However, this method is not practical. Hence, most of design methods employ the concept shown in Fig. 1.7.

In the limit state design of reinforced concrete structures, the member force S is calculated by the linear analysis. For the case of a combination of loads, by employing a principle of superposition, S can be taken as the sum of each member force S_i obtained by analyzing the structure subjected to each type of load F_{di}.

$$S = \sum_{i=1}^{k} S_i\left(F_{di}\right) \qquad (1.9)$$

The usual assumption of linear structural analysis of reinforced concrete is that sectional properties are computed based on the gross cross sections.

1.5 Material Properties

1.5.1 Concrete

There are various types of concrete such as ordinary concrete, air-entrained concrete, ultra high-early strength concrete, ultra rapid hardening concrete, self-compacting concrete, etc. However, it can be generally classified as:

(1) ordinary concrete and

(2) others

Properties of concrete (hardened concrete) are represented by:

(1) Strength characteristics such as static and fatigue strengths of compression, tension, flexural, bond, etc.

(2) Deformation characteristics including *time-independent* quantities such as modulus of elasticity and Poisson's ratio, and *time-dependent* quantities such as creep factor, drying shrinkage strain, etc.

(3) Mechanical characteristics such as stress-strain relationship.

(4) Physical properties such as specific gravity, thermal characteristics (coefficient of linear expansion and specific heat).

(5) Chemical characteristics (related to durability) including corrosion resistant properties.

In practical design of reinforced concrete structures, the following properties of concrete are normally required.

(1) Strength

The 28 days compressive strength of standard cylinder is usually used. In some cases of massive concrete structures like a concrete dam, the structure is firstly experienced with design load after very long period, therefore the 91-day compressive strength is used.

Based on the characteristic value of compressive strength, other characteristic values for tensile and bond strengths are determined empirically as follows:

Characteristic value of tensile strength

$$f_{tk} = 0.23 f'_{ck}{}^{2/3} \quad \text{(N/mm}^2\text{)} \qquad (1.10)$$

Characteristic value of bond strength

$$f_{bk} = 0.28 f'_{ck}{}^{2/3} \quad \text{(N/mm}^2\text{)} \qquad (1.11)$$

(2) Stress-strain relationship

(a) Design stress-strain curve

Under the uniaxial compression stress, the actual stress-strain relationship of concrete can be divided into three parts (Fig. 1.8):

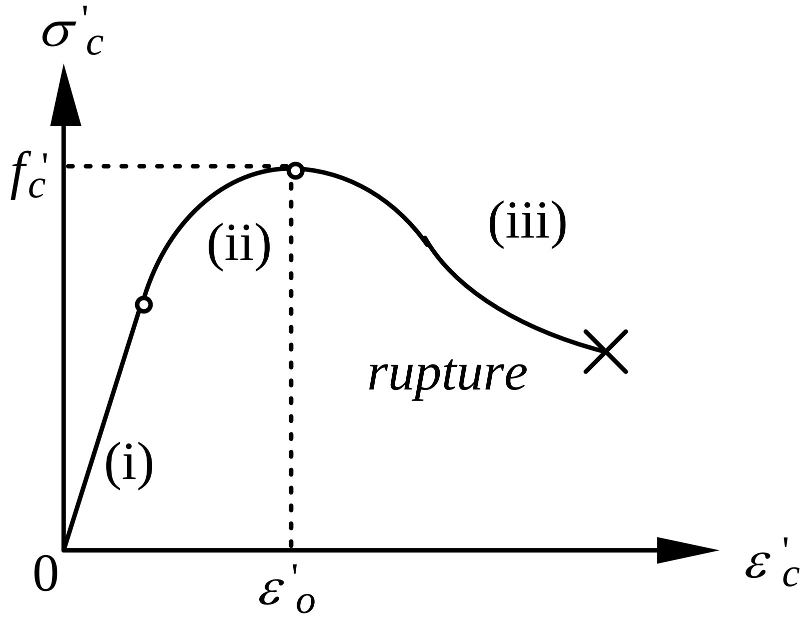

Fig. 1.8 Stress-strain curve for uniaxial compression of concrete

(i) almost straight line

(ii) curved line where both stress and strain increase up to the maximum point

(iii) the curved line after reaching the maximum point, where the decrease in stress and the increase in strain occur. However, it is very difficult to get part (iii) in the actual compression test.

In the limit state design of reinforced concrete structures, an idealized stress-strain curve is used for calculating the capacity of a member subjected to flexural moment and axial force.

$$\sigma'_c = k_3 f'_{cd} \times \frac{\varepsilon'_c}{0.002} \times \left(2 - \frac{\varepsilon'_c}{0.002} \right) \qquad \textbf{(1.12)}$$

where, σ'_c**: compressive stress**

ε'_c**: compressive strain (**$\leqq \varepsilon'_{cu}$**)**

$$\varepsilon'_{cu} = \frac{155 - f'_{ck}}{30000},\ 0.0025 \le \varepsilon'_{cu} \le 0.0035$$

k_3**: coefficient = 1 – 0.003** $f'_{ck} \leqq 0.85$

f'_{cd}**: design compressive strength of concrete**

This curve is applied until ε'$_{cu}$ (the ultimate compressive strain). In this curve, parts (i) and (ii) are combined and assumed by the parabolic function, and part (iii) is assumed to be horizontal line (constant stress) up to the ultimate compressive strain.

(b) Modulus of elasticity

In the examination of serviceability limit states, since the load level is relatively low, the linear analysis of reinforced concrete section is performed based on the constant modulus of elasticity. Generally, the modulus of elasticity of concrete can be defined as either of the initial modulus E_o, tangent modulus E_t, and secant modulus E_c (Fig. 1.9).

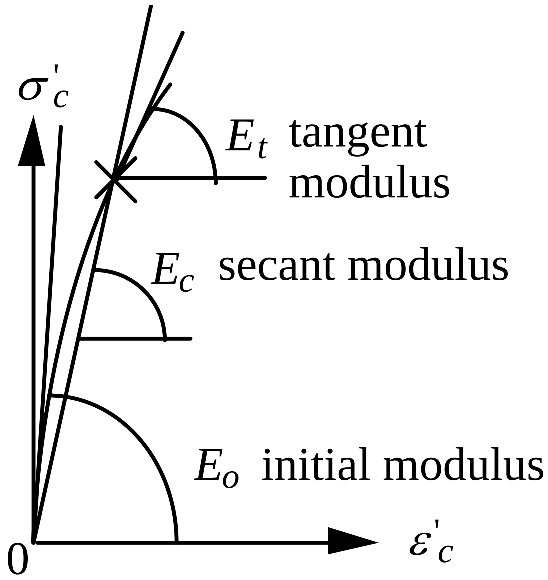

Fig. 1.9 Definition of various Young's moduli for concrete

In the design of reinforced concrete structures, the modulus E_c taken as a tested value at one third point of the compressive strength is employed. The recommended values E_c are shown in Table 1.4.

Table 1.4 Modulus of elasticity for concrete, E_c (kN/mm^2)

f'_{ck} (N/mm^2)		18	24	30	40	50	60	70	80
E_c (kN/mm^2)	Normal weight concrete	22	25	28	31	33	35	37	38
	Light weight concrete*	13	15	16	19	–	–	–	–

***: All aggregate are light weight aggregate.**

1.5.2 Reinforcing steel

In RC structures, normally deformed bars are used. Round bars for structural concrete are usually rare. According to JIS (Japanese Industrial Standard), the following steels are commonly used.

SR235, SR295 (R means "round" bar), SD295(A,B), SD345, SD390, SD490 (D means "deformed" bar). 295, 345, 390, 490 : nominal yield point of 295, 345, 390, 490 N/mm^2, respectively.

The actual stress-strain relationship is divided into three parts: (i) linear part, (ii) yield plateau part, and (iii) strain hardening part (Fig. 1.10).
Since the order of yield strain ε_y is nearly the same as that of the ultimate strain of concrete ε'_{cu}, the strain hardening part is not needed to be incorporated into the calculation for the ultimate capacity of RC section. Therefore, the idealized stress-strain curve for reinforcing steel is assumed as the elastic-perfectly plastic model (without strain hardening). As for the characteristic value of reinforcing steel f_{sk}, the nominal yield strength of reinforcing steel f_{yk} is employed in the limit state design method.

$$f_{sk} = f_{yk} \tag{1.13}$$

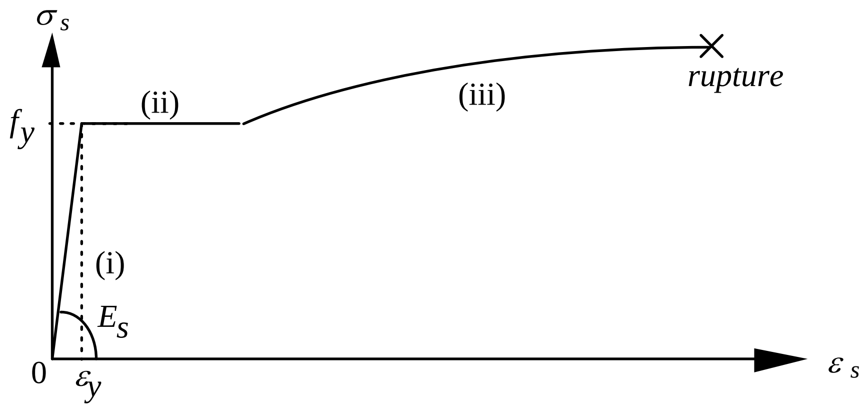

Fig.1.10 Schematic stress-strain diagram for mild steel