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COMPOSITE STEEL-CONCRETE STRUCTURES

- CURS 4-b -

Composite Columns

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Notele de curs pot fi descărcate de pe pagina de web
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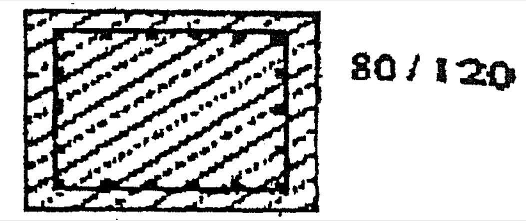
CHAPTER III – COMPOSITE COLUMNS
§ 3.1 Introduction

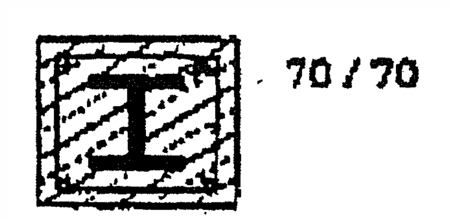
- Composite columns offer many advantages over bare steel or reinforced columns and are becoming increasingly used in multi-storey and tall buildings.
- A particular advantage of using a composite column is the reduction in column cross-sectional area, this being especially desirable in tall buildings where loads are high and space is usually a request.
- Another important consideration is fire resistance.

Example of composite advantage

Concrete section



Composite section

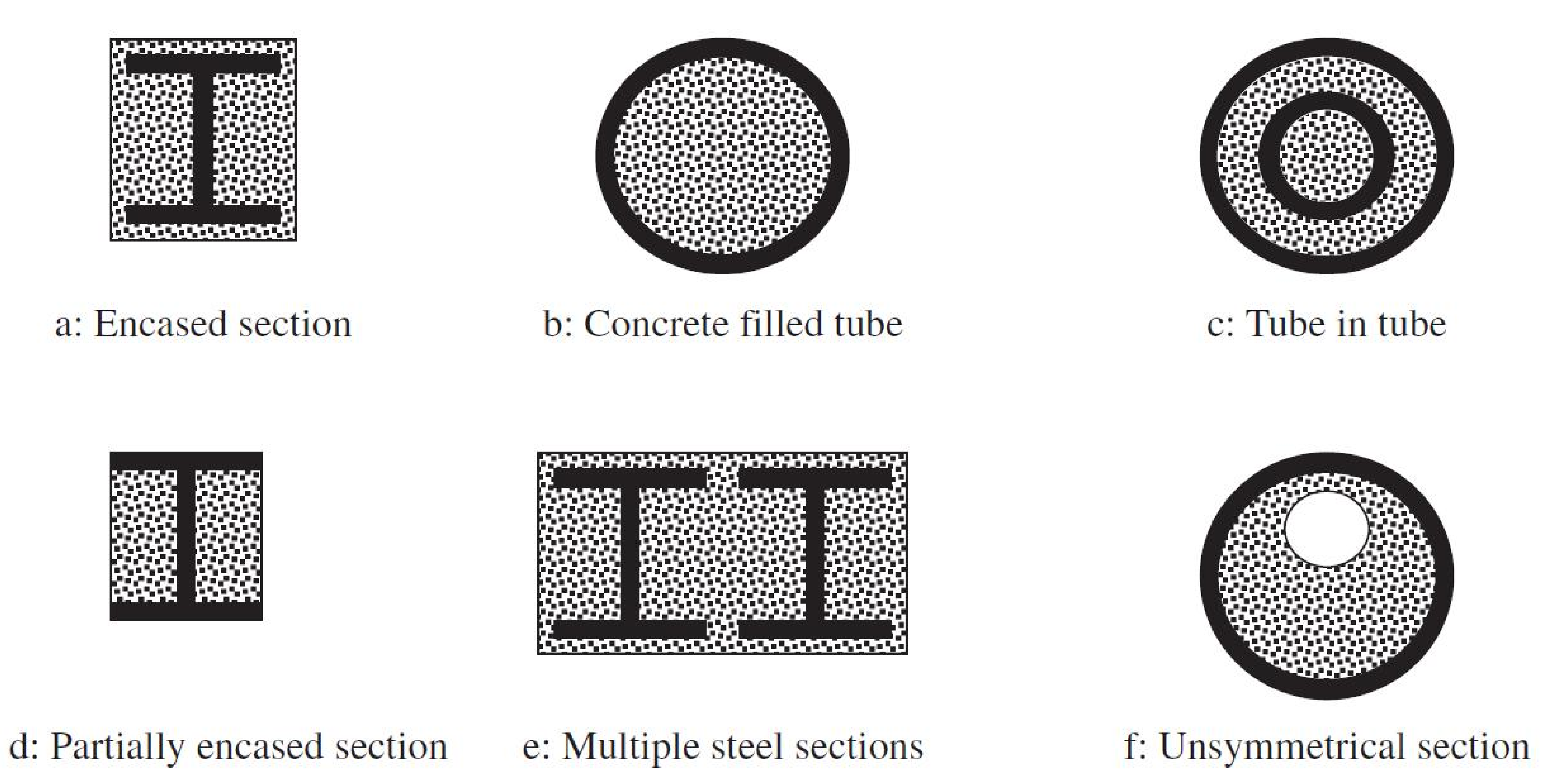


§ 3.1 Introduction

- Composite columns are available in many different types of cross-section a number of which are shown in figure below.
- Among these, the steel section encased in concrete perhaps represents the earliest type of composite cross-section. Initially, due to low grade, concrete was merely used as insulation to provide the steel section ṡ fire resistance. But later research studies showed that by using better quality concrete, significant enhancements in the column strength were possible, enabling smaller steel sections to be used.
- Nowadays, owing to unattractive appearance and the need for temporary formwork for concrete casting, composite columns made of steel sections encased in concrete are less often used than concrete filled hollow sections. Moreover, by using steel tubes as permanent formwork, construction speed is increased.

§ 3.1 Introduction

Types of composite columns



§ 3.1 Introduction

- Because of the inherently high fire resistance of concrete filled columns, fire protection of steel is in many cases not necessary and the steel can be exposed to achieve attractive appearance. Since construction speed is an important advantage, reinforcement is usually not used. But when required, a convenient reinforcement method is to insert a second tube inside the main one.

- To eliminate temporary formwork while still using universal sections in composite columns, partial encasement may be used. In this type of column, concrete is cast between the flanges of the steel section. Since the steel web is protected from fire attack, fire resistance of this type of composite column is reasonably high.

§ 3.1 Introduction

- If the applied load is particularly heavy, e.g. in the bottom storey of a tall building, composite columns can be made by encasing two or more universal steel sections together into concrete or by concrete filling tubes made of large welded plates.

- The above mentioned composite cross-sections are all symmetrical. Sometimes, unsymmetrical cross-sections may become unavoidable. For example, building services ducts may be arranged within concrete of a composite cross-section or due to difficult access the steel section may have to be aligned towards one side in an encased composite cross-section.

§ 3.1 Introduction

METHODS OF DESIGN FOR COLUMNS

- Eurocode 4 presents two methods of design:
  - A general method valid for all types of columns, including those of non-symmetrical or non-uniform cross-section over the column length. This method take into account the second-order effects for buckling, the imperfections, the non-linear behaviour of materials etc. It requests important computational resources.

  - A simplified method, used more often, for double-symmetrical columns having uniform cross-section over the column length. This method uses the European buckling curves given in Eurocode 3.

§ 3.1 Introduction

- Eurocode 4 is applicable only to normal strength concrete having a cylinder strength of up to $50N/mm^2$. As columns are mainly designed to carry compressive load, it is sometimes more economical to use high strength concrete whose cylinder strength may be up to $100N/mm^2$.

- Although high strength concrete may be used to encase steel sections, high strength concrete failure is brittle so it is more likely that such concrete will be used to infill hollow steel sections to form composite columns. Some recent research studies suggest that Eurocode 4 may be easily modified to design high strength concrete filled columns.

§ 3.2 Composite Columns Under Axial Load

LOCAL BUCKLING OF STEEL ELEMENTS

- To fully utilize steel strength, local buckling of a steel section should be prevented so that it does not occur before the steel reaches its yield stress. Thus, steel column sections should conform to Class 3 (semi-compact) or better. In composite columns, concrete strain at peak stress is about 0.0035 while the yield strain of grade S355 steel is only 0.00175.
- Therefore, when a composite cross-section is under axial compression and both steel and concrete attain the same strain, the steel will yield before the concrete reaches its peak compressive stress. For the concrete to reach its peak stress, the steel plates will therefore have to undergo further strain without local buckling to allow the concrete to take up additional load until it has also reached its peak stress. Thus, according to the definition of section classification, the steel plates should be Class 2 (Compact) to prevent local buckling in the composite cross-section.

§ 3.2 Composite Columns Under Axial Load

LOCAL BUCKLING OF STEEL ELEMENTS

- In this sense, requirements to control local buckling are more stringent in a composite column than in a bare steel column.
- However, since concrete provides substantial restraint to prevent local buckling of steel in a composite cross-section, the allowable steel width to thickness ratio is often significantly higher than in a bare steel cross-section.
- Eurocode 4 is only applicable to composite columns where local buckling of the steel plates is prevented. For steel sections encased in concrete, provided the code requirements of minimum thickness for concrete cover are met, local buckling will not occur and full steel strength can be achieved.
- For other types of composite cross-section, Table below lists the maximum allowable steel plate width to thickness ratio to prevent local buckling. These are contrasted with the requirements for bare steel cross-sections from Eurocode 3 - 1.1 for steel structures.

§ 3.2 Composite Columns Under Axial Load

LOCAL BUCKLING OF STEEL ELEMENTS

Table: Allowable limits of steel width to thickness ratio for local buckling

Section type	Eurocode 4 Part 1.1: Composite requirement	Eurocode 3 Part 1.1: Steel requirement
Rectangular hollow section	52ε	42ε
Circular hollow section	$90\varepsilon^2$	$90\varepsilon^2$
Partially encased I-section	44ε	30ε

- Concrete filling rectangular hollow sections can significantly improve the local buckling strength of steel. This is because the buckling pattern of an unfilled rectangular tube consists of both inwards and outwards buckles along the tube length. With concrete filling, the inwards buckles are unable to form, forcing a higher buckling mode.
- In contrast, the buckling half wavelength for an unfilled circular steel tube is small and consists predominantly of a single circumferential outwards buckle. Here, the concrete filling does not enhance the buckling strength of steel.

§ 3.2 Composite Columns Under Axial Load

SQUASH LOAD OF A COMPOSITE CROSS-SECTION

- If local buckling of steel is prevented before the concrete reaches peak stress, the maximum resistance to axial compression of a composite cross-section is given by:

$$N_{pl,Rd} = A_a f_y / \gamma_a + \alpha A_c f_{ck} / \gamma_c + A_s f_{sk} / \gamma_s$$

- Notations used in the above formula are:
  - *A* – cross-sectional area, *f* – design strength of material;
  - subscripts *a, c* and *s* refer to steel, concrete and reinforcement respectively;
  - *α* – factor for concrete which is:
    - *α = 1.0* for concrete filled steel sections with protected concrete,
    - *α = 0.85* for concrete encased sections (to allow for concrete deterioration due to environmental exposure and splitting).

Obs: As it could be seen, in case of concrete strength is used a factor of 0.85 to allow for concrete deterioration due to environmental exposure and splitting. For concrete filled steel sections where concrete is protected, its cylinder strength can be fully developed and the constant 0.85 may be omitted.

§ 3.2 Composite Columns Under Axial Load

SQUASH LOAD OF A COMPOSITE CROSS-SECTION

- Equation above is generally applicable to composite cross-sections. For concrete filled circular hollow sections, concrete confinement should be included. As concrete approaches plastic failure, its Poisson's ratio increases drastically. But this rapid lateral dilation is restrained by high stiffness of the steel hollow section whose Poisson's ratio is much lower. This gives rise to confinement, leading to an increase in failure strength of the concrete.
- Both rectangular and circular steel sections can confine concrete, but the confinement effect in rectangular sections is non-uniform and small and may be safely ignored. In design calculations, the advantage of concrete confinement is only considered for concrete filled circular steel sections. When steel is restraining concrete, a tensile stress is also produced in the circumferential direction of the steel tube, leading to a reduction in steel strength in the longitudinal direction. Despite this, the net effect is always an increase in the axial resistance of the composite cross-section.

§ 3.2 Composite Columns Under Axial Load

SQUASH LOAD OF A COMPOSITE CROSS-SECTION

- For long columns or columns under large bending moments, concrete failure strain is small and its Poisson's ratio is similar to that of steel. Therefore, both steel and concrete undergo similar lateral expansion under longitudinal compression and steel does not confine concrete. In general, the squash load of a concrete filled circular steel section including confinement effect may be calculated from:

$$N_{pl,Rd} = \eta_2 A_a f_y / \gamma_a + A_c f_{ck} \left(1 + \eta_1 \frac{t}{D} \frac{f_y}{f_{ck}} \right) / \gamma_c + A_s f_{sk} / \gamma_s$$

where:

$$\eta_1 = \eta_{10}\left(1 - \frac{10e}{D}\right) \text{ but } >0.0 \text{ with } \eta_{10} = 4.9 - 18.5\bar{\lambda} + 17\bar{\lambda}^2 \text{ and}$$

$$\eta_2 = \left(\eta_{20} + (1 - \eta_{20})\frac{10e}{D}\right) \text{ but } <1.0 \text{ with } \eta_{20} = 0.25(3 + 2\bar{\lambda})$$

in which where *e* is eccentricity, *D* outer diameter of the steel section and $\bar{\lambda}$ column slenderness.

§ 3.2 Composite Columns Under Axial Load

SQUASH LOAD OF A COMPOSITE CROSS-SECTION

- In the above formula, $\bar{\lambda}$ is computed by:

$$\bar{\lambda} = \sqrt{\frac{N_{pl,R}}{N_{cr}}}$$

where:

- $N_{pl,R}$ represents the $N_{pl,Rd}$ defined above, but computed by taking the partial safety factors γ_a, γ_c and γ_s taken equal to 1.
- N_{cr} elastic critical load (Euler's load), computed by:

$$N_{cr} = \frac{\pi^2 (EI)_e}{L_e^2}$$

- $(EI)_e$ is the effective flexural rigidity of the composite cross-section and L_e the column effective length.

- The effective flexural rigidity of a composite cross-section is given by:

$$(EI)_e = E_a I_a + 0.8 E_{cd} I_c + E_s I_s$$

§ 3.2 Composite Columns Under Axial Load

SQUASH LOAD OF A COMPOSITE CROSS-SECTION

- In the above formula:
  - *E* is the modulus of elasticity of a material
  - *I* the second moment of area of the component material (*a*, *c* and *s*) about the relevant principal axis of the composite cross-section.
- The reduced modulus of elasticity of concrete E_{cd} is obtained from:

$$E_{cd} = E_{cm}/\gamma_m = E_{cm}/1.35$$

where:

- E_{cm} is the concrete secant modulus
- γ_m (= 1.35) is a material safety factor.

- This factor of 1.35 in combination with a factor of 0.8 used in equation of effective flexural rigidity is used to account for the effect of cracking in concrete so that design calculations may be carried out on an un-cracked section.

§ 3.2 Composite Columns Under Axial Load

SQUASH LOAD OF A COMPOSITE CROSS-SECTION

- If a composite column were perfect and under pure axial compression, the column would shorten uniformly, without causing any additional bending moment.
- However, in realistic columns, due to initial imperfections, second order bending moments are generated. These bending moments give rise to strain gradients (curvature) in composite cross-sections. Under the influence of creep and shrinkage, these strain gradients are magnified, leading to increased bending moment and earlier failure of a composite column.
- To account for the effects of creep and shrinkage, the effective design stiffness of concrete is further reduced in Eurocode 4 and E_{cd} in the corresponding equation is replaced by E_c:

$$E_c = E_{cd}\left(1 - 0.5\frac{N_{G,Sd}}{N_{Sd}}\right)$$

SQUASH LOAD OF A COMPOSITE CROSS-SECTION

where:

- $N_{G,Sd}$ is the permanent (long-term) design load;
- N_{Sd} is the total design load.

- Creep and shrinkage induce secondary bending moments in a composite column by magnifying the lateral deflection due to initial imperfection. Depending on the column slenderness and eccentricity, the effects of creep and shrinkage may be small enough to be neglected. Therefore, when using the above equation, the following ranges of application should be observed:
  - The development of second order bending moments depends mainly on the column slenderness, the more slender a column, the higher the second order bending moment. Thus, the effect of creep and shrinkage is more pronounced in more slender columns. In short columns, the effect of creep and shrinkage is small and may be neglected. Eurocode 4 has set some limits on column slenderness below which the effect of concrete creep and shrinkage does not have to be considered.

§ 3.2 Composite Columns Under Axial Load

SQUASH LOAD OF A COMPOSITE CROSS-SECTION

- The importance of second order bending moments depends on the magnitude of the primary bending moment. With small primary bending moments, secondary bending moments are relatively important and creep induced $P-\delta$ effect should be considered. In contrast, under large primary bending moments, the creep induced bending moment is relatively small and may be ignored. Eurocode 4 sets the upper limit of eccentricity at twice the relevant dimension of the composite cross-section above which the secondary bending moment may be ignored. This is a very high limit and it is not very often that columns have to sustain such large moments.

COLUMN DESIGN STRENGTH

- The composite cross-section squash load and Euler buckling load are upper bounds on column strength. Under realistic conditions, various imperfections will generate second order bending moment and the column design strength will be lower. For composite column design, either the steel or concrete based approach may be used. Eurocode 4 takes the steel column design approach and the strength of a composite column is calculated using:

$$N_{Rd} = \chi N_{pl,Rd}$$

§ 3.2 Composite Columns Under Axial Load

COLUMN DESIGN STRENGTH

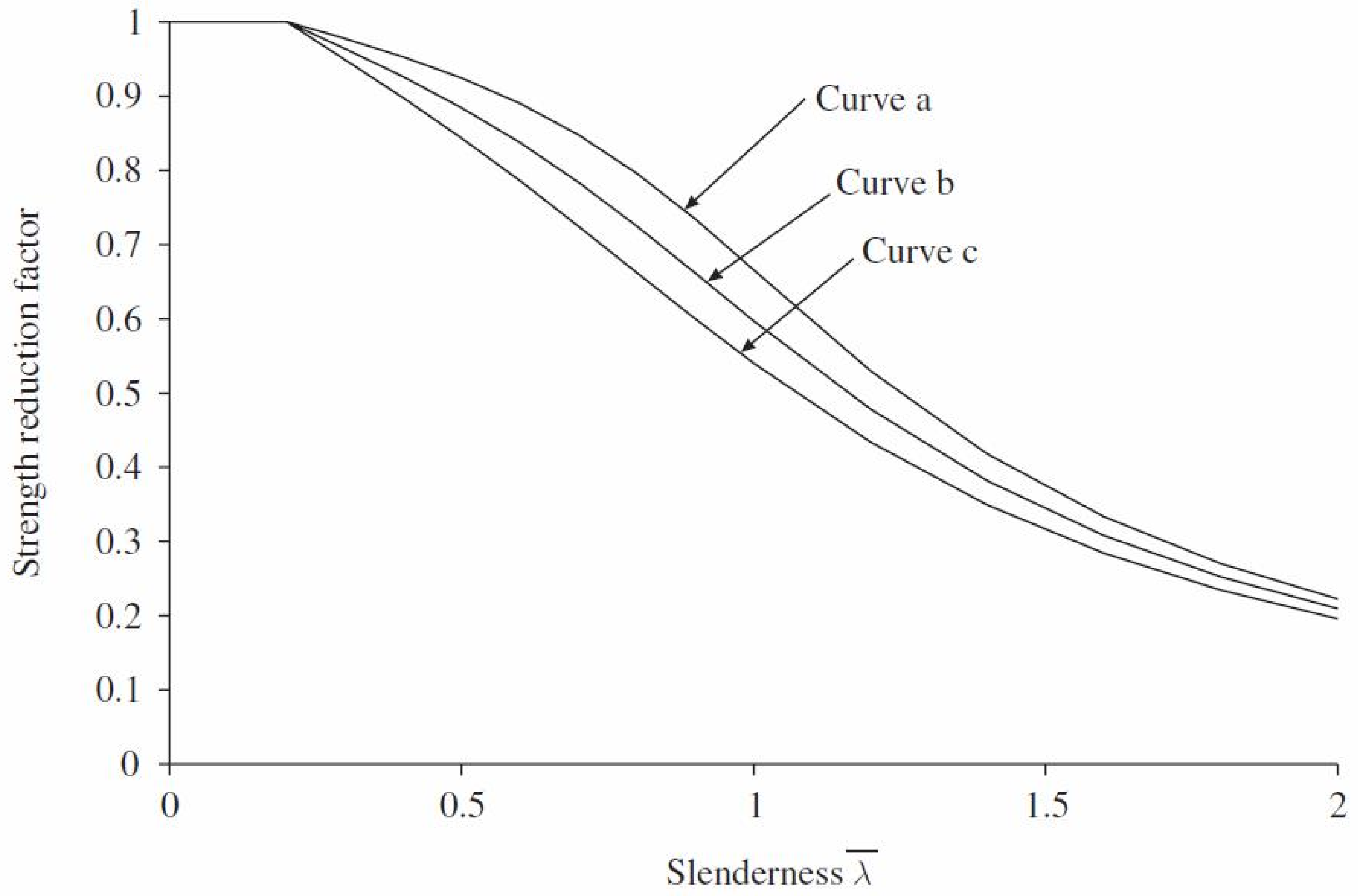
$$N_{Rd} = \chi N_{pl,Rd}$$

where χ is the column strength reduction factor and is a function of the column slenderness $\bar{\lambda}$.

- The relationship between the column strength reduction factor χ and the column slenderness is given by a column buckling curve. Figure below shows three column buckling curves used in Eurocode 4. The selection of a column buckling curve depends on the column cross-section type and its axis of buckling. Based on calibration against test results, column buckling curve “a” may be used for concrete filled steel sections and column buckling curves “b” and “c” used for concrete encased steel sections bending about the major and minor axis of the steel section.

§ 3.2 Composite Columns Under Axial Load

COLUMN DESIGN STRENGTH



Column buckling curves

§ 3.2 Composite Columns Under Axial Load

UNSYMMETRICAL SECTIONS

- The aforementioned calculation method is only suitable to composite columns with symmetrical cross-sections. For unsymmetrical composite cross-sections, this method can still be used. However, in this case, even under pure compression, a column with an unsymmetrical cross-section should be designed for combined axial compression and bending. This is because the resultant compression force acts at the elastic centroid of the composite cross-section according to the distribution of axial stiffness, but the column axial resistance acts at its plastic centroid according to the distribution of axial resistance. For an unsymmetrical cross-section, these two centroids do not coincide.
- Instead of carrying out full design calculations for combined compression and bending, a simple method may be used. In this method, the column design resistance for axial load with regard to the plastic centroid ($N_{Rd,pl}$) is given by:

§ 3.2 Composite Columns Under Axial Load

UNSYMMETRICAL SECTIONS

$$N_{Rd,pl} = \chi_{pl} N_{pl,Rd}$$

where the column strength reduction factor with regard to the plastic centroid (χ_{pl}) is related to that with regard to the elastic centroid (χ_{el}) according to:

$$\chi_{pl} = \left(\frac{\alpha}{2} - \sqrt{\frac{\alpha^2}{4} - \frac{\chi_{el}}{\bar{\lambda}^2}} \right)$$

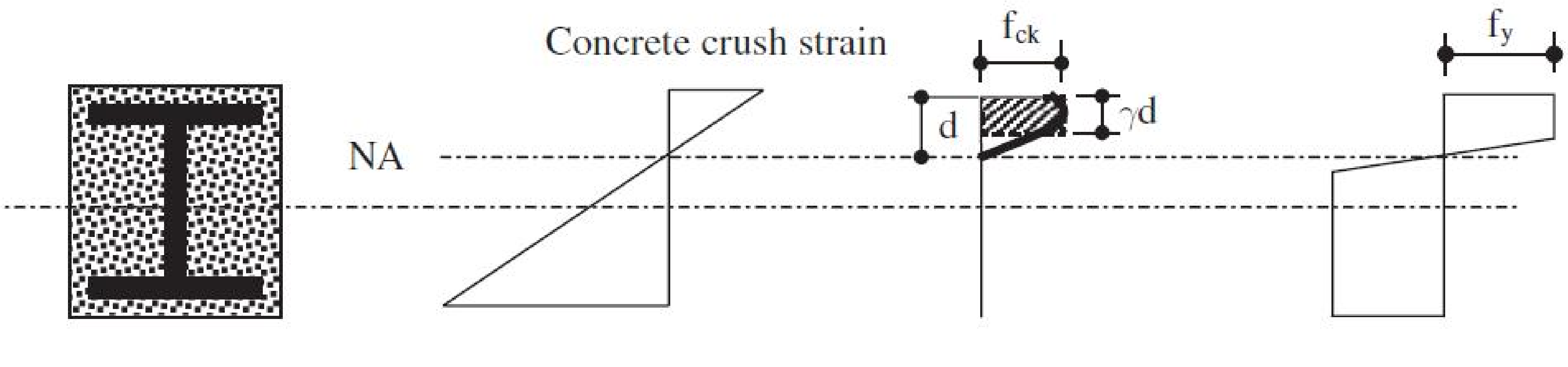
where α is given by:

$$\alpha = \left(\chi_{el} + \frac{1.1}{\bar{\lambda}^2} \right)$$

- Where the column slenderness $\bar{\lambda}$ and strength reduction factor with regard to the elastic centroid (χ_{el}) are calculated in the same way as for a symmetrical cross-section.

§ 3.3 Combined Axial Compression and Bending Moment

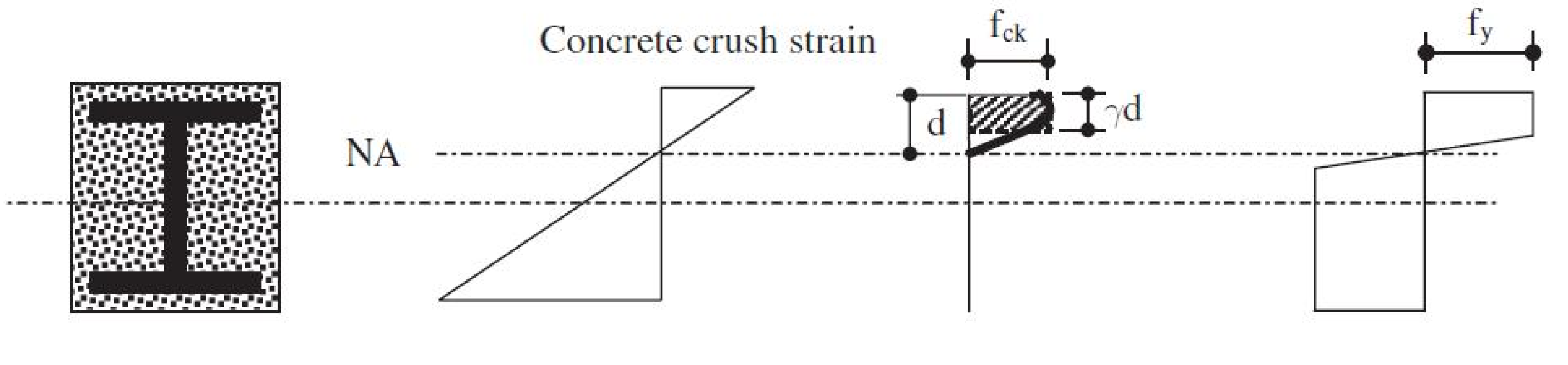
- To design a composite column under axial compression combined with bending moments, it is necessary to evaluate the axial load–bending moment (*N*–*M*) interaction diagram of the composite cross-section. This diagram gives the failure condition of the composite cross-section under combined axial load and bending moment and forms the basis of design for the composite column.



a: Composite cross-section
b: Strain distribution
c: Stress distribution in concrete
d: Stress distribution in steel

§ 3.3 Combined Compression and Bending

AXIAL LOAD–BENDING MOMENT (N–M) INTERACTION DIAGRAM

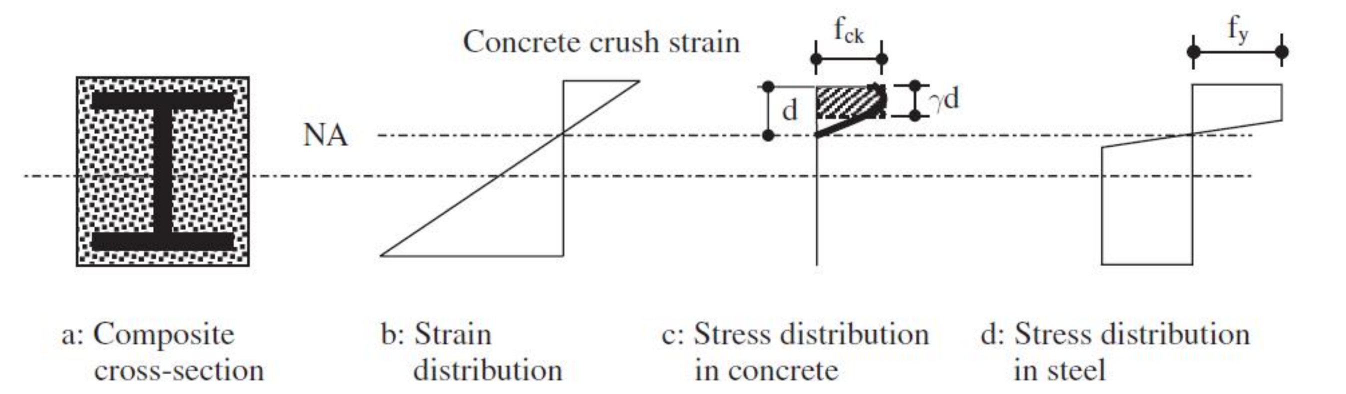


a: Composite cross-section — b: Strain distribution — c: Stress distribution in concrete — d: Stress distribution in steel

- The figure above offers the general procedure for evaluating the *N–M* interaction diagram of a composite cross-section as follows:
  - Set the concrete strain at the furthest compression fibre to its crushing strain.
  - Assume an arbitrary position for the neutral axis (NA). Assuming the strain distribution in the composite cross-section is linear, strains in the composite cross-section are now determined (figure b).

§ 3.3 Combined Compression and Bending

N –M INTERACTION DIAGRAM



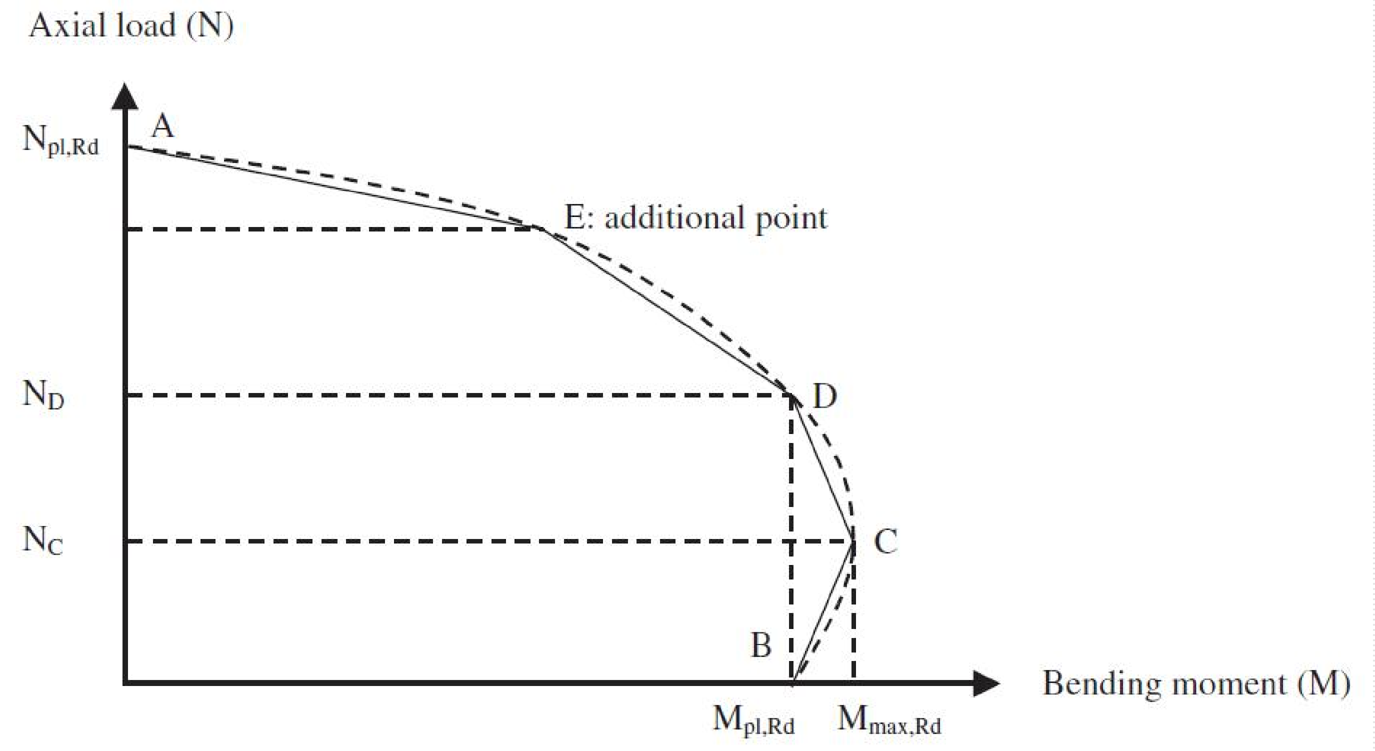
- Evaluate the stress distribution of the composite cross-section according to its strain distribution and stress–strain relationships of the constituent materials. It is assumed that concrete does not have any tension resistance. The stress distributions are now obtained as in figures c and d.
- The axial load is obtained by integration of stress over the whole composite cross-section. The bending moment is obtained by taking moments about the plastic centroid of the cross-section. This determines one point in the *N–M* interaction diagram.
- Changing positions of the neutral axis, other points in the *N–M* diagram are obtained.

§ 3.3 Combined Compression and Bending

N –M INTERACTION DIAGRAM

- Due to the assumption that concrete has no tensile strength, the *N*–*M* interaction curve is convex as shown in figure below:

Axial force – bending moment diagram of a composite cross-section



Obs: The above described general approach is time consuming and is best carried out by computers. To simplify calculations, the concrete stress distribution may be approximated by a uniform stress block with a reduced depth of compression as shown in figure c.