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Research/Technical Note

Assessment of Fatigue Life and Stress in Conventional and Hybrid 6206 Ball Bearings by Theoretical and Finite Element Analysis

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Abstract

Ball bearings are essential in mechanical systems. Fatigue life and stress distribution affect performance and reliability of system. Recently hybrid bearings have attracted attention because they may have advantages over traditional steel bearings, such as reduced friction, better wear resistance, and a longer service life. This study gives a comparative analysis of the analytical and real-life simulation fatigue life of 6206 deep groove ball bearings for conventional (AISI 52100 steel) and hybrid (AISI 52100 races with Si_3N_4 ceramic balls) specification. The main goal of this research is to find the fatigue life and stress behaviour of both types of bearings under similar operating conditions. The study calculates analytical life using the ISO 281 bearing life equation, and the stress distribution in bearing is evaluated using finite element analysis in ANSYS Workbench. The results show that the hybrid bearings have about 30% longer fatigue life compared to conventional steel bearing based on analytical calculations. finite element analysis shows that hybrid bearing experiences a higher von Mises stress due to the ceramic balls but it also shows lower maximum principal stress indicating reduced subsurface stress and improved fatigue resistance. The relation between analytical and ANSYS life estimation shows close agreement, with a life ratio of 1.30 (analytical) and 1.32 (simulation), respectively. In conclusion, hybrid bearing shows higher fatigue life, good stress distribution and suitable for high-load or high-speed applications where longer life and reduced friction is required.

Keywords

Hybrid Bearing, Conventional Bearing, L_{10} Life, ANSYS, Fatigue Life, Stress

1. Introduction

Bearings are the most critical components in rotating machinery [16]. responsible for supporting loads, reducing friction, and ensuring smooth motion between machine parts [2]. The life of a bearing is largely driven by the contact stresses developed at the raceway interface [3]. Conventional ball bearings are manufactured using high-carbon chromium steel (AISI 52100), which provides good wear resistance and hardness, but under high-speed or high-temperature conditions, steel bearing can face limitations due to thermal expansion, lubrication breakdown, and rolling contact fatigue.

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To overcome these problems, hybrid bearings which made up of steel races with ceramic (silicon nitride – Si_3N_4) balls, Ceramic balls have lower density, higher hardness, and greater stiffness compared to steel balls, resulting in reduced centrifugal forces and lower friction [10]. Due to these advantages of hybrid bearing have enhanced bearing life [18], especially in high-speed applications such as aerospace, electric vehicles, and precision spindles. The analytical life of a bearing is calculated using the ISO 281 standard [1], which relates the bearing life to the dynamic load rating and equivalent load. But analytical calculations assume ideal conditions and is not responsible for actual contact stress distribution. Therefore, finite element analysis (ANSYS) provides a more realistic understanding of stress behavior, allowing for direct comparison with analytical life prediction [12].

In this study, a 6206 deep groove ball bearing is analyzed to calculate and compare the contact stresses and fatigue life for both conventional (AISI 52100 steel) and hybrid (steel–ceramic) specifications. The analytical bearing life is calculated using the ISO 281 formula [1] with reliability and fatigue factors, and the stress distribution is analyzed in ANSYS software. The aim is to establish a relation between analytical and simulation-based fatigue life predictions and to validate the performance improvement offered by hybrid bearings.

2. Literature Review

Most of the researchers found that the hybrid bearing has better performance and life compared to conventional bearing. The hybrid specification, consisting of ceramic balls and steel races, shows significant improvement in fatigue life [17], thermal stability [19], and wear resistance under dynamic operating conditions.

F. Xu et al (2023) [5] This Paper highlights that bearing failures occur due to wear, fatigue, fracture, corrosion, and deformation, with wear and fatigue being the most common failure. The primary causes are cyclic loads, friction, lubrication issues, and improper assembly or maintenance. P. Borghesani (2022) [6] This paper study focuses on signal models used for rolling-element bearing diagnostics. It proposes a generalized model combining both approaches and evaluates their effectiveness using real bearing signals. The research highlights the impact of bearing parameters on time and frequency domain responses and helps in selecting better diagnostic indicators for fault detection. S. M. M (2019) [7] The study develops a new GPR technique for predicting the RUL of a gyroscope, considering the uncertainties involved in the dynamic behavior of the system. A degradation model is employed, with particular emphasis placed on the deterioration of ball bearings as an important determinant of performance. The model facilitates accurate predictions at an early stage and exhibits greater efficiency than conventional techniques. X. Z. Liang (2022) [8] The current research examines the impact of hydrogen on RCF in bearing materials. The researchers introduce a theoretical model to elucidate the role of hydrogen in the formation of white etching regions and subsequent fatigue damage. The findings reveal that hydrogen-dislocation interaction lowers the fatigue life of the material. I. Durazo-Cardenas *et al.* (2016) [9] The paper presents a study on the application of hybrid ceramic bearings in high-speed aircraft starter/generator applications, where higher speed operation results in heavy loads. The work is concerned with investigating the deterioration of bearings to enable condition-based maintenance and health management. The solution presented combines a monitoring technique and is validated with promising results. K. Holmberg et al. (2018) [10] studied rolling contact fatigue mechanisms and found that hybrid bearings show lower surface fatigue due to reduced adhesion and lower friction coefficients. A. Kumar et al. (2016) [11] analyzed the impact of material properties on the contact stress of deep groove ball bearings using FEA and concluded that the use of ceramic balls reduces subsurface stress and improves bearing life. J. Zhang et al. (2019) [12] Compared hybrid and all-steel bearings under high-speed operation and observed that the hybrid bearings have 40–60% longer life because of the lower density and higher stiffness of Si_3N_4 balls. P. Ramesh and S. Rajesh (2020) [13] Reported that the fatigue life of a bearing can be correlated to the max shear or principal stress obtained from finite element analysis, it proves that hybrid materials experience less stress at ball raceway. B. B. Farande and V. V. Kulkarni (2016) [14] Using Finite element analysis found stress concentration effect around countersunk hole in composite plate. B. B. Farande and V. V. Kulkarni (2016) [15] Using experimental setup found Stress Concentration factor around countersunk hole in composite plate.

Overall, previous research consistently indicated that ceramic–steel hybrid bearings offer enhanced performance, particularly in high-load or high-speed conditions. However, limited studies have correlated theoretical life estimation (ISO 281) with finite element stress-based fatigue prediction for hybrid configurations. This study aims to fill that gap by combining theoretical and simulation approaches for the 6206 deep groove ball bearing.

3. Methodology

This study involves both theoretical analysis and finite element simulation of the 6206 deep groove ball bearing for two configurations.

1) Conventional bearing (AISI 52100 steel balls and races)
2) Hybrid bearing (AISI 52100 races with Si_3N_4 ceramic balls)

3.1. Theoretical Analysis

The analytical bearing life is calculated using the ISO 281 life equation [1]:

$$L_{10}=10^6\left(\frac{C}{P}\right)^p$$

Where,
C-Basic Dynamic Load Rating
P-Equivalent Dynamic Bearing Load
P -Life Exponent

$$P = XFr + YFa$$

Where,
X-Radial Load Factor
Y-Axial Load Factor
Fr-Radial Load
Fa-Axial Load
The theoretical life in hours is obtained as:

$$L_{10}(\text{hrs})=\frac{\boldsymbol{L(10)rev}}{\boldsymbol{60n}}$$

3.2. Simulation Methodology (ANSYS Workbench)

Finite Element Analysis was performed in ANSYS Workbench (Static Structural) to determine the stress distribution within the bearing assembly.

Step-by-Step Procedure:

a. Geometry Creation:

The 3D geometry of a 6206 bearing was modelled or created (Figure 1) in SolidWorks, including inner race, outer race, and balls, using precise dimensions from the bearing catalogue [4].

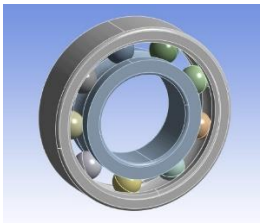


Figure 1. *Bearing Model.*

b. Material Assignment:

Conventional: All parts assigned AISI 52100 steel (E = 210 GPA, ν = 0.3).

Hybrid: Races assigned AISI 52100 steel balls assigned Silicon Nitride (E = 310 GPA, ν = 0.26).

c. Meshing:

Fine mesh with contact refinement was applied at ball–raceway regions. Element size was controlled using inflation layers for accurate contact stress prediction [11].

d. Boundary Conditions:

Inner race constrained with rotational freedom.

Outer race fixed radially.

Applied Pressure on Inner ring.

e. solution setup

Solved for Von Mises stress and Max Principal stress to identify critical zones of stress concentration [20].

3.3. Fatigue Life Correlation

The rolling contact fatigue life is related to the maximum shear or principal stress using the relation [13]:

$$L \propto \frac{1}{\tau_{max}^m}$$

Where
M=8 for bearing steel
Life ratio between hybrid and steel configurations:

$$\frac{L_{hyb}}{L_{steel}} = \left(\frac{\tau_{steel}}{\tau_{hyb}}\right)^8$$

The simulated life ratio obtained from ANSYS stress values were compared with the theoretical life ratio to validate the improvement in fatigue life of the hybrid bearing.

4. Results and Discussion

The analysis of the 6206 wo configurations — conventional (AISI 52100 steel balls and races) and hybrid (AISI 52100 races with Si_3N_4 ceramic balls). The results from both theoretical life estimation and ANSYS finite element simulation were compared deep groove ball bearing was carried out for t to evaluate the performance improvement of the hybrid ball bearing.

4.1. Theoretical Life Estimation

Using the ISO 281 [1] bearing life formula, the life of the bearing was computed based on catalogue dynamic load rating, applied radial load, and operating speed of 1500 rpm.

Table 1. *Comparison of theoretical bearing life.*

Bearing Type	L_{10} (rev)	L_{10} (hrs)	Life Ratio (Hybrid/steel)
Conventional Bearing	7.058×10^8	7842	-
Hybrid Bearing	9.176×10^8	10195	1.30

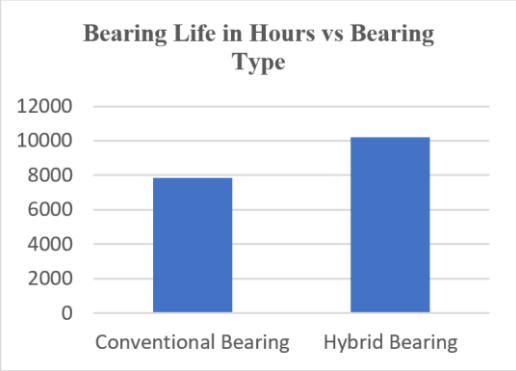


Figure 2. Bearing Life in Hours vs Bearing Type Graph.

4.2. Ansys Simulation Result

Finite element analysis was performed in ANSYS Workbench under a load condition the results obtained are summarized below (Table 2).

Table 2. Comparison of Von misses and max Principal Stresses.

Parameter	Conventional Bearing	Hybrid Bearing
Von misses Stress (MPA)	38.246	71.024
Max principal stress (MPA)	34.123	32.937

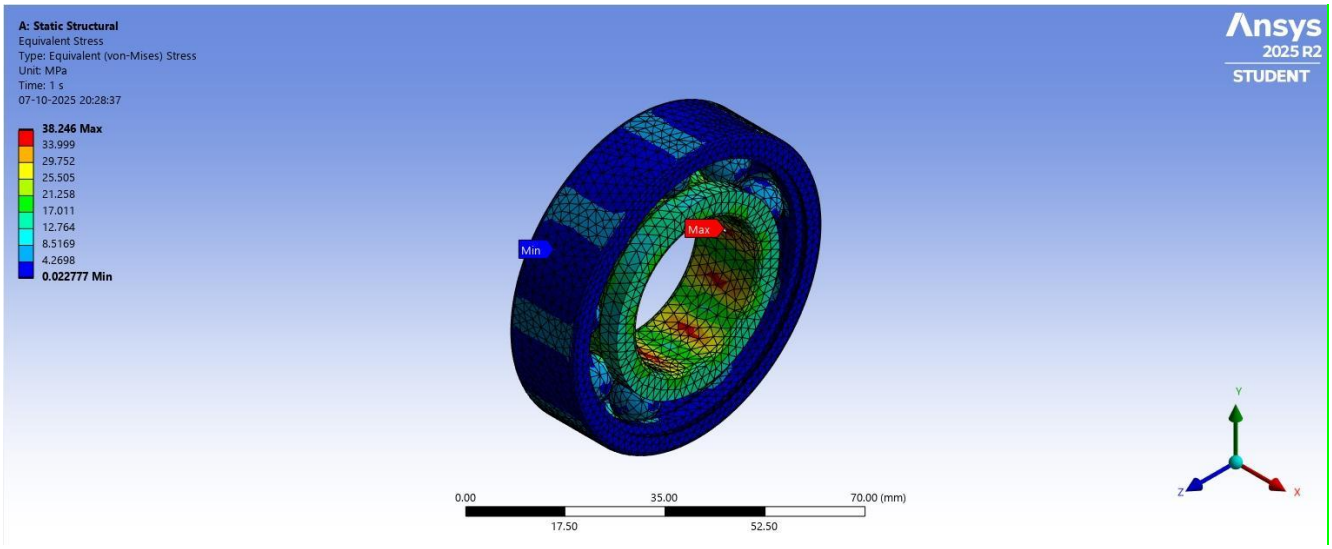


Figure 3. Von mises Stress for Conventional.

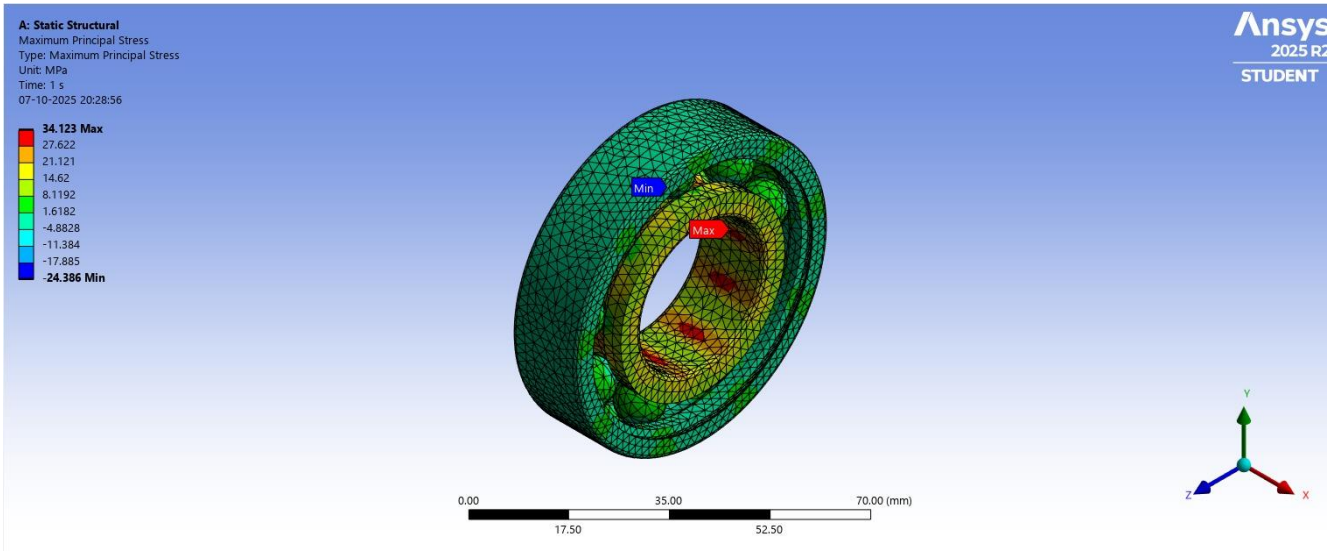


Figure 4. *Max Principle Stress for Conventional.*

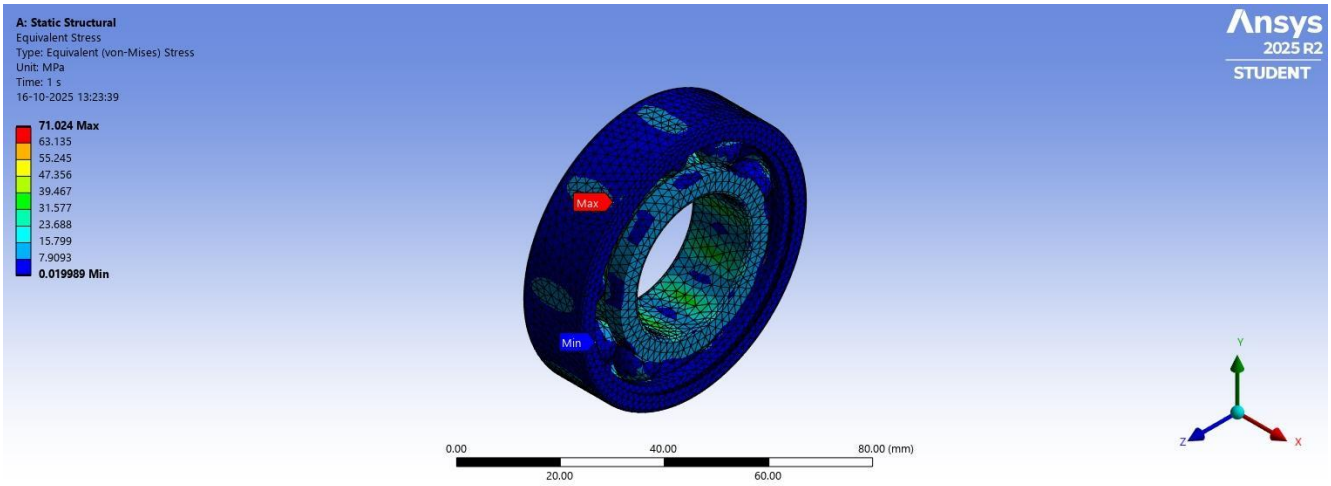


Figure 5. *Von mises Stress for Hybrid.*

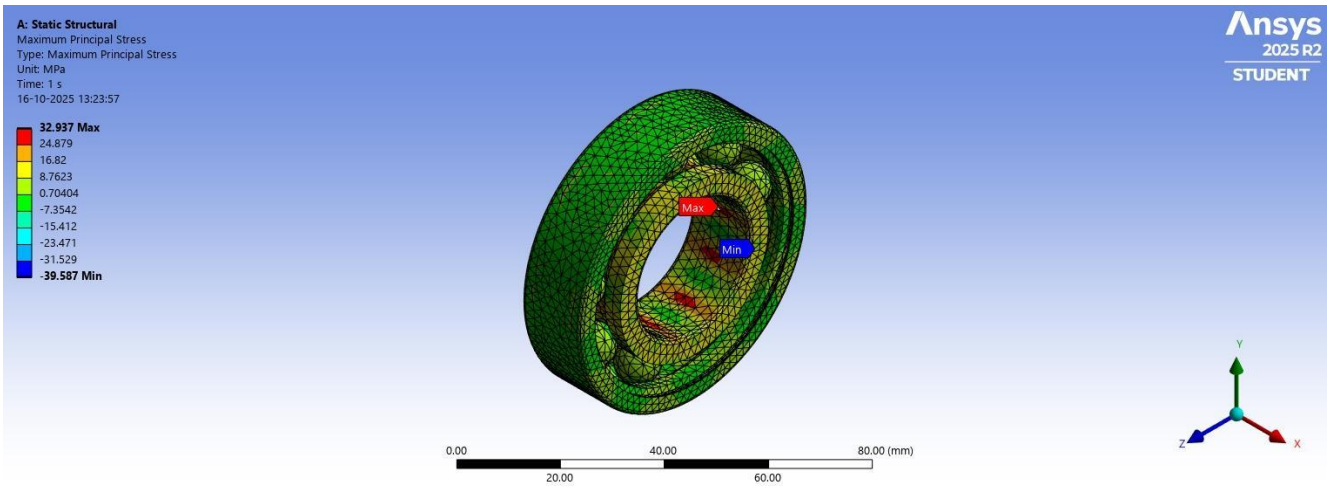


Figure 6. *Max Principle Stress for Hybrid.*

The Von Mises stress (Figure 5) is higher for the hybrid bearing due to the stiffer ceramic balls which reduce contact deformation and localize the load in a smaller contact area.

However, the maximum Principal Stress (Figure 6) which governs rolling contact fatigue is slightly lower in the hybrid bearing (by ~3.5%) indicating reduced subsurface stress and better fatigue resistance.

This finding is consistent with literature as hybrid bearings typically demonstrate improved stress distribution despite localized stiffness increase.

4.3. Fatigue Life Comparison Using ANSYS Results

The fatigue life was correlated with the maximum principal stress using the empirical relation [13].

$$\frac{L_{hyb}}{L_{steel}} = \left(\frac{\tau_{steel}}{\tau_{hyb}}\right)^8 = \left(\frac{34.123}{32.937}\right)^8 = 1.32\text{times}$$

The simulated fatigue life of the hybrid bearing is approximately 1.32 times higher than that of the conventional steel bearing.

In term of percentage from Ansys result hybrid bearing life is 32% higher than the conventional bearing.

4.4. Theoretical and Simulation Results

Table 3. *Comparison of Theoretical and Simulation Results.*

Method	Life Ratio	Increase of life in%
Theoretical	1.30	30%
Ansys	1.32	32%

Both the theoretical and simulated results show the hybrid bearing achieving around 30–32% higher fatigue-life (Table 3).

The small variation between analytical and numerical values is due to the simplified assumptions in ISO 281 compared to the more realistic stress distribution captured by ANSYS.

4.5. Discussion

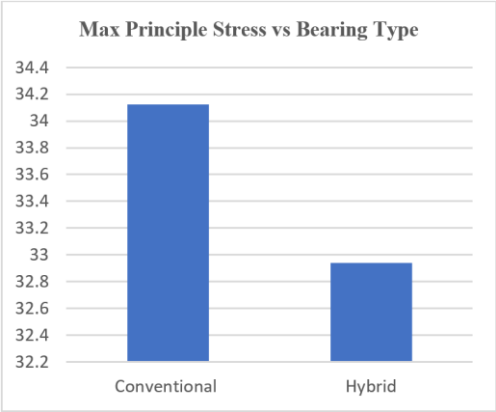


Figure 7. *Max Principle Stress vs Bearing Type Graph.*

The reduction in maximum principal stress for the hybrid bearing as shown in Figure 7 indicates improved contact mechanics between the ceramic balls and steel races. The higher stiffness of Si_3N_4 results in reduced elastic deformation and smaller contact areas leading to a lower magnitude of subsurface stresses that drive fatigue failure.

Additionally, the lighter weight of ceramic balls reduces centrifugal forces at high speeds which further contributes to longer fatigue life and improved dynamic performance.

Thus, both theoretical and simulation analyses confirm that hybrid bearing perform better than the conventional steel bearing in terms of stress behavior and service life.

5. Conclusion

The analysis of the 6206 deep groove ball bearing for conventional and hybrid specification is carried out using theoretical (ISO 281) and finite element analysis (ANSYS) approaches. The following conclusions are derived from this study.

1. The analytical bearing life calculated using the ISO 281 standard (L_{10}) yielded 7842 hours for the conventional bearing (AISI 52100 steel) and 10195 hours for the hybrid bearing (AISI 52100 races with Si_3N_4 ceramic balls), indicates that by

using hybrid bearing approximately 30% improvement in service life can be archived.

2. Finite element analysis in ANSYS shows that the Von mises stress increased from 38.246 n/mm^2 (conventional) to 71.024 n/mm^2 (hybrid) due to the higher stiffness of the ceramic balls. but maximum principal stress decreased from 34.123 n/mm^2 to 32.937 n/mm^2, which shows the reduction in subsurface fatigue stress.

3. Using the relation, fatigue life is correlating with the max principal stress, the FEA fatigue life of the hybrid bearing is found approx. 1.32 times (32%) longer than the conventional steel bearing, which matches the analytical improvement (30%).

4. Analytical and simulation results confirms that the hybrid bearing provides higher fatigue resistance, lower stress concentration, and longer service life compared to the conventional steel bearing.

5. The use of ceramic (Si_3N_4) balls results in reduced deformation, lower friction, and better stress distribution, making hybrid bearings highly suitable for high-speed, high-load, and precision applications.

Abbreviations

FEA	Finite Element Analysis
C	Basic Dynamic Load Rating
P	Equivalent Dynamic Bearing Load
P	Life Exponent
X	Radial Load Factor
Y	Axial Load Factor
Fr	Radial Load
Fa	Axial Load

Author Contributions

Bahubali Balaso Farande: Conceptualization, Project administration, Supervision, Validation

Soham Suraj Biranje: Conceptualization, Formal Analysis, Investigation, Methodology, Software, Writing – original draft

Suyash Santosh Tupe: Conceptualization, Data curation, Resources, Writing – original draft, Writing – review & editing

Swanand Balkrishna Shinde: Resources, Writing – original draft

Sayali Prakash Kamble: Investigation

Sujit Mahadev Patil: Investigation

Conflicts of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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