

Structures, materials & vibration

Carry load without hiding the failure path

Starting question — What makes a structure survive launch, landing and years of repeated service?

Intuition. A safe structure is not merely strong once. It must carry known load paths, avoid unstable modes, tolerate fatigue and damage, and retain margin after manufacturing and environmental uncertainty.

- Explain the governing idea before calculating.
- Name the units, evidence source and operational boundary of every key quantity.
- Check the result with an inverse, bound, refinement or independent physical estimate.

A space structure must survive launch, operate in vacuum, endure thermal cycles, preserve precise alignment and sometimes deploy after months of storage. Adding material everywhere makes the vehicle too heavy; removing it without analysis creates imaginary margin. Structural engineering is therefore about load paths, failure modes and qualification environments.

Before you start — Prerequisites: modules 01 to 09 recommended. Every important symbol is defined again at first use.

Mastery objectives

- explain concepts with units and assumptions
- redo a simple calculation by hand before using a tool
- identify at least one failure mode or model limitation
- connect the discipline to a complete Mars architecture

Zero-prerequisite concepts

These four concept cards establish the vocabulary needed before the calculations and mission decisions in this module.

mechanical stress

Definition. Mechanical stress is internal force intensity, commonly expressed as force per unit area.

Example. The same axial load creates greater stress in a narrow tie rod than in a thick one.

Pitfall. Stress is not the total force and should not be reported in newtons.

Mental check. At the same force, increasing resisting area must reduce average axial stress.

Guided exercise — mechanical stress

In a Mars mission scenario, identify one situation in which “mechanical stress” changes an engineering or operational decision. State the evidence you would inspect, the mistake you must avoid, and one independent check you would perform before accepting the decision.

Detailed correction — mechanical stress

Core meaning. Mechanical stress is internal force intensity, commonly expressed as force per unit area.

Mission example. The same axial load creates greater stress in a narrow tie rod than in a thick one.

Error to reject. Stress is not the total force and should not be reported in newtons.

Independent check. At the same force, increasing resisting area must reduce average axial stress.

Quantification

Use the physical unit that belongs to mechanical stress when it is quantitative; if it is qualitative, do not invent a numerical unit.

Verification

Compare the conclusion with the mission example, the stated pitfall and the mental check before using mechanical stress operationally.

strain

Definition. Strain measures deformation relative to original dimension and is dimensionless.

Example. A one-metre bar that lengthens by one millimetre has strain 0.001, or 0.1%.

Pitfall. Strain and displacement are different; the same displacement gives different strain for different original lengths.

Mental check. Divide the change in length by original length and verify that the units cancel.

Guided exercise — strain

In a Mars mission scenario, identify one situation in which “strain” changes an engineering or operational decision. State the evidence you would inspect, the mistake you must avoid, and one independent check you would perform before accepting the decision.

Detailed correction — strain

Core meaning. Strain measures deformation relative to original dimension and is dimensionless.

Mission example. A one-metre bar that lengthens by one millimetre has strain 0.001, or 0.1%.

Error to reject. Strain and displacement are different; the same displacement gives different strain for different original lengths.

Independent check. Divide the change in length by original length and verify that the units cancel.

Quantification

Use the physical unit that belongs to strain when it is quantitative; if it is qualitative, do not invent a numerical unit.

Verification

Compare the conclusion with the mission example, the stated pitfall and the mental check before using strain operationally.

natural frequency

Definition. A natural frequency is a frequency at which a structure tends to vibrate in one of its modes.

Example. A solar array may have bending modes that must remain separated from launch forcing or control-system excitation.

Pitfall. A component has multiple natural modes, not one universal resonance frequency.

Mental check. Compare forcing frequencies with the relevant mode spectrum and damping, not with a single remembered number.

Guided exercise — natural frequency

In a Mars mission scenario, identify one situation in which “natural frequency” changes an engineering or operational decision. State the evidence you would inspect, the mistake you must avoid, and one independent check you would perform before accepting the decision.

Detailed correction — natural frequency

Core meaning. A natural frequency is a frequency at which a structure tends to vibrate in one of its modes.

Mission example. A solar array may have bending modes that must remain separated from launch forcing or control-system excitation.

Error to reject. A component has multiple natural modes, not one universal resonance frequency.

Independent check. Compare forcing frequencies with the relevant mode spectrum and damping, not with a single remembered number.

Quantification

Use the physical unit that belongs to natural frequency when it is quantitative; if it is qualitative, do not invent a numerical unit.

Verification

Compare the conclusion with the mission example, the stated pitfall and the mental check before using natural frequency operationally.

safety margin

Definition. A safety margin compares allowable capability with predicted demand under a stated rule and load case.

Example. A structural member may retain positive margin after applying qualification load factors and temperature-degraded material allowables.

Pitfall. A positive nominal margin is meaningless if loads, material condition or the margin convention are undefined.

Mental check. Reconstruct both demand and allowable with the same units and the same design basis before interpreting the sign.

Guided exercise — safety margin

In a Mars mission scenario, identify one situation in which “safety margin” changes an engineering or operational decision. State the evidence you would inspect, the mistake you must avoid, and one independent check you would perform before accepting the decision.

Detailed correction — safety margin

Core meaning. A safety margin compares allowable capability with predicted demand under a stated rule and load case.

Mission example. A structural member may retain positive margin after applying qualification load factors and temperature-degraded material allowables.

Error to reject. A positive nominal margin is meaningless if loads, material condition or the margin convention are undefined.

Independent check. Reconstruct both demand and allowable with the same units and the same design basis before interpreting the sign.

Quantification

Use the physical unit that belongs to safety margin when it is quantitative; if it is qualitative, do not invent a numerical unit.

Verification

Compare the conclusion with the mission example, the stated pitfall and the mental check before using safety margin operationally.

Calculation laboratory — formula, units, inverse check and limits

Each relation is taught from zero prerequisites: what it asks, what every symbol means, why the operation is valid, how to calculate it and how to catch a wrong result independently.

Canonical quantitative mini-lessons

This block is the module quantitative reference; exercise values are pedagogical and must not be confused with mission data.

Average normal stress

$$\sigma = F / A$$

1 — Concrete question

What does “ $\sigma = F / A$ ” compute in “Average normal stress”?

2 — Intuition without symbols

Average stress distributes a force over the area carrying it.

3 — Quantities

σ : average stress; F : normal force; A : resisting area

4 — Formula

$$\sigma = F / A$$

5 — Read aloud

Read “ $\sigma = F / A$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

σ : average stress; F : normal force; A : resisting area

7 — Pronunciation

Say subscripts, powers, Greek letters and parentheses explicitly so the relation can be reconstructed without seeing the page.

8 — Units

σ in Pa; F in N; A in m^2

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Division compares one quantity with a homogeneous reference and produces a proportion indicator.

11 — Assumptions

Both quantities must belong to the same scope and time period.

12 — Unit check

σ in Pa; F in N; A in m^2 Verify that dimensional reduction reaches the unit of the requested output.

13 — Numerical case

With $F=18,000$ N and $A=1.20 \times 10^{-4} \text{ m}^2$, $\sigma=150$ MPa.

14 — Why the calculation works

Division compares one quantity with a homogeneous reference and produces a proportion indicator.

15 — Independent check

Multiplying the result by the denominator must recover the numerator.

16 — Mental estimate

Before calculating, compare numerator and denominator mentally to predict whether the result should be below, near or above one.

17 — Interpretation

Local stress can be higher near holes, fillets, welds or notches.

18 — What the result does not prove

The calculation proves neither that the inputs are correct nor that the model remains valid outside the declared scenario; those questions require separate evidence.

19 — Sensitivity

The result rises with the numerator and falls with the denominator, all else equal.

20 — Guided and autonomous exercises

Guided exercise. $F=10,000$ N, $A=2.0 \times 10^{-4} \text{ m}^2$.

Detailed guided correction — open after trying

$F=10,000$ N, $A=2.0 \times 10^{-4} \text{ m}^2$. $\sigma=50$ MPa.

Autonomous exercise. $F=25,000$ N, $A=5.0 \times 10^{-4} \text{ m}^2$.

Autonomous correction — open after trying

$F=25,000$ N, $A=5.0 \times 10^{-4} \text{ m}^2$. $\sigma=50$ MPa.

21 — Mission decision

Compare qualified local stresses with material allowables using required safety factors.

Normal strain

$$\epsilon = \Delta L / L$$

1 — Concrete question

What does “ $\epsilon = \Delta L / L$ ” compute in “Normal strain”?

2 — Intuition without symbols

Strain measures length change relative to initial length.

3 — Quantities

ϵ : strain; ΔL : length change; L : reference length

4 — Formula

$$\epsilon = \Delta L / L$$

5 — Read aloud

Read “ $\epsilon = \Delta L / L$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

ϵ : strain; ΔL : length change; L : reference length

7 — Pronunciation

Say subscripts, powers, Greek letters and parentheses explicitly so the relation can be reconstructed without seeing the page.

8 — Units

ϵ dimensionless; ΔL and L in the same unit

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Division compares one quantity with a homogeneous reference and produces a proportion indicator.

11 — Assumptions

Both quantities must belong to the same scope and time period.

12 — Unit check

ϵ dimensionless; ΔL and L in the same unit. Verify that dimensional reduction reaches the unit of the requested output.

13 — Numerical case

With $\Delta L=0.6$ mm and $L=600$ mm, $\epsilon=0.001 = 0.1\%$.

14 — Why the calculation works

Division compares one quantity with a homogeneous reference and produces a proportion indicator.

15 — Independent check

Multiplying the result by the denominator must recover the numerator.

16 — Mental estimate

Before calculating, compare numerator and denominator mentally to predict whether the result should be below, near or above one.

17 — Interpretation

Small global strain does not exclude local concentrations or local yielding.

18 — What the result does not prove

The calculation proves neither that the inputs are correct nor that the model remains valid outside the declared scenario; those questions require separate evidence.

19 — Sensitivity

The result rises with the numerator and falls with the denominator, all else equal.

20 — Guided and autonomous exercises

Guided exercise. $\Delta L=0.2$ mm, $L=200$ mm.

Detailed guided correction — open after trying

$\Delta L=0.2$ mm, $L=200$ mm. $\epsilon=0.001$.

Autonomous exercise. $\Delta L=1.5$ mm, $L=1000$ mm.

Autonomous correction — open after trying

$\Delta L = 1.5 \text{ mm}$, $L = 1000 \text{ mm}$. $\epsilon = 0.0015$.

21 — Mission decision

Compare with allowable strain and the material elastic range.

Linear elastic law

$\sigma = E \times \epsilon$

1 — Concrete question

What does “ $\sigma = E \times \epsilon$ ” compute in “Linear elastic law”?

2 — Intuition without symbols

Within the linear elastic range, stress and strain are proportional.

3 — Quantities

σ : stress; E : Young modulus; ϵ : strain

4 — Formula

$\sigma = E \times \epsilon$

5 — Read aloud

Read “ $\sigma = E \times \epsilon$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

σ : stress; E : Young modulus; ϵ : strain

7 — Pronunciation

Say subscripts, powers, Greek letters and parentheses explicitly so the relation can be reconstructed without seeing the page.

8 — Units

σ and E in Pa; ϵ dimensionless

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Multiplication converts a rate or specific quantity into a total over the chosen interval or population.

11 — Assumptions

Factors must describe the same scenario and their units must be compatible.

12 — Unit check

σ and E in Pa; ϵ dimensionless Verify that dimensional reduction reaches the unit of the requested output.

13 — Numerical case

With $E = 70 \text{ GPa}$ and $\epsilon = 0.001$, $\sigma = 70 \text{ MPa}$.

14 — Why the calculation works

Multiplication converts a rate or specific quantity into a total over the chosen interval or population.

15 — Independent check

Dividing the result by any non-zero factor must recover the other factor.

16 — Mental estimate

Estimating each factor separately predicts the order of magnitude of the product.

17 — Interpretation

The relation does not apply beyond the linear range or to anisotropic material without an appropriate model.

18 — What the result does not prove

The calculation proves neither that the inputs are correct nor that the model remains valid outside the declared scenario; those questions require separate evidence.

19 — Sensitivity

With independent factors, a relative change in one factor transfers directly to the product.

20 — Guided and autonomous exercises

Guided exercise. $E = 200 \text{ GPa}$, $\epsilon = 0.0005$.

[Detailed guided correction — open after trying](#)

E=200 GPa, epsilon=0.0005. sigma=100 MPa.

Autonomous exercise. E=110 GPa, epsilon=0.002.

Autonomous correction — open after trying

E=110 GPa, epsilon=0.002. sigma=220 MPa.

21 — Mission decision

Verify the operating point remains inside the qualified material range.

Bending stress

$\sigma_{\text{bend}} = M \times y / I$

1 — Concrete question

What does " $\sigma_{\text{bend}} = M \times y / I$ " compute in "Bending stress"?

2 — Intuition without symbols

Bending creates stress that grows with bending moment and distance from the neutral axis.

3 — Quantities

σ_{bend} : bending stress; M: bending moment; y: distance from neutral axis; I: second moment of area

4 — Formula

$\sigma_{\text{bend}} = M \times y / I$

5 — Read aloud

Read " $\sigma_{\text{bend}} = M \times y / I$ " by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

σ_{bend} : bending stress; M: bending moment; y: distance from neutral axis; I: second moment of area

7 — Pronunciation

Say subscripts, powers, Greek letters and parentheses explicitly so the relation can be reconstructed without seeing the page.

8 — Units

σ_{bend} in Pa; M in N·m; y in m; I in m⁴

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

The relation turns the mini-lesson mechanism into a quantitative statement that can be checked by numerical substitution.

11 — Assumptions

Inputs must come from the same scenario with units, signs and conventions explicitly aligned.

12 — Unit check

σ_{bend} in Pa; M in N·m; y in m; I in m⁴ Verify that dimensional reduction reaches the unit of the requested output.

13 — Numerical case

With M=5,000 N·m, y=0.05 m and I=2.5×10⁻⁵ m⁴, σ_{bend} =10 MPa.

14 — Why the calculation works

The relation turns the mini-lesson mechanism into a quantitative statement that can be checked by numerical substitution.

15 — Independent check

Recomputing with the inverse relation or a second method should recover the same order of magnitude.

16 — Mental estimate

Estimating the scale before using a calculator helps catch factor, sign or unit errors.

17 — Interpretation

The formula assumes a beam and bending regime compatible with the adopted theory.

18 — What the result does not prove

The calculation proves neither that the inputs are correct nor that the model remains valid outside the declared scenario; those questions require separate evidence.

19 — Sensitivity

Varying one input at a time reveals which variable drives the decision most strongly.

20 — Guided and autonomous exercises

Guided exercise. $M=8,000 \text{ N}\cdot\text{m}$, $y=0.04 \text{ m}$, $I=4.0\times 10^{-5} \text{ m}^4$.

Detailed guided correction — open after trying

$M=8,000 \text{ N}\cdot\text{m}$, $y=0.04 \text{ m}$, $I=4.0\times 10^{-5} \text{ m}^4$. $\sigma_{\text{bend}}=8 \text{ MPa}$.

Autonomous exercise. $M=3,000 \text{ N}\cdot\text{m}$, $y=0.03 \text{ m}$, $I=1.5\times 10^{-5} \text{ m}^4$.

Autonomous correction — open after trying

$M=3,000 \text{ N}\cdot\text{m}$, $y=0.03 \text{ m}$, $I=1.5\times 10^{-5} \text{ m}^4$. $\sigma_{\text{bend}}=6 \text{ MPa}$.

21 — Mission decision

Use finite-element analysis or a more complete theory when geometry, loading or material fall outside this regime.

Euler critical buckling load

$$P_{\text{cr}} = \pi^2 \times E \times I / (K \times L)^2$$

1 — Concrete question

What does “ $P_{\text{cr}} = \pi^2 \times E \times I / (K \times L)^2$ ” compute in “Euler critical buckling load”?

2 — Intuition without symbols

A slender column can lose stability well before reaching a material compression limit.

3 — Quantities

P_{cr} : critical load; E : Young modulus; I : second moment of area; K : effective-length factor; L : length

4 — Formula

$$P_{\text{cr}} = \pi^2 \times E \times I / (K \times L)^2$$

5 — Read aloud

Read “ $P_{\text{cr}} = \pi^2 \times E \times I / (K \times L)^2$ ” by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

P_{cr} : critical load; E : Young modulus; I : second moment of area; K : effective-length factor; L : length

7 — Pronunciation

Say subscripts, powers, Greek letters and parentheses explicitly so the relation can be reconstructed without seeing the page.

8 — Units

P_{cr} in N; E in Pa; I in m^4 ; K dimensionless; L in m

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

The relation turns the mini-lesson mechanism into a quantitative statement that can be checked by numerical substitution.

11 — Assumptions

Inputs must come from the same scenario with units, signs and conventions explicitly aligned.

12 — Unit check

P_{cr} in N; E in Pa; I in m^4 ; K dimensionless; L in m Verify that dimensional reduction reaches the unit of the requested output.

13 — Numerical case

With $E=70 \text{ GPa}$, $I=1.0\times 10^{-6} \text{ m}^4$, $K=1$ and $L=2 \text{ m}$, $P_{\text{cr}}\approx 172.7 \text{ kN}$.

14 — Why the calculation works

The relation turns the mini-lesson mechanism into a quantitative statement that can be checked by numerical substitution.

15 — Independent check

Recomputing with the inverse relation or a second method should recover the same order of magnitude.

16 — Mental estimate

Estimating the scale before using a calculator helps catch factor, sign or unit errors.

17 — Interpretation

Imperfections, eccentricity and real support conditions often reduce practical critical load.

18 — What the result does not prove

The calculation proves neither that the inputs are correct nor that the model remains valid outside the declared scenario; those questions require separate evidence.

19 — Sensitivity

Varying one input at a time reveals which variable drives the decision most strongly.

20 — Guided and autonomous exercises

Guided exercise. $E=200$ GPa, $I=2.0 \times 10^{-6}$, $K=1$, $L=3$ m.

Detailed guided correction — open after trying

$E=200$ GPa, $I=2.0 \times 10^{-6}$, $K=1$, $L=3$ m. $P_{cr} \approx 438.6$ kN.

Autonomous exercise. $E=70$ GPa, $I=0.5 \times 10^{-6}$, $K=1$, $L=1.5$ m.

Autonomous correction — open after trying

$E=70$ GPa, $I=0.5 \times 10^{-6}$, $K=1$, $L=1.5$ m. $P_{cr} \approx 153.5$ kN.

21 — Mission decision

Keep qualified margin against buckling including imperfections and envelope load cases.

Natural frequency of a mass-spring mode

$$f_n = (1/(2 \times \pi)) \times \sqrt{k/m}$$

1 — Concrete question

What does " $f_n = (1/(2 \times \pi)) \times \sqrt{k/m}$ " compute in "Natural frequency of a mass-spring mode"?

2 — Intuition without symbols

A stiffer structure vibrates naturally faster, while more mass lowers natural frequency.

3 — Quantities

f_n : natural frequency; k : modal stiffness; m : modal mass

4 — Formula

$$f_n = (1/(2 \times \pi)) \times \sqrt{k/m}$$

5 — Read aloud

Read " $f_n = (1/(2 \times \pi)) \times \sqrt{k/m}$ " by naming every operation, subscript and grouping explicitly.

6 — Symbols and meaning

f_n : natural frequency; k : modal stiffness; m : modal mass

7 — Pronunciation

Say subscripts, powers, Greek letters and parentheses explicitly so the relation can be reconstructed without seeing the page.

8 — Units

f_n in Hz; k in N/m; m in kg

9 — Convention

Keep the same frame, time basis, system boundary and sign convention throughout the substitution.

10 — Why this operation

Root-sum-square combines independent contributions without assuming they all add in the same direction.

11 — Assumptions

Contributions must be independent or sufficiently uncorrelated for this combination to be justified.

12 — Unit check

f_n in Hz; k in N/m; m in kg Verify that dimensional reduction reaches the unit of the requested output.

13 — Numerical case

With $k=100,000$ N/m and $m=10$ kg, $f_n \approx 15.92$ Hz.

14 — Why the calculation works

Root-sum-square combines independent contributions without assuming they all add in the same direction.

15 — Independent check

The square of the result must equal the sum of the squared contributions.

16 — Mental estimate

The result must be at least as large as the dominant contribution and below their arithmetic sum.

17 — Interpretation

A real vehicle has many coupled, damped modes that depend on boundary conditions.

18 — What the result does not prove

The calculation proves neither that the inputs are correct nor that the model remains valid outside the declared scenario; those questions require separate evidence.

19 — Sensitivity

The largest contribution influences the result more strongly because it is squared.

20 — Guided and autonomous exercises

Guided exercise. $k=40,000$ N/m, $m=10$ kg.

Detailed guided correction — open after trying

$k=40,000$ N/m, $m=10$ kg. $f_n \approx 10.07$ Hz.

Autonomous exercise. $k=90,000$ N/m, $m=25$ kg.

Autonomous correction — open after trying

$k=90,000$ N/m, $m=25$ kg. $f_n \approx 9.55$ Hz.

21 — Mission decision

Separate forcing and control bandwidths from critical modes identified by analysis and test.

1. Forces, moments and load paths

A force tends to accelerate mass; a moment tends to rotate it. In a structure, these actions travel through load paths. A small bracket can appear lightly loaded locally yet become critical if it concentrates the load of an entire panel. Sketching the load path from source to interfaces is often more valuable than using a complex model that nobody understands.

Engineering habit. For “forces, moments and load paths”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

2. Stress, strain and Young’s modulus

Normal stress $\sigma=F/A$ connects force and area. Strain ϵ measures relative extension. In the linear elastic domain, $\sigma=E\epsilon$, where E is Young’s modulus. This does not prove a part is safe: stress concentrations, material limits, temperature, manufacturing and cycle count still have to be checked.

Engineering habit. For “stress, strain and young’s modulus”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

Approfondissement — Stress concentrations: structures rarely fail in the middle of a perfect uniform section

Average stress in a bar is easy to calculate, but real hardware contains holes, threads, welds, thickness changes and fillets. Those details concentrate load. The effect is often represented by K_t , a stress-concentration factor: local peak stress is approximately K_t times nominal stress. If nominal stress is 80 MPa and $K_t = 2.4$, the critical location may reach 192 MPa before manufacturing uncertainty is added.

A hatch, window or cable penetration in a pressurized habitat is therefore a structural problem in its own right. A global model can show comfortable margin while hiding a local hot spot. Finite-element analysis helps identify these regions, but it has to represent the geometry that is actually built: weld defects, smaller radii, scratches and porosity. The design rule is simple: load paths should remain understandable and critical discontinuities should remain inspectable.

3. Bending, torsion and buckling

A beam can fail in tension, but a slender compression member may lose stability through buckling long before material strength is reached. Torsion loads sections and joints differently. Failure modes therefore depend on geometry as much as material. High nominal material strength cannot prevent geometric instability.

Engineering habit. For “bending, torsion and buckling”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

4. Fatigue: modest repeated loads can destroy a part

Fatigue results from load cycles. A stress below ultimate strength can still initiate a crack and grow it over thousands of cycles. Deployment mechanisms, wheels, pumps and thermally cycled structures are affected. The real load spectrum matters more than a single maximum value.

Engineering habit. For “fatigue: modest repeated loads can destroy a part”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

Approfondissement — Fatigue and load spectra: surviving ten thousand small events

A part can stay far below ultimate strength and still crack after repeated cycles. Fatigue depends on stress amplitude, cycle count, geometry, material and environment. A rover experiences launch vibration, deployment, driving loads, thermal cycling and shocks. A habitat experiences pressure and temperature cycles. Life is often described with an S–N curve: S is stress amplitude and N is the number of cycles to failure under the test conditions.

The trap is checking only the single worst event. Ten thousand lower-amplitude cycles can be more damaging. Miner’s rule provides a simple cumulative-damage approximation: $D = \sum(n_i/N_i)$, where n_i is the actual number of cycles at level i , N_i is the estimated cycles to failure at that level, $\sum$ means sum and D is cumulative damage. D approaching 1 means the calculated fatigue life is being consumed. The model is imperfect, but it forces the right question: how many times will the mission really do this?

5. Fracture and damage tolerance

Fracture mechanics examines how a crack concentrates stress. A damage-tolerant approach assumes a defect may exist and asks whether it remains detectable and slow-growing before it becomes critical. This changes maintenance philosophy: inspection method, allowable flaw size and inspection interval become design variables.

Engineering habit. For “fracture and damage tolerance”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

6. Vibration, natural modes and resonance

Every flexible structure has natural frequencies. If periodic excitation approaches one of them, response can be greatly amplified. During launch, random vibration, acoustics and shock can load fragile hardware. In operation, reaction wheels, pumps and mechanisms also excite structure. Engineers separate frequencies, add damping and qualify the hardware.

Engineering habit. For “vibration, natural modes and resonance”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

Approfondissement — Structure–control interaction: flexible hardware can confuse the software controlling it

Spacecraft are never perfectly rigid. Solar arrays, antennas, booms and large tanks have natural modes. If an attitude command excites one of those modes, the structure oscillates; sensors measure the motion; the controller may attempt to correct it and unintentionally amplify the response. Natural frequency f_n , where f denotes frequency and subscript n identifies the mode, therefore has to be compared with control-loop bandwidth.

The answer is not simply “make the structure stronger.” Added stiffness costs mass. Engineers can shift a mode, filter a signal, limit actuator rate or redesign the control law. This is systems engineering in miniature: the structural optimum can be poor for control and vice versa. The same issue will appear in Mars settlements with robotic arms, cranes, centrifuges, pumps and lightweight pressurized structures.

7. Materials: mass, stiffness, temperature and environment

Aluminium, titanium, steels, composites and polymers provide different trade-offs. The best terrestrial material is not automatically best for vacuum or Mars: outgassing, radiation, dust, temperature, chemical compatibility and repairability can dominate. Selection starts from function and environment, not an abstract strength ranking.

Engineering habit. For “materials: mass, stiffness, temperature and environment”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

8. Qualification and evidence: analysis, test and margin

Flight structures are justified through suitable analysis and test. Models predict stress, displacement and modes; vibration and load tests expose imperfections and real interfaces. A positive margin is credible only when the applied load, allowable strength and factors are defined clearly.

Engineering habit. For “qualification and evidence: analysis, test and margin”, write the inputs, outputs, units and validity range first. Then build one nominal and one degraded case. This two-case approach prevents a correct equation from being mistaken for an operationally robust Mars architecture.

Worked example step by step

The work method is always the same: state what every symbol represents, convert all units into a coherent system, perform the operation, then translate the result into a sentence. Finally perform an order-of-magnitude check. If the answer changes by a factor of one thousand because millimetres were treated as metres, the conversion must be visible in the calculation.

Progressive exercise

1. Choose a simple case and list every input with units.
2. Compute the nominal result without margin.
3. Vary the most uncertain parameter by $\pm 20\%$ and compare.
4. Inject one credible failure and explain which indicator detects it.

5. Decide whether the system continues, degrades or stops.

Reasoned solution

A good solution is not only the final number. It shows conversions, why the equation applies, sensitivity and the resulting decision. If different plausible assumptions lead to the same operational decision, the design is relatively robust to that uncertainty. If a small variation reverses the decision, the parameter becomes a priority for measurement or margin.

Validation mini-project

Build a two-to-four-page engineering note applying this course to one Mars subsystem. Include need, assumptions, functional sketch, hand calculation, second calculation or simulation, uncertainties, injected failure, decision criteria and three primary references. The goal is a chain of evidence that another reader can reproduce.

Common errors to detect

- mixing units or frames without explicit conversion;
- presenting calculated values as measured data;
- ignoring a model's validity range;
- confusing numerical precision with physical accuracy;
- sizing only the nominal case with no margin or degraded mode.

Mission reasoning laboratory — connect the calculation to a real decision

The purpose of this laboratory is not to memorise isolated definitions. It links the module to a Mars mission decision, identifies evidence, tests boundary cases and preserves an explicit recovery path.

Start from the load path

Every structural calculation should identify where the load enters, how it travels through parts and joints, and where reactions occur. A strong panel is useless if a small bracket or fastener is the true bottleneck. Draw arrows through the structure before selecting formulas. Mars hardware also experiences different load cases: launch vibration, landing shock, pressurisation, thermal gradients, handling, repeated rover travel and maintenance forces. The controlling load path may change between these phases.

Keep strength and stiffness separate

Strength asks whether material or a joint fails under load; stiffness asks how much it deforms. A structure can be strong enough yet too flexible for alignment, sealing or control stability. Antennas, optical instruments and pressure hatches can have tight deformation limits well below material yield. Young's modulus, geometry and boundary conditions drive stiffness. Engineering decisions should therefore compare both stress margins and deformation requirements rather than assuming a positive strength margin solves every structural problem.

Recognise instability before material failure

Buckling can destroy a slender column or shell at stress well below the material yield strength. Thin pressure vessels, rover struts and deployable structures are sensitive to geometry, imperfections and boundary conditions. A simple average-stress check can therefore look comfortable while the member is unstable. Compression members need an explicit buckling assessment, and qualification should consider manufacturing imperfections that reduce ideal analytical capacity.

Design for repeated loading

Fatigue damage accumulates over cycles. A wheel suspension, pump bracket or pressure vessel may survive one load easily yet crack after thousands or millions of repetitions. The relevant stress range, mean stress, surface finish, joint detail

and environment affect fatigue life. Mars dust can also change contact and wear behaviour. Track expected cycles by mission phase and inspect high-consequence locations rather than treating “below yield” as a lifetime guarantee.

Use damage tolerance where consequences demand it

Damage-tolerant design assumes flaws can exist and asks whether they can be found or safely tolerated before reaching critical size. Fracture toughness, crack-growth rate, inspection interval and residual strength become part of the safety argument. This approach is especially important for pressure structures and critical load paths where a hidden crack can grow over many cycles. Inspection itself must be practical in the mission environment; a method that requires equipment unavailable on Mars does not provide real protection.

Control vibration and resonance

Launch and machinery create dynamic loads that can excite structural modes. Resonance depends on forcing frequency, natural frequency and damping, so simply “making the structure stronger” may not solve the problem. Modal tests and analysis identify frequencies and shapes, while design changes can shift modes or add damping. Control systems can also interact with flexible structures. A mast or solar array that moves in a control bandwidth can destabilise pointing even when static stress is tiny.

Qualify the actual configuration

Structural evidence combines material allowables, analysis, component tests and system-level testing. Configuration matters: changing a fastener, cable routing, cut-out or bonded joint can alter load paths and modes. Qualification should therefore map to the hardware that will fly or operate on Mars. Record the load cases, factors, temperatures, boundary conditions and margins so later maintenance or modification can determine whether the existing evidence still applies.

Progressive exercises — solve first, then open the correction

Synthesis exercise — load path

A bracket carries 18 kN of axial load through a rectangular metal ligament 30 mm wide and 4 mm thick. Calculate average axial stress in MPa. If a local notch raises peak stress by a factor of 2.2, estimate that peak and explain why a material yield strength cannot be compared blindly with the first F/A result.

Detailed correction — Synthesis exercise — load path

Area. $30\text{ mm} \times 4\text{ mm} = 120\text{ mm}^2 = 1.20 \times 10^{-4}\text{ m}^2$.

Average stress. $18,000 / 1.20 \times 10^{-4} = 150\text{ MPa}$.

Notch estimate. $2.2 \times 150 \approx 330\text{ MPa}$. Real acceptance also needs load factors, material allowables at temperature, fatigue or fracture considerations and a validated stress-concentration model.

Beginner vocabulary checkpoint

Focus or tap each highlighted term for its definition. The goal is to remove hidden prerequisites before the learner reaches a safety-significant calculation or procedure.

- load path — Route by which applied forces and moments travel through a structure to their reactions.
- moment — Turning effect of a force about a point or axis.
- bending — Structural deformation produced by a moment that creates tension on one side and compression on the other.
- torsion — Twisting produced by torque about a structural axis.
- buckling — Sudden instability of a compressed member or shell, often before material strength is exhausted.
- Young's modulus — Material stiffness relating elastic normal stress to elastic normal strain.
- yield strength — Stress level associated with onset of significant permanent deformation under a defined test condition.

- ultimate strength — Maximum engineering stress a material specimen sustains before fracture or severe loss of load capacity.
- fatigue — Progressive damage caused by repeated cyclic loading.
- S–N curve — Relation between cyclic stress amplitude and number of cycles to failure for a material or detail.
- fracture toughness — Resistance of a material to propagation of an existing crack.
- damage tolerance — Design philosophy that assumes flaws can exist and requires detection or safe life before they become critical.
- stress concentration — Local stress amplification caused by geometry such as holes, notches, fillets or joints.
- factor of safety — Ratio or design factor used to maintain separation between allowable capacity and expected demand under a defined rule.
- margin of safety — Signed measure comparing allowable and applied demand according to a specified engineering convention.
- mode shape — Spatial deformation pattern associated with a structural natural frequency.
- resonance — Large vibration response that can occur when forcing frequency aligns with a lightly damped natural mode.
- damping — Mechanism that dissipates vibratory energy and reduces resonance response.
- random vibration — Broadband vibration environment commonly used to represent launch excitation statistically.
- sine vibration — Controlled single-frequency or swept-frequency excitation used in structural testing.
- proof load — Specified test load applied to demonstrate structural capability without intending damage.
- qualification load — Test or analysis load level used to demonstrate margin beyond expected operational conditions.
- allowable — Approved material or component limit used for structural comparison under specified conditions.
- creep — Time-dependent deformation under sustained stress, especially at elevated temperature.
- thermal expansion — Dimensional change caused by temperature change.
- composite — Material combining distinct constituents to obtain tailored stiffness, strength or other properties.
- joint — Interface that transfers load between structural parts, such as a bolted, bonded or welded connection.

Decision closeout — evidence before acceptance

Treat joints as part of the structure

Bolts, inserts, welds, adhesive bonds and interfaces often control structural reliability even when the surrounding material has comfortable stress margin. Joints introduce preload, bearing stress, slip, peel, local bending and assembly variability. They also determine whether a part can be replaced on Mars. A structural review should therefore follow load across every joint and ask what happens after repeated disassembly, dust contamination or thermal cycling. Designing only the ideal continuous member can hide the actual weak link.

Link inspection to crack-growth time

Damage tolerance becomes operational only when inspection can find a flaw before it reaches a critical size. That requires an estimate of how fast cracks could grow under the expected load spectrum and how sensitive the available inspection method is. A visual inspection may be adequate for one external bracket but useless for a hidden pressure-vessel flaw. The inspection interval, required access, crew training and decision threshold should be documented together with the structural analysis, especially when resupply or replacement is impossible for months.

Primary sources and pathways

- NASA — Small Spacecraft Structures, Materials and Mechanisms
- NASA Standards — Materials and Processes
- www.nasa.gov — institutional documentation
- standards.nasa.gov — institutional documentation

FR ↔ EN parity matrix

EN	FR
Average normal stress	Contrainte normale moyenne
Normal strain	Déformation unitaire
Linear elastic law	Loi élastique linéaire
Bending stress	Contrainte de flexion
Euler critical buckling load	Charge critique de flambage d'Euler
Natural frequency of a mass-spring mode	Fréquence propre masse-ressort