



Quadcopter Theoretical Weight Estimation and Comparison during Design Phase

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Abstract: Weight estimation of materials from their characteristic density has a great advantage on analyzing the basic weight parameter put at initial stage of the project. During the detail design stage, each component is designed with basic dimensions and material selection. The selected weight will be verified with other materials such as steel, aluminum and composites. The total weight of the Quadcopter when made of steel, aluminum and composites are compared with the reference value of parameter, total component weight and then the best material will be recommended for the Quadcopter airframe. The composite materials are found to be light and strong when compared to steel and aluminum frames. If we use this material the Quadcopter will have more flight time for spraying.

Keywords: Material Weight, Steel, Aluminium, Composite, Density, Quadcopter Frame, Parts Design

1. Introduction

Materials have different properties and knowing them will ensure that how to select them with the right properties to develop a given product. In this paper some basic types of materials that can be used for the project what and the properties of materials that needed to know in the production of new model are covered. Quadcopters are always built with an idea to be as efficient as possible dynamically and such efficiency is achieved by making the Quadcopter lightweight. This design feature helps in reducing the weight and increasing battery life. The initial weight calculation includes estimation for Quadcopter parts; main frame, battery flight controller, battery adapter, motor, ESC, propeller, wires and screws. The initial estimated Quadcopter parameters are a reference for the weight calculation and component weight can be estimated later but the optimal frame weight should be calculated at the initial of the project with different materials [1].

We add up all of the masses in grams or kilograms in order to find the total estimated mass of model Quadcopter and to get more accurate result, we use spreadsheet software like Google Sheets and Microsoft Excel. This exact value of the weight helps to get accurate power-to-weight ratio of the Quadcopter. The parameter represents the ratio between a vehicle's power and its total weight. If the PWR is higher means the faster the vehicle will accelerate this implies that lightweight can fly fast because they have a higher PWR. Lighter drone weight implies less motor power will be used and cost minimizes drastically [2].

The main characteristic for a drone dynamic is the TWR and in order a vehicle to fly, the TWR shall at least equal to 1 and for takeoff $TWR > 1$. $TWR = 2$ gives a fairly dynamic Quadcopter [3]. Frame is the main component of a Quadcopter and using a strong and lightweight material is essential to achieve good drone characteristics and the frame usually designed in different parts or pieces which then assembled together for to get the final configuration of the Quadcopter. The subassemblies, type and number of parts to be produced depend on the shape of the Quadcopter. The main frame is designed to hold and withstand the force from the motors and propellers of the Quadcopter at the end of each arm. The central chassis of the Quadcopter frame houses power distribution board, flight controller and electronic speed controller (ESC) will be installed. [4].

2. Material Properties and Methods

2.1 Methods

The methodology to be followed in this research paper is putting the weight of the Quadcopter basic parameter and final component weight as a reference in order to calculate the airframe weight from detail designs. The materials to be considered for the airframe are steel with bamboo arms, aluminium with bamboo arms and composite with bamboo arms. We will analyze with mathematical calculations the weights from different materials and comparing with the initial Quadcopter parameters whether it is overweight or underweight. The best steps followed are;

- Put the reference design weight of Quadcopter from initial parameter
- Sorting the Quadcopter airframe detail designs in type and put them in excel for weight calculation
- Calculating each parts weight with different methods such as steel, aluminum and composites
- Calculating total weight of each parts design with each material in excel
- Weight comparison to select the best light weight material

2.2 Quadcopter Frame Materials

All flying vehicles need to be lightweight and the frame of a Quadcopter should be as stiff as possible to provide good strength. Strength and light weight are two contradictory ideas to each other. The stiffer we make a frame, the heavier it will be but there are materials which fulfils these properties. Lighter structure means the more efficient to operate and longer range will be covered. Nowadays, almost all UAV structures are made from carbon fiber composites and these materials offer several advantages for lightweight aerial vehicles [5].

Quadcopter frame is important component of the vehicle and there are lots of Quadcopter frame sizes and configurations and each Quadcopter frame is designed according to the purpose of the vehicle whether it is for sprayer, sport racing, cameras, hobby and mini. Quadcopter frame is the main structure that holds all the components together and should be rigid to prevent them from vibrations. Quadcopter structures are made from aluminum alloy, magnesium alloy, titanium, carbon fiber or thermoplastics such as polyester, nylon and polystyrene. In addition to this they can be made from combinations of these materials used on different parts of the drone to maximize overall performance. Combining metals have many advantages such as increasing the material's resistance to corrosion and increase their mechanical strength. In some pesticide spraying Quadcopter use F450 frame Built from quality glass fiber and polyamide nylon Pre-threaded brass sleeves for the entire frame bolts [6]. Common materials used in drone frame technology are wood, carbon fiber, steels, plastics, G10 fiber glass and aluminum and others [5].

After selected materials the Quadcopter can be analyzed with different simulations according to the purpose of the drone. Simulation is performed by researchers to their Quadcopter made of acrylic (plexiglass) for different materials using Solid Works software to generate various analyses; one of the analyses used was the drop test. The test assesses an assembly or a part's impact with a flexible or rigid planar surface and the software generated three results as shown in figure 1. Von Mises Stress is used as a value to determine whether a given material is going to fracture

or yield. The displacement which shows how the model moves in the chosen direction and strain is a geometric response measure and the shape change due to its applied forces [7].

2.3 Material Properties

Material properties are factors that qualitatively or quantitatively influence the response of a given material to forces, stress, strain, temperature etc. and material properties determine whether a material is suitable or unsuitable for a specific purpose. The mechanical and physical properties of materials are identified by their chemical composition and internal structure such as grain size or crystalline structure [8]. Another important factor is stiffness-to-weight ratio sometimes referred to as specific stiffness or specific modulus and stiffness is the measure of how much a material stretches when a load is applied. Stiffer material will stretch less when compared to a less stiff material for a given load. Higher specific stiffness materials are usually used in aerospace. For instance aluminum has a specific stiffness of 26, and carbon composites have a specific stiffness of 113 [9].

Similarly aerospace structure design also needs high strength-to-weight ratio materials which are referred as specific strength. Strength is the amount of load a structure can take before it breaks or fails and the higher the specific strength, the better the material will be for a given structural load [9]. Carbon fiber has high stiffness and it can break with a small amount of elongation where as metals tend to stretch and deform significantly before breaking due to plastic deformation where as carbon fiber composites don't permanently deform but will fracture after a small percentage of elongation. This means carbon composites are very stiff and it takes a lot of load before they will break [10]. The specific strength is also known as the strength-to-weight ratio of a material's force per unit area at failure and divided by its density. The SI unit for specific strength is Pa·m³/kg. The formula of breaking length is given by [8];

$$L = \frac{T_s}{\rho \cdot g}$$

To analyze the frame for landing simulations, authors divided the Quadcopters in categories with the use of variables such as mesh type, jacobian points, element size, total nodes, total elements, maximum aspect ratio and others and performed the simulations. The following diagram shows landing simulation for ABS plus plastic (Max 3.2mm displacement) and carbon fiber (max 6.5mm displacement) for figure 2(a) and (b) respectively.

Based on the results, they highlighted that the highest stresses in landing mode occur on the arms near to the frame center. [11]. In figure 3, for aerospace, high specific stiffness and high specific strength materials are

preferable and stiff materials that keep their shape under load are better than materials that deform permanently. They must withstand high flight loads without break.

Specific strength of Aluminum is 115, titanium 76 and carbon composites 785 [12].

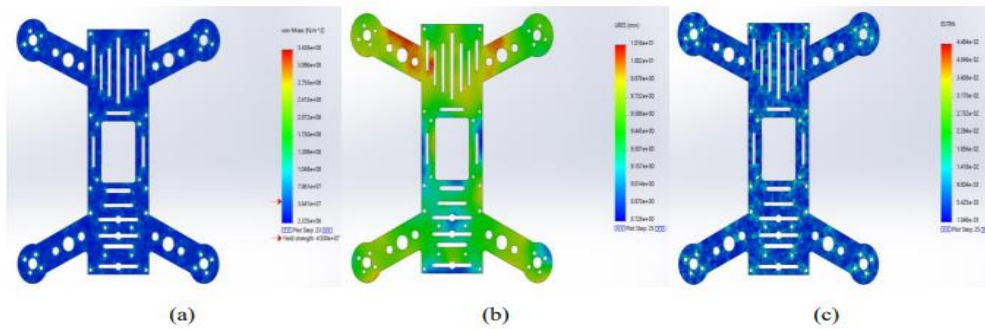


Figure 1. Airframe analyses made using Von Mises Stress, Displacement and Strain

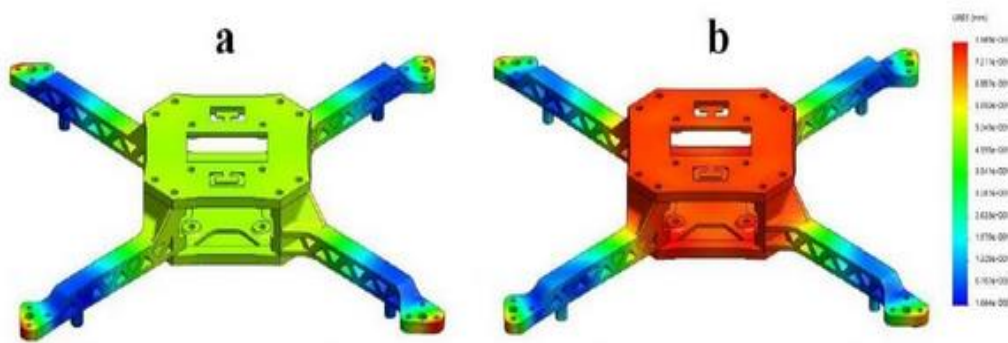


Figure 2. Simulation results for landing

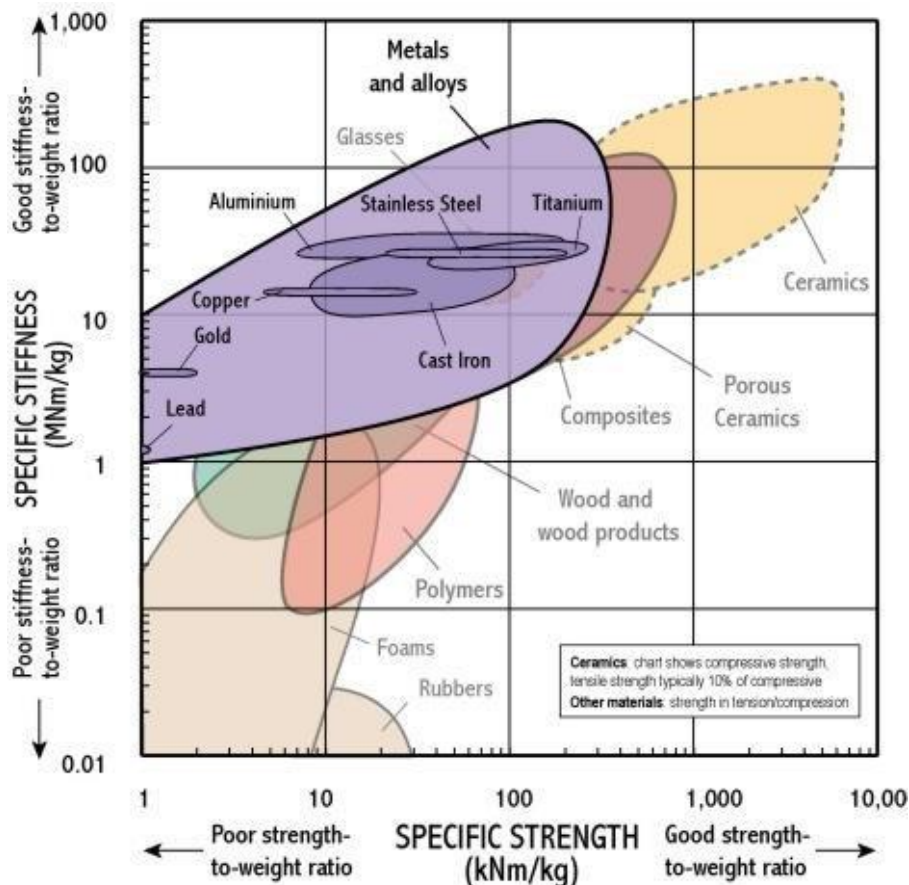


Figure 3. Specific Stiffness vs. Specific Strength [13]

Engineers need to have a necessary knowledge how to select materials. There are different types of properties that provide specific characteristics to the material but in this paper density is more influential factor for calculations. In the figure below various materials are mapped out for specific stiffness and specific strength. Carbon fiber composites are in the upper right quadrant showing a good combination of specific strength and stiffness [13].

a) Physical properties of materials

Physical properties are those that can be observed without changing the composition of the material. Some of the most important physical properties of metals are density, color, size and shape, specific gravity of the material and porosity among others [14]. A description of some common mechanical and physical properties will provide information that product designers could consider in selecting materials for a given application. These are conductivity, corrosion resistance, density, malleability, elasticity, stiffness, fracture toughness, hardness, plasticity, strength, fatigue, shear, tensile, yield, toughness and wear resistance [14].

b) Density

Density is expressed as grams per cubic centimeter and it describes the mass of the material per unit volume and it is the property of material which determines how much a component of a certain size will weigh. Density is an important factor in applications like aerospace or automotive where weight is important.

When we are looking for lower weight components better seek alloys that are less dense and consider the strength to weight ratio [15]. Density of a material is defined as the mass per unit volume and it is mathematically defined as mass divided by volume [15]:

$$\rho = m/V$$

Density of aluminium is 2.7g/cm³ [15].

The density of bamboo varies from 500 to 800 kg/m³ depending on the species, age, and anatomical structure [16]. There is no clear distinction to know the quality of bamboo. Typical Petung bamboo physical and mechanical properties are tabulated below [16].

There are different types of materials and software to calculate the weight. Steels, aluminum and composites are some of the materials applicable in Quadcopter technology.

c) Steel materials

There is basically four grade of steel which is classified on the basis of the different amounts of carbon and other added elements with different composition. Some of them are carbon steel, alloy steel, stainless steel and tool steel. The Weight of steel is calculated by using two methods namely by using the Density of Steel and by using the Standard formula [17]. Using density, the weight of steel is calculated by multiplying the density of the steel by the volume of steel and the standard density of steel is 7850 kg/m³. The formula used for calculating the volume of steel is different for different types of sections such as a plate specific length, thickness and width is calculated as follows [18];

Table 1. Physical and mechanical properties of Petung bamboo [16]

Character	Young	Adult	Old
Density (gr/cm ³)	0.695	0.809	0.742
Density of Sclerenchymal fibers (mm ² /mm ²)	0.4257	0.4290	0.4284
Compressive Strength (Mpa)	37.52	46.59	43.13
Stress Limit Proportio (Mpa)	33.10	42.33	38.40
Modulus of Elasticity (Mpa)	3773.15	4719.13	3783.93
Shear Strength (Mpa)	6.86	9.94	8.95
Tensile Strength (Mpa)	151.54	217.89	186.09

From figure 4, Volume = Length*Breadth*Thickness = l x b x t

Weight = Volume x Density

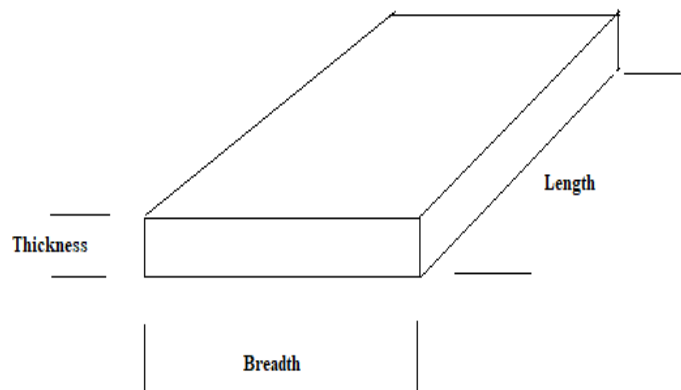


Figure 4. Steel plate

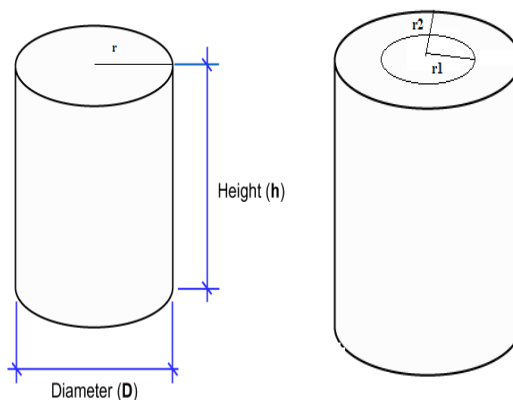


Figure 5. Formula for steel cylinder [18]

Using standard formula for steel weight calculation is used to calculate the weight of round re-bars and cylindrical sections as shown below [18]. From figure 5,

$$\text{Volume of a cylinder solid} = \pi r^2 L,$$

For hollow cylinder r_1 internal radius and with r_2 as shown in the figure below;

$$\text{Volume of a cylinder solid} = \pi(r_2^2 - r_1^2) L,$$

d) Aluminum materials

Aluminum is available with different grade such as 6061, 7075, 2024, 3003 and 5052. The mass density of aluminum is 2.7 g/cm³ which is about 1/3 of steel. If calculating the aluminum weight per square cm, we must first measure the thickness of the aluminum sheet or plate [19]. There are different grades of aluminum with different density and also table summaries for weight and density of various aluminum grades in g/cm³ or kg/m³ [20].

e) Carbon fiber

Carbon fiber composites have high specific stiffness and strength which makes it best choice for aerospace applications. Carbon fiber is a material that consisting of fibers greater than 92% carbon. Each carbon fiber filament has a diameter of 5 microns to 15 microns. Numerous parallel filaments are typically grouped together into what is referred to as a carbon fiber tow and carbon fiber is used as a reinforcement material in composites. Such composites are known as both carbon fiber composites and carbon fiber reinforced polymer (CFRP) [21]. The structure of carbon fibers is very important from microscopic to nano scale level in understanding the properties of fiber products and processing-related issues in order to improve the fiber quality and the performance of their composites. The University of Tennessee Space Institute (UTSI) were in a unique position to continue pitch-based carbon fiber (PBCF) research and development to improve certain technology areas such as a viable low-cost commercial process for carbon fiber production. Different forms of

carbon fibers were prepared in the UTSI Lab as shown in figure 6. Some of the Lab works are continuous fibers with a continuous long fiber that has many curves and is almost randomly aligned. Chopped fiber is a bundle of carbon fiber was cut to short fiber. Fiber rope is a bundle of carbon fiber was wound to form a rope and carbon fiber mat is a bundle of carbon fiber that can easily be fabricated into a carbon fiber mat by using polymers as binders.

3. Design Details for Analysis

Similar designs of the model Quadcopter is used to calculate its total weight made from different materials namely steel, aluminium and carbon fiber. The main objective of this procedure is to select the best light material for our design in order to avoid overweight. The model designs calculated for steel material is shown below. The same procedure is followed for aluminium and carbon fiber.

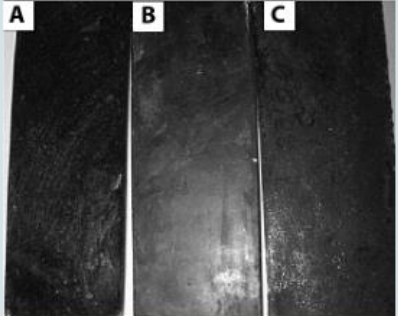
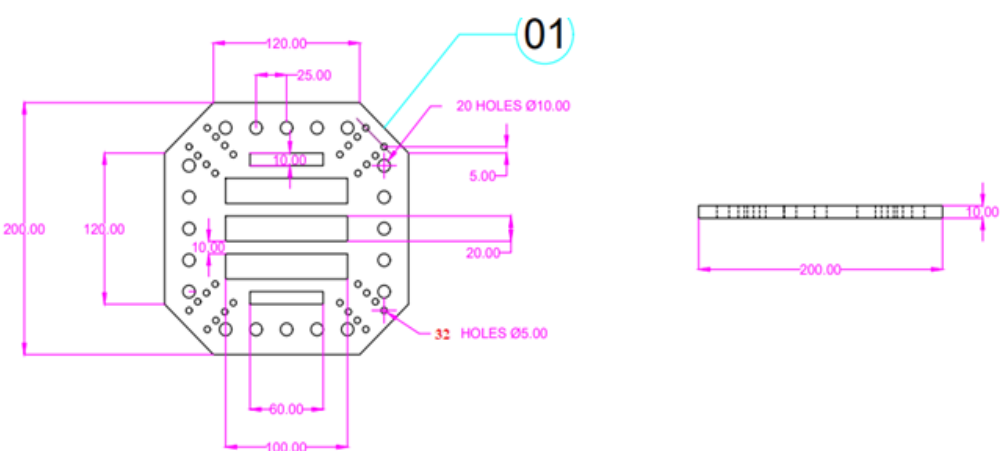
Fabrication Technique	Fiber Form	Resin	Sample
Hot Compression Molding	(A) Fiber rope (B) Chopped fiber (C) Continuous fiber (random)	Epoxy	

Figure 6. Different forms of carbon fibers

1. Steel mass calculation for central chassis (Drawing No 1)

Area/mass calculations

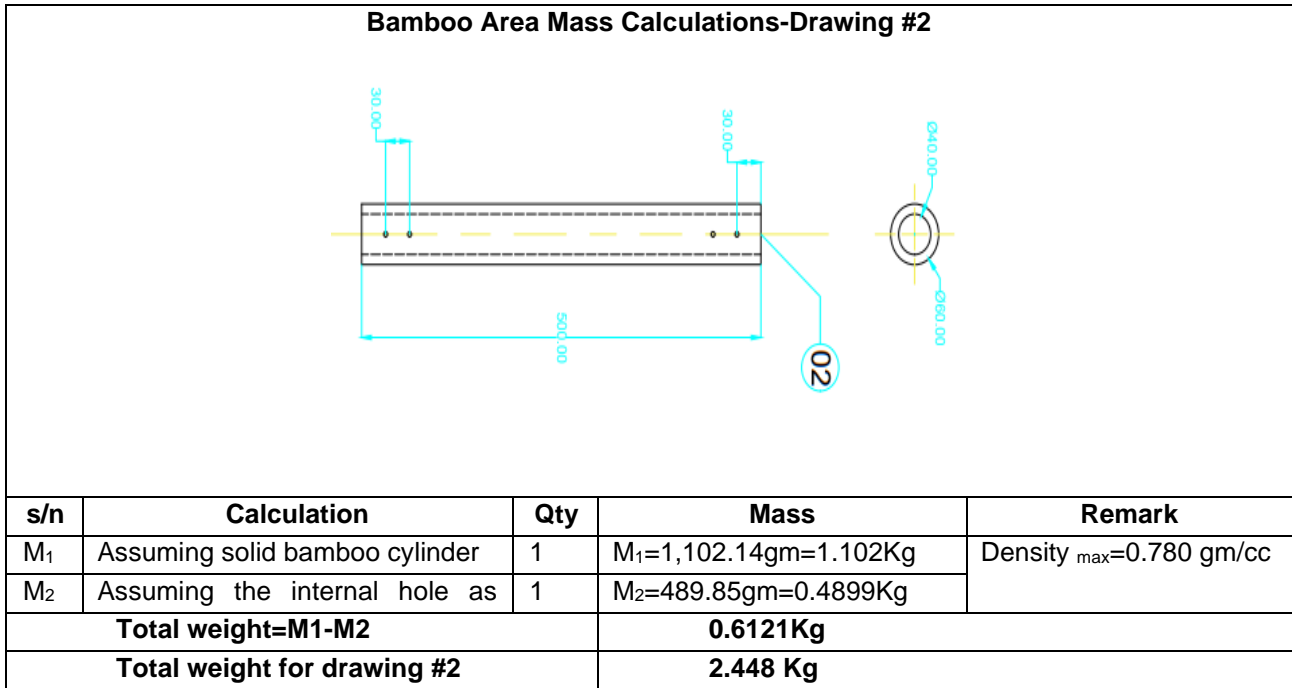


s/n	Calculation	Qty	Mass	Remark
A ₁	LXWXT =200X200X5	1	+1.574Kg	<i>Density=7870Kg/m³</i>
A ₂	φ=5 Holes	32	-0.025Kg	
A ₃	φ=10 Holes	20	-0.062 Kg	
A ₄	Cut triangles 40x40mm	4	-0.126 Kg	
A ₅	10X60 Holes	2	-0.047 Kg	
A ₆	20X100 Holes	3	-0.236 Kg	
Total mass = W_{A1} - W_{A2} - W_{A3} - W_{A4} - W_{A5} - W_{A6}				
Final total weight of plate (Drawing #1)			1.078 Kg	

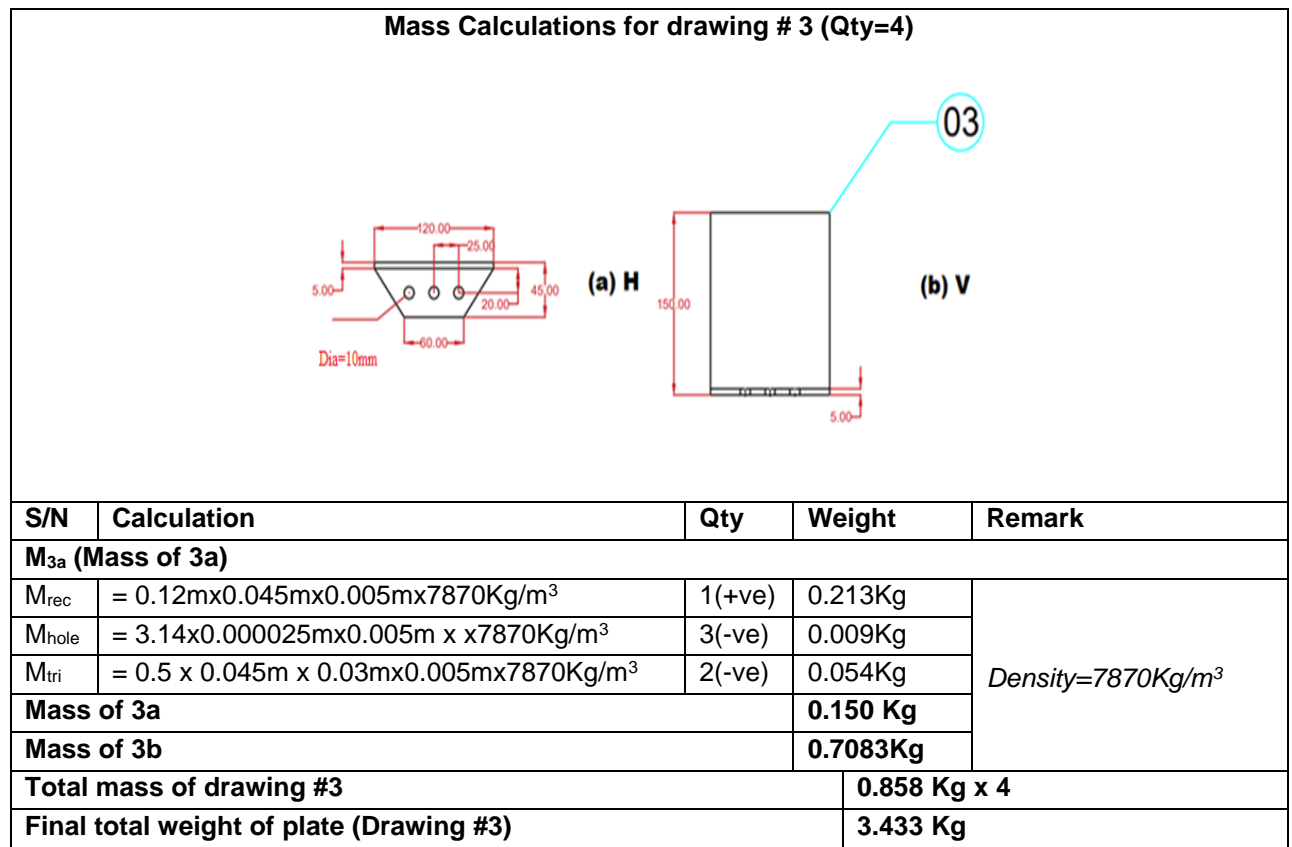
The results are also calculated for accuracy with Excel.

2. Mass calculation for bamboo arms (Drawing No 2)

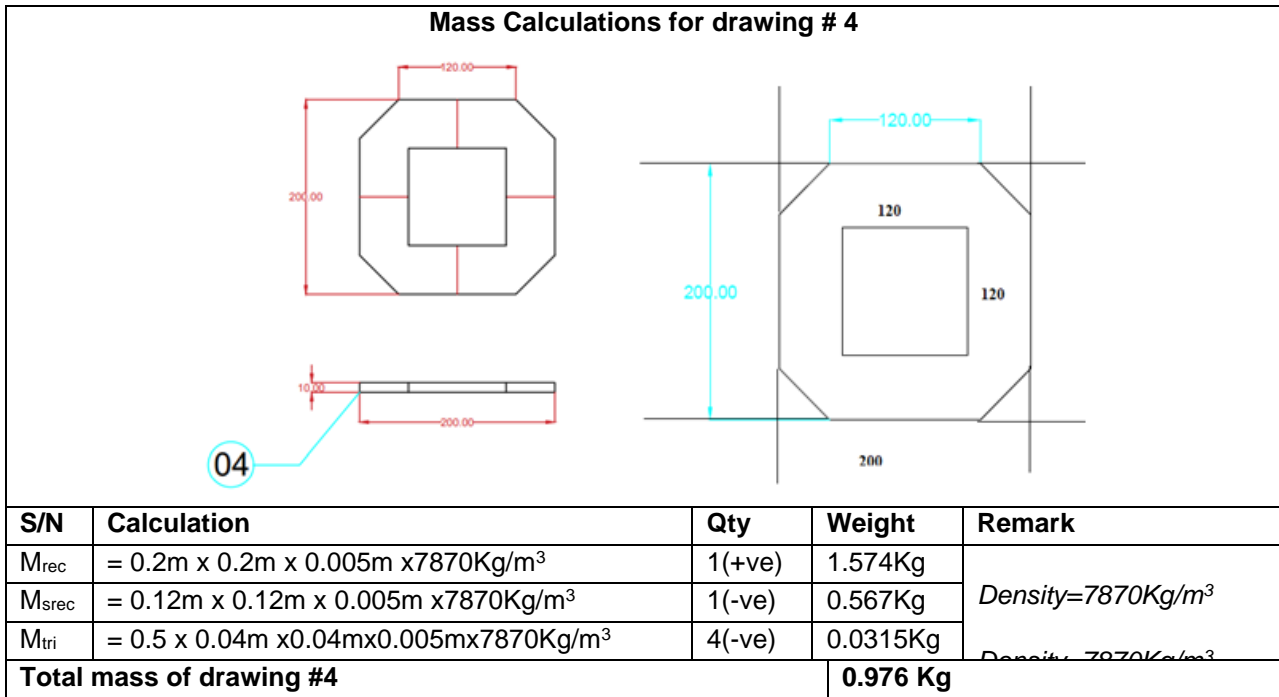
Density of bamboo = 0.451gm/cc to 0.780 gm/cc as shown in table 1. Let's take the maximum weight for our design with density=0.780gm/cc [16].



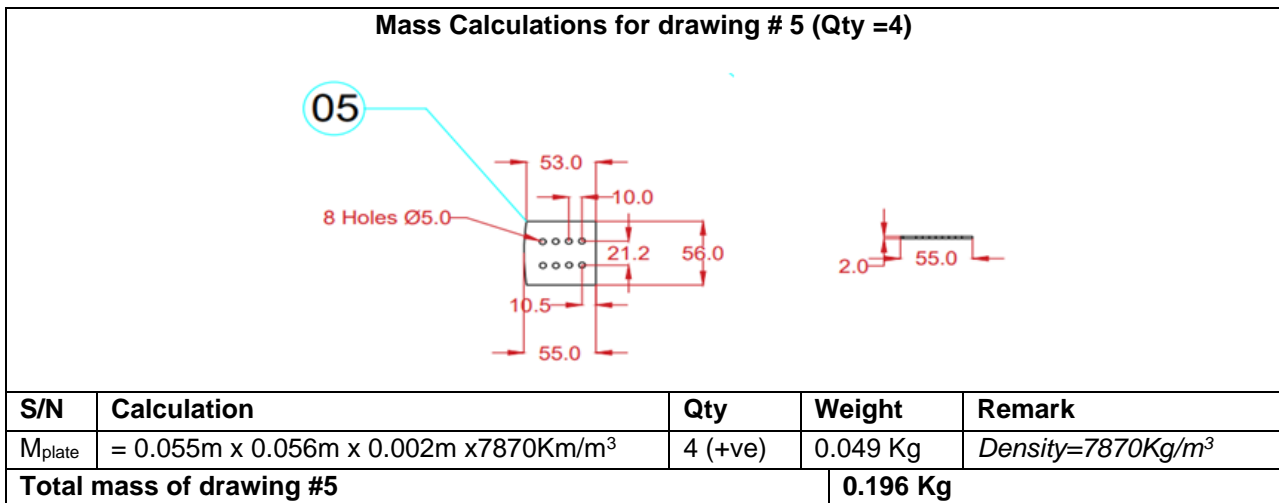
3. Steel mass calculation for side panels (Drawing No 3)



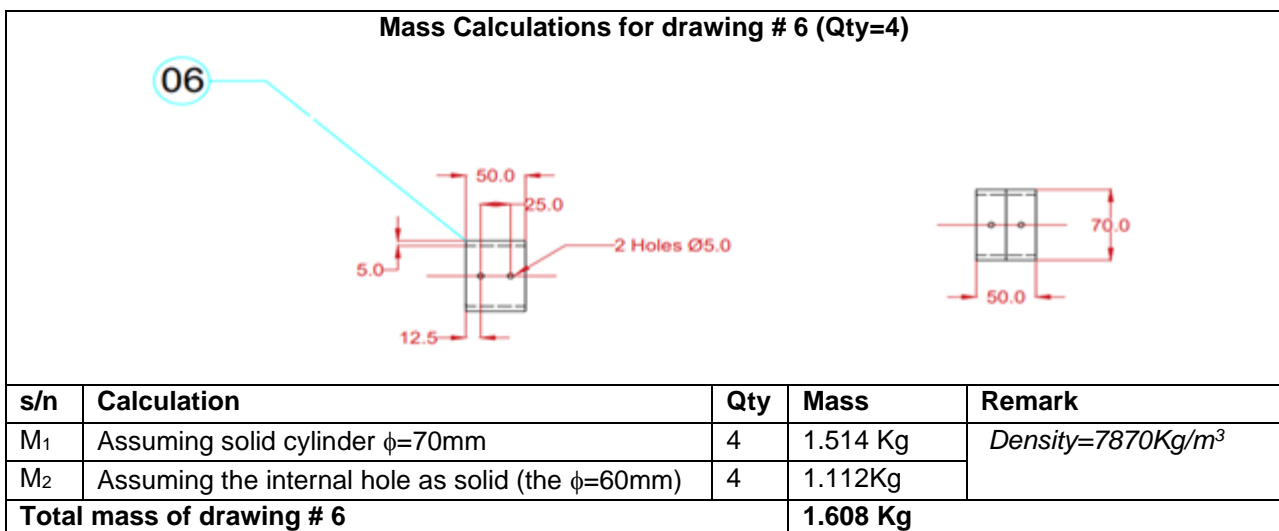
4. Steel mass calculation for upper panels (Drawing No 4)



5. Steel mass calculation for bamboo fixture (Drawing No 5)



6. Steel mass calculation for bamboo fixture (Drawing No 6)



7. Steel mass calculation for landing skid part (Drawing No 7)

Mass Calculations for drawing #7 (Qty =2)

S/N	Calculation	Qty	Weight	Remark
M _{plate}	= 0.13m x 0.04m x 0.005m x 7870Kg/m ³	2 (+ve)	0.205 Kg	Density =7870Kg/m ³
Total mass of drawing #7			0.410 Kg	

8. Steel mass calculation for landing skid part (Drawing No 8)

Mass Calculations for drawing # 8 (Qty =4)

S/N	Calculation	Qty	Weight	Remark
M _{plate}	= 0.015m x 0.04m x 0.005m x 7870Kg/m ³	4 (+ve)	0.024 Kg	Density =7870Kg/m ³
Total mass of drawing # 8			0.096 Kg	

9. Steel mass calculation for landing skid part (Drawing No 9)

Assuming the square hollow of size 300x30x30 and t=1

Assume a solid square beam of size 300x30x30

Assume a solid square beam of size 300x28x28

Mass Calculations for drawing # 9 (Qty=4)

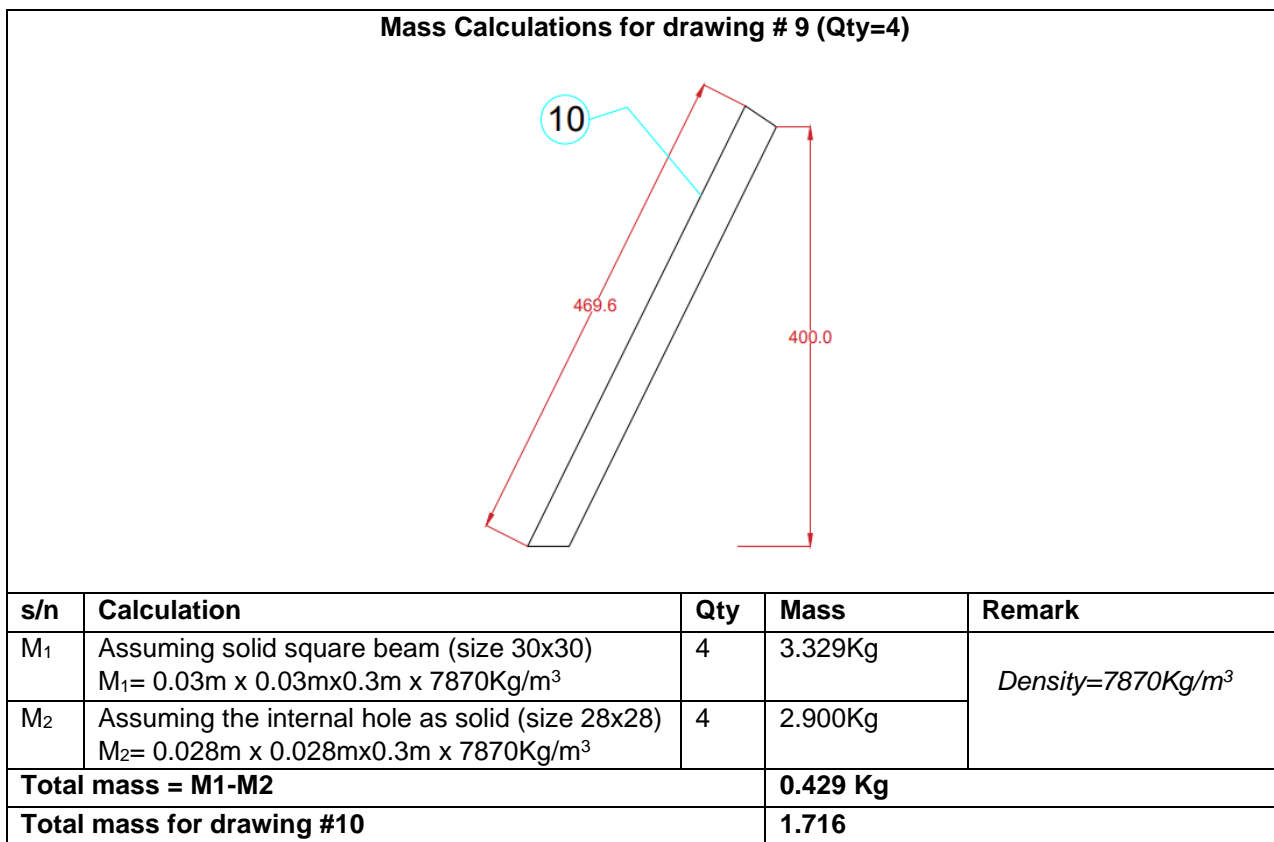
s/n	Calculation	Qty	Mass	Remark
M ₁	Assuming solid square beam (size 30x30) M ₁ = 0.03m x 0.03mx0.3m x 7870Kg/m ³	4	2.125 Kg	Density=7870Kg/m ³
M ₂	Assuming the internal hole as solid (size 28x28) M ₂ = 0.028m x 0.028mx0.3m x 7870Kg/m ³	4	1.851 Kg	
Total mass = M1-M2			0.274 Kg	
Total mass for drawing #9			1.096 Kg	

10. Steel mass calculation for landing skid part (Drawing No 10)

Assuming the square hollow of size 470x30x30 and t=1

Assume a solid square beam of size 470x30x30

Assume a solid square beam of size 470x28x28



4. Results and Discussion

4.1 Quadcopter mass initial stated parameter

The theoretical estimated weight of a Quadcopter is 13Kg as shown in the table below. Where the airframe, electrical and electronic components should be maximum of 8Kg. The weight reference can help to estimate the lighter material to be used for this particular Quadcopter design. The final product will be from the lightest material or a hybrid of two different light materials in some parts to get best airframe with strength to carry the pesticide payload.

4.2 Airframe material mass estimation calculation and results

From the material properties and weight calculation formula, weight of the model Quadcopter can be calculated from its density and design profile. The proposed model configuration is calculated for different materials for comparison. Steel, aluminium and carbon fiber. The same formula and procedure is used for

Plate mass = (Length x Width x Thickness) x Specific material density

Mass =Volume of steel x density

For cylindrical parts

Mass = $\pi r^2 \times \text{Length} \times \text{density}$

The model Quadcopter consists of 10 parts or components to be manufactured from selected material. Specific material density for carbon steel is 7870Kg/m³. Total theoretical mass of model Quadcopter parts made of steel and bamboo arms is calculated as 13.57Kg which is not compatible with total mass of Quadcopter 13Kg (Over weight).

Similarly from the above methodology of material weight estimation, the estimated weight of the Quadcopter parts if made from aluminium. Taking the same formula and aluminum density 2780Kg/m³ for 2024 grade for our calculation. The theoretical weight of model Quadcopter made of aluminium is calculated as 6.361Kg which is optimal value for comparison. The total weights of Quadcopter parts made from aluminium and bamboo arms are shown below;

According to the above methodology of material weight estimation used, the estimated weight of the Quadcopter parts if made from carbon fiber. We select a carbon fiber of density 0.06683549 (lbs/in³) = 1.85gm/cm³ for our calculation. The theoretical weight of model Quadcopter made of carbon fiber is calculated as

3.413Kg which is more optimal value for comparison according to its weight to strength ratio. The total weights of Quadcopter parts made from carbon fiber and bamboo arms are shown below;

different materials are calculated from mathematical formula and spreadsheet software like Microsoft Excel. The summary of results for the three different materials is tabulated below;

The final Quadcopter frame weight made of

Theoretical mass of the model Quadcopter parts (Kg) for Steel	
Mass of Dr. #1	1.078
Mass of Dr. #2	2.448
Mass of Dr. #3	3.433
Mass of Dr. #4	0.976
Mass of Dr. #5	0.196
Mass of Dr. #6	1.608
Mass of Dr. #7	0.410
Mass of Dr. #8	0.096
Mass of Dr. #9	1.096
Mass of Dr. #10	1.716
Grand Total	13.57 Kg

Theoretical mass of the model Quadcopter parts (Kg) for Aluminium	
Weight of Dr. #1	0.389
Weight of Dr. #2	2.448
Weight of Dr. #3	1.319
Weight of Dr. #4	0.312
Weight of Dr. #5	0.196
Weight of Dr. #6	0.524
Weight of Dr. #7	0.145
Weight of Dr. #8	0.033
Weight of Dr. #9	0.387
Weight of Dr. #10	0.608
Grand total	6.361 Kg

Theoretical mass of the model Quadcopter parts (Kg) for Carbon fiber	
Weight of Dr. #1	0.344
Weight of Dr. #2	2.448
Weight of Dr. #3	0.087
Weight of Dr. #4	0.209
Weight of Dr. #5	0.012
Weight of Dr. #6	0.094
Weight of Dr. #7	0.048
Weight of Dr. #8	0.006
Weight of Dr. #9	0.064
Weight of Dr. #10	0.101
GRAND TOTAL	3.413 Kg

Quadcopter materials	Theoretical weight	Remark
Theoretical mass of the model Quadcopter parts made from steel	13.057 Kg	Heavy
Theoretical mass of the model Quadcopter parts made from Aluminum	6.361 Kg	Medium
Theoretical mass of the model Quadcopter parts made from carbon fiber	3.413 Kg	Light

5. Conclusion

The Quadcopter weight analysis is done with different airframe materials but all the frame weight is calculated with a bamboo arms which is a unique design feature of the model pesticide spraying drone. From the detail weight material calculations of the Quadcopter airframe detail designs, it is found that composite material used for central chassis, cover and landing skid is found to be lighter than other materials with steel weight 13.057 Kg, Al 6.361 Kg and composite 3.413 Kg. In order to save battery life, increase the flight time and accommodate spraying tank with maximum for the required mission, the lightest material and a hybrid of aluminium materials in some parts are more optimal for our design.

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Conflict of interest

The Authors have no conflicts of interest to declare that they are relevant to the content of this article.

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Yes

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