Chapter 1
Concrete and Reinforced Concrete

Material Behavior

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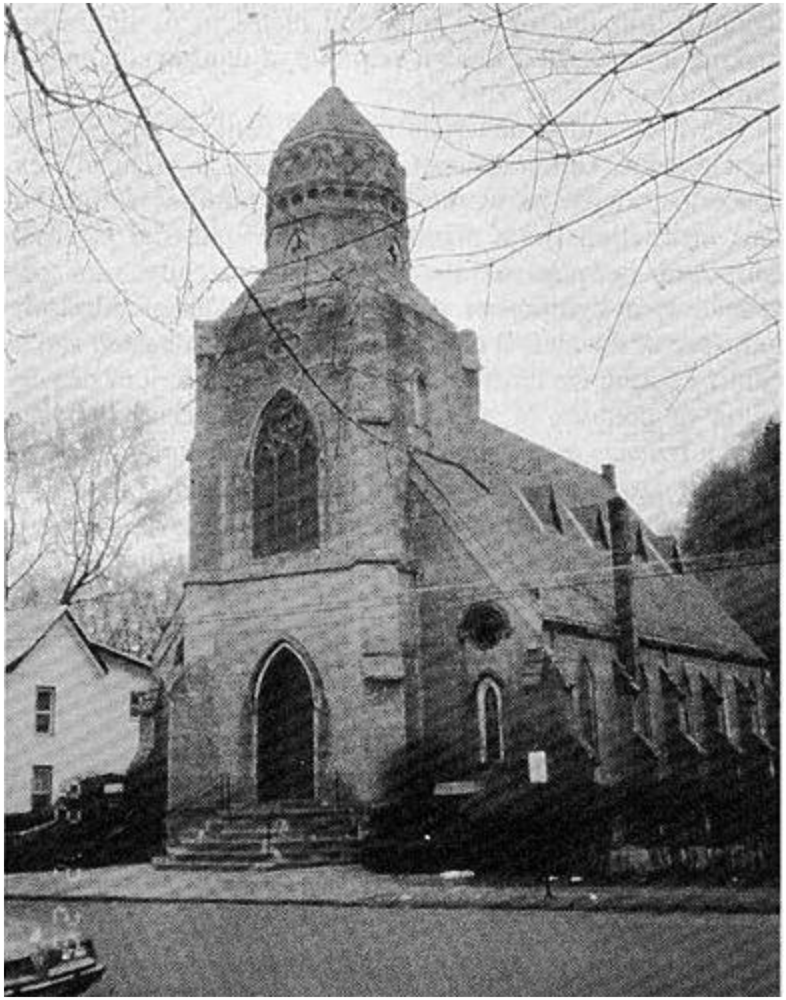

Ponckhockie Union Chapel, 1870

Kingston, New York

Oldest concrete structure in the United States

Behavior under Multiaxial Stresses

In many of the structural members, concrete is usually subjected to multiaxial stresses. Any state of stress can be reduced to three normal stresses, which act on planes with zero shears. These are the principal stresses.

i. Concrete Under Biaxial Stresses:

When the principal stress in one direction is zero, or negligably small, this can be considered as biaxial stress condition. An extensive test program was carried out at Munich Technical University on the behavior of concrete under biaxial stresses. These tests were conducted by Rüsch. In the test program, concrete plates were loaded in two directions.

Concrete Under Biaxial Stresses

Behavior of Concrete Under Biaxial Stresses

Helmut Kupfer, Hubert K. Hilsdorf, and Hubert Rusch

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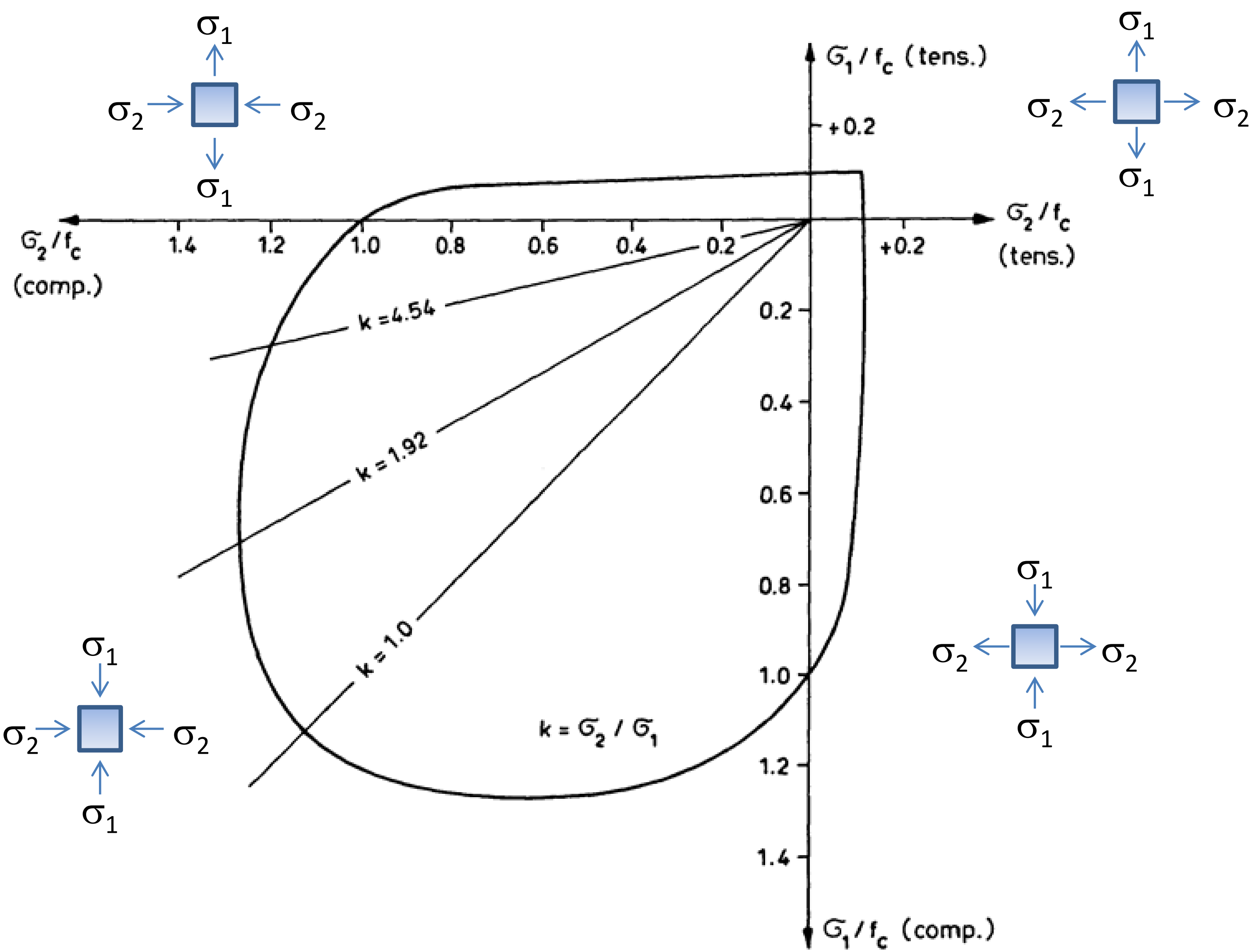
Concrete Under Biaxial Stresses



Original Figure from Rusch's Paper

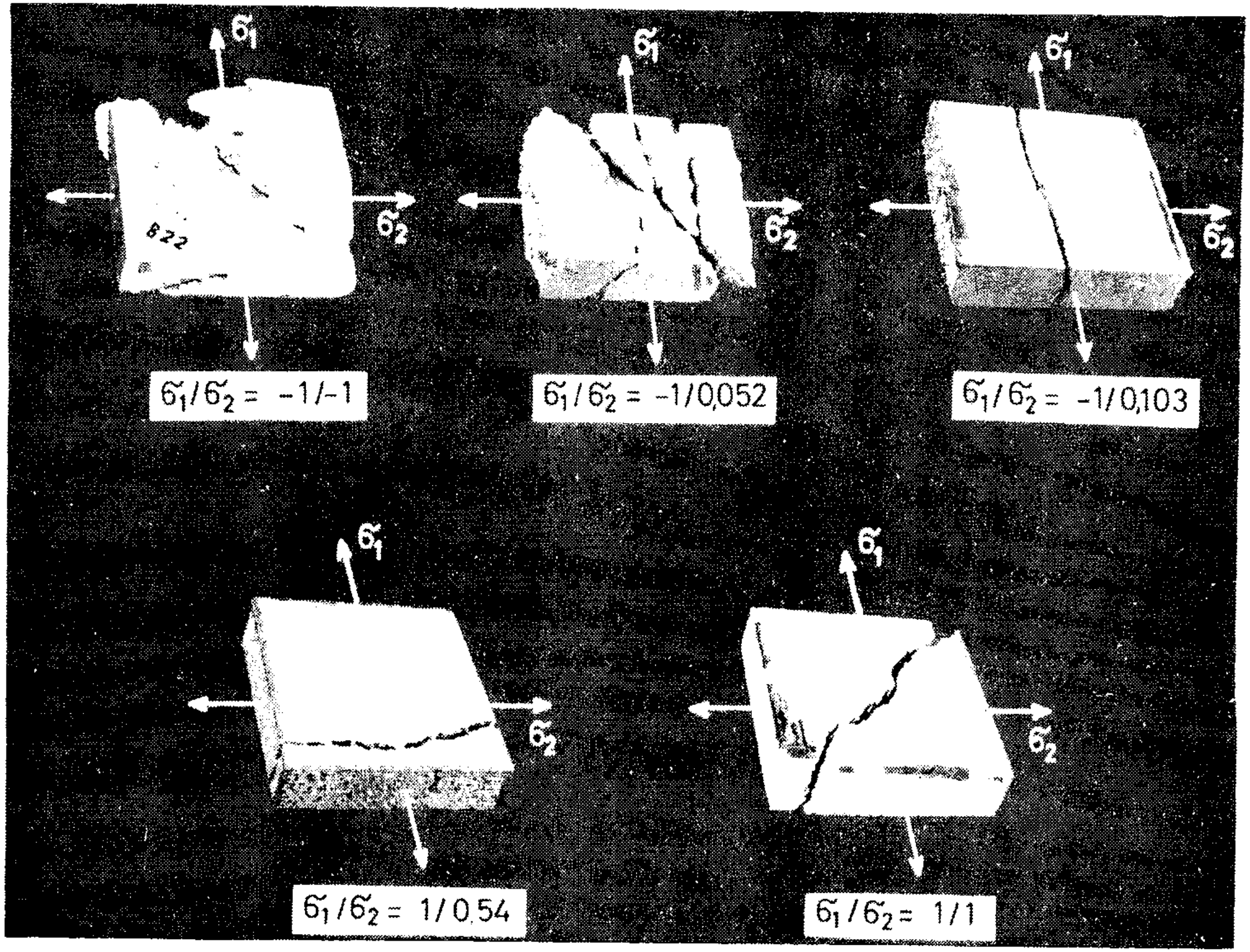


Fig. 5—Failure modes of specimens subjected to biaxial stresses

Original Figure from Rusch's Paper

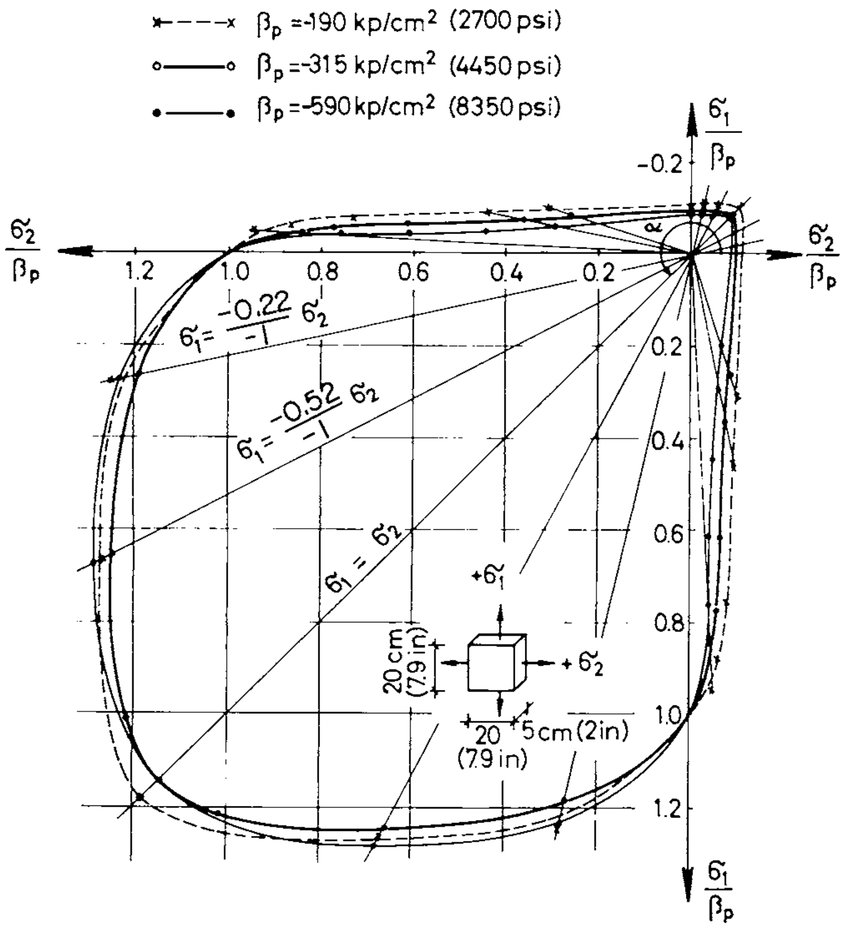
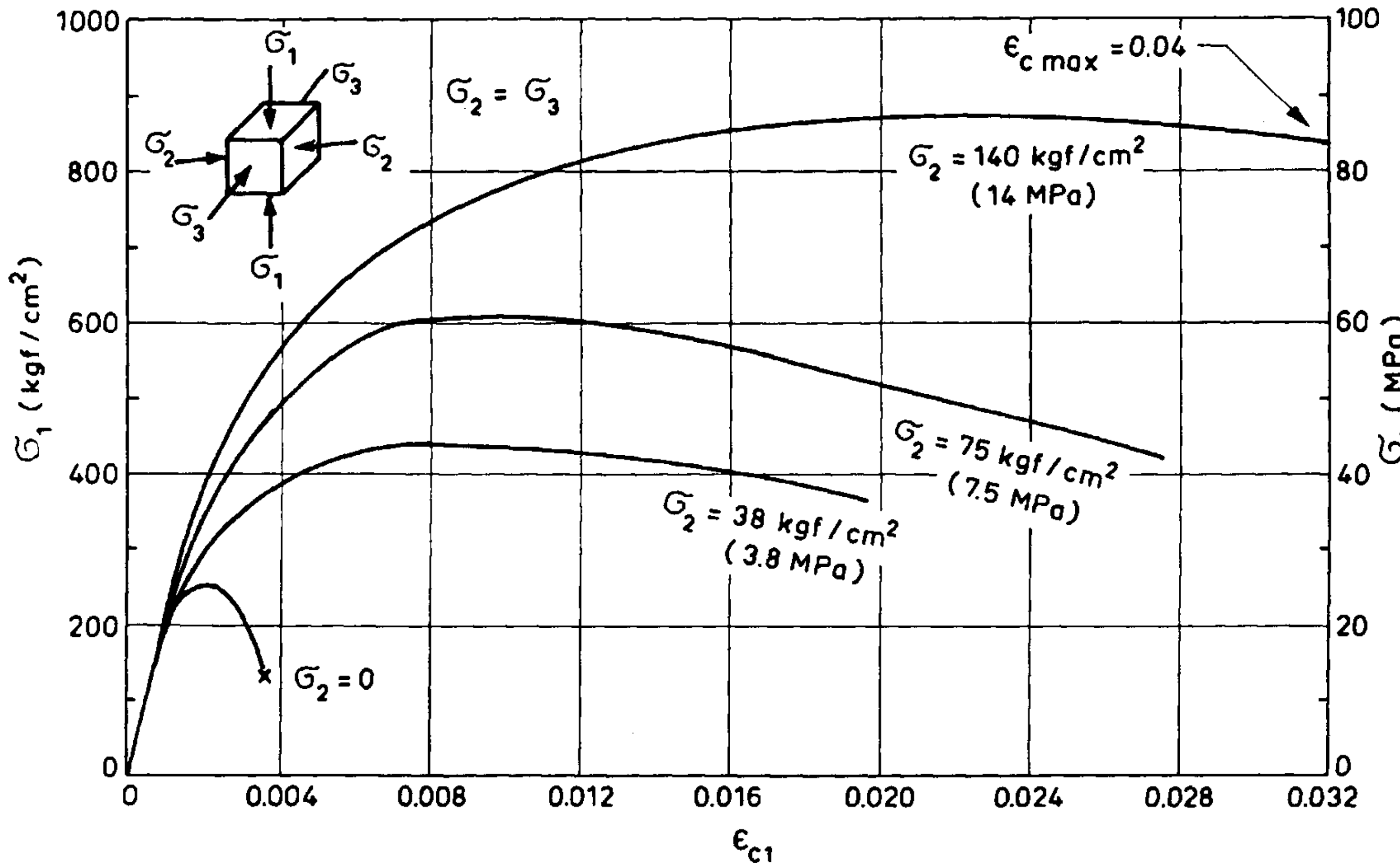


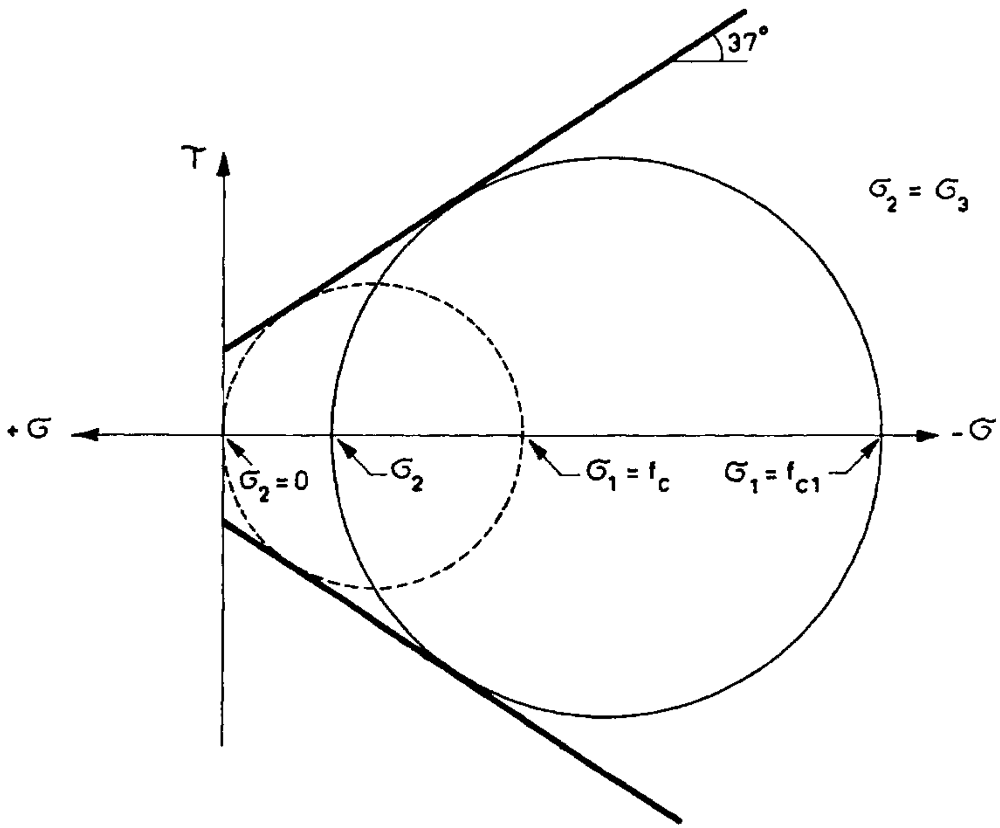
Fig. 6—Biaxial strength of concrete; results of experimental investigation

Concrete Subjected to Triaxial State



Concrete Subjected to Triaxial State

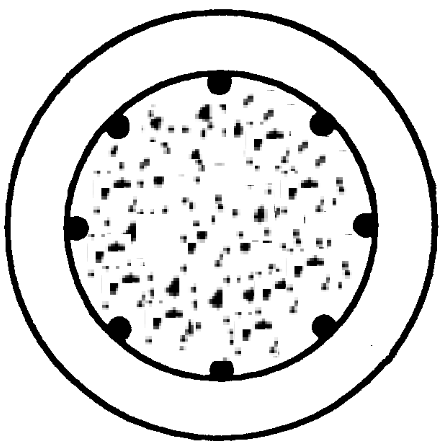
A failure theory for concrete under triaxial stresses has been developed by Zia and Cowan. This theory, which is a revised version of Mohr's Failure Theory



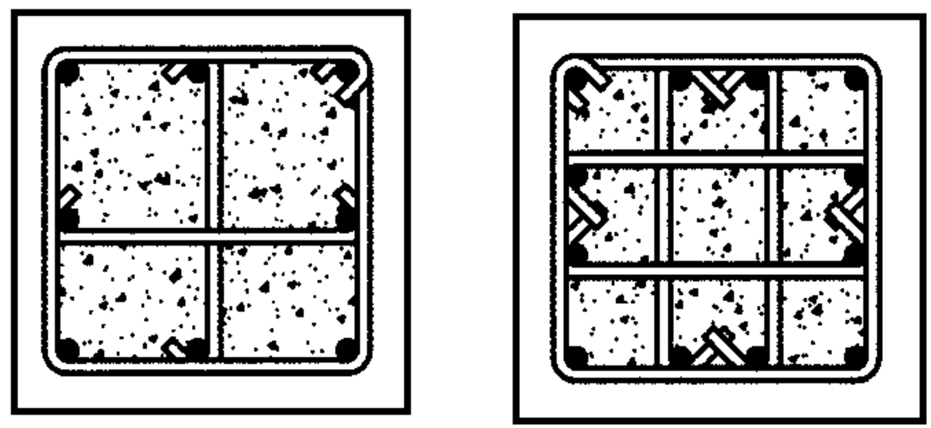
$$f_{cl} = f_c + 4.0\sigma_2$$

Behavior of Concrete Confined by Lateral Reinforcement

In most structural members, concrete is confined by lateral reinforcement either in the form of continuous spirals or rectangular hoops.

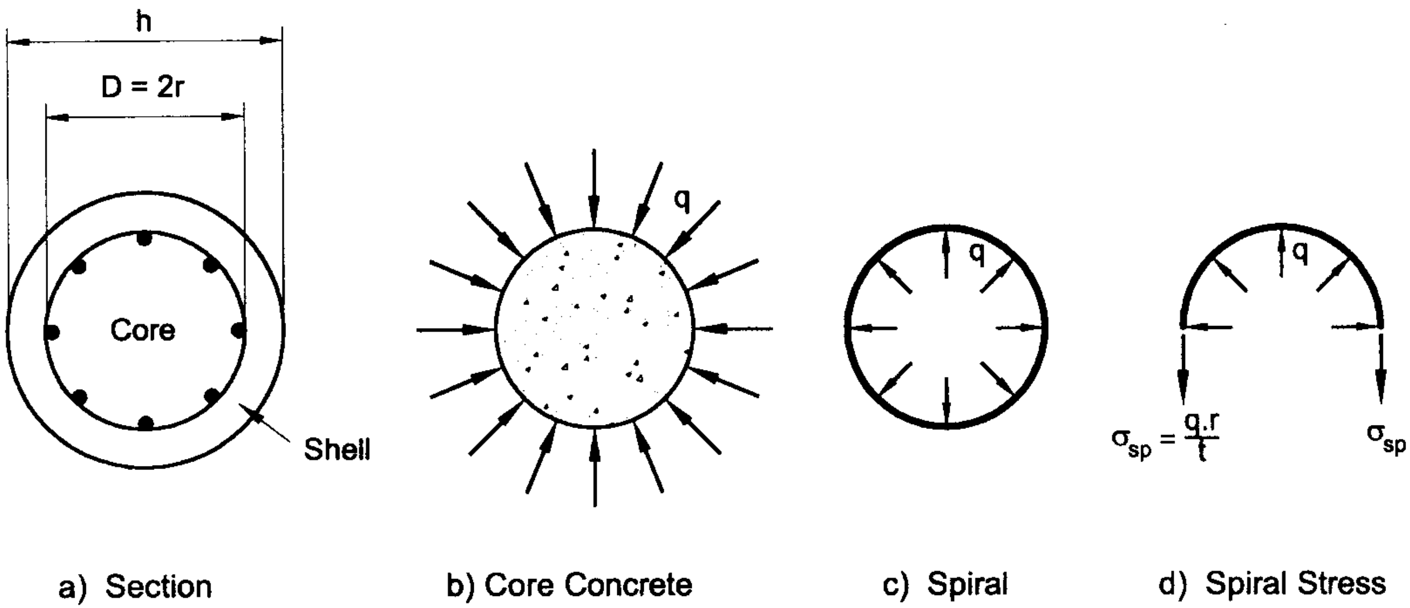


Spiral Column



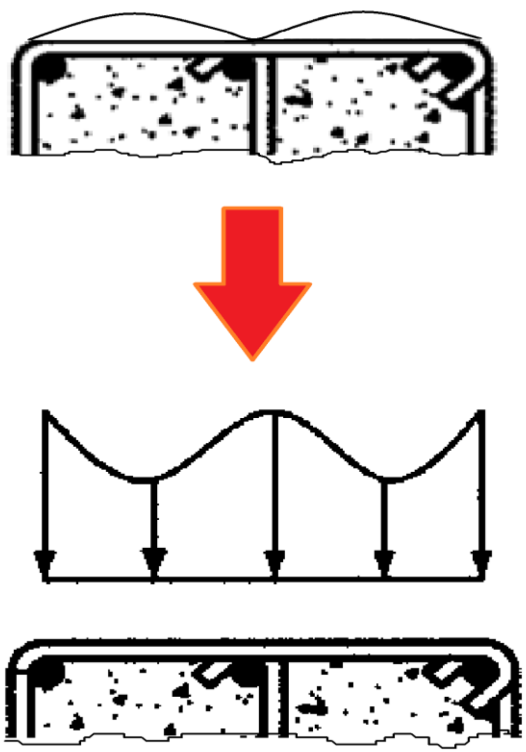
Tied Columns

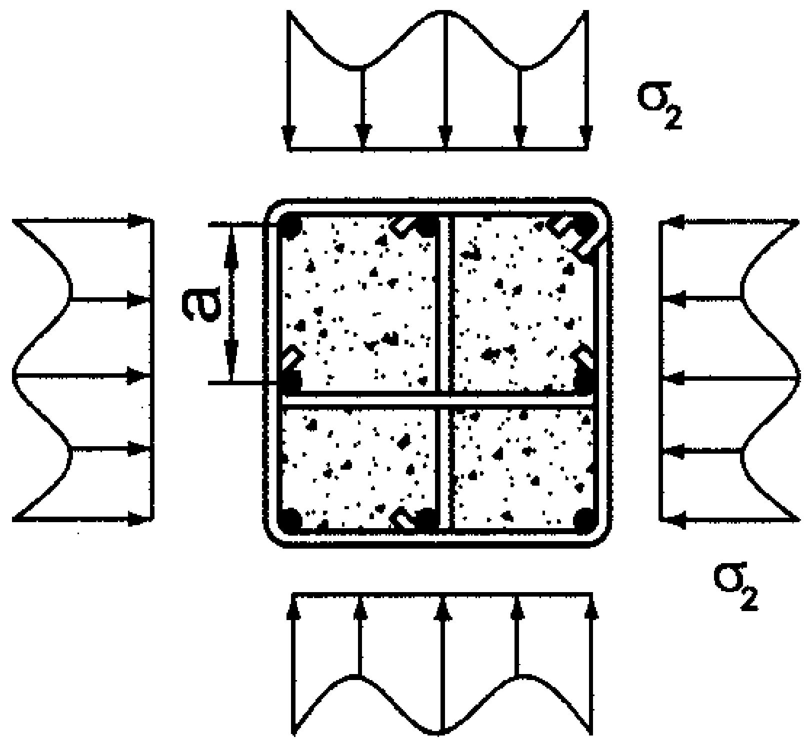
Concrete Confined by Spiral Reinforcement



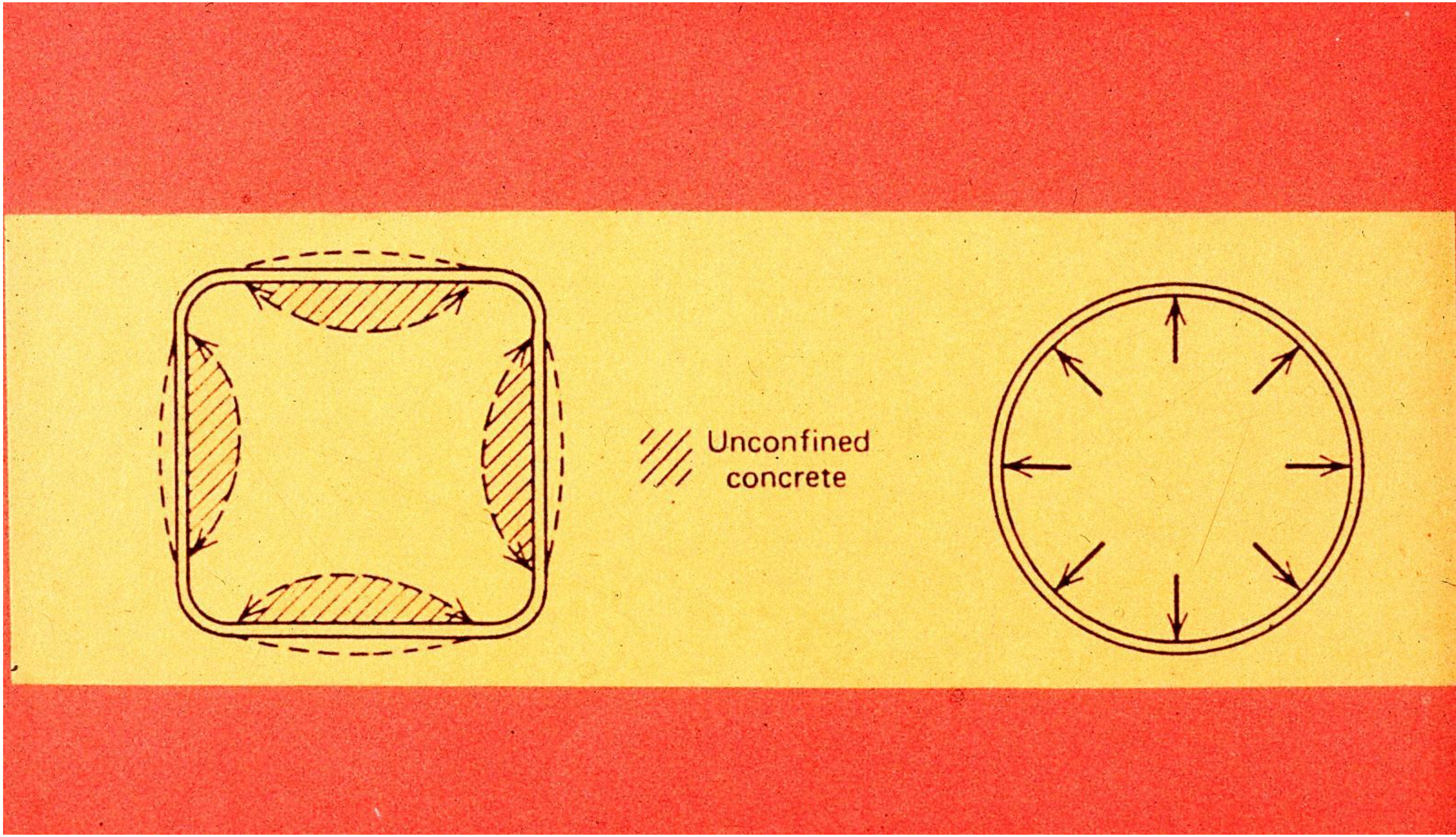
Under increasing axial deformations cover outside the spiral starts to crush. Due to the Poisson's effect, the concrete in the core tries to expand in the lateral direction. This expansion is prevented by the spiral reinforcement. This causes radial pressure on the core concrete as shown in figure. This pressure, q, is known as the confining pressure

Concrete Confined by Ties

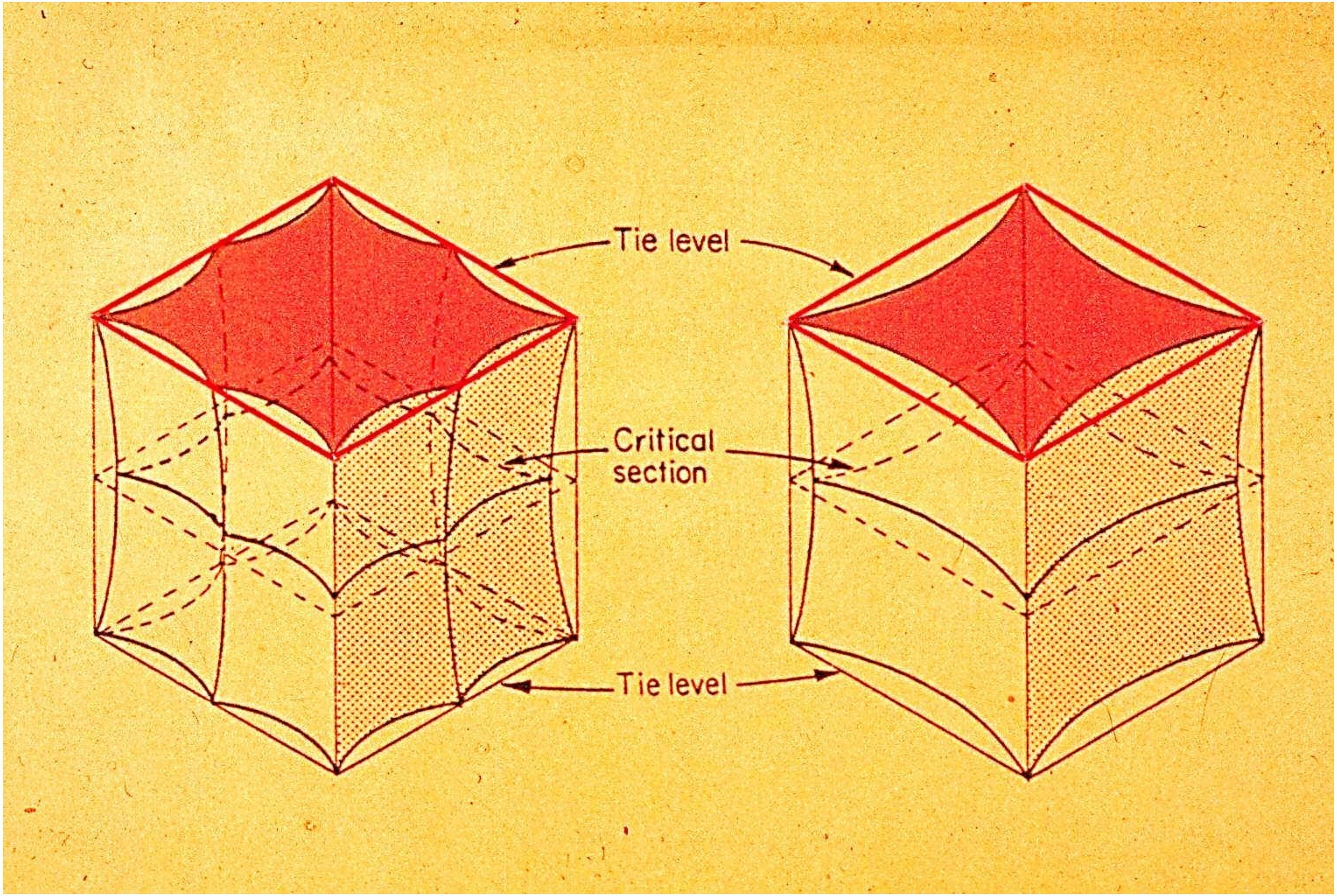




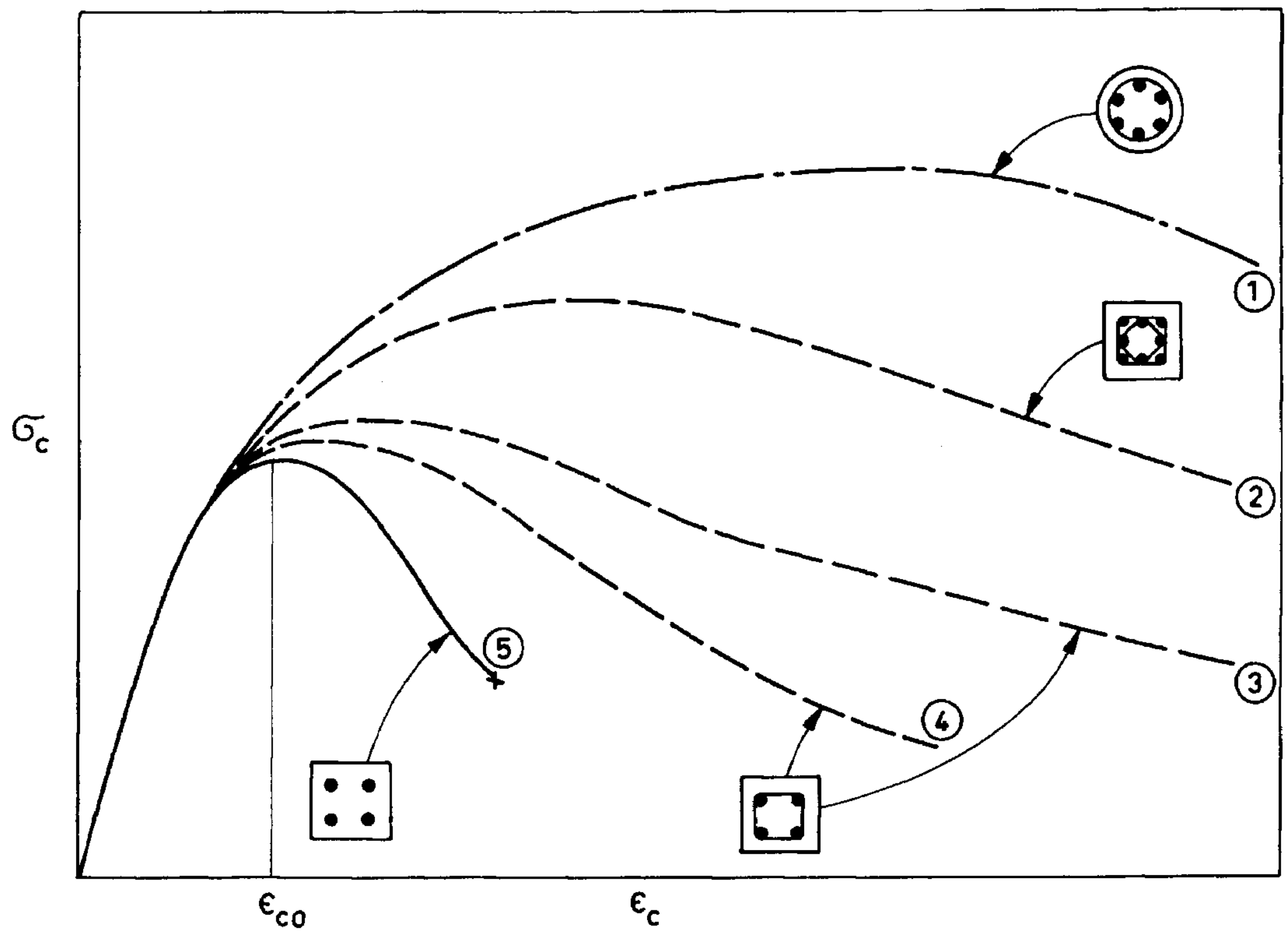
Effectively Confined Regions



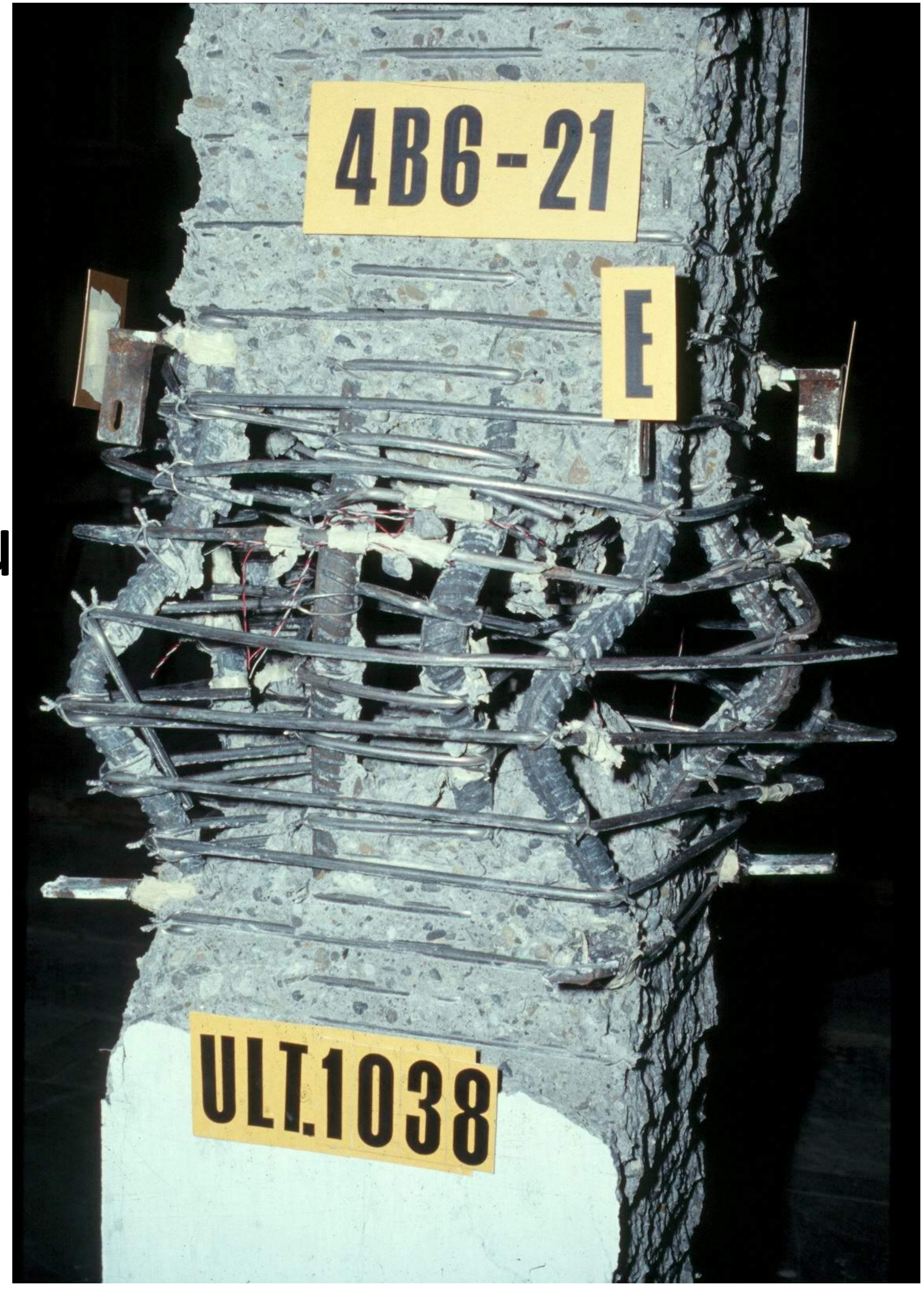
Effectively Confined Regions



Confined Concrete Response



Failure u



TIME DEPENDENT DEFORMATION OF CONCRETE

The deformations in concrete, under the same load or stress, increase with time. There are two types of time dependent deformation. These are:

- the creep deformations
- the shrinkage deformations

Time dependent deformations i.e. creep and shrinkage cause significant deformations and stresses in concrete structures and therefore can affect both the strength and serviceability of the structure.

SHRINKAGE

The water necessary for the hydration is approximately 20-25 percent of the cement by weight. However, in concrete mixes more water is used than what is needed for hydration. The reason for this is workability.

When concrete is placed in the forms, the excess water, which is not used in hydration, evaporates. As concrete loses water by evaporation, its volume decreases or simply it shrinks.

EFFECTS OF SHRINKAGE ON STRUCTURES

A plain concrete member that is not restrained by other members will shrink but there will be no stresses in the member due to shrinkage. In reinforced concrete members, steel bars do not shrink as concrete dries out, so its restraint tends to reduce the shortening of reinforced concrete member. This means that after a certain time, the concrete will have tensile stresses and the steel will be in compression due to shrinkage.

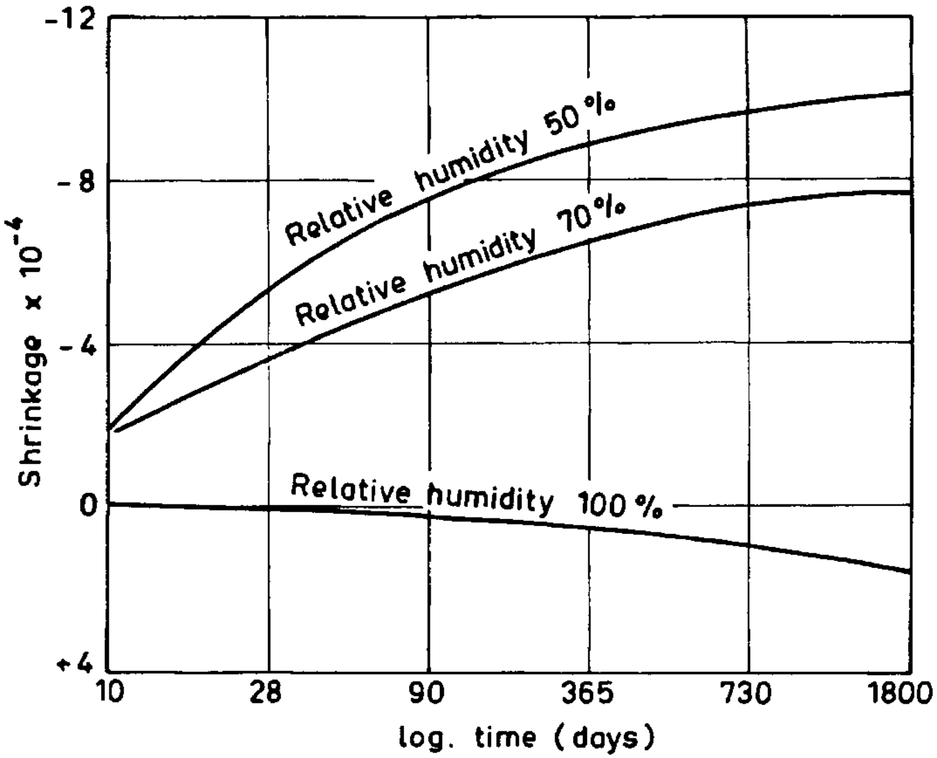
EFFECTS OF SHRINKAGE ON STRUCTURES

When restraining members (like structural walls or stiff columns) exist at the end of the beams, moments, shear and axial force will be produced in the beam due to restrained shrinkage deformations. The axial force in the beam due to shrinkage will be tension. Because of restrained shrinkage shear, moment and axial forces will also be introduced to the restraining members. The internal forces induced by restrained shrinkage will be more critical as the stiffness of the restraining members increase.

SHRINKAGE

The amount of shrinkage is a function:

- Humidity
- Type of curing
- Temperature
- Area of exposed surface
- Water content of the mix



Shrinkage is also a function of time and its rate decreases with time.

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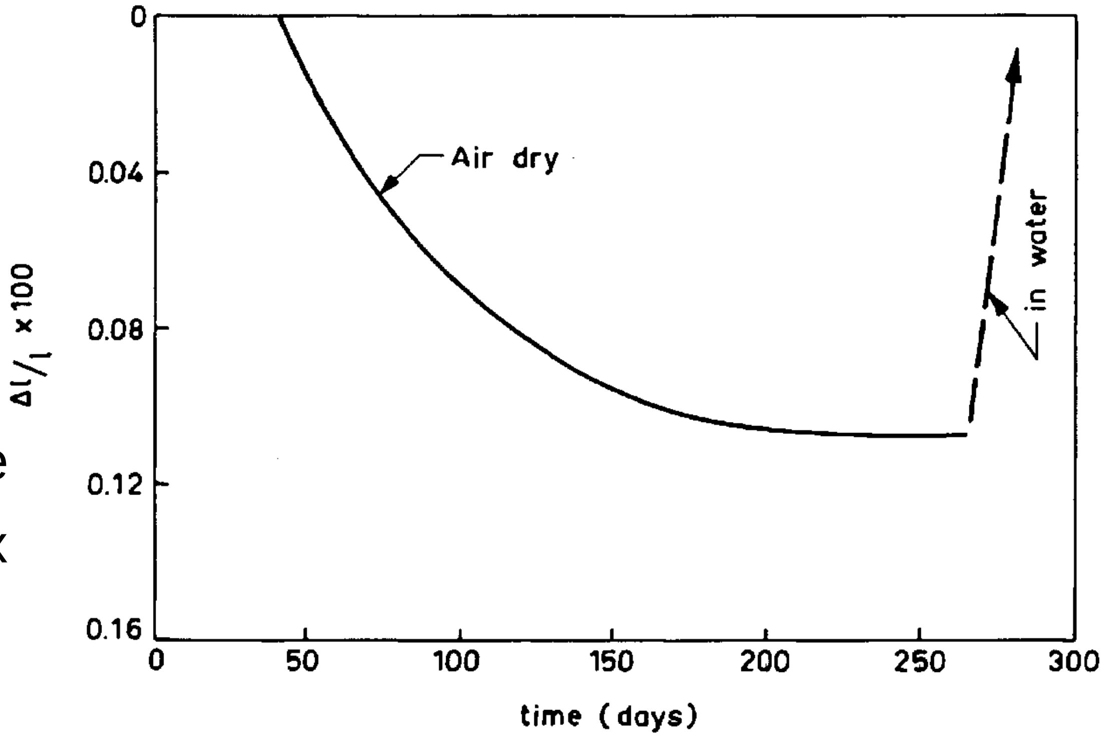

Shrinkage is also a function of time and its rate decreases with time.

SHRINKAGE

Shrinkage deformations are calculated using a proper shrinkage coefficient "ε_{cs}", which is the strain caused by shrinkage.

Although shrinkage coefficient is affected by all factors listed before, it is predominantly influenced by:

- Curing process of the concrete
- Relative humidity of the environment, and
- The equivalent thickness of the member.

The equivalent thickness ℓ_e is expressed as the ratio of twice cross-sectional area to the perimeter of the cross-section, which is in contact with the environment.

SHRINKAGE

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$$\ell_e = \frac{2A_c}{u}$$

where “$\boldsymbol{A_c}$“ is the cross-sectional area and “$\boldsymbol{u}$” is the perimeter in contact with the environment.

Shrinkage coefficients, ε_{cs}, given in TS500

Curing	Dry (relative humidity 50%)		Humid (relative humidity 80%)	
	ℓ_e =150 mm	ℓ_e = 600 mm	ℓ_e = 150 mm	ℓ_e = 600 mm
Inadequate	0.0006	0.0005	0.0004	0.0003
Adequate	0.0004	0.0004	0.00025	0.00025

It should be noted that the coefficients given in the table above are to be used in calculating the long-term shrinkage (at the end of three years).

INCLUSION OF SHRINKAGE IN STRUCTURAL ANALYSIS

The structural effects of shrinkage are similar to those of temperature drop. Therefore, in the structural analysis it is combined with temperature drop. For example, if there is a possibility of 20°C temperature drop and shrinkage coefficient is estimated to be 0.0004, in the design these two will be combined and taken into account as an equivalent temperature drop. The equivalent temperature is obtained by dividing the shrinkage coefficient by the coefficient of thermal expansion for concrete, i.e.

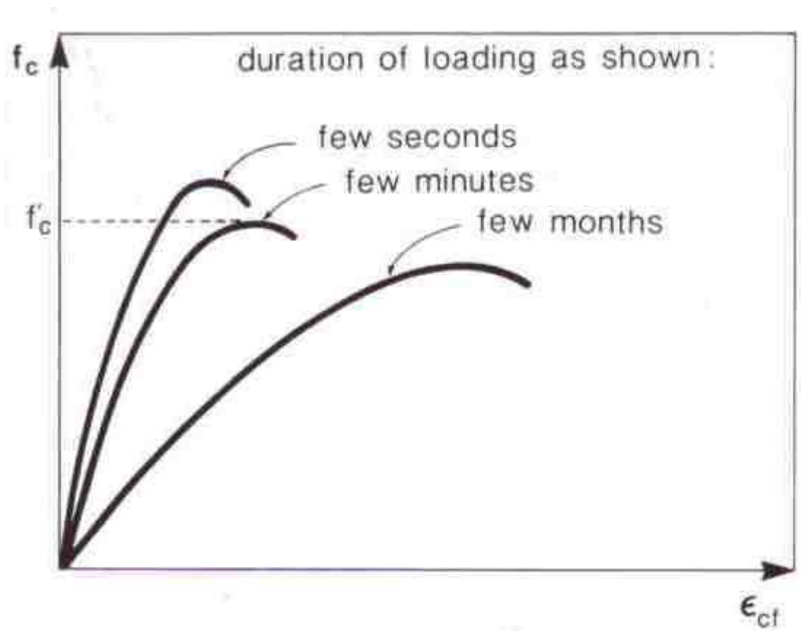
$$\Delta T = 20^\circ + 0.0004 / 10^{-5} = 60^\circ$$

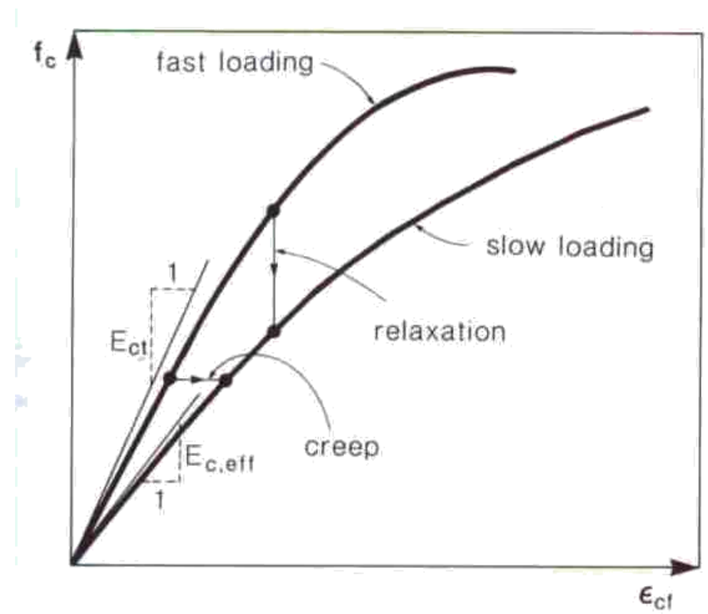
CREEP

Creep is the time dependent deformation of concrete, which is subjected to sustained loads.

Recall: The stress-strain response of concrete depends upon the rate of loading and the time history of the applied loading.

If the stress is held constant for some length of time, the strain increases – a phenomenon referred to as creep. If the strain is held constant for some time length of time stress will decrease – a phenomenon referred to as relaxation.





CREEP

Creep is the time dependent deformation of concrete, which is subjected to sustained loads.

Creep is dependent on many factors, most important of which are given below:

- **age of concrete**
- **w/c ratio**
- **humidity and the temperature.**
- **level of sustained stress**
- **time**

CREEP

The age of concrete when the sustained load is applied - **For older concrete creep is less.**

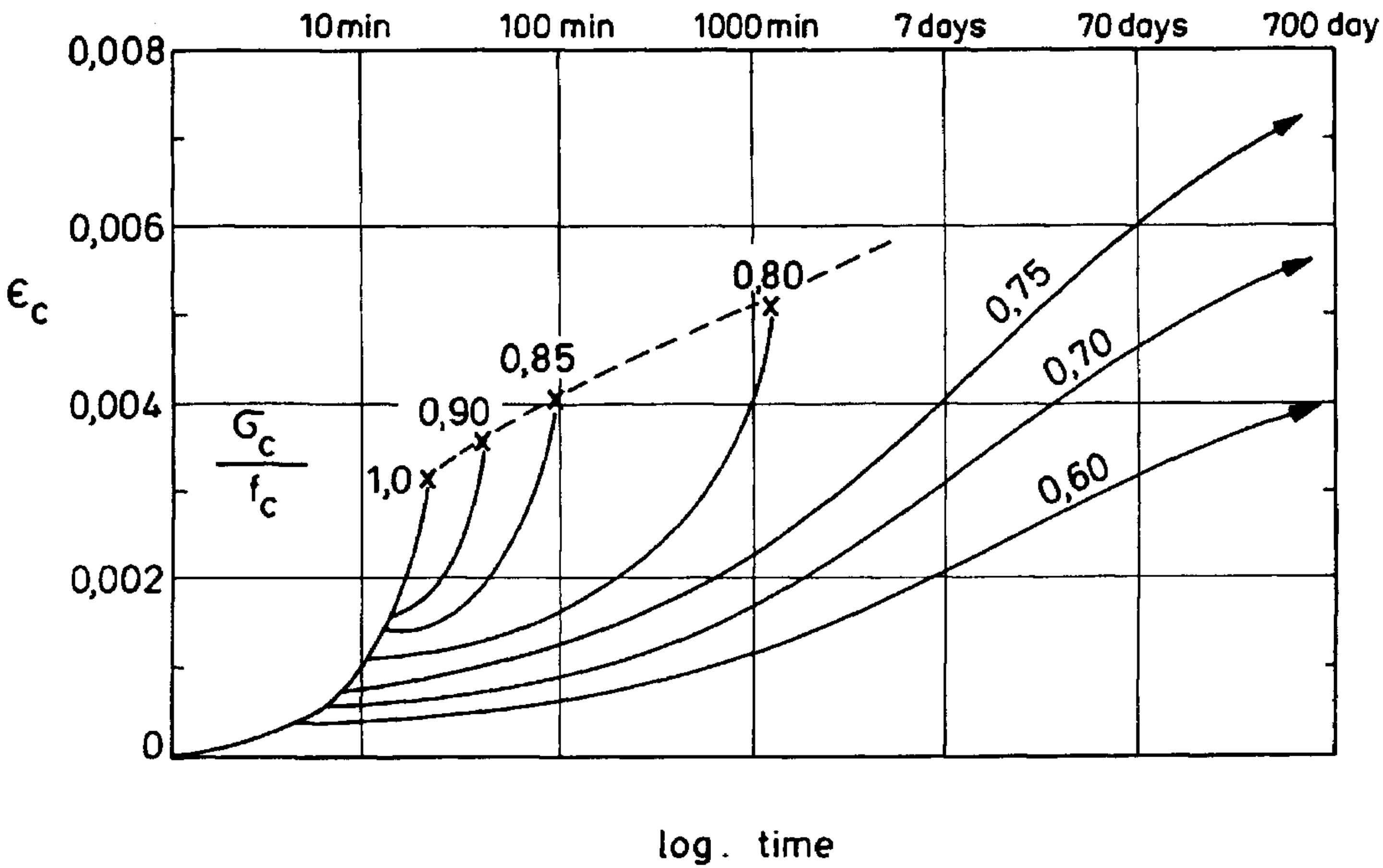
The water/cement ratio of the mix - **As the w/c ratio increases, creep increases.**

The humidity and the temperature - **Creep is less when the humidity is high.**

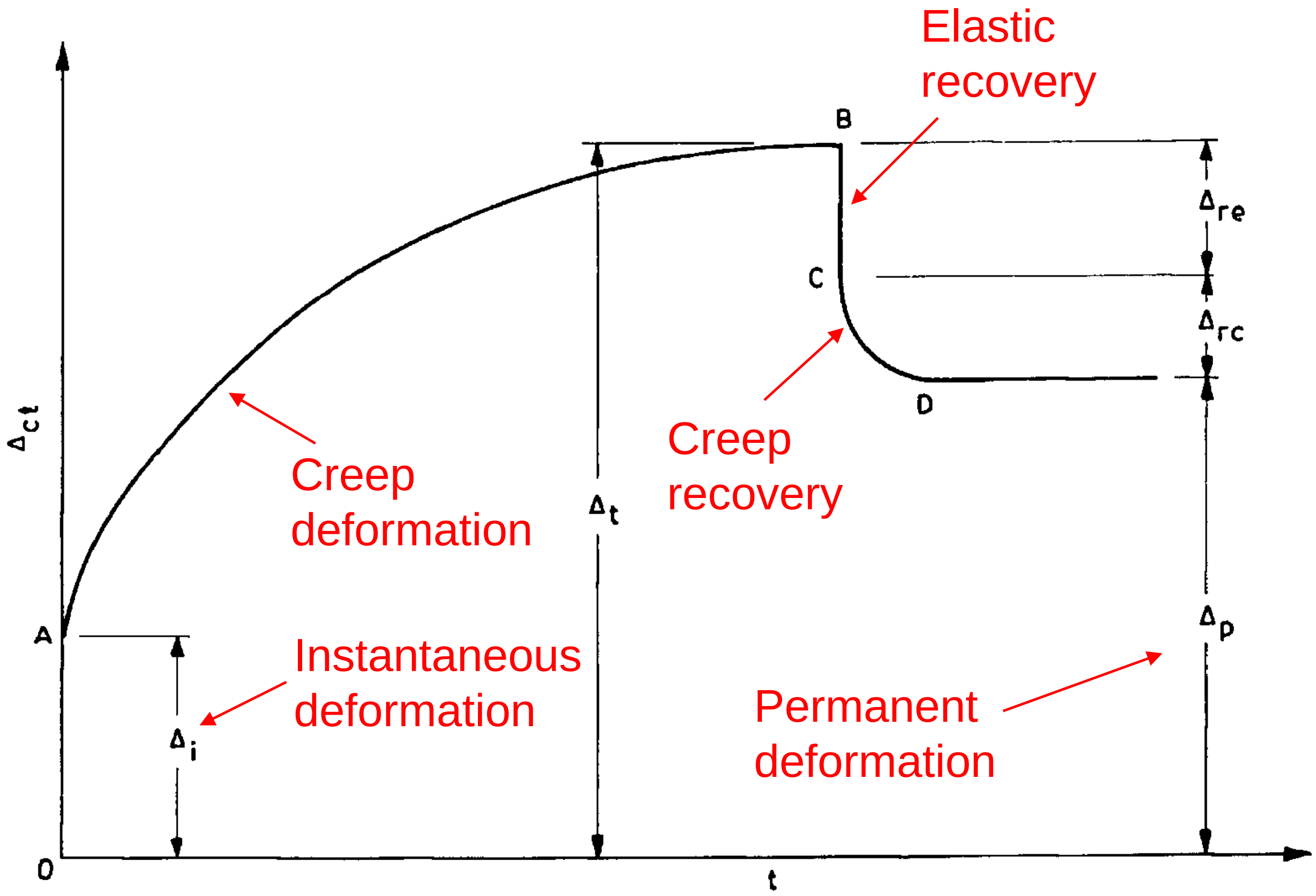
The level of sustained stress - **At low stress levels (at working stresses), creep is proportional to stress. However, at higher stress levels creep increases more rapidly and is not proportional to the stress.**

The time - **The creep rate decreases with time, but creep usually does have an effect almost for 3 years with a decreasing rate.**

EFFECT OF CREEP ON CONCRETE STRENGTH – CREEP LIMIT



CREEP DEFORMATIONS



CREEP DEFORMATIONS

$$\Delta_p \sim 2 - 3\ \Delta_i$$

In deformation calculations, one has to use a reduced stiffness to include the creep effect. It will be appropriate to use a reduced modulus of elasticity (1/2 or 1/3 of the instantaneous value) to compute the time dependent deformations.

E_c ~ 1/2 to 1/3 of its original value.

LONG TERM CREEP STRAINS

$$\varepsilon_{ce} = \frac{\sigma_{co}}{E_{c28}} \phi_{ce}$$

where; σ_{co} is the stress in concrete under sustained loading, E_{c28} is the modulus of elasticity of 28 days old concrete and ϕ_{ce} is the creep coefficient (to be taken from tables).

ϕ_{ce} -The creep coefficient (TS500)

Age at Loading	Dry (relative humidity 50%)			Humid (relative humidity 80%)		
	Equivalent thickness (mm), $\ell_e=2A_c/u$					
	50	150	600	50	150	600
1 day	5.4	4.4	3.6	3.5	3.0	2.6
7 days	3.9	3.2	2.5	2.5	2.1	1.9
28 days	3.2	2.5	2.0	1.9	1.7	1.5
90 days	2.6	2.1	1.6	1.6	1.4	1.2
365 days	2.0	1.6	1.2	1.2	1.0	1.0