



DEPARTMENT OF MECHANICAL ENGINEERING

Haldia, Purba Medinipur, West Bengal
HALDIA INSTITUTE OF TECHNOLOGY

PRACTICAL MANUAL

(Assessment Instrument and Instruction Items)

Course Name	Design Practice Lab
Course Code	PC –ME 693
Laboratory Name	Design Practice Laboratory
Programme	B. Tech in Mechanical Engineering
Semester / Year	6 th / 3 rd
Academic Session	2026–27

Faculty-in-Charge & Technical Staff

Faculty-in-Charge	Mr. Soumik Dutta
Co-Faculty (if any)	Dr. Supriyo Roy, Dr. Rahul Das



Vision

To impart quality, industry-relevant teaching-learning that blends knowledge and skill to produce industry-ready mechanical engineering graduates.

Mission Statements

M1: To create qualified and proficient technocrats having contemporary skills through outcome-based and self-learning strategies.

M2: To encourage innovation-oriented and problem-based research capabilities among young engineers through higher studies, in order to nurture the progress of society.

M3: To instill strong ethical values and good professional behaviour, enabling graduates to adopt and absorb emerging changes in the engineering profession.

Program Educational Objective

Graduates of B. Tech. Mechanical Engineering program, four years after graduation will

PEO1: Specify, design, supervise, test, and evaluate engineering skills to design, develop, and implement innovative solutions, systems, and applications in Mechanical Engineering and allied industries.

PEO2: Utilize Mechanical Engineering knowledge to address real-world and societal challenges while pursuing higher studies, research, and professional development.

PEO3: Demonstrate effective individual and collaborative capabilities in multidisciplinary professional environments, with a commitment to lifelong learning and adaptability to evolving technological, industrial, and societal requirements.

Program Specific Outcomes (PSOs)

PSO1: Design, analyze and evaluate mechanical components and systems such as thermal, fluid, manufacturing, design systems and allied engineering solutions.

PSO2: Utilize and evaluate modern engineering tools, software, and techniques to model, analyze, and solve real-world mechanical engineering problems.

PSO3: Demonstrate professional and ethical responsibility, effective communication, and the ability to work in multidisciplinary teams to address societal, industrial, and environmental challenges through sustainable mechanical engineering solutions.



PC-ME 693	Category: Professional Core courses	PCIE Marks	40
Design Practice Lab	Semester: Sixth	PSEE Marks	60
L-T-P:0-0-3	Credit: 1.5	Total Marks	100
Pre-Requisites: Design of Machine Elements, Machine Drawing			
Examination (PSEE): Theory/ Drawing Assignment/ Practical/ Viva-voce/Team work/ others			

Course Content:

Assignments and instruction items are to be framed based on these units:

Unit	Topics	Hours	CO
UNIT I	Design of a column or strut for strength and stability, covering material selection, allowable stress, factor of safety, choice of failure theory and buckling analysis by Euler's and Johnson's formulae, followed by 3-D modelling and 2-D production drawing of the designed column.	6	CO1
UNIT II	Design of a shaft under fluctuating load for finite and infinite life, considering endurance limit, S-N curve, stress concentration, size, surface finish and reliability factors, followed by 3-D modelling and 2-D detailed drawing of the shaft with fillets, shoulders and keyway.	3	CO2
UNIT III	Design of a cotter joint or knuckle joint, or a welded bracket under eccentric loading or a riveted joint of a boiler or structural member, followed by 3-D modelling of the components and preparation of the assembly drawing with exploded view and bill of materials.	9	CO3
UNIT IV	Design of a screw jack or turnbuckle or bolted bracket, including selection of thread type and standard size, self-locking and efficiency checks, and pre-stressed bolt considerations, followed by 3-D modelling of threaded parts and preparation of part and assembly drawings with a bill of materials.	9	CO4
UNIT V	Design of a solid or hollow shaft based on strength and torsional rigidity, together with a rigid or pin-bush flange coupling including key, hub, flange, pins and bushes, followed by 3-D modelling of all parts and preparation of the assembly drawing with fits, tolerances and bill of materials.	9	CO5
UNIT VI	Design of a helical compression spring, including springs in series and parallel, or of a multi-leaf spring with nipping, followed by 3-D modelling using helix or sweep features and preparation of a 2-D drawing with a load-deflection specification.	6	CO6
Total		42	

Suggested Reference Books

1. V. B. Bhandari, Design of Machine Elements, TMH.
2. Shigley and Mischke, Mechanical Engineering Design, TMH.
3. Hall, Holowenko and Laughlin, Theory and Problems of Machine Design, TMH.
4. P.C. Gope, Fundamentals of Machine Design, PHI.
5. M.F. Spotts, Design of Machine Elements, Prentice Hall.
6. P. Kannaiyah, Machine Design, Scitech Publications.



Course Outcomes:

Upon successful completion of the course, students will be able to:			
CO CODES	CO Statement	Knowledge Categories	Cognitive Level
PC-ME 693.1	Design a column or strut under static load by selecting the material, allowable stress and factor of safety, and checking strength and buckling stability using Euler's and Johnson's formulae, and prepare its 3-D model and 2-D production drawing using CAD software.	P	Ap
PC-ME 693.2	Analyse a stepped shaft under fluctuating load by accounting for endurance limit, stress concentration, size, surface finish and reliability factors, determine its finite and infinite life using Miner's equation, and prepare its 3-D model and detailed drawing.	P	An
PC-ME 693.3	Develop the design of a cotter or knuckle joint, and of a welded bracket or riveted joint, and create the 3-D part models, assembly drawing, exploded view and bill of materials using CAD software.	P	C
PC-ME 693.4	Apply design procedures to a turnbuckle by selecting the thread type and standard size and checking the strength of the rods and coupler, and	P	Ap



	prepare the 3-D models of the threaded parts and the assembly drawing with bill of materials.		
PC-ME 693.5	Develop the design of a solid or hollow shaft based on strength and torsional rigidity, together with a rigid or pin-bush flange coupling, and create its 3-D models and assembly drawing with fits and tolerances.	P	C
PC-ME 693.6	Analyse the design of a helical compression spring, or a multi-leaf spring with nipping, for load-deflection behaviour, and prepare its 3-D model using helix or sweep features and its 2-D drawing with specification.	P	An

ALIGNING OF COS IN [CL × KC] METRIC

Cognitive Levels (CL)	Knowledge Categories (KC)							
	Factual	Conceptual	Procedural	Meta-cognitive	Fundamental Design Principles	Criteria & Specifications	Practical Constraints	Design instrumentalities
Remember (R)								
Understand (U)								
Apply (Ap)			CO1, CO4					
Analyze (An)			CO2, CO6					
Evaluate (E)								
Create (C)			CO3, CO5					

Assessment Pattern and Assessment Instruments for PCIE & PSEE

	PCIE								PSEE (60)	
	PCAI (40)				PCAI (40)					
Marks allotted	10	10	10	10	10	10	10	10	40	20
CO	A1	A2	A3	VIVA I	A4	A5	A6	VIVA II	GR-A	GR-B (Viva)
CO1	10			10/3					40/6	20/6
CO2		10		10/3					40/6	20/6
CO3			10	10/3					40/6	20/6
CO4					10			10/3	40/6	20/6
CO5						10		10/3	40/6	20/6
CO6							10	10/3	40/6	20/6

CO-PO & CO-PSO Articulation Matrix

CO	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PSO1	PSO2	PSO3
PC-ME 693.1	3	2	3	-	3	1	1	-	2	-	2	3	3	-
PC-ME 693.2	3	3	3	1	3	1	1	-	2	-	2	3	3	-
PC-ME 693.3	2	2	3	-	3	1	1	1	3	1	2	3	3	1
PC-ME 693.4	2	2	3	-	3	-	1	-	2	-	2	3	3	-
PC-ME 693.5	2	2	3	-	3	1	1	1	3	1	2	3	3	1
PC-ME 693.6	3	3	3	1	3	1	1	-	2	-	2	3	3	-
Average	2.5	2.3	3	1	3	1	1	1	2.3	1	2	3	3	1





DESIGN PRACTICE LAB (PC-ME 693)

LIST OF ASSESSMENT ITEMS, INSTRUCTION ITEMS

Experiment No.	Title of the Assignment	Instruction Item	CO Congruence
A1-I	Design of a column for strength and buckling using Euler's or Johnson's formula; 3-D modelling and 2-D production drawing.	II-1	CO1
A2-I	Design of a stepped shaft for infinite life using the Soderberg or Goodman criterion, with a finite-life check by Miner's equation; 3-D modelling and detailed drawing.	II-2	CO2
A3-I	Design of the rod, spigot, socket and cotter for tension, shear and crushing; 3-D modelling, exploded assembly and assembly drawing with bill of materials.	II-3	CO3
A3-II	Design of the rod, eye, fork and pin for tension, shear, crushing and bending; 3-D modelling, assembly and assembly drawing with bill of materials.		
A3-III	Design of the weld size and length for combined direct and torsional or bending stresses; 3-D modelling and drawing with weld symbols.		
A3-IV	Design of a lap or butt riveted joint for the rivet diameter, pitch and margin, with joint efficiency; 3-D modelling, assembly and drawing with rivet layout.		
A4-I	Design of the threaded rods, coupler and lock nuts for tension, thread shear and bearing pressure; 3-D modelling, assembly and drawings with bill of materials.	II-4	CO4
A4-II	Design of the bolts for direct shear, moment and pre-tension, and selection of standard bolt size; 3-D modelling, assembly and drawing with bill of materials.		
A5-I	Design of a solid and a hollow shaft for strength and torsional rigidity, with a weight comparison; 3-D modelling and detailed drawings.	II-5	CO5
A5-II	Design of the hub, key, flange and bolts from torque and service factor; 3-D modelling, assembly and sectional assembly drawing with bill of materials.		
A5-III	Design of the hub, key, flange, pins and bushes for bearing pressure and shear; 3-D modelling, assembly and sectional assembly drawing with bill of materials.		
A6-I	Design of the wire diameter, coil diameter, number of coils and free length, with a buckling check; 3-D modelling using helix and sweep, and 2-D drawing with load-deflection specification.	II-6	CO6
A6-II	Design of a spring system for equivalent stiffness and load sharing; 3-D modelling, assembly and drawing with load-deflection specification.		
A6-III	Design of the number, width and thickness of leaves and the initial nip; 3-D modelling, assembly and drawing with bill of materials.		



INSTRUCTION ITEM-1(II-1)		
Assignment No.	Name of the experiment	CO Congruence
A1-I	Design of a column for strength and buckling using Euler's or Johnson's formula; 3-D modelling and 2-D production drawing.	[CO1]

Design of a Column for Strength and Buckling

Problem Statement

A village cooperative in a drought-prone rural area is installing a small elevated water storage tank to supply a community irrigation and drinking-water system. To keep the tank above the delivery line for gravity flow and to save ground space, the tank will be mounted on top of a single vertical solid circular steel column. The column base is rigidly embedded in a concrete foundation, and the tank end is free. The local fabricator proposes an arbitrary pipe size based on past experience, so there are doubts about whether the column is safe against buckling under the full tank load.

As a design engineer applying the principles of Design of Machine Elements, you are tasked with determining the design load, deciding between Euler's and Johnson's formula, selecting a safe standard diameter for the column, and preparing its 3-D model and production drawing using CAD software.

Given Data

Parameter	Value
Application	Elevated water storage tank on a single column
Tank capacity (water)	5000 litres
Density of water	1000 kg/m ³
Weight of empty tank and fittings	500 kg
Length of column (L)	3 m
End conditions	One end fixed (foundation), other end free (tank)
Column cross-section	Solid circular
Column material	Structural steel Fe 410 (IS 2062)
Yield strength (σ_y)	250 MPa
Modulus of elasticity (E)	200 GPa
Factor of safety against buckling	3
Acceleration due to gravity (g)	9.81 m/s ²
Available standard diameters	80, 90, 100, 110, 120 mm
Alternative case for Task 4	Column length reduced to 1.2 m by shifting the tank to a lower platform

Tasks (Problem-Solving Component)

- Design load and effective length:** Calculate the total axial load on the column when the tank is full, and determine the effective length of the column from the given end conditions. Hence find the design (critical) buckling load using the given factor of safety.
- Trial diameter and choice of formula:** Assume a trial diameter and calculate the least radius of gyration and the slenderness ratio. Compare it with the critical slenderness ratio for the material to decide whether Euler's or Johnson's formula is applicable.
- Column design and checks:** Using the applicable formula, determine the required diameter, select the next standard diameter, and verify that the actual critical load meets the requirement. Also check the direct compressive (crushing) stress against the yield strength.



4. **Short column case (Johnson's formula):** For the alternative case with a reduced column length, recalculate the slenderness ratio, identify the applicable formula, and determine the safe diameter using Johnson's formula. Compare it with the diameter obtained in Task 3.
5. **CAD modelling and drafting:** Create the 3-D model of the final column by extrusion, adding a base plate and a top plate with a chamfer or fillet as required. Prepare a 2-D production drawing with front and sectional views, dimensions, tolerances, material specification and title block.

Tasks (Interpretation Component)

6. **Design justification:** Interpret and justify why buckling, rather than crushing, governs the design of this long slender column. Explain why the "free" tank end makes the design more severe than a column with both ends fixed or hinged.
7. **Trade-off analysis:** If the community decides to increase the tank capacity from 5000 litres to 7500 litres, interpret how the design load and required diameter would change, and discuss whether increasing the diameter, reducing the column length, or providing intermediate bracing is the more practical way to keep the structure safe.
8. **Sustainability interpretation:** Comment on how selecting the correct column size, rather than over-designing with a heavy section or under-designing with a weak one, reduces material use, cost and transport effort for the village, and improves the safety and service life of the structure. Also comment on why a hollow section could be considered for the same load.

Solution steps

Task 1: Design Load and Effective Length

1. Calculate the mass of water: $m = \text{volume} \times \text{density}$ ($5000 \text{ L} = 5 \text{ m}^3$).
2. Add the mass of the empty tank and fittings to get the total mass.
3. Calculate the axial load: $W = \text{total mass} \times g$.
4. Find the effective length for a fixed-free column: $L_e = 2L$.
5. Calculate the design (critical) buckling load: $P_{cr} = W \times \text{factor of safety}$.

Task 2: Trial Diameter and Choice of Formula

1. Assume a trial diameter d (for example, 100 mm).
2. Calculate the area $A = \pi d^2/4$ and the moment of inertia $I = \pi d^4/64$.
3. Calculate the least radius of gyration: $k = \sqrt{I/A} = d/4$.
4. Calculate the slenderness ratio: $\lambda = L_e/k$.
5. Calculate the critical slenderness ratio: $\lambda_c = \sqrt{(2\pi^2 E/\sigma_y)}$.
6. If $\lambda > \lambda_c$, use Euler's formula; if $\lambda < \lambda_c$, use Johnson's formula.

Task 3: Column Design and Checks

1. Write Euler's formula: $P_{cr} = \pi^2 EI/L_e^2$.
2. Substitute $I = \pi d^4/64$ and solve for the required diameter d .
3. Select the next higher standard diameter from the given list.
4. Recalculate λ for the selected diameter and confirm that it still lies in the Euler range.
5. Calculate the actual critical load and check that it is not less than the design buckling load from Task 1.
6. Calculate the direct compressive stress $\sigma = W/A$ and check that it is well below σ_y .

Task 4: Short Column Case (Johnson's Formula)

1. Calculate the new effective length: $L_e = 2 \times 1.2 \text{ m}$.
2. Assume a trial diameter and calculate k and λ .
3. Compare λ with λ_c to confirm that Johnson's formula applies.



4. Write Johnson's formula: $P_{cr} = A \cdot \sigma_y [1 - \sigma_y \lambda^2 / (4\pi^2 E)]$.
5. Substitute $A = \pi d^2/4$ and solve for d by trial and error until P_{cr} equals the design buckling load.
6. Select the next standard diameter, and compare it with the diameter from Task 3.

Task 5: CAD Modelling and Drafting

1. Sketch a circle of the final diameter on the top plane and extrude it to the column length.
2. Add the base plate and top plate as separate features, with chamfers or fillets.
3. Create the front view and a sectional view in the drafting environment.
4. Add dimensions, tolerances, material specification and the title block.

Task 6: Design Justification

1. Compare the slenderness ratio with the critical value to show that buckling governs.
2. Compare the crushing stress with the buckling stress at the critical load.
3. Compare the effective length factors: 2.0 for fixed-free, 0.7 for fixed-hinged, 0.5 for fixed-fixed, 1.0 for hinged-hinged.
4. Explain that a larger effective length reduces the critical load in proportion to $1/L_e^2$.

Task 7: Trade-off Analysis

1. Recalculate the load for a 7500 L tank and the new design buckling load.
2. Estimate the new required diameter and note the percentage increase ($P_{cr} \propto d^4$, so $d \propto P_{cr}^{(1/4)}$).
3. Compare the options: larger diameter (more material), shorter column ($P_{cr} \propto 1/L^2$), or intermediate bracing (reduces the effective length).
4. Conclude which option is the most practical.

Task 8: Sustainability Interpretation

1. Compare the mass of the selected column with that of an oversized column.
2. Relate the correct size to material use, cost, transport and safety.
3. Compare a solid section with a hollow section of the same load capacity (a hollow section gives a higher I for the same mass).

INSTRUCTION ITEM-2(II-2)		
Assignment No.	Name of the experiment	CO Congruence
A2-I	Design of a stepped shaft for infinite life using the Soderberg or Goodman criterion, with a finite-life check by Miner's equation; 3-D modelling and detailed drawing.	[CO2]

A2-I Design of a Stepped Shaft for Infinite Life and Finite-Life Verification

Problem Statement

A small rural agro-processing unit uses a motor-driven shaft to transmit power from an electric motor to a belt-driven agricultural processing machine. The shaft operates continuously for several hours each day and is subjected to combined bending and torsional loading due to the transmitted power, belt tension and pulley arrangement. Since the shaft rotates continuously, the bending stress at a fixed location changes from tension to compression during each revolution, while the torsional stress is primarily steady. The existing shaft has two different diameters connected through a shoulder. The local fabricator proposes the shaft dimensions based on previous practice, but there are concerns regarding fatigue failure at the stepped section. As the shaft is expected to operate for a long service period, the shaft must be designed for infinite fatigue



life using an appropriate fatigue criterion. The design should also be checked for a finite number of operating cycles using Miner's cumulative damage theory.

As a design engineer applying the principles of Design of Machine Elements, you are required to determine the design torque and bending moment, calculate the fluctuating and mean stresses, select either the Soderberg or Goodman criterion, determine the required shaft diameter, select suitable standard diameters, and verify the design for fatigue and yielding. The effect of the shaft shoulder and stress concentration must also be considered. Finally, prepare a 3-D CAD model and detailed production drawing of the stepped shaft.

Given Data

Parameter	Value
Application	Motor-driven agricultural processing machine
Motor power, P	15 kW
Shaft speed, N	750 rpm
Shaft material	Medium carbon steel, C45
Ultimate tensile strength, σ_u	600 MPa
Yield strength, σ_y	350 MPa
Endurance limit, S_e	300 MPa
Factor of safety, n	2
Shaft type	Stepped solid circular shaft
Total shaft length	600 mm
Large diameter, trial D	60 mm
Small diameter, trial d	45 mm
Diameter ratio, D/d	1.33
Shoulder fillet radius, r	3 mm
Bending moment at critical section, M	1.2 kN·m
Torque due to transmitted power	To be calculated
Loading due to rotation	Completely reversed bending
Torsional loading	Steady
Surface condition	Machined
Reliability	90%
Temperature	Normal ambient temperature
Design objective	Infinite fatigue life
Finite-life check	$N_f = 10^6$ cycles
Cumulative damage criterion	Miner's equation
Available standard small diameters	40, 45, 50, 55, 60 mm
Available standard large diameters	50, 55, 60, 65, 70 mm

Additional fatigue data

For the stepped section, the theoretical stress concentration factors may be obtained from standard design charts or supplied data. For the present design exercise, use:

Parameter	Value
Theoretical bending stress concentration factor, K_t	1.60
Theoretical torsional stress concentration factor, K_{ts}	1.40
Notch sensitivity in bending, q_b	0.85
Notch sensitivity in torsion, q_t	0.80



Tasks (Problem-Solving Component)

- 1. Design torque and loading:** Calculate the torque transmitted by the shaft from the motor power and rotational speed. Determine the design torque and bending moment acting at the critical stepped section.
- 2. Identification of critical section and stress concentration:** (i) Identify the most critical section of the stepped shaft. (ii) Explain why the shoulder between the large and small diameters is critical. (iii) Calculate the bending fatigue stress (iv) concentration factor K_f (v) Calculate the torsional fatigue stress concentration factor K_{fs} (vi) Discuss the effect of the shoulder fillet radius on fatigue strength.
- 3. Calculation of mean and alternating stresses:** Calculate the nominal bending stress and torsional shear stress at the critical stepped section. Determine the alternating bending stress and mean torsional shear stress by considering the corresponding fatigue stress concentration factors. Since the shaft is subjected to completely reversed bending and steady torsional loading, determine the equivalent alternating and mean stresses using the appropriate combined-stress relation.
- 4. Selection of Soderberg or Goodman criterion:** Calculate the required shaft diameter using either Soderberg criterion, or Modified Goodman criterion.
- 5. Shaft diameter design:** Determine the required small shaft diameter d using the selected Soderberg or Goodman fatigue criterion. Select the next higher standard diameter from 40, 45, 50, 55 and 60 mm. Determine a suitable large shaft diameter D from 50, 55, 60, 65 and 70 mm. Verify the selected stepped shaft dimensions by recalculating the alternating and mean stresses and confirming that the required fatigue safety factor is satisfied.
- 6. Static strength and yielding check:** Calculate the maximum bending stress and torsional shear stress in the selected shaft. Determine the equivalent vonMises stress and compare it with the allowable stress based on the given yield strength and factor of safety. Verify that the selected shaft is safe against static yielding and determine the corresponding factor of safety.
- 7. Finite-life check using S–N relation and Miner's equation:** Using the given fatigue data, establish the appropriate S–N relationship and determine the fatigue life corresponding to the specified stress levels. Calculate the cumulative fatigue damage using Miner's equation:
- 8. Effect of changing the shaft diameter:** Investigate the effect of selecting different standard small shaft diameters, such as 45, 50 and 55 mm. For each diameter, calculate the alternating stress, mean stress, fatigue safety factor, static safety factor and fatigue damage. Compare the results and discuss how increasing the shaft diameter affects fatigue strength, service life and material consumption.

Tasks (Interpretation Component)

- 9. Design justification:** Explain why fatigue failure, rather than simple static yielding, is the primary design consideration for the rotating shaft. Discuss the effect of repeated bending and steady torsional loading, stress concentration at the stepped section, and the possibility of fatigue crack initiation during long-term operation.
- 10. Soderberg versus Goodman criterion:** Compare the Soderberg and Goodman criteria for the design of the stepped shaft. Explain how each criterion considers alternating stress and mean stress, and discuss the effect of using yield strength and ultimate tensile strength in the respective criteria. Justify the selection of the criterion used for the final shaft design.
- 11. Effect of shoulder and fillet radius:** Interpret the importance of the shoulder fillet in the stepped shaft. Explain how the change in shaft diameter produces stress concentration and how the fillet radius affects the fatigue strength of the shaft. Discuss why an appropriate fillet radius can reduce local stress concentration and improve fatigue life.



12. Trade-off analysis: If the motor power is increased from 15 kW to 20 kW while maintaining the same shaft speed, interpret how the transmitted torque, bending and torsional stresses, and required shaft diameter would change. Discuss whether increasing the shaft diameter, increasing the fillet radius, reducing the applied load, reducing the operating speed, or selecting a higher-strength material would be the more practical way to maintain safe operation.

13. Sustainability interpretation: Comment on how selecting the correct shaft diameter, rather than over-designing with a heavy shaft or under-designing with an unsafe shaft, reduces material use, manufacturing cost, transportation effort and maintenance requirements. Explain how adequate fatigue life improves the reliability and service life of the machine. Also comment on why a hollow shaft could be considered as an alternative to a solid shaft for reducing weight while maintaining adequate bending and torsional strength.

14. CAD Modelling and Detailed Drafting: Create the 3-D CAD model of the final stepped shaft by generating the shaft profile and using the revolve operation. Include the required shoulder, fillet radius, chamfers and keyway, if applicable. Prepare a 2-D production drawing with front, end and sectional views, showing all important dimensions, tolerances, surface-finish requirements, material specification and title block.

Solution steps

Task 1: Design Torque and Loading

1. Calculate the transmitted torque from the motor power and shaft speed
2. Convert the motor power from kW to W and calculate the design torque.
3. Use the given bending moment $M=1.2 \text{ kN}\cdot\text{m}$ at the critical section.
4. Identify the stepped shoulder as the critical section because of the change in diameter and associated stress concentration.

Task 2: Stress Concentration and Critical Section

1. Assume the trial small diameter $d=45 \text{ mm}$.
2. Calculate the theoretical bending stress concentration factor:
3. Calculate the torsional fatigue stress concentration factor:
4. Identify the shoulder fillet as the main source of local stress concentration.
5. Use the fatigue concentration factors in the subsequent stress calculations.

Task 3: Alternating and Mean Stresses

1. Calculate the nominal bending stress:
2. Calculate the alternating bending stress:
3. Calculate the nominal torsional shear stress:
4. Calculate the mean torsional stress:
5. Since bending is completely reversed: $\tau_a=0$
6. Calculate the equivalent alternating stress:
7. Calculate the equivalent mean stress:

Task 4: Choice of Soderberg or Goodman Criterion

1. Write the Soderberg criterion:
2. Write the Goodman criterion:
3. Substitute the calculated alternating and mean stresses.
4. Determine the required shaft diameter using the selected fatigue criterion.



5. Compare the Soderberg and Goodman results and justify the criterion selected for the final design.

Task 5: Shaft Diameter Design and Checks

1. Solve the selected fatigue equation for the required small diameter d
2. Select the next higher standard diameter from: 40, 45, 50, 55, 60 mm
3. Select a suitable large diameter DD from the given standard sizes.
4. Recalculate the alternating and mean stresses for the selected diameter.
5. Confirm that the fatigue criterion is satisfied.
6. Calculate the equivalent vonMises stress:
7. Check that:

Task 6: Finite-Life Check Using Miner's Equation

1. Establish the S–N relationship for the shaft material.
2. Determine the fatigue life N_i corresponding to each operating stress level.
3. Calculate the damage fraction for each loading condition:
4. Calculate the total cumulative damage:
5. Check that: $D < 1$
6. Comment on the remaining fatigue-life margin of the selected shaft.

Task 7: Design Justification

1. Explain that rotating bending produces repeated and reversed stresses in the shaft.
2. Explain why repeated stress cycles can cause fatigue failure even when the static stress is below the yield strength.
3. Compare the fatigue stresses with the endurance limit.
4. Explain the effect of the stepped shoulder and stress concentration on fatigue crack initiation.
5. State that fatigue, rather than simple static yielding, governs the design because the shaft operates under repeated loading for a large number of cycles.

Task 8: Soderberg versus Goodman Criterion

1. Compare the use of yield strength in the Soderberg criterion and ultimate strength in the Goodman criterion.
2. Calculate the required diameter using both criteria.
3. Compare the resulting fatigue safety factors.
4. Explain that the Soderberg criterion generally provides a more conservative design against fatigue and yielding.
5. Select the appropriate criterion based on the required design safety.

Task 9: Effect of Shoulder and Fillet Radius

1. Calculate the fatigue stress concentration factors K_t and K_{fs}
2. Explain how the sudden change in diameter increases local stress.
3. Examine the effect of increasing the shoulder fillet radius.
4. Explain that a larger fillet radius generally reduces stress concentration.
5. Discuss how reducing stress concentration improves fatigue strength and shaft service life.



Task 10: Trade-off Analysis

1. Recalculate the transmitted torque when motor power increases from 15 kW to 20 kW.
2. Calculate the corresponding increase in torsional stress.
3. Determine the new required shaft diameter using the selected fatigue criterion.
4. Compare the original and modified shaft designs.
5. Compare the options of increasing shaft diameter, increasing fillet radius, reducing applied load, reducing speed, or selecting higher-strength material.
6. Discuss the practical balance between strength, fatigue life, manufacturing cost and material consumption.

Task 11: Sustainability Interpretation

1. Compare the mass of the selected shaft with an oversized shaft.
2. Relate the correct shaft size to material consumption, manufacturing cost and transportation effort.
3. Explain how adequate fatigue life reduces maintenance, replacement and material waste.
4. Discuss how an oversized shaft increases material use without necessarily providing proportional benefits.
5. Compare a solid shaft with a hollow shaft for similar bending and torsional requirements.
6. Explain that a hollow shaft can reduce weight while retaining a large proportion of the required bending and torsional strength because material near the outer surface contributes strongly to section strength.

Task 12: CAD Modelling and Detailed Drafting

1. Create the 2-D stepped shaft profile with the selected diameters and lengths.
2. Add the shoulder fillet, chamfers and keyway, if required.
3. Use the Revolve feature to generate the 3-D shaft model.
4. Create front, end and sectional views in the drafting environment.
5. Add shaft diameters, lengths, fillet radius and keyway dimensions.
6. Specify dimensional tolerances, geometric tolerances and surface finish.
7. Add material specification and heat-treatment requirement, if applicable.
8. Complete the title block with drawing number, scale, units, projection method, material, revision and approval details.

INSTRUCTION ITEM-3(II-3)		
Assign ment No.	Name of the experiment	CO Congru ence
A3-I	Design of the rod, spigot, socket and cotter for tension, shear and crushing; 3-D modelling, exploded assembly and assembly drawing with bill of materials.	[CO3]
A3-II	Design of the rod, eye, fork and pin for tension, shear, crushing and bending; 3-D modelling, assembly and assembly drawing with bill of materials.	
A3-III	Design of the weld size and length for combined direct and torsional or bending stresses; 3-D modelling and drawing with weld symbols.	
A3-IV	Design of a lap or butt riveted joint for the rivet diameter, pitch and margin, with joint efficiency; 3-D modelling, assembly and drawing with rivet layout.	



A3-I Design of a Rod, Spigot, Socket and Cotter for Tension, Shear and Crushing

Problem Statement

A rural agricultural cooperative operates a manually controlled water-lifting and material-handling mechanism in which a cotter joint is used to connect two coaxial rods. The joint consists of a solid circular rod connected to a spigot and socket arrangement, with a tapered cotter passing through the spigot and socket to lock the two parts together. The joint is subjected to a direct tensile load during operation. Since the mechanism is used repeatedly in a rural environment, the connecting joint must be designed to withstand tension, shear and crushing stresses safely. The dimensions of the rod, spigot, socket and cotter are initially unknown and must be determined from the design load and allowable stresses.

As a design engineer applying the principles of Design of Machine Elements, you are required to design the complete cotter joint, determine the dimensions of the rod, spigot, socket and cotter, and check all critical sections against tensile, shear and crushing failure. Suitable standard dimensions should then be selected. Finally, prepare the 3-D CAD model and detailed production drawing of the complete joint.

Given Data

Parameter	Value
Application	Agricultural water-lifting mechanism
Type of joint	Cotter joint
Joint arrangement	Rod with spigot and socket
Design tensile load, P	40 kN
Material of rod	Mild steel
Material of spigot and socket	Mild steel
Material of cotter	Medium carbon steel
Yield strength of rod	250 MPa
Yield strength of spigot/socket	250 MPa
Yield strength of cotter	350 MPa
Allowable tensile stress, σ_t	80 MPa
Allowable shear stress, τ	50 MPa
Allowable crushing stress, σ_c	120 MPa
Factor of safety	2.5
Type of cotter	Flat rectangular tapered cotter
Cotter taper	1 in 24
Rod cross-section	Solid circular
Loading	Axial tension
Design objective	Safe transmission of tensile load
Standard rod diameters available	25, 30, 35, 40, 45, 50 mm
Standard cotter thickness available	8, 10, 12, 14, 16 mm

Tasks (Problem-Solving Component)

1. Design load and rod diameter:

1. Calculate the design tensile load acting on the joint.
2. Determine the required diameter of the solid rod based on the allowable tensile stress.
3. Select the next higher standard rod diameter from the given list.



2. Design of spigot:

1. Determine the diameter of the spigot based on the possibility of tensile failure at the weakened section caused by the cotter slot.
2. Calculate the required spigot diameter and select a suitable standard dimension.
3. Check the spigot for Tensile failure, Shear failure and Crushing failure.

3. Design of socket:

1. Determine the outside diameter and required dimensions of the socket.
2. Check the socket against Tensile failure, Shear failure and Crushing failure. Ensure that the socket provides sufficient material around the cotter slot.

4. Design of cotter:

1. Determine the dimensions of the cotter considering Double shear, Crushing between the cotter and spigot, Crushing between the cotter and socket and Bending of the cotter.
2. Select a suitable cotter thickness and width. Use the specified taper of 1:24:1:24

5. Failure mode checks:

1. Check all important sections of the cotter joint for i) Tensile failure of rod. ii) Tensile failure of spigot. iii) Tensile failure of socket. iv) Shear failure of cotter. v) Shear failure of spigot. vi) Shear failure of socket. vii) Crushing failure between cotter and spigot. viii) Crushing failure between cotter and socket. ix) Bending failure of cotter.
2. Confirm that the calculated stresses are within the specified allowable values.

6. Selection of final dimensions:

1. Prepare a final dimensional table containing i) Rod diameter. ii) Spigot diameter. iii) Socket outside diameter. iv) Socket length. v) Cotter thickness. vi) Cotter width. vii) Cotter length. viii) Cotter taper. ix) Required clearances and fillet/chamfer dimensions.
2. Select practical standard dimensions wherever possible.

Tasks (Interpretation Component)

7. Design justification: Explain why the rod, spigot, socket and cotter must be designed together rather than designing only the rod for the applied tensile load. Discuss how the cotter slot reduces the effective cross-sectional area and why the spigot and socket require additional material around the joint.

8. Failure mode interpretation: Explain the difference between tensile, shear and crushing failure in a cotter joint. Discuss why the cotter is mainly checked for shear and crushing, while the rod, spigot and socket are primarily checked for tensile failure.

9. Trade-off analysis: If the applied tensile load is increased from 40 kN to 60 kN, interpret how the dimensions of the rod, spigot, socket and cotter would need to change. Discuss whether increasing the rod diameter, increasing cotter thickness, increasing socket thickness, or changing the material would be the more practical way to improve the load-carrying capacity.



10. Sustainability interpretation: Comment on how selecting appropriate dimensions for the rod, spigot, socket and cotter avoids unnecessary material consumption while maintaining adequate safety. Discuss how proper sizing improves service life, reduces maintenance and replacement requirements, and lowers manufacturing and transportation effort.

11. CAD Modelling and Detailed Drafting: Create the 3-D CAD model of the complete cotter joint, including the rod, spigot, socket and tapered cotter. Prepare a 2-D production drawing with front, top and sectional views, showing all important dimensions, tolerances, cotter taper, material specifications, surface-finish requirements and title block.

Solution Steps

Task 1: Design Load and Rod Diameter

1. Take the given tensile load of 40 kN as the design load.
2. Calculate the required rod diameter from the allowable tensile stress.
3. Select the next higher standard rod diameter.
4. Check the tensile stress in the selected rod and confirm that it is within the allowable limit.

Task 2: Design of Spigot

1. Select a trial spigot diameter greater than the rod diameter.
2. Determine the net cross-sectional area after considering the cotter slot.
3. Check the tensile strength of the spigot.
4. Check the shear strength of the spigot around the cotter slot.
5. Check the crushing stress between the spigot and cotter.
6. Increase the spigot diameter if any condition is not satisfied.
7. Select the final suitable spigot diameter.

Task 3: Design of Socket

1. Select a trial socket outside diameter greater than the spigot diameter.
2. Determine the available net area around the cotter slot.
3. Check the socket for tensile failure.
4. Check the socket for shear failure.
5. Check the bearing or crushing stress between the socket and cotter.
6. Ensure sufficient wall thickness is available around the slot.
7. Select the final socket diameter and length.

Task 4: Design of Cotter

1. Select a trial cotter thickness from the available standard sizes.
2. Determine the required cotter width from the double-shear condition.
3. Check the cotter for crushing between the cotter and spigot.
4. Check the cotter for crushing between the cotter and socket.
5. Check the cotter for bending.
6. Increase the cotter thickness or width if required.
7. Provide the specified taper of 1:24.
8. Select the final cotter dimensions.

Task 5: Failure Mode Checks

1. Check the rod for tensile failure.
2. Check the spigot for tensile failure.
3. Check the socket for tensile failure.
4. Check the cotter for double-shear failure.
5. Check the spigot for shear failure.
6. Check the socket for shear failure.
7. Check crushing between the cotter and spigot.
8. Check crushing between the cotter and socket.



9. Check the cotter for bending failure.
10. Confirm that all calculated stresses are within their allowable limits.

Task 6: Selection of Final Dimensions

1. Select the final rod diameter from the available standard sizes.
2. Select the spigot diameter based on all strength checks.
3. Select the socket outside diameter and length.
4. Select the cotter thickness and width.
5. Provide the 1:24 cotter taper.
6. Add suitable clearances, fillets and chamfers.
7. Prepare the final dimensional table of the complete joint.

Task 7: Design Justification

1. Explain that the rod, spigot, socket and cotter carry the same applied tensile load.
2. Explain that the cotter slot reduces the effective area of the spigot and socket.
3. Explain why additional material is required around the cotter slot.
4. Explain why the cotter requires checks for shear, crushing and bending.
5. Confirm that all components must be designed together for safe load transmission.

Task 8: Failure Mode Interpretation

1. Explain tensile failure as failure caused by excessive pulling stress.
2. Explain shear failure as failure caused by sliding or cutting action.
3. Explain crushing failure as local deformation caused by excessive bearing pressure.
4. Identify tensile failure as an important check for the rod, spigot and socket.
5. Identify shear and crushing as important checks for the cotter.
6. Explain the role of bending in the cotter.

Task 9: Trade-off Analysis

1. Increase the applied load from 40 kN to 60 kN.
2. Recalculate the required rod diameter.
3. Recalculate the required spigot and socket dimensions.
4. Recalculate the cotter thickness and width.
5. Check all failure modes again.
6. Compare increasing component dimensions with using stronger material.
7. Select a practical design considering strength, weight and manufacturing cost.

Task 10: Sustainability Interpretation

1. Compare the mass of the selected joint with an oversized joint.
2. Relate the selected dimensions to material consumption and manufacturing cost.
3. Explain how proper sizing reduces premature failure.
4. Explain how longer service life reduces maintenance and replacement.
5. Relate lower component weight to easier transportation and handling.
6. Avoid unnecessary material while maintaining the required safety.

Task 11: CAD Modelling and Detailed Drafting

1. Create the 3-D model of the rod.
2. Create the spigot with the cotter slot.
3. Create the socket with the required bore and cotter slot.
4. Create the tapered cotter with 1:24 taper.
5. Assemble all components to form the complete cotter joint.
6. Generate front, top and sectional views.
7. Add all component dimensions and tolerances.
8. Add fillets, chamfers, clearances and surface-finish specifications.
9. Specify the material of each component.
10. Complete the production drawing with scale, projection method, drawing number and title block.



A3 –II Design of the rod, eye, fork and pin for tension, shear, crushing and bending;

Problem Statement

A manually operated material-handling mechanism uses a rod–eye–fork–pin joint to connect two structural members and transmit an axial tensile load. The joint consists of a solid circular rod connected to an eye, which is fitted between the two arms of a fork and secured using a cylindrical pin. During operation, the joint is subjected to a direct tensile load. The eye, fork and pin must safely transmit the applied load without tensile, shear, crushing or bending failure. Since the mechanism is operated repeatedly under static and fluctuating loading conditions, the joint must be designed with suitable safety against all critical failure modes. The dimensions of the rod, eye, fork and pin are initially unknown and must be determined from the design load and allowable stresses.

As a design engineer applying the principles of Design of Machine Elements, you are required to design the complete rod–eye–fork–pin joint, determine the dimensions of the rod, eye, fork and pin, and check all critical sections against tension, shear, crushing and bending failure. Suitable standard dimensions should then be selected. Finally, prepare the 3-D CAD model, complete assembly, assembly drawing and Bill of Materials (BOM) of the joint.

Given Data

Parameter	Value
Application	Manual material-handling mechanism
Type of joint	Rod–eye–fork–pin joint
Joint arrangement	Solid rod with eye, fork and pin
Design tensile load, P	30 kN
Material of rod	Mild steel
Material of eye	Mild steel
Material of fork	Mild steel
Material of pin	Medium carbon steel
Yield strength of rod	250 MPa
Yield strength of eye	250 MPa
Yield strength of fork	250 MPa
Yield strength of pin	350 MPa
Allowable tensile stress, σ_t	80 MPa
Allowable shear stress, τ	50 MPa
Allowable crushing stress, σ_c	120 MPa
Allowable bending stress	100 MPa
Factor of safety	2.5
Rod cross-section	Solid circular
Pin type	Cylindrical solid pin
Loading	Axial tension
Load transmission	Through eye and fork
Design objective	Safe transmission of tensile load
Standard rod diameters available	25, 30, 35, 40, 45, 50 mm
Standard pin diameters available	20, 22, 25, 28, 30, 32 mm
Standard eye thickness available	12, 14, 16, 18, 20 mm
Standard fork arm thickness available	10, 12, 14, 16, 18, 20 mm

Tasks (Problem-Solving Component)

1. Design Load and Rod Diameter

1. Calculate the design tensile load acting on the joint.
2. Determine the required diameter of the solid rod based on the allowable tensile stress.
3. Select the next higher standard rod diameter from the given list.
4. Check the selected rod for tensile failure.



2. Design of Eye

1. Determine the required dimensions of the eye for transmitting the applied tensile load.
2. Determine the eye thickness.
3. Determine the outside diameter of the eye.
4. Determine the pin-hole diameter.
5. Check the eye for tensile failure at the minimum cross-section.
6. Check the eye for shear failure around the pin hole.
7. Check the eye for crushing failure between the eye and pin.
8. Select suitable practical dimensions for the eye.

3. Design of Fork

1. Determine the required dimensions of the fork.
2. Determine the thickness of each fork arm.
3. Determine the outside width of the fork.
4. Provide sufficient clearance for the eye between the fork arms.
5. Check the fork for tensile failure at the critical section.
6. Check the fork for shear failure around the pin hole.
7. Check the fork for crushing failure between the fork and pin.
8. Select suitable practical dimensions for the fork.

4. Design of Pin

1. Determine the required diameter of the pin considering double shear.
2. Check the pin for crushing between the pin and eye.
3. Check the pin for crushing between the pin and fork.
4. Check the pin for bending due to the load transmitted through the eye and fork.
5. Select a suitable standard pin diameter.
6. Check the selected pin for shear, crushing and bending stresses.

5. Failure Mode Checks

Check all important sections of the rod–eye–fork–pin joint for:

1. Tensile failure of rod.
2. Tensile failure of eye.
3. Shear failure of eye.
4. Crushing failure between eye and pin.
5. Tensile failure of fork.
6. Shear failure of fork.
7. Crushing failure between fork and pin.
8. Shear failure of pin.
9. Crushing failure of pin.
10. Bending failure of pin.

Confirm that the calculated stresses are within the specified allowable values.

6. Selection of Final Dimensions

Prepare a final dimensional table containing:

1. Rod diameter.
2. Eye thickness.
3. Eye outside diameter.
4. Pin-hole diameter.
5. Eye length.



6. Fork arm thickness.
7. Fork outside width.
8. Fork inside width.
9. Fork length.
10. Pin diameter.
11. Pin length.
12. Pin-head dimensions.
13. Required clearances.
14. Fillet dimensions.
15. Chamfer dimensions.
16. Material specifications.

Select practical standard dimensions wherever possible.

Tasks (Interpretation Component)

7. Design Justification

Explain why the rod, eye, fork and pin must be designed together rather than designing only the rod for the applied tensile load.

Discuss:

1. Load transfer from the rod to the eye.
2. Load transfer from the eye to the pin.
3. Load transfer from the pin to the fork.
4. Importance of sufficient material around the pin hole.
5. Effect of the pin hole on the effective cross-sectional area.
6. Importance of fork-arm thickness.
7. Need for adequate clearance between the eye and fork.

8. Failure Mode Interpretation

Explain the difference between:

1. Tensile failure.
2. Shear failure.
3. Crushing failure.
4. Bending failure.

Discuss why:

1. The rod is mainly checked for tensile failure.
2. The eye is checked for tension, shear and crushing.
3. The fork is checked for tension, shear and crushing.
4. The pin is checked for shear, crushing and bending.

9. Trade-Off Analysis

If the applied tensile load is increased from 30 kN to 45 kN, interpret how the dimensions of the rod, eye, fork and pin would need to change.

Discuss the effects of:

1. Increasing rod diameter.
2. Increasing eye thickness.
3. Increasing eye outside diameter.



4. Increasing fork-arm thickness.
5. Increasing pin diameter.
6. Changing the material.
7. Increasing the factor of safety.

Identify which design changes would be practical for improving the load-carrying capacity of the joint.

10. Sustainability Interpretation

Comment on how appropriate sizing of the rod, eye, fork and pin can avoid unnecessary material consumption while maintaining adequate safety.

Discuss how proper design can:

1. Reduce material usage.
2. Reduce component weight.
3. Improve service life.
4. Reduce maintenance requirements.
5. Reduce component replacement.
6. Reduce manufacturing effort.
7. Reduce transportation requirements.
8. Improve overall sustainability of the mechanism.

11. 3-D CAD Modelling, Assembly and Assembly Drawing

Create the 3-D CAD model of the complete rod–eye–fork–pin joint, including:

1. Solid circular rod.
2. Eye.
3. Fork.
4. Cylindrical pin.
5. Pin head/retaining arrangement, where applicable.

Prepare the complete assembly showing the correct positional relationship between the rod, eye, fork and pin. Prepare a 2-D assembly drawing containing:

1. Front view.
2. Top view.
3. Side view.
4. Sectional view through the pin and eye.
5. Overall assembly dimensions.
6. Important component dimensions.
7. Required clearances.
8. Material specifications.
9. Surface-finish requirements.
10. General tolerances.
11. Part identification numbers.
12. Title block.

12. Bill of Materials (BOM)

Prepare a Bill of Materials for the complete assembly containing:

Sl. No.	Part Name	Part No.	Material	Quantity	Principal Dimensions
1	Rod	P-01	Mild steel	1	To be designed
2	Eye	P-02	Mild steel	1	To be designed
3	Fork	P-03	Mild steel	1	To be designed



4	Pin	P-04	Medium carbon steel	1	To be designed
5	Pin retaining element	P-05	Suitable steel	1	To be selected

Final objective: Design the complete rod–eye–fork–pin joint for the specified tensile load, verify all critical failure modes, select practical dimensions, and prepare the 3-D model, assembled model, assembly drawing and BOM.

Solution Steps

Task 1: Design Load and Rod Diameter

1. Take the given tensile load of 30 kN as the design load.
2. Calculate the required rod diameter from the allowable tensile stress.
3. Select the next higher standard rod diameter.
4. Check the tensile stress in the selected rod.
5. Confirm that the rod tensile stress is within the allowable limit.

Task 2: Design of Eye

1. Select a trial eye thickness based on the selected rod and pin dimensions.
2. Select a suitable pin-hole diameter.
3. Determine the net cross-sectional area of the eye after considering the pin hole.
4. Check the eye for tensile failure at the minimum section.
5. Check the eye for shear failure around the pin hole.
6. Check the crushing stress between the eye and pin.
7. Increase the eye thickness or outside diameter if any condition is not satisfied.
8. Select the final suitable eye dimensions.

Task 3: Design of Fork

1. Select a trial fork-arm thickness greater than the minimum required value.
2. Determine the required inside width of the fork to accommodate the eye.
3. Determine the overall fork width.
4. Check the fork for tensile failure at the critical section.
5. Check the fork for shear failure around the pin hole.
6. Check the crushing stress between the fork and pin.
7. Ensure sufficient material is available around the pin hole.
8. Provide suitable clearance between the eye and fork arms.
9. Select the final fork dimensions.

Task 4: Design of Pin

1. Select a trial pin diameter from the available standard sizes.
2. Determine the required pin diameter from the double-shear condition.
3. Check the pin for crushing between the pin and eye.
4. Check the pin for crushing between the pin and fork.
5. Check the pin for bending under the applied load.
6. Increase the pin diameter if any condition is not satisfied.
7. Select the next suitable standard pin diameter.
8. Determine the required pin length based on the eye and fork dimensions.
9. Select the final pin dimensions.

Task 5: Failure Mode Checks

1. Check the rod for tensile failure.
2. Check the eye for tensile failure.
3. Check the eye for shear failure.
4. Check crushing between the eye and pin.



5. Check the fork for tensile failure.
6. Check the fork for shear failure.
7. Check crushing between the fork and pin.
8. Check the pin for double-shear failure.
9. Check the pin for crushing failure.
10. Check the pin for bending failure.
11. Confirm that all calculated stresses are within their respective allowable limits.

Task 6: Selection of Final Dimensions

1. Select the final rod diameter from the available standard sizes.
2. Select the eye thickness based on all strength checks.
3. Select the eye outside diameter.
4. Select the pin-hole diameter.
5. Select the eye length.
6. Select the fork-arm thickness.
7. Select the fork inside and outside width.
8. Select the fork length.
9. Select the final standard pin diameter.
10. Select the required pin length.
11. Add suitable clearances, fillets and chamfers.
12. Prepare the final dimensional table of the complete joint.

Task 7: Design Justification

1. Explain that the rod, eye, fork and pin must transmit the same applied tensile load.
2. Explain that the pin hole reduces the effective cross-sectional area of the eye and fork.
3. Explain why sufficient material is required around the pin hole.
4. Explain why the fork is provided with two arms.
5. Explain how the load is transferred from the rod to the eye, pin and fork.
6. Explain why the pin requires checks for shear, crushing and bending.
7. Confirm that all components must be designed together for safe load transmission.

Task 8: Failure Mode Interpretation

1. Explain tensile failure as failure caused by excessive pulling stress.
2. Explain shear failure as failure caused by sliding or cutting action.
3. Explain crushing failure as local deformation caused by excessive contact pressure.
4. Explain bending failure as failure caused by excessive bending stress.
5. Identify tensile failure as an important check for the rod, eye and fork.
6. Identify shear and crushing as important checks for the eye, fork and pin.
7. Explain why the pin is subjected to both shear and bending.
8. Explain the importance of maintaining adequate material around the pin hole.

Task 9: Trade-off Analysis

1. Increase the applied load from 30 kN to 45 kN.
2. Recalculate the required rod diameter.
3. Recalculate the required eye thickness and outside diameter.
4. Recalculate the required fork-arm thickness and width.
5. Recalculate the required pin diameter.
6. Check all failure modes again.
7. Compare increasing component dimensions with using stronger materials.
8. Examine the effect of increased dimensions on weight and manufacturing cost.
9. Select a practical design considering strength, weight and manufacturing requirements.

Task 10: Sustainability Interpretation



1. Compare the mass of the selected joint with an unnecessarily oversized joint.
2. Relate the selected dimensions to material consumption and manufacturing cost.
3. Explain how proper sizing reduces premature component failure.
4. Explain how longer service life reduces maintenance and replacement requirements.
5. Relate lower component weight to easier transportation and handling.
6. Discuss the effect of material selection on the service life of the joint.
7. Avoid unnecessary material consumption while maintaining the required safety.
8. Explain how an optimized joint can reduce the overall environmental impact of manufacturing.

Task 11: CAD Modelling, Assembly and Assembly Drawing

1. Create the 3-D model of the solid rod.
2. Create the eye with the required pin hole.
3. Create the fork with two arms and aligned pin holes.
4. Create the cylindrical pin with the required head or retaining arrangement.
5. Assemble the rod and eye with the fork.
6. Insert the pin through the aligned eye and fork holes.
7. Apply suitable assembly constraints to obtain the correct positioning.
8. Generate front, top and side views of the complete assembly.
9. Generate a sectional view through the eye, fork and pin.
10. Add all important component and assembly dimensions.
11. Add required tolerances, clearances, fillets and chamfers.
12. Specify the material of each component.
13. Add surface-finish requirements where necessary.
14. Prepare the complete assembly drawing with part numbers and balloons.
15. Prepare the Bill of Materials (BOM) showing part name, part number, material, quantity and principal dimensions.
16. Complete the drawing with scale, projection method, drawing number, revision and title block.

A3-III Design of the weld size and length for combined direct and torsional or bending stresses;

Problem Statement

A fabricated steel bracket is used to support a rotating and load-carrying component in an industrial material-handling system. The bracket is connected to a rigid base plate using fillet welds. During operation, the welded joint is subjected to a combination of direct load and torsional/bending moment. Therefore, the weld must be designed to safely resist the combined stresses without failure. The weld size and effective weld length are initially unknown and must be determined based on the applied loading and allowable weld stresses. The design should consider the effects of direct shear together with torsional or bending loading on the welded joint.

As a design engineer applying the principles of Design of Machine Elements, you are required to design the welded joint, determine the suitable weld size and effective weld length, and check the weld for all critical stress conditions. Suitable standard weld dimensions should then be selected. Finally, prepare the 3-D CAD model and detailed production drawing of the welded assembly, including appropriate weld symbols, dimensions, material specifications and fabrication details.

Given Data

Parameter	Value
Application	Industrial material-handling bracket
Type of joint	Fillet welded bracket joint
Joint arrangement	Steel bracket welded to base plate
Direct load, P	20 kN
Bending moment, M	1.5 kN·m
Torsional moment, T	1.0 kN·m
Material of bracket	Mild steel
Material of base plate	Mild steel
Weld type	Fillet weld



Weld material	Suitable mild-steel welding electrode
Yield strength of steel	250 MPa
Allowable normal stress in weld	80 MPa
Allowable shear stress in weld	50 MPa
Factor of safety	2.5
Weld configuration	Two longitudinal fillet welds
Weld orientation	Parallel to the direction of the bracket
Loading	Combined direct and torsional/bending loading
Design objective	Safe transmission of the applied load
Standard weld sizes available	4, 5, 6, 8, 10, 12 mm
Minimum practical fillet weld size	4 mm

Tasks (Problem-Solving Component)

1. Design Load and Weld Configuration

1. Determine the design loading acting on the welded joint.
2. Identify the direct load acting on the weld group.
3. Identify the bending moment acting on the weld group.
4. Identify the torsional moment acting on the weld group.
5. Establish the effective weld configuration for the bracket.
6. Select a suitable trial weld size and weld length.

2. Design of Weld Size

1. Determine the effective throat thickness of the fillet weld.
2. Determine the effective throat area of the weld group.
3. Calculate the direct shear stress in the weld.
4. Determine the stress produced by the applied bending moment.
5. Determine the stress produced by the applied torsional moment.
6. Combine the relevant stresses acting on the weld.
7. Compare the resulting stress with the allowable weld stress.
8. Increase the weld size if the allowable stress condition is not satisfied.
9. Select a suitable standard weld size.

3. Design of Weld Length

1. Select a suitable trial effective weld length.
2. Determine the total effective length of the weld group.
3. Determine the weld-group properties required for bending and torsional loading.
4. Check the weld length for direct loading.
5. Check the weld length for bending stress.
6. Check the weld length for torsional shear stress.
7. Increase the weld length if any condition is not satisfied.
8. Select the final effective weld length.

4. Combined Stress Analysis

1. Determine the direct shear stress in the weld.
2. Determine the bending stress in the weld.
3. Determine the torsional shear stress in the weld.
4. Identify the critical location in the weld group.
5. Combine the direct, bending and torsional stresses appropriately.
6. Determine the maximum resultant weld stress.
7. Compare the resultant stress with the allowable stress.
8. Confirm that the selected weld size and length are safe.



5. Failure Mode Checks

Check the welded joint for:

1. Direct shear failure.
2. Bending stress failure.
3. Torsional shear failure.
4. Combined stress failure.
5. Failure at the weld throat.
6. Failure due to insufficient effective weld length.
7. Failure at the critical end of the weld.
8. Confirm that all calculated stresses are within the specified allowable limits.

6. Selection of Final Weld Dimensions

Prepare a final dimensional table containing:

1. Weld type.
2. Weld size.
3. Effective throat thickness.
4. Effective weld length.
5. Total weld length.
6. Number of welds.
7. Weld configuration.
8. Weld spacing, where applicable.
9. Bracket dimensions.
10. Base-plate dimensions.
11. Required clearances.
12. Weld termination details.

Select practical standard weld dimensions wherever possible.

Tasks (Interpretation Component)

7. Design Justification

Explain why the weld size and weld length must be designed together.

Discuss:

1. The effect of direct load on the weld.
2. The effect of bending moment on the weld.
3. The effect of torsional moment on the weld.
4. The importance of effective throat thickness.
5. The importance of effective weld length.
6. The reason for checking the complete weld group rather than only one weld.
7. The importance of identifying the critical location in the weld.

8. Stress Interpretation

Explain the difference between:

1. Direct shear stress.
2. Bending stress.
3. Torsional shear stress.
4. Combined stress.



Discuss why a welded joint subjected to combined loading may require a larger weld size or length than a joint subjected only to direct loading.

9. Trade-off Analysis

If the direct load is increased from 20 kN to 30 kN, interpret how the welded joint would need to be redesigned.

Discuss the effects of:

1. Increasing weld size.
2. Increasing weld length.
3. Increasing the number of welds.
4. Increasing the bracket thickness.
5. Changing the weld material.
6. Changing the weld configuration.

Compare the alternatives in terms of strength, weight, manufacturing time and cost.

10. Sustainability Interpretation

Comment on how appropriate selection of weld size and length can avoid excessive use of welding material.

Discuss how proper weld design can:

1. Reduce filler-material consumption.
2. Reduce welding time.
3. Reduce energy consumption during fabrication.
4. Reduce material wastage.
5. Improve joint service life.
6. Reduce maintenance and repair requirements.
7. Reduce premature failure and replacement.
8. Maintain adequate safety without over-design.

11. 3-D CAD Modelling and Detailed Drafting

Create the **3-D CAD model** of the complete welded assembly, including:

1. Base plate.
2. Bracket.
3. Welded connection.
4. Supporting features, if required.

Prepare the complete assembly model showing the correct weld locations.

Prepare a **2-D production drawing** containing:

1. Front view.
2. Top view.
3. Side view.
4. Sectional view through the welded joint.
5. Bracket dimensions.
6. Base-plate dimensions.
7. Weld size.
8. Weld length.
9. Weld location.
10. Weld symbols according to standard drafting practice.
11. Material specifications.



12. Surface-finish requirements where applicable.
13. General tolerances.
14. Welding notes.
15. Welding sequence or fabrication notes, where required.
16. Scale.
17. Projection method.
18. Drawing number.
19. Revision information.
20. Complete title block.

12. Weld Symbols and Fabrication Details

Show the appropriate welding symbols on the drawing for:

1. Fillet weld location.
2. Weld size.
3. Weld length.
4. Continuous or intermittent weld, as applicable.
5. Both-side welding, where applicable.
6. Weld-all-around indication, if required.
7. Any special welding requirement.

Specify suitable welding process, electrode specification, weld quality requirements and inspection requirements in the drawing notes.

13. Bill of Materials

Prepare a Bill of Materials (BOM) for the complete assembly containing:

Sl. No.	Part Name	Part No.	Material	Quantity	Principal Dimensions
1	Base Plate	P-01	Mild steel	1	To be designed
2	Bracket	P-02	Mild steel	1	To be designed
3	Fillet Weld	W-01	Suitable electrode	As required	To be designed

Final Objective: Design the complete welded bracket for the specified combined direct, bending and torsional loading, determine the suitable weld size and length, verify the combined stresses, and prepare the 3-D CAD model, welded assembly, detailed drawing with standard weld symbols and BOM.

Solution Steps

Task 1: Design Load and Weld Configuration

1. Take the given direct load as the design load.
2. Identify the bending moment acting on the welded joint.
3. Identify the torsional moment acting on the welded joint.
4. Identify the number and arrangement of welds.
5. Select a suitable trial fillet weld size.
6. Select a suitable trial effective weld length.
7. Consider the weld group as a single load-carrying system.

Task 2: Design of Weld Size

1. Determine the effective throat thickness of the selected fillet weld.
2. Determine the effective throat area of the weld group.
3. Determine the direct shear stress due to the applied load.
4. Determine the stress produced by the bending moment.
5. Determine the shear stress produced by the torsional moment.



6. Identify the critical point in the weld group.
7. Combine the stresses at the critical location.
8. Compare the resultant stress with the allowable weld stress.
9. Increase the weld size if the stress exceeds the allowable value.
10. Select the next suitable standard weld size.

Task 3: Design of Weld Length

1. Select a trial effective weld length.
2. Determine the total effective length of the weld group.
3. Determine the required weld-group properties for bending.
4. Determine the required weld-group properties for torsion.
5. Check the weld length for direct shear.
6. Check the weld length for bending stress.
7. Check the weld length for torsional shear.
8. Increase the weld length if any condition is not satisfied.
9. Select the final practical weld length.

Task 4: Combined Stress Analysis

1. Determine the direct shear stress in the weld.
2. Determine the bending stress in the weld.
3. Determine the torsional shear stress in the weld.
4. Identify the location where the maximum combined stress occurs.
5. Combine the normal and shear stresses appropriately.
6. Determine the maximum resultant stress.
7. Compare the resultant stress with the allowable weld stress.
8. Modify the weld size or length if required.
9. Confirm that the final weld is safe under combined loading.

Task 5: Failure Mode Checks

1. Check the weld for direct shear failure.
2. Check the weld for bending stress failure.
3. Check the weld for torsional shear failure.
4. Check the weld throat for excessive stress.
5. Check the effective weld length for adequate load-carrying capacity.
6. Check the critical end region of the weld.
7. Check the combined stress condition.
8. Confirm that all calculated stresses are within the allowable limits.

Task 6: Selection of Final Weld Dimensions

1. Select the final weld size from the available standard sizes.
2. Select the final effective weld length.
3. Determine the total weld length.
4. Confirm the number of welds.
5. Confirm the weld configuration.
6. Provide suitable weld termination details.
7. Provide adequate clearances around the welded joint.
8. Prepare the final dimensional table of the welded assembly.

Task 7: Design Justification

1. Explain that the weld group must transmit the complete applied loading safely.
2. Explain the effect of direct load on the weld.
3. Explain the effect of bending moment on the weld.
4. Explain the effect of torsional moment on the weld.



5. Explain the importance of weld throat thickness.
6. Explain the importance of effective weld length.
7. Explain why the complete weld group must be considered.
8. Explain why the critical location of the weld must be identified.
9. Confirm that weld size and length must be selected together.

Task 8: Stress Interpretation

1. Explain direct shear stress as stress produced by the direct load.
2. Explain bending stress as stress produced by the bending moment.
3. Explain torsional shear stress as stress produced by the torsional moment.
4. Explain the difference between normal and shear stresses.
5. Explain how different stresses act simultaneously in a combined loading condition.
6. Explain why the maximum stress may occur at a particular location of the weld group.
7. Explain why combined loading may require a larger weld than direct loading alone.

Task 9: Trade-off Analysis

1. Increase the direct load from **20 kN to 30 kN**.
2. Recalculate the required weld size.
3. Recalculate the required weld length.
4. Check the effect on direct shear stress.
5. Check the effect on bending stress.
6. Check the effect on torsional shear stress.
7. Compare increasing weld size with increasing weld length.
8. Compare the use of additional welds with increasing individual weld size.
9. Compare the use of stronger weld material with increasing weld dimensions.
10. Select a practical design considering strength, weight, fabrication time and cost.

Task 10: Sustainability Interpretation

1. Compare the mass of the selected weld with an oversized weld.
2. Relate weld size to filler-material consumption.
3. Explain how proper weld sizing reduces welding time.
4. Explain how proper weld sizing reduces energy consumption.
5. Explain how avoiding excessive weld metal reduces material wastage.
6. Explain how adequate weld strength improves service life.
7. Explain how longer service life reduces maintenance and replacement.
8. Avoid unnecessary weld material while maintaining the required safety.

Task 11: 3-D CAD Modelling

1. Create the **3-D model of the base plate**.
2. Create the **3-D model of the bracket**.
3. Position the bracket correctly on the base plate.
4. Model the required welded regions.
5. Create the complete welded assembly.
6. Check the geometry and dimensions of the assembly.
7. Verify that the weld locations correspond to the design.
8. Apply suitable fillets or edge treatments where required.

Task 12: Detailed Drawing and Weld Symbols

1. Generate the front view of the welded assembly.
2. Generate the top view.
3. Generate the side view.
4. Generate a sectional view through the welded joint.
5. Add all important component dimensions.



6. Indicate the weld size.
7. Indicate the effective weld length.
8. Apply the appropriate fillet-weld symbol.
9. Indicate whether the weld is on one side or both sides.
10. Add continuous or intermittent weld information where required.
11. Add material specifications.
12. Add general tolerances.
13. Add surface-finish requirements where applicable.
14. Add welding and fabrication notes.
15. Complete the drawing with scale, projection method, drawing number and title block.

Task 13: Bill of Materials

1. Assign a part number to the base plate.
2. Assign a part number to the bracket.
3. Identify the weld specification.
4. Specify the material of each component.
5. Specify the quantity of each component.
6. Add the principal dimensions.
7. Prepare the final BOM.
8. Verify that the BOM agrees with the 3-D assembly and drawing.

A3-IV Design of a lap or butt riveted joint for the rivet diameter, pitch and margin, with joint efficiency;

Problem Statement

A fabricated steel cover plate is used in an industrial material-handling system and is connected using a lap riveted joint. The joint consists of two overlapping mild-steel plates joined by a single row of rivets. The joint is subjected to a direct tensile load during operation. The riveted connection must safely transmit the applied load without failure of the plates or rivets. The rivet diameter, pitch, margin and number of rivets are initially unknown and must be determined based on the applied load and allowable stresses. The design should consider the possible failure modes of the riveted joint, including tension of the plate, shear of the rivets and crushing between the rivets and plates. The joint efficiency must also be determined and compared with the required design performance.

As a design engineer applying the principles of Design of Machine Elements, you are required to design the complete lap riveted joint, determine suitable dimensions of the rivets and plates, check all critical failure modes, and determine the efficiency of the joint. Suitable standard dimensions should then be selected. Finally, prepare the 3-D CAD model, complete assembly, detailed drawing and rivet layout of the joint.

Given Data

Parameter	Value
Application	Industrial material-handling cover plate
Type of joint	Lap riveted joint
Rivet arrangement	Single-row riveted joint
Number of plates	Two
Plate material	Mild steel
Rivet material	Mild steel
Design tensile load, P	40 kN
Plate thickness, t	8 mm
Yield strength of plate	250 MPa
Yield strength of rivet	250 MPa
Allowable tensile stress, σ_t	80 MPa
Allowable shear stress, τ	50 MPa
Allowable crushing stress, σ_c	120 MPa
Factor of safety	2.5



Joint type	Lap joint
Rivet type	Solid round-head rivet
Rivet arrangement	Single row
Loading	Direct tensile load
Design objective	Safe transmission of tensile load
Standard rivet diameters available	8, 10, 12, 14, 16, 18, 20 mm
Minimum practical margin	1.5 times rivet diameter
Minimum practical pitch	3 times rivet diameter

Tasks (Problem-Solving Component)

1. Design Load and Rivet Diameter

1. Take the given tensile load as the design load.
2. Determine the required rivet diameter based on the shear condition.
3. Check the rivet diameter against the crushing condition.
4. Select the next higher standard rivet diameter.
5. Confirm that the selected rivet is safe under the applied load.

2. Design of Rivet Pitch

1. Select a trial rivet pitch.
2. Determine the strength of the solid plate per pitch length.
3. Determine the strength of the plate at the rivet-hole section.
4. Determine the strength of the rivets per pitch length.
5. Determine the crushing strength of the riveted joint.
6. Select a suitable pitch that satisfies all strength conditions.
7. Ensure that the selected pitch is greater than the specified minimum value.

3. Design of Margin

1. Select a suitable margin between the rivet centre and the plate edge.
2. Check the margin against possible tearing of the plate.
3. Ensure sufficient material is available around the rivet hole.
4. Select a practical margin based on the selected rivet diameter.

4. Number of Rivets

1. Determine the required number of rivets for transmitting the applied load.
2. Consider the strength of each rivet in shear.
3. Consider the crushing strength of the rivets.
4. Check the plate strength between adjacent rivets.
5. Select a suitable number of rivets.
6. Arrange the rivets uniformly along the joint.

5. Failure Mode Checks

Check the riveted joint for:

1. Tearing of the plate across the weakest section.
2. Shearing of the rivets.
3. Crushing of the rivets.
4. Crushing of the plate around the rivet holes.
5. Tearing of the plate at the edge.
6. Failure of the lap joint.
7. Confirm that all calculated stresses are within the allowable limits.



6. Joint Efficiency

Determine the efficiency of the riveted joint by comparing the strength of the riveted joint with the strength of the solid plate.

Determine:

1. Strength of the solid plate.
2. Strength of the plate considering rivet holes.
3. Shear strength of rivets.
4. Crushing strength of rivets and plate.
5. Governing strength of the joint.
6. Percentage joint efficiency.

Compare the obtained efficiency with the expected performance of the joint.

Tasks (Interpretation Component)

7. Design Justification

Explain why the rivet diameter, pitch and margin must be designed together.

Discuss:

1. Effects of rivet diameter on rivet shear strength.
2. Effect of rivet diameter on plate weakening.
3. Effect of pitch on joint strength.
4. Importance of adequate margin.
5. Importance of uniform rivet spacing.
6. Need to consider both rivet and plate strength.
7. Importance of joint efficiency in riveted-joint design.

8. Failure Mode Interpretation

Explain the difference between:

1. Tensile failure of the plate.
2. Shear failure of the rivet.
3. Crushing failure of the rivet.
4. Crushing of the plate around the rivet.
5. Tearing of the plate near the edge.

Explain why the weakest failure mode determines the safe load-carrying capacity of the joint.

9. Trade-off Analysis

If the applied tensile load is increased from 40 kN to 60 kN, interpret how the riveted joint would need to be redesigned.

Discuss the effects of:

1. Increasing rivet diameter.
2. Increasing rivet pitch.
3. Decreasing rivet pitch.
4. Increasing the number of rivets.
5. Increasing plate thickness.
6. Increasing the margin.
7. Using a stronger rivet material.



Compare the alternatives in terms of strength, weight, manufacturing cost and ease of assembly.

10. Sustainability Interpretation

Comment on how proper selection of rivet diameter, pitch and margin can reduce unnecessary material consumption.

Discuss how proper riveted-joint design can:

1. Reduce the number of rivets.
2. Reduce material consumption.
3. Reduce manufacturing effort.
4. Reduce assembly time.
5. Improve joint service life.
6. Reduce maintenance requirements.
7. Reduce premature failure and replacement.
8. Maintain required strength without over-design.

11. 3-D CAD Modelling and Assembly

Create the 3-D CAD model of the complete lap riveted joint, including:

1. Upper plate.
2. Lower plate.
3. Rivets.
4. Rivet heads.
5. Lap region.

Prepare the complete assembly showing the correct overlap between the two plates and the correct positioning of all rivets.

12. Rivet Layout

Prepare the rivet layout showing:

1. Rivet centre line.
2. Rivet diameter.
3. Rivet pitch.
4. End margin.
5. Side margin, where applicable.
6. Number of rivets.
7. Plate overlap.
8. Rivet-hole locations.

Ensure that the rivets are equally spaced and properly aligned.

13. Detailed Assembly Drawing

Prepare a **2-D assembly drawing** containing:

1. Front view.
2. Top view.
3. Side view.
4. Sectional view through the riveted joint.
5. Plate thickness.
6. Rivet diameter.
7. Rivet pitch.
8. Margin.
9. Plate overlap length.



10. Number of rivets.
11. Rivet layout.
12. Material specifications.
13. General tolerances.
14. Surface-finish requirements where applicable.
15. Riveting or assembly notes.
16. Scale.
17. Projection method.
18. Drawing number.
19. Revision information.
20. Complete title block.

14. Bill of Materials

Prepare a Bill of Materials (BOM) for the complete assembly.

Sl. No.	Part Name	Part No.	Material	Quantity	Principal Dimensions
1	Upper Plate	P-01	Mild steel	1	To be designed
2	Lower Plate	P-02	Mild steel	1	To be designed
3	Rivet	P-03	Mild steel	To be determined	To be designed

Final Objective: Design the complete lap riveted joint for the specified tensile load, determine the suitable rivet diameter, pitch, margin and number of rivets, verify all critical failure modes, determine the joint efficiency, and prepare the 3-D CAD model, assembly, rivet layout, detailed drawing and BOM.

Solution Steps

Task 1: Design Load and Rivet Diameter

1. Take the given tensile load of 40 kN as the design load.
2. Determine the required rivet diameter from the allowable shear stress.
3. Check the rivet diameter for the crushing condition.
4. Select the next higher standard rivet diameter.
5. Confirm that the selected rivet is safe under shear and crushing.

Task 2: Design of Rivet Pitch

1. Select a trial rivet pitch based on the selected rivet diameter.
2. Determine the strength of the solid plate for one pitch length.
3. Determine the net tensile strength of the plate after allowing for the rivet hole.
4. Determine the shear strength of the rivet for one pitch length.
5. Determine the crushing strength of the rivet and plate.
6. Identify the governing strength of the joint.
7. Adjust the pitch if any strength condition is not satisfied.
8. Ensure that the selected pitch satisfies the minimum practical pitch requirement.
9. Select the final rivet pitch.

Task 3: Design of Margin

1. Select a trial margin from the rivet centre to the plate edge.
2. Check the plate for tearing from the rivet hole to the edge.
3. Ensure sufficient material is available around the rivet hole.
4. Increase the margin if the edge-tearing condition is not satisfied.
5. Select the final practical margin.

Task 4: Determine Number of Rivets



1. Determine the load to be transmitted by the riveted joint.
2. Determine the load-carrying capacity of one rivet in shear.
3. Check the load-carrying capacity of one rivet in crushing.
4. Determine the number of rivets required to transmit the load.
5. Round the number of rivets to a practical whole number.
6. Check the plate strength for the selected number and arrangement of rivets.
7. Arrange the rivets uniformly along the joint.

Task 5: Failure Mode Checks

1. Check the plate for tensile failure across the weakest section.
2. Check the rivets for shear failure.
3. Check the rivets for crushing failure.
4. Check the plate for crushing around the rivet holes.
5. Check the plate for tearing near the edge.
6. Identify the weakest failure mode.
7. Confirm that the selected joint can safely transmit the design load.
8. Ensure that all calculated stresses are within the allowable limits.

Task 6: Calculation of Joint Efficiency

1. Determine the strength of the solid plate without rivet holes.
2. Determine the tensile strength of the plate after considering the rivet hole.
3. Determine the shear strength of the rivets.
4. Determine the crushing strength of the rivets and plate.
5. Identify the minimum strength among the different failure modes.
6. Use the governing joint strength to determine the joint efficiency.
7. Express the joint efficiency as a percentage.
8. Confirm that the obtained efficiency is suitable for the design requirement.

Task 7: Selection of Final Dimensions

1. Select the final standard rivet diameter.
2. Select the final rivet pitch.
3. Select the final margin.
4. Select the required number of rivets.
5. Determine the total overlap length of the plates.
6. Provide suitable rivet-hole dimensions.
7. Ensure uniform spacing between the rivets.
8. Prepare the final dimensional table of the complete riveted joint.

Task 8: Design Justification

1. Explain that the plate and rivets must be designed together to transmit the applied load.
2. Explain how the rivet diameter affects shear and crushing strength.
3. Explain how the rivet hole reduces the effective tensile area of the plate.
4. Explain why suitable pitch is required between adjacent rivets.
5. Explain why adequate margin is required from the rivet centre to the plate edge.
6. Explain why excessive pitch can reduce joint strength.
7. Explain why very small pitch can increase the number of rivets unnecessarily.
8. Explain the importance of joint efficiency in riveted-joint design.

Task 9: Failure Mode Interpretation

1. Explain tensile failure as failure caused by excessive pulling stress in the plate.
2. Explain shear failure as failure caused by cutting action on the rivet.
3. Explain crushing failure as local deformation between the rivet and plate.
4. Explain edge tearing as failure of the plate between the rivet hole and plate edge.



5. Identify the plate as an important member for tensile and tearing checks.
6. Identify the rivet as an important member for shear and crushing checks.
7. Explain why the weakest failure mode governs the joint strength.

Task 10: Trade-off Analysis

1. Increase the applied tensile load from 40 kN to 60 kN.
2. Recalculate the required rivet diameter.
3. Recalculate the required rivet pitch.
4. Recalculate the required number of rivets.
5. Recheck the margin.
6. Check all failure modes again.
7. Compare increasing rivet diameter with increasing the number of rivets.
8. Compare increasing plate thickness with using stronger rivets.
9. Examine the effect of each change on weight and manufacturing cost.
10. Select a practical design considering strength, material use and manufacturing requirements.

Task 11: Sustainability Interpretation

1. Compare the mass of the selected joint with an unnecessarily oversized riveted joint.
2. Relate the number of rivets to material consumption.
3. Explain how proper pitch reduces unnecessary rivet usage.
4. Explain how proper rivet sizing reduces material wastage.
5. Explain how suitable joint design improves service life.
6. Explain how longer service life reduces maintenance and replacement.
7. Relate reduced component weight to easier transportation and handling.
8. Avoid unnecessary material while maintaining the required joint strength.

Task 12: 3-D CAD Modelling

1. Create the 3-D model of the lower plate.
2. Create the 3-D model of the upper plate.
3. Create the required rivet holes in both plates.
4. Create the 3-D model of the rivet.
5. Position the two plates with the required overlap.
6. Align all rivet holes.
7. Insert the rivets into the holes.
8. Create the complete riveted assembly.
9. Check the correct rivet spacing and plate overlap.
10. Verify the final assembly dimensions.

Task 13: Rivet Layout and Detailed Drawing

1. Generate the front view of the riveted joint.
2. Generate the top view.
3. Generate the side view.
4. Generate a sectional view through the riveted joint.
5. Show the rivet centre line.
6. Show the rivet diameter.
7. Show the rivet pitch.
8. Show the margin.
9. Show the plate thickness.
10. Show the plate overlap.
11. Indicate the number of rivets.
12. Add all important dimensions.
13. Add material specifications.
14. Add general tolerances.
15. Add surface-finish requirements where applicable.



16. Add riveting and assembly notes.
17. Complete the drawing with scale, projection method, drawing number and title block.

Task 14: Bill of Materials

1. Assign a part number to the upper plate.
2. Assign a part number to the lower plate.
3. Assign a part number to the rivet.
4. Specify the material of each component.
5. Specify the quantity of each component.
6. Specify the principal dimensions.
7. Prepare the final BOM.
8. Verify that the BOM agrees with the 3-D assembly and detailed drawing.

INSTRUCTION ITEM-4(II-4)		
Assignment No.	Name of the experiment	CO Congruence
A4-I	Design of the threaded rods, coupler and lock nuts for tension, thread shear and bearing pressure; 3-D modeling, assembly and drawings with bill of materials.	[CO4]
A4-II	Design of the bolts for direct shear, moment and pre-tension, and selection of standard bolt size; 3-D modeling, assembly and drawing with bill of materials.	

A4-I Design of the threaded rods, coupler and lock nuts for tension, thread shear and bearing pressure;

Problem Statement

A mechanically operated material-handling mechanism uses a threaded rod and coupler assembly to connect two coaxial rods and transmit an axial tensile load. The connection consists of two threaded rods joined by a threaded coupler. Lock nuts are provided at both ends of the coupler to prevent loosening during repeated operation. The assembly is subjected to a direct tensile load during service. The threaded connection must safely transmit the applied load without failure of the threaded rods, coupler or lock nuts. The design must consider tensile failure of the threaded rods, shear failure of the threads and bearing pressure between mating threads. The dimensions of the threaded rods, coupler, threads and lock nuts are initially unknown and must be determined from the applied load and allowable stresses. Suitable standard thread dimensions should then be selected.

As a design engineer applying the principles of Design of Machine Elements, you are required to design the complete threaded connection, determine suitable dimensions for the threaded rods, coupler and lock nuts, and check all critical sections for tension, thread shear and bearing pressure. Finally, prepare the 3-D CAD models, complete assembly, detailed component drawings and Bill of Materials (BOM).

Given Data

Parameter	Value
Application	Material-handling mechanism
Type of connection	Threaded rod and coupler connection
Joint arrangement	Two threaded rods with coupler and lock nuts
Design tensile load, P	40 kN
Material of threaded rods	Mild steel
Material of coupler	Mild steel
Material of lock nuts	Medium carbon steel
Yield strength of threaded rods	250 MPa
Yield strength of coupler	250 MPa
Yield strength of lock nuts	350 MPa
Allowable tensile stress, σ_t	80 MPa



Allowable thread shear stress, T	50 MPa
Allowable bearing pressure, σ_b	120 MPa
Factor of safety	2.5
Loading	Axial tension
Thread type	Metric V-thread
Thread series	ISO metric coarse thread
Thread arrangement	External thread on rods and internal thread in coupler
Locking arrangement	Two lock nuts
Design objective	Safe transmission of tensile load
Standard nominal thread diameters available	20, 22, 24, 27, 30, 33, 36 mm
Standard pitch options	As per selected ISO metric coarse thread
Lock-nut type	Hexagonal lock nut

Tasks (Problem-Solving Component)

1. Design Load and Threaded Rod Diameter

1. Take the given tensile load as the design load.
2. Determine the required tensile core area of the threaded rod.
3. Determine the required nominal thread diameter.
4. Select a suitable standard metric thread size.
5. Check the threaded rod for tensile failure at the thread root.
6. Confirm that the selected threaded rod can safely carry the applied tensile load.

2. Selection of Thread Profile and Pitch

1. Select a suitable ISO metric coarse thread.
2. Determine the standard pitch corresponding to the selected nominal diameter.
3. Determine the major, pitch and minor diameters of the thread.
4. Determine the effective thread dimensions required for strength calculations.
5. Ensure that the selected thread provides adequate tensile and shear strength.

3. Design of Coupler

1. Select a trial coupler outside diameter.
2. Determine the required coupler length.
3. Provide an internal thread compatible with the selected threaded rods.
4. Check the coupler body for tensile and bearing requirements.
5. Check the internal threads for thread shear failure.
6. Check the bearing pressure between the internal and external threads.
7. Ensure sufficient wall thickness around the internal thread.
8. Increase the coupler diameter or length if any condition is not satisfied.
9. Select the final coupler dimensions.

4. Design of Threaded Connection

1. Determine the required length of thread engagement.
2. Check the external threads of the rod for shear failure.
3. Check the internal threads of the coupler for shear failure.
4. Check the bearing pressure between mating threads.
5. Ensure that the thread engagement length is sufficient to develop the required load.
6. Select a suitable standard thread engagement length.
7. Confirm that the threaded connection is safe under the design load.

5. Design of Lock Nuts

1. Select a suitable standard lock-nut size corresponding to the threaded rod.



2. Determine the required nut thickness.
3. Check the lock nut for thread shear.
4. Check the bearing pressure between the lock nut and mating surface.
5. Check the nut dimensions for adequate strength.
6. Ensure that sufficient thread engagement is available.
7. Select suitable standard lock-nut dimensions.
8. Provide suitable locking arrangement to prevent loosening during operation.

6. Failure Mode Checks

Check the complete threaded connection for:

1. Tensile failure of the threaded rod.
2. Tensile failure at the thread root.
3. Shear failure of external threads.
4. Shear failure of internal threads.
5. Bearing failure between mating threads.
6. Failure of the coupler due to insufficient wall thickness.
7. Failure of the lock-nut threads.
8. Bearing failure between lock nut and mating surface.
9. Insufficient thread engagement.
10. Confirm that all calculated stresses are within the specified allowable limits.

7. Selection of Final Dimensions

Prepare a final dimensional table containing:

1. Threaded rod nominal diameter.
2. Thread pitch.
3. Major diameter.
4. Pitch diameter.
5. Minor/core diameter.
6. Threaded rod length.
7. Thread engagement length.
8. Coupler outside diameter.
9. Coupler length.
10. Internal thread dimensions.
11. Lock-nut thickness.
12. Lock-nut across-flat dimension.
13. Lock-nut across-corner dimension.
14. Chamfer dimensions.
15. Required clearances.
16. Thread run-out dimensions.

Select practical standard dimensions wherever possible.

Tasks (Interpretation Component)

8. Design Justification

Explain why the threaded rods, coupler and lock nuts must be designed together rather than designing only the rod for the applied tensile load.

Discuss:

1. Effect of the thread on the effective rod cross-section.
2. Importance of the thread root diameter.



3. Importance of thread engagement length.
4. Effect of thread pitch on load-carrying capacity.
5. Importance of coupler wall thickness.
6. Importance of bearing pressure between mating threads.
7. Role of lock nuts in preventing loosening.
8. Need for compatibility between external and internal threads.

9. Failure Mode Interpretation

Explain the difference between:

1. Tensile failure.
2. Thread shear failure.
3. Bearing-pressure failure.
4. Thread stripping.
5. Failure due to insufficient thread engagement.

Discuss why:

- The threaded rod is mainly checked for tensile strength.
- The external and internal threads are checked for shear.
- The mating thread surfaces are checked for bearing pressure.
- The coupler requires sufficient wall thickness.
- The lock nuts require adequate thread strength and bearing area.

10. Trade-off Analysis

If the applied tensile load is increased from 40 kN to 60 kN, interpret how the threaded connection would need to be redesigned.

Discuss the effects of:

1. Increasing the nominal thread diameter.
2. Increasing the thread engagement length.
3. Increasing the coupler outside diameter.
4. Increasing the coupler length.
5. Increasing the lock-nut thickness.
6. Changing the thread pitch.
7. Using stronger material.

Compare the alternatives in terms of strength, weight, manufacturing cost and ease of assembly.

11. Sustainability Interpretation

Comment on how appropriate selection of threaded rod, coupler and lock-nut dimensions can avoid unnecessary material consumption.

Discuss how proper design can:

1. Reduce material usage.
2. Reduce component weight.
3. Improve service life.
4. Reduce thread damage.
5. Reduce maintenance requirements.
6. Reduce replacement frequency.
7. Reduce manufacturing and machining effort.
8. Maintain adequate safety without over-design.



12. 3-D CAD Modelling

Create separate 3-D CAD models for:

1. Threaded rod 1.
2. Threaded rod 2.
3. Coupler.
4. Lock nut 1.
5. Lock nut 2.

The models should include:

1. External threads on the rods.
2. Internal threads in the coupler.
3. Standard thread profile.
4. Thread run-out.
5. Chamfers.
6. Hexagonal geometry of lock nuts.
7. Appropriate dimensions and tolerances.

13. Assembly

Assemble the components in the following sequence:

Threaded Rod 1 → Lock Nut 1 → Coupler → Threaded Rod 2 → Lock Nut 2

Check:

1. Correct thread alignment.
2. Proper thread engagement.
3. Correct position of both lock nuts.
4. Adequate clearance between components.
5. Proper coaxial alignment of both threaded rods.
6. Correct tightening arrangement.
7. Overall assembly dimensions.

14. Detailed Component Drawings

Prepare individual production drawings for:

1. Threaded Rod 1.
2. Threaded Rod 2.
3. Coupler.
4. Lock Nut 1.
5. Lock Nut 2.

Each drawing should include:

1. Orthographic views.
2. Sectional views where required.
3. Thread dimensions.
4. Thread designation.
5. Length dimensions.
6. Diameter dimensions.
7. Tolerances.
8. Chamfers.
9. Fillets.



10. Surface-finish requirements.
11. Material specification.
12. Manufacturing notes.
13. Scale.
14. Projection method.
15. Drawing number.
16. Title block.

15. Assembly Drawing

Prepare the complete 2-D assembly drawing containing:

1. Front view.
2. Top view.
3. Side view.
4. Sectional view through the threaded connection.
5. Thread engagement details.
6. Lock-nut positions.
7. Overall dimensions.
8. Part numbers.
9. Balloons for component identification.
10. Assembly notes.
11. Material information.
12. General tolerances.
13. Scale.
14. Projection method.
15. Drawing number and revision.
16. Complete title block.

16. Bill of Materials (BOM)

Prepare a Bill of Materials for the complete assembly.

Sl. No.	Part Name	Part No.	Material	Quantity	Principal Dimensions
1	Threaded Rod 1	P-01	Mild steel	1	To be designed
2	Threaded Rod 2	P-02	Mild steel	1	To be designed
3	Coupler	P-03	Mild steel	1	To be designed
4	Lock Nut 1	P-04	Medium carbon steel	1	To be designed
5	Lock Nut 2	P-05	Medium carbon steel	1	To be designed

Final Objective: Design the complete threaded rod–coupler–lock nut connection for the specified tensile load, determine the suitable thread diameter, pitch, thread engagement, coupler dimensions and lock-nut dimensions, verify tensile, thread-shear and bearing-pressure conditions, and prepare the 3-D CAD models, assembly, detailed component drawings, assembly drawing and BOM.

Solution Steps

Task 1: Design Load and Threaded Rod Diameter

1. Take the given tensile load of 40 kN as the design load.
2. Determine the required tensile core area of the threaded rod.
3. Determine the required core or minor diameter of the threaded rod.
4. Select a suitable standard nominal thread diameter.
5. Select the corresponding standard metric coarse-thread pitch.
6. Check the tensile stress at the thread root.
7. Confirm that the selected threaded rod is safe in tension.



Task 2: Selection of Thread Profile and Pitch

1. Select a suitable ISO metric coarse thread corresponding to the selected rod diameter.
2. Identify the standard major diameter.
3. Identify the standard pitch diameter.
4. Identify the standard minor or core diameter.
5. Determine the effective thread dimensions required for strength checks.
6. Check that the selected thread size provides adequate tensile strength.
7. Confirm that the selected pitch is suitable for the applied load.

Task 3: Design of Coupler

1. Select a trial outside diameter of the coupler greater than the thread major diameter.
2. Select a trial coupler length.
3. Provide an internal thread matching the threaded rods.
4. Determine the available wall thickness around the internal thread.
5. Check the coupler for adequate tensile strength.
6. Check the internal threads for shear failure.
7. Check the bearing pressure between the internal and external threads.
8. Increase the coupler diameter or length if any condition is not satisfied.
9. Select the final coupler dimensions.

Task 4: Design of Thread Engagement

1. Select a trial thread engagement length.
2. Determine the available shear area of the external threads.
3. Check the external threads for shear failure.
4. Determine the available shear area of the internal threads.
5. Check the internal threads for shear failure.
6. Check the bearing pressure between the mating thread surfaces.
7. Increase the engagement length if any condition is not satisfied.
8. Select the final thread engagement length.
9. Ensure that both threaded rods have adequate engagement with the coupler.

Task 5: Design of Lock Nuts

1. Select a standard lock nut corresponding to the selected thread diameter.
2. Determine the required lock-nut thickness.
3. Check the lock-nut threads for shear failure.
4. Check the bearing pressure between the lock nut and mating surface.
5. Check the available thread engagement inside the lock nut.
6. Ensure sufficient material around the internal thread.
7. Select the final lock-nut dimensions.
8. Provide a suitable locking arrangement to prevent loosening during operation.

Task 6: Failure Mode Checks

1. Check the threaded rod for tensile failure.
2. Check the threaded rod at the thread-root section.
3. Check the external threads for shear failure.
4. Check the internal threads of the coupler for shear failure.
5. Check the mating threads for excessive bearing pressure.
6. Check the coupler wall thickness for adequate strength.
7. Check the lock-nut threads for shear failure.
8. Check the bearing pressure under the lock nut.
9. Check the thread engagement length.
10. Confirm that all calculated stresses are within their respective allowable limits.



Task 7: Selection of Final Dimensions

1. Select the final standard threaded rod diameter.
2. Select the standard thread pitch.
3. Select the major, pitch and minor diameters.
4. Select the final thread engagement length.
5. Select the coupler outside diameter.
6. Select the coupler length.
7. Select the lock-nut thickness.
8. Select the lock-nut across-flat dimension.
9. Provide suitable chamfers and fillets.
10. Provide suitable thread run-out.
11. Prepare the final dimensional table of the complete threaded connection.

Task 8: Design Justification

1. Explain that the threaded rods, coupler and lock nuts must transmit the applied tensile load safely.
2. Explain how the thread reduces the effective cross-sectional area of the rod.
3. Explain why the thread-root diameter is important in tensile design.
4. Explain why sufficient thread engagement is required.
5. Explain the importance of adequate coupler wall thickness.
6. Explain why the internal and external threads must have compatible dimensions.
7. Explain the importance of checking bearing pressure between mating threads.
8. Explain the role of lock nuts in preventing loosening.
9. Confirm that all components must be designed together.

Task 9: Failure Mode Interpretation

1. Explain tensile failure as failure caused by excessive axial pulling stress.
2. Explain thread shear failure as stripping or shearing of the engaged threads.
3. Explain bearing-pressure failure as excessive local pressure between mating surfaces.
4. Explain thread-root failure as failure at the reduced section of the threaded rod.
5. Explain why the threaded rod requires a tensile-strength check.
6. Explain why both internal and external threads require shear checks.
7. Explain why the coupler requires a bearing-pressure and wall-thickness check.
8. Explain why the lock nut requires thread-shear and bearing checks.

Task 10: Trade-off Analysis

1. Increase the applied tensile load from 40 kN to 60 kN.
2. Recalculate the required threaded rod diameter.
3. Recalculate the required thread engagement length.
4. Recheck the external thread shear strength.
5. Recheck the internal thread shear strength.
6. Recheck the bearing pressure.
7. Recalculate the required coupler dimensions.
8. Recalculate the lock-nut dimensions if required.
9. Compare increasing thread diameter with increasing thread engagement length.
10. Compare increasing component dimensions with using stronger materials.
11. Consider the effects on strength, weight, machining cost and manufacturing requirements.
12. Select a practical design.

Task 11: Sustainability Interpretation

1. Compare the mass of the selected threaded assembly with an oversized assembly.
2. Relate thread dimensions to material consumption.
3. Explain how proper thread sizing reduces unnecessary machining.
4. Explain how appropriate coupler dimensions reduce material usage.



5. Explain how correct thread engagement improves service life.
6. Explain how adequate locking reduces loosening and maintenance.
7. Explain how longer service life reduces component replacement.
8. Avoid unnecessary material while maintaining the required safety.

Task 12: 3-D CAD Modelling

1. Create the 3-D model of threaded rod 1.
2. Create the 3-D model of threaded rod 2.
3. Create the 3-D model of the coupler.
4. Create the 3-D model of lock nut 1.
5. Create the 3-D model of lock nut 2.
6. Apply the selected external thread to both rods.
7. Apply the corresponding internal thread to the coupler.
8. Create the internal threads of the lock nuts.
9. Add chamfers, fillets and thread run-outs.
10. Check all component dimensions against the final design table.

Task 13: Assembly

1. Position threaded rod 1 along the common axis.
2. Position threaded rod 2 along the same axis.
3. Insert the threaded rods into the coupler.
4. Apply the required thread engagement.
5. Position lock nut 1 against the coupler.
6. Position lock nut 2 against the coupler.
7. Apply suitable assembly constraints.
8. Check the coaxial alignment of both rods.
9. Check the thread engagement and clearances.
10. Verify the complete assembly.

Task 14: Detailed Component Drawings

1. Generate the production drawing of threaded rod 1.
2. Generate the production drawing of threaded rod 2.
3. Generate the production drawing of the coupler.
4. Generate the production drawing of the lock nuts.
5. Add front, top and side views as required.
6. Add sectional views for internal threads.
7. Specify thread designation and pitch.
8. Add major, pitch and minor diameter information.
9. Add length dimensions.
10. Add tolerances.
11. Add chamfers and fillets.
12. Add thread run-out details.
13. Specify material.
14. Add surface-finish requirements.
15. Complete each drawing with scale, projection method, drawing number and title block.

Task 15: Assembly Drawing

1. Generate the front view of the complete threaded assembly.
2. Generate the top and side views.
3. Generate a sectional view through the coupler and threaded rods.
4. Show the thread engagement clearly.
5. Show the positions of both lock nuts.
6. Add overall assembly dimensions.
7. Add part numbers.



8. Add balloons for component identification.
9. Add assembly and tightening notes.
10. Complete the drawing with scale, projection method, drawing number and title block.

Task 16: Bill of Materials

1. Assign a part number to threaded rod 1.
2. Assign a part number to threaded rod 2.
3. Assign a part number to the coupler.
4. Assign a part number to lock nut 1.
5. Assign a part number to lock nut 2.
6. Specify the material of each component.
7. Specify the quantity of each component.
8. Specify the principal dimensions and thread designation.
9. Prepare the final BOM.
10. Verify that the BOM agrees with the 3-D assembly and assembly drawing.

A4-II Design of the bolts for direct shear, moment and pre-tension, and selection of standard bolt size

Problem Statement

A steel mounting bracket is bolted to a rigid support plate in an industrial material-handling system. The bolted connection is subjected to a combination of direct shear load, bending moment and bolt pre-tension during operation. The bolts must safely transfer the applied loads while maintaining adequate clamping force between the connected members. The number of bolts, bolt diameter, bolt grade, bolt spacing and pre-tension are initially unknown. The connection must be designed considering direct shear in the bolts, additional load caused by the applied moment, and the effect of bolt pre-tension. The selected bolts must also have adequate strength against tensile and shear loading.

As a design engineer applying the principles of Design of Machine Elements, you are required to design the complete bolted connection, determine the required bolt size and number of bolts, calculate the required pre-tension, and check the bolts and connected members for the critical loading conditions. A suitable standard bolt size and grade should then be selected. Finally, prepare the 3-D CAD model, complete assembly, detailed drawing and Bill of Materials (BOM) of the bolted joint.

Given Data

Parameter	Value
Application	Industrial material-handling mounting bracket
Type of connection	Bolted bracket connection
Joint arrangement	Steel bracket bolted to rigid support plate
Direct shear load, P	30 kN
Applied bending moment, M	1.5 kN·m
Number of bolts	4
Bolt arrangement	Rectangular pattern
Bolt material	High-strength alloy steel
Connected-member material	Mild steel
Bolt grade	To be selected
Yield strength of connected plate	250 MPa
Allowable bolt shear stress	120 MPa
Allowable bolt tensile stress	200 MPa
Allowable bearing stress	180 MPa
Factor of safety	2.5
Loading	Direct shear + bending moment + pre-tension
Joint type	Preloaded bolted joint
Bolt head type	Hexagonal-head bolt
Thread type	ISO metric coarse thread
Standard bolt diameters available	M12, M14, M16, M18, M20, M22, M24



Standard bolt grades available	8.8, 10.9
Minimum edge distance	$1.5 \times \text{bolt diameter}$
Minimum bolt spacing	$3 \times \text{bolt diameter}$
Design objective	Safe and rigid load transmission

Tasks (Problem-Solving Component)

1. Design Load and Bolt Arrangement

1. Take the given direct shear load as the design load.
2. Identify the bending moment acting on the bolt group.
3. Identify the number and arrangement of bolts.
4. Determine the centre of the bolt group.
5. Determine the distance of each bolt from the centre of the bolt group.
6. Determine the load distribution among the bolts due to direct shear.
7. Determine the additional load on each bolt due to the applied moment.

2. Design of Bolt Size for Direct Shear

1. Select a trial standard bolt diameter.
2. Determine the shear area of the selected bolt.
3. Determine the direct shear stress in each bolt.
4. Compare the calculated shear stress with the allowable bolt shear stress.
5. Increase the bolt diameter if required.
6. Select a suitable standard bolt size.

3. Design of Bolts for Applied Moment

1. Determine the moment acting about the centre of the bolt group.
2. Determine the distance of each bolt from the group centre.
3. Determine the additional load caused by the moment.
4. Identify the bolt subjected to the maximum load.
5. Determine the combined bolt load due to direct shear and moment.
6. Check the maximum bolt load against the allowable bolt capacity.
7. Increase the bolt size or modify the bolt arrangement if required.

4. Design of Bolt Pre-Tension

1. Determine the required clamping force for the joint.
2. Select a suitable bolt pre-tension based on the selected bolt grade.
3. Determine the tensile stress produced by the pre-tension.
4. Check the bolt for combined tensile and shear loading.
5. Ensure that the pre-tension is sufficient to prevent joint separation or slip.
6. Confirm that the bolt is not overloaded due to excessive pre-tension.

5. Check of Connected Members

1. Check the bearing pressure between the bolt and connected plate.
2. Check the connected plate for net-section tensile failure.
3. Check the plate for edge tearing.
4. Check the plate around the bolt holes for bearing failure.
5. Check the bolt-hole spacing and edge distance.
6. Increase the plate thickness or bolt spacing if required.

6. Combined Failure Mode Checks

Check the complete bolted connection for:



1. Direct shear failure of bolts.
2. Additional bolt loading due to bending moment.
3. Combined shear loading of bolts.
4. Tensile loading due to pre-tension.
5. Combined tensile and shear stress in the critical bolt.
6. Bearing failure between bolt and plate.
7. Net-section failure of the connected plate.
8. Edge tearing of the plate.
9. Joint separation due to insufficient pre-tension.
10. Excessive bolt stress due to over-tightening.

Confirm that all calculated stresses are within their specified allowable limits.

7. Selection of Standard Bolt Size

1. Select the final bolt diameter from the available standard sizes.
2. Select the appropriate bolt grade.
3. Select the corresponding standard thread pitch.
4. Determine the required bolt length.
5. Select suitable standard nuts and washers.
6. Confirm the required pre-tension.
7. Check the final bolt against all loading conditions.
8. Select the final standard bolt specification.

Tasks (Interpretation Component)

8. Design Justification

Explain why the bolts must be designed considering direct shear, moment and pre-tension together.

Discuss:

1. Effect of direct shear on the bolt group.
2. Effect of moment on individual bolt loading.
3. Importance of bolt-group geometry.
4. Role of bolt pre-tension.
5. Importance of adequate clamping force.
6. Effect of bolt diameter on load-carrying capacity.
7. Importance of bolt grade.
8. Importance of proper bolt spacing and edge distance.

9. Failure Mode Interpretation

Explain the difference between:

1. Bolt shear failure.
2. Bolt tensile failure.
3. Combined tensile and shear failure.
4. Bearing failure.
5. Net-section failure of the plate.
6. Edge tearing.
7. Joint separation.
8. Bolt loosening due to inadequate pre-tension.

Explain why the most highly loaded bolt requires particular attention in the design.

10. Trade-off Analysis



If the direct shear load is increased from 30 kN to 45 kN, interpret how the bolted joint would need to be redesigned.

Discuss the effects of:

1. Increasing bolt diameter.
2. Increasing the number of bolts.
3. Increasing bolt grade.
4. Increasing bolt pre-tension.
5. Increasing bolt spacing.
6. Increasing plate thickness.
7. Changing the bolt arrangement.

Compare the alternatives in terms of strength, weight, cost, assembly requirements and maintenance.

11. Sustainability Interpretation

Comment on how proper selection of bolt size, grade and pre-tension can avoid unnecessary material use.

Discuss how proper bolt design can:

1. Reduce unnecessary bolt size.
2. Reduce material consumption.
3. Reduce component weight.
4. Improve joint service life.
5. Reduce loosening and maintenance.
6. Reduce replacement requirements.
7. Reduce manufacturing and assembly effort.
8. Maintain adequate safety without over-design.

12. 3-D CAD Modelling

Create separate 3-D CAD models for:

1. Mounting bracket.
2. Support plate.
3. Bolts.
4. Nuts.
5. Washers.

The models should include:

1. Standard bolt head.
2. External thread.
3. Nut geometry.
4. Washer geometry.
5. Bolt-hole locations.
6. Appropriate chamfers and fillets.

13. Assembly

Assemble the components in the following sequence:

Support Plate → Mounting Bracket → Washers → Bolts → Nuts

Check:



1. Correct bolt-hole alignment.
2. Correct bolt spacing.
3. Correct edge distance.
4. Proper washer and nut placement.
5. Proper bolt engagement.
6. Coaxial alignment of bolts and holes.
7. Correct overall assembly dimensions.

14. Detailed Component Drawings

Prepare production drawings for:

1. Mounting bracket.
2. Support plate.
3. Bolt.
4. Nut.
5. Washer.

Each drawing should contain:

1. Orthographic views.
2. Sectional views where required.
3. Principal dimensions.
4. Hole dimensions.
5. Thread dimensions.
6. Bolt grade.
7. Material specification.
8. Tolerances.
9. Chamfers.
10. Fillets.
11. Surface-finish requirements.
12. Manufacturing notes.
13. Scale.
14. Projection method.
15. Drawing number.
16. Title block.

15. Assembly Drawing

Prepare a 2-D assembly drawing containing:

1. Front view.
2. Top view.
3. Side view.
4. Sectional view through the bolt group.
5. Bolt arrangement.
6. Bolt spacing.
7. Edge distances.
8. Bolt size and grade.
9. Nut and washer details.
10. Overall assembly dimensions.
11. Part numbers.
12. Balloons for component identification.
13. Assembly and tightening notes.
14. Pre-tension requirement.
15. General tolerances.
16. Scale.
17. Projection method.



18. Drawing number and revision.
19. Complete title block.

16. Bill of Materials (BOM)

Prepare a Bill of Materials for the complete assembly.

Sl. No.	Part Name	Part No.	Material/Grade	Quantity	Principal Dimensions
1	Mounting Bracket	P-01	Mild steel	1	To be designed
2	Support Plate	P-02	Mild steel	1	To be designed
3	Hexagonal Bolt	P-03	Alloy steel	4	To be selected
4	Hexagonal Nut	P-04	Alloy steel	4	To be selected
5	Washer	P-05	Steel	4	To be selected

Final Objective: Design the complete preloaded bolted connection for the specified direct shear load and bending moment, determine the suitable standard bolt diameter, grade, length, spacing and pre-tension, verify all critical failure modes, and prepare the 3-D CAD models, assembly, detailed drawings and BOM.

Solution Steps

Task 1: Design Load and Bolt Arrangement

1. Take the given direct shear load of 30 kN as the design load.
2. Identify the bending moment of 1.5 kN·m acting on the bolt group.
3. Consider the given four-bolt rectangular arrangement.
4. Locate the centre of the bolt group.
5. Determine the distance of each bolt from the centre of the bolt group.
6. Determine the direct shear load shared by each bolt.
7. Determine the additional load produced in each bolt due to the applied moment.
8. Identify the bolt subjected to the maximum combined load.

Task 2: Design of Bolt Size for Direct Shear

1. Select a trial standard bolt diameter from the given sizes.
2. Determine the effective shear area of the bolt.
3. Determine the direct shear stress in each bolt.
4. Compare the calculated shear stress with the allowable shear stress.
5. Increase the bolt diameter if the allowable limit is exceeded.
6. Select the next suitable standard bolt diameter.
7. Confirm that the selected bolt is safe under direct shear.

Task 3: Design of Bolts for Applied Moment

1. Determine the moment acting about the centre of the bolt group.
2. Determine the distance of each bolt from the group centre.
3. Determine the relative load carried by each bolt due to the moment.
4. Identify the most highly loaded bolt.
5. Determine the combined load on the critical bolt due to direct shear and moment.
6. Check the critical bolt for shear.
7. Increase the bolt size or modify the arrangement if required.
8. Confirm that the selected bolt group can safely resist the applied moment.

Task 4: Design of Bolt Pre-Tension

1. Determine the required clamping force for the joint.
2. Select a suitable pre-tension based on the selected bolt grade.
3. Determine the tensile stress produced by the pre-tension.



4. Check the bolt for tensile loading due to pre-tension.
5. Combine the tensile and shear effects on the critical bolt.
6. Check the combined bolt stress against the allowable limit.
7. Ensure that the pre-tension is sufficient to maintain proper clamping.
8. Confirm that excessive pre-tension does not overload the bolt.

Task 5: Check of Connected Members

1. Check the bearing pressure between the bolt and the mounting bracket.
2. Check the bearing pressure between the bolt and support plate.
3. Check the net-section tensile strength of the connected plate.
4. Check the plate for edge tearing.
5. Check the material around the bolt holes.
6. Check the bolt-hole spacing.
7. Check the edge distance.
8. Increase the plate thickness or modify the bolt arrangement if any condition is not satisfied.

Task 6: Combined Failure Mode Checks

1. Check the bolts for direct shear failure.
2. Check the bolts for additional loading due to the bending moment.
3. Check the critical bolt for combined shear loading.
4. Check the bolts for tensile stress due to pre-tension.
5. Check the critical bolt for combined tensile and shear stress.
6. Check the connected plates for bearing failure.
7. Check the plates for net-section tensile failure.
8. Check the plates for edge tearing.
9. Check the joint for possible separation.
10. Check the bolt pre-tension for excessive loading.
11. Confirm that all calculated stresses are within their allowable limits.

Task 7: Selection of Final Standard Bolt Size

1. Select the final bolt diameter from the available standard sizes.
2. Select the suitable bolt grade.
3. Select the corresponding standard metric thread.
4. Select the suitable bolt length.
5. Select compatible standard nuts.
6. Select suitable washers.
7. Determine the final bolt pre-tension.
8. Check the final bolt specification under all loading conditions.
9. Confirm that the selected standard bolt is safe.

Task 8: Selection of Final Dimensions

1. Select the final bolt diameter.
2. Select the bolt pitch and spacing.
3. Select the minimum edge distance.
4. Select the mounting plate thickness.
5. Select the bracket thickness.
6. Select the bolt length.
7. Select the washer dimensions.
8. Select the nut dimensions.
9. Provide suitable clearances, chamfers and fillets.
10. Prepare the final dimensional table of the complete bolted joint.

Task 9: Design Justification



1. Explain that the bolt group must transmit the complete applied loading safely.
2. Explain the effect of direct shear on the bolts.
3. Explain the effect of bending moment on individual bolts.
4. Explain why the bolt farthest from the group centre may experience higher moment-related loading.
5. Explain the role of bolt pre-tension.
6. Explain why adequate clamping force is required.
7. Explain the importance of bolt grade.
8. Explain the importance of bolt spacing and edge distance.
9. Confirm that bolt size, number, arrangement and pre-tension must be considered together.

Task 10: Failure Mode Interpretation

1. Explain bolt shear failure as failure caused by excessive transverse loading.
2. Explain bolt tensile failure as failure caused by excessive axial loading.
3. Explain combined tensile and shear failure.
4. Explain bearing failure as local deformation around the bolt hole.
5. Explain net-section failure of the connected plate.
6. Explain edge tearing of the plate.
7. Explain joint separation caused by inadequate clamping.
8. Explain loosening caused by insufficient pre-tension.
9. Identify the most highly loaded bolt as the critical bolt for design verification.

Task 11: Trade-off Analysis

1. Increase the direct shear load from 30 kN to 45 kN.
2. Recalculate the load carried by each bolt.
3. Recalculate the additional load due to the moment.
4. Recheck the critical bolt for combined loading.
5. Recalculate the required bolt diameter.
6. Recheck the required pre-tension.
7. Check the connected plates again.
8. Compare increasing bolt diameter with increasing the number of bolts.
9. Compare increasing bolt grade with increasing bolt size.
10. Consider the effects on strength, weight, cost and assembly.
11. Select a practical design.

Task 12: Sustainability Interpretation

1. Compare the mass of the selected bolted joint with an oversized joint.
2. Relate bolt size and number to material consumption.
3. Explain how proper bolt selection reduces unnecessary material.
4. Explain how appropriate pre-tension reduces loosening and maintenance.
5. Explain how proper joint design improves service life.
6. Explain how longer service life reduces replacement requirements.
7. Relate reduced component weight to easier transportation and handling.
8. Avoid excessive bolt size or number while maintaining the required safety.

Task 13: 3-D CAD Modelling

1. Create the 3-D model of the mounting bracket.
2. Create the 3-D model of the support plate.
3. Create the 3-D model of the standard bolt.
4. Create the 3-D model of the nut.
5. Create the 3-D model of the washer.
6. Create the required bolt holes in the bracket and support plate.
7. Position the holes according to the selected bolt layout.
8. Add bolt threads or simplified thread representation as required.
9. Add chamfers and fillets.



10. Check all component dimensions against the final design.

Task 14: Assembly

1. Position the support plate.
2. Position the mounting bracket on the support plate.
3. Align all bolt holes.
4. Position the washers.
5. Insert the bolts through the aligned holes.
6. Position the nuts on the bolts.
7. Apply suitable assembly constraints.
8. Check bolt spacing and edge distances.
9. Check proper bolt engagement.
10. Verify the complete assembly.

Task 15: Detailed Component Drawings

1. Generate the production drawing of the mounting bracket.
2. Generate the production drawing of the support plate.
3. Generate the standard bolt drawing or specify the standard bolt designation.
4. Generate the nut and washer drawings or specify their standard designations.
5. Add front, top and side views as required.
6. Add sectional views where necessary.
7. Add bolt-hole dimensions.
8. Add bolt spacing and edge distances.
9. Add thread designation.
10. Add material and bolt-grade specifications.
11. Add tolerances.
12. Add chamfers and fillets.
13. Add surface-finish requirements.
14. Complete the drawings with scale, projection method, drawing number and title block.

Task 16: Assembly Drawing

1. Generate the front view of the complete bolted assembly.
2. Generate the top view.
3. Generate the side view.
4. Generate a sectional view through the bolt group.
5. Show the bolt arrangement clearly.
6. Show bolt spacing and edge distances.
7. Indicate bolt size and grade.
8. Show nuts and washers.
9. Add overall assembly dimensions.
10. Add part numbers and balloons.
11. Add assembly and tightening notes.
12. Specify the required bolt pre-tension.
13. Complete the drawing with scale, projection method, drawing number and title block.

Task 17: Bill of Materials

1. Assign a part number to the mounting bracket.
2. Assign a part number to the support plate.
3. Assign a part number to the bolts.
4. Assign a part number to the nuts.
5. Assign a part number to the washers.
6. Specify the material or grade of each component.
7. Specify the quantity of each component.
8. Specify the principal dimensions and standard designations.



9. Prepare the final BOM.
10. Verify that the BOM agrees with the 3-D assembly and assembly drawing.

INSTRUCTION ITEM-5 (II-5)		
Assign ment No.	Name of the experiment	CO Congru ence
A5-I	Design of a solid and a hollow shaft for strength and torsional rigidity, with a weight comparison; 3-D modelling and detailed drawings.	[CO5]
A5-II	Design of the hub, key, flange and bolts from torque and service factor; 3-D modelling, assembly and sectional assembly drawing with bill of materials.	
A5-III	Design of the hub, key, flange, pins and bushes for bearing pressure and shear; 3-D modelling, assembly and sectional assembly drawing with bill of materials.	

A5-I Design of a solid and a hollow shaft for strength and torsional rigidity, with a weight comparison

Problem Statement

A village cooperative runs a rice and pulse milling unit in a rural area. An electric motor drives a line shaft, and the drive passes through a rigid flange coupling to the milling machine. The shaft transmits a steady power at a constant speed and is subjected mainly to torsion. The existing shaft was sized by the local workshop on the basis of strength alone, but the milling machine shows noticeable vibration and uneven running. This suggests that the torsional rigidity of the shaft, that is, its angle of twist per unit length, may not be adequate. The diameter of the solid shaft, and the dimensions of an alternative hollow shaft for the same drive, are initially unknown.

As a design engineer applying the principles of Design of Machine Elements, you are required to develop the design of a solid shaft and a hollow shaft for the same duty on the basis of both strength and torsional rigidity, select standard dimensions, compare the masses of the two shafts, and verify the final designs. Finally, prepare the 3-D CAD models and the detailed production drawings of both shafts, including the keyway, tolerances and surface finish.

Given Data

Parameter	Value
Application	Line shaft of a rice and pulse milling unit
Power transmitted, P	20 kW
Shaft speed, N	300 rpm
Type of loading	Steady torsion (bending neglected)
Shaft material	Medium carbon steel, C45
Allowable shear stress, τ	40 MPa
Modulus of rigidity, G	80 GPa
Density of steel, ρ	7850 kg/m ³
Permissible angle of twist	0.5 degree per metre length
Length of shaft, L	1.2 m
Solid shaft	Solid circular section
Hollow shaft	Hollow circular section, $d_i/d_o = 0.6$
Available standard shaft diameters	40, 45, 50, 55, 60, 65, 70 mm
Shaft end feature	Keyway for the hub of a flange coupling
Fit of shaft at coupling seat	k6 (hub bore H7)
Surface finish at coupling seat	Ra 1.6 μ m
Design objective	Minimum mass satisfying strength and torsional rigidity
Alternative case for Task 8	Power increased from 20 kW to 30 kW at the same speed

Tasks (Problem-Solving Component)



1. Design Torque and Design Criteria

1. Calculate the torque transmitted by the shaft from the given power and speed.
2. Identify the allowable shear stress and the permissible angle of twist given for the shaft.
3. Convert the permissible angle of twist from degrees per metre to radians per metre.
4. Identify the two design criteria: torsional strength and torsional rigidity.
5. Identify the shaft length over which the total angle of twist is to be checked.

2. Design of the Solid Shaft

1. Determine the diameter of the solid shaft from the torsional strength.
2. Determine the diameter of the solid shaft from the torsional rigidity.
3. Compare the two diameters and identify the governing criterion.
4. Select the next higher standard diameter from the available sizes.
5. Recalculate the shear stress and the angle of twist for the selected diameter.
6. Confirm that both the strength and the rigidity criteria are satisfied.

3. Design of the Hollow Shaft

1. Take the diameter ratio $d_i/d_o = 0.6$ and express the polar section properties in terms of the outside diameter.
2. Determine the outside diameter from the torsional strength.
3. Determine the outside diameter from the torsional rigidity.
4. Identify the governing criterion and calculate the corresponding inside diameter.
5. Select a standard outside diameter and a practical inside (bore) diameter.
6. Recalculate the shear stress and the angle of twist for the selected hollow shaft.

4. Weight Comparison

1. Calculate the cross-sectional area of the selected solid and hollow shafts.
2. Calculate the mass per metre length and the total mass of each shaft.
3. Determine the percentage mass saving of the hollow shaft over the solid shaft.
4. Compare the torsional stiffness of the two shafts.
5. Compare the torsional stiffness per unit mass of the two shafts.
6. Identify which shaft makes more efficient use of the material.

5. Keyway and Shaft End Details

1. Select the standard parallel key for the selected shaft diameter.
2. Determine the width, depth and length of the keyway.
3. Specify the chamfers at the shaft ends and the fillet radius at the shoulders.
4. Specify the fit and the surface finish at the coupling seat.
5. Prepare the final dimensional table for the solid and the hollow shafts.

Tasks (Interpretation Component)

6. Design Justification

Explain why the torsional rigidity, rather than the torsional strength, governs the design of this shaft.

Discuss:

1. Difference between the stress-based criterion and the twist-based criterion.
2. Effect of excessive twist on vibration, alignment and the running of the milling machine.
3. Effect of shaft length and modulus of rigidity on the angle of twist.
4. Reason why the actual shear stress in the selected shaft is much lower than the allowable stress.

7. Design Development: Solid versus Hollow Shaft



Develop a recommendation on whether the cooperative should install the solid shaft or the hollow shaft.

Justify the choice by considering:

1. Mass and material consumption.
2. Torsional stiffness per unit mass.
3. Machining effort for boring and the availability of standard tube stock.
4. Balancing, straightness and ease of fitting the keyway and coupling.
5. Cost and maintenance in a rural workshop.

8. Trade-off Analysis

If the power is increased from 20 kW to 30 kW at the same speed, interpret how the torque and the required diameters would change.

Discuss the effects of:

1. Increasing the diameter of the solid shaft.
2. Increasing the outside diameter of the hollow shaft.
3. Selecting a higher-strength steel.
4. Reducing the shaft length.
5. Increasing the shaft speed so that the torque is reduced for the same power.

Explain why a higher-strength steel does not improve the torsional rigidity. Compare the alternatives in terms of strength, rigidity, mass and cost.

9. Sustainability Interpretation

Comment on how correct sizing of the shaft avoids unnecessary material use.

Discuss how the design can:

1. Reduce material consumption and transport effort by using a hollow shaft.
2. Reduce the starting energy and the load on bearings through a lighter rotating mass.
3. Avoid oversized and undersized shafts that waste material or fail early.
4. Account for the extra machining energy needed to bore a hollow shaft.
5. Improve the reliability and the service life of the milling unit.

10. 3-D CAD Modelling

Create separate 3-D CAD models for:

1. The solid shaft.
2. The hollow shaft.

The models should include:

1. The shaft profile created by the Revolve feature.
2. The bore of the hollow shaft.
3. The keyway at the coupling seat.
4. Chamfers at the ends and fillets at the shoulders.
5. Mass properties obtained from the CAD model for comparison with the calculated masses.

11. Detailed Component Drawings

Prepare production drawings for the solid shaft and the hollow shaft.



Each drawing should contain:

1. Front view and a sectional view showing the bore (hollow shaft) and the keyway.
2. End view or a removed section of the keyway.
3. All diameters, lengths, keyway dimensions, chamfers and fillets.
4. Dimensional tolerance (k6) and surface-finish requirements at the coupling seat.
5. Material specification and the title block with scale, projection method and drawing number.

Final Objective: Develop the design of a solid shaft and a hollow shaft for the specified torque on the basis of strength and torsional rigidity, determine the standard shaft dimensions, compare their masses, and create the 3-D models and detailed drawings of both shafts.

Solution Steps

Task 1: Design Torque and Design Criteria

1. Convert the power to watts: $P = 20 \text{ kW} = 20\,000 \text{ W}$.
2. Calculate the torque: $T = 60 P / (2\pi N)$.
3. Note the allowable shear stress $\tau = 40 \text{ MPa}$ and $G = 80 \text{ GPa}$.
4. Convert the permissible twist: $\theta = 0.5^\circ/\text{m} = 0.5 \times \pi/180 \text{ rad/m}$.
5. Note that the shaft is to be designed for both strength and rigidity and the larger diameter is to be adopted.

Task 2: Design of the Solid Shaft

1. Write the torsion equation for strength: $T = (\pi/16) \tau d^3$ and solve for d .
2. Write the torsion equation for rigidity: $\theta = T L / (G J)$, with $J = \pi d^4/32$, for unit length, and solve for d .
3. Compare the two diameters; the larger value governs.
4. Select the next higher standard diameter from 40, 45, 50, 55, 60, 65 and 70 mm.
5. Recalculate $\tau = 16 T / (\pi d^3)$ and $\theta = T L / (G J)$ for the selected diameter.
6. Confirm that τ is below 40 MPa and that θ per metre is below 0.5° .

Task 3: Design of the Hollow Shaft

1. Take $k = d_i/d_o = 0.6$ and write $J = \pi d_o^4 (1 - k^4) / 32$.
2. Write the strength equation: $T = (\pi/16) \tau d_o^3 (1 - k^4)$ and solve for d_o .
3. Write the rigidity equation: $\theta = T / (G J)$ per unit length and solve for d_o .
4. Adopt the larger value of d_o and calculate $d_i = 0.6 d_o$.
5. Select the next higher standard outside diameter and round the bore to a practical value.
6. Recalculate the shear stress and the twist per metre for the selected hollow shaft.

Task 4: Weight Comparison

1. Calculate the areas: $A = \pi d^2/4$ (solid) and $A = \pi (d_o^2 - d_i^2)/4$ (hollow).
2. Calculate the mass per metre: $m = \rho A$ (per metre length).
3. Calculate the total mass for the shaft length of 1.2 m.
4. Calculate the percentage saving: $(m_{\text{solid}} - m_{\text{hollow}}) / m_{\text{solid}} \times 100$.
5. Calculate the torsional stiffness GJ / L of each shaft.
6. Divide the stiffness by the mass and compare the two values.

Task 5: Keyway and Shaft End Details

1. Read the standard key section ($b \times h$) for the selected diameter from the key table.
2. Take the keyway width b and the depth in the shaft from the standard.
3. Take the keyway length equal to the hub length or as specified by the coupling.
4. Add chamfers of suitable size (for example $2 \times 45^\circ$) and fillet radii at shoulders.
5. Specify the coupling seat with tolerance k6 and finish $R_a 1.6 \mu\text{m}$.
6. Tabulate all final dimensions.



Task 6: Design Justification

1. Compare the diameter required for strength with that required for rigidity.
2. Show that the diameter for rigidity is larger, so rigidity governs.
3. Explain that θ is proportional to $T L / (G d^4)$, so it falls rapidly with diameter.
4. Explain how twist causes vibration, misalignment and uneven running of the machine.
5. Conclude that the actual shear stress is well below the allowable value because the shaft is sized for rigidity.

Task 7: Design Development: Solid versus Hollow Shaft

1. Tabulate the mass, stiffness and stiffness-to-mass ratio of both shafts.
2. Consider the extra boring cost and the availability of tube stock.
3. Consider the keyway, balancing and fitting of the coupling.
4. Consider the workshop facilities available to the cooperative.
5. Choose one option and write a short justification.

Task 8: Trade-off Analysis

1. Recalculate the torque for 30 kW at 300 rpm.
2. Note that, for strength, d is proportional to $T^{1/3}$; for rigidity, d is proportional to $T^{1/4}$.
3. Calculate the new diameters for the solid and the hollow shafts.
4. Compare the options: larger diameter, higher-strength steel, shorter length, higher speed.
5. Note that all steels have nearly the same G , so a stronger steel does not reduce the twist.
6. Select the most practical option.

Task 9: Sustainability Interpretation

1. Compare the mass of the selected shaft with that of an oversized shaft.
2. Relate the mass saving of the hollow shaft to material and transport effort.
3. Consider the extra energy used in boring against the material saving.
4. Explain how a lighter shaft reduces the starting load.
5. Relate the correct size to reliability, service life and reduced maintenance.

Task 10: 3-D CAD Modelling

1. Sketch the half profile of the stepped shaft with the selected diameters and lengths.
2. Use the Revolve feature to generate the solid shaft.
3. Generate the hollow shaft by revolving the tube profile or by cutting the bore.
4. Add the keyway using a cut extrusion, and add chamfers and fillets.
5. Read the mass from the mass-properties tool and compare it with the calculated value.

Task 11: Detailed Component Drawings

1. Create the front view and a sectional view of each shaft.
2. Add the keyway section and the end view.
3. Add diameters, lengths, keyway dimensions, chamfers and fillets.
4. Add the tolerance k6 and the surface finish.
5. Add the material specification.
6. Complete the title block with scale, projection method and drawing number.

A5-II Design of the hub, key, flange and bolts from torque and service factor

Problem Statement

The 60 mm shaft designed for the rice and pulse milling unit must be joined to the input shaft of the milling machine through a protected-type rigid flange coupling. A rigid flange coupling connects two coaxial shafts; the torque is transmitted from the shaft to the hub through a key, from the hub to the flange, and across the flange face through bolts loaded in shear. Since



milling involves shock at starting and a variable grain load, the coupling must be designed for a design torque obtained by multiplying the rated torque by a service factor. The dimensions of the hub, key, flange and bolts are initially unknown.

As a design engineer applying the principles of Design of Machine Elements, you are required to develop the design of the complete rigid flange coupling, determine the dimensions of the hub, key, flange and bolts, check them for shear and crushing, select standard key and bolt sizes, and specify suitable fits and tolerances. Finally, prepare the 3-D CAD models of all parts, the assembly, the sectional assembly drawing with fits and tolerances, and the Bill of Materials (BOM).

Given Data

Parameter	Value
Application	Coupling for the drive of a rice and pulse milling unit
Type of coupling	Protected-type rigid flange coupling
Power transmitted, P	20 kW
Speed, N	300 rpm
Shaft diameter, d	60 mm (from A5-I)
Allowable shear stress of shaft	40 MPa
Service factor, K _s	1.5
Material of hubs and flanges	Cast iron FG 200
Allowable shear stress of cast iron	15 MPa
Material of key and bolts	Steel 45C8
Allowable shear stress of key	50 MPa
Allowable crushing stress of key	100 MPa
Allowable shear stress of bolts	30 MPa
Number of bolts	4
Trial proportions	Hub outside diameter D = 2d; hub length L = 1.5d; bolt pitch circle diameter D ₁ = 3d; flange outside diameter D ₂ = 4d; flange thickness t _f = 0.5d; protecting rim thickness t ₂ = 0.25d
Standard key section for 60 mm shaft	18 mm × 11 mm
Available standard key lengths	36, 40, 45, 50, 56, 63, 70, 80, 90 mm
Available standard bolt sizes	M10, M12, M14, M16, M20
Fits for the assembly drawing	Shaft–hub H7/k6; spigot–recess H7/h6; bolt–reamed hole H7/g6
Alternative case for Task 8	Service factor increased from 1.5 to 2.0

Tasks (Problem-Solving Component)

1. Design Torque and Shaft Check

1. Calculate the rated torque from the power and the speed.
2. Calculate the design torque using the service factor.
3. Calculate the shear stress in the 60 mm shaft at the design torque.
4. Confirm that the shaft diameter is adequate for the design torque.

2. Design of the Hub

1. Calculate the hub outside diameter and the hub length from the trial proportions.
2. Treat the hub as a hollow shaft transmitting the design torque.
3. Calculate the shear stress in the hub.
4. Compare the shear stress with the allowable stress of cast iron.
5. Confirm that the hub length is sufficient to accommodate the key.

3. Design of the Key

1. Select the standard key section for the 60 mm shaft.
2. Calculate the force acting on the key from the design torque.
3. Determine the key length required to resist shear.



4. Determine the key length required to resist crushing.
5. Select the standard key length and check it against the hub length.

4. Design of the Flange

1. Calculate the flange outside diameter, thickness and protecting rim thickness from the trial proportions.
2. Treat the flange as sheared across the cylindrical surface at the junction with the hub.
3. Calculate the shear stress in the flange.
4. Compare it with the allowable shear stress of cast iron.
5. Increase the flange thickness if required.

5. Design of the Bolts

1. Calculate the load on each bolt from the design torque, the number of bolts and the pitch circle diameter.
2. Determine the bolt diameter from the allowable shear stress.
3. Select the next higher standard bolt size.
4. Check the crushing stress between the bolt and the flange.
5. Check the bolt spacing along the pitch circle and the edge distance.

6. Fits, Tolerances and Final Dimensions

1. Interpret the fit designations H7/k6, H7/h6 and H7/g6.
2. Find the limits of size for the hub bore and the shaft.
3. Specify the keyway tolerances and the surface finish at the mating faces.
4. Prepare the final dimensional table of the coupling.

Tasks (Interpretation Component)

7. Design Justification

Explain why the coupling must be designed for the design torque rather than for the rated torque.

Discuss:

1. Meaning and selection of the service factor.
2. Effect of starting shock and variable load on the coupling.
3. Path of the torque from the shaft through the key, hub, flange and bolts.
4. Function of the spigot and recess in aligning the two halves.
5. Function of the protecting rim over the bolt heads and nuts.
6. Reason why a rigid coupling requires accurate alignment of the shafts.

8. Failure Mode Interpretation and Trade-off Analysis

Explain the difference between:

1. Shear failure of the key.
2. Crushing failure of the key.
3. Shear failure of the hub.
4. Shear failure of the flange at the hub junction.
5. Shear failure of the bolts.
6. Crushing failure between the bolts and the flange.

If the service factor is increased from 1.5 to 2.0, interpret how the design torque and the dimensions of the coupling would need to change. Discuss the effects of increasing the bolt diameter, increasing the number of bolts, increasing the pitch circle diameter and increasing the flange thickness. Identify the most practical way to provide the additional capacity.

9. Sustainability Interpretation



Comment on how correct sizing of the coupling avoids unnecessary material use.

Discuss how the design can:

1. Reduce the consumption of cast iron and steel by using proportions matched to the torque.
2. Use standard keys, bolts and nuts that are easily available and replaceable.
3. Protect the workers in the unit from rotating bolts through the protecting rim.
4. Reduce wear of bearings and shafts through accurate alignment.
5. Extend the service life of the drive and reduce maintenance and waste.

10. 3-D CAD Modelling

Create separate 3-D CAD models for:

1. Flange half 1 (with spigot).
2. Flange half 2 (with recess).
3. Keys.
4. Bolts, nuts and washers.
5. Shaft ends of the driving and the driven shafts.

The models should include:

1. Hub, flange, protecting rim, spigot and recess.
2. Keyways in the hubs and the shafts.
3. Reamed bolt holes on the pitch circle.
4. Chamfers and fillets.

11. Assembly

Assemble the components in the following sequence:

Shaft 1 → Key → Flange half 1 → Flange half 2 → Bolts → Washers → Nuts → Key → Shaft 2

Check:

1. Alignment of the two shafts on a common axis.
2. Engagement of the spigot in the recess.
3. Alignment of the bolt holes.
4. Interference between the parts.
5. Clearance between the nuts and the protecting rim.

12. Detailed Component Drawings

Prepare production drawings for the flange halves, the key and the bolt.

Each drawing should contain:

1. Front view and a sectional view.
2. Side view showing the bolt holes on the pitch circle.
3. All dimensions, tolerances and surface-finish requirements.
4. Material specification.
5. Title block with scale, projection method and drawing number.

13. Sectional Assembly Drawing

Prepare a sectional 2-D assembly drawing containing:



1. Sectional front view through the axis of the shafts.
2. Side view showing the bolt pattern and the protecting rim.
3. Overall dimensions and the pitch circle diameter.
4. Fits and tolerances at the shaft–hub, spigot–recess and bolt–hole interfaces.
5. Part numbers and balloons.
6. Assembly notes.
7. Title block with scale, projection method and drawing number.

14. Bill of Materials (BOM)

Prepare a Bill of Materials for the complete assembly.

Sl. No.	Part Name	Part No.	Material/Grade	Quantity	Principal Dimensions
1	Flange half 1 (with spigot)	P-01	Cast iron FG 200	1	To be designed
2	Flange half 2 (with recess)	P-02	Cast iron FG 200	1	To be designed
3	Key	P-03	Steel 45C8	2	To be designed
4	Bolt	P-04	Steel 45C8	4	To be selected
5	Nut	P-05	Steel	4	To be selected
6	Washer	P-06	Steel	4	To be selected
7	Driving and driven shafts	P-07	Steel C45	2	60 mm diameter

Final Objective: Develop the design of the complete protected-type rigid flange coupling for the specified power, speed and service factor, determine the dimensions of the hub, key, flange and bolts, specify the fits and tolerances, and create the 3-D models, the sectional assembly drawing and the Bill of Materials.

Solution Steps

Task 1: Design Torque and Shaft Check

1. Calculate the rated torque: $T = 60 P / (2\pi N)$.
2. Calculate the design torque: $T_d = K_s \times T$.
3. Calculate the shear stress in the shaft: $\tau = 16 T_d / (\pi d^3)$.
4. Check that τ is not greater than 40 MPa.

Task 2: Design of the Hub

1. Calculate $D = 2d$ and $L = 1.5d$.
2. Write the torsion equation for the hollow hub: $T_d = (\pi/16) \tau (D^4 - d^4) / D$.
3. Solve for the hub shear stress τ .
4. Compare τ with the allowable shear stress of cast iron (15 MPa).
5. Confirm that the hub length is not less than the key length.

Task 3: Design of the Key

1. Take the key section $b \times h = 18 \times 11$ mm.
2. Calculate the tangential force on the key: $F = 2 T_d / d$.
3. Key length from shear: $l = F / (b \tau_k)$.
4. Key length from crushing: $l = F / ((h/2) \sigma_c)$.
5. Adopt the larger length and select the next standard key length.
6. Confirm that the key length does not exceed the hub length.

Task 4: Design of the Flange



1. Calculate $D_2 = 4d$, $t_f = 0.5d$ and $t_2 = 0.25d$.
2. Write the shear equation at the hub-flange junction: $T_d = (\pi/2) \tau D^2 t_f$.
3. Solve for the shear stress in the flange.
4. Compare it with 15 MPa.
5. Increase t_f if required.

Task 5: Design of the Bolts

1. Take $D_1 = 3d$ and $n = 4$.
2. Calculate the load per bolt: $F = T_d / (n D_1/2)$.
3. Write the shear equation: $F = (\pi/4) d_b^2 \tau_b$ and solve for d_b .
4. Select the next higher standard bolt size.
5. Check the crushing stress: $\sigma_c = F / (d_b t_f)$.
6. Check that the bolt spacing along the pitch circle is sufficient for the wrench and washer.

Task 6: Fits, Tolerances and Final Dimensions

1. Read the tolerance grades for H7, k6, h6 and g6 from the standard tables for the respective size ranges.
2. Calculate the upper and lower limits of the hub bore and the shaft.
3. Classify each fit as clearance, transition or interference.
4. Specify the keyway width tolerance and the surface finish.
5. Prepare the final dimensional table.

Task 7: Design Justification

1. Compare the rated torque with the design torque.
2. Explain the reasons for applying the service factor to the milling duty.
3. Trace the load path: shaft, key, hub, flange, bolts, flange, hub, key, shaft.
4. Explain the role of the spigot, the recess and the protecting rim.
5. Explain why misalignment introduces extra loads on a rigid coupling.

Task 8: Failure Mode Interpretation and Trade-off Analysis

1. Describe each failure mode and identify the stressed area involved.
2. Compare the calculated stress of each part with its allowable stress.
3. Recalculate the design torque for $K_s = 2.0$.
4. Recalculate the key length, the flange stress and the bolt diameter.
5. Compare the options of larger bolts, more bolts, larger pitch circle and thicker flange.
6. Select the most practical option.

Task 9: Sustainability Interpretation

1. Compare the mass of the designed coupling with that of an oversized coupling.
2. Explain how standard parts reduce cost and waste.
3. Explain the safety benefit of the protecting rim.
4. Relate accurate alignment to the life of bearings and shafts.
5. Explain how correct design reduces maintenance and material waste.

Task 10: 3-D CAD Modelling

1. Create the revolved profile of flange half 1, including the hub, flange, rim and spigot.
2. Create the revolved profile of flange half 2, including the recess.
3. Cut the keyways and the bolt holes (circular pattern on the pitch circle).
4. Create the keys, bolts, nuts and washers from the standard dimensions.
5. Create the shaft ends with their keyways.
6. Add chamfers and fillets.



Task 11: Assembly

1. Position shaft 1 along the common axis.
2. Insert the key and assemble flange half 1 on shaft 1.
3. Assemble flange half 2 on shaft 2 with its key.
4. Mate the spigot with the recess.
5. Insert the bolts, washers and nuts.
6. Check the alignment, clearances and interference.

Task 12: Detailed Component Drawings

1. Generate the front and sectional views of the flange halves.
2. Generate the side view with the bolt holes on the pitch circle.
3. Generate the drawings of the key and the bolt.
4. Add dimensions, tolerances and surface finish.
5. Add the material specification.
6. Complete the title block.

Task 13: Sectional Assembly Drawing

1. Generate the sectional front view through the axis.
2. Generate the side view showing the bolt pattern.
3. Show the fits and tolerances at the important interfaces.
4. Add the overall dimensions and the pitch circle diameter.
5. Add part numbers and balloons.
6. Add assembly notes.
7. Complete the title block.

Task 14: Bill of Materials

1. Assign a part number to each flange half.
2. Assign part numbers to the keys, bolts, nuts, washers and shafts.
3. Specify the material or grade of each part.
4. Specify the quantity of each part.
5. Specify the principal dimensions and standard designations.
6. Verify that the BOM agrees with the 3-D assembly and the assembly drawing.

A5-III Design of the hub, key, flange, pins and bushes for bearing pressure and shear

Problem Statement

A rural drinking-water and irrigation pumping station uses a 22 kW electric motor running at 960 rpm to drive a centrifugal pump. The two shafts cannot be aligned perfectly, and the pump starts against load, so a pin-bush type flexible coupling is proposed. In this coupling, steel pins fixed in one flange carry rubber bushes that fit into holes in the other flange. The bushes transmit the torque, absorb shock, and accommodate a small misalignment between the shafts. The pins are loaded in bending and shear, and the rubber bushes are limited by bearing pressure. The dimensions of the hub, key, flange, pins and bushes are initially unknown.

As a design engineer applying the principles of Design of Machine Elements, you are required to develop the design of the complete pin-bush flexible coupling, determine the design torque, the dimensions of the hub, key, flange, pins and bushes, and check them for shear, bending and bearing pressure. Suitable standard sizes and fits must be selected. Finally, prepare the 3-D CAD models of all parts, the assembly, the sectional assembly drawing with fits and tolerances, and the Bill of Materials (BOM).

Given Data



Parameter	Value
Application	Motor-driven centrifugal pump of a rural water-pumping station
Type of coupling	Pin-bush type flexible coupling
Power transmitted, P	22 kW
Speed, N	960 rpm
Shaft diameter, d (motor and pump shafts)	35 mm
Allowable shear stress of shaft	40 MPa
Service factor, K _s	1.5
Material of hubs and flanges	Cast iron FG 200
Allowable shear stress of cast iron	15 MPa
Material of key and pins	Steel 45C8
Allowable shear stress of key	50 MPa
Allowable crushing stress of key	100 MPa
Allowable shear stress of pins	40 MPa
Allowable bending stress of pins	80 MPa
Allowable bearing pressure on rubber bush	1.0 N/mm ²
Number of pins, n	6
Trial proportions	Hub outside diameter D = 2d; hub length L = 1.5d; pin pitch circle diameter D ₁ = 3d; flange thickness t _f = 0.5d
Bush outside diameter	Pin diameter + 16 mm (2 mm steel sleeve and 6 mm rubber on each side)
Trial effective length of bush, l _b	40 mm
Clearance between the two flanges, c	5 mm
Standard key section for 35 mm shaft	10 mm × 8 mm
Available standard pin diameters	10, 12, 14, 16, 18, 20 mm
Fits for the assembly drawing	Shaft–hub H7/k6; pin–flange H7/k6; bush–flange bore H7/h6
Alternative case for Task 8	Power increased from 22 kW to 30 kW at the same speed

Tasks (Problem-Solving Component)

1. Design Torque and Shaft Check

1. Calculate the rated torque from the power and the speed.
2. Calculate the design torque using the service factor.
3. Calculate the shear stress in the 35 mm shaft at the design torque.
4. Confirm that the shaft diameter is adequate.

2. Design of the Key and Hub

1. Calculate the tangential force on the key from the design torque.
2. Determine the key length required for shear and for crushing.
3. Select the standard key length.
4. Calculate the hub outside diameter and hub length from the trial proportions.
5. Take the hub length as not less than the key length.
6. Calculate the shear stress in the hub and compare it with the allowable value.

3. Load on the Pins

1. Take the number of pins and the pitch circle diameter.
2. Calculate the load on each pin from the design torque.
3. Assume that the load acts at the middle of the effective bush length.
4. Determine the bending arm of the load on the pin, including the clearance between the flanges.

4. Design of the Pins

1. Calculate the bending moment on the pin.
2. Determine the pin diameter from the allowable bending stress.



3. Select the next higher standard pin diameter.
4. Check the direct shear stress in the pin.
5. Check the combined stress if required.

5. Design of the Bushes and Flange

1. Calculate the outside diameter of the bush from the selected pin diameter.
2. Calculate the bearing pressure on the rubber bush.
3. Increase the bush length or the pin size if the bearing pressure exceeds the allowable value.
4. Calculate the flange outside diameter from the pitch circle diameter, the bush diameter and the edge clearance.
5. Check the shear stress in the flange at the hub junction.
6. Check the spacing between adjacent bushes on the pitch circle.

6. Fits, Tolerances and Final Dimensions

1. Interpret the fit designations used for the assembly.
2. Find the limits of size for the shaft and the hub bore.
3. Specify the tolerances of the pin seat and the bush bore.
4. Prepare the final dimensional table of the coupling.

Tasks (Interpretation Component)

7. Design Justification

Explain why a flexible coupling is preferred to a rigid coupling for this motor and pump.

Discuss:

1. Effect of the rubber bush on shock and torsional vibration.
2. Permissible misalignment accommodated by the coupling.
3. Load path through the key, hub, flange, pin and bush.
4. Effect of the starting torque of the pump on the coupling.
5. Reason for using a service factor.

8. Failure Mode Interpretation and Trade-off Analysis

Explain the difference between:

1. Bending failure of the pin.
2. Shear failure of the pin.
3. Excessive bearing pressure and wear of the rubber bush.
4. Ageing and hardening of the rubber.
5. Shear failure of the key.
6. Shear failure of the hub and flange.

If the power is increased from 22 kW to 30 kW at the same speed, interpret how the coupling would need to be modified. Discuss the effects of increasing the pin diameter, increasing the number of pins, increasing the bush length and increasing the pitch circle diameter. Identify the most practical way to provide the additional capacity.

9. Sustainability Interpretation

Comment on how correct design of the flexible coupling reduces waste and cost.

Discuss how the design can:

1. Protect the expensive pump and motor bearings from shock and misalignment.



2. Allow the rubber bushes to be replaced without replacing the coupling.
3. Reduce the energy loss caused by misalignment and vibration.
4. Reduce the material used through properly proportioned parts.
5. Support reliable water supply to the community through longer service life.

10. 3-D CAD Modelling

Create separate 3-D CAD models for:

1. Driving flange half with hub and pins.
2. Driven flange half with hub and bush holes.
3. Keys.
4. Pins with nuts and washers.
5. Rubber bushes with steel sleeves.
6. Shaft ends of the motor and the pump.

The models should include:

1. Keyways in the hubs and the shafts.
2. Pin holes and bush holes on the pitch circle.
3. Threads or thread representation at the pin ends.
4. Chamfers and fillets.

11. Assembly

Assemble the components in the following sequence:

Motor shaft → Key → Driving half → Pins → Bushes → Driven half → Key → Pump shaft → Washers → Nuts

Check:

1. Alignment of the two shafts on a common axis.
2. Engagement of the bushes in the holes of the driven flange.
3. The clearance of 5 mm between the flanges.
4. Interference between the parts.

12. Detailed Component Drawings

Prepare production drawings for the flange halves, the pin, the bush and the key.

Each drawing should contain:

1. Front view and a sectional view.
2. Side view showing the pins or holes on the pitch circle.
3. All dimensions, tolerances and surface-finish requirements.
4. Material specification.
5. Title block with scale, projection method and drawing number.

13. Sectional Assembly Drawing

Prepare a sectional 2-D assembly drawing containing:

1. Sectional front view through the axis and through a pin.
2. Side view showing the pin and bush arrangement.
3. Overall dimensions and the pitch circle diameter.
4. Fits and tolerances at the important interfaces.



5. Part numbers and balloons.
6. Assembly notes.
7. Title block with scale, projection method and drawing number.

14. Bill of Materials (BOM)

Prepare a Bill of Materials for the complete assembly.

Sl. No.	Part Name	Part No.	Material/Grade	Quantity	Principal Dimensions
1	Driving flange half with hub	P-01	Cast iron FG 200	1	To be designed
2	Driven flange half with hub	P-02	Cast iron FG 200	1	To be designed
3	Key	P-03	Steel 45C8	2	10 × 8 mm × length to be designed
4	Pin	P-04	Steel 45C8	6	To be designed
5	Rubber bush with steel sleeve	P-05	Rubber and mild steel	6	To be designed
6	Washer	P-06	Steel	6	To be selected
7	Nut	P-07	Steel	6	To be selected
8	Motor and pump shafts	P-08	Steel C45	2	35 mm diameter

Final Objective: Develop the design of the complete pin-bush flexible coupling for the specified power, speed and service factor, determine the dimensions of the hub, key, flange, pins and bushes from shear, bending and bearing pressure, specify the fits and tolerances, and create the 3-D models, the sectional assembly drawing and the Bill of Materials.

Solution Steps

Task 1: Design Torque and Shaft Check

1. Calculate the rated torque: $T = 60 P / (2\pi N)$.
2. Calculate the design torque: $T_d = K_s \times T$.
3. Calculate the shear stress in the shaft: $\tau = 16 T_d / (\pi d^3)$.
4. Check that τ is not greater than 40 MPa.

Task 2: Design of the Key and Hub

1. Calculate the tangential force on the key: $F = 2 T_d / d$.
2. Key length from shear: $l = F / (b \tau_k)$; key length from crushing: $l = F / ((h/2) \sigma_c)$.
3. Adopt the larger value and select the next standard key length.
4. Calculate $D = 2d$ and $L = 1.5d$; adopt L not less than the key length.
5. Calculate the hub shear stress: $\tau = 16 T_d D / (\pi (D^4 - d^4))$.
6. Compare τ with the allowable value of cast iron.

Task 3: Load on the Pins

1. Take $n = 6$ and $D_1 = 3d$.
2. Calculate the load per pin: $P = T_d / (n D_1/2) = 2 T_d / (n D_1)$.
3. Take the effective bush length $l_b = 40$ mm.
4. Calculate the bending arm: $a = l_b/2 + c$.

Task 4: Design of the Pins

1. Calculate the bending moment: $M = P \times a$.
2. Write the bending equation: $M = (\pi/32) \sigma_b d_1^3$ and solve for the pin diameter d_1 .
3. Select the next higher standard pin diameter.



4. Calculate the shear stress: $\tau = 4 P / (\pi d_1^2)$.
5. Check that τ and σ_b are within their allowable values.

Task 5: Design of the Bushes and Flange

1. Calculate the bush outside diameter: $d_2 = d_1 + 16 \text{ mm}$.
2. Calculate the bearing pressure: $p_b = P / (d_2 l_b)$.
3. Compare p_b with 1.0 N/mm^2 ; increase l_b if required.
4. Calculate the flange outside diameter: $D_2 = D_1 + d_2 + 2 \times (\text{edge clearance})$.
5. Check the flange shear stress: $T_d = (\pi/2) \tau D^2 t_f$.
6. Check that the spacing $\pi D_1 / n$ is greater than the bush diameter.

Task 6: Fits, Tolerances and Final Dimensions

1. Read the tolerance grades from the standard tables for the respective size ranges.
2. Calculate the limits of size for the shaft and the hub bore.
3. Classify each fit as clearance, transition or interference.
4. Specify the pin seat and the bush bore tolerances.
5. Prepare the final dimensional table.

Task 7: Design Justification

1. Explain how the rubber bush reduces shock and vibration.
2. Explain how the bushes allow small misalignment.
3. Trace the load path through the coupling.
4. Explain the effect of the pump starting torque.
5. Explain why the service factor is applied.

Task 8: Failure Mode Interpretation and Trade-off Analysis

1. Describe each failure mode and identify the stressed area involved.
2. Compare the calculated stresses and pressure with the allowable values.
3. Recalculate the design torque for 30 kW at 960 rpm.
4. Recalculate the load per pin, the pin diameter and the bearing pressure.
5. Compare the options of a larger pin, more pins, longer bush and larger pitch circle.
6. Select the most practical option.

Task 9: Sustainability Interpretation

1. Explain how the coupling protects the pump and motor bearings.
2. Explain how replaceable bushes extend the life of the coupling.
3. Relate reduced vibration to energy saving.
4. Compare the mass of the designed coupling with an oversized one.
5. Relate the design to reliable water supply and low maintenance.

Task 10: 3-D CAD Modelling

1. Create the revolved profile of the driving half with the hub and the flange.
2. Create the pins on the pitch circle using a circular pattern.
3. Create the revolved profile of the driven half and cut the bush holes.
4. Create the rubber bushes with steel sleeves, the keys, nuts and washers.
5. Create the shaft ends with keyways.
6. Add chamfers and fillets.

Task 11: Assembly

1. Position the motor shaft along the common axis.



2. Insert the key and assemble the driving half with its pins.
3. Fit the bushes over the pins.
4. Assemble the driven half with the pump shaft and key.
5. Insert the washers and nuts.
6. Check the alignment, the flange clearance and interference.

Task 12: Detailed Component Drawings

1. Generate the front and sectional views of the flange halves.
2. Generate the side views showing the pins and the bush holes.
3. Generate the drawings of the pin, the bush and the key.
4. Add dimensions, tolerances and surface finish.
5. Add the material specification.
6. Complete the title block.

Task 13: Sectional Assembly Drawing

1. Generate the sectional front view through the axis and a pin.
2. Generate the side view showing the pin and bush arrangement.
3. Show the fits and tolerances at the important interfaces.
4. Add the overall dimensions and the pitch circle diameter.
5. Add part numbers and balloons.
6. Add assembly notes.
7. Complete the title block.

Task 14: Bill of Materials

1. Assign a part number to each flange half.
2. Assign part numbers to the key, pin, bush, washer, nut and shafts.
3. Specify the material or grade of each part.
4. Specify the quantity of each part.
5. Specify the principal dimensions and standard designations.
6. Verify that the BOM agrees with the 3-D assembly and the assembly drawing.

INSTRUCTION ITEM-6 (II-6)		
Assignment No.	Name of the experiment	CO Congruence
A6-I	Design of the wire diameter, coil diameter, number of coils and free length, with a buckling check; 3-D modelling using helix and sweep, and 2-D drawing with load-deflection specification.	[CO6]
A6-II	Design of a spring system for equivalent stiffness and load sharing; 3-D modelling, assembly and drawing with load-deflection specification.	
A6-III	Design of the number, width and thickness of leaves and the initial nip; 3-D modelling, assembly and drawing with bill of materials.	

A6-I Design of the wire diameter, coil diameter, number of coils and free length, with a buckling check

Problem Statement

A farmers' group uses a four-wheeled hand-pulled trolley to carry vegetables and grain from the fields to the local market over rough rural tracks. The produce is damaged by the shocks transmitted through the frame, so a helical compression spring is to be fitted at each of the four suspension points. Each spring carries a maximum load at a given deflection, with squared and ground ends, and works between flat parallel plates. The wire diameter, coil diameter, number of coils and free length of the spring are initially unknown. The spring must be safe in shear, must not buckle, and must not close solid under the maximum load.



As a design engineer applying the principles of Design of Machine Elements, you are required to analyse and design the helical compression spring for the specified load and deflection, determine the wire diameter, mean coil diameter, number of coils and free length, check the spring for shear stress and buckling, and establish its load–deflection behaviour. Finally, prepare the 3-D CAD model of the spring using the helix and sweep features and the 2-D production drawing with the load–deflection specification.

Given Data

Parameter	Value
Application	Suspension spring of a hand-pulled farm-produce trolley
Type of spring	Helical compression spring, round wire
Type of ends	Squared and ground
Maximum working load, W	1000 N
Deflection at maximum working load, δ	60 mm
Spring index, C	8
Spring material	Oil-hardened and tempered carbon steel wire
Allowable shear stress, τ	480 MPa
Modulus of rigidity, G	81 GPa
Modulus of elasticity, E	207 GPa
Available standard wire diameters	6, 7, 8, 9, 10, 12 mm
Total number of coils	Active coils + 2 (squared and ground ends)
Clash allowance	15% of the maximum working deflection
End conditions for buckling check	Case (a): both ends between parallel flat plates; Case (b): one end fixed, the other end hinged
Maximum outside diameter allowed	90 mm
Direction of coil	Right hand
Design objective	Safe spring with stable, linear load–deflection behaviour
Alternative case for Task 10	Maximum working load increased from 1000 N to 1500 N at the same deflection

Tasks (Problem-Solving Component)

1. Loading and Spring Index

1. Identify the maximum working load and the corresponding deflection.
2. Calculate the required stiffness of the spring.
3. Identify the spring index and the relation between the mean coil diameter and the wire diameter.
4. Calculate the Wahl stress factor for the given spring index.

2. Wire Diameter and Coil Diameter

1. Determine the wire diameter from the shear stress equation using the Wahl factor.
2. Select the next higher standard wire diameter.
3. Calculate the mean coil diameter from the spring index.
4. Calculate the outside and inside diameters of the spring.
5. Check the outside diameter against the maximum diameter allowed.

3. Number of Coils and Stiffness

1. Determine the number of active coils from the deflection equation.
2. Adopt a whole number of active coils.
3. Calculate the total number of coils.
4. Calculate the actual stiffness of the spring.
5. Calculate the actual deflection at the maximum working load.

4. Solid Length, Free Length and Pitch



1. Calculate the solid length of the spring.
2. Calculate the clash allowance from the maximum deflection.
3. Calculate the free length of the spring.
4. Calculate the pitch of the coils.
5. Calculate the length of the spring under the maximum working load.

5. Stress Check

1. Calculate the shear stress at the maximum working load.
2. Calculate the load acting on the spring at its solid length.
3. Calculate the shear stress at the solid length.
4. Compare both stresses with the allowable value.

6. Buckling Check

1. Calculate the ratio of the free length to the mean coil diameter.
2. Identify the end-condition constant for each end case.
3. Determine whether the spring is unconditionally stable.
4. Calculate the critical deflection, if required, and compare it with the working deflection.
5. Decide whether a guide rod or a guide tube is required.

7. Load–Deflection Characteristic

1. Calculate the load at several deflections between zero and the maximum deflection.
2. Calculate the load at the solid length.
3. Plot the load–deflection diagram.
4. Calculate the energy stored at the maximum working load.

Tasks (Interpretation Component)

8. Design Justification

Explain why the Wahl factor is used in the design of the helical spring.

Discuss:

1. Direct shear stress and the effect of coil curvature on the wire.
2. Effect of the spring index on the stress and on the manufacture of the spring.
3. Reason for providing a clash allowance.
4. Reason for using squared and ground ends.
5. Reason for checking the spring for buckling.

9. Load–Deflection Interpretation

Interpret the load–deflection diagram of the spring.

Discuss:

1. Meaning of the stiffness of the spring.
2. Effect of the wire diameter, the coil diameter and the number of active coils on the stiffness.
3. Linear behaviour of the spring and the limit imposed by the solid length.
4. Effect of the end coils and the ground ends on the working range.
5. Energy stored and its role in absorbing shock.

10. Trade-off Analysis



If the maximum working load is increased from 1000 N to 1500 N at the same deflection, interpret how the spring would need to be redesigned.

Discuss the effects of:

1. Increasing the wire diameter.
2. Reducing the spring index.
3. Reducing the number of active coils.
4. Using two springs in parallel at each suspension point.
5. Selecting a wire material of higher allowable stress.

Compare the alternatives in terms of stress, stiffness, free length, buckling, mass and cost.

11. Sustainability Interpretation

Comment on how correct sizing of the spring avoids unnecessary material use.

Discuss how the design can:

1. Reduce the consumption of spring steel by avoiding oversized wire.
2. Avoid premature failure through adequate stress and buckling margins.
3. Use four identical standard springs to simplify manufacture and replacement.
4. Reduce damage to vegetables and grain during transport and thereby reduce food loss.
5. Support recycling of the spring steel at the end of its life.

12. 3-D CAD Modelling Using Helix and Sweep

Create the 3-D CAD model of the spring using the following features:

1. A helix curve defined by pitch, height and number of revolutions.
2. Reduced pitch at both ends to form the closed (squared) end coils.
3. A circular profile of the wire diameter swept along the helix.
4. A cut at each end to grind the end coils flat.
5. Verification of the free length, the number of coils and the solid length in the model.

13. 2-D Drawing with Load–Deflection Specification

Prepare a 2-D production drawing of the spring containing:

1. Front view and a sectional or end view.
2. Wire diameter, outside diameter, inside diameter and free length.
3. Number of active coils, total number of coils and direction of coil.
4. Type of ends and the solid length.
5. Specification table giving the spring rate, the load at the working length and the maximum working load.
6. Load–deflection diagram.
7. Material and heat-treatment specification.
8. Title block with scale, projection method and drawing number.

Final Objective: Analyse and design the helical compression spring for the specified load and deflection, determine the wire diameter, coil diameter, number of coils and free length, check the spring for stress and buckling, establish its load–deflection behaviour, and create the 3-D model using the helix and sweep features and the 2-D drawing with the load–deflection specification.

Solution Steps

Task 1: Loading and Spring Index



1. Take $W = 1000 \text{ N}$ at $\delta = 60 \text{ mm}$.
2. Calculate the required stiffness: $k = W / \delta$.
3. Write the spring index: $C = D / d$, so that $D = C d$.
4. Calculate the Wahl factor: $K = (4C - 1) / (4C - 4) + 0.615 / C$.

Task 2: Wire Diameter and Coil Diameter

1. Write the shear stress equation: $\tau = K \times 8 W D / (\pi d^3) = K \times 8 W C / (\pi d^2)$.
2. Solve for the wire diameter d .
3. Select the next higher standard wire diameter from 6, 7, 8, 9, 10 and 12 mm.
4. Calculate $D = C d$, $D_o = D + d$ and $D_i = D - d$.
5. Check that D_o is not greater than 90 mm.

Task 3: Number of Coils and Stiffness

1. Write the deflection equation: $\delta = 8 W D^3 N / (G d^4)$ and solve for N .
2. Round N up to a whole number of active coils.
3. Calculate the total number of coils: $N_t = N + 2$.
4. Calculate the stiffness: $k = G d^4 / (8 D^3 N)$.
5. Calculate the deflection at W : $\delta = W / k$.

Task 4: Solid Length, Free Length and Pitch

1. Calculate the solid length: $L_s = N_t d$.
2. Calculate the clash allowance: $0.15 \times \delta$.
3. Calculate the free length: $L_f = L_s + \delta + \text{clash allowance}$.
4. Calculate the pitch: $p = (L_f - 2d) / N$.
5. Calculate the length at maximum load: $L_f - \delta$.

Task 5: Stress Check

1. Calculate the stress at W : $\tau = K \times 8 W D / (\pi d^3)$.
2. Calculate the deflection to solid length: $L_f - L_s$.
3. Calculate the load at solid length: $W_s = k (L_f - L_s)$.
4. Calculate the stress at solid length using W_s .
5. Compare both stresses with 480 MPa.

Task 6: Buckling Check

1. Calculate L_f / D .
2. Take the end-condition constant α : 0.5 for case (a) and 0.707 for case (b).
3. Write the effective slenderness ratio: $\lambda_{\text{eff}} = \alpha L_f / D$.
4. Calculate $C_1 = E / (2(E - G))$ and $C_2 = 2\pi^2(E - G) / (2G + E)$.
5. If λ_{eff}^2 is less than C_2 , the spring is unconditionally stable.
6. Otherwise calculate the critical deflection: $\delta_{\text{cr}} = L_f C_1 [1 - \sqrt{(1 - C_2 / \lambda_{\text{eff}}^2)}]$ and compare it with the working deflection.
7. Decide whether a guide is required.

Task 7: Load-Deflection Characteristic

1. Write the load equation: $F = k \delta$.
2. Calculate F for $\delta = 0, 15, 30, 45$ and 60 mm and at the solid length.
3. Plot F against δ .
4. Calculate the energy stored: $U = \frac{1}{2} W \delta$.

Task 8: Design Justification



1. Explain that the Wahl factor combines the direct shear and curvature effects.
2. Explain that a small index raises the stress and a large index makes the spring flexible and prone to tangling.
3. Explain the clash allowance as a margin to prevent the coils closing solid.
4. Explain that the ground ends give a flat seat and a square load application.
5. Explain that a long slender spring may buckle sideways.

Task 9: Load–Deflection Interpretation

1. Interpret the slope of the load–deflection line as the spring stiffness.
2. Write $k = G d^4 / (8 D^3 N)$ and examine the effect of each variable.
3. Explain that the behaviour is linear up to the solid length.
4. Explain the effect of the end coils on the working range.
5. Explain that the area under the line is the energy stored.

Task 10: Trade-off Analysis

1. Recalculate the required stiffness and stress for $W = 1500 \text{ N}$.
2. Determine the new wire diameter, coil diameter and number of coils.
3. Examine the effect of a lower spring index and fewer active coils.
4. Examine the use of two springs in parallel, each carrying half the load.
5. Compare the alternatives and select the most practical option.

Task 11: Sustainability Interpretation

1. Compare the mass of wire in the designed spring with that of an oversized spring.
2. Explain how adequate margins extend the spring life.
3. Explain the benefit of using standard wire sizes and identical springs.
4. Relate the reduction of shock to the reduction of damage to the produce.
5. Explain how recycling of steel reduces the environmental load.

Task 12: 3-D CAD Modelling Using Helix and Sweep

1. Create a sketch plane and a circle of the mean coil diameter.
2. Create a helix using pitch and height, or pitch and revolutions.
3. Add the reduced pitch region at both ends.
4. Sketch a circle of the wire diameter at the start of the helix.
5. Use the Sweep feature to generate the wire along the helix.
6. Cut the ends flat to form the ground ends.
7. Check the free length, the number of coils and the solid length.

Task 13: 2-D Drawing with Load–Deflection Specification

1. Generate the front view and a sectional or end view.
2. Add the wire diameter, the outside diameter, the inside diameter and the free length.
3. Add the coil data: active coils, total coils and direction of coil.
4. Add the specification table with the spring rate and the loads at the working lengths.
5. Add the load–deflection diagram.
6. Add the material and heat-treatment notes.
7. Complete the title block.

A6-II Design of a spring system for equivalent stiffness and load sharing

Problem Statement

A village cooperative uses a tractor-drawn farm trailer to carry harvested crops to the market. When the tractor starts or stops with a heavily loaded trailer, a large shock is transmitted through the drawbar. To absorb the shock within a limited housing, the drawbar buffer uses two concentric helical compression springs acting in parallel. The outer and the inner



springs are wound in opposite hands, deflect by the same amount, and share the load in proportion to their stiffnesses. The dimensions of the two springs are initially unknown.

As a design engineer applying the principles of Design of Machine Elements, you are required to analyse and design the spring system for the specified total load and deflection, determine the load shared by each spring, the dimensions of each spring and the equivalent stiffness of the system, and compare the parallel arrangement with a series arrangement. Finally, prepare the 3-D CAD models of the springs, the assembly, and the drawings with the load–deflection specification.

Given Data

Parameter	Value
Application	Drawbar buffer of a tractor-drawn farm trailer
Type of spring system	Two concentric helical compression springs in parallel
Maximum buffer load, W	6000 N
Deflection at maximum load, δ	50 mm
Spring index of both springs, C	6
Spring material	Oil-hardened and tempered spring steel wire
Allowable shear stress, τ	450 MPa
Modulus of rigidity, G	81 GPa
Type of ends	Squared and ground
Direction of coil	Outer spring right hand; inner spring left hand
Design conditions	Both springs have the same free length and deflect equally
Clash allowance	10% of the maximum deflection
Available standard wire diameters	8, 9, 10, 11, 12, 14, 16 mm
Inside diameter of housing tube	105 mm
Diameter of central guide rod	36 mm
Minimum diametral clearance	6 mm between the outer spring and the housing, between the two springs, and between the inner spring and the guide rod
Elastic modulus, E (for buckling check)	207 GPa
Alternative case for Task 11	Maximum buffer load increased from 6000 N to 9000 N at the same deflection

Tasks (Problem-Solving Component)

1. System Requirements and Equivalent Stiffness

1. Calculate the equivalent stiffness required for the spring system from the load and the deflection.
2. State the relation between the stiffnesses of the two springs in a parallel arrangement.
3. State the relation between the loads carried by the two springs.
4. State the relation between the deflections of the two springs.

2. Load Sharing Between the Springs

1. Determine the relation between the loads on the two springs for equal shear stress and equal spring index.
2. Calculate the Wahl factor for the spring index.
3. Select trial wire diameters for the outer and the inner springs from the available sizes.
4. Check the trial diameters against the diametral clearances with the housing, between the springs and with the guide rod.
5. Calculate the load carried by each spring.

3. Design of the Outer Spring

1. Calculate the wire diameter required for the load carried by the outer spring.
2. Select the standard wire diameter.
3. Calculate the mean coil diameter, and the outside and inside diameters.
4. Determine the number of active coils from the deflection.



5. Calculate the stiffness of the outer spring.

4. Design of the Inner Spring

1. Calculate the wire diameter required for the load carried by the inner spring.
2. Select the standard wire diameter that satisfies the clearances.
3. Calculate the mean coil diameter, and the outside and inside diameters.
4. Determine the number of active coils from the deflection.
5. Calculate the stiffness of the inner spring.

5. Equivalent Stiffness and Stress Check

1. Calculate the equivalent stiffness of the system from the two stiffnesses.
2. Compare it with the required equivalent stiffness.
3. Calculate the actual load shared by each spring at the maximum deflection.
4. Calculate the shear stress in each spring at the maximum load.
5. Compare the stresses with the allowable value.

6. Lengths of the Springs

1. Calculate the solid length of each spring.
2. Calculate the free length required for each spring.
3. Adopt a common free length for both springs.
4. Identify the spring that governs the free length and calculate the resulting clash allowance of the other spring.
5. Calculate the pitch of each spring.

7. Comparison with a Series Arrangement

1. State the relation between the loads on two springs connected in series.
2. State the relation between their deflections.
3. Calculate the equivalent stiffness if the two designed springs were connected in series.
4. Calculate the total deflection under the maximum load for the series arrangement.
5. Compare the series and the parallel arrangements.

8. Buckling Check

1. Calculate the ratio of free length to mean coil diameter for the outer spring.
2. Identify the end-condition constant.
3. Determine whether the outer spring is unconditionally stable.
4. Decide whether the guide rod is required for the inner spring.

Tasks (Interpretation Component)

9. Design Justification

Explain why two concentric springs are used instead of a single spring.

Discuss:

1. Effect of the limited housing diameter on the choice of spring system.
2. Reason for winding the two springs in opposite hands.
3. Reason for using the same spring index and the same deflection for both springs.
4. Reason for the diametral clearances.
5. Reason for providing a guide rod.

10. Load–Deflection Interpretation



Interpret the load–deflection behaviour of the spring system.

Discuss:

1. Load shared by the springs in proportion to their stiffnesses.
2. Why the parallel arrangement is stiffer than either spring alone.
3. Why the series arrangement is softer than either spring alone.
4. Effect of unequal free lengths on the load–deflection curve.
5. Progressive (two-stage) behaviour when the inner spring engages after the outer spring.

11. Trade-off Analysis

If the maximum buffer load is increased from 6000 N to 9000 N at the same deflection, interpret how the spring system would need to be redesigned.

Discuss the effects of:

1. Increasing the wire diameters of both springs.
2. Reducing the number of active coils.
3. Adding a third concentric spring.
4. Increasing the housing diameter.
5. Changing the spring index.

Compare the alternatives in terms of stress, space, mass, cost and manufacture.

12. Sustainability Interpretation

Comment on how correct design of the spring system avoids unnecessary material use.

Discuss how the design can:

1. Reduce the mass of steel by sharing the load in proportion to the wire sizes.
2. Use standard wire diameters and identical parts for easy replacement.
3. Reduce shock damage to the trailer, the drawbar and the tractor.
4. Extend the service life and reduce the maintenance effort in rural use.
5. Support recycling of the spring steel at the end of its life.

13. 3-D CAD Modelling

Create separate 3-D CAD models for:

1. The outer spring (right hand).
2. The inner spring (left hand).
3. The guide rod.
4. The housing tube and the end plates.

The models should include:

1. Helix and sweep features for both springs.
2. Reduced pitch at the ends and ground end faces.
3. Correct free lengths and number of coils.

14. Assembly

Assemble the components in the following sequence:



Housing Tube → Guide Rod → Outer Spring → Inner Spring → End Plate

Check:

1. Coaxial alignment of the springs and the guide rod.
2. Clearances between the springs and the housing and guide rod.
3. Interference between the parts.
4. The positions of the springs at the free length, the maximum working length and the solid length.

15. Detailed Component Drawings

Prepare production drawings for the outer spring and the inner spring.

Each drawing should contain:

1. Front view and an end view.
2. Wire diameter, outside diameter, inside diameter and free length.
3. Number of active coils, total coils and direction of coil.
4. Specification table with the spring rate and loads at the working lengths.
5. Material and heat-treatment specification.
6. Title block with scale, projection method and drawing number.

16. Assembly Drawing with Load–Deflection Specification

Prepare a 2-D assembly drawing containing:

1. Sectional front view showing the outer spring, the inner spring and the guide rod.
2. End view showing the concentric arrangement.
3. Overall dimensions and the clearances.
4. Part numbers and balloons with a parts list.
5. Load–deflection specification table giving the stiffness and the load carried by each spring.
6. Combined load–deflection diagram of the spring system.
7. Title block with scale, projection method and drawing number.

Final Objective: Analyse and design the concentric spring system for the specified load and deflection, determine the load shared by each spring, the dimensions of each spring and the equivalent stiffness, compare the parallel and series arrangements, and create the 3-D models, the assembly and the drawings with the load–deflection specification.

Solution Steps

Task 1: System Requirements and Equivalent Stiffness

1. Calculate the required equivalent stiffness: $k = W / \delta$.
2. For parallel springs: $k = k_1 + k_2$.
3. For parallel springs: $W = P_1 + P_2$.
4. For parallel springs: the deflection is the same, $\delta_1 = \delta_2 = \delta$.

Task 2: Load Sharing Between the Springs

1. Write the stress: $\tau = K \times 8 P C / (\pi d^3)$.
2. For equal stress and equal C: $P_1 / P_2 = (d_1 / d_2)^3$.
3. Calculate the Wahl factor $K = (4C - 1) / (4C - 4) + 0.615 / C$.
4. Take a trial d_1 and find the largest d_2 that satisfies the clearance: outer inside diameter – inner outside diameter ≥ 6 mm, i.e. $(C - 1) d_1 - (C + 1) d_2 \geq 6$.
5. Check the inner spring against the guide rod: $C d_2 - d_2 - 36 \geq 6$.
6. Check the outer spring against the housing: $105 - (C + 1) d_1 \geq 6$.



7. Calculate $P1 = W d1^2 / (d1^2 + d2^2)$ and $P2 = W - P1$.

Task 3: Design of the Outer Spring

1. Solve the stress equation for $d1$ using $P1$ and $\tau = 450$ MPa.
2. Confirm the selected standard diameter is not less than the required value.
3. Calculate $D1 = C d1$, $Do1 = D1 + d1$ and $Di1 = D1 - d1$.
4. Calculate the active coils: $N1 = \delta G d1 / (8 P1 C^3)$.
5. Round $N1$ to a whole number and calculate $k1 = G d1 / (8 C^3 N1)$.

Task 4: Design of the Inner Spring

1. Solve the stress equation for $d2$ using $P2$ and $\tau = 450$ MPa.
2. Select the standard diameter that satisfies both the stress and the clearance conditions.
3. Calculate $D2 = C d2$, $Do2 = D2 + d2$ and $Di2 = D2 - d2$.
4. Calculate the active coils: $N2 = \delta G d2 / (8 P2 C^3)$.
5. Round $N2$ to a whole number and calculate $k2 = G d2 / (8 C^3 N2)$.

Task 5: Equivalent Stiffness and Stress Check

1. Calculate $k = k1 + k2$ and compare it with W / δ .
2. Calculate the actual loads: $P1 = k1 \delta$ and $P2 = k2 \delta$.
3. Calculate the stresses: $\tau = K \times 8 P D / (\pi d^3)$ for each spring.
4. Compare both stresses with 450 MPa.
5. Adjust the number of coils if the stresses or the stiffness are not acceptable.

Task 6: Lengths of the Springs

1. Calculate the solid lengths: $Ls = (N + 2) d$ for each spring.
2. Calculate the free lengths: $Lf = Ls + \delta + \text{clash allowance } (0.10 \delta)$.
3. Adopt the larger free length as the common free length.
4. Calculate the extra clash allowance of the spring with the shorter solid length.
5. Calculate the pitch of each spring: $p = (Lf - 2d) / N$.

Task 7: Comparison with a Series Arrangement

1. For springs in series: the load is the same in both springs.
2. For springs in series: the total deflection is $\delta = \delta1 + \delta2$.
3. Calculate the equivalent stiffness: $1/k = 1/k1 + 1/k2$.
4. Calculate the deflection under the maximum load: $\delta = W / k$.
5. Compare the stiffness and the deflection with those of the parallel arrangement.

Task 8: Buckling Check

1. Calculate $Lf / D1$ for the outer spring.
2. Take $\alpha = 0.5$ for ends between parallel plates.
3. Calculate $C1 = E / (2(E - G))$ and $C2 = 2\pi^2(E - G) / (2G + E)$.
4. If $(\alpha Lf / D1)^2$ is less than $C2$, the spring is unconditionally stable.
5. Otherwise calculate the critical deflection and compare it with the working deflection.
6. Decide whether the guide rod is required.

Task 9: Design Justification

1. Explain that the limited housing diameter makes one large spring impractical.
2. Explain that opposite hands prevent the coils of the two springs from locking.
3. Explain that the same index and the same deflection produce equal stress in both springs.
4. Explain that the clearances allow free deflection without rubbing.



5. Explain the function of the guide rod.

Task 10: Load–Deflection Interpretation

1. Plot the load–deflection lines of the outer spring, the inner spring and the system.
2. Show that the system line has a slope equal to $k_1 + k_2$.
3. Plot the series arrangement and compare the slopes.
4. Show the effect of a shorter inner spring on the characteristic.
5. Explain the progressive behaviour of a two-stage system.

Task 11: Trade-off Analysis

1. Recalculate the load sharing for $W = 9000$ N.
2. Determine the new wire diameters and check the clearances.
3. Examine the effect of reducing the number of coils.
4. Examine the option of a third spring and of a larger housing.
5. Compare the options and select the most practical one.

Task 12: Sustainability Interpretation

1. Compare the total mass of wire of the concentric system with that of an oversized single spring.
2. Explain the benefit of standard wire sizes.
3. Relate the shock absorption to the life of the trailer and the tractor.
4. Relate the design to reliability and reduced maintenance.
5. Explain the recycling of spring steel.

Task 13: 3-D CAD Modelling

1. Create the outer spring using a right-hand helix and a circular sweep.
2. Create the inner spring using a left-hand helix and a circular sweep.
3. Reduce the pitch at the ends and cut the ends flat.
4. Create the guide rod, the housing tube and the end plates.
5. Check the free lengths and the number of coils.

Task 14: Assembly

1. Position the housing tube and the guide rod on a common axis.
2. Insert the outer spring and then the inner spring.
3. Fit the end plate.
4. Check the clearances and the interference.
5. Check the positions at the free length, the working length and the solid length.

Task 15: Detailed Component Drawings

1. Generate the front and end views of each spring.
2. Add the wire diameter, the outside diameter, the inside diameter and the free length.
3. Add the coil data and the direction of coil.
4. Add the specification table.
5. Add the material and heat-treatment notes.
6. Complete the title block.

Task 16: Assembly Drawing with Load–Deflection Specification

1. Generate the sectional front view and the end view.
2. Add the overall dimensions and the clearances.
3. Add part numbers, balloons and a parts list.
4. Add the load–deflection specification table.



5. Add the combined load–deflection diagram.
6. Complete the title block.

A6-III Design of the number, width and thickness of leaves and the initial nip

Problem Statement

A village transport cooperative uses a light goods carrier to bring farm produce to the market. The vehicle uses semi-elliptic multi-leaf springs made up of full-length leaves and graduated leaves. On rough roads, the full-length (master) leaves have broken repeatedly, because in a spring without initial nip the full-length leaves are stressed 50% more than the graduated leaves. To equalise the stresses in all the leaves, the springs are to be made with an initial nip, that is, an initial gap between the full-length and the graduated leaves that is closed when the centre bolt is tightened. The number of leaves, their width and thickness, and the initial nip are initially unknown.

As a design engineer applying the principles of Design of Machine Elements, you are required to analyse and design the multi-leaf spring with nip for the specified load and span, determine the number, width and thickness of the leaves, the initial nip and the pre-load, compare the design with and without nip, and establish the load–deflection behaviour. Finally, prepare the 3-D CAD models of the leaves, the assembly, the assembly drawing and the Bill of Materials (BOM).

Given Data

Parameter	Value
Application	Rear suspension of a light goods carrier for farm produce
Type of spring	Semi-elliptic multi-leaf spring
Maximum load at the centre of the spring, $2P$	9 kN
Effective span of the spring, $2L$	1000 mm
Number of full-length leaves, n_f	2 (including the master leaf)
Number of graduated leaves, n_g	To be determined
Spring material	Spring steel 55Si2Mn90 (oil hardened and tempered)
Allowable bending stress, σ	450 MPa
Modulus of elasticity, E	207 GPa
Ratio of width to thickness of leaf, b/t	Between 6 and 10
Available standard strip widths	40, 45, 50, 55, 60 mm
Available standard strip thicknesses	5, 6, 7, 8, 9, 10 mm
Permissible deflection at maximum load	Not more than 70 mm
Width of central band	60 mm
Lengths of the graduated leaves	In equal steps, with the shortest leaf not less than 160 mm
Free camber for the drawing	100 mm
Standard centre bolt sizes	M8, M10, M12
Rebound clips	2 nos.
Design objective	Equal stress in all leaves
Alternative case for Task 11	Maximum load at the centre increased from 9 kN to 12 kN

Tasks (Problem-Solving Component)

1. Loading and Basic Dimensions

1. Calculate the load at each end of the spring from the load at the centre.
2. Calculate the half-span of the spring.
3. Identify the permissible deflection and the allowable bending stress.
4. Identify the range of the ratio of width to thickness.

2. Analysis of the Spring Without Nip

1. Take trial values of the width, thickness and the number of graduated leaves.



2. Calculate the bending stress in the full-length leaves without nip.
3. Calculate the bending stress in the graduated leaves without nip.
4. Compare the two stresses and the ratio between them.
5. Compare the stress in the full-length leaves with the allowable stress.

3. Design of the Leaves with Nip

1. Write the equal-stress condition for all leaves.
2. Determine the number of leaves required for trial standard values of width and thickness.
3. Select the standard width and thickness within the allowed b/t range.
4. Adopt a whole number of leaves and determine the number of graduated leaves.
5. Recalculate the bending stress in the leaves.

4. Deflection Check

1. Calculate the deflection of the spring at the maximum load.
2. Compare it with the permissible deflection.
3. Modify the thickness or the number of leaves if required.
4. Calculate the stiffness of the spring.

5. Initial Nip and Pre-Load

1. Calculate the initial nip (gap) between the full-length and the graduated leaves.
2. Calculate the initial pre-load between the full-length and the graduated leaves.
3. Calculate the bending stress in the full-length leaves due to the pre-load.
4. Verify that the stresses in the full-length and the graduated leaves are equal at the maximum load.

6. Length of the Leaves and Central Band

1. Take the length of the master leaf and of the second full-length leaf.
2. Take the length of the shortest leaf.
3. Determine the equal step in the lengths of the graduated leaves.
4. Tabulate the length of each leaf.
5. Check that the shortest leaf extends beyond the central band.

7. Centre Bolt and Clips

1. Select the standard centre bolt and nut.
2. Select the rebound clips and their rivets or bolts.
3. Decide on the eye dimensions of the master leaf.
4. Note that the centre bolt hole lies at the section of maximum bending moment, and discuss how the clamping effect of the central band compensates for the reduced section.

8. Load–Deflection Characteristic

1. Calculate the deflection at several loads between zero and the maximum load.
2. Plot the load–deflection diagram.
3. Compare the deflection with and without nip.
4. Calculate the energy stored at the maximum load.

Tasks (Interpretation Component)

9. Design Justification

Explain why a multi-leaf spring is made with graduated leaves and with full-length leaves.

Discuss:



1. Strength of the graduated leaves as an approximation to a beam of uniform strength.
2. Function of the full-length leaves in carrying the side loads and supporting the eyes.
3. Effect of the width and thickness of the leaves on the stress and the deflection.
4. Reason for using a central band and a centre bolt.
5. Reason for using rebound clips.

10. Interpretation of the Initial Nip

Interpret the effect of the initial nip on the stresses in the leaves.

Discuss:

1. Reason why the full-length leaves are more highly stressed without nip.
2. Initial stresses produced when the gap is closed by the centre bolt.
3. Redistribution of stress between the full-length and the graduated leaves.
4. Effect of too small and too large a nip.
5. Effect of the nip on the stiffness and on the fatigue life of the spring.

11. Trade-off Analysis

If the maximum load at the centre is increased from 9 kN to 12 kN, interpret how the spring would need to be redesigned.

Discuss the effects of:

1. Increasing the number of leaves.
2. Increasing the width of the leaves.
3. Increasing the thickness of the leaves.
4. Using a steel of higher allowable stress.
5. Changing the span.

Compare the alternatives in terms of stress, deflection, mass, cost and ride comfort.

12. Sustainability Interpretation

Comment on how correct design of the leaf spring avoids unnecessary material use.

Discuss how the design can:

1. Reduce the mass of steel by equalising the stress in all leaves.
2. Extend the service life by avoiding repeated failure of the master leaf.
3. Allow a broken leaf to be replaced in a local workshop without replacing the complete spring.
4. Reduce vehicle damage and produce loss on rough rural roads.
5. Support recycling of the spring steel at the end of its life.

13. 3-D CAD Modelling

Create separate 3-D CAD models for:

1. The master leaf with eyes.
2. The second full-length leaf.
3. The graduated leaves of different lengths.
4. The centre bolt and nut.
5. The rebound clips.

The models should include:



1. Curved leaf profile with the specified camber.
2. Correct width, thickness and length of each leaf.
3. The centre bolt hole in every leaf.
4. The eye of the master leaf.

14. Assembly

Assemble the components in the following sequence:

Master Leaf → Full-Length Leaf → Graduated Leaves (longest to shortest) → Centre Bolt → Nut → Rebound Clips

Check:

1. Alignment of the leaves on the centre bolt.
2. The initial gap between the full-length and the graduated leaves before tightening.
3. Closure of the gap after tightening.
4. Interference between the parts.

15. Detailed Component Drawings

Prepare production drawings for the master leaf, the second full-length leaf, a graduated leaf and the centre bolt.

Each drawing should contain:

1. Front and side views.
2. Length, width, thickness, camber and eye dimensions.
3. Dimensions, tolerances and surface-finish requirements.
4. Material and heat-treatment specification.
5. Title block with scale, projection method and drawing number.

16. Assembly Drawing

Prepare a 2-D assembly drawing containing:

1. Front view showing the camber, the eyes and the leaf arrangement.
2. Sectional view through the centre bolt and the central band.
3. Overall dimensions, the span and the camber.
4. Initial nip and load-deflection specification.
5. Part numbers and balloons.
6. Title block with scale, projection method and drawing number.

17. Bill of Materials (BOM)

Prepare a Bill of Materials for the complete assembly.

Sl. No.	Part Name	Part No.	Material/Grade	Quantity	Principal Dimensions
1	Master leaf with eyes	P-01	55Si2Mn90	1	To be designed
2	Full-length leaf	P-02	55Si2Mn90	1	To be designed
3	Graduated leaves	P-03	55Si2Mn90	To be determined	Lengths to be designed
4	Centre bolt with nut	P-04	Steel	1	To be selected
5	Rebound clip with rivet	P-05	Mild steel	2	To be selected

Final Objective: Analyse and design the semi-elliptic multi-leaf spring with initial nip for the specified load and span, determine the number, width and thickness of the leaves, the initial nip and the pre-load, compare the design with and without nip, and create the 3-D models, the assembly drawing and the Bill of Materials.



Solution Steps

Task 1: Loading and Basic Dimensions

1. Calculate the end load: $P = 9 \text{ kN} / 2 = 4.5 \text{ kN}$.
2. Calculate the half-span: $L = 1000 / 2 = 500 \text{ mm}$.
3. Note $\sigma = 450 \text{ MPa}$, $E = 207 \text{ GPa}$ and the deflection limit of 70 mm.
4. Note the allowed range $6 \leq b/t \leq 10$.

Task 2: Analysis of the Spring Without Nip

1. Take trial values of b , t and n_g , with $n = n_f + n_g$.
2. Stress in the full-length leaves: $\sigma_f = 18 P L / (b t^2 (2 n_g + 3 n_f))$.
3. Stress in the graduated leaves: $\sigma_g = 12 P L / (b t^2 (2 n_g + 3 n_f))$.
4. Show that $\sigma_f = 1.5 \sigma_g$.
5. Compare σ with 450 MPa.

Task 3: Design of the Leaves with Nip

1. With nip, the stress in all the leaves is equal: $\sigma = 6 P L / (n b t^2)$.
2. Solve for the number of leaves: $n = 6 P L / (\sigma b t^2)$ for trial standard b and t .
3. Select the standard b and t so that b/t lies between 6 and 10.
4. Round n up to a whole number and calculate $n_g = n - n_f$.
5. Recalculate $\sigma = 6 P L / (n b t^2)$ and check it against 450 MPa.

Task 4: Deflection Check

1. Calculate the deflection: $\delta = 6 P L^3 / (E n b t^3)$.
2. Compare δ with 70 mm.
3. Change t or n if the deflection is not acceptable.
4. Calculate the stiffness of the spring at the centre: $k = 2P / \delta$.

Task 5: Initial Nip and Pre-Load

1. Calculate the initial nip: $C = 2 P L^3 / (E n b t^3)$.
2. Calculate the pre-load between the leaves: $P_i = P n_f n_g / (n (2 n_g + 3 n_f))$.
3. Calculate the stress in the full-length leaves due to P_i , in the opposite sense to the load stress.
4. Verify that the final stresses in the full-length and the graduated leaves are equal.

Task 6: Length of the Leaves and Central Band

1. Take the length of the master leaf and of the second full-length leaf as the full length of the spring.
2. Take the shortest leaf not less than 160 mm.
3. Calculate the equal step between the lengths of the graduated leaves: $(\text{length of the longest graduated leaf} - \text{length of the shortest leaf}) / (n_g - 1)$.
4. Tabulate the length of each leaf.
5. Check that the shortest leaf extends beyond the central band of 60 mm.

Task 7: Centre Bolt and Clips

1. Select the centre bolt from M8, M10 and M12 according to the width of the leaves.
2. Select the nut and the rebound clips.
3. Decide the eye bore and the eye thickness of the master leaf.
4. Confirm the positions of the centre bolt hole and the clips.

Task 8: Load-Deflection Characteristic



1. Write the load–deflection relation: load at centre = $k \delta$.
2. Calculate δ for loads of 0, 2, 4, 6, 8 and 9 kN.
3. Plot the load–deflection diagram.
4. Calculate the deflection without nip: $\delta = 12 P L^3 / (E b t^3 (2 n_g + 3 n_f))$, and compare it with that of the nipped spring.
5. Calculate the energy stored: $U = \frac{1}{2} \times 2P \times \delta$.

Task 9: Design Justification

1. Explain that graduated leaves approximate a beam of uniform strength.
2. Explain that full-length leaves hold the spring eyes and take the side loads.
3. Explain that stress varies with $1/(b t^2)$ and deflection with $1/(b t^3)$.
4. Explain the function of the central band, the centre bolt and the clips.

Task 10: Interpretation of the Initial Nip

1. Explain why the full-length leaves carry 50% higher stress without nip.
2. Explain how closing the gap by the centre bolt produces initial stress in the opposite sense.
3. Compare the stresses with and without nip.
4. Explain the effect of too small and too large a nip.
5. Explain the effect on fatigue life.

Task 11: Trade-off Analysis

1. Recalculate the end load for 12 kN.
2. Recalculate the number of leaves for the same b and t .
3. Examine the effect of a larger width and a larger thickness.
4. Check the deflection and the nip for the modified design.
5. Compare the options and select the most practical one.

Task 12: Sustainability Interpretation

1. Compare the mass of steel in the nipped design with a design without nip having the same stress limit.
2. Explain how the nip extends the life of the master leaf.
3. Explain how leaf replacement in a local workshop reduces waste.
4. Relate the design to the reduced produce loss on rural roads.
5. Explain the recycling of spring steel.

Task 13: 3-D CAD Modelling

1. Sketch the curved leaf profile using the camber and the span.
2. Extrude the profile by the leaf width.
3. Create the master leaf with its eyes.
4. Create the graduated leaves with the calculated lengths.
5. Cut the centre bolt hole in every leaf.
6. Create the centre bolt, nut and clips.

Task 14: Assembly

1. Insert the master leaf and the second full-length leaf.
2. Insert the graduated leaves from the longest to the shortest.
3. Insert the centre bolt and the nut.
4. Fit the rebound clips.
5. Check the gap before tightening and its closure after tightening.
6. Check for interference.

Task 15: Detailed Component Drawings



1. Generate the front and side views of the master leaf, the full-length leaf and a graduated leaf.
2. Generate the drawing of the centre bolt.
3. Add the lengths, width, thickness, camber and eye dimensions.
4. Add the tolerances and the surface finish.
5. Add the material and heat-treatment notes.
6. Complete the title block.

Task 16: Assembly Drawing

1. Generate the front view with the camber and the eyes.
2. Generate the sectional view through the centre bolt.
3. Add the overall dimensions, the span and the camber.
4. Add the initial nip and the load-deflection specification.
5. Add part numbers and balloons.
6. Complete the title block.

Task 17: Bill of Materials

1. Assign a part number to the master leaf and to the full-length leaf.
2. Assign part numbers to the graduated leaves, the centre bolt, the nut and the clips.
3. Specify the material or grade of each part.
4. Specify the quantity of each part.
5. Specify the principal dimensions.
6. Verify that the BOM agrees with the 3-D assembly and the assembly drawing.