SEK Design Technology

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A3.1 Material Classification

Material classification and properties

Understanding materials involves recognizing their fundamental characteristics, which fall into categories like **physical, chemical, and mechanical properties**. These properties influence a material's suitability for different applications. For instance, high thermal conductivity is beneficial for heat sinks, while low electrical resistivity is ideal for electrical conductors.

Materials are broadly classified into natural and human-made categories. Natural materials like timber and metals have properties determined by their composition and structure. Human-made materials, such as polymers and composites, offer greater design flexibility as their properties can be engineered to meet specific needs.

Key Idea

The connection between material properties and material selection lies in how these properties align with the requirements of a particular application.

For example:

- durability is linked to strength and corrosion resistance,
- functionality depends on properties like electrical conductivity or thermal insulation,
- aesthetics are influenced by appearance and texture.

Beyond traditional materials, composites and smart materials offer unique advantages. Composites combine multiple materials to enhance their properties, such as fiberglass. Smart materials possess properties that change in response to external stimuli, making them valuable in areas like robotics and medicine.

Additionally, biodegradable materials contribute to sustainability by decomposing naturally.

Important

By understanding material properties and classifications, designers can make informed choices that result in products that are functional, durable, and sustainable.

Main Categories of Material Properties

Category	Description
Physical Properties	Measurable characteristics that describe the material’s state
Mechanical Properties	Properties related to stress, strain, and applied forces
Chemical Properties	Properties related to chemical reactions and interactions

1. Physical Properties

> **Physical properties** are measurable characteristics of materials that describe their state.

These properties include:

- density,
- thermal expansion,
- electrical conductivity,
- thermal conductivity,
- melting point.

These properties can usually be determined without damaging the material.

Examples of Physical Properties

- Density
- Thermal conductivity
- Electrical resistivity
- Melting point
- Optical properties

Key Idea

Physical properties help designers understand how materials behave under environmental conditions.

2. Mechanical Properties

> **Mechanical properties** involve the relationship between stress and strain, or a material's reaction to applied force.

These properties are usually determined through destructive testing.

Examples of Mechanical Properties

- Tensile strength
- Hardness
- Toughness
- Elasticity
- Ductility

> **Important**
>
> Mechanical properties are critical when materials must withstand loads or impacts.

3. Chemical Properties

> **Chemical properties** describe how a material reacts chemically with other substances.

These properties influence:

- corrosion resistance,
- flammability,
- oxidation,
- chemical stability.

Examples of Chemical Properties

- Corrosion resistance
- Reactivity
- Toxicity
- Combustibility

Key Idea

Chemical properties help determine the durability and safety of materials in different environments.

Quick Recap

- Materials are classified according to their physical, mechanical, and chemical properties
- Physical properties describe measurable characteristics without damaging the material
- Mechanical properties involve stress, strain, and force
- Chemical properties describe how materials react chemically
- Understanding material properties helps designers select suitable materials for applications

A3.2 Introduction to Structural Systems

How do structures carry loads, resist forces and remain stable?

Learning goals

- recognise structures in nature and designed products;
- distinguish **frame, shell and solid** structures;
- identify structural members, loads and the five main forces;
- use stress, strain, Young's modulus and safety factor in design decisions.

Starter · Look around the classroom

Find one structure that is mainly a **frame**, one that behaves like a **shell**, and one **solid** component. Be ready to justify each choice.

3.2.1 Structures in Nature and the Built Environment

A **structure** is a system of parts designed to **support loads, resist forces and maintain its shape**. Structures are not limited to buildings: a leaf, a bicycle and the human skeleton all depend on an organised arrangement of material.

A structure is defined by what it does, not only by what it looks like.

Nature as a designer

Natural structures often achieve high performance with little material. Their form has developed in response to a function:

Natural structure	What to notice	Structural benefit
Spider web	radial and spiral threads	carries tension with very little material
Honeycomb	repeated hexagonal cells	encloses space efficiently and shares loads
Leaf veins	branching network	supports the leaf and transports nutrients
Eggshell	thin, curved surface	protects the contents and spreads load

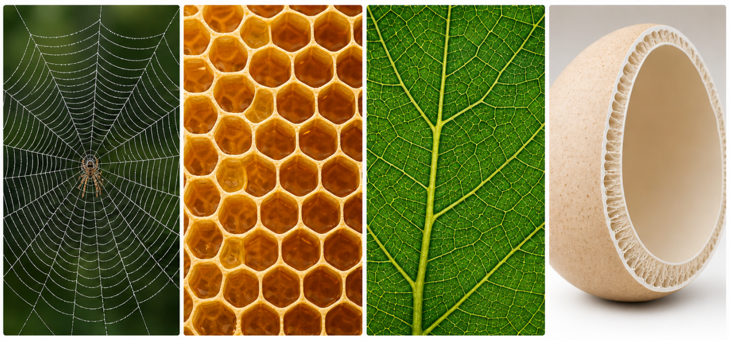


Figure 1. Spider web, honeycomb, leaf veins and eggshell. In each case, geometry reduces the amount of material required.

Spot it

Trace the **load path** with your finger: where does an applied force travel, and which parts finally support it?

Human-made structures

Designed structures respond to a purpose and a context. A bridge spans a gap; a building provides shelter; a dam holds back water; a chair supports a user. Designers balance:

Figure 2. Bridge, Building, Dam, Chair.

form · **function** · **materials** · **forces** · **culture** · **cost**

Think like a designer

Do not write only, “It is strong.” Explain **why**: “The curved shell spreads the load over its surface, so a thin layer of material can resist the force.”

A six-question analysis routine

1. What is its **purpose**?
2. What **loads** act on it?
3. Where are the **supports**?
4. How does the **shape** carry the load?
5. Why is this **material** suitable?
6. Where might it **deform or fail**?

Common mistake

Naming a structure is **description**. Explaining how its parts, shape and material resist forces is **analysis**.

3.2.2 Classification of Structures

The three main structural types are **frame**, **shell** and **solid**. Many real products combine more than one type.

Frame

A skeleton of interconnected members.

Strength comes from: arrangement and joints.

Clue: you can see spaces between the members.

Shell

A thin surface that encloses a space.

Strength comes from: surface and shape.

Clue: the skin carries and spreads the load.

Solid

A mass of material that resists through its bulk.

Strength comes from: material and cross-section.

Clue: little or no internal empty space.

Frame structure · bicycle

Figure 2. A bicycle frame connects the wheels, saddle and handlebars.

The tubes form interconnected triangles. This provides **rigidity and load distribution** while keeping mass low. Frames are useful when the goal is high strength with low weight.

Look for the same principle in scaffolding, cranes, roof trusses, furniture and skeletons.

Shell structure · drinks can

A can uses a very thin sheet of aluminium. Its cylindrical form creates rigidity, encloses liquid and distributes loads. Shells are useful for **protection, enclosure, aerodynamics and watertightness**.

Other examples include helmets, eggshells, domes, vehicle bodies and aircraft skins.

Figure 3. The curved wall of a can spreads forces across its surface.

Solid structure · dam and engine block

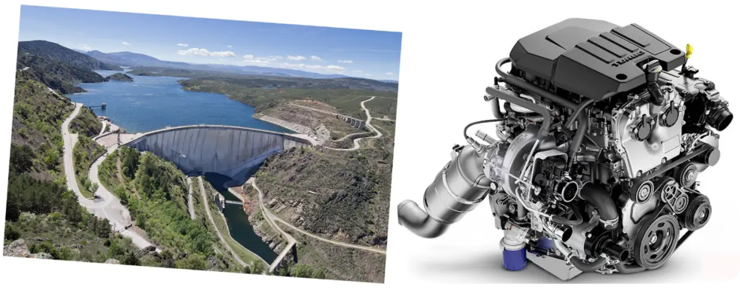


Figure 4. Solid structures resist large forces through material strength and bulk.

Solid structures are usually **stable, durable and difficult to deform**, but they often have greater mass, material use and cost. Examples include dams, foundations, hammer heads, teeth and machine parts.

Quick check

A crash helmet has a hard outer skin and a thick foam liner. Is it frame, shell or solid? **Answer:** it is a combination—the outer shell spreads impact while the foam behaves as a solid energy-absorbing layer.

Why combine types?

Product	Frame	Shell	Solid
Car	chassis	body panels	engine block
Building	columns and beams	cladding	foundations
Aircraft	fuselage ribs	external skin	landing gear components
3D printer	rigid gantry	enclosure	motor housings

Classification depends on how each part carries load; one product may contain all three types.

3.2.3 Structural Components

Structural members create a path that transfers loads safely to the supports and, eventually, to the ground.

Beams and columns

- A **beam** usually carries loads across a horizontal distance.
- A **column** usually carries compressive loads vertically towards the foundations.

Figure 5 · Beam. A beam carries loads across a span and transfers them to its supports. In an I-section, the flanges resist most of the bending while the web resists shear.

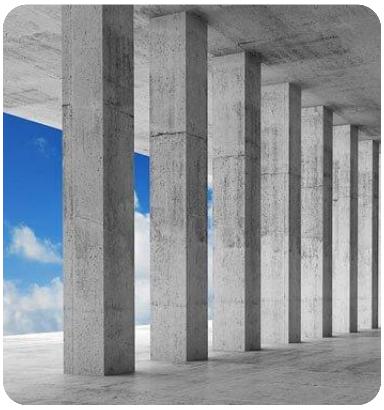


Figure 6 · Column. Columns carry loads mainly in compression, transferring the weight of slabs and beams down towards the foundations.

Beam type	How it is supported	Easy-to-recognise example
Simply supported	support at both ends; ends may rotate	shelf resting on two brackets
Fixed	rigidly fixed at both ends	beam cast into concrete walls
Cantilever	fixed at one end; other end is free	balcony or diving board
Continuous	extends over more than two supports	long multi-span bridge deck

Photo challenge · Identify the beam type

A

B

C

D

Identify the beam types

Which beam type is shown in each photograph **A–D**? Choose the best description from **simply supported, fixed, cantilever** or **continuously supported**.

For each answer, justify your decision by describing:

1. the **number and position of the supports**;
2. whether either end appears free to **move or rotate**;
3. any additional support that makes the real structure more complex than the simplified model.

Suggested analysis

- **A — Simply supported:** the bridge deck spans between supports at each end.
- **B — Stayed cantilever:** the balcony projects from the building, but diagonal tension stays provide additional support. It is not a pure cantilever.
- **C — Continuously supported:** one deck extends across several piers, so the load is shared between multiple supports.
- **D — Insufficient evidence from this view:** the visible end is rigidly fixed. If the unseen end is free, it is a cantilever; it is a fixed beam only if the other end is also fixed.

Recognition technique

Cover the object itself and inspect only its **supports**. Beam names describe the support condition, not the material or appearance.

Columns

Columns are **vertical structural members** designed primarily to transfer **compressive loads**.

They carry loads from above, such as:

- roofs,
- upper floors,
- beams.

These forces are transferred downward towards the **foundations**.

Columns therefore contribute to the stability of the complete structure.

Examples

- columns in classical Greek temples,
- timber or steel columns in buildings,

- table legs,
- chair legs.

In residential buildings, columns can replace some load-bearing walls, allowing designers to create more open interior spaces.

Key Idea

Beams mainly carry loads across horizontal distances, while columns transfer loads vertically towards the foundations.

Load-path example

> **Person on a balcony** → balcony beam → fixed connection → building frame → foundations → ground

The free end of a cantilever needs no column below it, but the fixed connection must resist a large bending effect.

Check your understanding

Why is a diving board a **cantilever** but a shelf on two brackets is usually **simply supported**?

Answer

The diving board is fixed at one end and free at the other. The shelf transfers load to supports near both ends.

3.2.4 Static, Dynamic and Structural Forces

A **load** is an external action on a structure. Loads create internal forces and stresses in its members.

Static and dynamic loads

Static	Dynamic
constant or slowly changing	changes with time or movement
little impact or vibration	may include impact or vibration
roof weight, books on a shelf	traffic, wind gusts, a person jumping

⚠ **Important distinction**

“Static” does not mean “small,” and “dynamic” does not mean “large.” The distinction is whether the load changes significantly with time.

The five actions

Action	What the material does	Everyday memory cue
Compression	shortens or squashes	chair leg
Tension	lengthens or pulls apart	rope in tug-of-war
Bending	curves; one side compresses and the other stretches	diving board
Torsion	twists around an axis	screwdriver shaft
Shear	adjacent parts slide in opposite directions	scissors cutting paper

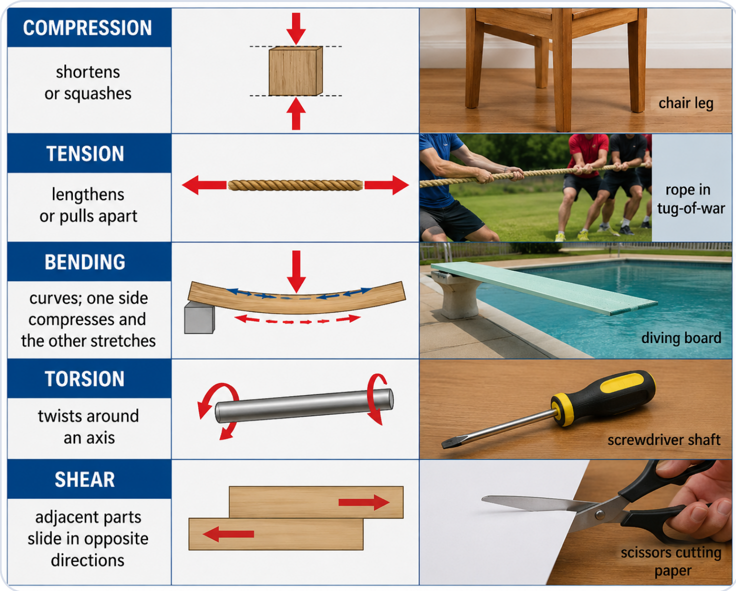


Figure 7 · The five structural actions. The arrows show how each action affects a material; the photographs connect each action to an everyday example.

Push = compression · **Pull** = tension · **Curve** = bending · **Twist** = torsion · **Slide** = shear

Use your hands

Mime each action while saying its name. Linking a technical term to a physical movement makes it easier to retrieve later.

Forces act together

When a beam bends, the inside of the curve is in **compression** and the outside is in **tension**. Bolts at its connection may also experience **shear**. Analyse the complete load path rather than assigning only one force to an entire product.

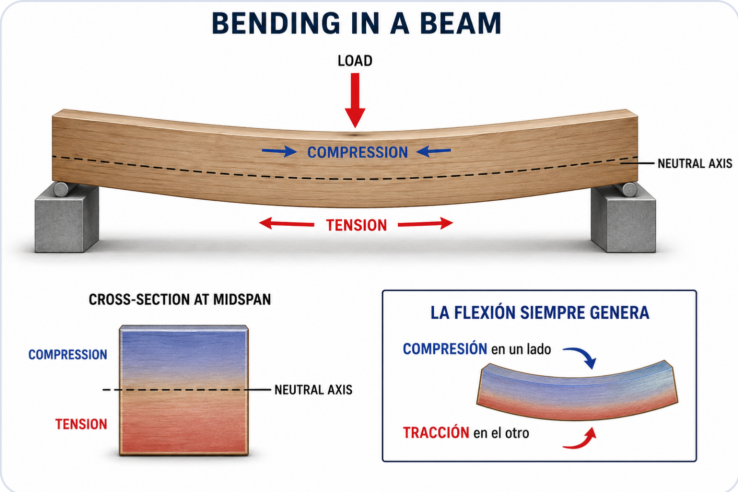


Figure 8 · Forces acting together. Bending creates compression above the neutral axis and tension below it; stress increases with distance from the neutral axis.

Bending always creates tension on one side and compression on the other.

3.2.5 Stress, Strain and Material Failure

Force alone does not tell us how severely a material is loaded. The same force becomes more critical when it acts through a smaller area.

Stress

Stress σ is the applied **force** divided by the **cross-sectional area** carrying that force:

$$\text{Stress} = \frac{\text{Force}}{\text{Cross-sectional area}}$$

Using symbols, the same relationship is:

$$\sigma = \frac{F}{A}$$

Stress is measured in **pascals (Pa)**:

$$1\ \text{Pa} = 1\ \text{N}/\text{m}^2$$

The prefix **mega (M)** means **one million**:

$$1 \text{ MPa} = 1,000,000 \text{ Pa} = 1 \text{ N/mm}^2$$

For this reason, **MPa** and **N/mm²** are commonly used in product design and engineering.

Worked example

A 10,000 N tensile force acts on a rod with an area of 200 mm^2.

$$\sigma = \frac{10\,000}{200} = 50 \text{ N/mm}^2 = 50 \text{ MPa}$$

Strain

Strain ε compares the change in length with the original length:

$$\varepsilon = \frac{\Delta L}{L_0}$$

Strain has **no unit** because it is a ratio of two lengths.

Connecting stress, strain and stiffness

Stress describes how intensely a material is loaded; **strain** describes how much it deforms in response. Comparing them tells us how easily the material changes shape.

Within the elastic region:

$$E = \frac{\text{stress}}{\text{strain}}$$

This ratio is **Young's modulus**. A high value means that a large stress produces only a small strain, so the material is **stiff**. A low value means that the material deforms more easily and is therefore more **flexible**.

Reading a stress–strain graph

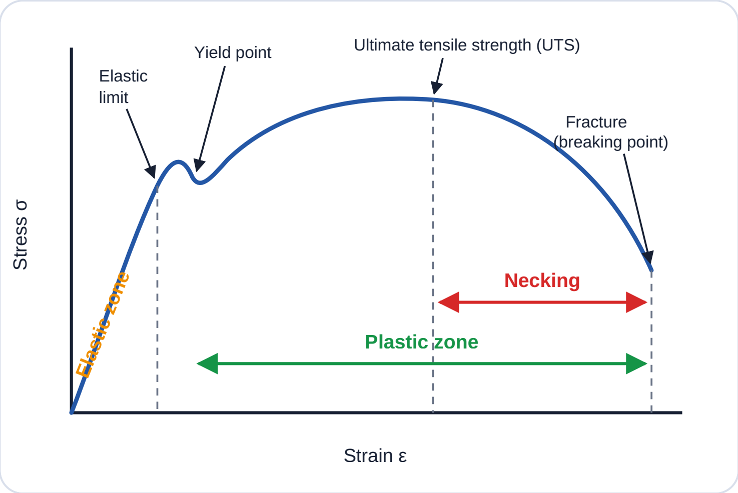


Figure 9 · Reading a stress–strain graph. Stress is plotted vertically and strain horizontally. The curve shows the transition from reversible elastic deformation to permanent plastic deformation, necking and final fracture.

1. **Elastic region:** deformation is reversible; when the load is removed, the specimen returns to its original length.
2. **Yield strength:** permanent deformation begins. From this point, the specimen will not fully return to its original shape.
3. **Plastic region:** the specimen continues to stretch permanently while still carrying an increasing tensile load.
4. **Ultimate tensile strength (UTS):** the highest engineering tensile stress recorded during the test.
5. **Necking and fracture:** after UTS, deformation becomes concentrated in a narrow region. The specimen carries less load until it finally separates.

Ultimate tensile strength (UTS)

UTS is the maximum engineering tensile stress a material reaches during a tensile test. It is calculated using the greatest tensile load and the specimen's original cross-sectional area:

$$UTS = \frac{F_{max}}{A_0}$$

At UTS, the material has reached its peak load-carrying capacity. **Necking normally begins after this point**, but the specimen has not broken yet. **Fracture occurs later**, when the remaining section can no longer carry the load.

Yield → permanent deformation begins · **UTS** → highest engineering tensile stress · **Fracture** → the specimen separates

Do not confuse UTS with fracture

UTS is the peak of the engineering stress–strain curve, not the breaking point. A ductile material can continue stretching and necking between UTS and final fracture.

Common mistake

Stiffness is resistance to elastic deformation. **Strength** is resistance to yielding or failure. A material can be stiff but brittle, or flexible but strong.

3.2.6 Young's Modulus and Material Selection

Young's modulus E measures **stiffness** in the linear elastic region:

$$E = \frac{\text{stress}}{\text{strain}} = \frac{\sigma}{\varepsilon}$$

High Young's modulus	Low Young's modulus
steep stress–strain slope	shallow stress–strain slope
small elastic deformation under load	larger elastic deformation under load
useful for frames, beams and precision machines	useful for seals, cushions and flexible components

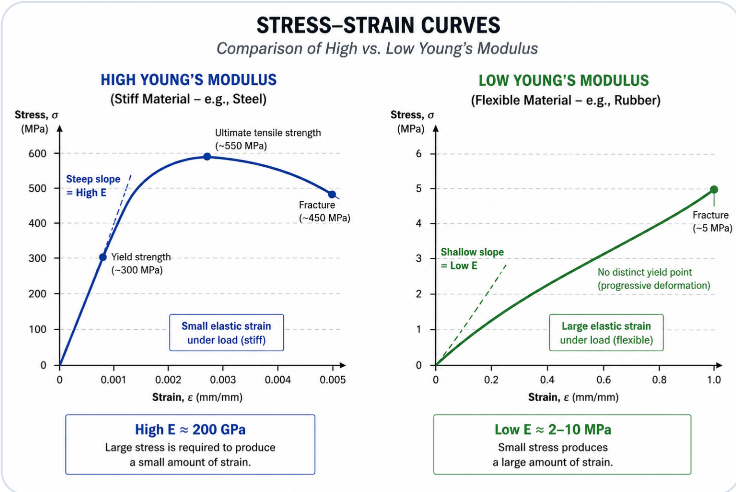


Figure 10 · High and low Young's modulus. A steep initial slope indicates a stiff material with a high Young's modulus; a shallow slope indicates a more flexible material with a low Young's modulus.

Material type	Materials	Modulus of elasticity (GPa)	Typical applications
Polymers (low)	Polyethylene, PVC, nylon	0.1–4	Packaging, piping, textiles, insulation
Natural materials	Wood (softwood/hardwood), bamboo	5–15	Furniture, construction, flooring
Composites (low modulus)	Glass fibre-reinforced polymer (GFRP)	10–25	Boat hulls, automotive panels, sports equipment
Concrete	Standard concrete	20–40	Buildings, bridges, pavements
Composites (high modulus)	Carbon fibre-reinforced polymer (CFRP)	70–150	Aerospace, racing cars and high-performance sporting goods
Metals (low modulus)	Aluminium alloys	69–80	Aircraft structures, automotive parts and packaging
Metals (mid modulus)	Titanium alloys	100–120	Aerospace, biomedical implants and military applications
Metals (high modulus)	Steel (carbon, alloy, stainless)	190–210	Skyscrapers, bridges, machinery and automotive frames
Ceramics	Alumina, silicon carbide	300–450	Cutting tools, armour, electronics and high-temp components
Advanced materials	Graphene, diamond	1000+	Nanoelectronics, quantum devices and ultra-strong composites

Figure 11 · Typical Young's modulus values. These approximate ranges help compare material stiffness; actual values depend on composition, processing, orientation and test conditions.

A high Young's modulus means stiff, not automatically strong.

Material-selection sentence frames

Complete both sentences before opening the model answers:

1. **High Young's modulus:** “I would select ___ because its **high Young's modulus** means it will ___ under the expected load, which is important because ___.”
2. **Low Young's modulus:** “I would select ___ because its **low Young's modulus** means it will ___ under the expected load, which is important because ___.”

Show model answers

1. **High Young's modulus — machine frame:** “I would select **steel** because its **high Young's modulus** means it will **deform very little** under the expected load, which is important because the machine must remain **rigid and accurate**.”
2. **Low Young's modulus — sealing strip:** “I would select **rubber** because its **low Young's modulus** means it will **deform easily and conform to the surfaces** under the expected load, which is important because it must create an effective **air- and watertight seal**.”

Design context matters

An earthquake-resistant building needs strength but may also need controlled flexibility and energy dissipation. The “best” material is therefore not always the stiffest one: designers balance stiffness, strength, toughness, mass, cost and manufacturing.

3.2.7 Equilibrium and Structural Stability

A structure is in **equilibrium** when its forces and moments are balanced, so it has no overall linear or rotational acceleration. Both conditions below must be satisfied at the same time.

Translational equilibrium

The resultant force is zero:

$$\sum F = 0$$

Upward reactions balance downward loads, and horizontal reactions balance horizontal loads.

Rotational equilibrium

The resultant moment about any point is zero:

$$\sum M = 0$$

Clockwise moments balance anticlockwise moments.

Moment reminder

Moment = Force × perpendicular distance from the pivot

When can a structure fail?

A structure may fail when **equilibrium is lost** or when its **load-carrying capacity is exceeded**. Failure does not always mean immediate collapse: it may begin as excessive movement, permanent deformation, cracking, buckling or foundation settlement.

Cause of failure	How it affects the structure	Possible result or example
Overloading	The applied load produces internal stresses greater than the strength of a member or connection.	Permanent deformation, buckling or collapse; for example, a floor carrying more weight than it was designed for.
Uneven force distribution	Loads become concentrated in one area or act away from the centre, creating excessive local stress or an unbalanced turning moment.	Local cracking, twisting or overturning; for example, a shelf loaded heavily at one end.
Foundation instability	A support shifts, sinks or rotates, changing the reactions and disrupting the intended load path.	Tilting, cracking and possible progressive collapse; for example, uneven settlement in soft ground.
Dynamic impacts	Sudden or changing loads create acceleration, vibration and inertia forces faster than the structure can respond safely.	Oscillation, connection failure or collapse during an earthquake, wind gust, collision or impact.

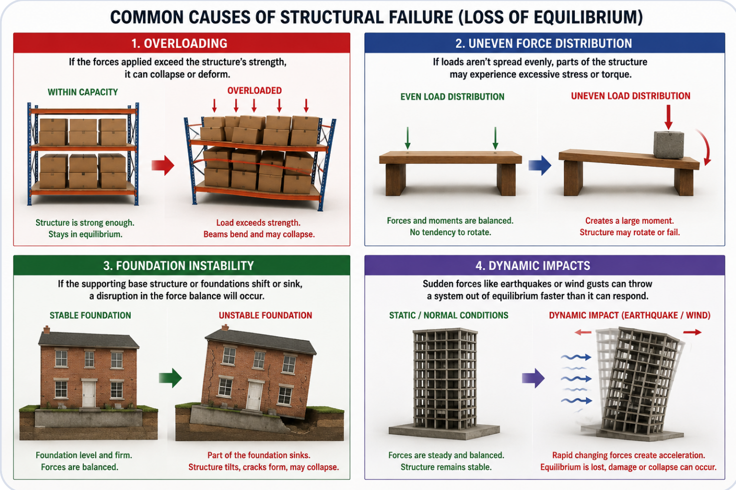


Figure 12 · Common causes of structural failure. Each comparison shows how a change in load, load position, support condition or dynamic action can disrupt the intended structural behaviour.

> ⚠ **Important distinction**
>
> A structure can be in external equilibrium and still fail if its members are not strong or stiff enough. **Equilibrium describes balance; strength describes whether the structure can resist the resulting internal stresses.**

Failure risk increases when: loads are too large · loads are badly distributed · supports move · forces change suddenly

3.2.8 Strengthening Structures

Structures can be strengthened **without simply adding more material**. Designers improve the way a structure carries and distributes loads by using four main techniques:

struts · shape · lamination · composite materials

Efficient strengthening places material and geometry where they contribute most to the load path.

1. Struts

A **strut** is a structural member designed mainly to resist **compression**. Struts reinforce frames by creating additional load paths.

They can:

- distribute loads through different parts of a structure;
- reduce stress concentrations at individual joints;
- prevent long members from bending or **buckling**;
- increase the rigidity and stability of a frame.

From a rectangle to triangles

Adding a diagonal strut divides a rectangular frame into triangles:

Without a diagonal strut	With a diagonal strut
The rectangle can distort into a parallelogram.	The frame is divided into two triangles.
Loads may concentrate at the joints.	The diagonal provides a new compression load path.
The frame has low resistance to sideways deformation.	The frame becomes much more rigid and stable.

This works because a rectangle can change shape without changing the length of its sides, whereas a triangle is **geometrically stable** unless one of its members changes length.

Typical applications include **roof trusses, truss bridges and aircraft structures**.

Key idea · Struts

Struts strengthen a structure by resisting **compression**, distributing loads and preventing deformation or buckling.

Check your understanding

Why does adding a diagonal strut make a rectangular frame more stable?

Show answer

The diagonal creates triangular sections. Triangles resist changes in shape, while the strut carries compressive force through the frame and away from individual joints.

2. Shape

The **geometry** of a structure can greatly increase its strength and stiffness without necessarily increasing the amount of material. Different shapes control forces in different ways.

Triangles

Triangles are geometrically stable and resist distortion. This is why they are widely used in **trusses, bridges, bicycle frames and roof structures**.

Arches and domes

Arches and domes redirect much of an applied load into **compression** and transfer it towards their supports. This reduces the bending that would occur in a flat beam spanning the same opening.

Corrugation

Folding a thin sheet into a corrugated profile increases its depth and makes it much more resistant to bending. The amount of material may be almost unchanged, but its geometry produces far greater stiffness.

Typical examples are **corrugated cardboard and metal roofing**.

I-beams

An I-beam places most of its material away from the **neutral axis**, where bending stresses are greatest:

- the upper and lower **flanges** provide most of the bending resistance;
- the central **web** resists much of the shear force and keeps the flanges apart.

This creates a high resistance to bending without using a completely solid section, giving an efficient **strength-to-weight ratio**.

Structural shape	Main mechanism	Typical example
Triangle	prevents a frame changing shape	roof truss
Arch or dome	redirects loads through compression	stone bridge or stadium roof
Corrugation	increases section depth and bending stiffness	cardboard or roof sheet
I-section	positions material away from the neutral axis	steel floor beam

Key idea · Shape

Shape strengthens a structure by using geometry to distribute forces efficiently and resist deformation without necessarily adding more material.

3. Lamination

Lamination means bonding multiple layers of material together to form a stronger and more reliable structural material.

Lamination can:

- increase strength and stiffness;
- improve toughness;
- slow or redirect the propagation of cracks;
- allow different layers to perform different functions;
- combine useful levels of strength and flexibility.

Loads are shared between the bonded layers, so a weakness in one layer can be supported by the others.

Plywood

Plywood is made by bonding thin sheets of wood veneer. The grain direction of adjacent layers is usually rotated:

Layer 1 → → → → → **Layer 2** ↑ ↑ ↑ ↑ ↑ **Layer 3** → → → → →

Natural timber is much stronger in some directions than others. Crossed grain directions make plywood more dimensionally stable and resistant in more than one direction.

Cross-laminated timber (CLT)

CLT uses thicker timber layers arranged crosswise to adjacent layers. The crossed arrangement produces large structural panels with increased rigidity and strength.

Key idea · Lamination

Lamination strengthens a structure by bonding layers so that loads are shared and weaknesses or cracks in individual layers are less likely to continue through the whole material.

4. Composite materials

A **composite material** combines two or more different materials whose properties complement each other. The aim is to obtain structural performance that the materials cannot provide as effectively on their own.

Composites can provide:

- a high strength-to-weight ratio;
- strength and stiffness in selected directions;
- improved durability;
- improved corrosion resistance.

In fibre-reinforced composites, designers can orientate the fibres to resist forces in the directions where strength and stiffness are most needed.

Reinforced concrete

Reinforced concrete clearly demonstrates complementary material properties:

Material	Performs well in	Function in a reinforced-concrete member
Concrete	compression	carries much of the compressive stress and protects the reinforcement
Steel reinforcement	tension	carries tensile stress where concrete would crack

Concrete — strong in compression + **Steel** — strong in tension → **Reinforced concrete**

When a reinforced-concrete beam bends, concrete carries much of the compression while steel bars positioned in the tensile region help prevent tensile failure.

Carbon-fibre composite

A carbon-fibre-reinforced polymer combines:

- **carbon fibres**, which provide strength and stiffness;
- a **polymer matrix**, which holds the fibres together, protects them and transfers loads between them.

The fibres can be orientated to match the direction of the expected forces, allowing high performance with relatively low mass.

Key idea · Composite materials

Composite materials strengthen structures by combining materials with complementary properties, allowing each material to perform the function it does best.

Comparing the four strengthening techniques

Technique	How it strengthens the structure	Simple example
Struts	resist compression, distribute loads and prevent deformation or buckling	roof truss
Shape	uses geometry to distribute forces efficiently and increase rigidity	triangle, arch, corrugation or I-beam
Lamination	bonds layers so loads are shared and weaknesses or crack propagation are reduced	plywood or CLT
Composite materials	combines materials with complementary properties	reinforced concrete or carbon fibre

Choose the strengthening technique

Identify the main technique in each example: a corrugated cardboard box, a plywood panel, a roof truss and a reinforced-concrete beam.

Show answer

- Corrugated cardboard box → **shape**.
- Plywood panel → **lamination**.
- Roof truss → **struts and triangulation**.
- Reinforced-concrete beam → **composite materials**.

3.2.9 Safety Factor

The **factor of safety** compares the load that causes failure with the maximum expected working load:

$$SF = \frac{\text{failure load}}{\text{working load}}$$

Worked example

A hook fails at 12 kN and is rated for a 3 kN working load:

$$SF = \frac{12}{3} = 4$$

The failure load is four times the intended working load.

Why include a margin?

Real conditions contain uncertainty:

- variation in material properties and dimensions;
- manufacturing defects;
- unexpected or uneven loads;
- impact, vibration and fatigue;
- corrosion, wear and ageing;
- errors in use, inspection or maintenance.

Important

A higher safety factor is not free: it can increase mass, cost and environmental impact. The required value depends on consequences of failure, uncertainty, standards and the design method used.

3.2.10 Designing Above the Required Load

A safety factor of 1 means the predicted failure load equals the expected maximum load. This leaves no allowance for uncertainty or deterioration.

Safe design separates normal working conditions from failure.

A balanced decision

The designer must balance:

safety · **reliability** · **mass** · **cost** · **material use** · **regulation**

Values should come from the applicable engineering standards and evidence—not from a universal table applied to every product.

Exit ticket · 60 seconds

Choose one classroom product and write three sentences:

1. classify its structural type;
2. identify its main load and internal force;
3. explain one way to strengthen it without adding unnecessary mass.

Topic recap

1. Structures **support loads, resist forces and maintain shape**.
2. Frame, shell and solid structures obtain strength in different ways.
3. Supports determine the behaviour of beams; columns transfer compression vertically.
4. Loads may be static or dynamic and can create compression, tension, bending, torsion and shear.
5. Stress describes force per area; strain describes relative deformation.
6. Young's modulus measures stiffness in the elastic region.
7. Equilibrium requires balanced forces and moments.
8. Geometry, lamination and composites can strengthen structures efficiently.
9. Safety factors provide a margin between working conditions and failure.

You should now be able to...

Analyse a product by tracing its load path, naming the structural system and forces, and justifying material and strengthening choices with technical evidence.

B1.1 User-Centred Design

B1.1.4 Usability Objectives

> **Usability objectives** are criteria used by designers to evaluate how easy, efficient, memorable, safe, and satisfying a product is to use.

Usability objectives help designers analyse products from the user's perspective and identify opportunities for improvement.

They are important because they help create products that are:

- easier to use,
- more intuitive,
- more efficient,
- safer,
- and more enjoyable for users.

Key Idea

Usability objectives help designers improve the interaction between products and users.

Main Usability Objectives

Usability Objective	Main Focus
Learnability	How easily users learn to use the product
Efficiency	How quickly users can perform tasks
Memorability	How easily users remember how to use the product
Errors	How many mistakes users make and recover from
Satisfaction	How pleasant and enjoyable the product is to use

1. Learnability

> **Learnability** refers to how easily users can accomplish basic tasks when they first encounter a product.

Products with high learnability are:

- intuitive,
- easy to understand,
- simple for first-time users.

Key Aspects

- intuitive design,
- clear instructions or labeling,
- logical layout of controls or features.

Evaluation Methods

Designers may evaluate learnability by measuring:

- time needed to complete a task,
- number of attempts required,
- frequency of referring to instructions.

> ### Example: Coffee Maker
>
> A coffee maker with clearly labelled buttons and a simple step-by-step brewing process would score highly in learnability.

Key Idea

Products with good learnability reduce confusion and improve first-time user experiences.

2. Efficiency

> **Efficiency** measures how quickly users can perform tasks once they have learned how to use the product.

Efficient products:

- reduce wasted time,
- simplify interactions,
- improve productivity.

Key Aspects

- streamlined processes,
- minimal steps required,
- well-positioned controls and features.

Evaluation Methods

Designers may analyse:

- task completion time,
- number of steps needed,
- user productivity metrics.

> **Example: Professional Camera**
>
> A professional-grade camera with customizable buttons for quick access to common settings demonstrates high efficiency.

Key Idea

Efficient products allow users to complete tasks quickly and effectively.

3. Memorability

> **Memorability** assesses how easily users can reestablish proficiency after a period of not using the product.

Products with good memorability:

- are consistent,
- use familiar layouts,
- avoid unnecessary complexity.

Key Aspects

- consistent design patterns,
- logical organisation of features,
- memorable icons and labels.

Evaluation Methods

Designers may measure:

- task success after periods of non-use,
- relearning time,
- user recall of functions.

Example: Microwave

A microwave with clear and familiar buttons for common functions such as popcorn or defrost demonstrates good memorability.

Key Idea

Good memorability reduces the need for users to relearn how products work.

4. Errors

> **Errors** focuses on how many mistakes users make, how serious the mistakes are, and how easily users can recover from them.

Good product design aims to minimise user mistakes and improve recovery processes.

Key Aspects

- error prevention features,
- clear warning messages,
- simple recovery processes.

Evaluation Methods

Designers may analyse:

- frequency of user errors,
- severity of mistakes,
- recovery time after errors.

> ### Example: Washing Machine
>
> A washing machine with a child lock feature and warning messages before irreversible cycles demonstrates good error management.

> **Important**
>
> Products should minimise user mistakes and make recovery from errors easy and safe.

5. Satisfaction

> **Satisfaction** measures how pleasant and enjoyable a product is to use.

This objective focuses on the emotional response users experience while interacting with the product.

Key Aspects

- aesthetic appearance,
- comfort,
- positive emotional experience,
- sense of accomplishment.

Evaluation Methods

Designers may use:

- satisfaction surveys,
- recommendation likelihood,
- emotional response analysis.

> ### Example: Office Chair
>
> An ergonomic office chair that is both comfortable and visually attractive would likely score highly in satisfaction.

Key Idea

Products that create positive user experiences are more likely to be successful and appreciated by users.

Quick Recap

- Learnability focuses on how easily users understand a product
- Efficiency measures speed and productivity
- Memorability evaluates how easily users remember the product
- Error analysis helps improve safety and usability
- Satisfaction focuses on comfort and positive user experiences

B1.1.5 Task Analysis

> **Task analysis** is a strategy used by designers to develop empathy and better understand how users perform tasks in order to achieve a goal.

Task analysis helps designers understand:

- how users interact with products,
- what steps users follow,
- what difficulties users experience,
- and where improvements can be made.

By studying user behaviour, designers can create products that are more intuitive, efficient, and user-friendly.

Key Idea

Task analysis helps designers understand the user's experience when completing a task.

What is Task Analysis?

Task analysis involves **breaking a complex activity into smaller and manageable steps**.

This allows designers to study:

- the sequence of actions,
- user behaviour,
- decision-making processes,
- and potential usability problems.

Why is Task Analysis Important?

Task analysis helps designers:

- develop empathy for users,
- understand user needs,
- identify pain points,
- improve efficiency,
- discover opportunities for redesign.

> **Example: Using a Coffee Machine**
>
> A designer may analyse how users prepare coffee using a coffee machine by observing every action performed during the process.

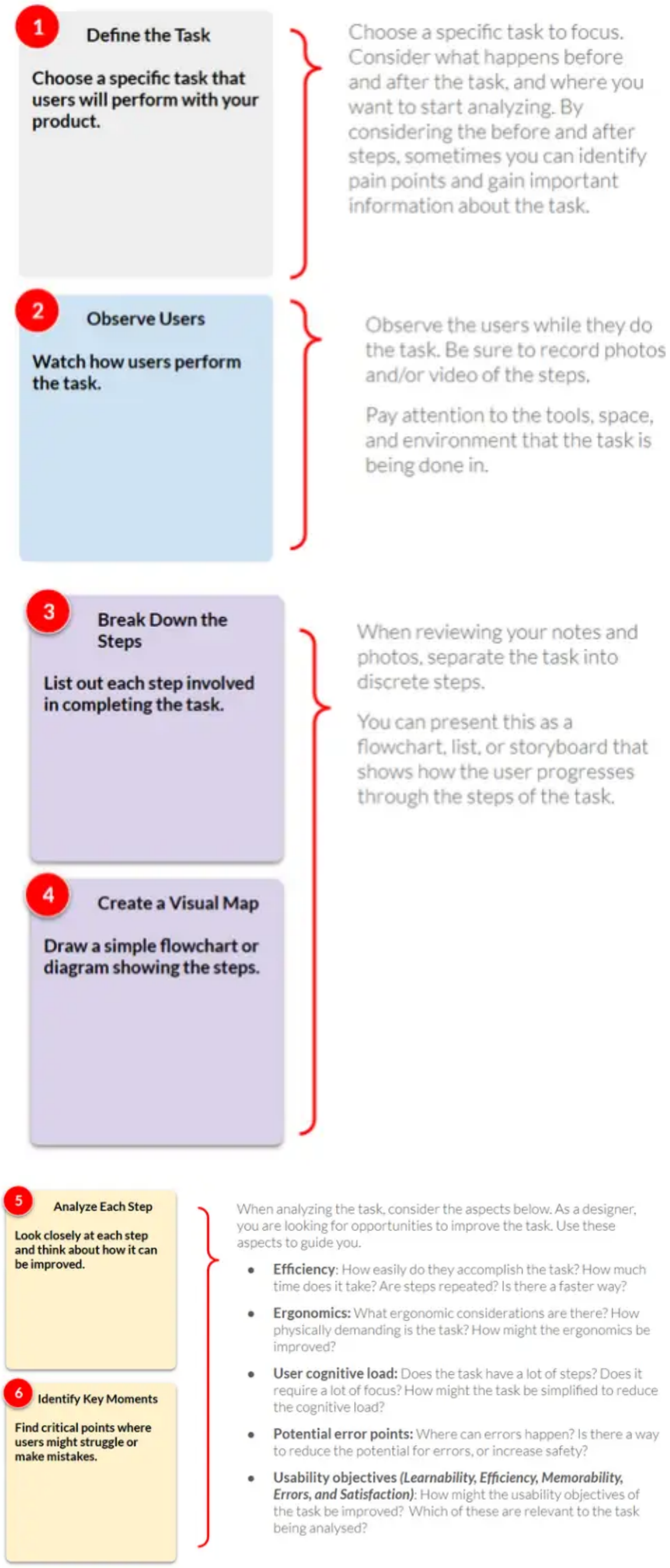
> **Key Idea**
>
> Designers must understand not only the product, but also how users interact with it.

Main Objectives of Task Analysis

Objective	Purpose
Understand user behaviour	Identify how users interact with products
Identify difficulties	Detect usability problems and frustrations
Improve efficiency	Reduce unnecessary actions and complexity
Develop empathy	Understand the user’s experience and needs
Support redesign	Discover opportunities for improvement

Conducting a Task Analysis

Task analysis usually follows a structured process.



1. Identify the Task

Designers first define the specific activity they want to analyse.

Example

Preparing a cup of coffee using a coffee machine.

2. Gather Information

Designers collect information by:

- observing users,
- conducting interviews,
- recording user actions,
- analysing existing instructions or documentation.

Observation

Observing real users often reveals problems that may not appear during technical testing.

3. Break Down the Task

The activity is divided into smaller sequential steps.

Example: Coffee Machine Task Steps

1. Fill the water container
2. Insert coffee capsule
3. Close the machine
4. Select coffee type
5. Press start button
6. Pour coffee into cup

Key Idea

Breaking tasks into smaller steps helps designers understand user interactions more clearly.

4. Analyse Each Step

Designers evaluate:

- time required,
- physical effort,
- mental effort,
- possible confusion,
- potential errors.

> **Example**
>
> Users may struggle to correctly insert the coffee capsule because the compartment design is unclear.

5. Identify Critical Points

Critical points are steps where:

- users frequently make mistakes,
- tasks become slow,
- frustration occurs,
- safety risks appear.

These areas often become priorities for redesign.

> **Example**
>
> Users may accidentally spill hot coffee when removing the cup due to limited space below the machine.

> ⚠ **Important**
>
> Critical points often reveal the best opportunities for product improvement.

Benefits of Task Analysis

Task analysis helps designers create products that are:

- easier to use,
- safer,
- more efficient,
- more intuitive,
- better adapted to user needs.

Quick Recap

- Task analysis studies how users complete tasks
- Complex activities are divided into smaller steps
- Designers observe user behaviour and difficulties
- Task analysis helps identify pain points and inefficiencies
- The process supports empathy and product improvement

Case of Use: Marcos’ Assignment Submission

> **Use case:** Marcos is a Year 12 student who needs to submit a History assignment online before 23:59.

Marcos has finished his document at 21:30 and needs to upload it to the school platform. However, the process creates uncertainty because:

- he has several files with similar names,
- the platform contains many subjects and assignments,
- the submission process is not completely clear,
- he is not fully sure whether the file has been submitted correctly.

Objective for the Student

Carry out a task analysis for this use case and identify opportunities for improvement.

User Context

Marcos has saved his assignment as:

> “Historia_final_definitivo_v3.pdf”

However, he also has other similar files, such as:

- “Historia_borrador”
- “Historia_final_BUENO.pdf”

This creates confusion and increases the risk of uploading the wrong file.

Task Analysis Application Step by Step

1. Define the Task

> **Chosen task:** Submit an assignment online correctly.

Stage	User Action
Before	The student completes the assignment
During	The student uploads the file
After	The student checks that it has been submitted

2. Observe Users

When observing students using a school platform, designers should analyse how they actually complete the task.

Students usually:

- search for the assignment,
- upload a file,
- sometimes upload the wrong file,
- do not always check if the file has been submitted.

IMPORTANT THINGS TO OBSERVE

- whether students use a phone or computer,
- internet speed,
- clarity of the platform interface,
- file organisation habits,
- how students react to confirmation messages.

> ### Typical Problem
> Students may upload the wrong file because several documents have similar names.

3. Break Down the Steps

The task can be broken down into smaller sequential actions.

ACTUAL STEPS

1. Log into the platform
2. Find the subject
3. Locate the assignment
4. Click “Submit”
5. Select the file
6. Upload the file
7. Confirm submission
8. Check that the submission was successful

Key Idea

Breaking the task into steps helps designers identify where users may experience confusion or frustration.

4. Create a Visual Map

The process can be represented as a storyboard or sequence map.

Example: Storyboard Sequence

1. Marcos opens the school platform
2. He logs in
3. He enters the History subject
4. He searches for the correct assignment
5. He clicks “Submit”
6. He selects a file from his folder
7. He uploads the file
8. He confirms the submission
9. He checks whether the assignment appears as submitted

Important

The order of actions must be clear so designers can understand the user journey.

5. Analyse Each Step

Designers analyse the task to identify usability problems and areas for improvement.

Problem Area	Issue Identified
Efficiency	Too many clicks are needed to reach the assignment
Ergonomics	The platform may be difficult to use on a mobile device
Cognitive Load	It is not clear whether the file has been submitted
Errors	The student may upload the wrong file

6. Identify Key Moments

Critical points are the steps where users struggle the most.

CRITICAL POINTS IN MARCOS' TASK

- searching for the assignment,
- selecting the correct file,
- uploading the file,
- confirming the submission,
- checking whether the file has been submitted.

> ⚠ **Important**
>
> Critical points are the moments where design improvements can have the greatest impact.

7. Suggest Improvements

Based on the task analysis, designers can suggest improvements to reduce confusion and improve usability.

POSSIBLE DESIGN SOLUTIONS

- make the "Submit" button more visible,
- show a clear message: **"SUBMITTED SUCCESSFULLY"**,
- provide a file preview before final submission,
- add a double confirmation message,
- highlight the selected file name clearly,

- show a checklist before submitting.

Design Improvement Focus

A good redesign should reduce user errors, lower cognitive load, and make the submission process clearer and more efficient.

Quick Recap

- Task analysis breaks a user activity into smaller steps
- Marcos' goal is to submit the correct assignment online
- The main risks are confusion, wrong file upload, and unclear confirmation
- Critical points include finding the assignment, selecting the file, and confirming submission
- Design improvements should make the process clearer, faster, and safer

B3.2 Structural Systems — Application and Selection

B3.2.1 Structures in Everyday Products

Structures are present in the design of **everyday products**.

In engineering and architecture, a structure is a **system of interconnected parts designed to support weight and resist forces**.

Structures can be found in cars, machinery, bridges, dams, buildings and everyday products such as chairs and tables. Each structure is designed to perform a specific function, remain stable, support loads and resist forces.

> **Key Idea**
>
> A successful structure must perform its intended function while remaining stable and safely resisting the loads and forces acting on it.

Structural Analysis

Structural analysis is used to understand **how a structure responds to loads**.

When analysing an existing product, designers and engineers consider:

- the loads acting **on** the structure,
- the stresses created **within** the structure,
- where the structure may deform or fail,
- how the structure could be strengthened.

Structural designs are assessed to ensure that they perform their intended function, withstand expected loads, include appropriate safety factors and comply with relevant standards and codes.

Modelling Structures

During the initial design stage, engineers often model structures before they are manufactured or constructed.

Computer-based methods such as **Finite Element Analysis (FEA)** can be used to predict how a structure responds to expected loads and to identify areas of high stress, possible deformation and potential failure.

Key Idea

Structural modelling allows designers to predict how forces will affect a structure before the final product is manufactured.

Structural Assessment Throughout a Product's Life

During construction and throughout the life of a structure, engineers may continue to use:

- visual inspections,
- testing,
- structural analysis.

These assessments can identify potential issues or deficiencies and help maintain safety, structural integrity and regulatory compliance.

Forces and Stresses Within Structures

There are **five basic types of stress** that may occur within a structure:

1. tension,
2. compression,
3. shear,
4. torsion,
5. bending.

Structural analysis requires designers to understand **where and how these stresses develop within a product**.

1. Tension

Tension is produced by forces trying to **pull apart or lengthen a material**.

Tensile stress is distributed uniformly across the cross-section.

Key Idea

Tension stretches or pulls a structural member apart.

2. Compression

Compression is produced by forces trying to **compress or shorten a material**.

Compressive stress is distributed uniformly across the cross-section.

Key Idea

Compression pushes material together and tends to shorten a structural member.

3. Shear

Shear stress is produced when forces try to **slide one part of a material over another**.

Shear may occur as:

- single shear,
- double shear,
- punching shear.

Unlike tensile and compressive stress, shear stress is **not uniformly distributed across a cross-section**. Its distribution depends on the shape of the cross-section.

Shear stress is typically:

- **maximum at the neutral axis**,
- **zero at the outermost surfaces**.

Example

A bolt connecting structural components may experience shear when the connected parts are forced in opposite directions.

> **Important**
>
> Shear stress varies through the cross-section. It is typically greatest around the neutral axis rather than at the outer surface.

4. Torsion

Torsion is stress induced by a **twisting force**, also known as torque.

Torsional stress:

- is highest at the outer surface,
- decreases towards the centre,
- tends towards zero at the centre.

Why Are Drive Shafts Often Hollow?

Because torsional stress is highest towards the outside of a shaft, material near the centre contributes less to torsional resistance.

A **hollow drive shaft** can therefore provide the same torsional strength as a solid shaft of the same outer diameter while using less material and therefore less weight.

Design Insight

Understanding where stress occurs allows designers to remove material from areas where it contributes relatively little to structural performance.

5. Bending

Bending, also known as **flexural stress**, causes a structural member to curve.

Bending produces:

- **tensile stress on one side**,
- **compressive stress on the opposite side**.

Between these regions is the **neutral axis**, with maximum stresses at the outer surfaces.

Key Idea

Bending creates tension and compression on opposite sides of a neutral axis.

Comparing the Five Types of Stress

Stress	Action	Important Structural Behaviour
Tension	Pulling	Attempts to lengthen the material
Compression	Pushing	Attempts to shorten the material
Shear	Sliding	Parts of the material try to slide past each other
Torsion	Twisting	Stress is greatest towards the outer surface
Bending	Curving	Produces tension and compression on opposite sides

Loads Acting on Structures

A **load** is an external force acting on a structure.

Loads create internal stresses such as tension, compression, shear, torsion and bending.

> **Load → external action on the structure**
>
> **Stress → internal response produced within the material**

> ⚠ **Important**
>
> A load applied to a structure may create more than one type of internal stress.

1. Dead Loads

Dead loads are **permanent, unchanging static loads**.

They include the weight of the structure itself and permanent fixtures, such as walls and floors.

Dead loads are primarily vertical and may produce:

- compression,
- bending moments.

They are important when determining whether foundations and other structural components can support the total weight.

> **Key Idea**
>
> Dead loads are permanent loads that remain part of the structure.

2. Live Loads

Live loads, also called **imposed loads**, are temporary or variable loads that are not permanently part of the structure.

Examples include:

- people,
- furniture,
- vehicles.

These loads are often primarily vertical and compressive. If unevenly distributed, they may also create bending stresses.

Unforeseen loads and misuse are typically considered through safety factors.

> **Key Idea**
>
> Live loads change during the use of a structure and must be anticipated during structural design.

Dead Loads vs Live Loads

Dead Loads	Live Loads
Permanent	Temporary or variable
Part of the structure	Not permanently part of the structure
Structural wall	Person
Floor structure	Furniture
Permanent fixture	Vehicle

3. Environmental Loads

Environmental loads include:

- wind,
- rain,
- snow,
- seismic activity,
- flooding,
- thermal expansion and contraction.

They may create compression, tension, shear and bending depending on their magnitude, direction and distribution.

Example: Wind Load

Wind pressure against a building wall can create **bending**, inducing:

- compression on the windward side,
- tension on the leeward side.

> **Wind load → Bending → Compression + Tension**

Example: Thermal Loads

Thermal expansion and contraction can create tensile and compressive stresses depending on how the structural components are constrained.

Example: Seismic Loads

Earthquakes can create a rapidly changing combination of:

- tension,
- compression,
- shear.

Their magnitude and direction can change throughout the seismic event.

Key Idea

The same structure may experience different stresses depending on the type, direction and distribution of the applied load.

4. Other Structural Loads

SETTLEMENT

Settlement is the **downward vertical movement of soil or ground** under an applied load as soil compresses or consolidates.

HYDROSTATIC LOADS

Groundwater can create hydrostatic loads on subsurface structures such as foundations.

These loads act horizontally, normal to the structure, and increase in magnitude with depth.

VIBRATIONAL LOADS

Vibration from machinery, wind or seismic activity can create combinations of:

- compression,
- tension,
- shear,
- torsion,
- bending.

IMPACT LOADS

Impact can also create a complex combination of tensile, compressive and shear stresses that varies across the structure.

Key Idea

Real structures rarely experience only one simple force. Loads often create several interacting stresses within different structural components.

Analysing and Modelling Forces in Existing Products

When analysing an existing product, determine:

- what loads act on it,
- where those loads act,
- how loads are transferred through the structure,
- what stresses develop within its components,
- where structural weaknesses may exist.

A useful sequence is:

> **Product → Loads → Supports → Load Path → Internal Stresses → Potential Weaknesses**

Step 1 — Identify the Structure

Ask:

- Which parts support the load?
- Which parts connect the structure?
- Where are the supports?
- Which components provide rigidity?

Step 2 — Identify the Loads

Consider:

- dead loads,
- live loads,
- environmental loads,
- impact,
- vibration,
- possible misuse.

Step 3 — Model Load Direction

Represent the loads using **arrows** showing their direction.

For example:

- downward weight,
- horizontal wind,
- rotational torque,
- side impact.

Step 4 — Identify Supports and Reactions

Identify where the product is supported and the reaction forces that oppose the applied loads.

Step 5 — Follow the Load Path

A **load path** describes how a load is transferred through the structural components.

For example:

> **Person → Chair seat → Frame → Legs → Floor**

Step 6 — Identify Internal Stresses

Determine which components experience:

- tension,
- compression,
- shear,
- torsion,
- bending.

Step 7 — Identify Potential Weaknesses

Look for vulnerable areas such as:

- joints,
- connections,
- thin sections,
- unsupported spans,
- areas experiencing bending,
- areas subjected to impact or repeated loading.

Step 8 — Suggest Improvements

Propose a change that responds to the **specific weakness identified**.

> ⚠ **Important**
>
> Do not simply state that a structure needs "more material". Explain **where**, **how** and **why** the modification improves structural performance.

Example Analysis: Chair

A person sitting on a chair creates a **live load** acting vertically downward. The chair itself creates a **dead load**.

Load Path

> **Person → Seat → Chair Frame → Legs → Floor**

Internal Stresses

Possible stresses include:

- **bending** in the seat,
- **compression** in the legs,
- **shear** at joints and connections.

If the person moves or sits down suddenly, additional dynamic or impact loads may occur.

Potential Weaknesses

Weaknesses may occur at:

- seat-to-leg connections,
- joints in the frame,
- long unsupported members.

Possible Strengthening

The chair could potentially be strengthened by:

- adding bracing between the legs,
- reinforcing joints,
- using stronger connections,
- increasing the thickness of critical members.

Analysis Principle

Structural analysis connects the external load to the internal stresses and then uses that information to justify design improvements.

Strengthening Existing Structures

There are four basic methods of strengthening a structure:

1. **reinforcement with additional materials**,
2. **adding bracing**,
3. **increasing material thickness or density**,
4. **improving connections**.

1. Reinforcement

Additional material can increase:

- strength,
- load-bearing capacity.

Reinforcement should be placed where structural analysis indicates additional strength is required.

2. Adding Bracing

Bracing can increase resistance to lateral forces such as:

- wind,
- seismic forces.

It can increase rigidity and reduce unwanted deformation.

3. Increasing Thickness or Density

Increasing the thickness or density of existing materials can improve their strength and ability to resist loads.

4. Improving Connections

Connections can be strengthened using:

- stronger bolts,
- welding.

Improved connections help transfer forces safely between structural components.

⚠ **Important**

A structure may contain strong individual components but still fail if the connections between those components are inadequate.

Comparing Strengthening Methods

Method	How It Strengthens	Possible Application
Reinforcement	Adds material and load-bearing capacity	Weak or highly stressed area
Bracing	Increases rigidity and lateral resistance	Frames exposed to lateral forces
Increase Thickness / Density	Provides more material to resist loads	Structural member requiring greater strength
Improve Connections	Improves transfer of forces between components	Bolted or welded joints

From Analysis to Improvement

A strong structural analysis establishes the relationship:

> **Load → Stress → Weakness → Structural Improvement**

Example

Observation: A horizontal load causes a rectangular frame to deform.

Analysis: The frame has insufficient resistance to lateral loading.

Structural effect: The members and joints are subjected to forces that distort the frame.

Improvement: Add bracing.

Explanation: The bracing increases rigidity and improves resistance to lateral forces.

Structural Analysis Checklist

When analysing an existing product, ask:

1. What is the structure designed to do?
2. What are its main structural components?
3. What loads act on the structure?
4. Where and in which direction do the loads act?
5. Where are the supports and reaction forces?
6. What is the load path through the product?
7. Where do tension, compression, shear, torsion or bending occur?
8. Where could structural failure occur?
9. How could the structure be strengthened?
10. Why would the proposed modification improve the structure?

Final Concept

To analyse an existing product, designers identify the loads acting on the structure, model how those loads are transferred, determine the stresses created within its components and identify potential weaknesses. Structural improvements should then be proposed and justified according to the forces and weaknesses identified.

B3.2.2 Young's Modulus

Young's Modulus is a measure of the **stiffness of a material**.

It describes how resistant a material is to **elastic deformation** when subjected to tensile or compressive stress.

Young's Modulus is represented by the symbol:

$$E$$

and is calculated using:

$$E = `\frac{\sigma}{\varepsilon}` = \text{tex}$$

where:

- **E** = Young's Modulus,
- **σ** = tensile stress,
- **ε** = tensile strain.

Key Idea

Young’s Modulus describes **stiffness**. It relates the stress applied to a material to the strain produced within its elastic region.

Stress and Strain

Before calculating Young's Modulus, it is necessary to understand **stress** and **strain**.

Tensile Stress

Stress (σ) relates the applied load to the cross-sectional area of the material.

$$`\sigma` = tex = ` \frac{F}{A} ` = tex$$

where:

- **σ** = stress,
- **F** = force,
- **A** = cross-sectional area.

Stress is measured in **pascals (Pa)**.

$$1 , Pa = 1 , N / m\backslash^{2}$$

In engineering calculations, dimensions are often measured in millimetres. In this case:

$$1 , N / mm\backslash^{2} = 1 , MPa$$

Therefore, stress is commonly expressed in **MPa**.

Calculation Tip

If force is in **N** and area is in **mm^2**, the resulting stress is in **N/mm^2**, which is equivalent to **MPa**.

Tensile Strain

Strain (ε) measures the change in length relative to the material's original length.

$$`\varepsilon` = tex = ` \frac{\Delta L}{L_0} ` = tex$$

where:

- **ε** = strain,
- **ΔL** = change in length,
- **L_0** = original length.

Strain has **no units** because it is a ratio between two lengths measured using the same units.

<h6>

Example

```
</h6>
```

A 120 mm steel rod stretches to 120.2 mm.

Change in length:

$$`\Delta` = texL = 120.2 - 120 = 0.2\,,\mathrm{mm}$$

Therefore:

$$`\varepsilon` = tex = `\frac{0.2}{120}` = tex$$

$$`\varepsilon` = tex = 0.00167$$

> ⚠ **Important**
>
> The original length and change in length must use the **same units** before calculating strain.

Calculating Young's Modulus

Within the elastic region:

$$E = `\frac{\sigma}{\varepsilon}` = tex$$

Young's Modulus therefore compares:

> **how much stress is applied**

with

> **how much elastic strain is produced**

A material that requires a large stress to produce a small strain has a **high Young's Modulus** and is therefore stiff.

A material that produces greater strain for the same stress has a **lower Young's Modulus** and is more flexible.

Worked Example 1 --- Young's Modulus from Stress and Extension

An 18 mm square steel section is **3 m long**. It is subjected to a stress of **21.6 MPa** and extends by **0.2 mm**.

Calculate Young's Modulus.

STEP 1 --- CONVERT THE ORIGINAL LENGTH

$$3 \, , m = 3000 \, , mm$$

STEP 2 --- CALCULATE STRAIN

$$`\varepsilon` = tex = ` \frac{\Delta L}{L_0} ` = tex$$

$$`\varepsilon` = tex = ` \frac{0.2}{3000} ` = tex$$

$$`\varepsilon` = tex = 6.67` \times 10` = tex\backslash^{-5}$$

STEP 3 --- APPLY THE YOUNG'S MODULUS FORMULA

$$E = ` \frac{\sigma}{\varepsilon} ` = tex$$

$$E = ` \frac{21.6}{6.67 \times 10^{-5}} ` = tex$$

$$E` \approx 324000` = tex \, , MPa$$

Since:

$$1000 \, , MPa = 1 \, , GPa$$

then:

$$E` \approx 324` = tex \, , GPa$$

Calculation Process

When extension is given instead of strain:

1. Calculate strain → 2. Use E = σ/ε → 3. Convert MPa to GPa if required

Worked Example 2 --- Calculate Stress First

A tensile force of **45 kN** is applied to a circular specimen with a cross-sectional area of approximately **113.1 mm²**.

The resulting strain is **0.0015**.

Calculate Young's Modulus.

STEP 1 --- CONVERT FORCE TO NEWTONS

$$45 , kN = 45000 , N$$

STEP 2 --- CALCULATE STRESS

$$`\sigma` = tex = `\frac{F}{A}` = tex$$

$$`\sigma` = tex = `\frac{45000}{113.1}` = tex$$

$$`\sigma` = tex` \approx 397.9` = tex , MPa$$

STEP 3 --- CALCULATE YOUNG'S MODULUS

$$E = `\frac{\sigma}{\varepsilon}` = tex$$

$$E = `\frac{397.9}{0.0015}` = tex$$

$$E` \approx 265267` = tex , MPa$$

$$E` \approx 265` = tex , GPa$$

Calculation Strategy

A Young's Modulus question may not give stress and strain directly.

You may first need to calculate:

$$\sigma = \frac{F}{A}$$

and/or:

$$\varepsilon = \frac{\Delta L}{L_0}$$

before using:

$$E = \frac{\sigma}{\varepsilon}$$

::: page-break :::

The Stress-Strain Graph

A stress-strain graph shows the relationship between **tensile stress applied to a material** and the resulting **strain**.

The axes are:

- **vertical axis (y)** → Stress (σ),
- **horizontal axis (x)** → Strain (ε).

A typical stress-strain curve can provide information about many mechanical properties.

For B3.2.2, the most important are:

- Young's Modulus,
- yield strength,
- ultimate tensile strength,
- fracture.

1. Elastic Region

At the beginning of a typical stress-strain curve, stress and strain have a **straight-line relationship**.

In this region:

- deformation is elastic,
- stress is proportional to strain,
- the material returns to its original length when the load is removed.

This relationship is associated with **Hooke's Law**.

> **Hooke's Law**
>
> Within the linear elastic region, stress is directly proportional to strain.

2. Young's Modulus on the Graph

Young's Modulus is represented by the **slope of the straight-line elastic region**.

$$E = `\frac{\text{Stress}}{\text{Strain}}` = tex$$

or, when using two points from the linear region:

$$E = `\frac{\Delta\sigma}{\Delta\varepsilon}` = tex$$

A graph with a **steeper elastic slope** represents a material with a higher Young's Modulus.

A graph with a **shallower elastic slope** represents a material with a lower Young's Modulus.

> **Steeper slope → Higher E → Stiffer material**
>
> **Shallower slope → Lower E → More flexible material**

> **Important**
>
> Young’s Modulus must be determined from the **linear elastic region** of the stress-strain graph.

Calculating E from a Stress-Strain Graph

Suppose a point in the linear elastic region has:

$$`\sigma` = tex = 200 \, , \mathrm{MPa}$$

and:

$$`\varepsilon` = tex = 0.001$$

Then:

$$E = ` \frac{200}{0.001} ` = tex$$

$$E = 200000 \, , \mathrm{MPa}$$

$$E = 200 \, , \mathrm{GPa}$$

Graph Question

To calculate Young's Modulus from a graph:

1. Select a point in the straight-line elastic region.
2. Read stress from the y-axis.
3. Read strain from the x-axis.
4. Calculate E = σ/ε.

3. Elastic Limit

The **elastic limit**, or proportional limit, marks the end of the linear elastic behaviour.

Up to this region, the material behaves elastically.

Beyond the elastic limit, the stress-strain relationship becomes non-linear and the material may begin to experience plastic deformation.

4. Yield Strength

The **yield point** occurs when the material begins to undergo significant **plastic deformation**.

Once the yield point has been passed:

- permanent deformation occurs,
- the specimen will not completely return to its original dimensions when the load is removed.

For structural applications, yield strength is particularly important because a structure may become unusable due to permanent deformation **before it actually fractures**.

> **Important**
>
> Structural failure does not always mean that a component has broken. Permanent deformation beyond acceptable limits can also represent failure.

Yield Point and Proof Stress

Not every material has a clearly defined yield point.

Low-carbon steels may display clearly identifiable yield behaviour, but materials such as:

- aluminium alloys,
- copper,
- titanium,
- magnesium,
- some polymers,
- medium and high-carbon steels,

may transition gradually from elastic to plastic deformation.

For these materials, engineers can use **proof stress**, also known as **offset yield stress**.

A common value is the **0.2% proof stress**.

This provides a practical yield-like value for materials without an obvious yield point.

> **Interpretation**
>
> If a graph does not show a clear yield point, a specified proof stress may be used to define a practical limit for permanent deformation.

5. Plastic Region

After yielding, the material enters the **plastic region**.

In this region:

- deformation is permanent,
- removing the load will not return the material completely to its original dimensions,
- strain can continue to increase.

The curve eventually reaches its maximum stress.

6. Ultimate Tensile Strength

The **Ultimate Tensile Strength (UTS)** is the maximum engineering stress reached during the tensile test.

On the stress-strain graph:

> **UTS = highest point on the engineering stress-strain curve**

After this point, a ductile specimen may begin to **neck**.

> **Key Idea**
>
> Yield strength identifies the beginning of unacceptable permanent deformation, while UTS identifies the maximum engineering stress reached by the material.

7. Necking

Necking is a **localised reduction in cross-sectional area**.

It occurs in ductile materials as the specimen continues to elongate after reaching UTS.

The reduction becomes concentrated in one area of the specimen.

Eventually, fracture occurs in this region.

Both:

- elongation,
- reduction in area,

can be used as measures of **ductility**.

8. Fracture

Fracture is the point where the tensile specimen **breaks**.

It represents the final failure of the specimen during the tensile test.

On the stress-strain graph, fracture occurs at the end of the curve.

Reading a Typical Stress-Strain Graph

The sequence for a typical ductile material can be interpreted as:

> **Linear elastic region → Elastic limit → Yield → Plastic deformation → UTS → Necking → Fracture**

Feature What It Represents What the Designer Learns

Elastic region Reversible deformation Material returns to original dimensions

Young's Modulus Slope of linear elastic region Stiffness

Elastic limit End of linear elastic behaviour Limit of proportional behaviour

Yield strength Beginning of significant permanent deformation Practical structural limit

Plastic region Permanent deformation Material will not fully recover

UTS Maximum engineering stress Maximum stress reached

Necking Local reduction in cross-sectional area Specimen approaching fracture

Fracture Specimen breaks Final failure

::: page-break :::

Interpreting Stress-Strain Graphs

When given a stress-strain graph, use a systematic approach.

Step 1 --- Check the Axes

Identify:

- stress and its units,
- strain and how it is expressed.

Strain may be shown as:

- a decimal,
- a percentage.

Percentage Strain

If strain is given as a percentage, convert it to a decimal before using it in:

$$E = \frac{\sigma}{\varepsilon}$$

For example:

$$0.15\% = \frac{0.15}{100} = 0.0015$$

Step 2 --- Find the Linear Elastic Region

Locate the initial straight section.

Its slope represents **Young's Modulus**.

Step 3 --- Identify Yield Strength

Find the point where significant plastic deformation begins.

If there is no obvious yield point, the graph may use **proof stress**.

Step 4 --- Identify UTS

Find the **maximum stress** on the engineering stress-strain curve.

This is the Ultimate Tensile Strength.

Step 5 --- Identify Fracture

Follow the curve to its endpoint.

This represents fracture or breaking of the specimen.

Interpreting Two Materials

Stress-strain graphs can also be used to compare materials.

If Material A has a steeper elastic slope than Material B:

$$E_A \; E_B$$

Therefore Material A is **stiffer**.

However, the graph must be analysed further before making conclusions about:

- yield strength,
- UTS,
- ductility,
- fracture behaviour.

> **Do Not Confuse These Properties**
>
> **Young’s Modulus = stiffness**
>
> **Yield strength = stress at which significant permanent deformation begins**
>
> **UTS = maximum engineering stress**
>
> **Fracture = breaking point**
>
> A material with a high Young’s Modulus does not necessarily have the highest yield strength or UTS.

Engineering Stress and True Stress

Most conventional stress-strain graphs use **engineering stress**.

Engineering stress uses the specimen's **original cross-sectional area**:

$$\text{`}\sigma\text{`} = \text{tex\_engineering} = \text{`}\frac{F}{A_0}\text{`} = \text{tex}$$

During a tensile test, however, the cross-sectional area changes, particularly during necking.

True stress uses the actual changing cross-sectional area:

$$\text{`}\sigma\text{`} = \text{tex\_true} = \text{`}\frac{F}{A_{actual}}\text{`} = \text{tex}$$

True stress-strain curves provide a more accurate representation during significant plastic deformation and may be useful in applications such as:

- metal forming,
- crash simulations.

For B3.2.2

The main syllabus requirement is interpreting the standard stress-strain graph and identifying **Young's Modulus, yield strength, ultimate strength and fracture**. Engineering versus true stress provides useful additional context.

Temperature and Young's Modulus

Young's Modulus is affected by temperature.

As temperature rises, Young's Modulus will generally decrease.

The material therefore tends to become:

- less stiff,
- more flexible,
- less resistant to elastic deformation.

This occurs because increased thermal energy causes greater atomic vibration and affects the resistance of interatomic bonds to deformation.

::: page-break :::

Worked Exam-Style Questions

Question 1

A material experiences a tensile stress of **160 MPa** and a tensile strain of **0.0008** while remaining within its elastic region.

Calculate Young's Modulus.

ANSWER

$$E = ` \frac{\sigma}{\varepsilon} ` = \text{tex}$$

$$E = ` \frac{160}{0.0008} ` = \text{tex}$$

$$E = 200000 \, \text{MPa}$$

`E = 200 GPa` = tex

Question 2

A 500 mm long specimen extends by 0.25 mm while subjected to a tensile stress of 100 MPa.

Calculate Young's Modulus.

STEP 1 --- CALCULATE STRAIN

$$`\varepsilon` = tex = `\frac{0.25}{500}` = tex$$

$$`\varepsilon = 0.0005` = tex$$

STEP 2 --- CALCULATE YOUNG'S MODULUS

$$E = `\frac{100}{0.0005}` = tex$$

$$E = 200000\,,\mathrm{MPa}$$

$$`E = 200\ \mathrm{GPa}` = tex$$

Question 3

A stress-strain graph shows that a material reaches:

- 150 MPa at a strain of 0.001 in its linear region,
- yield at 260 MPa,
- maximum stress at 410 MPa,
- fracture after the maximum point.

Identify:

a) Young's Modulus\ **b)** Yield strength\ **c)** Ultimate tensile strength

ANSWER

a) Young's Modulus

$$E = `\frac{150}{0.001}` = tex$$

`E = 150 GPa` = tex

b) Yield strength

`260 MPa` = tex

c) Ultimate tensile strength

`410 MPa` = tex

The fracture point would be identified at the **endpoint of the curve**.

B3.2.2 Analysis Checklist

When solving a Young's Modulus or stress-strain graph question:

1. Identify the **stress**.
2. Identify or calculate the **strain**.
3. Ensure strain is expressed as a **decimal**, not a percentage.
4. Confirm the data point is within the **linear elastic region** when calculating E.
5. Use:

$$E = \text{`}\frac{\sigma}{\varepsilon}\text{`} = \text{tex}$$

1. State the appropriate units for E, usually **MPa or GPa**.
2. Identify the **yield strength**.
3. Identify the **UTS** as the maximum engineering stress.
4. Identify **fracture** at the end of the curve.
5. Interpret what each point means for the material's behaviour.

Final Concept

Young's Modulus is the measure of a material's stiffness and is calculated from the ratio of tensile stress to tensile strain within the linear elastic region:

$$E = \frac{\sigma}{\varepsilon}$$

A stress-strain graph can then be interpreted to identify the material's **Young's Modulus, yield strength, ultimate tensile strength and fracture point**.

B3.2.3 Structural Failure

Structures can fail due to:

- **overloading**,
- inappropriate **material choice**,
- inadequate **size**,
- inappropriate **shape**.

Structural failure occurs when a structure or one of its components can no longer perform its intended function safely.

All structures must therefore be designed with careful consideration of the **forces and loads that will act on them**.

Failure to correctly assess these forces can result in:

- excessive deformation,
- instability,
- buckling,
- collapse,
- increased costs,
- injury.

Key Idea

When investigating a structural failure, identify **what failed, where it failed and what evidence explains why it failed**.

Causes of Structural Failure

The four key factors for B3.2.3 are:

1. **Overloading**
2. **Material choice**
3. **Size**
4. **Shape**

These factors may act individually or in combination.

1. Overloading

Overloading occurs when the forces acting on a structure exceed the load that its components can safely withstand.

Loads may be underestimated during design or may become greater than originally expected.

This can cause:

- excessive stress,
- excessive deformation,
- buckling,
- fracture,
- collapse.

> **Analysis**
>
> When investigating overloading, compare the **applied load or resulting stress** with the structure's allowable capacity.

Buckling

Buckling is particularly associated with **long, thin structural members subjected to compression**.

If a critical compressive load is exceeded, the member becomes unstable and deforms laterally.

This can cause the member to lose its ability to support the load and may lead to collapse.

> **Compression + slender member + critical load exceeded → Buckling**

Important

A compression member does not necessarily need to fracture before it fails. **Loss of stability through buckling is itself a structural failure.**

2. Material Choice

A structure can fail if the selected material does not have suitable properties for the conditions it experiences.

When investigating material choice, consider whether the material can adequately resist the:

- stresses,
- deformation,
- environmental conditions,
- repeated loading,

experienced by the structure.

FEA data can help determine whether the stress or deformation predicted in a component is acceptable for the selected material.

Key Idea

A material should be selected according to the loads and conditions the component will experience.

3. Size

The dimensions of a structural component affect its ability to withstand loads.

Structural problems may occur when components are:

- too thin,
- too slender,
- inadequately sized for the applied load.

Reducing the dimensions of a structural component may reduce its structural capacity.

For example, a long, thin member under compression may be particularly vulnerable to **buckling**.

4. Shape

The geometry of a structure affects:

- how loads are carried,
- how forces are distributed,
- structural stiffness,
- stability.

A structure can therefore fail even if it contains strong materials if its geometry does not adequately resist the loads acting on it.

Key Idea

Structural performance depends on more than material strength. **Load, material, dimensions and geometry work together.**

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Case Study --- Quebec Bridge Collapse, 1907

The Quebec Bridge collapse demonstrates the consequences of **underestimating structural loads and inadequately designing structural members**.

During construction, the central span collapsed.

The investigation found that:

- the weight of the bridge had been significantly underestimated,
- the required strength of structural members had therefore been assessed incorrectly,
- the lower compression chords near the main pier were inadequately designed,
- buckling was observed before collapse.

The bridge eventually collapsed after the lower compression chords became unstable.

Failure Analysis

> **Underestimated weight → Inadequate member design → Excessive compression → Buckling → Collapse**

This failure also demonstrated the importance of:

- rigorous design checks,
- adequate supervision,
- responding to evidence of structural distress,
- clear engineering responsibility.

What Can We Learn?

Visible deformation such as buckling can provide evidence that a structural member is approaching or has exceeded an acceptable structural condition.

Case Study --- Tacoma Narrows Bridge, 1940

The Tacoma Narrows Bridge was exceptionally **slender** for a suspension bridge of its time.

Its main span had:

- a very shallow stiffening girder,
- a narrow roadway,
- unusually slender proportions.

These characteristics made the bridge susceptible to **wind-induced oscillation**.

Wind produced aeroelastic flutter and increasingly severe twisting of the bridge deck.

The bridge eventually collapsed after torsional oscillation developed during strong winds.

Failure Analysis

> **Slender geometry → Susceptibility to wind → Aeroelastic flutter → Torsional oscillation → Structural failure**

At the time, engineers had limited understanding of these aerodynamic effects and limited access to wind-tunnel testing.

The failure subsequently influenced:

- suspension bridge design,
- wind-load analysis,
- aerodynamic stability assessment,
- development of more sophisticated analytical methods.

Key Idea

The Tacoma Narrows Bridge shows how **shape and proportions** can affect the way a structure responds dynamically to environmental loads.

Case Study --- Sampoong Department Store, 1995

The Sampoong Department Store collapse resulted from a combination of:

- design changes,
- construction errors,
- increased loading,
- reduced structural capacity,
- inadequate engineering evaluation,
- negligence.

Changes included:

- adding an additional above-ground floor,
- removing some columns to accommodate escalators,
- using thinner columns,
- increasing column spacing,
- installing a heavy rooftop air-conditioning unit.

These modifications simultaneously:

- **increased the dead load**,
- **reduced structural capacity**.

Cracking was observed before the collapse but was ignored or dismissed.

Failure Analysis

> **Increased load + reduced column capacity + design/construction problems → Structural distress → Collapse**

> ⚠ **Important**
>
> Structural failure may result from **several interacting causes**, rather than one isolated problem.

Comparing the Failure Examples

Case Important Cause Structural Effect

Quebec Bridge Underestimated weight and inadequate compression members Buckling and collapse

Tacoma Narrows Bridge Extremely slender geometry and wind interaction Torsional oscillation and collapse

Sampoong Department Store Increased loads and reduced structural capacity Progressive structural distress and collapse

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Finite Element Analysis --- FEA

Finite Element Analysis (FEA) is a computerised method used to test virtual models under different loading conditions.

FEA can be used to:

- test new product designs,
- analyse existing products,
- simulate service conditions,
- predict structural behaviour,
- identify critical regions before physical manufacture.

FEA is particularly useful for **stress calculations**.

Key Idea

FEA allows designers to investigate how loads are distributed through a virtual structure and identify areas that may require further attention.

How FEA Works

FEA divides a complex virtual model into many smaller, simpler regions called **finite elements**.

These elements are connected through **nodes**.

Instead of analysing the entire complex structure as one object, the software analyses the behaviour of these interconnected elements.

The results are then combined to predict the behaviour of the complete structure.

> **Complex model → Finite elements → Nodes → Numerical analysis → Structural results**

What Can Be Simulated?

The structural component of FEA can simulate how an object responds to service loads and conditions.

Loads may result from:

- external forces,
- pressure,
- temperature changes,
- vibration.

Static and dynamic loads can be simulated to investigate behaviour such as:

- extension,
- bending,
- twisting.

FEA can provide information about:

- stress,
- strain,
- displacement,
- stiffness,
- strength.

Interpreting FEA Data

The syllabus requires you to be able to use FEA information to help identify **why a structure may fail**.

FEA results are often presented using:

- contour plots,
- colour maps,
- numerical scales,
- displacement plots,
- Safety Factor simulations.

The important skill is not simply recognising an FEA image.

You must be able to **interpret the data shown**.

1. Read the Result Type

First identify **what the FEA plot is showing**.

It may represent:

- stress,
- strain,
- displacement,
- Safety Factor,
- another structural quantity.

> **Important**
>
> Do not interpret every FEA image as a stress plot. Always identify the **result being displayed** first.

2. Read the Legend and Units

Contour plots use a scale to show the magnitude of the result across the model.

In the examples described in the source material:

- **red** identifies high-stress or danger zones,
- **blue** identifies low-stress or safer zones,
- intermediate colours show the transition between them.

However, the numerical **legend or scale** is what gives the colours their meaning.

> **FEA Interpretation**
>
> Do not conclude that a component has failed simply because an area is red.
>
> Red indicates a high value on the displayed scale in the examples described here. The numerical value must be interpreted in relation to the result being plotted and the acceptable limits of the design.

3. Locate Critical Regions

Look for areas where the FEA result indicates particularly high values.

These may identify:

- stress concentrations,
- highly loaded members,
- vulnerable joints,
- critical welds,
- areas of excessive displacement.

Ask:

> **Where is the highest value located?**

and then:

> **Why might that location be critical?**

4. Interpret Stress Contour Plots

Stress contour plots show how stress is distributed through the structure.

Look for:

- areas of high stress,
- areas of low stress,
- sudden changes in stress,
- localised stress concentrations.

A local region of high stress may indicate a possible weakness requiring further investigation.

FEA can, for example, be used to determine **peak stresses around welds** and help assess fatigue resistance.

5. Interpret Displacement Plots

Displacement plots show how much parts of the structure move when loads are applied.

High displacement may indicate:

- insufficient stiffness,
- excessive deformation,
- a possible structural problem.

The important question is whether the predicted movement is **acceptable for the intended design**.

Remember

Stress plots show how intensely the material is being loaded.

Displacement plots show how much the structure moves or deforms.

6. Interpret Safety Factor Results

Safety Factor simulations compare structural capacity with the stress or load experienced by the structure.

A Safety Factor result can help identify regions with a lower margin against failure.

When analysing the result, identify where the **lowest Safety Factor** occurs.

That location may be more critical than regions with a larger Safety Factor.

From FEA Data to a Failure Diagnosis

A useful sequence is:

> **Load condition → FEA result → Critical region → Structural behaviour → Possible cause of failure**

For example:

> **Applied load → High stress around connection → Local stress concentration → Connection vulnerable → Possible failure associated with connection design**

The FEA result provides **evidence** for the diagnosis.

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FEA and Structural Failure

FEA can help investigate whether failure is associated with the four syllabus factors.

OVERLOADING

Evidence may include:

- very high predicted stress,
- excessive displacement,
- low Safety Factor,
- highly loaded structural members.

MATERIAL CHOICE

FEA may show that the predicted stresses or deformation are inappropriate for the material selected.

SIZE

FEA may identify excessive stress or displacement in structural members whose dimensions are inadequate for the simulated loading.

SHAPE

FEA can show how geometry affects the distribution and concentration of stresses.

Particular shapes or transitions may produce localised regions requiring further investigation.

Example FEA Interpretation

Imagine an FEA stress plot of a bracket under load.

The legend shows:

- maximum stress = **280 MPa**,
- minimum stress = **5 MPa**.

The maximum stress is concentrated around a connection.

A correct interpretation would be:

Observation:\ The highest stress occurs around the connection.

Evidence:\ The FEA predicts a maximum stress of 280 MPa in this region.

Interpretation:\ The connection is the most highly stressed region in the simulated load case.

Diagnosis:\ This region should be investigated as a possible structural weakness.

To determine whether failure is actually predicted, the designer would need to compare this result with the relevant allowable limit or material/design criterion.

⚠ **Strong FEA Answer**

Separate **what the simulation shows** from **what you conclude from it**.

Evidence: "The maximum stress is 280 MPa around the connection."

Interpretation: "This is the most highly stressed region."

Failure conclusion: Requires comparison with an appropriate structural or material limit.

FEA in Product Design

FEA data can assist designers with decisions involving:

- weight minimisation,
- material selection,
- manufacturing processes,
- cost,
- structural strengthening.

Complex connections can be analysed to determine:

- force flow,
- peak stresses around welds,
- fatigue resistance.

FEA may also be used to verify simplified design methods.

FEA in the Automotive Industry

FEA can be used to simulate vehicle collisions.

A simulation may show:

- distributed forces,
- twisting,
- buckling,
- movement,
- failure of structural elements.

The results can inform decisions about where strengthening may be required.

This allows designers to investigate crash scenarios before manufacturing and physically testing every design iteration.

Modelling Defects

FEA can also investigate defects in components.

For example, an internal flaw in a casting may be modelled as:

- a **crack**,
- a **void**.

A sharp crack representation may be appropriate when investigating:

- fracture mechanics,
- crack propagation.

A void may be more appropriate when investigating the overall behaviour of a component containing a larger manufacturing defect.

Advantages and Limitations of FEA

Advantages

FEA can:

- analyse complex structures,
- simulate multiple loading conditions,
- reduce development time,
- reduce the need for some physical prototypes,
- identify critical regions before manufacture,
- assist design optimisation.

It can also be used to assess existing structures and investigate whether continued service or proposed repairs may be acceptable.

Limitations

FEA does **not automatically guarantee a correct result**.

Results may be inaccurate if the analysis uses:

- incorrect assumptions,
- inappropriate modelling techniques,
- flawed input data.

These problems can lead to incorrect interpretations of:

- stress,
- strain,
- displacement,
- other critical parameters.

Important

An FEA result is only as reliable as the **model, assumptions and input data** used to generate it.

FEA and Physical Testing

FEA can reduce the cost and time associated with manufacturing and testing physical prototypes.

However, computer simulation may only inform a design to a certain point.

Physical testing may still be required to confirm the performance and specifications of the final product.

Key Idea

FEA complements physical testing; it does not necessarily replace it.

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How to Identify Why a Structure Failed

When given a failed structure, photograph, case study, test result or FEA output, use the following process.

STEP 1 --- IDENTIFY THE LOAD

Ask:

- What forces were acting?
- Was the load static or dynamic?
- Was it expected or unexpected?
- Could the structure have been overloaded?

STEP 2 --- IDENTIFY THE FAILURE LOCATION

Look for:

- buckling,
- cracking,
- excessive deformation,
- fractured members,
- damaged joints,
- highly stressed regions in FEA.

STEP 3 --- USE THE EVIDENCE

Use available:

- dimensions,
- loads,
- material data,
- FEA values,
- displacement data,
- Safety Factor data,
- observations.

Do not diagnose failure only from appearance.

STEP 4 --- CONNECT THE EVIDENCE TO A CAUSE

Consider:

- **Overloading** --- Was the load too high?
- **Material choice** --- Was the material appropriate?
- **Size** --- Were the structural members adequately sized?
- **Shape** --- Did the geometry respond adequately to the load?

STEP 5 --- EXPLAIN THE FAILURE MECHANISM

State how the identified cause produced structural failure.

For example:

> **Excessive compressive load → slender member becomes unstable → buckling → loss of load-bearing capacity**

Exam-Style FEA Question

An FEA simulation of a structural component shows a highly stressed region around a welded connection and much lower stress throughout the rest of the component.

QUESTION

What can be concluded from the FEA result?

ANSWER

The FEA indicates that the welded connection is a **stress concentration** and is the most highly stressed part of the simulated structure.

This makes the connection an important area to investigate when assessing possible structural failure.

The numerical stress value should be compared with an appropriate allowable material or design limit before concluding that failure will occur.

Exam-Style Failure Question

A long, thin structural member bends sideways while carrying a large compressive load.

QUESTION

Identify the likely failure mechanism.

ANSWER

The likely mechanism is **buckling**.

The member is slender and subjected to compression. If the critical compressive load is exceeded, it can become unstable, deform laterally and lose its ability to support the load.

B3.2.3 Analysis Checklist

When identifying why a structure failed:

1. Identify the **applied loads**.
2. Identify **where failure occurred**.
3. Look for evidence of **overloading**.
4. Consider whether the **material choice** was appropriate.
5. Consider whether structural members were adequately **sized**.
6. Consider whether the **shape or geometry** contributed to the problem.
7. If FEA is provided, identify the **result type**.
8. Read the **legend, numerical values and units**.
9. Locate areas of high stress, displacement or low Safety Factor.
10. Relate the FEA evidence to the observed or predicted failure.
11. Distinguish between **simulation evidence** and your **failure conclusion**.
12. Remember that FEA results depend on the quality of the model and input data.

Final Concept

Structural failure can result from **overloading, inappropriate material choice, inadequate size or unsuitable shape**. To diagnose failure, evidence from the structure and from tools such as FEA must be interpreted to connect the applied loads with stress, deformation, instability and the final failure mechanism.

B3.2.4 Force Diagrams

Forces acting on a structure, or within structural components such as beams and trusses, can be represented **diagrammatically**.

Force diagrams simplify a real structure so that the forces acting on it can be identified and interpreted.

The most common type is a **Free Body Diagram (FBD)**.

Key Idea

A force diagram uses **arrows (force vectors)** to show the **magnitude and direction** of forces acting on an object or structure.

To interpret a force diagram, ask:

What forces are acting? → In which direction? → Where are they acting? → Are they balanced? → How will the structure respond?

Free Body Diagrams

A **Free Body Diagram (FBD)** isolates an object from its surroundings and represents the external forces acting on it.

The real object is simplified so that the forces can be analysed clearly.

Forces are represented using **arrows**.

An arrow communicates:

- the **direction** of the force,
- the **line of action** of the force,
- and, when drawn to scale or labelled, its **magnitude**.

For example:

```
↑ 50 N
|
●
|
↓ 50 N
```

The two forces are equal and opposite.

Therefore:

$$F_R = 0$$

and the object is in **translational equilibrium**.

> **Reading an FBD**
>
> Never look only at the number written beside a force.
>
> Always identify:
>
> **Magnitude + Direction + Point/line of action**

Resultant Force

The **resultant force** is the single force that represents the combined effect of all the forces acting on an object.

It may be written as:

$$F_R$$

If two forces act in opposite directions, their magnitudes can be subtracted.

For example:

```
50 N ←  ●  → 80 N
```

Therefore:

$$F_R = 80 - 50$$

$$F_R = 30 , N$$

acting to the **right**.

> **Unbalanced forces → Resultant force ≠ 0**

If all forces balance:

$$F_R = 0$$

the object has no resultant translational force.

Equilibrium

For a structure to remain stable, it must be in **equilibrium**.

In simple terms:

> **The forces and turning effects acting on the structure must balance.**

For translational equilibrium:

$$`\sum` = texF_x = 0$$

and:

$$`\sum` = texF_y = 0$$

For rotational equilibrium:

$$`\sum` = texM = 0$$

where **M** represents moment.

> **Interpreting Equilibrium**
>
> If the arrows representing forces balance horizontally and vertically, and their turning effects also balance, the structure is in equilibrium.

Forces Acting at Angles

Forces do not always act horizontally or vertically.

A force acting at an angle has:

- a horizontal component,
- a vertical component.

For example:

```
      ↗ F
     /
    /
   ●
```

The force can be resolved into:

```
   ↑ Fy
   |
   ●──────────→ Fx
```

where:

$$F_x = F`\cos` = tex`\theta` = tex$$

and:

$$F_y = F`\sin` = tex`\theta` = tex$$

depending on how the angle is defined.

For B3.2.4

The key requirement is to **interpret simple force diagrams**. You should understand that an angled force has horizontal and vertical effects, even when a full vector calculation is not required.

::: page-break :::

Loads on Beams

Two common ways of representing loads on beams are:

- **concentrated or point loads**,
- **uniformly distributed loads (UDL)**.

Point Load

A **concentrated load** or **point load** acts over such a small length that it is treated as acting at a single point.

It is represented by a single force arrow.

```
          ↓ 10 kN
          |
────────────┼────────────
```

Examples could include a load transferred to a beam through a particular connection or support point.

Uniformly Distributed Load --- UDL

A **Uniformly Distributed Load (UDL)** acts evenly over a specified length.

It is normally expressed as force per unit length, for example:

$$kN / m$$

A UDL may be represented as:

```
   ↓   ↓   ↓   ↓   ↓
   ↓   ↓   ↓   ↓   ↓
──────────────────────────────
      3 kN/m
```

The arrows indicate that the load is distributed across the beam rather than concentrated at one point.

Recognising Loads

Single arrow → point load

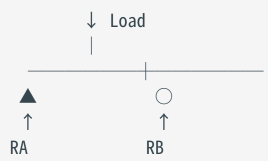
Repeated/evenly distributed arrows → distributed load

Support Reactions

When a structure applies a force to its supports, the supports provide **reaction forces**.

These reactions help keep the structure in equilibrium.

A simply supported beam may be represented as:



The downward load is balanced by upward reactions at the supports.

Key Idea

Applied loads act on the structure.

Support reactions oppose the effects of those loads and help maintain equilibrium.

Pinned Support

A **pinned (hinged) support** can provide a reaction whose components may act horizontally and vertically as required to maintain equilibrium.

It prevents translation at the support but allows rotation in the idealised model.

A reaction may therefore be represented using components such as:

$$R_x$$

and:

R_y

Roller or Rocker Support

A **roller or rocker support** allows movement along the supporting surface.

Its reaction acts **perpendicular to the supporting surface**.

For a horizontal surface, the reaction is therefore vertical.

```
    Beam
_______________

     ○
     ↑ R
```

Roller or rocker supports are useful in structures such as bridges because they can allow movement caused by **temperature variations**.

Diagram Interpretation

A roller support on a horizontal surface can provide a **vertical reaction**, but it allows horizontal movement.

::: page-break :::

Forces Within a Beam

A beam subjected to transverse loading tends to bend.

When a simple beam bends:

- one side is placed in **compression**,
- the opposite side is placed in **tension**,
- between them is the **neutral axis**.

For a typical simply supported beam bending downward:

```
       ↓ LOAD
_____________________

  COMPRESSION
-----------------
  NEUTRAL AXIS
-----------------
    TENSION
```

The upper layers shorten and are therefore in **compression**.

The lower layers extend and are therefore in **tension**.

At the neutral axis, longitudinal bending stress is zero.

> **Beam Bending**
>
> For the simple downward-bending case:
>
> **Top → Compression**
>
> **Centre → Neutral axis**
>
> **Bottom → Tension**

Stress Distribution Through a Beam

Bending stress varies through the depth of the beam.

The greatest tensile and compressive bending stresses occur at the **outer surfaces**, furthest from the neutral axis.

The stress reduces towards the neutral axis.

At the neutral axis:

`σ = 0` = tex

for longitudinal bending stress.

This is important when interpreting why beam cross-sectional shape affects structural performance.

Beam Cross-Section and Force Resistance

The location of material relative to the **neutral axis** affects resistance to bending.

An **I-beam** places a large amount of material away from the neutral axis.

It consists of:

- two horizontal **flanges**,
- a vertical **web**.

```
───────────────────   ← flange
    |
    |          ← web
    |
───────────────────   ← flange
```

This arrangement gives an efficient resistance to bending for its cross-sectional area.

A **box beam** has two webs and two flanges and provides greater resistance to twisting or **torsion**, making it useful where torsional forces are important.

> **Interpretation**
>
> When comparing beam shapes, consider **where the material is positioned relative to the neutral axis**, not simply how much material is present.

::: page-break :::

Trusses

A **truss** is a framework consisting of straight structural members connected at joints.

Trusses are commonly used in:

- bridges,
- roofs,
- buildings,
- other lightweight structural frameworks.

Idealised trusses are often based on **triangles**.

Triangles are structurally useful because their geometry allows loads to be transferred through members while maintaining a stable shape.

Forces in Truss Members

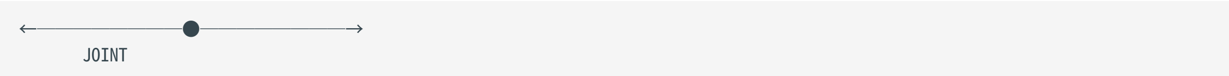
For the idealised pin-jointed trusses considered here:

- loads act at the **joints**,
- members carry axial forces,
- members are therefore primarily in either **tension** or **compression**.

This makes force diagrams particularly useful for interpreting trusses.

Identifying Tension

If the force in a member acts **away from a joint**, the member is being treated as being in **tension**.



The member is resisting a stretching action.

> **Forces pulling away from the joint → Tension**

Identifying Compression

If the force in a member acts **towards a joint**, the member is being treated as being in **compression**.

```
──────────────→●←──────────────
       JOINT
```

The member is resisting a compressive action.

> **Forces pushing towards the joint → Compression**

Quick Rule

At an isolated truss joint:

Arrow away from joint → Tension

Arrow towards joint → Compression

Interpreting a Simple Truss

When examining a truss force diagram:

1. Identify the **external loads**.
2. Identify the **support reactions**.
3. Identify the direction of the forces at the joints.
4. Determine which members are in **tension**.
5. Determine which members are in **compression**.
6. Check whether the forces are consistent with **equilibrium**.

A truss distributes loads through multiple members and transfers them towards its supports.

Force Polygons

When several forces act at different angles, their vectors can be arranged **tip-to-tail**.

If the final vector returns to the starting point, the force polygon closes.

A closed force polygon indicates:

$$`\sum` = tex`` \to = tex F = 0$$

and therefore translational equilibrium.

If the polygon does not close, the gap represents the **resultant force**.

> **Graphical Interpretation**
>
> **Closed force polygon → balanced forces**
>
> **Open force polygon → resultant force remains**

::: page-break :::

Shear Force Diagrams

Internal forces within a beam can vary along its length.

A **Shear Force Diagram (SFD)** represents the magnitude of the internal shear force at different positions along a beam.

A simple example may look like:

```
Shear Force

 +3 kN ────────────────────┐
                │
  0 ──────────────────────────┼───────────────────────────
                │
 -3 kN          └───────────────────────────
```

Changes in the shear force diagram correspond to loads and reactions acting on the beam.

For a beam in equilibrium, the shear force diagram returns to zero after all loads and reactions have been accounted for.

> **Interpretation**
>
> The SFD shows **how internal shear force changes along the beam**.

Bending Moment Diagrams

A **Bending Moment Diagram (BMD)** represents how bending moment changes along a beam.

Moment is the turning effect of a force about a point:

$$M = F`\times`= texd$$

where:

- **M** = moment,
- **F** = force,
- **d** = perpendicular distance from the force to the point.

Moment is commonly measured in:

$$\mathrm{N\,,m}$$

or:

$$\mathrm{kN\,,m}$$

Interpreting the Bending Moment Diagram

For a typical simply supported beam, the bending moment may:

- start at zero at one support,
- increase towards the loaded region,
- reach a maximum,
- return to zero at the other support.

The source material highlights an important relationship:

> **Maximum bending moment occurs where the shear force diagram equals zero.**

> **Connecting the Diagrams**
>
> **FBD → shows external loads and reactions**
>
> **SFD → shows internal shear force along the beam**
>
> **BMD → shows bending moment along the beam**

These diagrams represent different but related information about the same loaded structure.

Cantilever Force Diagrams

A **cantilever beam** is fixed at one end and unsupported at the other.

```
FIXED                      FREE
████ | ____________________________________________
     |                   ↓ Load
```

Examples include:

- balconies,
- some bridge structures,
- stadium roofs,
- aircraft wings.

Because the cantilever is supported at only one end, the fixed support must resist both forces and the turning effect created by the load.

For a point load (F) acting at a distance (L) from the fixed end:

$$M = F`\times` = texL$$

The largest bending moment occurs at the **fixed end**.

Cantilever

Free end → no additional support

Fixed end → carries the reaction forces and bending moment

::: page-break :::

Interpreting Force Diagrams --- Step by Step

When given a force diagram in an IB question, use the following process.

Step 1 --- Identify the Structure

Determine what is being represented:

- object,
- beam,
- cantilever,
- truss,
- joint.

Step 2 --- Identify External Loads

Look for arrows representing applied forces.

Record:

- magnitude,
- direction,
- position.

Step 3 --- Identify the Supports

Determine whether the diagram contains:

- pinned/hinged supports,
- roller/rocker supports,
- fixed supports.

Then identify the possible reaction directions.

Step 4 --- Identify Reactions

Look for forces generated by the supports.

Ask:

> Which applied forces are these reactions balancing?

Step 5 --- Check Equilibrium

Consider:

$$`\sum` = texF_x = 0$$

$$`\sum` = texF_y = 0$$

and, where relevant:

$$`\sum` = texM = 0$$

You do not always need to calculate the values to interpret whether the diagram represents balanced or unbalanced forces.

Step 6 --- Identify Internal Structural Effects

Depending on the structure, look for:

- tension,
- compression,
- shear,
- bending.

For a truss, identify whether individual members are in tension or compression.

For a beam, identify the compression side, tension side and neutral axis.

Step 7 --- Interpret What the Diagram Means

Do not simply list the arrows.

Explain the structural behaviour.

For example:

> The downward point load causes the simply supported beam to bend. The supports provide upward reaction forces. Under this bending condition, the upper region of the beam is in compression and the lower region is in tension.

This is **interpretation**, rather than simple identification.

Worked Interpretation 1 --- Simply Supported Beam

Consider:

```
           ↓ 10 kN
           |
   ────────────┼────────────
   ▲                 ○
   ↑                 ↑
  5 kN              5 kN
```

INTERPRETATION

A downward **10 kN point load** acts on the beam.

The two supports each provide an upward **5 kN reaction**.

Therefore:

$$`\sum` = texF_y = 5 + 5 - 10 = 0$$

The vertical forces are balanced.

The beam is in vertical equilibrium.

The downward loading also produces bending within the beam.

Worked Interpretation 2 --- Unbalanced Forces

```
40 N ←  ●  → 65 N
```

The horizontal resultant is:

$$65 - 40 = 25 \, N$$

to the right.

Therefore the forces are **not balanced**.

The object has a resultant force of:

$$25 \, N$$

acting to the right.

Worked Interpretation 3 --- Truss Joint

Consider an isolated joint:

```
 ↖
  \
   ●────────→
  /
 ↙
```

If the arrows representing member forces point **away from the joint**, those members are interpreted as being in **tension**.

If the arrows point **towards the joint**, they are interpreted as being in **compression**.

The combined forces at the joint must balance for the joint to remain in equilibrium.

::: page-break :::

Additional Context --- Bending Stress

When a beam bends, the bending stress at a particular position can be related to:

- the bending moment,
- the distance from the neutral axis,
- the geometry of the beam cross-section.

The relationship is:

$$`\sigma` = tex = ` \frac{My}{I} ` = tex$$

where:

- **σ** = bending stress,
- **M** = bending moment,
- **y** = distance from the neutral axis,
- **I** = second moment of area of the beam section.

The equation helps explain why the maximum bending stress occurs at the outer surfaces:

> As **y** increases, bending stress increases.

At the neutral axis:

$$y = 0$$

therefore:

`σ = 0` = tex

> **B3.2.4 Focus**
>
> The syllabus expectation for B3.2.4 is to **interpret simple force diagrams**.
>
> The bending stress equation provides useful structural context, but the central skill in this section is interpreting forces and diagrams rather than performing advanced beam calculations.

Second Moment of Area

The **second moment of area (I)** describes how the cross-sectional area is distributed relative to the neutral axis.

A larger second moment of area generally reduces bending stress for the same bending moment and distance from the neutral axis:

`σ` = tex = ` $\frac{My}{I}$ ` = tex

This explains why beam geometry can significantly affect bending performance.

The source material notes that, in current IB examinations, the second moment of area will be **provided** when required.

Common Interpretation Errors

1. Confusing Load and Reaction

A downward load is an **applied force**.

An upward force at a support is typically a **reaction**.

2. Ignoring Arrow Direction

The arrow direction is essential. Two forces with the same magnitude can have completely different effects if they act in different directions.

3. Confusing Tension and Compression

For an isolated truss joint:

away from joint = tension

towards joint = compression

4. Assuming Equal Forces Automatically Mean Equilibrium

Forces must balance in **direction and turning effect**, not only in magnitude.

5. Confusing SFD and BMD

A shear force diagram represents **shear force**.

A bending moment diagram represents **bending moment**.

They are related but do not show the same quantity.

B3.2.4 Force Diagram Checklist

When interpreting a simple force diagram, ask:

1. **What structure or component is represented?**
2. **What loads are acting?**
3. **What is the magnitude of each force?**
4. **In which direction does each force act?**
5. **Where does each force act?**
6. **What supports are present?**
7. **What reaction forces are shown or implied?**
8. **Are the horizontal forces balanced?**
9. **Are the vertical forces balanced?**
10. **Are the turning effects balanced?**
11. **Is the structure in equilibrium?**
12. **Are structural members in tension or compression?**
13. **Is the beam experiencing bending or shear?**
14. **What does the diagram tell you about the behaviour of the structure?**

Final Concept

Force diagrams provide a simplified visual representation of the forces acting on and within structures.

To interpret them correctly, identify the **loads, directions, support reactions and internal structural effects**, and determine how these forces interact to produce **equilibrium, tension, compression, shear or bending**.

B3.2.5 Safety Factors

A **Safety Factor (SF)**, also called a **Factor of Safety (FOS)**, provides a margin between the load or stress a structure is expected to experience in service and the load or stress that would cause unacceptable structural failure.

In its simplest form:

> **Safety Factor describes the extent to which the design strength exceeds the expected service requirement.**

For B3.2.5, the required relationship is:

$$SF = `\frac{\text{Ultimate Load (Stress)}}{\text{Allowable Load (Stress)}}` = tex$$

Safety Factor is a **ratio**, so it has **no units**.

Key Idea

Safety factors introduce **contingency** into structural design.

A structure should not normally operate close to its ultimate capacity because actual loads, material properties and service conditions may differ from the values assumed during design.

Ultimate, Allowable and Intended Loads

It is important to distinguish between three related ideas.

Ultimate Load or Stress

The **ultimate load** is the load associated with the limiting strength used in the safety-factor calculation.

Similarly, an **ultimate stress** represents the corresponding limiting material stress.

The source material commonly relates this to **Ultimate Tensile Strength (UTS)**.

Allowable Load or Stress

The **allowable load** is the maximum load permitted in normal design use after the Safety Factor has been applied.

The corresponding **allowable stress**, also called **working stress**, can be calculated using:

$$`\text{Allowable Stress}` = tex = `\frac{\text{Ultimate Stress}}{\text{SF}}` = tex$$

or:

$$`\sigma` = tex\_working = `\frac{\text{UTS}}{\text{SF}}` = tex$$

Intended or Service Load

The **intended load** is the load the structure is expected to carry in service.

The design must provide sufficient capacity so that the intended load remains within the allowable design limit.

A useful design relationship is:

$$\text{Required Ultimate Load} = \text{Intended Load} \times SF$$

Do Not Confuse the Values

Ultimate load/stress → limiting structural or material capacity used in the calculation.

Allowable load/stress → maximum permitted design value after applying the SF.

Intended/service load → load expected during normal use.

Calculating Safety Factor

The syllabus formula is:

$$SF = \frac{\text{Ultimate Load (Stress)}}{\text{Allowable Load (Stress)}}$$

This formula can be used with either **loads** or **stresses**, but the numerator and denominator must represent the same type of quantity.

For loads:

$$SF = \frac{F_{\text{ultimate}}}{F_{\text{allowable}}}$$

For stresses:

$$SF = \frac{\sigma_{\text{ultimate}}}{\sigma_{\text{allowable}}}$$

Units

The numerator and denominator must use compatible units.

For example:

$$\frac{60\ \text{kN}}{20\ \text{kN}} = 3$$

or:

$$\frac{450\ \text{MPa}}{150\ \text{MPa}} = 3$$

Do not divide a load in kN directly by a stress in MPa.

Worked Example 1 --- Calculate SF

A structural component has an ultimate load of **90 kN** and an allowable load of **30 kN**.

Calculate the Safety Factor.

$$\text{SF} = ` \frac{90}{30} ` = tex$$

$$`\text{SF} = 3` = tex$$

INTERPRETATION

The ultimate capacity used in the calculation is three times the allowable load.

Rearranging the Safety Factor Formula

The same relationship can be rearranged depending on the unknown quantity.

TO FIND SAFETY FACTOR

$$`\text{SF} = \frac{\text{Ultimate}}{\text{Allowable}} ` = tex$$

TO FIND ALLOWABLE LOAD OR STRESS

$$`\text{Allowable} = \frac{\text{Ultimate}}{\text{SF}}` = \text{tex}$$

TO FIND THE REQUIRED ULTIMATE CAPACITY

$$`\text{Ultimate} = \text{Allowable} \times \text{SF}` = \text{tex}$$

> **Formula Triangle**
>
> Think of the relationship as:
>
> ```
>       ULTIMATE
>      ─────────────
>      SF  ×  ALLOWABLE
> ```
>
> Therefore:
>
> **Ultimate = SF × Allowable**
>
> **SF = Ultimate ÷ Allowable**
>
> **Allowable = Ultimate ÷ SF**

::: page-break :::

Calculating Maximum Intended Loads

A common design problem is to determine the maximum load that may safely be applied to a component.

If the ultimate load is known:

$$\text{F\_allowable} = `\frac{F_{\text{ultimate}}}{\text{SF}}` = \text{tex}$$

Worked Example 2 --- Maximum Allowable Load

A component has an ultimate load capacity of **48 kN** and is designed with:

$$\text{SF} = 4$$

Calculate the maximum allowable load.

$$F\_allowable = ` \frac{48}{4} ` = tex$$

$$`F_{allowable} = 12\ kN` = tex$$

Therefore, the design load should not exceed **12 kN** under the assumptions of this calculation.

Designing a Structure with a Safety Factor

Sometimes the expected load and required Safety Factor are known, and the designer must determine the minimum structural capacity required.

Use:

$$F\_ultimate = F\_intended` \times ` = texSF$$

Worked Example 3 --- Required Design Capacity

A structural support is expected to carry a maximum intended load of:

$$8\,,\,kN$$

The required Safety Factor is:

$$SF = 3$$

The required ultimate capacity is:

$$F\_ultimate = 8` \times 3` = tex$$

$$`F_{ultimate} = 24\ kN` = tex$$

Therefore, the structure must be designed around an ultimate capacity of at least **24 kN** under the stated design assumptions.

Safety Factor Using Stress

Safety Factor can also be applied to stress.

The source material gives the relationship:

$$FOS = ` \frac{UTS}{\sigma_{working}} ` = tex$$

Therefore:

$$`\sigma` = tex\_working = ` \frac{UTS}{FOS} ` = tex$$

where:

- **UTS** = Ultimate Tensile Strength,
- **σworking** = allowable or working stress,
- **FOS** = Factor of Safety.

Worked Example 4 --- Allowable Stress

A steel has:

$$UTS = 590 \, , MPa$$

and:

$$FOS = 4$$

Calculate the allowable working stress.

$$`\sigma` = tex\_working = ` \frac{590}{4} ` = tex$$

$$`\sigma_{working} = 147.5 \ MPa` = tex$$

Since:

$$1 \, , MPa = 1 \, , N / mm\backslash^{2}$$

this can also be written as:

$$`147.5 \ N / mm^{2}` = tex$$

::: page-break :::

Designing a Tensile Rod with a Safety Factor

Safety Factor calculations can be combined with the stress equation:

$$`\sigma` = tex = `\frac{F}{A}` = tex$$

This allows a designer to determine the required cross-sectional area of a structural component.

For a circular rod:

$$A = `\frac{\pi d^2}{4}` = tex$$

where:

- **A** = cross-sectional area,
- **d** = diameter.

The calculation sequence is:

> **Material strength → Apply SF → Allowable stress → Required area → Required dimensions**

Worked Example 5 --- Maximum Working Load of a Steel Rod

A steel rod has:

- diameter = **16 mm**,
- UTS = **590 MPa**,
- Safety Factor = **4**.

Calculate the maximum working load.

STEP 1 --- CALCULATE CROSS-SECTIONAL AREA

$$A = `\frac{\pi d^2}{4}` = tex$$

$$A = `\frac{\pi (16)^2}{4}` = tex$$

$$A` \approx 201.06` = tex\,, mm\backslash^2$$

STEP 2 --- CALCULATE ALLOWABLE STRESS

$$`\sigma` = tex\_working = ` \frac{UTS}{FOS} ` = tex$$

$$`\sigma` = tex\_working = ` \frac{590}{4} ` = tex$$

$$`\sigma` = tex\_working = 147.5 \, , MPa$$

Since:

$$1 \, , MPa = 1 \, , N / mm\backslash^{2}$$

then:

$$`\sigma` = tex\_working = 147.5 \, , N / mm\backslash^{2}$$

STEP 3 --- CALCULATE MAXIMUM WORKING LOAD

From:

$$`\sigma` = tex = ` \frac{F}{A} ` = tex$$

rearrange:

$$F = `\sigma` = texA$$

Therefore:

$$F = 147.5` \times 201.06` = tex$$

$$F` \approx 29656` = tex \, , N$$

$$F` \approx 29.7` = tex \, , kN$$

Rounded appropriately:

$$`F \approx 30 \, kN` = tex$$

Calculation Route

$$d \rightarrow A \rightarrow \sigma_{allowable} \rightarrow F_{allowable}$$

In words:

Diameter → Area → Apply Safety Factor → Maximum working load

Worked Example 6 --- Minimum Diameter of a Steel Rod

A steel rod must carry a tensile load of:

$$30 , kN$$

The steel has:

$$UTS = 590 , MPa$$

and the required Safety Factor is:

$$SF = 4$$

Calculate the **minimum rod diameter**.

STEP 1 --- CALCULATE ALLOWABLE STRESS

$$`\sigma` = tex\_allowable = `\frac{UTS}{SF}` = tex$$

$$`\sigma` = tex\_allowable = `\frac{590}{4}` = tex$$

$$`\sigma` = tex\_allowable = 147.5 , MPa$$

STEP 2 --- CALCULATE REQUIRED AREA

From:

$$`\sigma` = tex = `\frac{F}{A}` = tex$$

rearrange:

$$A = \frac{F}{\sigma}$$

Convert the load:

$$30\,kN = 30000\,N$$

Therefore:

$$A = \frac{30000}{147.5}$$

$$A \approx 203.4\,mm^2$$

STEP 3 --- CALCULATE DIAMETER

For a circular section:

$$A = \frac{\pi d^2}{4}$$

Therefore:

$$d^2 = \frac{4A}{\pi}$$

$$d = \sqrt{\frac{4A}{\pi}}$$

Substituting:

$$d = \sqrt{\frac{4(203.4)}{\pi}}$$

$$d \approx 16.1\,mm$$

So the theoretical minimum is approximately:

$$d \approx 16\ mm$$

Design Interpretation

In a real design, the designer would select an appropriate available dimension that satisfies the required design criterion rather than deliberately selecting a smaller section than the calculated requirement.

::: page-break :::

Choosing an Appropriate Safety Factor

The size of the Safety Factor is not arbitrary.

The source material identifies several considerations.

Certainty of Loads

If the loads acting on a structure are difficult to predict, greater contingency may be required.

Design Life

Structures expected to remain in service for long periods may experience:

- ageing,
- wear,
- deterioration,
- changing conditions.

Quality of Manufacture

Manufacturing variation and defects can affect structural performance.

Higher confidence in manufacturing quality reduces uncertainty.

Consequences of Failure

The consequences of structural failure may range from inconvenience to catastrophic loss.

Where failure could cause severe injury or major damage, the design margin becomes particularly important.

Environmental Influences

Structures may be affected by:

- corrosion,
- weather,
- temperature,
- moisture,
- other environmental exposure.

These factors can reduce structural capacity over time.

Criticality of the Component

Some components are more important to the overall safety of a structure than others.

Failure of a critical component may lead to much greater consequences.

Ease of Repair or Maintenance

Components that are difficult to:

- inspect,
- maintain,
- repair,
- replace,

may require additional consideration during design.

Certainty of Material Properties

Material properties are not perfectly identical in every manufactured component.

Variation and uncertainty must therefore be considered.

Statutory and Code Requirements

Engineering structures may be required to comply with:

- regulations,
- standards,
- engineering codes.

These may specify required design approaches and safety margins.

SAFETY FACTOR SELECTION SUMMARY

Consideration Question for the Designer

Certainty of loads How predictable are the loads?

Design life How long must the structure remain safe?

Manufacturing quality How consistent is production?

Consequences of failure What happens if the component fails?

Environment Will corrosion, temperature or weather affect it?

Component criticality How important is this component to overall safety?

Maintenance Can it be inspected and repaired easily?

Material certainty How reliable are the material properties?

Codes What do regulations and standards require?

UTS, Yield Strength and Safety Factors

The source material makes an important distinction between **brittle** and **ductile** materials.

Brittle Materials

For brittle materials, **UTS** may be used as the limiting strength because yielding may not provide a useful warning before failure.

A simplified relationship is:

$$\text{SF} = \text{`}\,\frac{\text{UTS}}{\text{Working Stress}}\,\text{`} = \text{tex}$$

Ductile Materials

For ductile materials, **yield strength** is generally more relevant when permanent deformation is considered unacceptable.

A component may still be physically intact after yielding but may no longer satisfy its design requirements.

Therefore:

$$\text{SF} = \text{`}\,\frac{\text{Yield Strength}}{\text{Allowable Stress}}\,\text{`} = \text{tex}$$

may be the more appropriate design relationship.

> ⚠ **Important**
>
> **Failure does not always mean fracture.**
>
> For many ductile structural components, **permanent deformation after yielding can itself represent failure**.

Safety Factor Throughout a Structure's Life

A Safety Factor established during initial design does not mean that a structure will retain the same safety margin forever.

Structural capacity can change over time.

Material Degradation

Materials may deteriorate because of:

- corrosion,
- environmental exposure,
- wear,
- ageing,
- other degradation mechanisms.

If structural strength decreases while service loads remain unchanged:

`Effective safety margin decreases` = tex

Changes in Use

The actual loading of a structure may also change.

For example, a bridge may experience:

- heavier vehicles,
- more vehicles,
- different traffic patterns,

than were originally assumed.

Therefore:

> **Original design assumptions may no longer represent current service conditions.**

Monitoring and Reassessment

Structural safety therefore requires more than an initial calculation.

During the life of a structure, engineers may need to:

- inspect,
- monitor,
- reassess,
- maintain,
- repair,
- strengthen,

the structure.

Key Idea

Safety Factor is applied during design, but maintaining structural safety requires continued **inspection, maintenance and reassessment**.

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Case Study --- Genoa Morandi Bridge

The Morandi Bridge collapse illustrates how structural capacity can deteriorate during the life of a structure.

The source material identifies important issues including:

- corrosion of steel cables,
- deterioration of concrete,
- reduction in structural strength,
- concerns about maintenance.

The bridge eventually suffered catastrophic structural failure.

SAFETY FACTOR INTERPRETATION

The important principle is:

> **If structural capacity decreases while the loads remain similar or increase, the effective margin against failure becomes smaller.**

A simplified representation is:

$$\text{SF} = \text{`}\frac{\text{Structural Capacity}}{\text{Service Requirement}}\text{`} = \text{tex}$$

If the numerator decreases because of deterioration:

$$SF`\downarrow`=tex$$

This demonstrates why inspection and maintenance are essential for ageing infrastructure.

Designing with Safety Factor --- A General Method

When asked to design a structural component with a specified Safety Factor, use the following sequence.

STEP 1 --- IDENTIFY THE INTENDED LOAD

Determine the maximum expected service load.

STEP 2 --- IDENTIFY THE REQUIRED SAFETY FACTOR

For example:

$$SF=4$$

STEP 3 --- DETERMINE THE REQUIRED CAPACITY

For a load-based problem:

$$UltimateLoad=IntendedLoad`\times`=texSF$$

or, for a material-stress problem:

$$AllowableStress=`\frac{\text{Limiting Material Strength}}{SF}`=tex$$

STEP 4 --- DETERMINE THE REQUIRED SIZE

Use the appropriate structural relationship.

For axial stress:

$$`\sigma`=tex=`\frac{F}{A}`=tex$$

therefore:

$$A = \frac{F}{\sigma}$$

STEP 5 --- CONVERT AREA INTO COMPONENT DIMENSIONS

For a circular rod:

$$A = \frac{\pi d^2}{4}$$

Therefore:

$$d = \sqrt{\frac{4A}{\pi}}$$

STEP 6 --- CHECK THE DESIGN

Confirm that:

$$ActualCapacity \geq RequiredCapacity$$

and that the intended load does not exceed the allowable design load.

Exam-Style Questions

Question 1 --- Calculate SF

A structural member has an ultimate capacity of **120 kN** and an allowable load of **40 kN**.

Calculate its Safety Factor.

ANSWER

$$SF = \frac{120}{40}$$

$$SF = 3$$

Question 2 --- Calculate Maximum Intended Load

A component can withstand an ultimate load of **75 kN** and must have:

$$SF = 5$$

Calculate the maximum allowable load.

ANSWER

$$F\_allowable = `\frac{75}{5}` = tex$$

$$`F_{allowable} = 15\,kN` = tex$$

Question 3 --- Design for an SF

A support is intended to carry:

$$12\,,kN$$

It must have:

$$SF = 3$$

Determine the required ultimate load capacity.

ANSWER

$$F\_ultimate = 12` \times 3` = tex$$

$$`F_{ultimate} = 36\,kN` = tex$$

Question 4 --- Calculate Allowable Stress

A material has an ultimate stress of:

$$480\,,MPa$$

The required Safety Factor is:

$$SF = 3$$

Calculate the allowable stress.

ANSWER

$$`\sigma` = tex\_allowable = `\frac{480}{3}` = tex$$

$$`\sigma_{allowable} = 160\,\text{MPa}` = tex$$

Question 5 --- Select Between Two Designs

A product must carry a maximum intended load of **20 kN** with:

$$SF = 3$$

Two designs are available:

- **Design A:** ultimate load = 50 kN
- **Design B:** ultimate load = 65 kN

Determine which design satisfies the required Safety Factor.

REQUIRED CAPACITY

$$F\_required = 20`\times 3` = tex$$

$$F\_required = 60\,,\text{kN}$$

DESIGN A

$$SF_A = `\frac{50}{20}` = tex = 2.5$$

Does not meet the required SF of 3.

DESIGN B

$$SF_B = `\frac{65}{20}` = tex = 3.25$$

Meets the requirement.

Therefore:

$$`\text{Design B}` = \text{tex}$$

is acceptable according to the stated Safety Factor criterion.

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Common Calculation Errors

1. Using the Formula Backwards

Correct:

$$SF = \frac{\text{Ultimate}}{\text{Allowable}}$$

Not:

$$SF = \frac{\text{Allowable}}{\text{Ultimate}}$$

2. Multiplying When You Should Divide

To find allowable load:

$$\text{Allowable} = \frac{\text{Ultimate}}{SF}$$

To find required ultimate capacity:

$$\text{Ultimate} = \text{Allowable} \times SF$$

3. Mixing Loads and Stresses

Use:

$$\frac{\text{kN}}{\text{kN}}$$

or:

$$\frac{\text{MPa}}{\text{MPa}}$$

Do not mix a load with a stress in the same SF ratio.

4. Forgetting Unit Conversion

Remember:

$$1 \text{ kN} = 1000 \text{ N}$$

and:

$$1 \text{ MPa} = 1 \text{ N} / \text{mm}^2$$

5. Treating SF as a Unit

Safety Factor is **dimensionless**.

Write:

$$SF = 4$$

not:

$$SF = 4 \text{ MPa}$$

B3.2.5 Calculation Checklist

Before finishing a Safety Factor problem, check:

1. What is the **intended or allowable load**?
2. What is the **ultimate load or limiting strength**?
3. What Safety Factor is required?
4. Are you working with **loads or stresses**?
5. Are the units compatible?
6. Do you need:

$$\mathrm{SF} = \text{`} \frac{\mathrm{Ultimate}}{\mathrm{Allowable}} \text{`} = \mathrm{tex}$$

1. Or:

$$\mathrm{Allowable} = \text{`} \frac{\mathrm{Ultimate}}{\mathrm{SF}} \text{`} = \mathrm{tex}$$

1. Or:

$$\mathrm{Ultimate} = \mathrm{Allowable}\text{`} \times \text{`} = \mathrm{texSF}$$

1. Do you need to calculate stress using:

$$\text{`}\sigma\text{`} = \mathrm{tex} = \text{`} \frac{F}{A} \text{`} = \mathrm{tex}$$

1. Do you need to calculate the dimensions of the component?
2. Is UTS or yield strength the appropriate limiting property in the stated problem?
3. Does the final design actually achieve the required Safety Factor?

Final Concept

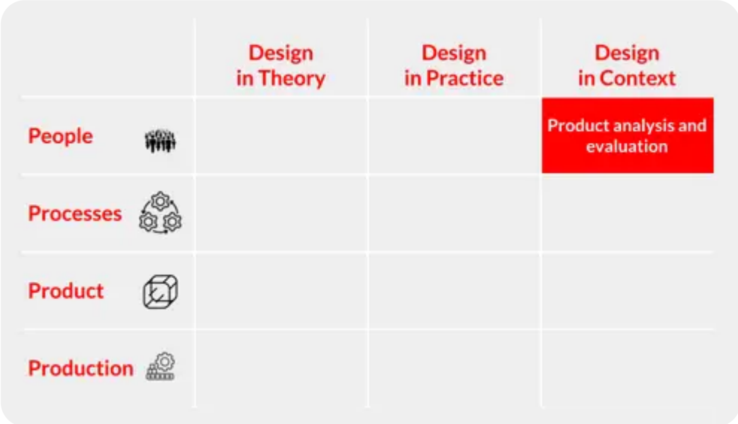
Safety Factors provide a design margin between structural capacity and the load or stress permitted in service.

For B3.2.5:

$$SF = \frac{\text{Ultimate Load (Stress)}}{\text{Allowable Load (Stress)}}$$

You must be able to **calculate the Safety Factor, calculate the maximum intended or allowable load, and determine the structural capacity or dimensions required to design a structure with a specified Safety Factor**.

C3.1 Product Analysis



C3.1.1 The Process

Product analysis is an important stage in the design process. Before creating a new product, **designers study existing products already available on the market**. This helps them understand what works well, what problems users experience, and what aspects could be improved.

By analysing products, designers can identify:

- strengths and weaknesses
- user needs and preferences
- functional and aesthetic features
- manufacturing considerations
- opportunities for innovation

This process benefits all stakeholders involved in product development, including **designers, engineers, manufacturers, marketers, and consumers**. Each group can use the information gathered during the analysis to make better decisions and improve the final product.

Summary

Analysing existing products allows designers to learn from previous solutions and develop improved products that better satisfy users' needs.

C3.1.2 How Product Analysis Helps Stakeholders

1. Designers and Engineers

Designers and engineers use product analysis to identify:

- problems
- limitations
- opportunities for improvement
- possible innovations

Example: Vacuum Cleaner

Traditional vacuum cleaners presented several problems:

- they were heavy
- required cables
- had limited mobility

After analysing these issues, companies developed:

- cordless vacuum cleaners
- lighter products
- compact designs
- smart features

> **Key Idea**
>
> Product analysis helps designers and engineers create improved and more innovative solutions.

2. Manufacturers and Production Teams

Manufacturers analyse products to:

- optimise material selection
- simplify assembly processes
- reduce manufacturing costs
- improve production efficiency

Example: Coffee Maker

By reverse engineering a high-end coffee maker, manufacturers can:

- study how the product is assembled
- identify efficient production methods
- explore alternative materials

> **Key Idea**
>
> Product analysis helps companies manufacture products more efficiently and economically.

3. Marketing and Retail Teams

Marketing and retail teams analyse products to:

- understand consumer preferences
- identify unique selling points
- position products effectively in the market

Example: Inverted Umbrella

Traditional umbrellas drip water when closed.

The inverted umbrella was designed to solve this problem by folding inwards.

This innovation became:

- a practical solution,
- a strong marketing advantage.

Key Idea

Product analysis allows companies to better understand customer needs and market opportunities.

C3.1.3 SWOT Analysis

A SWOT analysis is **a standard product analysis tool** used to identify a product's:

- **Strengths**
- **Weaknesses**
- **Opportunities**
- **Threats**

SWOT analysis helps designers evaluate existing products and guide future innovations.

It allows designers to analyse:

- **internal factors** → strengths and weaknesses
- **external factors** → opportunities and threats

Internal vs External Factors

Internal Factors (Strengths, Weaknesses)

These are factors that belong to the product itself and can usually be controlled by the designer or company.

Examples:

- materials,
- ergonomics,
- product quality,
- usability,
- functionality,
- manufacturing quality.

External Factors (Opportunities, Threats)

These are factors outside the product that designers cannot directly control.

Examples:

- competitors,
- new technologies,
- environmental changes,
- market trends,
- legislation,
- economic conditions.

Strengths

Strengths are the **internal positive** attributes of a product.

They are the areas where the product performs well and provides value to users.

When identifying strengths, consider:

- unique features,
- quality of materials,
- ergonomics,
- ease of use,
- reliability,
- strong brand reputation,
- innovative technology.

Example: High-End Chef's Knife

Strengths:

- premium steel that keeps a sharp edge,
- ergonomic handle for comfort,
- balanced weight distribution,
- strong reputation among professional chefs.

> **Key Idea**
>
> Strengths are the features that make a product attractive and competitive.

Weaknesses

Weaknesses are **internal factors** that place the product at a **disadvantage**.

These are areas that reduce the product's effectiveness or limit its success.

When identifying weaknesses, consider:

- design flaws,
- functional limitations,
- high production costs,
- outdated technology,
- poor durability,
- complicated user interfaces.

Example: High-End Chef's Knife

Weaknesses:

- expensive retail price,
- requires frequent sharpening,
- not dishwasher safe,
- limited versatility for casual users.

Key Idea

Weaknesses highlight areas that may need redesign or improvement.

Opportunities

Opportunities are **external** situations that could help the product **improve or succeed** in the future.

They usually come from changes in the market or society.

Examples of opportunities:

- new technologies,
- changing consumer needs,
- environmental awareness,
- new markets,
- social media trends,
- government incentives.

Example: Electric Vehicles

Opportunities:

- growing environmental awareness,
- improvements in battery technology,
- expansion of charging infrastructure,
- government support for sustainable transport.

> **Key Idea**
>
> Opportunities can help products evolve and become more successful.

Threats

Threats are **external factors** that could **negatively affect** the product.

These are risks that may reduce sales or make the product less competitive.

Examples:

- new competitors,
- cheaper alternatives,
- changing trends,
- economic problems,
- stricter regulations,
- technological obsolescence.

Example: Streaming Services

Threats:

- increasing competition,
- rising subscription costs,
- piracy,
- changing consumer habits.

> **Key Idea**
>
> Threats are external risks that companies must anticipate and manage.

Example of a Simple SWOT Table

Product: Reusable Water Bottle

Try to identify the strengths, weaknesses, opportunities, and threats of this reusable water bottle.

Strengths	**Weaknesses**
Durable stainless steel	Heavy
Keeps water cold for hours	Expensive
Sustainable product	Can dent if dropped
Opportunities	**Threats**
Growing eco-awareness	Cheap competitors
Reduction of single-use plastics	Market saturation
Social media trends	New bottle technologies

Final Idea

SWOT analysis is not just about describing a product.

It is a tool that helps designers think critically about:

- the product,
- the users,
- the market,
- competitors,
- and the future of the design.

Final Concept

SWOT analysis helps designers create better, more competitive, and more innovative products.

C3.1.4 Function, Performance and Usability

Function, performance, and usability evaluation **is a process** used by designers **to analyse** how well a product works, how efficiently it performs, and how easy it is to use.

This process helps designers identify problems and improve products based on testing, measurements, and user feedback.

The Three Main Areas of Product Evaluation

Aspect	Main Question
Function	Does the product do its job?
Performance	How well does the product work?
Usability	Is the product easy and comfortable to use?

1. Function

Function refers to the main purpose of a product.

It answers the question:

> Does the product perform its intended task correctly?

Function Testing

Function describes the main purpose of a product, while function testing is the process used to verify whether the product performs that purpose correctly. Function testing checks whether the product works properly.

Example: Electric Kettle

Function testing may involve checking whether the kettle can successfully perform its main functions, such as:

- boiling water to the correct temperature,
- automatically switching off after boiling,
- allowing the lid to open and close properly,
- pouring water safely without spilling.

Example of Function Testing Data

Test	Result
Water temperature	100°C
Auto shut-off reliability	Failed 2 out of 20 tests
Lid mechanism	Works correctly

Design Improvements from Function Testing

Testing may reveal that the automatic shut-off occasionally fails.

This insight could lead designers to:

- improve the thermostat system,
- redesign safety mechanisms,
- increase reliability.

Key Idea

Function testing helps designers verify whether a product performs its intended purpose correctly.

2. Performance

Performance evaluates how efficiently and effectively a product works.

It answers the question:

> How well does the product work?

A product may function correctly but still perform poorly.

Performance Testing

Performance testing measures:

- speed,
- efficiency,
- durability,
- energy consumption,
- reliability under different conditions.

Example: Electric Kettle

Performance testing may include:

- measuring boiling time,
- testing energy efficiency,
- durability testing through repeated use cycles.

Example of Performance Data

Water Volume	Boiling Time
250 ml	45 seconds
1 litre	2 minutes
1.5 litres	5 minutes

Design Improvements from Performance Testing

Testing may show that the kettle becomes less efficient with larger water volumes.

This could lead designers to:

- redesign the heating element,
- improve insulation,
- modify the kettle capacity.

Key Idea

Performance testing helps designers improve efficiency, reliability, and overall product quality.

3. Usability

Usability refers to how easy, intuitive, and comfortable a product is to use.

It answers the question:

> Is the product easy and comfortable to use?

Even if a product functions correctly, poor usability can create frustration for users.

Usability Testing

Usability testing often **involves real users** interacting with the product.

Designers observe:

- user behaviour,
- difficulties,
- comfort,
- efficiency of interaction.

Example: Electric Kettle

Usability testing may evaluate:

- ease of filling,
- pouring comfort,
- clarity of controls,
- handle ergonomics,
- visibility of indicators.

Example of Usability Problems

Users may struggle to see the water level indicator in low-light conditions.

Possible redesign solutions:

- illuminated water window,
- improved contrast,
- repositioned indicator.

Key Idea

Usability testing helps designers create products that are easier, safer, and more enjoyable to use.

4. Reverse Engineering

Function, Performance, and Usability are areas of product evaluation, while reverse engineering **is a method designers use to better understand these aspects** in existing products.

Reverse engineering involves disassembling and analysing existing products to understand:

- how they work,
- how they are manufactured,
- what materials are used,
- what design solutions have been implemented.

Why is Reverse Engineering Important?

Designers use reverse engineering to:

- learn from competitors,
- discover innovative solutions,
- identify weaknesses,
- improve their own products.

Example: Electric Kettle

Reverse engineering may reveal:

- more efficient heating elements,
- better insulation materials,
- improved safety systems,
- advanced filter designs.

Design Improvements from Reverse Engineering

A competitor's kettle may contain a more effective scale filter.

This could inspire designers to:

- redesign their own filter system,
- improve maintenance,
- increase product lifespan.

> ⚠ **Important**
>
> Reverse engineering is used to learn and improve products, not simply to copy them.

Summary Table

Aspect	Main Focus
Function	Does the product work correctly?
Performance	How efficiently does it work?
Usability	Is it easy and comfortable to use?
Reverse Engineering	How have other designers solved problems?

C3.1.5 Product Weaknesses and Opportunities for Improvement

Identifying weaknesses in products is an essential part of product analysis and innovation.

Main Methods Used to Identify Improvement Opportunities

1. Weakness Identification

Designers analyse products to identify shortcomings in areas such as:

- functionality,
- usability,
- aesthetics,
- durability,
- efficiency.

Example: School Backpack

Traditional school backpacks had several weaknesses:

- poor weight distribution,
- uncomfortable shoulder straps,
- limited organisation compartments,
- lack of waterproof protection.

Design Opportunity

These weaknesses created opportunities for:

- ergonomic padded straps,
- lightweight materials,
- modular storage compartments,
- waterproof fabrics,
- integrated USB charging ports.

> **Key Idea**
>
> Identifying weaknesses helps designers discover opportunities for product improvement and innovation.

2. Competitive Analysis

Competitive analysis involves **comparing products with similar products** already available on the market.

This helps designers understand:

- market standards,
- competitor advantages,
- missing features,
- areas where products can improve.

Example:

A kettle may boil water in 5 minutes, while competitor products boil water in only 2 minutes.

This reveals an opportunity to:

- improve heating efficiency,
- redesign internal components,
- optimise performance.

> **Key Idea**
>
> Comparing products helps designers identify opportunities for competitive improvement.

3. User Feedback Integration

User feedback involves **collecting opinions and experiences from real users**.

Users often identify problems that designers may not notice during technical testing.

Examples of User Feedback

Users may report:

- uncomfortable handles,
- confusing controls,
- poor visibility,
- difficult cleaning processes.

Why is User Feedback Important?

User feedback helps designers identify:

- pain points,
- frustrations,
- practical usability problems.

> ⚠ **Important**
>
> Real users provide valuable insights into how products perform in everyday situations.

4. Market Trend Analysis

Designers study:

- social changes,
- technological developments,
- environmental concerns,
- consumer preferences.

This helps identify **future opportunities for product improvement**.

Example

Modern urban homes are becoming smaller.

This creates demand for products that are:

- compact,
- lightweight,
- multifunctional,
- easy to store.

Design Opportunity

This trend encouraged the development of:

- stick vacuum cleaners,
- foldable furniture,
- compact appliances.

Key Idea

Market trends often influence future product design opportunities.

5. Cross-Product Comparison

Designers sometimes **analyse solutions used in completely different product categories**.

This can inspire innovative ideas and new approaches.

Example: Sports Shoes Inspired by Car Tyres

PROBLEM

Traditional running shoes often lose grip on wet surfaces, increasing the risk of slipping and reducing athlete performance.

CROSS-PRODUCT INSPIRATION

Designers analysed the tread patterns and rubber compounds used in car tyres, which are specifically designed to maximise grip and water dispersion on wet roads.

SOLUTION DEVELOPED

Sports shoe manufacturers adapted:

- tyre-inspired tread patterns,
- specialised rubber materials,
- multidirectional grooves,

to improve traction and stability in running shoes.

RESULT

The redesigned shoes provided:

- improved grip,
- safer movement on wet surfaces,
- better athletic performance,
- increased durability.

Cross-Product Innovation

Designers often solve problems by adapting successful ideas from completely different industries.

C3.1.6 Constructive Discontent

Constructive discontent is an important concept in product design that **helps drive innovation** and product improvement.

Instead of simply accepting products as they are, **designers critically analyse them** and ask:

> "How could this product be improved?"

It encourages continuous improvement rather than accepting products as "good enough".

Key Idea

Constructive discontent means using dissatisfaction in a positive and productive way to improve products.

Types of User Needs

Functional Needs

These relate to **how well the product performs** its task.

Example:

- short battery life,
- weak materials,
- poor durability.

Emotional Needs

These relate to how users **feel when interacting** with the product.

Example:

- unattractive appearance,
- frustrating experience,
- lack of personalisation.

Experiential Needs

These relate to the **overall user experience**.

Example:

- uncomfortable use,
- confusing controls,
- difficult handling.

Key Idea

Designers must consider both technical performance and user experience.

Solution-Oriented Thinking

Constructive discontent does **not focus only on identifying problems**.

It also focuses on finding solutions and opportunities for improvement.

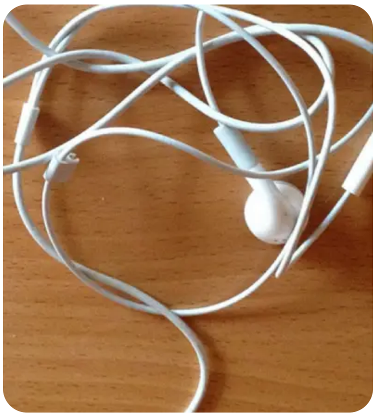
Problem

Wired earphones become tangled and inconvenient.

Opportunity for Improvement

Development of:

- wireless earbuds,
- Bluetooth headphones,
- compact charging cases.



User-Centred Perspective

Designers must analyse products **from the user’s point of view**.

Example

An engineer may believe a product works perfectly.

However, users may think the product is:

- too heavy,
- confusing,
- uncomfortable,
- difficult to use.

Key Idea

Good design is not only about technology — it is about people and user experiences.

Continuous Improvement Mindset

Constructive discontent encourages designers **to continuously improve products**.

Even successful products can be redesigned and enhanced.

EXAMPLE: SMARTPHONES

Every year smartphones are improved through:

- better cameras,
- improved batteries,
- lighter materials,
- enhanced software,
- new features.

This process happens because companies constantly search for areas of improvement.

Constructive Discontent as a Driver of Innovation

Constructive discontent often **leads to major innovations and entirely new product categories**.

Example: Vacuum Cleaners

PROBLEMS WITH TRADITIONAL VACUUM CLEANERS

- heavy,
- difficult to manoeuvre,
- bulky,
- inconvenient cables.

INNOVATIONS CREATED

These problems led to the development of:

- cordless vacuum cleaners,
- stick vacuums,
- robotic vacuum cleaners.

RESULT

Designers transformed user frustrations into opportunities for innovation.

Innovation

Many successful products were created because designers identified problems that users experienced in everyday life.

Difference Between Criticism and Constructive Discontent

Negative Criticism	Constructive Discontent
Focuses only on problems	Focuses on solutions
Negative mindset	Improvement mindset
Complaining	Innovation and redesign

Final Idea

Constructive discontent helps designers:

- question existing products,
- identify unmet needs,
- improve user experiences,
- create innovative solutions.