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CHAPTER 1

INTRODUCTION

1.1. SCOPE

It is common practice to use reinforced or pre-stressed concrete structures for the storage of water and other aqueous liquids. Similar design methods may also be used to design basements in buildings where ground water must be excluded. Concrete is generally the most economical material of construction and, when correctly designed and constructed, will provide long life and low maintenance costs. The types of structure which are covered by the design methods given in this book are: storage tanks, reservoirs, swimming pools, elevated tanks, ponds, settlement tanks, basement walls, aqueducts and similar structures.

Due to the internal pressure of the liquid stored in such structures, the walls and floors are mainly subject to tensile forces, bending moments and eccentric tension which cause in most cases critical tensile stresses on the surface of the different elements facing the liquid. If such elements are designed according to the general principles adopted in ordinary reinforced concrete, cracks will be developed and the liquid contained in the tank has the possibility to penetrate under its hydrostatic pressure through the cracks and cause rusting of the steel reinforcement. Therefore, special provisions must be taken to prevent the formation of such cracks. Such provisions generally lead to an increased thickness of the walls towards their foot and at their other corners. If the effect of this increase is not considered, it may lead to serious defects so that a thorough investigation is absolutely essential.

The present work is concerned with the theory and design of liquid tanks and containers giving the necessary provisions aiming to satisfy the final goal of structural engineering by designing safely, economically and efficiently. It is designed to adapt the teaching requirements in our universities and higher schools for undergraduate and advanced studies. It gives the practicing designer a simple, scientific and basic reference not only in liquid containers but also in many other fields such as surfaces of revolution, high towers, circular beams, rectangular and circular flat plates, deep beams ...etc., as they are needed in design of tanks and containers. The statistical behavior of bunkers and silos is similar to that of tanks; for this reason, it has been decided to show their design in a separate chapter of this edition.

One of the main aims of this book is to show that careful scientific designs based on sound theoretical basis do not need necessarily complicated calculations and. in most cases, an attempt has been made to simplify complicated problems. In complicated cases, for which solutions could not be derived without going beyond the limit of the usual standard in structural engineering studies or in cases which need tedious or lengthy calculations, the final results were given and where possible simplified by design tables and curves. It was taken for granted that the reader has a thorough knowledge of the strength of materials and fundamentals of reinforced concrete that is usually covered by our faculties of engineering.

In this manner, a complete treatment of the design fundamentals is given and fully discussed and illustrated with numerical examples and full constructional details showing the engineer how to attack structural problems with confidence.

1.2. GENERAL DESIGN OBJECTIVES

Structural concrete elements are exposed to varying types of environmental conditions. For design purposes, it is convenient to classify exposure conditions, and in Egyptian code (EC) this was achieved by using building categories for various situations. Table 1.1. Specifies the various exposure conditions, which are recommended in EC.

Table 1.1: Category of structures.

Categories	Degree of Exposure	Examples
One	Protected	a- All internal structural element in ordinary buildings. b- Concrete surfaces continuously under water or dry. c- The upper isolated roofs.
Two	Unprotected	a- Bridges, unisolated roofs. b- The protected structures but are near the seas. c- Concrete subject to condensation (e.g. open halls and Garages).
Three	Severely Exposed	a- Concrete surfaces exposed to rain, altering wetting and drying, or high relative humidity. b- Water tanks. c- Concrete exposed to moderate chemicals or gases.
Four	Very Severely Exposed	a- Concrete exposed to chemicals or gases cause steel corrosion. b- Marine structures. c- Sewage or industrial liquid tanks.

In the design of normal building structures, the most critical aspect of the design is to ensure that the structures retain its stability under the imposed loads. Experience has shown that, as the exposure conditions become more severe, precautions should be taken to ensure that moisture and air do not cause carbonation in the concrete cover. The carbonation removes the protection to the steel and causes corrosion, which, in turn, will cause the concrete surface to spall.

A structure that is designed to retain liquids must fulfill the requirements for normal structures having adequate strength, durability, and freedom from cracks or deflections. In addition, it must be designed so that the liquid is not allowed to leak or percolate through the concrete structures. Equally, the concrete itself must be of good quality, and properly compacted; good workmanship during construction is critical.

1.3. FUNDAMENTAL DESIGN METHODS

Historically, the design of structural concrete has been based on elastic theory, with specified maximum design stresses in the materials at working loads. More recently, limit state philosophy has been introduced, providing a more logical basis for determining factors of safety. In ultimate design, being multiplied by a partial safety factor enhances the working or characteristic loads. The enhanced or ultimate loads are then used with the failure strengths of the materials to design the structure. Limit state design methods are now widely used throughout the world for normal structural design.

Formerly, the design of liquid-retaining structures was based on the use of elastic design, with material stresses so low that no flexural tensile cracks developed. This led to the use of thick concrete sections with copious quantities of mild steel reinforcement. The probability of shrinkage and thermal cracking was not dealt with on a satisfactory basis, and nominal quantities of reinforcement were specified in most codes of practice. More recently, analytical procedures have been developed to enable flexural crack widths to be estimated and compared with specified maxim. A method of calculating the effects of thermal and shrinkage strains has also been published. These two developments enable limit state methods to be extended to the design of liquid-retaining structures.

Limit state design methods enable the possible modes of failure of a structure to be identified and investigated so that a particular premature form of failure may be prevented. Limit states may be 'ultimate' (where ultimate loads are used) or 'serviceability' (where design or service loads are used).

In the EC, limit state design has been used successfully for over 10 years for the design of liquid- retaining structures. The former EC allowed a designer to choose between elastic design and limit state design.

1.4. CODES OF PRACTICE

Structural design is often governed by a Code of Practice Appropriate to the location of the structure. Whilst the basic design objectives are similar in each code, the specified stresses and factors of safety may vary. It is important to consider the climatic conditions at the proposed site, and not to use a code of practice written for temperate zones in parts of the world with more extreme weather conditions.

1.4.1. Concrete Cover

During the useful lifetime of the structure, the concrete cover must ensure protection of the reinforcement against corrosion and adequate bond between the steel and the concrete. The protecting effect of the concrete cover against corrosion is of physical and chemical nature and its function may be summarized as:

1- Provide chemical protection by virtue of the inhibitive action of the hydroxyl ion.
2- Provide a physical barrier to the ingress of moisture, oxygen, carbon dioxide, and to the conductance of electrolytic currents.
3- Provide a physical and chemical barrier to the ingress of aggressive substances.

For this purpose, the concrete cover must be of adequate thickness, highly impermeable, and free from cracks of a significant width. The minimum thickness of the concrete cover depends on the diameter of the steel bar and the permeability of the concrete to gases liquids and ambient conditions.

Up to a certain degree, the increase of cover thickness increases the corrosion protection of the reinforcement. A thick cover has greater mechanical strength against abrasion, impacts, spalling, ... etc. Furthermore, the permeability of the concrete cover depends markedly on its thickness, as shown in Figure 1.1. In addition to these functions, the thickness of the cover influences the progress of penetration of carbonation.

At a given rate of penetration, the smaller the thickness of cover the sooner carbon dioxide and chloride will reach the reinforcement for concrete with the same quality. Clearly, increasing cover is particularly beneficial and, in practice, few cases of corrosion have been reported where the cover exceeded 50 mm.

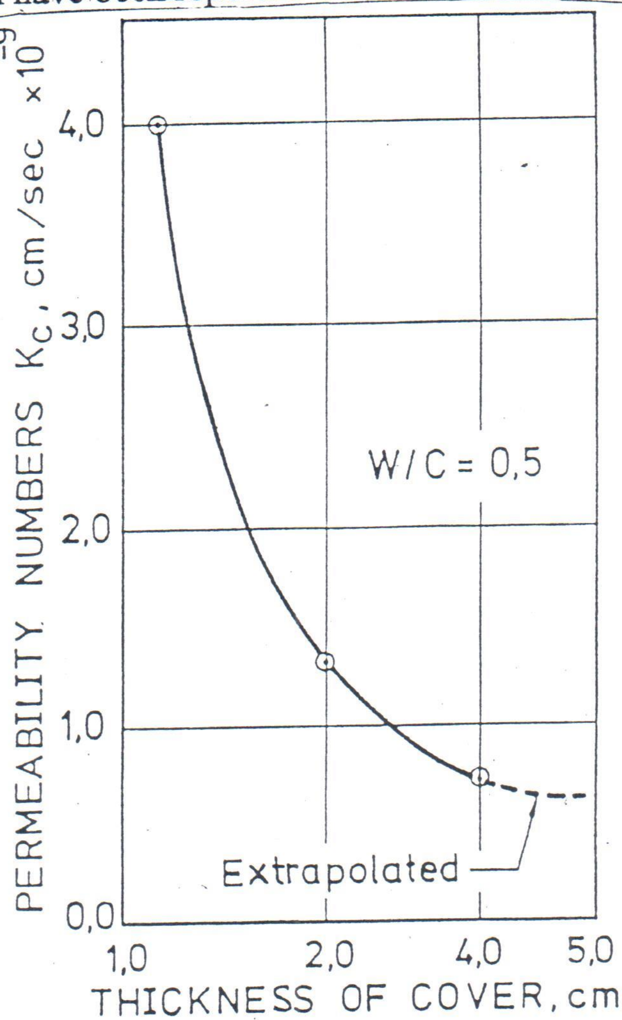

Fig. 1.1: Thickness of concrete cover and permeability to water.

Egyptian Code provides guidance to the cover thickness necessary to protect reinforcement with different qualities of concrete, (Table 1.2). Quality is expressed in terms of strength. It might be more satisfactory if this quality was defined in terms of permeability.

Table 1.2: Minimum concrete cover.

Category	External Concrete Cover to Reinforcement * (cm)			
	All elements except Slabs		Walls & Solid Slabs	
	$f_{cu} \leq 250$	$f_{cu} > 250$	$f_{cu} \leq 250$	$f_{cu} > 250$
One	2.50	2.00	2.00	1.50
Two	3.00	2.50	2.50	2.00
Three	3.50	3.00	3.00	2.50
Four	4.50	4.00	4.00	3.50

*The concrete cover should never be less than the largest diameter of steel bars used for the reinforcement.

1.4.2. Quality of Concrete:

The concrete used for reinforced concrete structures must have two principal functions. From the structural aspect, it must have adequate strength and ductility and it must provide good bond with the embedded steel. For durability, the concrete must be resistant to weathering and any aggressive conditions encountered and the concrete must provide the reinforcement a satisfactory protection against corrosion. The concrete must have a high reserve of alkalinity throughout and the materials used must be free from substances, which encourage corrosion. The composition of the concrete mix must be such as to produce concrete of uniformly high density with a sufficient quantity of fine mortar to ensure an even and continuous coating of cement paste over the steel. The concrete must be less permeable to aggressive conditions.

The most important quality of the concrete as regards corrosion is the permeability of the concrete to water, chloride, oxygen and carbon dioxide. For concrete made from dense aggregate and compacted so that it is practically free from air voids, the permeability of the concrete cover, in the absence of cracking, is mainly determined by the permeability of the cement paste. The permeability of cement paste to water depends on the water/cement ratio (w/c) and the degree of hydration of the cement. Figures 1.2, 1.3 and 1.4 show the effect of water/cement ratio on the permeability of concrete or cement paste to water, chloride and oxygen. It is clear that the increase of water/cement ratio increase the permeability. The permeability of cement paste to oxygen is influenced not only by the water/cement ratio and the degree of hydration of the cement but it also depends essentially on the content of free water in the hardened cement paste (Fig. 1.5). The higher the moisture content, the lower will be the permeability to oxygen.

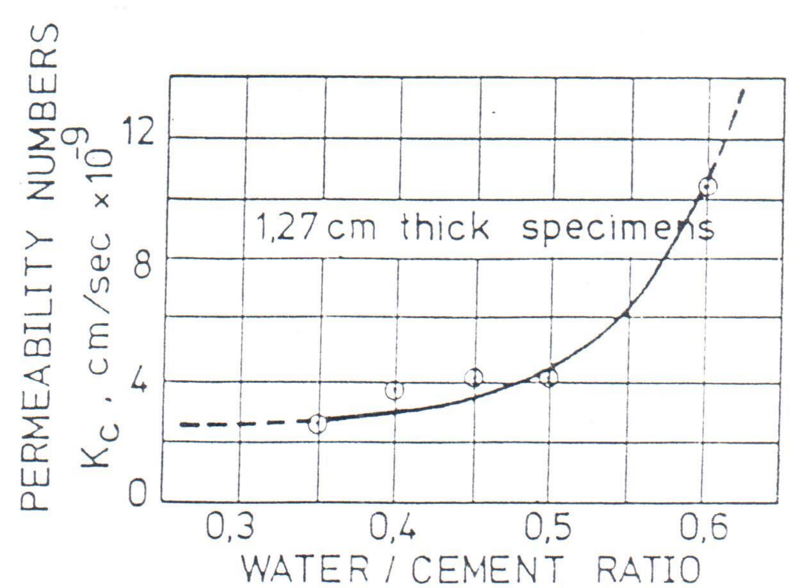

Fig. 1.2: Effect of water/cement ratio on permeability of concrete to water.

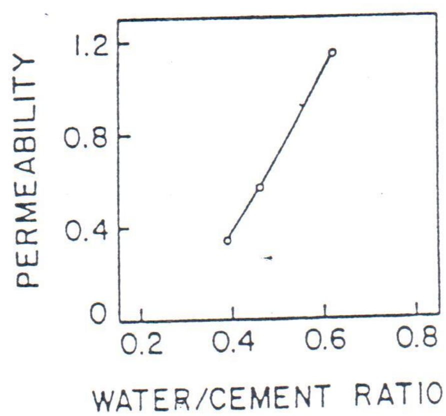

Fig. 1.3: Effect of water/cement ratio on permeability of hydrated pastes to chloride ions, mg / (g.cm.day).

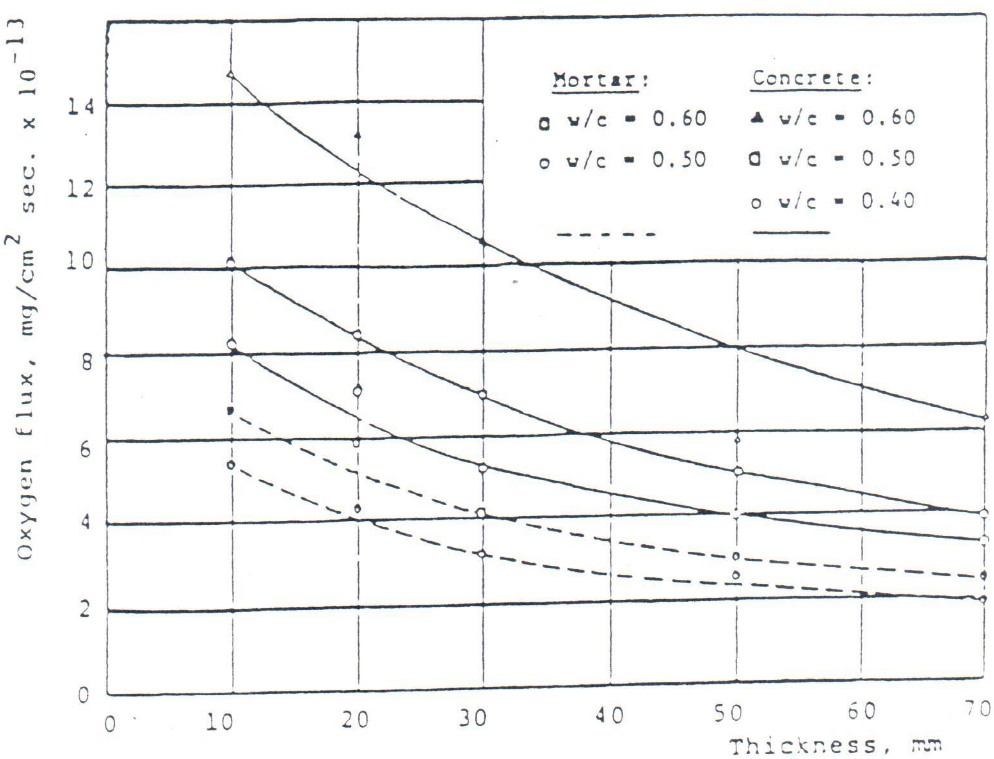

Fig. 1.4: Effect of water/cement ratio and thickness on the diffusion of oxygen through mortar and concrete.

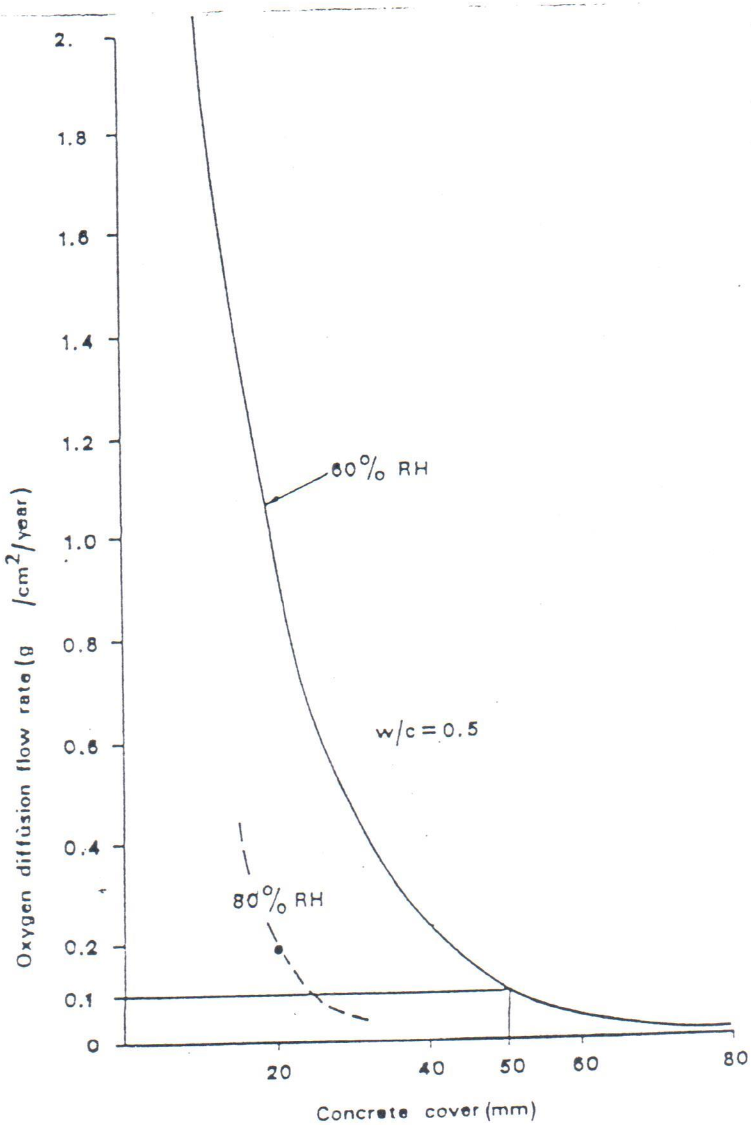

Fig. 1.5: Oxygen diffusion through non-saturated concrete.

It is important to say that high w/c ratios are undesirable with respect to the quality of concrete. So, an overly dry mix reduces the ability of the fresh concrete to surround the reinforcement completely and is unable to furnish the even alkaline film on the surface of the reinforcement required for corrosion protection. Therefore, the desired water/cement ratio ranges between 0.4 and 0.5. Concrete with good quality allows the use of thinner. Concrete cover than concrete with poor quality.

The concrete constituents affect the quality of concrete as follow:

Cements: Normal Portland cement is generally used for liquid-retaining structures. It is not desirable to use rapid-hardening cement because of its greater evolution of heat, which tends to increase shrinkage cracking. However, its use may be considered in cold weather. When there are sulphates in the ground water, or other chemical contaminants, the use of sulphate-resisting cement or super-sulphated cement may be essential.

Aggregates: The maximum size of aggregate must be chosen in relation to the thickness of the structural member. A maximum size of 20 mm is always specified up to member thickness of about 300 - 400 mm, and may be used above this limit. Size 40 mm may be specified in very thick members. The use of a large maximum size of aggregate has the effect of reducing the amount of shrinkage cracking.

It is important to choose aggregates that have low drying shrinking and absorption. Most quartz aggregates are satisfactory in these respects but, where limestone aggregate is proposed, some check on the porosity is desirable. Certain aggregates obtained from igneous rocks exhibit high shrinkage properties and are quite unsuitable for use in liquid - retaining structures.

Local suppliers can often provide evidence of previous use, which will satisfy the requirements, but some care is necessary in using material from a new quarry, and tests of the aggregate properties are recommended.

Admixtures: Admixtures containing calcium chloride are not desirable, as there is a risk of corrosion of the reinforcement. Other admixtures, which improve workability or frost resistance, may be used on their merits.

Concrete mix design: The concrete must be designed to provide a mix, which is capable of being fully compacted by the means available. Any areas of concrete, which have not been properly compacted, are likely to leak. The use of poker-type internal vibrators is recommended.

The cement content in kg/m^3 of finished concrete must be judged in relation to a minimum value to ensure durability, and a maximum value to avoid a high temperature rise in the freshly placed concrete.

There has recently been a considerably increased use of pulverized fuel ash (pfa) and ground granulated blast-furnace slag (ggbs) as replacement materials for a proportion of the cement. The reason for considering these materials is to counteract the increase (over the years) of the strength of cement. In order to have sufficient cement content in the mix to give adequate durability, it is now necessary to specify high strengths with consequent high evolution of heat. In 1950 a concrete strength of 250 kg/cm^2 was a normal specification, but now 350 kg/cm^2 is normal and sometimes 400 kg/cm^2. The proportion of pfa or ggbs that can be used to replace cement is not considered in EC, but it is limited in BS 8007 to 35 % for pfa and 50 % for ggbs.

1.4.3. Allowable Tensile Stresses in Concrete.

As concrete, which has to withstand tensile stresses, is normally reinforced its tensile strength has not received much attention, although it is of great importance in determining the ability of concrete to resist cracking due to shrinkage on drying and thermal movements. The tensile strength develops more quickly than the compressive strength and is usually about 10 to 15 per cent of the compressive strength at ages of up to about 14 days, falling to about 5 per cent at later ages. The tensile strength of concrete may be measured in direct tension or in bending, the extreme fiber stress in tension being calculated in the latter case and often being quoted as the modulus of rupture.

The tensile strength of concrete is of particular importance in water retaining structures and the Egyptian Code of practice permits a tensile strength according to the following relation:

$$f_{ct} = \frac{f_{ctr}}{\eta}$$

Where: f_{ct} = The allowable tensile stress

f_{ctr} = The cracking limit stress and is evaluated from the following expression:

$$f_{ctr} = 0.75\,(f_{cu})^{2/3} \quad \text{..........(1.1)}$$

And η is a factor for reducing the stresses due to creep and the possibility of a redistribution of stress in the bending test, resulting in the neutral axis not being exactly at the geometric center of the beam. Table 1.3 gives the value of η according to the virtual thickness (tv).

Table 1.3: The values of factor η.

virtual thickness tv in cm	≤ 10	20	40	≥ 60
Factor η	1.0	1.3	1.6	1.7

Where: $$tv = t\left\{1 + \frac{f_{ct}(N)}{f_{ct}(M)}\right\}$$

Where: t = Thickness of the section

$f_{ct}(N)$ = Tensile stresses due to axial force (-ve if the force is compression).

$f_{ct}(M)$ = Tensile stresses due to bending moment.

Table 1.4 gives the value of f_{ct} for different values of f_{cu} and different virtual thickness tv.

Table 1.4: Allowable tensile stresses.

f_{cu} / tv	175	200	225	250	275	300
≤ 10 cm	23	25	27	29	31	33
20 cm	18	19	21	22	24	25
40 cm	14	16	17	18	19	21
≥ 60 cm	14	15	16	17	18	19

1.4.4. Allowable Stresses in Reinforcing Steel

Although the service tensile stress in the reinforcement in liquid - retaining structures is not always very high, it is usual to high - strength steel with a ribbed or deformed surface. The difference in cost between high - strength ribbed steel and plain-surface mild steel only about 3 %. This small extra cost is less than saved by the extra strength available and increased bond performance. Similar arguments affect the use of welded fabric reinforcement, where fixing costs is very much reduced and time saved. Traditionally, fabric has been used only in ground slabs but where the quantity is sufficient, can now be obtained in sizes and types that allow it to be used in walls, floors and roofs.

The specified characteristic strengths of reinforcement available in Egypt are given in Table 1.5, 1.6. The specified characteristic strength is a statistical measure of the yield or proof stress of a type of reinforcement. A material partial safety factor γ_s = 1.15 is applied to the specified characteristic strength to obtain the ultimate design strength.

Reinforcement embedded in concrete is protected from corrosion by the alkalinity of the cement. As time passes, the surface of the concrete reacts with carbon dioxide from the air and carbonates are formed which remove the protection. The specified cover of at least 40-mm is adequate for normal conditions, but where particularly aggressive conditions apply; it is worth considering the use of a special type of reinforcement. The possibilities are:

a) Galvanized bars (x1.5)
b) Epoxy-coated bars (x2.0)
c) Stainless steel bars (x10)

The numbers in brackets give an indication of the average cost of the special bars compared with normal steel. Special bars may sometimes be convenient to use in a particularly thin element where it is not possible to obtain the proper cover with several layers of steel.

Table 1.5: Stresses in reinforcing steel (St 24/35, smooth round bars).

f_s* kg/cm^2	Reduction factor β_{cr}	Category One	Category Two	Categories Three & Four
		Largest Bar Diameter in mm.		
1400	1.00	25	22	13
1200	0.84	28	28	19
1000	0.69	32	32	28

Table 1.6: Stresses in high tensile steel (ribbed bars).

f_s* kg/cm^2	Reduction factor β_{cr}		Category One	Category Two	Categories Three & Four
	St.36 / 52	St.40 / 60	Largest Bar Diameter in mm.		
2200	1.00	0.92	13	10	6
2000	0.93	0.83	16	13	8
1800	0.85	0.75	25	19	10
1600	0.75	0.67	32	22	16
1400	0.65	0.58	--	28	22
1200	0.56	0.50	--	--	32

* f_s are the allowable stresses in reinforcement for the working stress design method. Where limit state of cracking and the analysis of the section is done according to the ultimate strength limit state, the yield or proof strength must be multiplied by the factor β_{cr}.

1.4.5. Loading

1.4.5.1. Load Arrangements

Liquid-retaining structures are subject to loading by pressure from the retained liquid. Typical values of weights are listed in Table 1.7.

Table 1.7: Density of retained liquids

Liquid	Weight/m^3
Water	1.0
Raw sewage	1.1
Digested sludge aerobic	1.04
Digested sludge anaerobic	1.13
Sludge from vacuum filters	1.2

The designer must consider whether sections of the complete reservoir may be empty, when other sections are full, and design each structural element for the maximum bending moments and forces that can occur. Several loading cases may need to be considered. Internal partition walls should be designed for liquid loading on each side separately.

1.4.5.2. Partial Safety Factors for Loads

When designing a structural element for the ultimate limit state, it is necessary to use partial safety factors (in conjunction with the characteristic applied loading) to provide the necessary margin against failure. The factors take account of the likely variability of the loading and the consequences of failure.

The partial safety factors appropriate for liquid retaining design are defined in EC. The dead load factor is identical to that used for normal reinforced concrete design and $\gamma_f = 1.4$. As the imposed load due to a liquid is known precisely, a partial safety factor of $\gamma_f = 1.4$ may be used for loads due to retained liquid. A similar value of $\gamma_f = 1.4$ may also be used for pressures due to soil. These values are also recommended in EC for normal design. The roofs of underground structures are frequently covered with a layer of soil and hence any imposed loads due to vehicles will be distributed before reaching the structural roof slab. In these circumstances it will normally be appropriate to consider a single load case when designing the roof.

In design, liquid levels should be taken to the top of walls (or the level of the underside of the roof slab) assuming that any outlet pipes at a lower level are blocked. This condition only applies to the ultimate limit state calculations and not to serviceability considerations.

Depending on the type of construction, and in particular, whether the roof is joined to the walls without a movement joint, any thermal expansion of the roof may cause loading on the perimeter walls. This effect is accentuated if there is effective passive pressure at the back of the walls.

1.5. CORROSION OF STEEL IN CONCRETE

1.5.1. General Introduction

The corrosion of metals in concrete, especially steel, has received increasing attention in recent years, because of its widespread occurrence in certain types of structures, and because of the high cost of repair. The corrosion of steel reinforcement was first observed in marine structures and chemical manufacturing plants. More recently, numerous reports of its occurrence in bridge decks, parking structures, and other structures exposed to chlorides or carbon dioxide (CO_2) have made the problem particularly prominent.

The corrosion of steel in concrete generally initiated by a chemical reaction related to the composition of the constituent parts and the influence of one or more of the following:

1- Chloride concentration.
2- Carbonation penetration.
3- Other acid radicals.
4- Oxygen concentration.
5- Degree of moisture ingress.
6- Bacterial action.

Any one of these can have an effect on the chemical state, at the steel - concrete interface of the reinforcement, which is not necessarily uniform over the whole structure. Some variations can be traced to the fact that no structures completed in one day from one batch of concrete or that the finished construction is not necessarily exposed to exactly similar atmospheric condition throughout its whole life. Consequently variations in chemical composition can slowly build up, often relatively localized, and affect the steel - concrete interface. As soon as the localized surface of this steel is changed the surrounding environment (concrete) permits an electron movement from one part of the metallic surface (the reinforcement) to another. This creates a current flow which starts to dissolve the metal, in areas where it flows off the steel, and thereby initiates corrosion. Because of these two motivating processes the overall phenomenon becomes an electrochemical process. Electrochemical corrosion can result from dissimilar or non-uniform metals or dissimilar environments. The instances of electrochemical corrosion in concrete result from the existence of differences in electrochemical potential within concrete may arise in various ways:

- Differences in metals.
- Differences in chemical environment from site to site along the metal.
- Such differences may also result from the presence of cracks where leaching of alkali by carbonation and intrusion of chloride and oxygen could occur.
- Bleeding, segregation, or poor consolidation of the concrete would also cause a difference in environment between the upper and lower sides or reinforcing steel.
- Temperature differences within concrete can also create differences in electrochemical potential, but the primary effect of increased temperature

is that of acceleration of the electrochemical reactions and the corrosion.

Four basic elements are necessary for an electrochemical cell to function:

1- An anode: where corrosion takes place.
2- A cathode: which does not corrode but maintains the ionic balance of the corrosion reactions.
3- An electrolyte: which is a solution capable of conducting electric current by ionic flow.
4- A conductor: which connects the anode and cathode.

In the case of steel in concrete, the anodes and cathodes occur on the reinforcing steel, which also acts as the conductor. Moist concrete acts as the electrolyte. This is illustrated schematically in Figure 1.6.

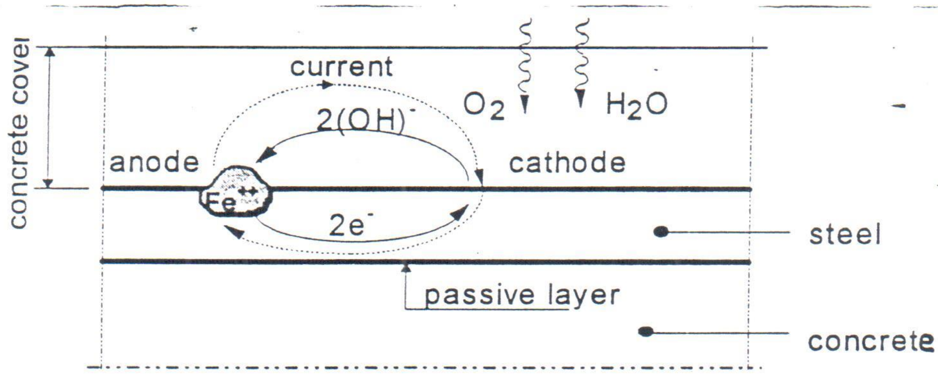

Fig. 1.6: Schematic representation of corrosion in concrete

The electrochemical reaction at the anodic and cathodic sites can be summarized as:

1- The anode reaction:

Metal → Metal ions (dissolved in solution) + electrons

$Fe \rightarrow Fe^{++} + 2e^-$

2 - The cathode reaction:

Electrons + Water + Oxygen → hydroxyl ions

$2e^- + 2\,H_2O + \frac{1}{2}\,O_2 \rightarrow 2\,OH^-$

The hydroxyl ions react with ferrous ions at the anode sites and form hydrous iron oxides.

$Fe^{++} + 2\,OH^{-} \rightarrow Fe\,(OH)_2$

$4\,Fe\,(OH)_2 + 2H_2O + O_2 \rightarrow 4\,Fe\,(OH)_3$ (red rust)

The speed at which corrosion proceeds will depend on the following three factors:

1 - The Potential difference between the anodic and cathodic sites.
2 - The ease with which the Passage of electricity can occur both through the metal and across the surrounding electrolyte.
3 - The availability of the reaction at the anode and the cathode surfaces.

The quantity of metal lost by the anode undergoing corrosion is related to the magnitude of current flowing in the corrosion cell. The parameters defining this relationship are known as Faraday 's Laws of Electrolysis. Using a set of equation based on the above laws it is possible to calculate the amount of metal lost from the anodic sites as a quantity of electricity passed through the cell. To put it in relevant practical terms, a current flow of 1 A for one year will result in the dissolution of 9 kg of steel (1.03 gm / A. hour).

CHAPTER 2

DESIGN OF SECTIONS CONSIDERING CRACK CONTROL

2.1. INTRODUCTION

Sections of liquid containers must be designed that no cracks in concrete are allowed in the fibers facing the liquid, because if such cracks are allowed, the liquid in the containers will penetrate through these cracks and causes rusting of steel reinforcement which must be prevented by all possible means.

In order to satisfy this requirement, the concrete dimensions must be chosen so that the tensile stresses in concrete-if they take place on the liquid side - are smaller than its tensile strength, i.e. The section is design according to stage 1.

The basic design philosophy of liquid containers is discussed in chapter 1. In this chapter, detailed design methods are described to ensure compliance with the basic requirement of strength and serviceability considerations control the design. The procedure is therefore:

a) Estimate concrete member dimensions.
b) Check strength.
c) Calculate the reinforcement required limiting the design crack widths.
d) Check other limit states, if any.
e) Repeat as necessary.

2.2. SECTIONS SUBJECT TO AXIAL TENSION

Sections subject to axial tension present in the case of ties in rectangular tanks, ring beams (supporting dome or cone) or horizontal strip in cylindrical walls in circular tanks (ring tension force). In this section, the steel alone must be sufficient to resist all the tensile force (T) acting on the section, i.e.

$$A_s = \frac{T}{f_s} \qquad \text{(in case of working stress design method)}$$

Where: A_s = The area of steel.
f_s = The allowable working stress in steel.

$$f_{cto} = \frac{T}{A_c + nA_s}$$

Where:

A_c = The area of concrete section

n = Is the elastic modular ratio E_s/E_c and equal to 10 of uncracked section

E_c = Is young's modulus for concrete.

E_s = Is young's modulus for steel.

For rectangular section, $A_c = b.\ t$

$$f_{cto} = \frac{T}{b.t + 10\left(\frac{T}{f_S}\right)}$$

$$b.t.f_{cto} + 10 f_{cto}\left(\frac{T}{f_S}\right) = T$$

$$b.t.\ f_{cto} = T\left\{1 - 10\left(\frac{f_{cto}}{f_S}\right)\right\}$$

If b = 100 cm and T in tons

$$100\ t = 1000\frac{T}{f_{cto}}\left\{1 - 10\left(\frac{f_{cto}}{f_S}\right)\right\}$$

$$t\ (cm) = \frac{10}{f_{cto}}\left\{1 - 10\left(\frac{f_{cto}}{f_S}\right)\right\}\ T$$

For slabs and walls, in general, b = 100 cm and by substituting for f_{cto}, f_s in kg/cm^2, for t in cm and for T in tons, then:

$$t = K.T \text{ ....(2.1)}$$

The values of K are given in Table 2.1.

Table 2.1: Values of factor K

f_{cu} kg/cm^2	f_{cto} kg/cm^2	f_s kg/cm^2							
		∞	2000	1800	1600	1400	1200	1000	$K_{av.}$
175	14	0.71	0.66	0.66	0.65	0.64	0.63	0.62	0.653
200	15	0.67	0.62	0.61	0.60	0.59	0.58	0.57	0.606
225	16	0.63	0.58	0.57	0.56	0.55	0.54	0.53	0.564
250	17	0.59	0.54	0.53	0.53	0.52	0.51	0.49	0.527
275	18	0.56	0.51	0.50	0.49	0.48	0.47	0.46	0.495
300	19	0.53	0.48	0.47	0.46	0.46	0.44	0.43	0.466

If $b \neq 100$ cm, apply in the above equation as follows:

$$A_c\ (cm^2) = 100\ (K\ .\ T) \qquad (2.2)$$

Example (2.1):

By using $f_{cu} = 250$ kg/cm^2 and St. 24/35, design the section subject to tensile force of 40 ton in case of:

a) $b = 100$ cm.
b) $b = 25$ cm.

Solution:

a) If $b = 100$ cm

$f_s\,(\text{all}) = 1400$ kg /cm^2, $\qquad f_{cto} = 17$ kg / cm^2

From table: $\qquad K = 0.52$

$t = 0.52 \times 40 = 20.8$ cm take $t = 22$ cm

$$A_s = \frac{T}{f_s} = \frac{40 \times 10^3}{1400} = 28.57 \text{ cm}^2 \text{ choose } 16\ \phi\ 16 \text{ of } A_s = 32.16 \text{ cm}^2$$

Check of stresses:

$$f_{cto}\,(\text{actual}) = \frac{40 \times 10^3}{100 \times 22 + 10 \times 32.16} = 15.86 \text{ kg/cm}^2 < 18 \quad \text{O.K}$$

b) If $b = 25$ cm

$A_c = 100 \times 0.52 \times 40 = 2080$ cm^2

$$t = \frac{A_c}{b} = \frac{2080}{25} = 83.2 \text{ cm} \quad \text{use} \quad t = 85 \text{ cm}$$

$$A_s = \frac{40 \times 10^3}{1400} = 28.57 \text{ cm}^2 \text{ use } 16\ \phi\ 16$$

Check of stresses:

$$f_{cto}\text{ (actual)} = \frac{40 \times 10^3}{25 \times 85 + 10 \times 32.16} = 16.34 \text{ kg/cm}^2 < 17 \quad \text{O.K}$$

2.3. SECTIONS SUBJECT TO SIMPLE BENDING

If the tension side of the section is not facing the water, the section is designed as ordinary reinforced concrete without any precautions. It is preferable to name this section as **(air section).** If the tension side of the section is on the waterside **(water section)**, it must have:

a) Adequate resistance against cracking.
b) Adequate strength.

In order to satisfy condition (a), the section may be designed as plain concrete with the stress

$$f_{ct} = \frac{M}{Z}$$

$$t = \sqrt{\frac{6M}{b \cdot f_{ct}}} \quad \text{.......................... (2.3)}$$

Where: Z is the section modulus, for rectangular section $Z = \frac{I}{Y} = \frac{bt^2}{6}$ and,

M is the working bending moment.

In order to satisfy condition (b) proceed according to normal principles of reinforced concrete design as follows:

I) Using Working Stress Design Method (WSDM):

For the value of t determined according to equation (2.3), calculate the value of k_1 from the relation:

$$d = k_1 \sqrt{\frac{M}{b}} \quad \text{.... ....(2.4)}$$

Where: $d = t - 3$ to 6 cm

For this value of k_1 and the corresponding stress in steel and concrete, determine k_2 then:

$$A_s = \frac{M}{k_2 . d} \quad \text{..........................(2.5)}$$

$$A_s` = \alpha A_s \not< 0.2 A_s \quad \text{.........................(2.6)}$$

II) Using Limit State Design Method (LSDM):

a) $M_u = 1.4\, M$

b) $$d = c_1 \sqrt{\frac{Mu}{f_{cu} . b}} \quad \text{.......................(2.7)}$$

c) Calculate $\frac{c}{d}$ and check it with $\frac{c_{max}}{d}$

d) Choose the maximum diameter of tension steel and fix β_{cr}.
e) Find the factor j from curves or tables.

f) Calculate $A_s = \frac{M_u}{j . \beta_{cr} . f_y . d}$.

g) Calculate $A_s` = \alpha .\, A_s \nless 0.2\, A_s$.

Example (2.2):

Design a water section subject to a working moment equal to 10 m.t with the following data:

a) Use $f_{cu} = 250$ kg/cm^2 and normal mild steel (St. 24/35).
b) $b = 100$ cm.

Solution:

From table: f_{ct} (all) = 17 kg / cm^2 and f_s (all) = 1400 kg / cm^2.

$$t = \sqrt{\frac{6M}{f_{ct} . b}} = \sqrt{\frac{6 \times 10 \times 10^5}{17 \times 100}} = 59.4 \text{ cm} \qquad \text{use} \quad t = 60 \text{ cm}$$

Check of stresses:

$$f_{ct}\,(\text{ actual }) = \frac{M}{I} . y = \frac{6M}{bt^2} = \frac{6 \times 10 \times 10^5}{100 \times (60)^2} = 16.67 \ \text{kg / cm}^2 < 17 \ \text{O.K}$$

I) To find A_s by using WSDM:

$$d = k_1\sqrt{\frac{M}{b}}$$

$$56 = k_1\sqrt{\frac{10\times10^5}{100}} \qquad \therefore\ k_1 = 0.56$$

From curves: $f_c = 28\ kg/cm^2 < f_c\,(all)$ O.K

$k_2 = 1290$ & $\alpha = 0.2$

$$A_s = \frac{M}{k_2.d} = \frac{10\times10^5}{1290\times56} = 13.84\ cm^2 \text{ use } 7\ \phi\ 16$$

$$A_s` = 0.2\times13.84 = 2.76\ cm^2 \text{ use } 6\ \phi\ 8$$

If the designer choose ϕ 19 for the tension steel, he must recalculate A_s as follows:

Use $f_s\,(all) = 1200\ kg/cm^2$ and from curves:

$f_c = 28\ Kg/cm^2 < f_c\,(all)$

$k_2 = 1100$ & $\alpha = 0.2$

$$A_s = \frac{10\times10^5}{1100\times56} = 16.23\ cm^2\text{, use } 6\ \phi\ 19$$

$$A_s` = 0.2\times16.23 = 3.24\ cm^2\text{, use } 7\ \phi\ 8$$

II) To find As by using LSDM:

$M_u = 10\times1.4 = 14$ m.t

$$56 = c_1\sqrt{\frac{14\times10^5}{250\times100}} \qquad \text{then } c_1 = 7.48$$

$$\frac{c}{d} = 0.125 < \frac{c_{max}}{d}$$

From curve: $j = 0.826$

$$A_s = \frac{M_u}{j.\beta_{cr}.f_y.d} = \frac{14\times10^5}{0.826\times2400\times56} = 12.61\ \text{cm}^2\text{ , use } 7\ \phi\ 16\text{ m}$$

If ϕ 19 used:

$$A_s = \frac{14\times10^5}{0.826\times0.84\times2400\times56} = 15.01\ \text{cm}^2\text{ , use } 6\ \phi\ 19$$

$A_s` = 0.2 \times 15.01 = 3.00\ \text{cm}^2$, use 6 ϕ 8

2.4: SECTIONS SUBJECT TO ECCENTRIC TENSION OR COMPRESSION

If the resultant stress on the liquid side is compression, the section is to be designed as ordinary reinforced concrete. But if the resultant stress on the liquid side is tension, the section must have:

a) Adequate resistance to cracking.
b) Adequate strength.

To satisfy condition (a), the section may be designed as plain concrete such that:

$$\frac{M}{Z} \pm \frac{N}{A} \leq f_{ct}$$

For rectangular sections:

$$\frac{6M}{bt^2} \pm \frac{N}{bt} \leq f_{ct}$$

As a good approximation take:

$$t = \sqrt{\frac{6M}{f_{ct}.b}} \quad \pm\ 2\ \text{to}\ 4\ \text{cm}$$

Positive sign is for eccentric tension and negative sign for eccentric compression. The amount of increase or decrease depends on the magnitude of N in proportion to M.

To satisfy condition (b), calculate the area of steel reinforcement required for the section as an ordinary reinforced concrete section.

Example (2.3):

Design a rectangular section of b = 100 cm and subject to $M = 8$ m.t, $N = 12$ ton (tension) with a tension stresses on liquid side. Use $f_{cu} = 300$ kg /cm^2 and $f_y = 3600$ kg /cm^2?

Solution:

Assume f_{ct} (all) = 20 kg/cm^2

$$t = \sqrt{\frac{6 \times 8 \times 10^5}{20 \times 100}} = 48.9 \text{ cm} \quad \text{use} \quad t = 54 \text{ cm}$$

Check of stresses:

$$f_{ct}(N) = \frac{12 \times 10^3}{100 \times 54} = 2.22 \text{ kg/cm}^2$$

$$f_{ct}(M) = \frac{6 \times 8 \times 10^5}{100 \times (54)^2} = 16.46 \text{ kg/cm}^2$$

$$f_{ct}(\text{actual}) = 2.22 + 16.46 = 18.68 \text{ kg/cm}^2$$

$$tv = t\left\{1 + \frac{f_{ct}(N)}{fct(M)}\right\} = 54\left\{1 + \frac{2.22}{16.46}\right\} = 61.3 \text{ cm}$$

$\therefore f_{ct}$ (all) = 20 kg/cm^2

f_{ct} (actual) < f_{ct} (all) O.K

I) To find As by using WSDM:

$$e = \frac{M}{N} = \frac{8}{12} = 0.667 \text{ m}$$

$$e_s = e - \frac{t}{2} + c = 0.667 - \frac{0.54}{2} + 0.04 = 0.437 \text{ m}$$

$e > \frac{t}{2}$ $\therefore$ big eccentricity

$M_s = N.\ e_s = 12 \times 0.437 = 5.244$ m . t

$$k_1 = \frac{50}{\sqrt{\frac{5.244 \times 10^5}{100}}} = 0.69$$

From curves for $f_s = 1600$ kg/cm^2:

$f_c = 25$ kg/cm^2 < 105 O.K

$k_2 = 1498$, $\alpha = 0.2$

$$A_s = \frac{M_s}{k_2.d} + \frac{N}{f_s} = \frac{5.244\times10^5}{1498\times50} + \frac{12\times10^3}{1600}$$

$A_s = 14.5$ cm^2 use 8 ϕ 16

$$A_s` = 0.2 \times \frac{5.244 \times 10^3}{1498 \times 50} = 1.4 \text{ cm}^2 \text{ use } 5\ \phi\ 8$$

II) To find A_s by using LSDM:

$M_u = 1.4 \times 8.0 = 11.2$ m.t.

$N_u = 1.4 \times 12 = 16.8$ m.t.

$$e = \frac{M_u}{N_u} = \frac{11.2}{16.8} = 0.667 \text{ m} > t/2 \qquad (\text{ big ecc. })$$

$$e_s = e - \frac{t}{2} + c = 0.667 - \frac{0.54}{2} + 0.04 = 0.437 \text{ m}$$

$M_{su} = N_u\ .\ e_s = 16.8 \times 0.437 = 7.34$ m.t.

$$d = c_1 \sqrt{\frac{M_{su}}{f_{cu}.b}}$$

$$50 = c_1 \sqrt{\frac{7.34 \times 10^5}{300 \times 100}}$$

$c_1 = 10.11 \rightarrow \frac{c}{d} = 0.125 < \frac{c_{max}}{d}$ O.K

From curves: $j = 0.826$

$$A_s = \frac{M_{su}}{j.\beta_{cr}.f_y.d} + \frac{N_u.\gamma_s}{\beta_{cr}.f_y}$$

$$A_s = \frac{7.34 \times 10^5}{0.826 \times 0.75 \times 3600 \times 50} + \frac{16.8 \times 10^3 \times 1.15}{0.75 \times 3600}$$

$$= 6.58 + 7.15 = 13.74 \text{ cm}^2 \text{ use } 7\ \phi\ 16$$

$$A_s` = 0.2 \times 6.58 = 1.32 \text{ cm}^2 \text{ use } 5\ \phi\ 8$$

Example (2.4):

Redesign example (2.3) if the normal force is compression?

Solution:

Assume $f_{ct} = 20$ kg/cm^2

$$t = \sqrt{\frac{6 \times 8 \times 10^5}{20 \times 100}} = 48.9 \text{ cm}^2 \quad \text{use} \quad t = 45 \text{ cm}$$

Check of stresses:

$$f_{ct}(N) = -\frac{12 \times 10^3}{100 \times 45} = -2.67 \text{ kg/cm}^2$$

$$f_{ct}(M) = \frac{6 \times 8 \times 10^5}{100 \times (45)^2} = 23.7 \text{ kg/cm}^2$$

$$f_{ct}(\text{ actual }) = 23.7 - 2.67 = 21.03 \text{ kg/cm}^2$$

$$tv = 45\left\{1 - \frac{2.67}{23.7}\right\} = 39.9 \text{ cm}$$

From tables: f_{ct} (all) $= 21$ kg/cm^2

f_{ct} (actual) $= f_{ct}$ (all) O.K

I) To find A_s by using WSDM:

$$e = \frac{8}{12} = 0.667\ m$$

$$e_s = e + \frac{t}{2} - c = 0.667 + \frac{0.45}{2} - 0.04 = 0.852 \text{ m}$$

$$\frac{e_s}{d} = \frac{0.852}{0.41} = 2.08 > 1.5 \quad \text{(big ecc.)}.$$

$$M_s = 12 \times 0.852 = 10.224 \text{ m.t.}$$

$$d = k_1 \sqrt{\frac{M_s}{b}}$$

$$41 = k_1 \sqrt{\frac{10.224 \times 10^5}{100}} \qquad \therefore\ k_1 = 0.405$$

From curve for $f_s = 1600$ kg/cm^2

$f_c = 42$ kg / cm^2 < 105 O.K

$k_2 = 1445$ & $\alpha = 0.2$

$$A_s = \frac{10.224 \times 10^5}{1445 \times 41} - \frac{12 \times 10^3}{1600} = 9.76 \text{ cm}^2 \ (5\ \phi\ 16)$$

$$A_s` = \frac{0.2 \times 10.224 \times 10^5}{1445 \times 41} = 4.1 \text{ cm}^2 \ (6\ \phi\ 10)$$

II) To find A_s by using LSDM:

$M_u = 1.4 \times 8 = 11.2$ m.t.

$N_u = 1.4 \times 12 = 16.8$ ton (compression)

To satisfy if the section is big or small eccentricity the interaction diagram is used:

$$\frac{N_u}{f_{cu}.b.t} = \frac{16.8 \times 10^3}{300 \times 100 \times 45} = 0.012 < 0.04 \qquad \therefore \text{ big ecc.}$$

$$e = \frac{M_u}{N_u} = \frac{11.2}{16.8} = 0.667 \text{ m}$$

$$e_s = 0.667 + \frac{0.45}{2} - 0.04 = 0.852 \text{ m}$$

$M_{su} = N_u \,.\, e_s = 16.8 \times 0.852 = 14.31$ m.t

$$d = c_1 \sqrt{\frac{M_{su}}{f_{cu}.b}}$$

$$41 = c_1 \sqrt{\frac{14.31 \times 10^5}{300 \times 100}} \qquad c_1 = 5.94$$

From curve: $\frac{c}{d} < 0.125$, and $j = 0.826$

$$A_s = \frac{14.31 \times 10^5}{0.826 \times 0.75 \times 3600 \times 41} - \frac{16.8 \times 10^3 \times 1.15}{0.75 \times 3600}$$

$A_s = 15.65 - 7.16 = 8.49$ cm^2 (5 ϕ 16)

$A_s` = 0.2 \times 15.65 = 3.13$ cm^2 (5 ϕ 10)