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A CONTACT STRESS AND FAILURE PITTING OF STRAIGHT BEVEL GEARS

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Abstract: Bevel gears find application in transmitting motion between shafts that are not aligned, typically forming a 90° angle relative to each other. Some of the several types that are available commercially are the straight bevel, the Zerol bevel, the spiral bevel and the hypoid. Stainless steel, gray cast iron, titanium alloy and structural steel were used for the behavioural assessment. The design and modelling of the straight bevel gears were carried out using SolidWorks 2015, while ANSYS 18.2 was employed for simulating the stress and deformation of the gears. The 3D solid model generated using SolidWorks was imported into ANSYS, where the analysis was conducted using the finite element software, ANSYS Workbench. Stress distribution plot, deformation plot, and equivalent strain plot were generated. The highest stress, measuring 73.16 MPa, became evident as the load concentrated near the base of the gear teeth. The finite element analysis revealed a minimal likelihood of gear failure, and the least deformation was observed in the structural steel configuration, resulting in a deformation of 8.2354 x 10^–3 mm. Consequently, the gear pair is capable of successfully transmitting 6 kW of power without experiencing any failures with a good factor of safety.

Keywords: bevel gears, contact stress, translational displacement, pitting, bending stress

INTRODUCTION

Bevel gears have their teeth intricately carved onto the frustum of a cone, diverging from the conventional cylinder–shaped teeth found in spur and helical gears. In order for two such cone–frustum–shaped gears to engage seamlessly without any slipping, they require a shared apex, necessitating careful alignment of bevel gears on their respective shafts. This alignment ensures that the gear teeth elements converge to form a singular apex point. This, in turn, guarantees that the pitch surfaces of the engaged bevel gears remain proportionate to their distance from the common apex, facilitating a state of pure rolling motion between them.

Due to the conical nature of the pitch surfaces on bevel gears, the thickness and height of the teeth vary from the front end (toe) to the back end (heel), the larger extremity of the bevel gear. Conventional practice in bevel gear technology involves precisely defining the size and configuration of the tooth profile at the gear's back end.

Bevel gears fall into distinct categories based on their geometry:

- Straight bevel gears exhibit conical pitch surfaces, with their teeth following a straight and tapering pattern towards the apex.
- Spiral bevel gears feature curved teeth set at an angle, enabling gradual and smooth tooth engagement.
- Zerol bevel gears closely resemble standard bevel gears, differing primarily in their curved teeth structure: the tooth ends lie on a common plane with the gear axis, while the middle portion of each tooth sweeps circumferentially around the gear. Zero level gears can be seen as a variation of spiral bevel gears, sharing curved teeth but having a spiral angle of zero, aligning the tooth ends with the gear axis.
- Hypoid bevel gears resemble spiral bevel gears, but their pitch surfaces follow a hyperbolic shape rather than a conical one

The validation of performance of the bevel gears occurred through a comparison between the outcomes of the Algorithm's computations and those generated by the software (Oladejo and Bamiro, 2009; Akinnuli, et al., 2015; Abu, et al., 2016). The efficacy of Bevel CAD was affirmed, attributing slight dissimilarities in the outcomes to approximation inaccuracies. Bevel CAD enhances efficiency while alleviating the tedium associated with extensive calculations, thus positioning it as a recommended instrument for both industrial and tertiary settings engaged in bevel gear design. Bevel gears are commonly situated on shafts with a 90–degree separation, although they can be customized to function effectively at varying angles (Rufus, et al., 2016; Oladejo and Ogunsade, 2014). These gears possess a pitch surface in the form of a cone. When two bevel gears mesh together, it is referred to as bevel gearing. Within this gearing system, the pitch cone angles of the pinion and gear depend on the angle of the shafts' intersection. The applications of bevel gears are extensive, including their use in locomotives, marine vessels, automobiles, printing presses, cooling towers, power plants, steel plants, and railway track inspection machines.

The modeling application enables the manipulation of a generated 3D gear model using pre–defined parameters that rely on geometric relationships and constraints (Ramana–Rao, et al., 2013; Ligata and Zhang, 2011). Altering these parameter values leads to modifications in the ultimate shape of the gear. This rapid parameter–driven model creation facilitates swift analysis of forces and stress through an analytical approach. The modeling methodology and functionality, illustrated through a specific example, hold potential applicability in the realm of cone crushers. Modify the software to enable the calculation of contact stress and acceleration variations in the driven wheel during the meshing process (Dong, et al., 2011; Oladejo, et al., 2018). This calculation is instrumental in directing the adjustments made to the spur bevel gear. The simulation outcomes demonstrate that tooth modification significantly influences the stress distribution on the gear surface. This modification proves instrumental in mitigating issues such as load concentration, agglutination, and pitting, effectively preventing their occurrence.

Assessment of the stress distribution at the tooth root of the bevel gear is conducted across diverse load scenarios, encompassing both uniformly varying loads and concentrated loads at the pitch point (Mohan and Jayaraj, 2013; Ligata and Zhang, 2011); Oluwole, et al., 2014). This study further delves into the load dispersion along the pitch line and examines stress patterns within the root fillet region.

This objective is effectively accomplished by recalculating the gear blanks, while keeping the flank geometry and tooth–cutting process unaltered (Karlis, et al., 2014; Jadeja et al., 2013; Edward and Lucky, 2018; Raj, and Jayaraj, 2013; Osakue and Anetor, 2017). Consequently, the optimized tooth ends of the gear pair can be machined without disrupting the standard tooth–cutting procedure. To substantiate this notion, an illustrative recalculation example is presented. These enhancements yield heightened tooth strength, streamline the gear blank geometry, align with contemporary machining practices, and lead to a reduced outer gear diameter.

Bevel gears find application in differential drives, enabling the transfer of power to two axles that rotate at varying speeds (Patil, et al., 2014; Gupta, et al., 2016; Oladejo et al., 2021). Examples include cornering automobiles and hand drills, where they redirect the shaft's orientation, or in cases like shifting power from a horizontal gas turbine engine to a vertical rotor. This study undertook a comparison between the Lewis equation and ANSYS Workbench, yielding closely aligned results.

Assessing the fitness of each individual through Monte Carlo simulation relies heavily on the quantity of samples used, which directly impacts accuracy (Jean–Yves, et al., 2008),. A higher volume of samples enhances precision but escalates computational expenses. To mitigate the computational burden associated with Monte Carlo simulation and genetic algorithm–based optimization, a strategy involves applying varied fitness levels. This entails introducing different sample quantities during the optimization process within our algorithms. Standards have been established to govern the design, analysis, and production of bevel gears (Ratnadeepsinh, et al., 2013; Shan and Zhang, 2012). The equation for calculating bending stress in the teeth of bevel gears is derived from the Lewis bending stress equation applied to beams. This equation yields bending stress values for various types of bevel gears, including spiral bevel gears, straight teeth bevel gears, and zerol bevel gears. To compare the analytical values with those obtained through ANSYS Workbench 14.0, the bending stress values for the aforementioned gears are evaluated. The application of parametric design to bevel gears could serve as a foundation for subsequent finite element stress analysis or assembly procedures (Shan and Zhang, 2012; Kurlapkar, et al., 2016). In this study, a set of bevel gears generated through the execution of macros was successfully assembled, demonstrating a precise meshing of the gears

Albert, et al. (2006) delved into the investigation of failure in a crown wheel and pinion set. Through the application of established metallurgical methods, a fractured gear underwent a comprehensive analysis aimed at determining the root cause of the failure. The findings of the study point to the failure being attributed to the manufacturer's decision to compromise the raw material composition. This compromise becomes evident in the notably elevated manganese content, coupled with the absence of nickel and molybdenum. As a consequence, the core hardness significantly increased, ultimately triggering the premature failure of the pinion. In the work by Alexander (2003), an engineering approach is outlined, aimed at harmonizing the bending stress distribution within both the pinion and the gear. Typically, these components possess distinct tooth profiles and widths, often comprising varying materials. The study introduces an equation that ensures equivalent bending safety factors for the highest bending stresses encountered in both the pinion and the gear. The objective is to establish teeth of equal strength for both the pinion and the gear.

Hasan et al. (2006) conducted a comprehensive analytical examination of elastic–plastic stress distribution within a rotating orthotropic annular disc. This disc is composed of a metal matrix infused with curvilinear reinforced steel fibers. Varied angular velocities were employed in the study to facilitate the observation of plastic region separation. The outcomes revealed pronounced differences, with the inner surface of the disc exhibiting greater values for both radial displacements and plastic flow compared to the outer surface. Suggested are a pair of dynamic models designed to explore the interplay between surface wear on a gear and its dynamic behaviour (Ahmad and Ahmet, 2007; Oladejo, et al., 2018). These models encompass the impact of worn surface profiles on dynamic tooth forces and transmission error, along with the effect of dynamic tooth forces on wear profiles. Explored was the application of an asymmetric toothed gear to enhance bending–related fillet strength (Kumar, et al., 2008; Abu et al., 2016). Additionally, an examination of the maximum fillet stress was undertaken to aid in enhancing this bending–related capacity. The study employed a non–standard asymmetric rack cutter for both the pinion and the gear. The findings indicated that employing an asymmetric gear configuration augments the fillet load–bearing capability of both the pinion and the gear, particularly at higher–pressure angles

Presenting a gear model derived from analytical simulation, followed by experimental tests using strain gauges, and subsequently comparing the outcomes with numerical results (Michele, et al., 2005); Yi and Chia, (2011); Oladejo and Bamiro, 2009). Strain gauge measurements were conducted on a modified bevel gear, disregarding alignment with the model's nodes. Consequently, stress estimation at corresponding strain gauge positions was unfeasible within the experiment. The primary objective revolves around the design and analysis of straight bevel gears, encompassing two key aspects:

- Creation of a 3D model for a Straight Bevel Gear utilizing SolidWorks.
- Execution of simulations on the 3D model, entailing an examination of bending stress, strain, and deformation across diverse materials such as Structural Steel, Stainless Steel, Gray Cast Iron, and Titanium Alloy.

MATERIALS AND METHODS

The purpose of this study is to design and analyse a straight bevel gear, create a 3D model using Solidworks, run stress simulations on the generated model and compare the simulation result to the numerical analysis result. Assessment of the behaviour of different materials under certain loading conditions will be done. The materials that will be used for the behavioural assessment of the bevel gear (Figure 1) under certain loading conditions include: Gray cast iron, Stainless steel, Structural steel, and Titanium alloy, and their properties are stated in Table 1.

Figure 1: Bevel Gear Profile

Table 1: Material Properties for Behavioural Assessment

Parameter	Gray cast iron	Stainless steel	Structural steel	Titanium alloy	Unit
Young's Modulus	1.1×10^5	1.93×10^5	2×10^5	96000	MPA
Specific Heat	4.47×10^5	4.8×10^5	4.34×10^5	5.22×10^5	mJ/kg·°C
Ultimate Tensile Strength	240	586	460	1070	MPA
Density	7.2×10^{-6}	7.75×10^{-6}	7.85×10^{-6}	4.62×10^{-6}	Kg/mm^3

Design Equations

For the design of the bevel gear, a nomenclature is defined for the gear in Figure 2 and the parameters and formulae for its design are stated in Tables 2 and 3

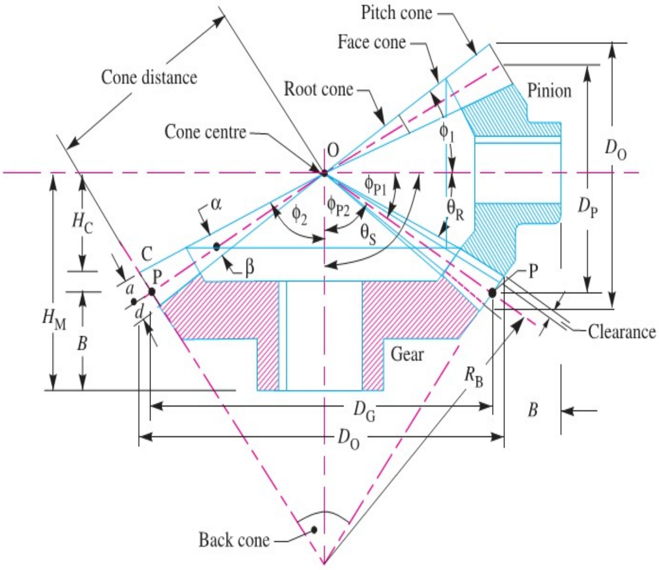

Figure 2: Bevel Gear Nomenclature (Khurmi and Gupta, 2005)

Table 3: Design Parameters

Parameters	Pinion	Gear	Unit
Power	6	6	kW
Number of teeth	20	30	No.
Pitch circle diameter	100	150	mm
Module	5	5	mm
Pressure angle	20°	20°	Deg.

Table 2: Bevel Gear Design Equations (Khurmi and Gupta, 2005)

Parameter	Formula
Velocity ratio or Gear ratio	$V.R = \frac{D_g}{D_p} = \frac{T_g}{T_p} = \frac{N_g}{N_p}$
Pitch angle of pinion	$\theta_{P1} = \tan^{-1}\left(\frac{1}{V.R.}\right) = \tan^{-1}\left(\frac{D_P}{D_G}\right) = \tan^{-1}\left(\frac{T_P}{T_G}\right) = \tan^{-1}\left(\frac{N_G}{N_P}\right)$
Pitch angle of gear	$\theta_{P2} = \tan^{-1}(V.R.) = \tan^{-1}\left(\frac{D_G}{D_P}\right) = \tan^{-1}\left(\frac{T_G}{T_P}\right) = \tan^{-1}\left(\frac{N_P}{N_G}\right)$
Addendum	$a = 1m$
Deddendum	$d = 1.2m$
Clearance	$c = 0.2m$
Working Depth	$w = 2m$
Thickness of tooth	$t = 1.5708m$
Face width	$b = 0.25 \times OC$
Mean Pitch Diameter	$D_m = D - b\sin\theta_p$
Circumferential velocity on the Mean pitch circle	$V_m = \frac{\pi D_m n}{6000}$
Nominal tangential load on the Mean	$F_t = \frac{P}{V_m}$pitch circle
Bending Stress	$\sigma_b = \frac{F_t}{b\,m\,j} K_v K_o K_m$

2.2 Bending Stress in Bevel Gear

As per the AGMA, the bending stress in bevel gear is calculated by the Equation (1).

$$\sigma_b = \frac{2T}{d}\,\frac{Gr}{FmJ}\,\frac{K_a K_m K_s}{K_v K_x} \tag{1}$$

Load Calculation

The load calculation involves calculating torque and tangential load acting on the bevel gear. Consider a bevel gear with the following:

The speed of bevel gear (n) = 500 rpm, and

Power transmitted = 6 kW

$$\text{Torque transmitted } (M_t) = 9.5488 \times \frac{\text{Power(w)}}{\text{speed(rpm)}} \tag{2}$$

$$M_t = 9.5488 \times \frac{6\times1000}{500}$$

$$M_t = 114.586 \text{ Nm} = 114586 \text{ Nmm}$$

Tangential component,

$$P_t = \frac{2\times M_t}{d} \tag{3}$$

$$P_t = \frac{2\times114586}{100} = Pt = 2291.72 \text{ N}$$

Bending Stress

$$\sigma_b = \frac{P_t}{m\times b\times y\left(1-\frac{b}{A_o}\right)} \tag{4}$$

where

$\left(1-\frac{b}{A_o}\right)$ = Bevel Factor

$$A_o = \sqrt{\left(\frac{D_p}{2}\right)^2 + \left(\frac{D_g}{2}\right)^2}$$

$$A_o = \sqrt{\left(\frac{100}{2}\right)^2 + \left(\frac{150}{2}\right)^2} = 90.139 \text{ mm}$$

$B = A_o / 3 = 30.05$ mm

$$\sigma_b = \frac{2291.72}{5\times30.05\times0.32\left(1-\frac{30.05}{90.139}\right)} = 71.50 \text{ N/mm}^2$$

MODEL DEVELOPMENT PROCESS USING SOLIDWORKS

A three–dimensional solid model of a bevel gear using SolidWorks was developed. The development involves the following steps.

▦ Sketch the Gear Profile:

Sketch the gear profile as shown in Figure 3 and produce the solid model as shown in Figure 4. Use sketch tools to draw a tooth profile of the bevel gear as shown in Figure 5. Create a tooth as shown in Figure 6.

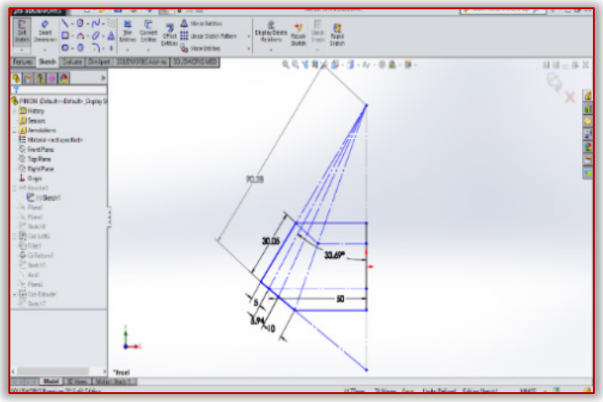

Figure 3: Sketch of the bevel gear

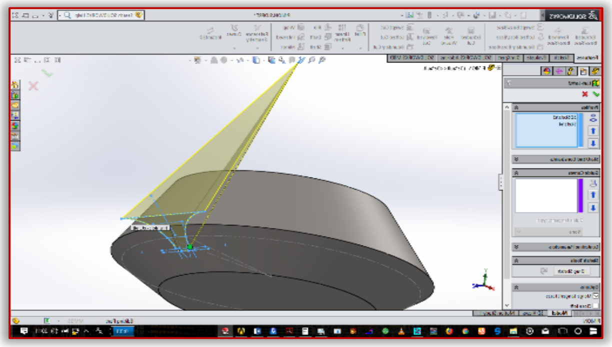

Figure 4: Solid model of the bevel gear

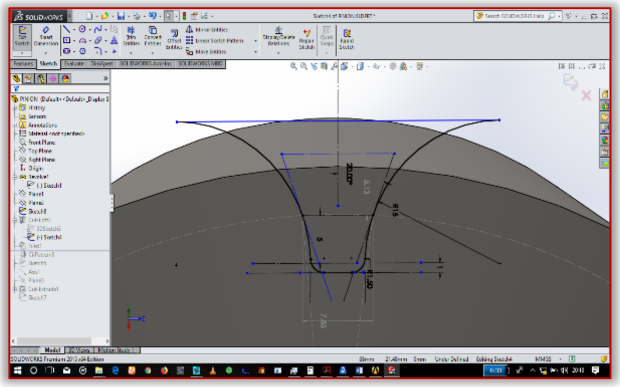

Figure 5: Using sketch tools to draw the tooth profile

▦ Revolve the Tooth Profile:

Use the "Revolve Boss/Base" feature. Select the sketch profile as the profile to revolve and specify the axis of rotation (centerline of the gear). Set the angle to 360 degrees to obtain the profile shown in Figure 7.

▦ Create the Bevel Gear Teeth:

The subtract tool in the "Combine" feature was used to create the teeth as shown in Figure 8.

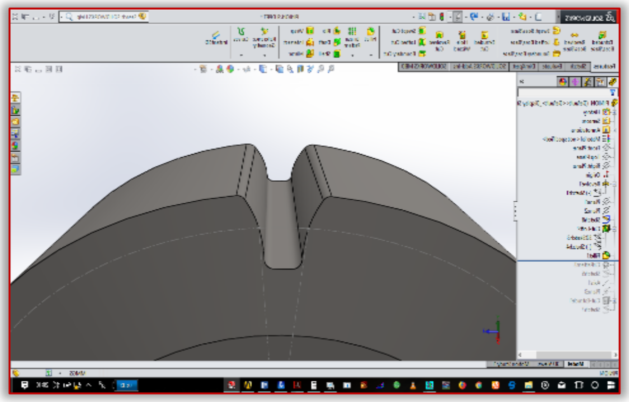

Figure 6: Development of a tooth profile

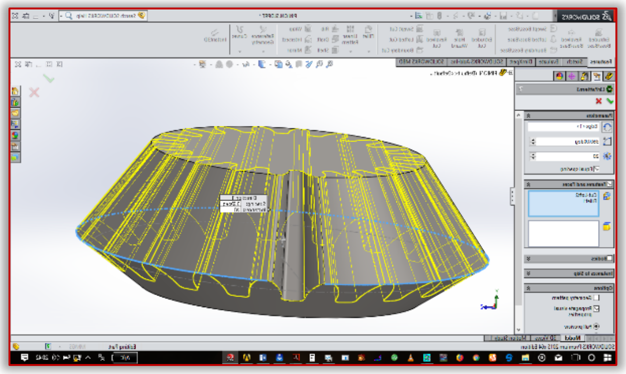

Figure 7: Revolving the tooth profile

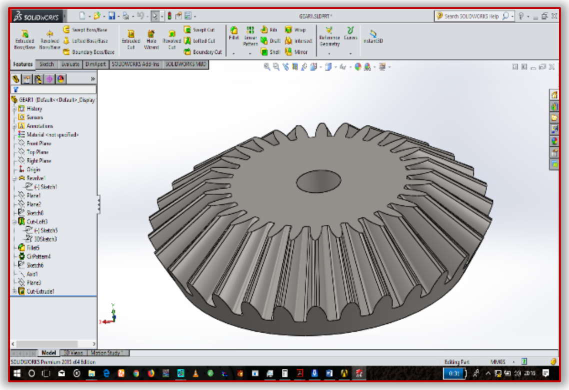

Figure 8: The developed 3D model of the gear

Add the Second Bevel Gear (Pinion):

Similar steps were followed to create the second bevel gear (Figure 9) which is pinion.

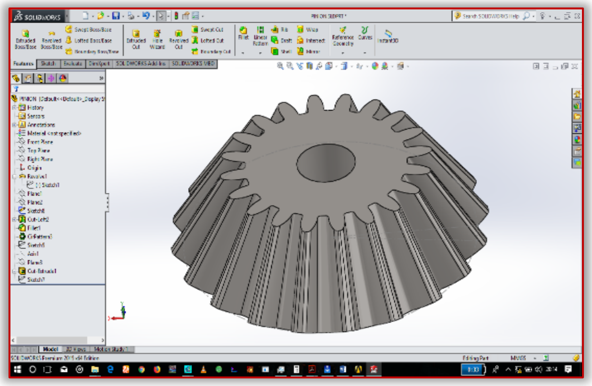

Figure 9: The developed 3D model of the gear

Combine Gears in an Assembly:

An assembly file was opened and the two gears were inserted into the assembly. The “Mate” tool was used to define the relationship and movement between the gears (Figure 10).

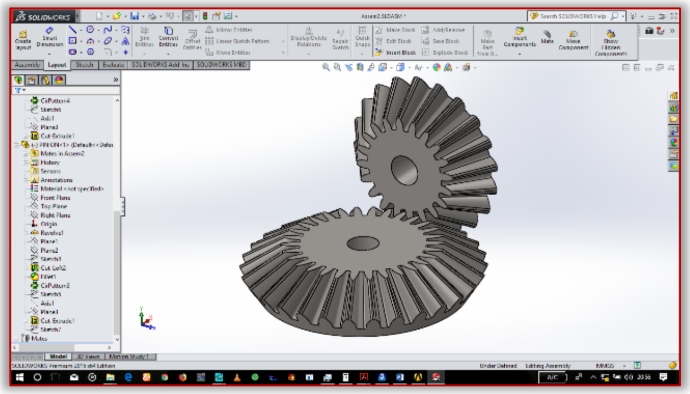

Figure 10: Assembling of Pinion and Gear

Save:

The SolidWorks file is save in “IGES” format for export to finite element analysis (FEA) software

ANALYSIS OF 3D MODEL OF THE BEVEL GEARS

Finite Element Model

The SolidWorks software was utilized to generate a comprehensive three–dimensional solid model, which was subsequently imported into ANSYS. The subsequent analysis involved the application of the finite element (FE) program, ANSYS Workbench 19.1. The initial 3D solid model constitutes an assembly comprising two interlocking gears, as depicted in Figure 11. This assembly consisted of a total of 598,289 elements. The subsequent step encompassed a stress analysis of the solid model, with the primary objective being the determination of both normal and shear stresses.

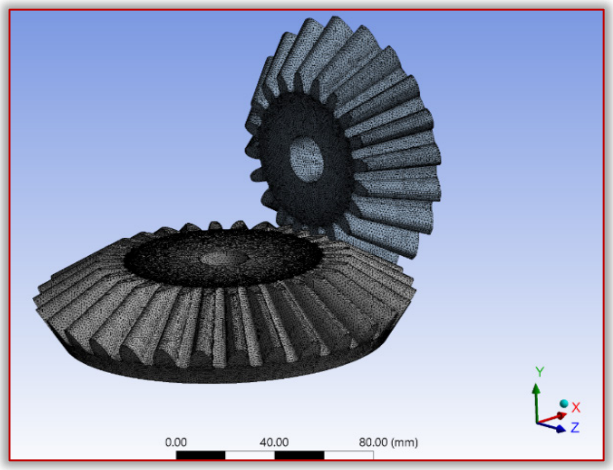

Figure 11: Meshing of Gear Pair

Loading and Boundary Conditions

The load is exerted as a moment, with a magnitude of 114,586 Nmm, acting upon both faces of the pinion. The pinion’s bore is supported without friction, while the gear is affixed with fixed support. The frictionless support on the bore enforces a normal constraint across the entire surface. This arrangement permits translational movement in all directions except perpendicular to the supported plane.

RESULTS AND DISCUSSION

The results of a mechanical analysis conducted on bevel gears using the ANSYS Workbench software on evaluating the bending stress, strain, and deformation of the gears made from different materials (structural steel, stainless steel, gray cast iron and titanium alloy) were obtained. Figure 11 presents a visual representation of the equivalent stress distribution across the bevel gears. It indicates that the highest stress occurs near the root of the teeth, and the maximum stress value observed is approximately 73.16 MPa.

Table 4 displays the numerical outcomes of the material analysis individually. The bending stress values resulting from the applied loads span a range of approximately 73.05 MPa to 73.54 MPa across various materials (depicted in Figures 12 to 15), with structural steel exhibiting the lowest stress level. Regarding strain values, they vary from around 4.2453 x 10^{-4} to 8.795 x 10^{-4} mm/mm among the different materials, with structural steel again demonstrating the least strain. The deformation measurements encompass a range of approximately 8.2354 x 10^{-3} to 1.7466 x 10^{-2} mm across diverse materials, with structural steel registering the lowest deformation.

Figure 11: Bending Stress analysis of Bevel Gears in ANSYS Workbench

Table 4: Bending Stress, Strain and Total Deformation of Bevel Gears in ANSYS

Materials	Bending Stress (N/mm^2)	Strain (mm/mm)	Deformation (mm)
Structural Steel	73.16	4.2453 x 10^{-4}	8.2354 x 10^{-3}
Stainless Steel	73.216	4.3954 x 10^{-4}	8.5613 x 10^{-3}
Gray Cast Iron	73.055	7.732 x 10^{-4}	1.4875 x 10^{-2}
Titanium Alloy	73.536	8.795 x 10^{-4}	5.1x 10^{-2}

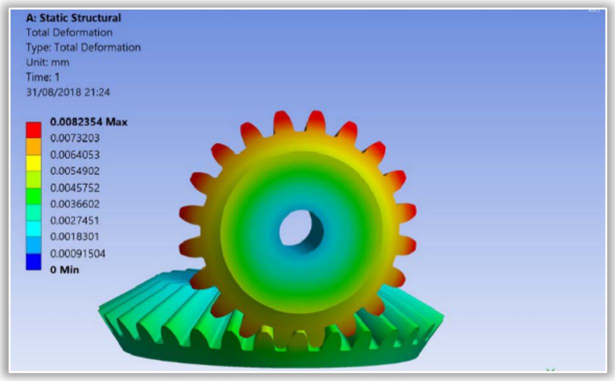

Figure 12: Deformation of Bevel Gears in ANSYS Workbench (Structural Steel)

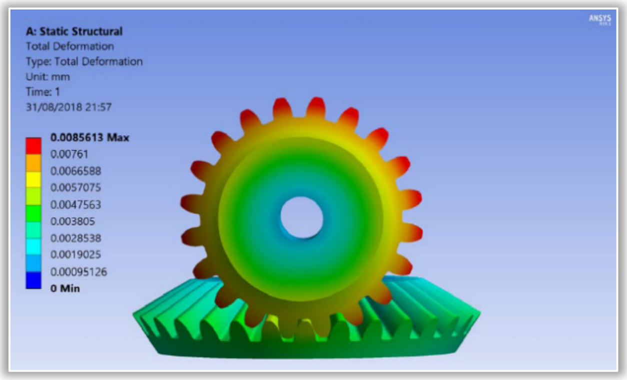

Figure 13: Deformation of Bevel Gears in ANSYS Workbench (Stainless Steel)

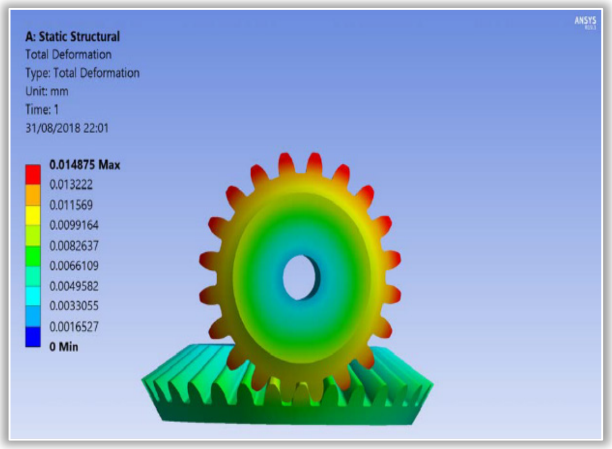

Figure 14: Deformation of Bevel Gears in ANSYS Workbench (Gray Cast Iron)

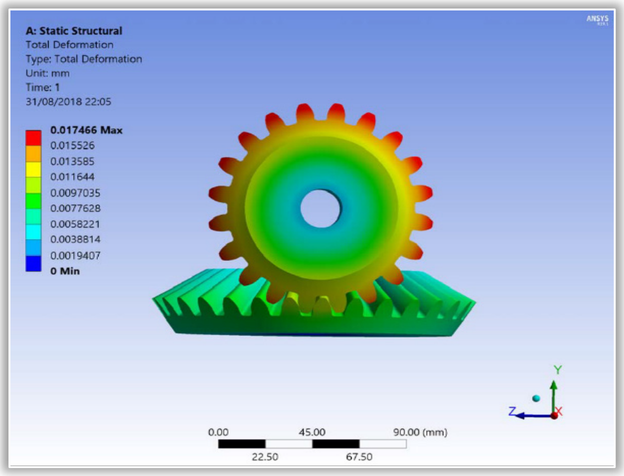

Figure 15: Deformation of Bevel Gears in ANSYS Workbench (Titanim Alloy)

CONCLUSIONS

The design of bevel gears results in thrust forces away from the apex. With the bearing limitations, the gears have to be carefully designed to ensure that they are not thrown out of alignment as they are loaded. Bending stress as a criterion of bevel gear capacity can be defined as the ability of the gear set to withstand repeated or continued operation under design load without the fracture of the teeth by fatigue bending. It is a function of the bending stresses in a cantilever beam and is directly proportional to the applied tooth load. It also involves the fatigue strength of the gear materials and shape of the teeth.

Pitting resistance as a criterion for wear failure on straight–bevel gear capacity can be defined as the ability of the gear set to withstand repeated operation under design load without suffering destructive pitting of the tooth surfaces. Destructive pitting progresses widely to destroy the geometry of the tooth surfaces and ultimately leads to failure.

In the present work, static structural analysis for bending strength by ANSYS Workbench has been done and the equivalent stress, total deformation and equivalent strain plots obtained. Finite element analysis manifests a minimum chance of gear failure. The material with the least deformation is Structural Steel with a maximum deformation of 8.2354 x 10^{-3}mm. The gear pair can be used to transmit the 6 kW power without failure of gear and with a good factor of safety.

These findings can guide material selection and design decisions for optimizing the gears' performance in various applications.

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NOMENCLATURE

T	Torque,
d	Diameter of gear,
F	Face width,
m	Module,
Gr	Gear ratio
J	Geometry factor of gear
Ka	Application factor = 1
Km	Load distribution factor 1.6
Ks	Size factor = 1
Kv	Dynamic factor = 1
Kx	Gear geometry factor = 1 for straight teeth bevel gear, = 1.15 for spiral bevel gear and zerol bevel gear.
Y	Lewis form factor,
M	Module,
b	Face width,

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