

Design And FEA Optimization Of Flywheel Using Composite Material

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Abstract: Flywheels is a kinetic energy storage and retrieval devices with the ability to deliver high output power at high rotational speeds as being one of the emerging energy storage technologies available today in various stages of development, especially in advanced technological areas, i.e., space-crafts , aeroplane , car . Mainly, the performance of a flywheel can be attributed to three factors, that is., material strength, geometry (cross-section) and rotational speed. While material strength directly determines kinetic energy level that could be produced safely combined (coupled) with rotor speed, this study solely focuses on exploring the effects of flywheel material on its energy storage/deliver capability per unit mass, further defined as Specific Energy. Proposed Computer aided analysis and optimization procedure results show that smart selection of flywheel material could both have a significant effect on the Specific Energy performance and reduce the operational loads exerted on the shaft/bearings due to reduced mass at high rotational speeds. Three rim type flywheels are designed on CATIA v5 software and structural analysis will be done using Ansys software. The first flywheel will be made up with mild steel and for reducing its weight composite flywheel will also be developed. Carbon fiber is used for making other flywheel. From the best suitable design and material fabrication will be made and speed test of flywheel will be compared by fabricating the speed testing device.

In these test we are optimized the weight of flywheel and reduces the cost of production of flywheel by using of different material. We use material that is mild steel, carbon fiber etc.after selecting material the flywheel is design on catia v5 software and then stress analysis is done using finite element method.

Introduction

A flywheel used in machine serves as a reservoir which stores energy when the supply of energy is more than the requirement and releases it during the period when the requirement of energy is more than the supply. A composite material allows a higher rotational speed and this result in flywheel rotors with high specific energy and light in weight. Composite materials are therefore a better choice than metals when designing flywheel rotors. The theoretical specific energy of composite rotors is around five times higher than metallic ones. The high-speed flywheel concept originated in the early 1970s. A researcher at Lawrence Livermore National Laboratory presented an article in Scientific American proposing a new approach to rotor design, recommending the use of composite materials instead of metal. Composite materials also have safety advantage over metallic material. If a potential failure at high angular velocity and the radial stresses exceeds the material strength composite. Use of composite material in flywheel has many advantages like composite material flywheel can run faster than metallic flywheel, less weight on machine and hence less fuel consumption and achieve high efficiency.

Background

In an era of intensive competition, the new challenges faced by industrial manufacturing processes include maximizing productivity, ensuring high product quality, and reducing the production time while minimizing the production cost simultaneously. With the more precise demands of modern engineering products, the control of surface texture together

has become more important. These processes work on a particular principle by making use of certain properties optimization of these processes.

Flywheel as energy store device

Fly wheel it is device which is use to store the energy when the energy is more than required energy and releases energy during the peroid when the requied energy is more than supply energy. Fly wheel it is use in kinetic energy store purpose and have been around since the early time of man every object which rotate around an axis is produce a kinetic energy and to store that energy we use flywheel.

Flywheel

Flywheels serve as kinetic energy storage and retrieval devices with the ability to deliver high output power at high rotational speeds as being one of the emerging energy storage technologies available today in various stages of development, especially in advanced technological areas, i.e., space-crafts. Mainly, the performance of a flywheel can be attributed to three factors, i.e., material strength, geometry (cross-section) and rotational speed. Proposed Computer aided analysis and optimization procedure results show that smart selection of flywheel material could both have a significant effect on the Specific Energy performance and reduce the operational loads exerted on the shaft/bearings due to reduced mass at high rotational speeds.

Literature Survey

It is usually necessary to draw the teeth profile on a pair of meshing gears, to understand the problems involved in the meshing of the touching teeth. Further, the drawings are not used for producing the teeth in the shop. Hence, approximate constructions may be followed to draw the tooth profiles. These approximate construction methods are described later. These methods form construction in SOLID WORKS .However accurate modeling methods can help to achieve accurate results and thus improve the gravity of study. It is a multi-platform CAD/CAM/CAE software developing by the French company Dassault Systems. Written in the C++ programming language, SOLID WORKS is developed by Dassault Systems commonly referred to as 3D Product Lifecycle Management software, SOLID WORKS supports multiple stages of product development from conceptualization, design (CAD), manufacturing (CAM), and engineering (CAE). SOLID WORKS including surfacing & shape design, mechanical engineering, equipment and systems engineering .SOLID WORKS can be applied to a wide variety of industries, from aerospace and defense, production engineering ,automotive, and industrial equipment, to high tech, shipbuilding, consumer goods, plant design, consumer packaged goods, life sciences, architecture and construction, process power and petroleum, and services .Parametric modeling also saves a lot of time as compared to the conventional modeling techniques. Their paper indicates that the time used for designing is reduced by 48 to 52 % due to the use of parameter modeling techniques and focusing on preparation phase.in this paper elementary relations are used to determine the material utilization efficiency of thin wall composite flywheel compared with other material. An algorithm was generated for the automatic selection of the optimum composite material for given thin wall flywheel environment. Subsequently computer programme NASTRAN (Nasal Structural Analysis) was used to perform a detail stress and vibrational analysis of both single and multi-rim thin wall composite flywheel for a specific application. The hoop wound thin wall cylindrical rim is most weight efficient

basic element flywheel configuration for carbon fiber composite. Multigrain flywheels combine both weight efficient and volume efficient rims to optimize the total energy capacity for single flywheel installation. NASTRAN can be used for stress and structural dynamic analysis of both single and multi-rim flywheel.

The process required to perform an engineering simulation consist of three step

1. Pre-processing
2. Solving/processing
3. Post-processing

Pre-Processing

To start pre-processing, a computer representation of the object is required; typically, this is a computer-aided design (CAD) geometry imported into the engineering simulation software. It is possible to construct a representative geometry from scratch using software tools from ANSYS. The CAD files sometimes import with rough, inaccurate edges that must be cleaned up, or they will render a simulation inaccurate. Tools from ANSYS can address this as well. The outer boundary for the model is set, which limits simulation to a defined area to speed the solving process. Next, a computational mesh is created that covers every surface of the geometry as well as all volumes of space in and around the geometry to the model's outer boundary. In some cases, the mesh can comprise millions of individual cells. The complexity of the mesh is a significant factor as well. When greater accuracy of results is required, such as a boundary layer, smaller cells must be used in localized mesh. The computer will solve sets of fundamental mathematical equations for each individual cell to arrive at an overall simulated prediction for the model. Known parameters are then assigned, such as flow velocities, temperature, pressure, stress loads and other factors, that will influence the operational performance of a product or process-system being studied. This prepares the model for solving.

Solving/Processing

Engineering simulation software uses a series of computational procedures involving applied forces and the properties of the elements to produce a model solution. Solving can be instigated at the click of a mouse button. The software and hardware work together to assert their power, performing millions of complex calculations per second. The physics equations upon which such simulations are based have been known by science for more than 100 years. Up until the 1940s, they were calculated by hand, with a number of engineers working in tandem to arrive at the solution. Today, one computer can conduct this work on far more complex problems, and, depending on the size and complexity of the model being simulated, a solution is possible in as little as a few minutes. Generally, the more cells there are in a simulation, the longer it will take a computer to arrive at a solution. The solution speed can be increased with greater compute power.

Post-Processing

Simulation results can be studied to fully identify implications of the analysis. Quantitative (numerical or tabular) and qualitative (graphical) tools allow the engineer to pinpoint the precise location of data, such as stresses and deflections. Tabular data is especially useful to engineers and analysts, providing precise numbers that can be used to meet design,

manufacturing, regulatory and other requirements. To help communicate this information to all stakeholders in the design process (engineer or not), visualization tools can help convey the simulation outcome quickly. A variety of still and animated graphical representations of the results can prove valuable in revealing problems and determining where further study work should be concentrated.

Materials and functional values

This disk has the properties such that the radial and tangential stress components remain equal throughout the disk. Depending on the material used the optimal flywheel shape will change. It mean if the material of flywheel is change according to it we have change it shape to achieve equal property in all direction and that property is radial and tangential stress remain constant Isotropic materials, such as steel, has equal strength in both the tangential and radial direction. Anisotropic materials, like fiber-reinforced composites, have unidirectional tensile strength, i.e. are stronger in the longitudinal fiber direction. A thin rim (hollow circular cylinder) flywheel is a very good candidate for composite material as this geometry exploit the high unidirectional strength of the fibers. Multiple sources state that a hollow circular cylinder is the optimal shape for a composite flywheel rotor.

Flywheel different material and value

Material	Density	Tensile strength	Specific energy
	[kg/m ³]	[GPa]	[Wh/kg]
Steel			
4320 Steel	7700	1.52	50
AISI 4340	7800	1.80	64
Alloy			
AlMnMg	2700	0.60	62
Titanium			
TiAl6Zr	4500	1.20	74
Composites			
E-glass	200	0.10	14
S-Glass	1920	1.4	210
Carbon T-1000	1520	1.95	350
Projected composites	1780	10	780

Problem Definition

If flywheel is heavy it increases fuel consumption. It has a high rotational inertia, which reduces how fast engine slowdown, which latter increases stress on the engine and reduces life. It has to exactly balanced to avoid severe vibration. It adds somewhat to the cost of materials and manufacture. Slowing a flywheel wastes the energy used previously to accelerate it, unless special provision is made to recapture the energy .If a flywheel comes adrift while the engine is running, it can cause disastrous damage. That's a rare event, but it has happened .One of the things you consider doing when you are turning a street car into a race car is installing a lighter flywheel. The intention is to allow the engine to accelerate faster and to minimize the parasitic loss of horsepower due to moving the weight of the flywheel. Lighter flywheel reduce the loss of power and horsepower of engine and also reduce stress on engine and achieve good performance in racing car.

Objectives

A composite material allows a higher rotational speed and this result in flywheel rotors with high specific energy and light in weight. Composite materials are therefore a better choice than metals when designing flywheel rotors. The theoretical specific energy of composite rotors is around five times higher than metallic ones. The high-speed flywheel concept originated in the early 1970s. A researcher at Lawrence Livermore National Laboratory present and recommending the use of composite materials instead of metal flywheel .Composite materials also have safety advantage over metallic material. If a potential failure at high angular velocity and the radial stresses exceeds the material strength composite flywheel is less likely to break apart in free flying projectiles. Instead, circumferential cracks develop and the flywheel breaks apart gradually .The main objectives of this project are:

1. To reduce weight of automobile flywheel by using composite material.
2. We take automobile flywheel and analyze it using ANSYS (finite element modeling and analysis software) to optimize weight and find out the resulting stresses.
3. Manually calculate stress using design parameters for all three steel, carbon fiber and composite flywheel.
4. Compare the theoretical and manual stress results.

Methodology

Definition of Flywheel:

A flywheel used in machine serves as a reservoir which stores energy during the period when the supply of energy is more than the requirement and releases it during the period when the requirement of energy is more than the supply.

Working of Flywheel:

The excess energy is developed during power stroke is absorbed by flywheel and releases it to the crankshaft during the other stroke in which no energy is developed, thus rotating the crankshaft at a uniform speed. A little consideration will show that when the flywheel absorbs energy, its speed increases and when it releases energy, the speed decreases. Hence a flywheel does not maintain a constant speed, it simply reduces the fluctuation of speed. In other words, a flywheel controls the speed variations caused by the fluctuation of the engine turning moment during each cycle of operation Common uses of a flywheel include:

- * Providing continuous energy when the energy source is discontinuous. For example, flywheels are used in reciprocating engines because the energy source, torque from the engine, is intermittent.
- * Delivering energy at rates beyond the ability of a continuous energy source. This is achieved by collecting energy in the flywheel over time and then releasing the energy quickly, at rates that exceed the abilities of the energy source.
- * Controlling the orientation of a mechanical system. In such applications, the angular momentum of a flywheel is purposely transferred to a load when energy is transferred to or from the flywheel.

Flywheels are typically made of steel and rotate on conventional bearings; these are generally limited to a revolution rate of a few thousand RPM. Some modern flywheels are made of carbon fiber materials and employ magnetic bearings, enabling them to revolve at speeds up to 60,000 RPM.

We know that in a four-stroke cycle internal combustion engine, there is one working stroke after the crank has turned through two revolutions, i.e., 720° (or 4π radians).

Since the pressure inside the engine cylinder is less than the atmospheric pressure during the suction stroke, therefore a negative loop is formed as shown in above figure. During the compression stroke, the work is done on the gases, therefore a higher negative loop is obtained.

During the expansion or working stroke, the fuel burns and the gases expands, therefore a large positive loop is obtained. In this stroke, the work is done by the gases. During exhaust stroke, the work is done on the gas, therefore a negative loop is formed.

Types of Flywheel Applications:

There are three distinct types of flywheels

1. Constant driving torque and variable load torque
2. Variable driving torque and constant load torque
3. Variable driving torque and variable load torque

Recent developments:

Mission critical technology programs are recently focused on storing energy more efficiently using flywheel than rechargeable chemical batteries while also providing some control advantages. Flywheel is essentially a simple device for storing energy in a rotating mass has been known for centuries. It is only since the development of high-strength materials and magnetic bearings that this technology is gaining a lot more attention. Exploration of high strength materials allows designers to reach high operating speeds, yielding more kinetic energy. Using magnetic bearings make it possible to reach high operating speeds providing cleaner, faster and more efficient bearing equipment at extreme temperatures. Recently designed flywheels could offer orders of magnitude increases in both performance and service life and in addition, large control torques and momentum storage capability for spacecraft, launch vehicles, aircraft power systems and power supply The flywheel system mainly consists of flywheel rotor, motor/generator, magnetic bearings, housing and power transformation electronic system. In the development of the flywheel, current researches have focused on increasing the performance while meeting the safety considerations, i.e., material, housing and bearing failures. Investigation of energy storage and failure considerations starts with the calculation of kinetic energy.

Terms used in flywheel:

Through a series of workshops and meetings, the automobile flywheel community has defined some common terms as they appear to high performance (i.e., high specific energy) flywheels. Following definitions have been agreed upon:

- Rotor: The complete rotating assembly, include rim, hub, shaft and other device parts.

- Rim: The main rotating mass of the flywheel rotor system. Rim is contained in the most of the stored energy
- Hub: The part of the rotor that connects the rim to the shaft. Because the hub mass contributes minimally to the total stored energy for the flywheel system, it should be as light as possible.
- Shaft: The shaft is rotating axial part that lies on the spin axis of the rotor and is the rotor interface connection to the portions of the magnetic bearings and motor generators. Some flywheel rotor systems may not require a shaft.
- Flywheel Energy Storage (FES): A flywheel-based system used only for charge and discharge of energy. For spaceship or satellite applications, this implies the use of at least two flywheels in a counter-rotating configuration.
- Total Stored Energy (TSE): The TSE of the flywheel system is the total energy stored in the rotor of the flywheel system (as defined above).
- Energy Storing Density (ESD): Energy stored divided by mass.

Use of composite materials for flywheel:

When a flywheel energy storage system is rotating at high speed, the stress distribution in thin rims is mainly concentric (or hoop), so composite materials with the high unidirectional strength of their fibers can be used to advantage. A composite flywheel rotor was designed and developed by Potter and Medicott (1986), as part of a program to develop a flywheel energy storage system, which used in vehicle applications. In the following decade, advanced composite flywheels have been developed in order to meet the demands for energy storage systems with both a high energy density and long life. In the study of Curtiss (1995), it was shown that the composite Carbon fiber-Epoxy disk rotor is capable of a 38% higher rim speed or 91% greater rotor energy density, than a comparable rotor built of high strength weight ratio isotropic Titanium or steel alloys.

Generally, the flywheel energy storage system consists of a flywheel rotor, a supporting device, a charge/discharge device, and a safety device. Composite flywheel energy storage technologies currently compete with advanced electro-chemical batteries in applications, which require high specific energy and power.

Many investigators in the field have advanced new designs and manufacturing technologies to increase the storing density and ensure the safety operation of the flywheel. Among them, technological advances in high strength, low-density composite materials have been interested in increasing the energy storing density.

Kojima (1997), proposed a carbon fiber reinforced plastic (CFRP) flywheel. The study results show that a flywheel, with high-modulus graphite/epoxy filament wound composites that are designed for better stress distribution, is able to rotate at a higher speed. In 1999, Huang tested a polar woven flywheel design; this dual function capability provides weight savings and an improvement in life and reliability of the total spacecraft system. The life expectancy of a satellite flywheel system is at least 10 years, during which it is expected to undergo 50,000 cycles (charge/discharge) while supplying 3 to 5 kW-h of usable energy. In 2002, a new approach to strengthen flywheels with additional reinforcement in the radial direction along with the typical hoop direction reinforcement—Multi-Direction Composite (MDC) flywheel systems—was reported by Gowayed and Flowers.

Calculations

Theoretical calculation

Here we have to find out the permissible design stress for the three different material flywheels theoretically.

Case 1: Fully Steel Flywheel:

Given:

Power, [P] = 552 KW

Speed, N = 2000 rpm

Torque, T = 274 N-m

Factor Of Safety, FOS = 3

Now,

$$\text{Mean Rim Speed, } v = \frac{\pi DN}{60}$$

Where, D = mean diameter of rim (m) = 0.2623 m

N = speed (rpm)

$$\therefore v = \frac{(\pi \times 0.2623 \times 19000)}{60}$$

$$\therefore v = 260.945 \text{ m/sec}$$

Now,

Tensile stress due to centrifugal force, $\sigma = \frac{\gamma \times v^2}{g}$

Where, γ = specific weight = $\rho \times g$

g = gravitational acceleration $\approx 10 \text{ m/sec}^2$

$$\therefore \sigma = \frac{(\rho \times g) \times v^2}{g}$$

$$\therefore \sigma = \rho \times v^2$$

Where, ρ = density of steel = 7850 kg/m³

$$\therefore \sigma = 7850 \times (260.945)^2$$

$$\therefore \sigma = 534.528 \text{ Mpa}$$

Considering, Factor of safety, FOS = 3

$$\therefore \text{Design Stress } [\sigma] = \sigma / \text{FOS}$$

$$\therefore [\sigma] = 534.528 / 3$$

$$\therefore [\sigma] = 178.176 \text{ Mpa}$$

Case 2: Fully Carbon Fiber Flywheel:

Given:

Power, [P] = 552 KW

Speed, $N = 19000$ rpm

Torque, $T = 274$ N-m

Factor Of Safety, $FOS = 3$

Now,

$$\text{Mean Rim Speed, } v = \frac{\pi DN}{60}$$

Where, $D =$ mean diameter of rim (m) = 0.2623 m

$N =$ speed (rpm)

$$\therefore v = \frac{(\pi \times 0.2623 \times 19000)}{60}$$

$$\therefore v = 260.945 \text{ m/sec}$$

Now,

$$\text{Tensile stress due to centrifugal force, } \sigma = \frac{\gamma \times v^2}{g}$$

Where, $\gamma =$ specific weight = $\rho \times g$

$g =$ gravitational acceleration $\approx 10 \text{ m/sec}^2$

$$\therefore \sigma = \frac{(\rho \times g) \times v^2}{g}$$

$$\therefore \sigma = \rho \times v^2$$

Where, $\rho =$ Density of Carbon Fiber = 2050 kg/m³

$$\therefore \sigma = 2050 \times (260.945)^2$$

$$\therefore \sigma = 139.59 \text{ Mpa}$$

Considering, Factor of safety, $FOS = 3$

$$\therefore \text{Design Stress } [\sigma] = \sigma / FOS$$

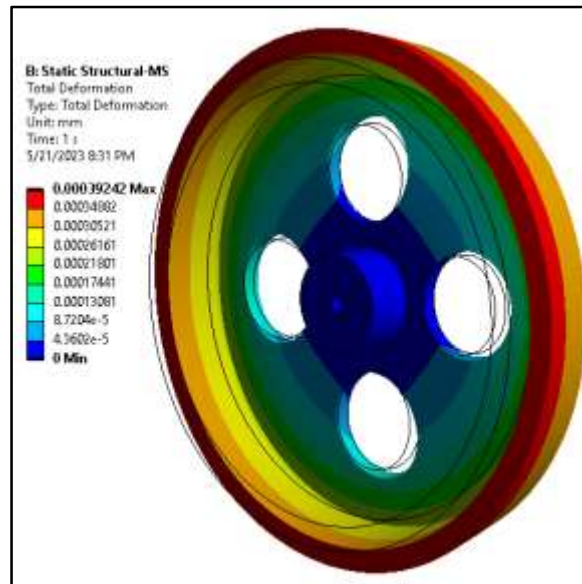
$$\therefore [\sigma] = 139.59 / 3$$

$$\therefore [\sigma] = 46.53 \text{ Mpa}$$

Static Analysis Results:

Static analysis results in form of total deformation and Stresses are tabulated below

Sr. No	Material	Deformation(mm)	Stresses (MPa)
1	Metal (MS)	3.9242e-004	1.0706
2	CF only	7.0525e-004	0.36053
3	Composite (CF+Steel)	7.0525e-004	0.9001



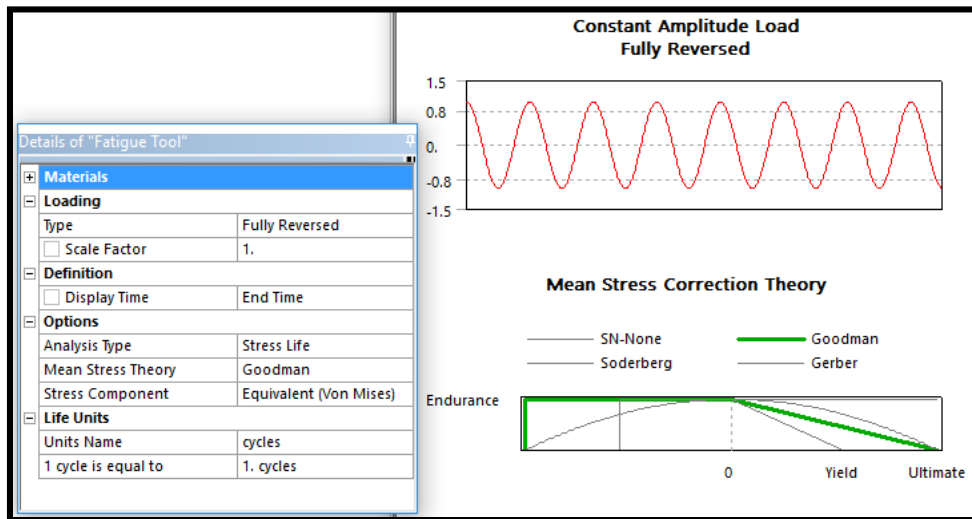
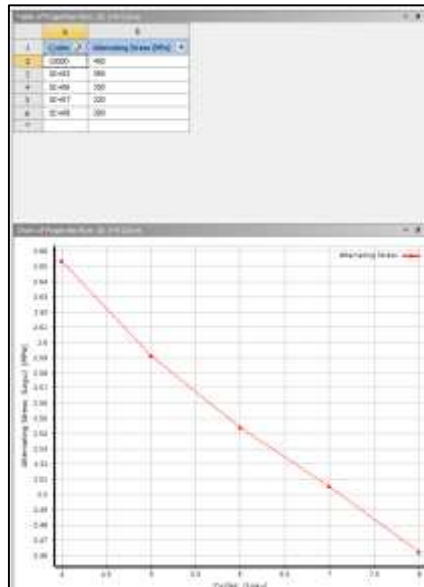
Fatigue Analysis Results:

Fatigue Basics

While many parts may work well initially, they often fail in service due to fatigue failure caused by repeated cyclic loading. Characterizing the capability of a material to survive the many cycles a component may experience during its lifetime is the aim of fatigue analysis. In a general sense, Fatigue Analysis has three main methods, Strain Life, Stress Life, and Fracture Mechanics; the first two being available within the ANSYS Fatigue Module. The Strain Life approach is widely used at present. Strain can be directly measured and has been shown to be an excellent quantity for characterizing low-cycle fatigue. Strain Life is typically concerned with crack initiation, whereas Stress Life is concerned with total life and does not distinguish between initiation and propagation. In terms of cycles, Strain Life typically deals with a relatively low number of cycles and therefore addresses Low Cycle Fatigue (LCF), but works with high numbers of cycles as well. Low Cycle Fatigue usually refers to fewer than 10⁵ cycles. Stress Life is based on S-N curves (Stress – Cycle curves) and has traditionally dealt with relatively high numbers of cycles and therefore addresses High Cycle Fatigue (HCF), greater than 10⁵ cycles inclusive of infinite life. Fracture Mechanics starts with an assumed flaw of known size and determines the crack's growth as is therefore sometimes referred to as "Crack Life". Fracture Mechanics is widely used to determine inspection intervals. For a given inspection technique, the smallest detectable flaw size is known. From this detectable flaw size we can calculate the time required for the crack to grow to a critical size. We can then determine our inspection interval to be less than the crack growth time. Sometimes, Strain Life methods are used to determine crack initiation with Fracture Mechanics used to determine the crack life. In this situation, crack initiation plus crack life equals the total life of the part. The main factors that contribute to fatigue failures include number of load cycles experienced, range of stress and mean stress experienced in each load cycle and presence of local stress concentration.

Fatigue Analysis of Axle

Stress Life based on empirical S-N curves is considered here to calculate fatigue life of leaf spring. Constant amplitude with fully reverse loading were considered with Goodman theory for the mean stress



Discussion on result

Result section

Sr.No	Material	Total Deformation in mm	Stress in mm	Rotational velocity rad /sc
1.	Steel	0.00039242	1.0706	209.44
2.	Glass fiber	0.00064989	0.2463	209.44
3.	Carbon fiber	0.00003981	0.1342	209.44

The results of the design and structural analysis of the composite flywheel utilizing epoxy glass fiber woven material showcase remarkable performance characteristics, with a total deformation of only 0.000649 mm and a stress level of 0.246 MPa. These outcomes not only demonstrate the exceptional stiffness and strength properties of the composite material but also highlight its superiority over traditional steel flywheels in terms of deformation resistance and stress distribution. Additionally, the slight margin of improvement over carbon fiber reinforces the competitive advantage of the epoxy glass fiber composite in terms of both mechanical performance and potentially lower manufacturing costs.

This underscores the viability of composite flywheel technology as a compelling alternative for applications requiring high-performance energy storage systems, offering superior performance compared to conventional materials.

Applications of flywheel:

- Transportation
- Uninterruptible power supply
- Amusement ride
- Motor sports

Advantages:

Flywheels store energy very efficiently (high turn-around efficiency) and have the potential for very high specific power (~ 130 W•h/kg, or ~ 500 kJ/kg) compared with batteries. Flywheels have very high output potential and relatively long life. Flywheels are relatively unaffected by ambient temperature extremes. The energy efficiency (ratio of energy out per energy in) of flywheels can be as high as 90%. Typical capacities range from 3 kWh to 133 kWh. Rapid charging of a system occurs in less than 15 minutes.

Result

- Stresses of MS material is less than material yield and ultimate tensile strength and hence it is material are meeting static analysis acceptance limit.
- Flywheel with MS material are has infinite life for the velocity of 2000RPM loading.

Hence in next step 100% composite with carbon fiber body will be compared and mass reduction optimization strategy will be used for determination of stress and deformable properties in order make it low weighed, high rotational velocity & high strength with the application of composites.

Sr. No	Material	Type of result	Value
1.	MS	Deformation	3.92e-4 mm
2.	MS	Stress	1.0706 MPa
3.	MS	Life	1.0e6

Conclusion

Composite material produces higher inertia per unit mass than old material flywheel. Composite material flywheel has high strength and uniform stress distribution in flywheel. It is light in weight hence less fuel consumption and more efficient