Technical Journal, University of Engineering and Technology (UET) Taxila, Pakistan *Vol. 30 No. 4-2025*
ISSN:1813-1786 (Print) 2313-7770 (Online)

Mechanical Analysis of Solid and Hollow Shaped Flywheels Made of Through Cast Iron and Gray Cast Iron Through Simulation

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Abstract- Flywheel is used to store energy and supply when it is required to complete the cycle of an engine and or any mechanical machine. The variation in storing and supplying energy may vary the loads on the flywheel. The other common problem is the variation of centrifugal forces based on the variable torque. These loads during storing and supplying energy creates unwanted stresses on flywheel. These unwanted stresses produced premature failure of flywheel when crossed ultimate point. Numerous investigation through experimental, empirical and simulation have been carried. This research work is investigating the mechanical stresses and deformation of flywheel at torque value of 2500 Nm. The mechanical stresses and deformation were calculated through ANSYS v17.2. The stresses and deformation of two different materials: cast iron and gray cast iron, and solid and hollow shapes of flywheel were evaluated. The simulated results demonstrated that the solid flywheel offered better mechanical stresses than hollow flywheel. Whereas, for comparing the material, gray cast iron had better mechanical results than cast iron for a particular geometry of flywheel. Based on it, it can be concluded that gray cast iron with solid geometry flywheel is far better than hollow flywheel made through cast iron.

Keywords- Flywheel, Mechanical Stresses, Cast Iron and Gray Cast Iron, Solid and Hollow Shapes Flywheel, ANSYS v17.2.

I. INTRODUCTION

Flywheel is an internal energy-storage device. It maintains mechanical energy and serves as a repository, storing energy when the stockpile exceeds the need and releasing it when the need for energy exceeds the stockpile. A flywheel's primary function is to even out variations in a shaft's speed caused by force fluctuations [1]. Flywheels may be divided into two categories based on their geometrical makeup. A rim-type flywheel has spokes between the flywheel hub and the thin disc, whereas a solid disc flywheel has both. Tensile stress from centrifugal force, tensile bending stress, and shrinkage stress from uneven cooling rates can all be produced by a flywheel's rim. Because these stressors might be really severe, there is no easy way to decide for them [2].

Increased power and faster speeds are the main development goals for flywheel energy storage systems (FESSs) [3]. The idea of a flywheel is as ancient as the wheel of an axe grinder, but it may contain the solution to the issues with effective energy storage that we will face in the future [4]. The foremost purpose of flywheel is to absorbs mechanical energy and serves as a storage tank, releasing it when need exceeds supply and keeping it when supply exceeds need [5]. The primary function of a flywheel is to decrease shaft speed fluctuations caused by rapid changes in torque [6]. The torque time function varies from cycle to cycle due to the various machine load patterns. One or two-cylinder internal combustion engines are a good example [7]. A flywheel is usually necessary if the driving or load torque source is changeable [8]. Due to the recently attained high specific energy densities, the flywheel has a promising future. A simple example of a flywheel is a flat, solid revolving disc [9].

Flywheels are essential in mechanical systems because of their flexibility and new advancements [10]. They are important in energy storage and regulation with flywheel energy storage system (FESS) used for grid support and renewable energy management [11]. Flywheels are used in automobiles Kinetic Energy Recovery System (KERS) and industrial machines to give out a steady power supply and also to stabilize power [12]. Flywheels are also used to enhance energy efficiency by storing and reutilizing energy as evident in flywheel energy recovery systems for cars [13]. Flywheels also get enhanced with the development of technology to enhance performance and increase their applicability in various mechanical systems [14].

The size and rotating speed of the flywheel determine the storage capacity; however, the rotating speed has a major influence as the storage capacity varies inversely with the square of the flywheel speed. The power density is preferred to be high in cars that have to accelerate to a high peak power and brake or decelerate enough to store a big amount of energy [15].

Flywheel systems are typically intended to produce up to 130 kWh of energy [16]. Higher rotational speeds enable more energy to be recovered, but because of windage losses also known as frictional losses more heat is produced inside the flywheel annulus. In a steady-state operation, too much heat could cause the carbon fiber composite rim's epoxy to soften, lowering its mechanical qualities, especially its tensile strength. Furthermore, through localized thermal stress and distortion, excess heat can also change the mechanical characteristics of the steel hub, causing crack formation and propagation and premature burst failure [17].

It has been pointed out that during mechanical analysis of a flywheel, it is necessary to take into account many important parameters to obtain the best characteristics and avoid potential difficulties. The first of such factors is the choice of material for the flywheel construction because this has a direct bearing on the strength, weight and lifespan of the flywheel. It also has to do with such factors as tensile strength, density, fatigue strength, and cost of the material. For instance, improved tensile strength requirements of the material result in better capability to store more energy, low density allows for increased throughput and reduced stress on centreline support structures, and the improvement to yield strength and fatigue strength [18].The choice of the material must be able to meet the expected loads and operating conditions with regard to The also, force and density, mass, and inertia are also relevant in the analysis [18]. Mass and the second moment of area are utilized to characterize the energy storage flywheel along with its inherent stability. Consequently, if stress/strain analysis is omitted in the design of the flywheel, it will be impossible for the analyst to know the structural health of the complex component. Stress and strain distribution within a specific design under different points of loading could be predicted applying FEA methods and subsequently used to guide the design optimization. These factors could be used to design satisfactory flywheel systems that meet specific performance, reliability and safety standards [19]. Flywheel rotor energy storage methods rely on mass and speed of the flywheel. The energy storage of the flywheel relates to the moment of inertial and the angular velocities of the fly wheel where energy storage is found to be proportional to the square of the speed. Inertia depends on the geometry, mass distribution and material of the flywheel's rotor hence these factors play a crucial role in performance of the flywheel [20]. In theory, every rotating object that stores some kinetic energy could be referred to as a flywheel [21]. However, the term "flywheel" is typically applied to a rotating, cylinder object, typically with a large mass, whose primary function is to store energy or increase the moment of inertia of a particular system [13, 22].

An important numerical method is the finite element method, by which approximate solutions for a large number of engineering problems can be determined. Consequently, two types of materials, cast iron and gray cast iron have been selected for the mechanical analysis of the flywheels in solid and hollow forms and to compare the performance under simulated load conditions.

II. MATERIALS AND METHODOLOGY

2.1. Materials

The density, ultimate tensile stress, hardness, and Poisson's ratio of these materials are presented in Table 1. These values, acquired from Mat Web - the Online Materials Information Resource, show the relative strength and elastic properties of each material. A torque of 2500 N was applied to both the solid and hollow flywheel models. The use of cast iron and gray cast iron allows us to compare their different behaviors under the mechanical load to assess stress, strain and possible deformation. Cast iron with slightly higher density and tensile strength is anticipated to demonstrate better performance under load, whereas gray cast iron which is known for its brittleness and lower tensile strength gives information about stress constraints under dynamic loads. These simulations form the basis of how material characteristics affect the structural and functional performance of flywheels especially in areas of weight, toughness and material utilization. This analysis will provide useful information for choosing the right material in the design and optimization of flywheel systems.

Table-1: Material Properties of Cast Iron and Gray Cast Iron [23]

Material	**Density (g/cm^3)**	**Ultimate Tensile Stress (MPa)**	**Hardness VHN**	**Poisson's Ratio**
Cast Iron	7.23	496	273	0.286
Gray Cast Iron	7.20	310	235	0.294

2.2 Geometries and Meshing of Fly Wheel

This work also highlights the best choices of flywheel geometry to improve energy storage density in systems that involve power control and stability [24]. Thus, while enhancements in the performance of various flywheel geometries may not be very high, those improvements are critical in operations that are important to the mission, where even small improvements in efficiency translate to large improvements in system reliability [24]. In this research, two geometries of the flywheel; solid and hollow flywheel were considered. The solid flywheel has a greater mass concentration at the outer radius, which is believed to improve its energy storage density. On the other hand, the hollow flywheel which has mass concentrated at the rim offers a different strategy for energy storage and may save on material which in turn may lead to a lighter design with adequate moment of inertia. Both of these configurations were created using CAD software to provide a geometrically correct model for analysis. Next, the models were meshed using finite element meshing of ANSYS v17.2 as depicted in (Fig. 1) below.

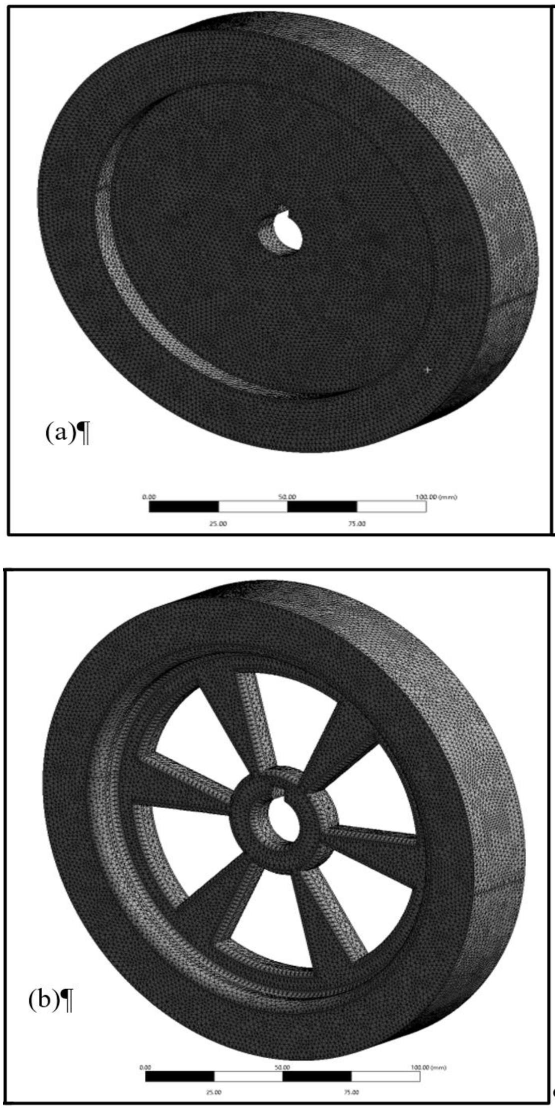


Fig. 1: Meshing of Solid and Hollow Flywheel

The meshing process is important to obtain stress distributions and deformation under load condition so that the two designs can be compared accurately. Table 2 shows the meshing details of both flywheel geometries; the element sizes and density used to achieve accuracy in the simulation outcome. Through this comparison, this study seeks to identify the effects of various mass distributions and structural geometries on the efficiency of the flywheel and its applicability to high reliability and energy storage applications.

Table 2: Meshing Data of Flywheels

S. No	**Type**	**Material**	**Element Size (mm)**	**Nodes**	**Elements**
1	Solid flywheel	Cast Iron	1.0	275709	160235
2		Gray Cast Iron			
3	Hollow flywheel	Cast Iron		278634	161090
4		Gray Cast Iron			

After creating the geometries and generating the meshing of flywheels, total deformation, maximum principal and maximum shear stresses, and maximum principal elastic strains were calculated of the flywheels using ANSYS v17.2. Detailed discussions of results are presented in the sections below.

III. RESULTS AND DISCUSSION

A flywheel operates as an inertial energy storage system which is essential in cases where energy can be produced in excess and then absorbed in equal measure at a later time. A flywheel works as an energy storage system; it collects mechanical energy when the supply is more than the demand and releases the energy when the demand is more than the supply thus regulating the energy output [13]. This ability makes flywheels indispensable in numerous engineering applications across automotive, aerospace, and industrial equipment, where constant energy delivery and performance are critical. This research concerns the computer aided modeling and simulation of solid and hollow flywheels made from cast iron and gray cast iron flywheels subjected to a torque of 2500 Nm. By creating CAD models of the geometry and performing FEA in ANSYS v17.2, this work presents a detailed comparison of the response of each geometry and material under load. It is seen that both the solid and the hollow flywheel designs have different energy storage characteristics; the solid flywheel with more mass concentration can provide higher inertial resistance and the hollow flywheel with mass concentration on the rim may reduce the overall weight and therefore may require less torque to obtain the desired speeds. The results of this analysis show that geometry contributes to the improvement of energy efficiency and mechanical stress decrease. The specific energy efficiency can be enhanced by flywheel designs that have adequate inertia at a reduced mass, especially when the flywheel is at high rpm. This makes it possible to reduce the mass which in turn reduces operating loads on the shaft and bearings, hence increasing their useful life. This balance is important for applications that call for high speeds of rotation and stability since it minimizes the likelihood of mechanical failure and enhances the stability of the overall system.

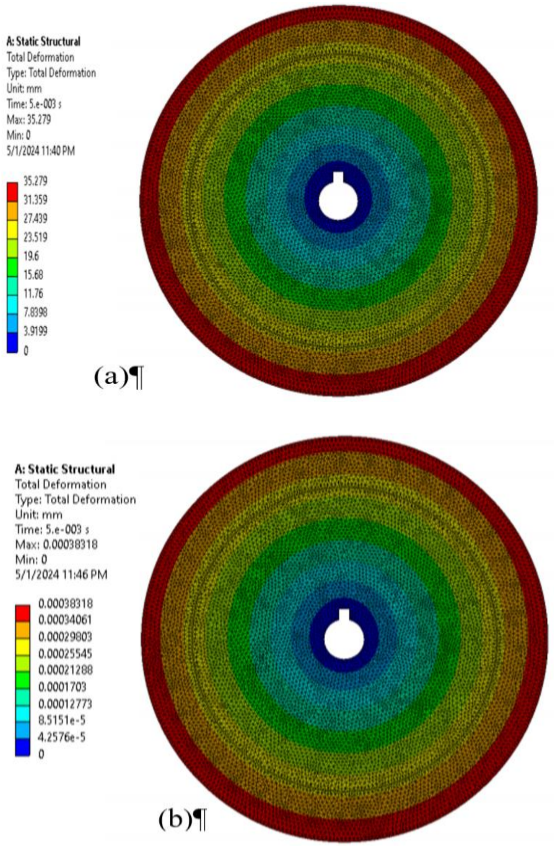


Fig. 2: Total Deformation of Solid Flywheel
(a) Cast Iron and (b) Gray Cast Iron

Figure 2 (a) shows the simulation result of Total Deformation of solid flywheel for Cast Iron. The result depicted that the max value of 35.279 mm was located at the outer edge of the filled flywheel whereas the mini value of 3.9199 mm was located at the center of the filled flywheel. Figure 2 (b) shows the simulation result of Total Deformation of solid flywheel for grey cast iron. The result depicted that the max value of 38.32 e-5 mm was located at the outer edge of the filled flywheel whereas the mini value of 4.2576 e-5 mm was located at the center of the filled flywheel. The obtained results for total deformation of the flywheel depicted that gray cast iron material has lower resistance to the applied torque. This is reason the higher value of total deformation was achieved for gray cast iron material for solid shape. Figure 3 (a) shows the simulation result of total deformation of a hollow flywheel with 6 arms for cast iron. The result depicted that the max value of 182.73 mm was located at the outer edge of the hollow flywheel whereas the mini value of 20.3 mm was located at the center of the hollow flywheel. Figure 3 (b) shows the simulation result of total deformation of a hollow flywheel with 6 arms for gray cast iron. The result depicted that the max value of 199.37 e-5 mm was located at the outer edge of the hollow flywheel whereas the mini value of 22.15 e-5 mm was located at the center of the hollow flywheel. The same situation is observed here, as the higher value of total deformation for hollow flywheel for gray cast iron is achieved. The reason is that the outer edge experiences the highest centrifugal forces, leading to greater deformation, while the center of the flywheel, being closer to the axis of rotation, and experiences less deformation due to lower centrifugal forces [25-26]. Comparing to results presented in Figures 2 (a) and (b) with Figures 3 (a) and (b), the solid shape offered better resistance to the applied torque. Far lower values of total deformation for solid shape flywheel (for both cast iron and gray cast iron) have been achieved as compared to hollow shaped flywheel for both cast iron and gray cast iron).

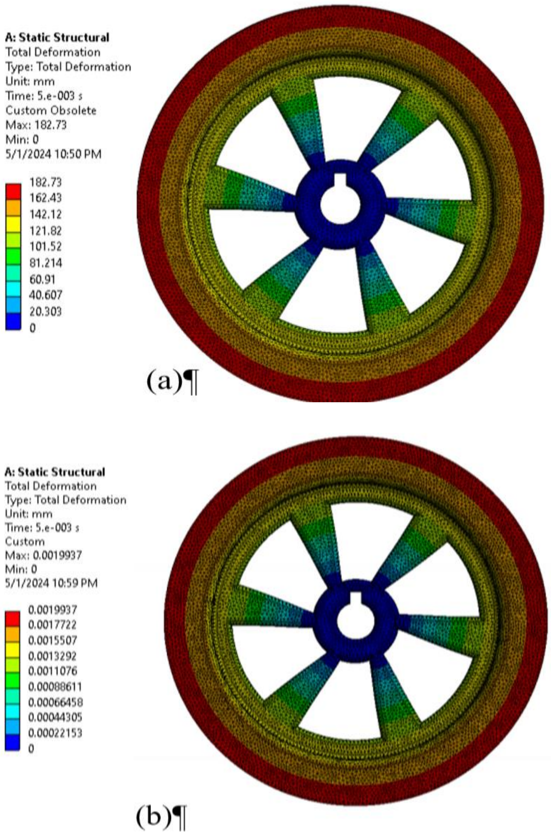


Fig. 3: Total Deformation of Hollow Flywheel
(a) Cast Iron and (b) Gray Cast Iron

Figure 4 (a) shows the simulation result of maximum principal stress of a filled flywheel for cast iron. The result depicted that the max value of 0.75855 MPa was located at the center of the solid flywheel. Figure 4 (b) shows the simulation result of maximum principal stress of a solid flywheel for gray cast iron. The result depicted that the max value of 0.75577 MPa was located at the center of the solid flywheel.

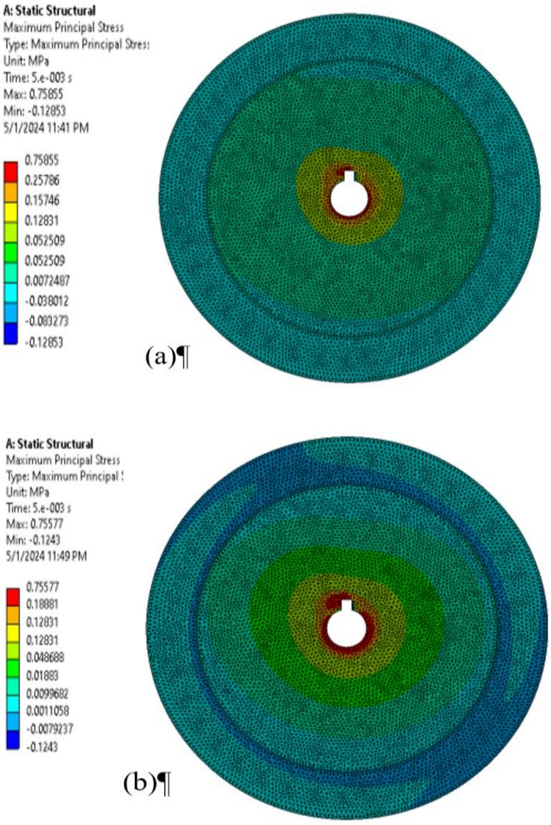


Fig. 4: Maximum Principal Stress of Solid Flywheel (a) Cast Iron and (b) Gray Cast Iron

Both values of maximum principal stresses are almost same for cast iron and gray cast iron for the same geometry of the flywheel. The values of maximum principal stress for solid flywheel depicted that gray cast iron showed better resistance to applied torque. This is the reason that lower value of 0.75577 MPa is observed for gray cast iron material for solid flywheel. Nonetheless, the location of maximum value for maximum principal stress is same for both materials.

Figure 5 (a) shows the simulation result of maximum principal stress of a hollow flywheel with 6 arms for cast iron. The result depicted that the max value of 3.8051 MPa was located at the center of the hollow flywheel and on its arms. Figure 5 (b) shows the simulation result of maximum principal stress of a hollow flywheel with 6 arms for gray cast iron. The result depicted that the max value of 3.8001 MPa was located at the center of the hollow flywheel and on its arms. Comparing the value of maximum principal stress for both materials, a minor increment is observed for cast iron material as compared to gray cast iron. Further, the location of occurring of maximum principal stress is same locations for both materials.

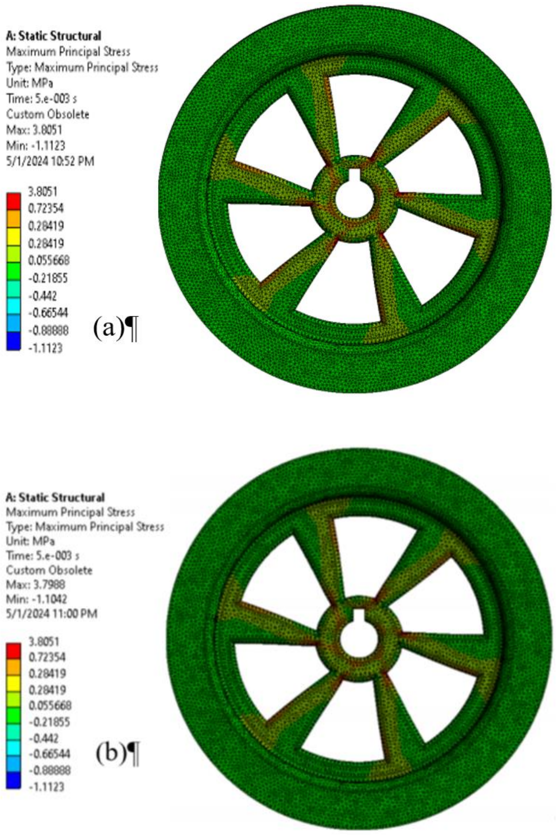
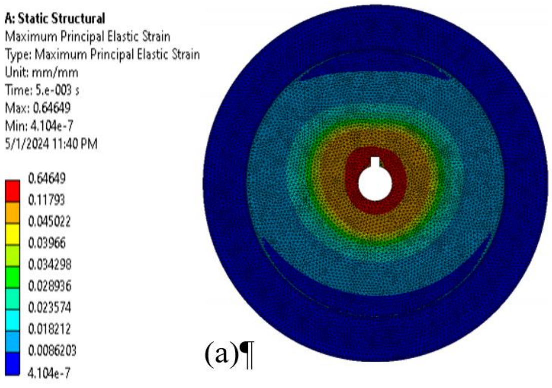


Fig. 5: Maximum Principal Stress of Hollow Flywheel (a) Cast Iron and (b) Gray Cast Iron

In comparison to both geometries of the flywheel for a particular material; the hollow flywheel is facing higher amount of maximum principal stresses. The main reason of it is due to mass moment of inertia of the flywheel. The hollow flywheel is offering less mass moment of inertia than solid flywheel. The other reason for the location of maximum principal stress for a particular geometry and material of the both flywheels is that the center of the flywheel experiences higher stresses due to the material's resistance to deformation, while the edges experience lower stresses as they are freer to deform under centrifugal [24].



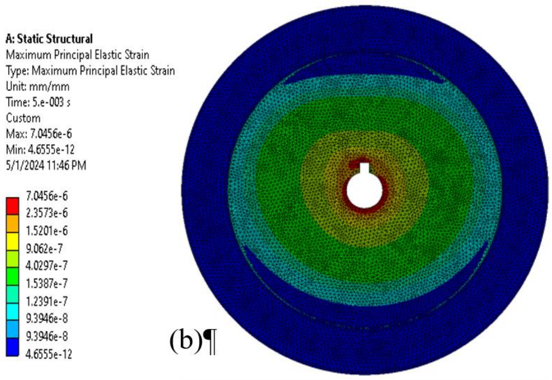


Fig. 6: Maximum Principal Elastic Strain of Solid Flywheel (a) Cast Iron and (b) Gray Cast Iron

Figure 6 (a) shows the simulation result of maximum principal elastic strain of a solid flywheel for cast iron. The result depicted that the max value of 0.64649 mm/mm was located at the center of the solid flywheel. Figure 6 (b) shows the simulation result of maximum principal elastic strain of a solid flywheel for grey cast iron. The result depicted that the max value of 7.0456 e-6 mm/mm was located at the center of the solid flywheel. Both results showed that gray cast iron offered more resistance to applied torque, and is the reason of less value of maximum principal elastic strain of solid flywheel for gray cast iron.

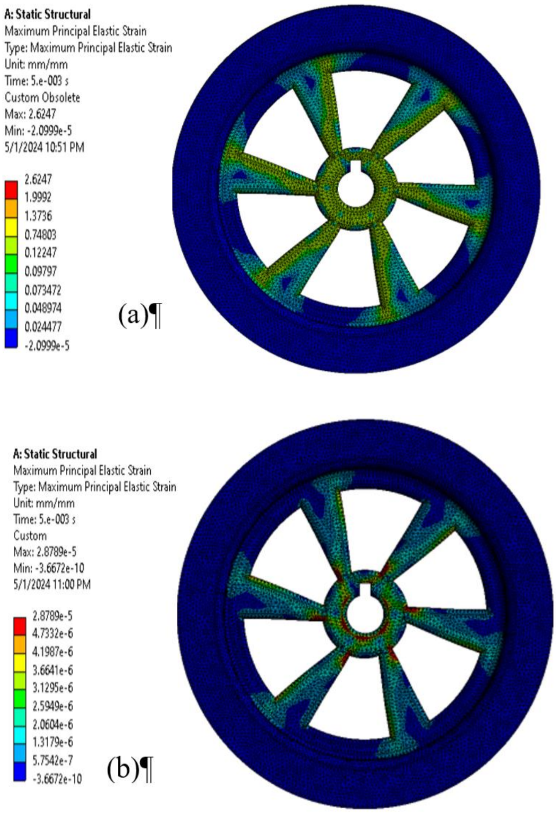


Fig. 7: Maximum Principal Elastic Strain of Hollow Flywheel (a) Cast Iron and (b) Gray Cast Iron

Figure 7 (a) shows the simulation result of maximum principal elastic strain of a hollow flywheel with 6 arms for cast iron. The result depicted that the max value of 2.6247 mm/mm was located at the center of the hollow flywheel and on its arms. Figure 7 (b) shows the simulation result of maximum principal elastic strain of a hollow flywheel with 6 arms for gray cast iron. The result depicted that the max value of 2.8789 e-5 mm/mm was located at the center of the hollow flywheel and on its arms.

In comparing the maximum principal elastic strain for both geometries of flywheel made through cast iron and gray cast iron; solid flywheel is offering more resistance to applied torque than hollow flywheel for gray cast iron. However, the location of maximum principal elastic strain is at center of the both flywheel for geometrical and material point of view. The reason is that the center of the flywheel experiences higher elastic strain due to the material's resistance to deformation, while the edges experience lower strain as they are freer to deform under centrifugal forces [24].

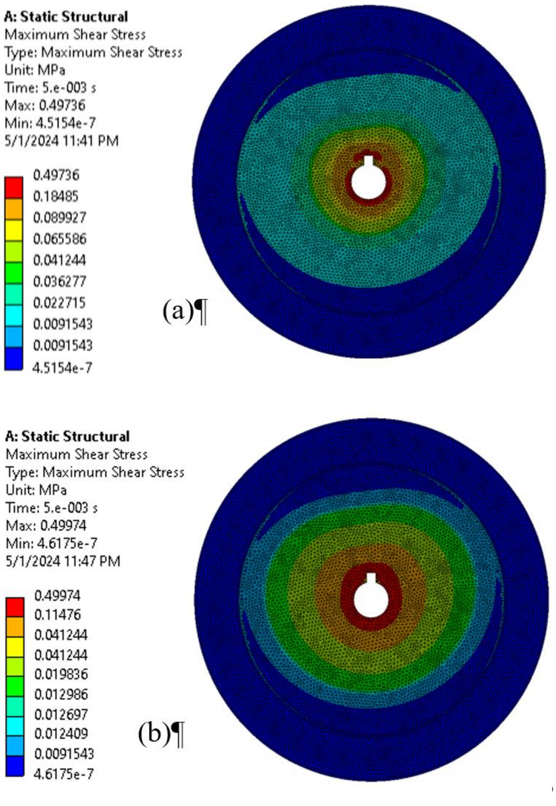


Fig. 8: Maximum Shear Stress of Solid Flywheel (a) Cast Iron and (b) Gray Cast

Figure 8 (a) shows the simulation result of maximum shear stress of a solid flywheel for cast iron. The result depicted that the max value of 0.49736 MPa was located at the center of the solid flywheel. Figure 8 (b) shows the simulation result of maximum shear stress of a solid flywheel for gray cast iron. The result depicted that the max value of

0.49974 MPa was located at the center of the filled flywheel. Both values of maximum shear stress are almost same for solid flywheel made through cast iron and gray cast iron. Comparing the obtained values of maximum shear stress values for both materials, a minor increment is observed for gray cast iron.

Figure 9 (a) shows the simulation result of maximum shear stress of a hollow flywheel with 6 arms for cast iron. The result depicted that the max value of 0.81921 MPa was located at the center of the hollow flywheel and at the starting of the arms from the center. Figure 9 (b) shows the simulation result of Maximum Shear Stress of a hollow flywheel with 6 arms for gray cast iron. The result depicted that the max value of 0.8003 MPa was located at the center of the hollow flywheel and at the starting of the arms from the center. The obtained values of maximum shear stress values for both materials of hollow flywheel show that the cast iron has better resistance to applied torque.

The reason is that the center of the filled flywheel experiences higher shear stresses due to the material's resistance to deformation, while the edges of the hollow flywheel experience lower shear stresses as they are freer to deform under centrifugal forces [24].

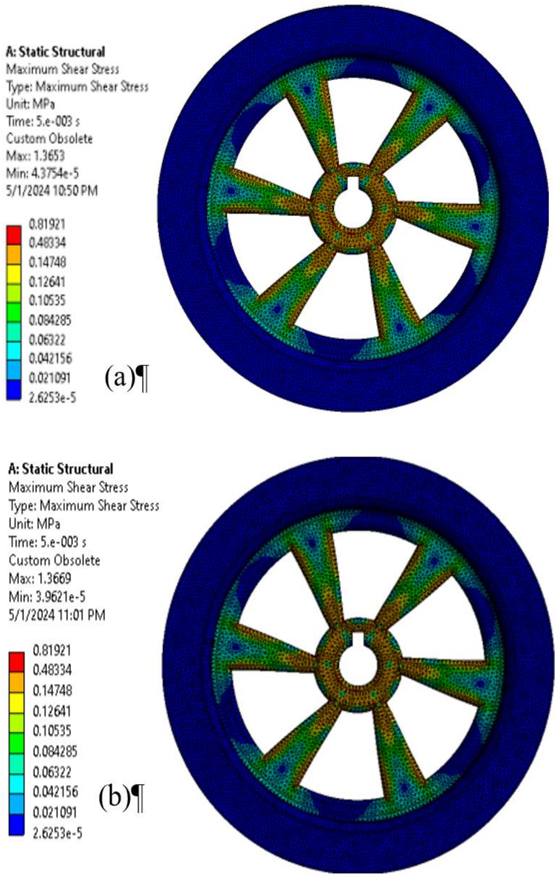


Fig. 9: Maximum Shear Stress of Hollow Flywheel (a) Cast Iron and (b) Gray Cast Iron

IV. CONCLUSION

Flywheel is considered one of the main components of an engine and or machine, and is utilized mainly for storing and supplying the energy at respective moment. The geometry of the flywheel significantly affects the storing of the energy in it, and resistance to applied torque. Therefore, two different geometries of flywheel made through two different materials were investigated for mechanical analysis of flywheel. Following conclusions have been drawn based on the obtained simulation results:

i. The simulation results of this investigation showed that solid flywheel is offering more resistance to applied torque than hollow flywheel. Due to it, the mechanical analysis of solid flywheel is far better than hollow flywheel at the same applied torque.
ii. For materials consent, gray cast iron offered better mechanical results than cast iron for a particular geometry of the flywheel.
iii. The maximum and minimum values of 35.279 mm and 22.15 e-5 mm for Total Deformation of solid flywheel for Cast Iron and hollow flywheel with 6 arms for gray cast iron respectively.
iv. The maximum value of 3.8051 MPa maximum principal stress is observed for hollow flywheel with 6 arms for cast iron. Whereas, the minimum value of maximum principal stress is observed for of 0.75855 MPa is achieved for solid flywheel for cast iron.
v. The highest and lowest values of 0.64649 mm/mm and 2.8789 e-5 mm/mm of maximum principal elastic strain was observed for solid flywheel for cast iron and hollow flywheel with 6 arms for gray cast iron respectively.
vi. Comparing the maximum shear stress value, the highest value of 0.81921 MPa was obtained for hollow flywheel with 6 arms for cast iron. Whereas, the lowest value of 0.49736 MPa of maximum shear stress is achieved for solid flywheel for cast iron.

V. FUTURE RECOMMENDATIONS

The main object of this research work is obtained, discussed in detail and solid conclusions have been drawn. However, few more ideas are presented below, where this research work could be explored further:

i. The simulation results of this study provide a foundation for future investigations to enhance the design and performance of the flywheel.
ii. Further work could continue this work by examining other materials, especially those with higher strength-to-weight ratios such as composite or high strength alloys. These materials may provide enhanced energy density and wear resistance, which enables flywheels to

deliver higher performance at lesser weights, which is beneficial for high-speed applications where weight reduction is important.

iii. This research could incorporate simulations with higher torque values, to challenge the flywheel to work under more strenuous conditions.

iv. In practical applications, the flywheels may be subjected to varying loads and speeds as a result of system requirements or interference. To evaluate the material and geometry of a flywheel for stable performance under dynamic conditions, these conditions can be simulated to understand how flywheels respond to unpredictable forces.

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