manage and mitigate such challenges, ensuring operational flexibility and ease of maintenance in river monitoring systems.

3.2 Adaptive Structure Properties

This section explores critical aspects governing the design and performance of adaptive structures. Subsections include geometric specifications outlining dimensional requirements and mechanical and physical properties assessing structural integrity and material characteristics essential for optimal functionality.

3.2.1 Geometric specifications

According to our findings, the adaptive structure supporting the RMS Camera ranges between 1 meter and 2 meters in length. Using the maximum and minimum values of 1 meter and 2 meters, respectively, we calculated the natural frequency using equations 1, 2, and 4. The calculations for the case of 2 meters are provided as follows and the result for 1 meter and 2 meters are summarized in Table 3.

Moment of inertia,

$$I = \frac{1}{12} \times b \times t^3$$
$$I = \frac{1}{12} \times (0.2) \times (0.005)^3$$
$$I = 2.08 \times 10^{-9} m^4$$

Stiffness,

$$k = \frac{E \times I}{L}$$
$$k = \frac{(133 \times 10^9) \times (2.08 \times 10^{-9})}{1}$$
$$k = 276.64 \text{ N/m}$$

Natural frequency,

$$f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$
$$f_n = \frac{1}{2\pi} \sqrt{\frac{276.64}{19.84}}$$
$$f_n = 0.84 \text{ Hz}$$

Table 3
Structural Characteristics of Materials at Different Lengths

Length, L (m)	1	2
Weight, m (kg)	9.92	12.84
Stiffness, k (N/m)	276.64	138.32
Natural Frequency, f_n (Hz)	0.84	0.42

Based on the calculated natural frequencies presented in Table 3, it is evident that the adaptive structure supporting the RMS Camera, ranging from 1 meter to 2 meters in length, exhibits varying dynamic responses. For instance, at 1 meter, the structure demonstrates a natural frequency of 0.84 Hz, indicating a relatively lower frequency response compared to the 2-meter length, which shows a natural frequency of 0.42 Hz. Importantly, neither length falls within the critical range of 1 Hz to 15 Hz, which is a range to be avoided in the construction of adaptive structures for river monitoring systems. Therefore, any selection of length within the range of 1 to 2 meters is considered acceptable in terms of natural frequency characteristics for constructing an adaptive structure for a river monitoring system. For the purposes of this study, a length of 1 meter was arbitrarily selected to proceed with further analysis and design considerations.

Setting the length at 1 meter not only ensures that the structure operates outside the typical vibrational frequencies encountered in its operational environment but also enhances the stability and accuracy of RMS camera measurements. Additionally, this length strikes a balance between structural robustness and weight optimization, both crucial for maintaining operational integrity while minimizing excess load. A longer extension would increase structural weight, potentially compromising maneuverability and deployment efficiency, while a shorter length would result in a higher natural frequency, increasing the risk of resonance with environmental vibrations. Thus, setting the length at 1 meter ensures the adaptive structure's stability and reliability in mitigating resonance with bridge vibrations, thereby ensuring robust performance and prolonged operational efficiency of the RMS Camera system.

Based on our survey, we identified several available thickness options: 4mm, 5mm and 7mm. Considering the fabrication process, which involves metal bending, we selected a 5mm thickness, as per the request from our collaborator. This decision ensures the material can endure the bending process while supporting efficient manufacturing. The 5mm thickness strikes a balance between durability and manufacturability, effectively meeting the functional and practical requirements of the project.

3.2.2 Mechanical and physical properties

Six materials were analysed using Fusion 360 software to determine their precise weights and other mechanical properties of the adaptive structure. The mechanical and physical properties of these materials are detailed in Table 4.

Table 4 presents a comparative analysis of six materials considered for fabricating an adaptive structure for a river monitoring system: HDPE, ABS Plastic, CFRP, Aluminium 6061, Mild Steel, and Stainless Steel AISI 304. HDPE and ABS Plastic, weighing 7.20 kg and 8.04 kg respectively, exhibit lower mechanical strength with Young’s moduli of 0.911 GPa and 2.24 GPa, and yield strengths of 20.67 MPa and 20 MPa, making them less suitable for high-load applications. CFRP stands out with a Young’s modulus of 133 GPa, yield strength of 300 MPa, ultimate tensile strength of 577 MPa, and a weight of 9.92 kg, offering the best strength-to-weight ratio. Aluminium 6061 provides a balanced option with a Young’s modulus of 68.9 GPa, yield strength of 275 MPa, ultimate tensile strength of 310 MPa, and weight of 17.16 kg. Mild Steel and Stainless Steel AISI 304, while strong with yield strengths of 207 MPa and 215 MPa, and ultimate tensile strengths of 345 MPa and 505 MPa, are too heavy at 45.45 kg and 47.37 kg respectively, limiting their practicality. Therefore, CFRP is recommended for its optimal combination of lightweight design and robust mechanical properties, while Aluminium 6061 serves as a viable alternative with a good balance of strength and weight. Further evaluation of HDPE and ABS Plastic under real-world conditions is advised to assess their suitability for less demanding components of the structure.

Table 4
Material Mechanical and Physical Properties

Material	Density (kg/mm^3)	Young' Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Thermal Conductivity (W/m·K)	Thermal Coefficient (°C^{-1})	Specific Heat Capacity (J/kg°C)	Weight (kg)
HDPE	9.52×10^{-7}	0.911	0.392	20.67	20.67	2.11×10^{-4}	1.5×10^{-4}	2859	7.20
ABS Plastic	1.06×10^{-6}	2.24	0.38	20	29.6	1.6×10^{-4}	8.57×10^{-5}	1500	8.04
CFRP	1.43×10^{-6}	133	0.39	300	577	0.105	9.93×10^{-6}	1130	9.92
Aluminium 6061	2.7×10^{-6}	68.9	0.33	275	310	0.167	2.36×10^{-5}	897	17.16
Mild Steel (Existing)	7.85×10^{-6}	220	0.275	207	345	0.045	1.2×10^{-5}	480	45.45
Stainless Steel AISI 304	8×10^{-6}	195	0.29	215	505	0.016	1.73×10^{-5}	500	47.37

Figure 4 shows the weight comparison of various materials considered for fabricating an adaptive structure for a river monitoring system. HDPE (7.2 kg) and ABS Plastic (8.04 kg) are the lightest materials, offering significant advantages in terms of ease of deployment, handling, and cost-effective transportation. CFRP, with a weight of 9.92 kg, also remains relatively lightweight while providing an excellent strength-to-weight ratio and high resistance to environmental degradation, making it an ideal choice for durable applications in harsh environments. Aluminium 6061, weighing 17.16 kg, presents a moderate weight option, offering good corrosion resistance and ease of fabrication, making it a viable middle-ground solution. In contrast, Mild Steel (46.45 kg) and Stainless Steel AISI 304 (47.37 kg) are the heaviest materials evaluated. While they offer superior strength and durability, their significant weight poses challenges for installation and increases logistical costs, necessitating stronger supporting structures. Therefore, although Mild Steel and Stainless Steel AISI 304 provide excellent corrosion resistance and long-term reliability, lighter materials such as CFRP and Aluminium 6061 are preferred for their optimal balance of weight, strength, and environmental resistance, making them more suitable for adaptive structures in river monitoring systems.

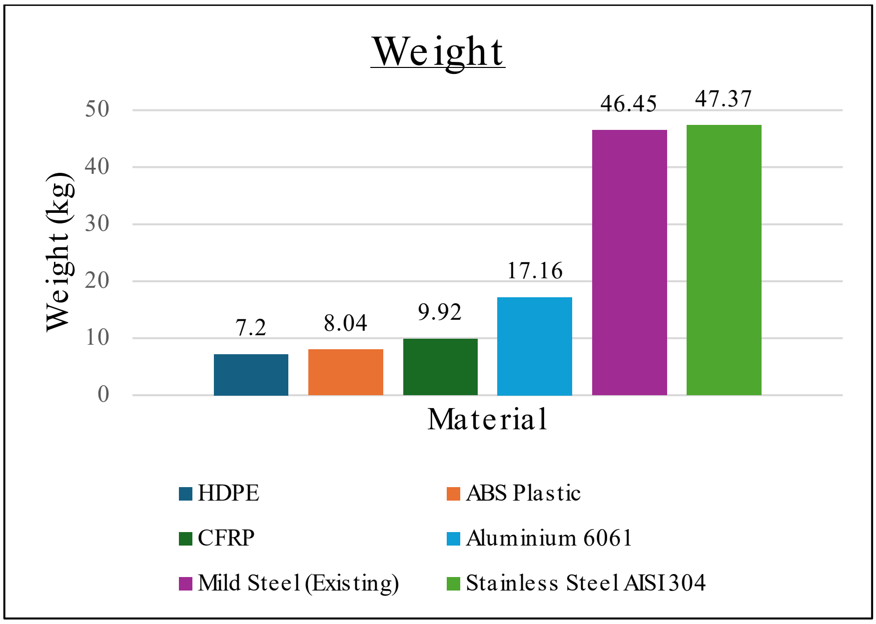

Fig. 4. Comparison with 5 Materials with Existing Mild Steel

3.3 Optimization Analysis

This section delves into the strategic process of optimizing material selection for an adaptive structure used in river monitoring, with a dual focus on vibration resistance and cost-effectiveness.

3.3.1 Vibration analysis

Figure 5 illustrates the natural frequencies of six materials considered for fabricating an adaptive structure for a river monitoring system attached to a bridge railing: HDPE, ABS Plastic, CFRP, Aluminium 6061, Mild Steel, and Stainless Steel AISI 304. HDPE and ABS Plastic have the lowest natural frequencies at 4.41 Hz and 6.56 Hz, respectively, making them more prone to resonance and potential instability under bridge vibrations. Stainless Steel AISI 304 and Aluminium 6061 exhibit intermediate natural frequencies of 22.28 Hz and 22.8 Hz, respectively, while Mild Steel is slightly higher at 23.88 Hz, indicating moderate resistance to dynamic loads from bridge vibrations. CFRP stands out with the highest natural frequency at 43.52 Hz, offering superior resistance to resonance and ensuring stable performance under varying vibration conditions of a bridge environment. Given these considerations, CFRP (Carbon Fiber Reinforced Polymer) is the most suitable material for this application due to its high resistance to vibrations, ensuring the highest level of stability and performance under bridge vibrations. HDPE and ABS Plastic may be less ideal due to their low natural frequencies. Stainless Steel, Aluminium 6061, and Mild Steel provide balanced options with adequate frequency resistance and material properties for the adaptive structure, but CFRP's superior characteristics make it the recommended choice.

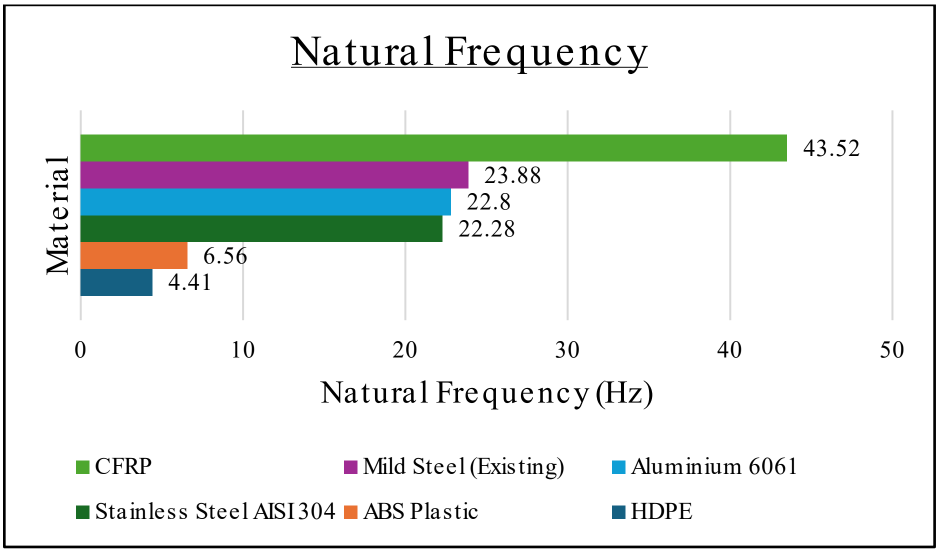

Fig. 5. Comparison of Natural Frequency from 5 materials with Mild Steel

Figure 6 shows the displacement of various materials used in fabricating an adaptive structure for a river monitoring system. CFRP exhibits the lowest displacement at 0.007 cm, indicating its exceptional rigidity and suitability for applications where minimal deformation is crucial. Mild Steel (0.05 cm) and Stainless Steel AISI 304 (0.06 cm) also demonstrate low displacement, highlighting their stiffness and suitability for robust structures. Aluminium 6061, with a moderate displacement of 0.64 cm, offers a good balance of flexibility and strength. In contrast, ABS Plastic (1.82 cm) and HDPE (3.39 cm) exhibit higher displacements, reflecting their lower stiffness and greater flexibility. These results suggest that while ABS Plastic and HDPE are advantageous for their lightweight properties, their higher displacement may compromise structural integrity. Therefore, CFRP and Aluminium 6061 are preferred due to their optimal combination of low weight and minimal displacement, making them more suitable for adaptive river monitoring structures that require durability and stability.

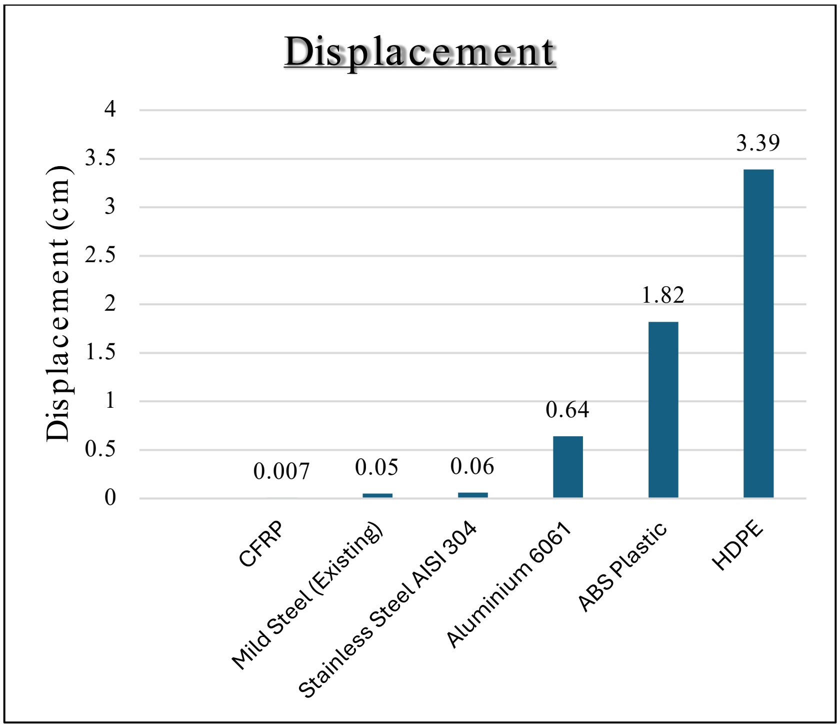

Fig. 6. Comparison of Displacement from 5 materials with Mild Steel

This comparative displacement analysis is crucial for selecting the optimal material for the adaptive structure of the RMS Camera. It offers a quantitative basis for decision-making, ensuring that the chosen material meets both the weight and strength requirements discussed in previous sections, while also exhibiting the desired vibrational behaviour. This is essential for maintaining the camera's stability and operational integrity in varying environmental conditions.

3.3.2 Cost Analysis

Figure 7 presents a comprehensive breakdown of costs associated with different materials for fabricating an adaptive structure for a river monitoring system, expressed in RM. The most significant costs are attributed to Mild Steel (Existing) and Stainless Steel AISI 304, accounting for RM 10,623.66 (32.3%) and RM 10,098.65 (30.7%) respectively, indicating their substantial role in the overall expenditure. Aluminium 6061 and CFRP are comparatively lower in cost, at RM 1,756.01 and RM 1,300, respectively, while HDPE and ABS Plastic incur the least costs, with HDPE at RM 421.52 and ABS Plastic at RM 622.8. This distribution highlights the predominance of steel materials in the cost structure, suggesting their importance due to durability and structural integrity. However, the significant cost disparity may influence material selection decisions. In conclusion, while Mild Steel and Stainless Steel are preferred for their performance and durability, budget constraints may necessitate considering Aluminium 6061 or CFRP as alternative materials that balance cost and functionality for the adaptive structure in the river monitoring system.

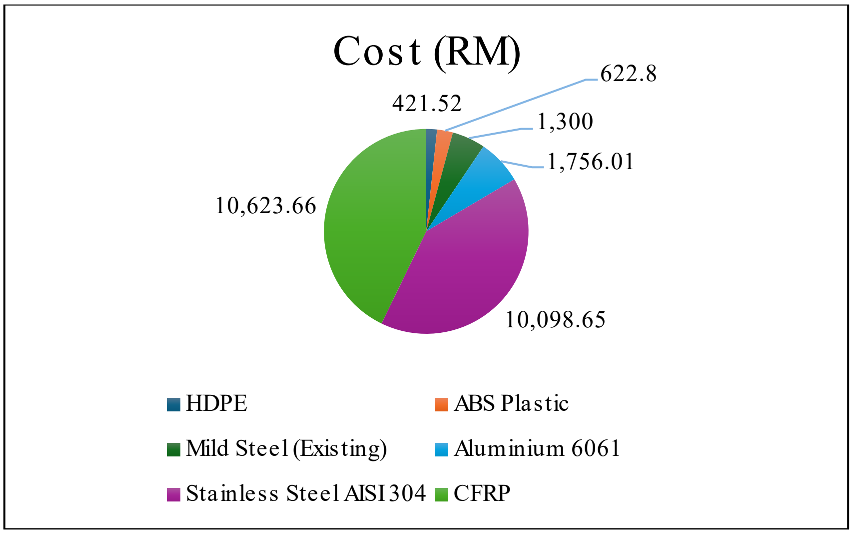

Fig. 7. Comparison of Displacement from 5 materials with Mild Steel

3.4 Pugh Chart

The Pugh Chart is indispensable for material comparison as it offers a structured method to evaluate multiple parameters concurrently, providing a clear visual representation of each material's strengths and weaknesses. This systematic approach facilitates informed decision-making by illuminating trade-offs between material properties, ensuring optimal selection aligned with specific application requirements. Ultimately, the Pugh Chart enhances decision-making efficiency by prioritizing key performance indicators and streamlining the evaluation of material alternatives. Table 5 presents a comprehensive comparison of each material against mild steel, assessing attributes such as weight, natural frequency, stiffness, damping coefficient, and cost, crucial for the fabrication of adaptive structures.

Table 5
Pugh Chart of 5 Materials Compared with Existing Mild Steel

Material	ABS Plastic	Aluminium 6061	CFRP	HDPE	Stainless Steel AISI 304	Mild Steel (Existing)
Weight (kg)	+	+	+	+	-	< 46.45
Natural Frequency (Hz)	-	-	+	-	-	> 23.88
Stiffness k (N/m)	-	-	-	-	-	> 431.70
Damping coefficient, c (Ns/m)	-	-	-	-	-	> 283.21
Displacement (cm)	-	-	+	-	-	< 0.05
Cost (RM)	+	-	-	+	-	< 1,300
Total number of positive (+)	2	1	3	2	0	-
Total number of negative (-)	4	5	3	4	5	
Total	-2	-4	0	-2	-5	
Rank	2	3	1	2	4	

Based on Table 5, Carbon Fiber Reinforced Plastic (CFRP) emerges as the top-ranking material, demonstrating superior attributes essential for dynamic river environments. CFRP excels in reducing weight, enhancing natural frequency, and minimizing displacement, crucial for maintaining stability and accuracy in monitoring systems. Its high stiffness and moderate cost, although higher than Mild Steel, justify its selection for applications requiring robustness and adaptability. ABS Plastic and Aluminium 6061 exhibit moderate potential but fall short in stiffness and other critical parameters compared to CFRP. Stainless Steel AISI 304 and Mild Steel rank lower due to their inherent weight and cost constraints, limiting their suitability for agile and precise river monitoring structures. HDPE, while cost-effective and lightweight, lacks the necessary stiffness and damping coefficients vital for ensuring structural integrity over time. In conclusion, CFRP emerges as the optimal choice among the evaluated materials, offering a balanced combination of performance, durability, and adaptability crucial for effective river monitoring systems. Table 6 shows the comparison between CFRP with Existing Mild Steel

Table 6
Comparison between CFRP with Existing Mild Steel

Material	CFRP	Mild Steel (Existing)
Weight (kg)	9.92	46.45
Natural Frequency (Hz)	43.52	23.88
Stiffness k / (N/m)	260.98	431.70
Damping coefficient, c / (Ns/m)	101.76	283.21
Displacement (cm)	0.007	0.05
Cost (RM)	1,623.66	1,300

3.5 Prototype CAD Drawing

Figure 8 presents the final design of the adaptive structure for a river monitoring system, developed based on the preceding analysis. Rendered in an isometric view, it provides a comprehensive three-dimensional representation on a two-dimensional surface. The drawing highlights a central beam engineered for optimal load-bearing capacity, and flanges with pre-drilled fastening holes for secure attachment, indicating its role in alignment and support within a larger mechanical system. This design, refined through detailed evaluation of material properties and structural requirements, ensures robust performance and adaptability for its intended application in river monitoring systems.

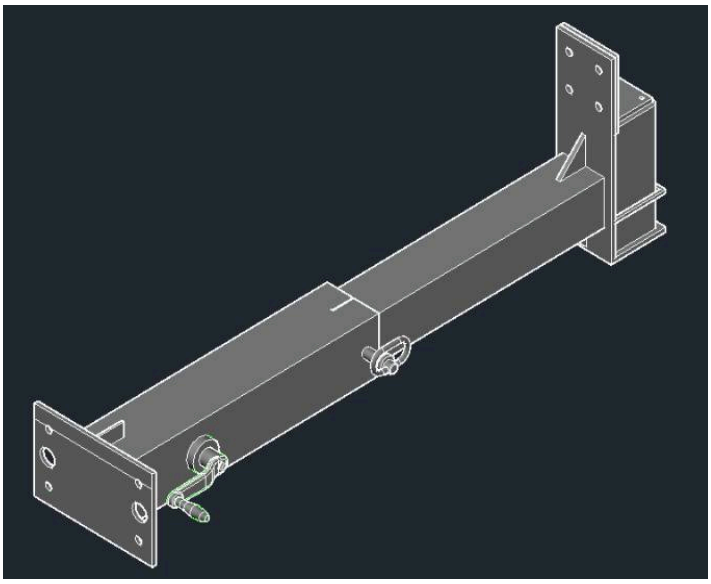

Fig. 8. 3D CAD Drawing for Designated Adaptive Structure

4. Conclusions

The research embarked on a mission to develop an adaptive structure for River Monitoring Cameras to enhance monitoring capabilities. This goal was achieved by creating a structurally adaptable and extendable design. The resulting prototype not only met the initial design objectives but also introduced innovative solutions for environmental surveillance. Furthermore, the project succeeded in designing a user-friendly structure that allows for straightforward removal from the casing. This design consideration significantly simplifies the maintenance and repair processes, thereby improving the overall efficiency and reliability of the monitoring system. The ease of access and user-centric approach in the design ensures that the structure can be maintained with minimal downtime, which is crucial for continuous monitoring applications. Additionally, the research conducted a thorough vibration analysis of the developed structure to assess its stability and identify areas for improvement. Through a combination of manual calculations and modern software simulations, the study provided valuable insights into the vibrational behaviour of the structure. This analysis was vital in confirming that the design would remain stable under operational conditions, ensuring the integrity and longevity of the River Monitoring System. Analysis shows that CFRP ranks highest among the alternatives, demonstrating superior performance in most categories, particularly in terms of weight and natural frequency, which are critical for the operational efficiency of the RMS Camera's adaptive structure.

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