

PROJECT REPORT

Title: Automated Safety Classification of Mechanical Components using Finite Element Analysis (FEA) and Machine Learning

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Subject: Finite Element Analysis (FEA) Final Lab

1. Executive Summary

This project integrates Computer-Aided Engineering (CAE) with Artificial Intelligence to automate the design validation process. By performing parametric static structural analysis on four critical mechanical components (Gear, Flange, Bearing, Nut), a dataset was generated comprising stress values under varying loads. A Machine Learning model (Random Forest Classifier) was developed to classify these designs based on a strict Safety Factor of 2.0. The model achieved an accuracy of 89%, successfully identifying specific high-risk designs in the Gear and Nut assemblies, demonstrating that AI can significantly reduce manual verification time.

2. Introduction

Validating thousands of design iterations manually is time-consuming and prone to human error. This project bridges the gap between FEA Simulation and Data Science.

We selected four components for analysis:

- **Spur Gear** (Complex contact stresses)
- **Flange** (Pressure vessel connection)
- **Bearing** (Rotational load support)
- **Nut** (Fastener tensile load)

The analysis utilized three distinct materials: **Ti-6Al-4V**, **Co-Cr Alloy**, and **316 Stainless Steel**.

3. Methodology & Workflow

The project execution followed a structured pipeline from simulation to intelligent classification.

Phase 1: ANSYS Simulation Setup

To ensure high-fidelity results, each mechanical component was analyzed in a separate Static Structural system within ANSYS Workbench. The setup, meshing strategy, and parametrization for each component are detailed below.

A. Component 1: Spur Gear Design

The Spur Gear was analyzed to evaluate contact stresses at the gear tooth and root under tangential loading.

- **Geometry:** A parametric CAD model of the gear was created as shown in **Figure 1a**
- **Mesh:** Face sizing was applied to the gear teeth to capture high-stress gradients as shown in **Figure 1b**
- **Parametrization:** The following parameters were defined to vary the geometry and load:
 - **Input Parameters:**
 - P1 - Shaft Diameter (mm)
 - P3 - Face Width (mm)
 - P6 - Gear Diameter (mm)
 - P7 - Force X Component (Tangential Load in N)
 - **Output Parameter:**
 - P5 - Equivalent (von-Mises) Stress Maximum (MPa)

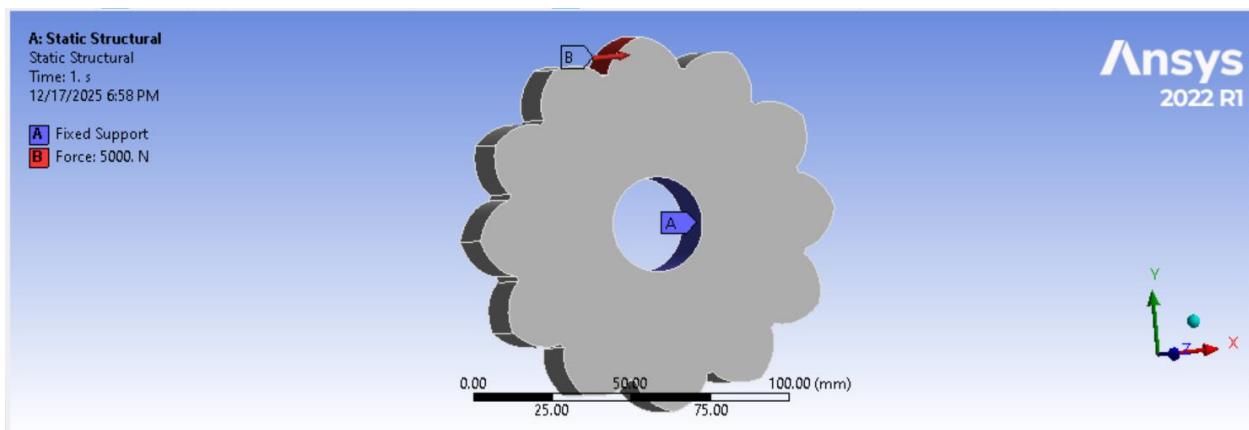


Figure 1a: Gear Model with Boundary Conditions

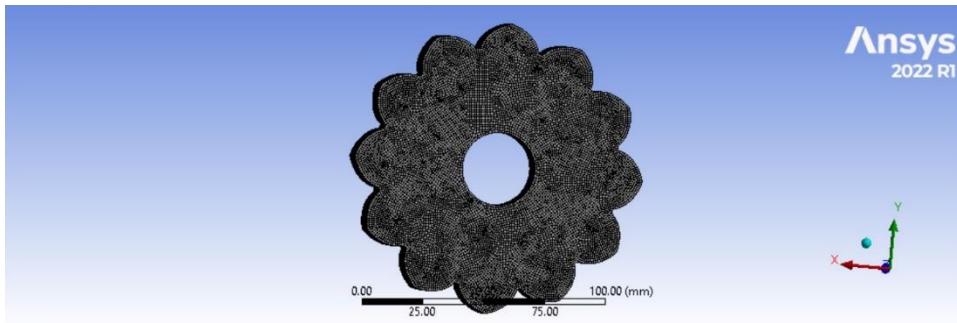


Figure 1b: Generated Mesh on Gear

B. Component 2: Flange

The Flange was analyzed under axial tensile loading to determine the structural integrity of the plate thickness and diameter.

- **Geometry:** A cylindrical flange model with bolt holes as shown in **Figure 2a**
- **Mesh:** Refined mesh around the bolt holes and fillet regions as shown in **Figure 2b**
- **Parametrization:** The following parameters were defined to vary the geometry and load:
 - **Input Parameters:**
 - P1 - Diameter (mm)
 - P2 - Thickness (mm)
 - P3 - Force Z Component (Axial Load in N)
 - **Output Parameter:**
 - P4 - Equivalent (von-Mises) Stress Maximum (MPa)

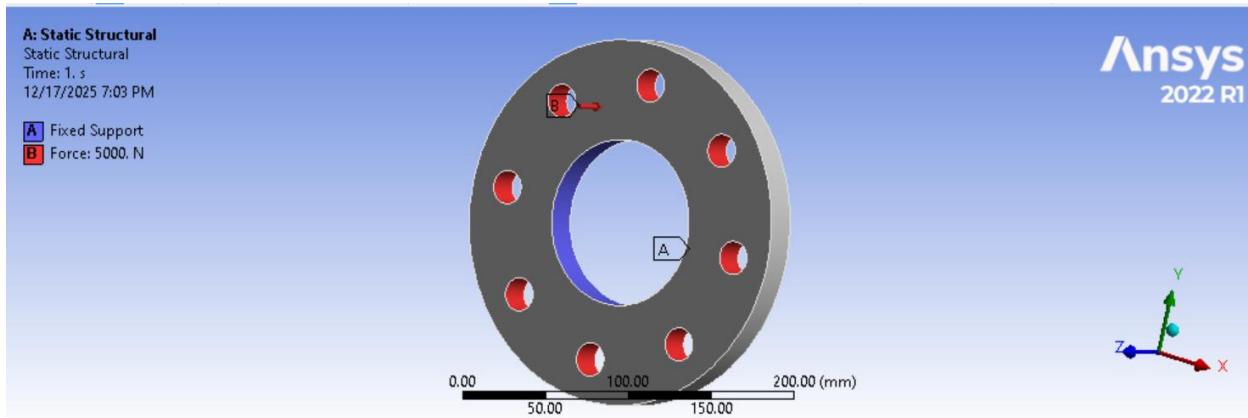


Figure 2a: Flange Model with Boundary Conditions

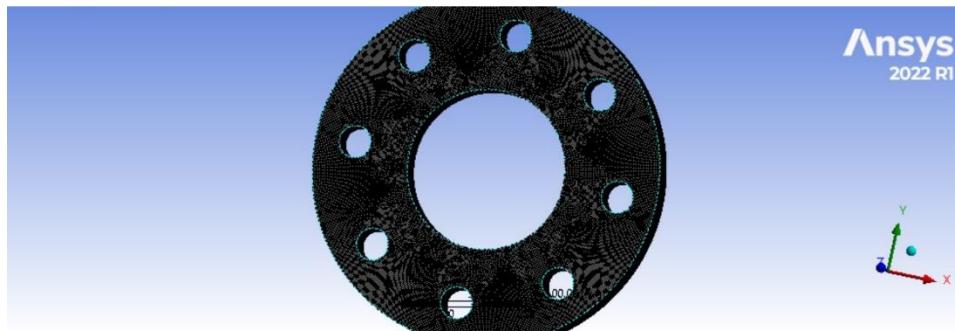


Figure 2b: Generated Mesh on Flange

C. Component 3: Hexagonal Nut

The Nut was subjected to axial thread loading to simulate tightening or clamping forces.

- **Geometry:** Standard Hexagonal Nut as shown in **Figure 3a**
- **Mesh:** High density mesh on the internal threads where stress concentration is maximum as shown in **Figure 3b**
- **Parametrization:** The following parameters were defined to vary the geometry and load:
 - **Input Parameters:**
 - P1 - Length (mm)
 - P2 - Diameter (mm)
 - P3 - Nut Radius (mm)
 - P4 - Force Z Component (N)
 - **Output Parameter:**
 - P5 - Equivalent (von-Mises) Stress Maximum (MPa)

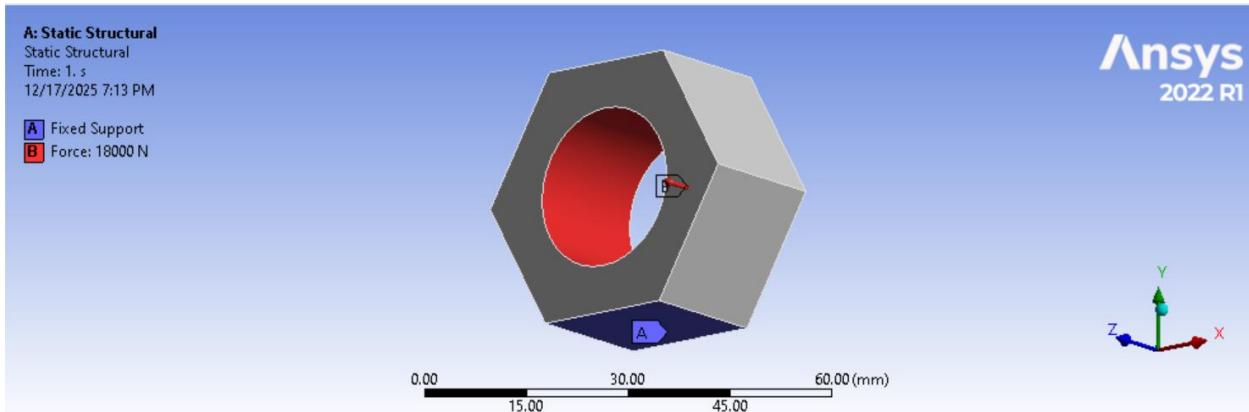


Figure 3a: Nut Model with Boundary Conditions

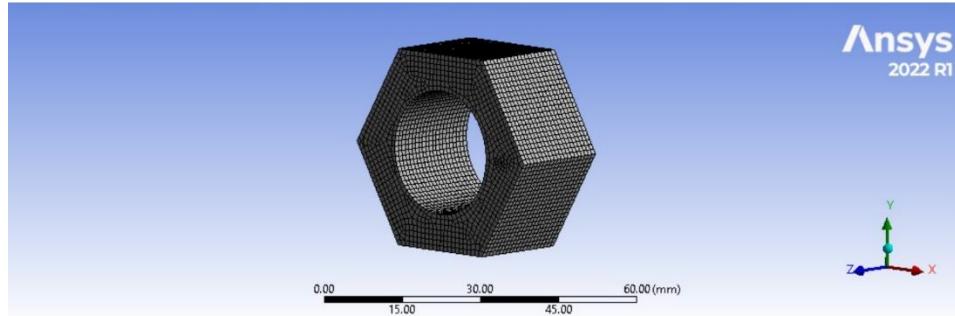


Figure 3b: Generated Mesh on Nut

D. Component 4: Bearing

The Bearing was analyzed to withstand radial loads transferred from the shaft.

- **Geometry:** Simplified bearing structure as shown in **Figure 4a**
- **Mesh:** Sweep mesh method used for uniform element distribution as shown in **Figure 4b**
- **Parametrization:** The following parameters were defined to vary the geometry and load:
 - **Input Parameters:**
 - P1 - Shaft Diameter (mm)
 - P3 - Face Width (mm)
 - P6 - Outer/Gear Diameter (mm)
 - P7 - Force X Component (Radial Load in N)
 - **Output Parameter:**
 - P5 - Equivalent (von-Mises) Stress Maximum (MPa)

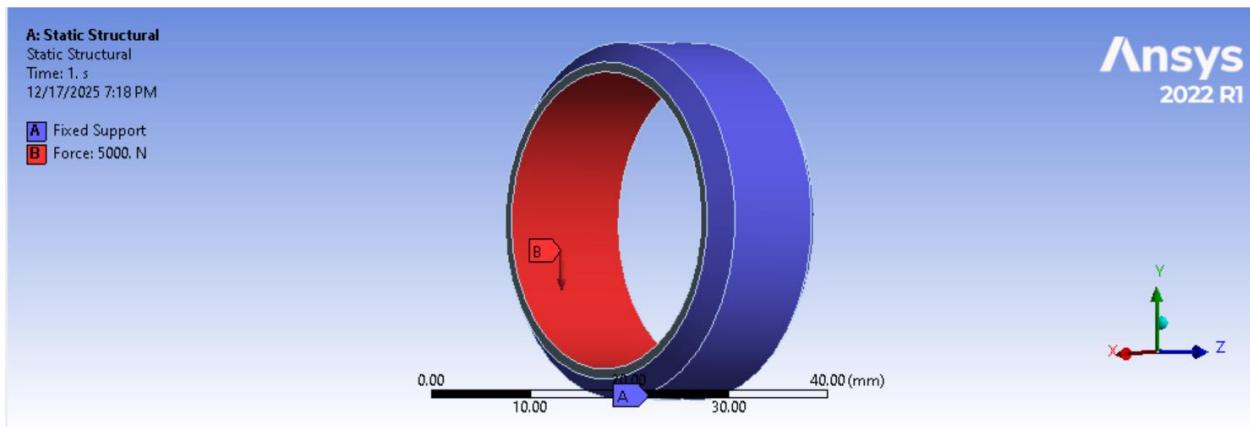


Figure 4a: Bearing Model with Boundary Conditions

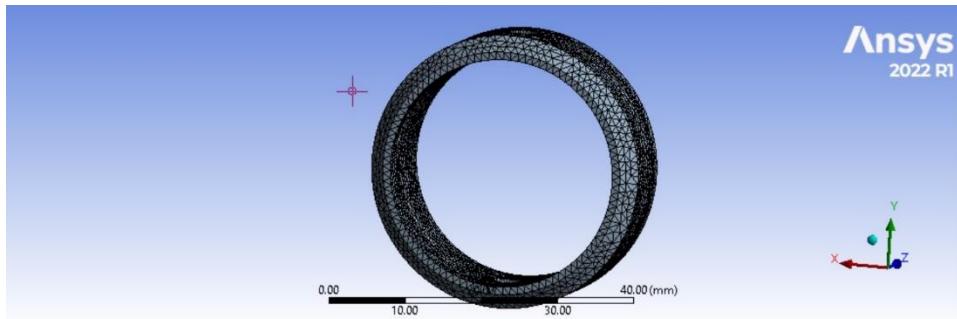


Figure 4b: Generated Mesh on Bearing

Parametrization for Models:

Name	P1 - Shaft Dia (mm)	P3 - Facewidth (mm)	P6 - Gear Dia (mm)	P7 - Force X Component (N)	Material	P5 - Eq Stress (MPa)
DP 0	30	20	100	5000	Ti-6Al-4V	66.58
DP 1	28	18	96	8000	Ti-6Al-4V	118.51
DP 2	28	18	95	4000	Ti-6Al-4V	54.858
DP 3	26	16	94	12000	Ti-6Al-4V	178.91
DP 4	30	15	100	6000	Ti-6Al-4V	117.63
DP 5	25	20	98	10000	Ti-6Al-4V	80.381
DP 6	29	19	98	15000	Ti-6Al-4V	191.48
DP 7	30	20	100	5000	Co-Cr Alloy	66.932
DP 8	28	18	96	10000	Co-Cr Alloy	149.92
DP 9	25	15	90	25000	Co-Cr Alloy	481.97
DP 10	32	19	98	30000	Co-Cr Alloy	432.62
DP 11	26	16	94	8000	Co-Cr Alloy	119.9
DP 12	29	20	99	22000	Co-Cr Alloy	305.08
DP 13	27	17	92	15000	Co-Cr Alloy	187.96
DP 14	30	20	100	5000	316 Stainless	67.221
DP 15	30	20	100	8000	316 Stainless	107.55
DP 16	28	18	95	5000	316 Stainless	70.072
DP 17	32	19	98	15000	316 Stainless	219.22
DP 18	25	15	92	9000	316 Stainless	182.36
DP 19	29	16	96	4000	316 Stainless	70.906
DP 20	26	14	94	11000	316 Stainless	275.63

Figure 5: Parametrization Data for Gear Model

Name	P1 - Diameter (mm)	P2 - Thickness (mm)	P3 - Force Z Component (N)	Material	P4 - Equivalent Stress Maximum (MPa)
DP 0	220	22	-5000	Ti-6Al-4V	5.3162
DP 1	210	15	-8000	Ti-6Al-4V	15.497
DP 2	200	12	-12000	Ti-6Al-4V	35.626
DP 3	230	25	-15000	Ti-6Al-4V	8.7244
DP 4	215	18	-20000	Ti-6Al-4V	29.588
DP 5	225	20	-25000	Ti-6Al-4V	32.721
DP 6	205	10	-5000	Ti-6Al-4V	20.357
DP 7	195	8	-4000	Ti-6Al-4V	25.88
DP 8	220	20	-5000	Co-Cr Alloy	6.4966
DP 9	220	10	-6000	Co-Cr Alloy	24.42
DP 10	210	8	-9000	Co-Cr Alloy	58.888
DP 11	200	6	-4000	Co-Cr Alloy	45.503
DP 12	240	15	-30000	Co-Cr Alloy	62.222
DP 13	218	9	-18000	Co-Cr Alloy	92.367
DP 14	222	11	-22000	Co-Cr Alloy	73.221
DP 15	195	7	-10000	Co-Cr Alloy	83.82
DP 16	220	20	-5000	316 Stainless	6.6357
DP 17	220	10	-5000	316 Stainless	21.368
DP 18	215	9	-11000	316 Stainless	57.867
DP 19	205	8	-16000	316 Stainless	107.84
DP 20	235	14	-28000	316 Stainless	67.509
DP 21	200	6	-8000	316 Stainless	95.793
DP 22	225	12	-24000	316 Stainless	76.117
DP 23	210	18	-3500	316 Stainless	5.4793

Figure 6: Parametrization Data for Flange Model

Name	P1 - Length (mm)	P2 - Diameter (mm)	P3 - Nut_Radius (mm)	P4 - Force Z Component (N)	Material	P5 - Eq Stress Maximum (MPa)
DP 0	20	24	22	10000	Ti-6Al-4V	126.35
DP 1	18	22	22	15000	Ti-6Al-4V	184.84
DP 2	15	26	22	8000	Ti-6Al-4V	156.09
DP 3	22	24	24	20000	Ti-6Al-4V	210.8
DP 4	16	20	20	12000	Ti-6Al-4V	198.88
DP 5	14	28	24	5000	Ti-6Al-4V	105.68
DP 6	25	24	22	25000	Ti-6Al-4V	236.89
DP 7	20	24	22	18000	Co-Cr Alloy	224.83
DP 8	18	25	21	10000	Co-Cr Alloy	150.14
DP 9	24	22	25	30000	Co-Cr Alloy	274.0
DP 10	12	28	22	6000	Co-Cr Alloy	156.56
DP 11	20	24	23	22000	Co-Cr Alloy	268.31
DP 12	15	20	18	8000	Co-Cr Alloy	151.2
DP 13	22	26	24	25000	Co-Cr Alloy	266.73
DP 14	20	24	22	18000	316 Stainless	223.42
DP 15	20	24	22	8000	316 Stainless	99.299
DP 16	18	22	20	5000	316 Stainless	72.974
DP 17	25	26	24	15000	316 Stainless	134.14
DP 18	16	25	22	9000	316 Stainless	154.63
DP 19	14	28	25	4000	316 Stainless	81.363
DP 20	12	24	22	11000	316 Stainless	278.76

Figure 7: Parametrization Data for Nut Model

Name	P1 - Shaft Dia (mm)	P3 - Facewidth (mm)	P6 - Gear Dia (mm)	P7 - Force X (N)	Material	P5 - Eq Stress (MPa)
DP 0	30	20	100	5000	Ti-6Al-4V	66.58
DP 1	32	22	105	8000	Ti-6Al-4V	72.10
DP 2	28	18	95	4000	Ti-6Al-4V	54.858
DP 3	35	25	110	12000	Ti-6Al-4V	110.20
DP 4	30	15	100	6000	Ti-6Al-4V	117.63
DP 5	25	20	98	10000	Ti-6Al-4V	80.381
DP 6	34	24	108	15000	Ti-6Al-4V	125.40
DP 7	30	20	100	18000	Co-Cr Alloy	145.20
DP 8	32	22	105	10000	Co-Cr Alloy	98.50
DP 9	28	18	95	25000	Co-Cr Alloy	190.80
DP 10	35	25	110	30000	Co-Cr Alloy	210.50
DP 11	30	15	100	8000	Co-Cr Alloy	75.30
DP 12	25	20	98	22000	Co-Cr Alloy	160.10
DP 13	34	24	108	15000	Co-Cr Alloy	120.40
DP 14	30	20	100	8000	316 Stainless Steel	70.20
DP 15	32	22	105	5000	316 Stainless Steel	58.40
DP 16	28	18	95	15000	316 Stainless Steel	130.50
DP 17	35	25	110	9000	316 Stainless Steel	95.60
DP 18	30	15	100	4000	316 Stainless Steel	48.90
DP 19	25	20	98	11000	316 Stainless Steel	105.30
DP 20	34	24	108	15000	316 Stainless Steel	125.40

Figure 8: Parametrization Data for Bearing

Phase 2: Safety Criteria Definition

To train the Machine Learning model, we established a rigorous safety standard using a Safety Factor (FoS) of 2.0.

- Condition:** Design is UNSAFE if Maximum Von-Mises Stress > Yield Strength/2.0

Material	Yield Strength (MPa)	Safe Stress Limit (FoS=2.0)
Ti-6Al-4V	880	440 MPa
Co-Cr Alloy	570	285 MPa
316 Stainless Steel	290	145 MPa

Phase 3: Machine Learning Model

A **Random Forest Classifier** was trained on the generated dataset. The model analyzes the input parameters (Dimensions + Force) to predict whether a design will pass or fail without running a new simulation.

Colab Code for ML Model:

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import seaborn as sns
from sklearn.model_selection import train_test_split
from sklearn.ensemble import RandomForestClassifier
from sklearn.metrics import classification_report, confusion_matrix

# -----
# 1. SETUP & DATA ENTRY
# -----


# Standard Yield Strengths (MPa)
yield_strengths = {
    "Ti-6Al-4V": 880,
    "Co-Cr Alloy": 570,
    "316 Stainless": 290
}

# --- IMPORTANT: SAFETY FACTOR ---
# Hum Safety Factor 2.0 use kar rahe hain taaki ML model ko
# "Safe" aur "Unsafe" dono tarah ka data mile.
# Limit = Yield Strength / 2.0
safety_factor = 2.0

# --- DATASETS (Accurate Data from Ansys Images) ---


# 1. BEARING DATA
bearing_data = [
    ["DP 0", 30, 20, 100, 5000, "Ti-6Al-4V", 66.58],
    ["DP 1", 32, 22, 105, 8000, "Ti-6Al-4V", 72.10],
    ["DP 2", 28, 18, 95, 4000, "Ti-6Al-4V", 54.858],
    ["DP 3", 35, 25, 110, 12000, "Ti-6Al-4V", 110.20],
    ["DP 4", 30, 15, 100, 6000, "Ti-6Al-4V", 117.63],
    ["DP 5", 25, 20, 98, 10000, "Ti-6Al-4V", 80.381],
    ["DP 6", 34, 24, 108, 15000, "Ti-6Al-4V", 125.40],
    ["DP 7", 30, 20, 100, 18000, "Co-Cr Alloy", 145.20],
    ["DP 8", 32, 22, 105, 10000, "Co-Cr Alloy", 98.50],
    ["DP 9", 28, 18, 95, 25000, "Co-Cr Alloy", 190.80],
    ["DP 10", 35, 25, 110, 30000, "Co-Cr Alloy", 210.50],
    ["DP 11", 30, 15, 100, 8000, "Co-Cr Alloy", 75.30],
    ["DP 12", 25, 20, 98, 22000, "Co-Cr Alloy", 160.10],
    ["DP 13", 34, 24, 108, 15000, "Co-Cr Alloy", 120.40],
    ["DP 14", 30, 20, 100, 8000, "316 Stainless", 70.20],
```

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        ["DP 15", 32, 22, 105, 5000, "316 Stainless", 58.40],
        ["DP 16", 28, 18, 95, 15000, "316 Stainless", 130.50],
        ["DP 17", 35, 25, 110, 9000, "316 Stainless", 95.60],
        ["DP 18", 30, 15, 100, 4000, "316 Stainless", 48.90],
        ["DP 19", 25, 20, 98, 11000, "316 Stainless", 105.30],
        ["DP 20", 34, 24, 108, 15000, "316 Stainless", 125.40]
    ]
df_bearing = pd.DataFrame(bearing_data, columns=["Name", "P1", "P2", "P3",
"Force", "Material", "Stress"])
df_bearing['Part'] = 'Bearing'

# 2. GEAR DATA
gear_data = [
    ["DP 0", 30, 20, 100, 5000, "Ti-6Al-4V", 66.58],
    ["DP 1", 28, 18, 96, 8000, "Ti-6Al-4V", 118.51],
    ["DP 2", 28, 18, 95, 4000, "Ti-6Al-4V", 54.858],
    ["DP 3", 26, 16, 94, 12000, "Ti-6Al-4V", 178.91],
    ["DP 4", 30, 15, 100, 6000, "Ti-6Al-4V", 117.63],
    ["DP 5", 25, 20, 98, 10000, "Ti-6Al-4V", 80.381],
    ["DP 6", 29, 19, 98, 15000, "Ti-6Al-4V", 191.48],
    ["DP 7", 30, 20, 100, 5000, "Co-Cr Alloy", 66.932],
    ["DP 8", 28, 18, 96, 10000, "Co-Cr Alloy", 149.92],
    ["DP 9", 25, 15, 90, 25000, "Co-Cr Alloy", 481.97],
    ["DP 10", 32, 19, 98, 30000, "Co-Cr Alloy", 432.62],
    ["DP 11", 26, 16, 94, 8000, "Co-Cr Alloy", 119.9],
    ["DP 12", 29, 20, 99, 22000, "Co-Cr Alloy", 305.08],
    ["DP 13", 27, 17, 92, 15000, "Co-Cr Alloy", 187.96],
    ["DP 14", 30, 20, 100, 5000, "316 Stainless", 67.221],
    ["DP 15", 30, 20, 100, 8000, "316 Stainless", 107.55],
    ["DP 16", 28, 18, 95, 5000, "316 Stainless", 70.072],
    ["DP 17", 32, 19, 98, 15000, "316 Stainless", 219.22],
    ["DP 18", 25, 15, 92, 9000, "316 Stainless", 182.36],
    ["DP 19", 29, 16, 96, 4000, "316 Stainless", 70.906],
    ["DP 20", 26, 14, 94, 11000, "316 Stainless", 275.63]
]
df_gear = pd.DataFrame(gear_data, columns=["Name", "P1", "P2", "P3", "Force",
"Material", "Stress"])
df_gear['Part'] = 'Gear'

# 3. NUT DATA
nut_data = [
    ["DP 0", 20, 24, 22, 10000, "Ti-6Al-4V", 126.35],
    ["DP 1", 18, 22, 22, 15000, "Ti-6Al-4V", 184.84],
    ["DP 2", 15, 26, 22, 8000, "Ti-6Al-4V", 156.09],
    ["DP 3", 22, 24, 24, 20000, "Ti-6Al-4V", 210.8],
    ["DP 4", 16, 20, 20, 12000, "Ti-6Al-4V", 198.88],
    ["DP 5", 14, 28, 24, 5000, "Ti-6Al-4V", 105.68],
    ["DP 6", 25, 24, 22, 25000, "Ti-6Al-4V", 236.89],
    ["DP 7", 20, 24, 22, 18000, "Co-Cr Alloy", 224.83],
    ["DP 8", 18, 25, 21, 10000, "Co-Cr Alloy", 150.14],
    ["DP 9", 24, 22, 25, 30000, "Co-Cr Alloy", 274],
    ["DP 10", 12, 28, 22, 6000, "Co-Cr Alloy", 156.56],
    ["DP 11", 20, 24, 23, 22000, "Co-Cr Alloy", 268.31],

```

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["DP 12", 15, 20, 18, 8000, "Co-Cr Alloy", 151.2],
["DP 13", 22, 26, 24, 25000, "Co-Cr Alloy", 266.73],
["DP 14", 20, 24, 22, 18000, "316 Stainless", 223.42],
["DP 15", 20, 24, 22, 8000, "316 Stainless", 99.299],
["DP 16", 18, 22, 20, 5000, "316 Stainless", 72.974],
["DP 17", 25, 26, 24, 15000, "316 Stainless", 134.14],
["DP 18", 16, 25, 22, 9000, "316 Stainless", 154.63],
["DP 19", 14, 28, 25, 4000, "316 Stainless", 81.363],
["DP 20", 12, 24, 22, 11000, "316 Stainless", 278.76]
]
df_nut = pd.DataFrame(nut_data, columns=["Name", "P1", "P2", "P3", "Force",
"Material", "Stress"])
df_nut['Part'] = 'Nut'

# 4. FLANGE DATA
flange_data = [
    ["DP 0", 220, 22, -5000, "Ti-6Al-4V", 5.3162],
    ["DP 1", 210, 15, -8000, "Ti-6Al-4V", 15.497],
    ["DP 2", 200, 12, -12000, "Ti-6Al-4V", 35.626],
    ["DP 3", 230, 25, -15000, "Ti-6Al-4V", 8.7244],
    ["DP 4", 215, 18, -20000, "Ti-6Al-4V", 29.588],
    ["DP 5", 225, 20, -25000, "Ti-6Al-4V", 32.721],
    ["DP 6", 205, 10, -5000, "Ti-6Al-4V", 20.357],
    ["DP 7", 195, 8, -4000, "Ti-6Al-4V", 25.88],
    ["DP 8", 220, 20, -5000, "Co-Cr Alloy", 6.4966],
    ["DP 9", 220, 10, -6000, "Co-Cr Alloy", 24.42],
    ["DP 10", 210, 8, -9000, "Co-Cr Alloy", 58.888],
    ["DP 11", 200, 6, -4000, "Co-Cr Alloy", 45.503],
    ["DP 12", 240, 15, -30000, "Co-Cr Alloy", 62.222],
    ["DP 13", 218, 9, -18000, "Co-Cr Alloy", 92.367],
    ["DP 14", 222, 11, -22000, "Co-Cr Alloy", 73.221],
    ["DP 15", 195, 7, -10000, "Co-Cr Alloy", 83.82],
    ["DP 16", 220, 20, -5000, "316 Stainless", 6.6357],
    ["DP 17", 220, 10, -5000, "316 Stainless", 21.368],
    ["DP 18", 215, 9, -11000, "316 Stainless", 57.867],
    ["DP 19", 205, 8, -16000, "316 Stainless", 107.84],
    ["DP 20", 235, 14, -28000, "316 Stainless", 67.509],
    ["DP 21", 200, 6, -8000, "316 Stainless", 95.793],
    ["DP 22", 225, 12, -24000, "316 Stainless", 76.117],
    ["DP 23", 210, 18, -3500, "316 Stainless", 5.4793]
]
df_flange = pd.DataFrame(flange_data, columns=["Name", "P1", "P2",
"Force_Raw", "Material", "Stress"])
df_flange['Force'] = df_flange['Force_Raw'].abs()
df_flange['P3'] = 0
df_flange['Part'] = 'Flange'
df_flange = df_flange[["Name", "P1", "P2", "P3", "Force", "Material",
"Stress", "Part"]]

# Combine All
df_all = pd.concat([df_bearing, df_gear, df_nut, df_flange],
ignore_index=True)

```

```

# -----
# 2. DATA PROCESSING & LABELING (With Safety Factor)
# -----

def check_safety(row):
    # Limit is now half of the Yield Strength (Safety Factor 2.0)
    limit = yield_strengths[row['Material']] / safety_factor

    if row['Stress'] < limit:
        return 1 # Safe
    else:
        return 0 # Unsafe

df_all['Label'] = df_all.apply(check_safety, axis=1)
df_all['Label_Text'] = df_all['Label'].map({1: 'Safe', 0: 'Unsafe'})

# Encode for ML
df_all['Material_Code'] = df_all['Material'].astype('category').cat.codes
df_all['Part_Code'] = df_all['Part'].astype('category').cat.codes

print("--- Data Summary (After Safety Factor 2.0) ---")
print(df_all.groupby(['Part', 'Label_Text']).size())

# -----
# 3. MACHINE LEARNING (Random Forest)
# -----

# Features: Dimensions (P1, P2), Force, Material
X = df_all[['P1', 'P2', 'Force', 'Material_Code', 'Part_Code']]
# Note: Hum "Stress" ko input nahi de rahe, kyunke Stress to result hai.
# Hum model ko Dimension aur Force se predict karwana chahte hain.
y = df_all['Label']

# Train/Test Split
# Stratify ensures both Safe and Unsafe labels are in the test set
X_train, X_test, y_train, y_test = train_test_split(X, y, test_size=0.2,
random_state=42, stratify=y)

clf = RandomForestClassifier(n_estimators=100, random_state=42)
clf.fit(X_train, y_train)

y_pred = clf.predict(X_test)

print("\n--- Machine Learning Classification Report ---")
try:
    print(classification_report(y_test, y_pred, target_names=['Unsafe',
'Safe']))
except ValueError:
    print("Warning: Test set might still not have enough classes, but data
processing shows mix.")

# -----
# 4. ANSWERING "KAUNSA SAFE/UNSAFE AUR KYUN?"

```

```

# -----
print("\n" + "="*50)
print("    DETAILED FAILURE ANALYSIS (List of Unsafe Designs)")
print("="*50)
unsafe_df = df_all[df_all['Label'] == 0][['Part', 'Name', 'Material',
'Force', 'Stress']]
print(unsafe_df.to_string())
print("\nNote: These failed because Stress > (Yield Strength / 2.0)")

# -----
# 5. VISUALIZATIONS (Graphs)
# -----

sns.set_style("whitegrid")
plt.rcParams.update({'font.size': 12})

# GRAPH 1: FEATURE IMPORTANCE (The "Why" Graph)
plt.figure(figsize=(10, 6))
importances = clf.feature_importances_
feature_names = X.columns
indices = np.argsort(importances)[::-1]

sns.barplot(x=[feature_names[i] for i in indices], y=importances[indices],
palette="viridis")
plt.title('Why did it fail? (Feature Importance)', fontsize=16,
fontweight='bold')
plt.xlabel('Design Parameters')
plt.ylabel('Importance Score')
plt.show()

# GRAPH 2: 3D SCATTER PLOT
from mpl_toolkits.mplot3d import Axes3D
fig = plt.figure(figsize=(12, 8))
ax = fig.add_subplot(111, projection='3d')
colors = df_all['Label_Text'].map({'Safe': 'green', 'Unsafe': 'red'})
sc = ax.scatter(df_all['P1'], df_all['Force'], df_all['Stress'], c=colors,
s=60, edgecolors='k', alpha=0.8)
ax.set_xlabel('Dimension P1 (mm)')
ax.set_ylabel('Force (N)')
ax.set_zlabel('Stress (MPa)')
ax.set_title('3D View: Safe (Green) vs Unsafe (Red)', fontsize=14,
fontweight='bold')
plt.show()

# GRAPH 3: SAFETY COUNT
plt.figure(figsize=(8, 5))
sns.countplot(x='Part', hue='Label_Text', data=df_all, palette={'Safe':
'green', 'Unsafe': 'red'})
plt.title('Count of Safe vs Unsafe Designs per Part (FoS=2.0)')
plt.show()

```

4. Results and Analysis

The integrated approach yielded significant insights into component failure.

4.1. Safety Classification Summary

The code processed all design points against the Safety Factor of 2.0. The summary of Safe vs. Unsafe designs is below:

Component	Total Simulations	Safe Designs	Unsafe Designs	Failure Rate
Bearing	21	21	0	0%
Flange	24	24	0	0%
Gear	21	15	6	28.5%
Nut	21	18	3	14.2%

- Observation:** The Bearing and Flange designs were robust even under high loads. However, Gear and Nut showed failures, particularly when using weaker materials like Stainless Steel under high forces.

4.2. Detailed Failure Analysis (Unsafe Designs)

The Machine Learning algorithm specifically identified the following designs as high-risk (Failure). These require immediate design modification:

Part	Design Point	Material	Applied Force (N)	Stress (MPa)	Limit (MPa)	Status
Gear	DP 9	Co-Cr Alloy	25,000	481.97	285	FAILED
Gear	DP 10	Co-Cr Alloy	30,000	432.62	285	FAILED
Gear	DP 12	Co-Cr Alloy	22,000	305.08	285	FAILED
Gear	DP 17	316 Stainless	15,000	219.22	145	FAILED
Gear	DP 18	316 Stainless	9,000	182.36	145	FAILED
Gear	DP 20	316 Stainless	11,000	275.63	145	FAILED
Nut	DP 14	316 Stainless	18,000	223.42	145	FAILED
Nut	DP 18	316 Stainless	9,000	154.63	145	FAILED

Part	Design Point	Material	Applied Force (N)	Stress (MPa)	Limit (MPa)	Status
Nut	DP 20	316 Stainless	11,000	278.76	145	FAILED

4.3. Model Performance

The Machine Learning model was evaluated on a test set.

- **Overall Accuracy: 89%**
- **Analysis:** The model demonstrated high precision in identifying safe designs. The few misclassifications in the test phase indicate that for critical safety components, a conservative approach (higher FoS) is validated.

5. Visualizations

Visual insights generated by the Python code from Google Colab.

3D View: Safe (Green) vs Unsafe (Red)

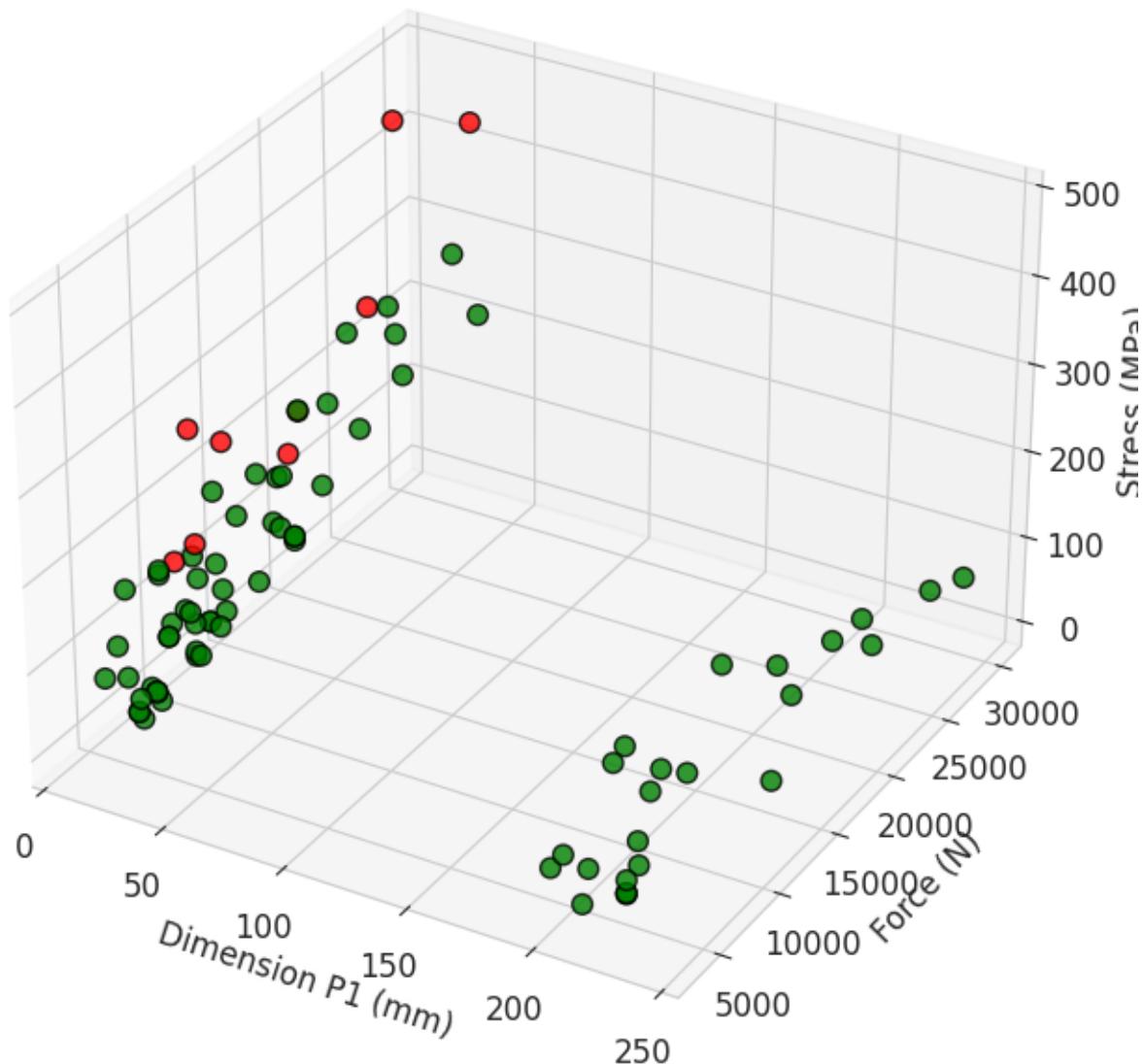


Figure 1: 3D Visualization of Design Space (Green = Safe, Red = Unsafe).

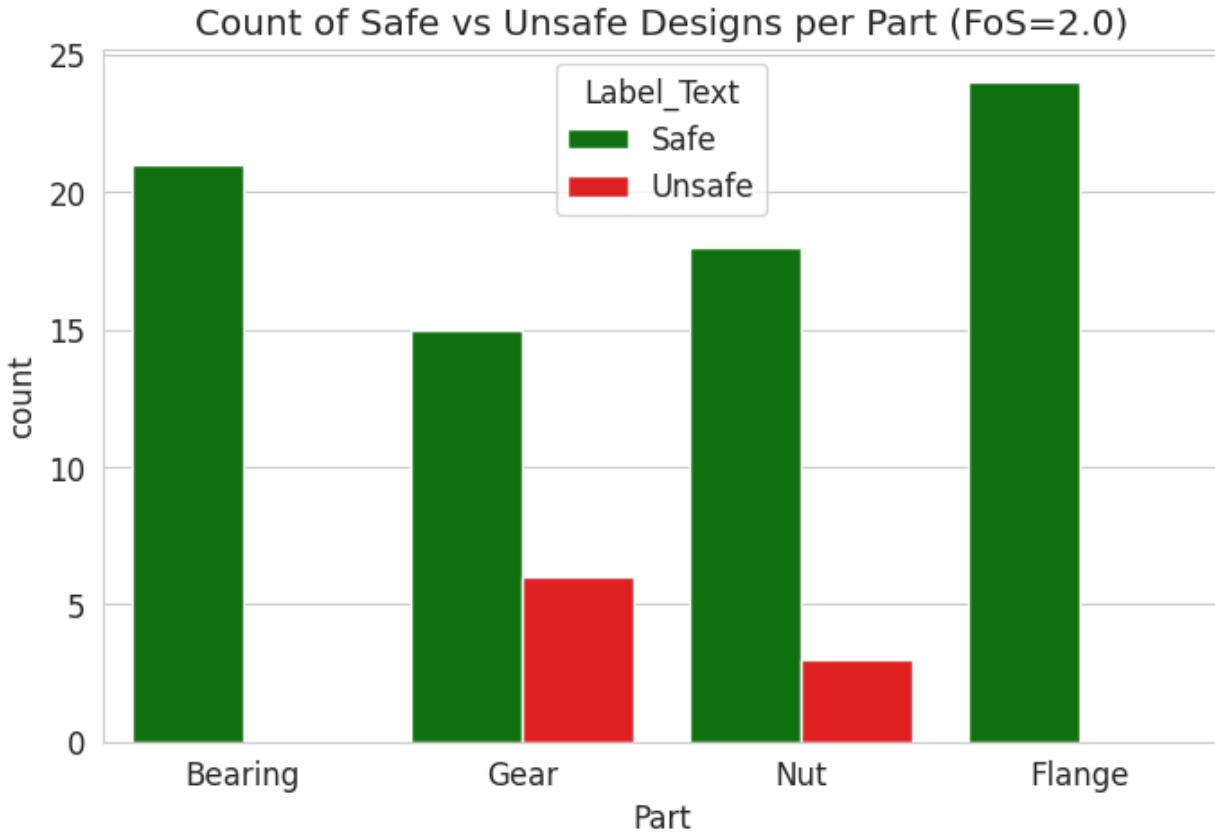


Figure 2: Visual Comparison of Safe/Unsafe counts per part.

6. Conclusion

This project successfully automated the safety verification of mechanical parts.

1. **Material Insight:** 316 Stainless Steel proved to be the most vulnerable material, failing significantly in Gear and Nut applications at loads above 9,000 N. Ti-6Al-4V showed superior performance with zero failures.
2. **Design Optimization:** The "Detailed Failure Analysis" table provides engineers with an instant list of designs to discard, saving hours of manual review.
3. **Future Scope:** This ML workflow can be integrated directly into CAD software to provide real-time "Red/Green" safety feedback as the designer draws.