

Chapter 2: Safety and regulatory requirements

2.1. General information:

Safety, defined as the absence of acceptable risk, rests in the field of construction on three fundamental requirements: the stability of the structure, the durability of the materials, and fitness for purpose. planned for the structure. However, absolute safety is impossible to achieve; a residual risk, linked to a non-zero probability of failure or accident, must be integrated. Thus, the sizing of structures and the verification of their safety cannot rely on an empirical approach. These processes are based on calculation rules, rigorous and codified standards, guaranteeing a scientific analysis of mechanical, environmental and usage constraints.

2.2. Actions and requests

2.2.1. Actions

In civil engineering, actions refer to the stresses (forces and moments) generated by external loads (permanent, climatic, use loads, etc.) and by stresses due to forced deformations (thermal changes, support settlements, etc.).

The BAEL 91 regulations classify these actions into three categories:

- Permanent actions (fixed charges),
- Variable actions (temporary charges),
- Accidental actions (exceptional events).

2.2.1.1. Permanent actions (G)

These demands, of constant or nearly stable intensity over time, include:

- THE self-weight of the structure (density of reinforced concrete: 25 KN/m^3),
- The loads of fixed equipment (partitions, permanent installations),
- The thrusts/pressures of earth or liquids at a stable level (e.g., reservoirs, retaining walls),
- The forces related to deformations imposed continuously (prestressing, delayed shrinkage).

2.2.1.2. Variable actions (Q)

Characterized by frequent and significant variations, they include:

(a) Operating expenses :

- Costs related to usage (human traffic, vehicles, storage), classified by duration (temporary/long-term),
- *Mobile* loads (industrial equipment, non-fixed furniture).

(b) Climate loads :

- Snow (depending on the region),
- Wind (dynamic pressure depending on exposure).

(c) Thermal effects : expansion/contraction due to temperature differences.

2.2.1.3. Accidental actions (FA)

Exceptional and unpredictable events, such as:

- Earthquakes (seismic stresses defined by zoning),
- Shocks (vehicle impacts, explosions)
- Other rare phenomena (major fires, extreme floods).

2.2.2. Requests:

Stresses correspond to the *internal* forces (such as the normal force N and the shear force T) and moments (such as the bending moment M_f and the torsional moment M_t) generated in a structure. These quantities are calculated from the **actions (loads, applied forces) using appropriate analysis methods (statics, strength of materials, etc.)**. Stresses are determined after combining the actions according to normative rules, systematically selecting the case the most unfavorable in order to ensure the safety and reliability of the structural design.

2.2.3 Combinations of actions

Combinations of actions make it possible to define the critical load cases to which a structure can be subjected, by superimposing the effects of different actions (permanent, variable, accidental) according to normative rules.

2.2.3.1 Notations and definitions of shares

a) Permanent actions (G)

- **G_{max}** : Set of permanent adverse actions , contributing to the aggravation of stresses (e.g., self-weight of the structure, uncompensated fixed loads).
- **G_{min}** : Set of permanent favorable actions , reducing adverse effects (ex: stabilizing weight of an embankment).
- **G** : Permanent neutral actions, without distinction of their favorable or unfavorable effect.

b) Principal variable actions (Q₁)

Dominant variable action, known as the "**basic**" **action** , chosen according to the context:

- **Q_B** : Building operating costs (e.g., furniture, occupants).
- **W** : Action of the wind (pressure or depression).
- **S** : Snow load (dependent on geographical location).

c) Variable support actions (Q_i, i ≥ 2)

Secondary variable actions, combined with reduction by a coefficient ψ (ψ_0 , ψ_1 , ψ_2) to reflect their probability of simultaneous occurrence:

- **Q_r** : Operating costs of road bridges standards (systems A and B, loads on sidewalks).
- **Q_{RP}** : Operating costs of road bridges specific (military convoys, exceptional transports).

d) Thermal actions

- **T** : Uniform temperature variation (overall expansion/contraction of the structure).
- **$\Delta\theta$** : Thermal gradient (temperature difference between faces of an element, inducing curvatures).

e) Accidental actions (**F_A**)

Rare but extreme events (e.g., earthquake, explosion, shock), characterized by a representative value (**F_A**) defined by standards.

2.2.3.2. Action combinations for design loads

The combinations of actions determine the **load cases** to be analyzed to verify the resistance and stability of a structure. They are divided into two main categories.

a) Combinations of Ultimate Limit States (ULS)

This combination is used to **verify** that the structure can withstand extreme loads without breakage or instability (safety of people and structural integrity).

- **Fundamental combination** (general case):

$$ELU = \gamma_G \cdot G_{max} + \gamma_{Q1} \cdot Q_1 + i \geq 2 \sum \gamma_{Qi} \cdot \psi_{0i} \cdot Q_i$$

γ_G, γ_Q : Partial safety factors (1.35 for G_{max} , 1.5 for Q_1).

ψ_1, ψ_2 : Combination coefficient for variable accompanying actions (e.g., 0.7 for operating expenses).

- **Accidental combination** (earthquake, explosion, etc.):

$$\text{Accidental ELECTED} = G + F_A + \psi_1 \cdot Q_1 + i \geq 2 \sum \psi_{2i} \cdot Q_i$$

F_A : Accidental action (representative value).

ψ_1, ψ_2 : Reduction coefficients for variable actions (e.g. 0.5 for frequent loads).

- **Example**

For a building subjected to its own weight (G_{max}), a live load (Q_B), and wind (W):

$$ELU = 1.35 \cdot G_{max} + 1.5 \cdot Q_B + 1.5 \cdot 0.6 \cdot W$$

$$ELU = 1.35 \cdot G_{max} + 1.5 \cdot Q_B + 1.5 \cdot 0.6 \cdot W \text{ (with } \psi_0 = 0.6 \text{)}.$$

b) Combinations of Service Limit States (SLS)

This combination aims to guarantee user comfort and the durability of the structure under normal loads (limiting deformations, cracking, vibrations).

- **Typical combination** (maximum service stresses):

$$ELS \text{ Characteristic} = G + Q_1 + \sum i \geq 2 \psi_{0i} \cdot Q_i$$

- **Common combination** (recurring effects):

$$ELS \text{ Frequent} = G + \psi_1 \cdot Q_1 + \sum i \geq 2 \psi_{2i} \cdot Q_i$$

- **Near-permanent combination** (long-term effects):

$$ELS \text{ Quasi Permanent} = G + \sum i \geq 1 \psi_{2i} \cdot Q_i$$

- **Example**

For a road bridge subjected to traffic loads (Q_r) and a thermal gradient ($\Delta\theta$):

$$\text{Frequent ELS} = G + 0.7 \cdot Q_r + 0.6 \cdot \Delta\theta$$

(with $\psi_1=0.7$ for Q_r , $\psi_2=0.6$ for $\Delta\theta$).

- **Noticed**

In the most common case, the only combination of actions to consider for the foundations and the columns is: $1.35 \cdot G + 1.5 \cdot Q$.

2.2.3.2. Common elements of reinforced concrete structures subjected only to permanent (G) and live (Q) loads (Exclusion of climatic actions – wind, snow, etc.) :

a) Beams on two supports extended by a cantilever:

- **Ultimate limit states (ULS):** (See Figure 2.1)

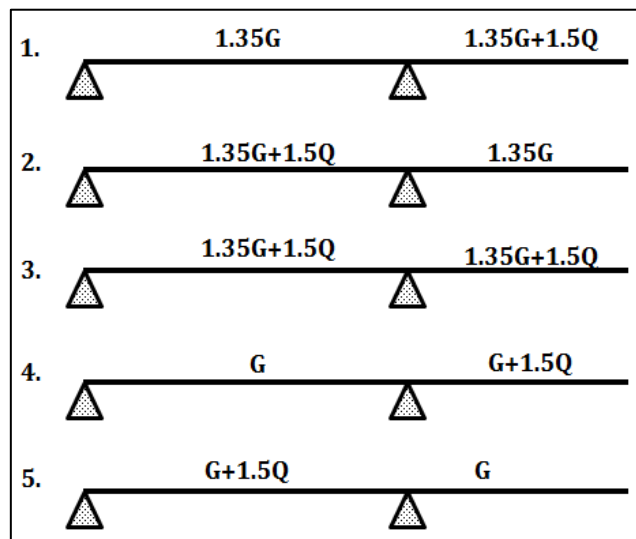


Figure 2.1. Load combination for a cantilevered beam on two supports at the ultimate limit state (ULS).

Combination 4 is taken into account for the justification of static equilibrium but with $0.9G$ instead of G in the span adjacent to the cantilever.

- **Serviceability limit states (SLS):** (See Figure 2.2)

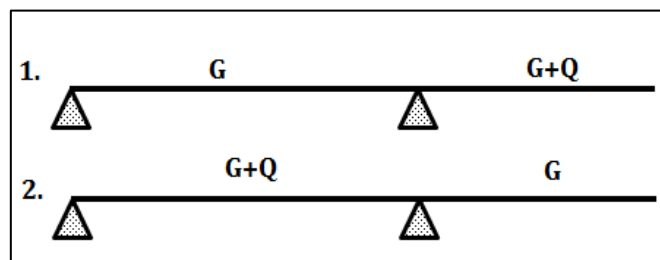


Figure 2.2. Load combination for a beam on two supports with a cantilever at the SLS

b) - Case of floors: slabs or beams with multiple spans:

The objective is to find the maximum stresses (bending moment, shear force) in each section of the structure, considering the most unfavorable loads possible.

- **Ultimate limit states (ULS) :**

This combination is used for checking for rupture or instability (See Table 2.1).

Table 2.1. Load combination for slabs or continuous beams at the ultimate limit state (ULS)

Combination	Loaded bays	Unloaded bays
1	$1.35 G + 1.5 Q$	$1.35 G$
2	$G + 1.5 Q$	G

- **Service Limit States (SLS):**

This combination is used for verification of deformations and cracking (See Table 2.2).

Table 2.2. Load combination for slabs or continuous beams at the SLS

Combination	Loaded bays	Unloaded bays
	$G + Q$	G

c) Case of posts:

In most common cases, the only combination to consider is:

$$1.35G + 1.5Q$$

d) Case of foundations:

Combination of actions if the support point does not contribute to stability under wind action:

$$1.35G + 1.5Q$$

2.3 Deformations and design constraints:

The design deformations and stresses represent respectively the geometric changes in the structure under loads (deflections, rotations, elongations) and the internal forces per unit area (in MPa) induced in the materials (concrete and steels) by the stresses.

These quantities are calculated to verify the Service Limit States (SLS) (functionality and durability) and the Ultimate Limit States (ULS) (resistance).

2.3.1 Ultimate limit state of resistance

2.3.1.1 Calculation Assumptions

These assumptions define the theoretical basis used to model the behavior of concrete and steel under extreme loading. They are essential for simplifying calculations while ensuring safety.

- **Deformation compatibility**
 - **Plane sections** : Straight sections remain planar after deformation (Bernoulli hypothesis).
 - **Perfect adhesion** : No slippage between steel and concrete → deformations are identical for both materials.
- **Neglecting concrete tensile strength**
 - Cracked concrete under tension does not contribute to mechanical strength → only the steel reinforcement resists tension.
- **Deformation limits**

- **Steel** : Maximum elongation limited to **10‰** (to avoid excessive plastic deformation).
- **Concrete** :

Maximum shortening of **3.5 ‰** for the case of bending (limit before crushing).

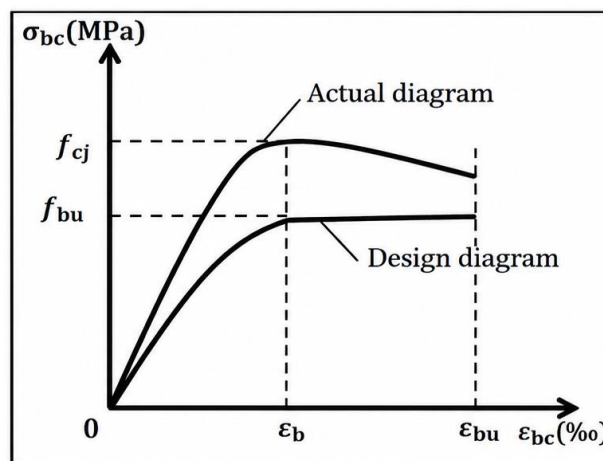
Maximum shortening of **2 ‰** for the case of compression (case of compressed columns or elements).

2.3.1.2. Stress-strain diagrams of concrete according to BAEL

The BAEL (French regulations for reinforced concrete) defines two models to represent the behavior of concrete in compression: (Figures 2.3 and 2.4)

a) "Parabola-Rectangle" Diagram

- **Parabolic phase** : The stress increases along a 2nd degree parabola until the deformation corresponding to the maximum strength of the concrete (ϵ_b).
- **Rectangular phase** : Beyond ϵ_b , the stress remains constant until the ultimate deformation (ϵ_{bu}).
- **Maximum constraint**: f_{bu} (design resistance in compression).
- **Limit deformations**: $\epsilon_b \approx 2‰$ and $\epsilon_{bu} \approx 3.5‰$ (typical values).



- Figure 2.3. Rectangular parabola diagram

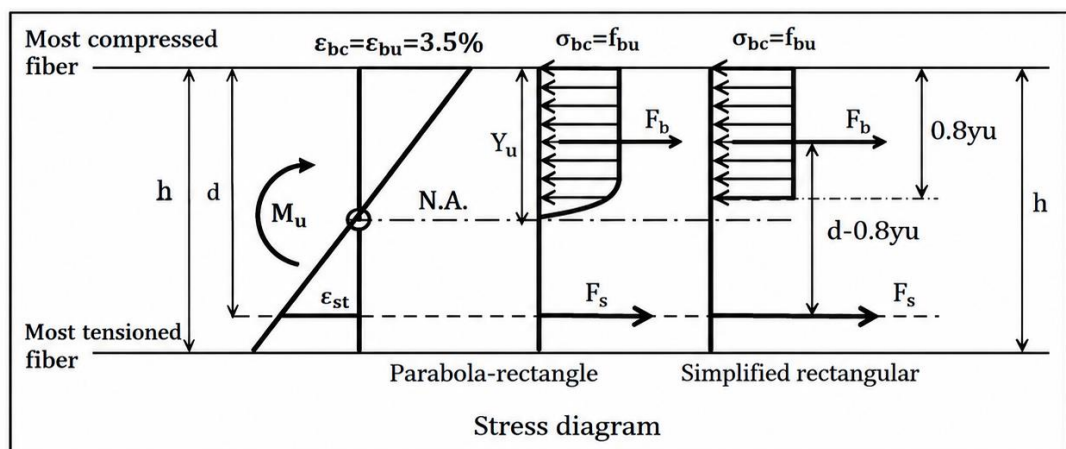


Figure 2.4 Stress-strain diagram of a deflected element

Notations:

h : the total height of the section;

d : useful height in simple bending;

y_u : position of the neutral fiber;

σ_{bc} : compressive stress of the concrete;

f_{bu} : ultimate conventional compressive strength;

ε_{bc} : deformation of concrete under compression.

The value f_{bu} of the design stress for a deformation between 2 ‰ and 3.5‰ is shown in equation 2.1:

$$f_{bu} = \frac{0.85 \cdot f_{cj}}{\theta \cdot \gamma_b} \quad \text{Eq.2.1)}$$

f_{cj} : characteristic compressive strength of concrete at day j

γ_b : safety factor

- $\gamma_b = 1.5$ in the general case

- $\gamma_b = 1.15$ for accidental combinations

θ : depends on the duration of application of the loads.

- $\theta = 1$: when the probable duration of application of the considered loads is greater than 24 hours;

- $\theta = 0.9$: when this duration is between 1 hour and 24 hours;

- $\theta = 0.85$: when it is less than 1 hour.

b) Simplified Rectangular Diagram:

A rectangular block of constant stress f_{bu} , extending over a height $0.8y$ (where y is the depth of the neutral axis).

Reduced height: $0.8y$ (to approximate the actual compressed area).

Uniform stress: f_{bu} .

c) Comparison and Justifications: Table 2.3 presents a comparison between the diagrams Parabola-Rectangle **and** Simplified Rectangular for the calculation of reinforced concrete .

Table 2.3. Comparison between the diagrams parabola-rectangle And Simplified Rectangular.

Appearance	Parabola-Rectangle	Simplified Rectangular
Precision	More precise (realistic model).	Simplified, but sufficient in bending.
Use	Completely/complicated sections.	Simple bending (partially compressed section).
Calculations	Integration required.	Force = $0.8y \cdot b \cdot f_{bu}$.
Example	Columns under axial compression.	Beams in bending.

2.3.1.3 Stress-strain diagram of steel (BAEL 4.3,2)

It is characterized by a **perfect elasto -plastic model** , adjusted by safety factors.
Here are the key elements:

a) Fundamental parameters

- **Guaranteed yield strength (f_e)** : Conventional breaking strength of steel (e.g.: Fe 500 $\rightarrow f_e = 500$ MPa).
- **Safety factor (γ_s)** :
 - **Common cases** : $\gamma_s = 1.15 \rightarrow$ reduces the design constraint for ultimate limit states (ULS).
 - **Accidental combinations** (earthquake, fire): $\gamma_s = 1 \rightarrow$ no reduction.
- **Longitudinal elasticity modulus (E_s)** : 200,000 MPa (slope of the elastic zone).

b) Calculation diagram: (Figure 2.5).

Elastic phase (linear deformation):

- **Constraint** : $\sigma = E_s \cdot \varepsilon_s$.
- **Until** : $\varepsilon_s = \frac{f_e/\gamma_s}{E_s}$

Plastic phase (deformation under constant stress):

- **Calculation constraint** : $\sigma_y = \frac{f_e}{\gamma_s}$
- **Unlimited deformation** : The stress remains constant until failure, without taking into account work hardening.

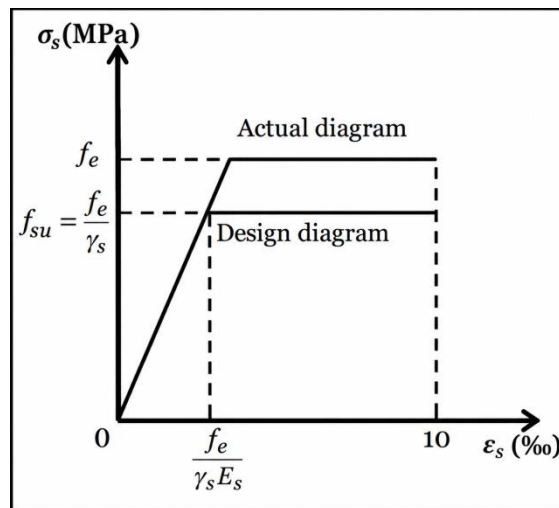


Figure 2.5. Stress-strain diagram of steel

2.3.1.4. Rule of three pivots (A, B, C):

The three-pivot rule (A, B, C) is a fundamental principle in reinforced concrete for determining the failure mode of a section subjected to stresses (bending, compression, etc.). It is based on the analysis of the limit deformations of the concrete and steel, allowing the failure scenarios to be classified according to the position of the neutral axis (Figure 2.6).

- **Pivot A** : The neutral axis is close to the compressed face → the tensioned steel reaches its maximum deformation (10‰).
- **Pivot B** : The neutral axis is at an intermediate position → concrete and steel simultaneously reach their limits.
- **Pivot C** : The neutral axis is close to the tension face → the compressed concrete crushes before the steel deforms plastically.

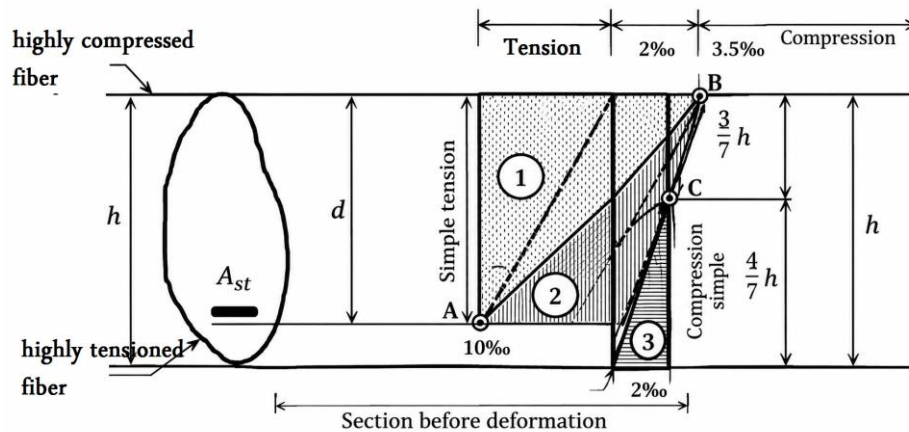


Figure 2.6. Limit deformation diagram of a reinforced concrete section

2.3.2 Service Limit State

The SLS checks ensure that the structure remains functional and durable under operational loads, by controlling concrete compression and crack opening .

2.3.2.1.. Calculation hypotheses (BAEL A.4.5,1)

- **Plane sections** : Straight sections remain planar after deformation (Navier-Bernoulli hypothesis).
- **Perfect adhesion** : No slippage between steel and concrete $\epsilon_b = \epsilon_s$.
- **Neglected tensile concrete** : The tensile strength of the concrete is ignored (only the compressed concrete is taken into account).
- **Linear elastic behavior** :
 - Concrete: Stress proportional to strain ($\sigma_b = E_b \cdot \epsilon_b$).
 - Steel: Stress proportional to strain ($\sigma_s = E_s \cdot \epsilon_s$).
- **Equivalence coefficient $n=15$** :

$n = E_s / E_b = 15$ (with $E_s = 200\,000$ MPa and $E_b \approx 13\,333$ MPa).

This coefficient allows the steel section to be transformed into an equivalent concrete section.

2.3.2.2. Concrete Compression Limit State (BAEL A.4.5,2)

The maximum compressive stress in concrete is limited to avoid:

- Premature crushing,
- Micro -cracking or excessive creep.

Allowable stress : (Equation 2.2)

$$\sigma_{bc} \leq 0.6 \cdot f_{cj} \quad (\text{Eq.2.2})$$

2.3.2.3 Limit state of crack opening

The dimensional and structural characteristics of the elements, as well as the arrangement of the reinforcement, are defined to reduce the risk of crack formation exceeding permissible widths, taking into account the function and environment of the structure. Excessive crack width can indeed detract from the aesthetics of exposed surfaces, compromise the watertightness of walls, or accelerate corrosion of the reinforcement. To control this phenomenon, the tensile stress in the steel is regulated and must not exceed a specified limit value, denoted $\overline{\sigma}_{st}$, as shown in Equation 2.3:

$$\sigma_{st} \leq \overline{\sigma}_{st} \quad (\text{Eq.2.3})$$

This limitation of tensile stresses ($\overline{\sigma}_{st}$) thus guarantees durability and structural performance in accordance with the project requirements.

- **Case of minor cracking**

(Covered and enclosed premises not subject to condensation) (Equation 2.4)

$$\overline{\sigma}_{st} = f_e \quad (\text{Eq.2.4})$$

- f_e : elastic limit of steel.
- No additional restrictions, as the environment is not aggressive.

- **Case of damaging cracking**

(Elements exposed to weathering or in contact with water) (Equation 2.5)

$$\overline{\sigma}_{st} = \min \left\{ \frac{2}{3} f_e, 110 \sqrt{\eta f_{tj}} \right\} \quad (\text{Eq.2.5})$$

- f_e : elastic limit of steel.
- η : cracking coefficient:
 - $\eta=1$ for smooth circles,
 - $\eta=1.6$ for HA steels (diameter ≥ 6 mm),
 - $\eta=1.3$ for HA steels (diameter < 6 mm).
- f_{tj} : characteristic tensile strength of concrete at j days (generally j=28 days).

- **Case of very damaging cracking**

(Elements in an aggressive environment: seawater, chemicals, etc.) (Equation 2.6)

$$\overline{\sigma}_{st} = \min \left\{ \frac{1}{2} f_e, 90 \sqrt{\eta f_{tj}} \right\} \quad (\text{Eq.2.6})$$

- $0.5f_e$: half the elastic limit of steel.
- $90\sqrt{\eta f_{tj}}$: term related to the strength of concrete.

2.4 Condition of non-brittleness (A.4.2,1)

Non -brittleness is a regulatory requirement designed to ensure that a structure does not suffer sudden failure when concrete cracks. It mandates a minimum amount of longitudinal reinforcement to ensure a ductile transition between the uncracked and cracked states.

A section is non-brittle if the stress causing cracking of the concrete results in a stress in the steels less than or equal to their elastic limit f_e .

- **Aim :**

- To avoid a sudden rupture after cracking of the concrete.
- Ensure that the reinforcements can withstand the tensile stress released by the cracked concrete.

2.4.1. Case of Simple tension

For a part subjected to simple tension : (Equation 2.7)

$$A_{smin} \geq \frac{B \cdot f_{t28}}{f_e} \quad (\text{Eq.2.7})$$

A_{smin} : Minimum steel section.

B: Total cross-section of the tensile concrete.

f_{t28} : Characteristic tensile strength of concrete at 28 days.

f_e : Elastic limit of steel.

- Unreinforced concrete cracks under the stress f_{t28} .
- The reinforcements must fully withstand this force without exceeding f_e .

2.4.2. Case of Simple Bending (Rectangular Section)

For a rectangular beam subjected to bending (Equation 2.8)

$$A_{smin} \geq \frac{0.23 \cdot b \cdot d \cdot f_{t28}}{f_e} \quad (\text{Eq.2.8})$$

b : Width of the section.

d : Effective height (distance between the compressed fiber and the center of gravity of the reinforcements).

- **Origin of the Coefficient 0.23**

The coefficient **0.23** comes from the balance of forces during cracking:

- **Cracking moment** M_{fs} : (Equation 2.8)

$$M_{fs} = \frac{b \cdot h^2}{6} \cdot f_{t28} \quad (\text{Eq.2.9})$$

(where h is the total height of the section).

Lever arm $z \approx 0.9d$:

$$A_s = f_e \cdot z = M_{fs} \Rightarrow A_s = \frac{M_{fs}}{f_e \cdot z}$$

Assuming $z \approx 0.9d$ and $h \approx 1.1d$ (for a rectangular section), we obtain above (Eq . 2.8).