LIMIT STATE DESIGN OF REINFORCED CONCRETE STRUCTURES

DR. KHALID MAHMOOD

BSc Engg ; PhD (NSW) ; MIE (Pakistan)
Assistant Professor of Civil Engineering
Engineering University,
LAHORE

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SYNOPSIS

In this paper the design methods of British Standard Code of Practice CP 114 and the American Standard ACI 318-63 are briefly reviewed to explain their inadequacies. Further, an object of structural design is outlined and the limit state design of reinforced concrete structures presented and discussed alongwith the safety provisions of revised standards CP 110 and ACI 318-71.

INTRODUCTION

In this country the structural engineers and architects are faced with the problem that they do not have a 'Pakistani code of practice' for designing reinforced concrete structures. Although some work is being done on this aspect by the Pakistan Standards Institution, it has not yet arrived at any conclusive stage. Consequently, most of concrete structures are normally designed by adopting British or American standards.

In the past few years considerable improvements have taken place in our understanding of structural concrete and been incorporated in the revised codes of practice. The British Standard CP 110, Code of Practice for the Structural Use of Concrete (Ref. 1), has superseded the British Standard Codes of Practice CP 114, for reinforced concrete (Ref. 2). CP 115 for prestressed concrete (Ref. 3) and CP 116, for precast concrete (Ref. 4). Similarily, in America the ACI Standard ACI 318-71 (Ref. 5), has replaced the previous standard ACI 318-63 (Ref. 6). One major aspect of the revised codes is the limit state approach for designing reinforced concrete structures.

The object of this paper is to outline and discuss the fundamentals of limit state design and safety provisions of CP 110 and ACI 318-71.

REVIEW OF CP 114 AND ACI 318-63 METHODS

The British Code of Practice CP 114 and ACI standard ACI 318-63 provided the use of one of the following two methods for the design of individual structural members *i.e.*, beams, columns, slabs and walls etc.

(*i*) Permissible stress method (CP 114), referred to as working stress method in ACI 318-63, or

(*ii*) Lead factor method (CP 114), indicated as ultimate strength method in ACI 318-63.

In permissible stress approach, allowable stresses are established as some fraction of the strength capacities of the materials *i.e.*, the yield strength of steel and the crushing strength of concrete. Using a triangular stress distribution for concrete the members are then proportioned so that these allowable stresses are not exceeded when working loads are applied.

In the load factor method, members are designed so that the full strength (ultimate strength) of the cross-sections is just utilized when the ultimate loads are applied. The ultimate loads are obtained by multiplying the working loads by appropriate load factors or overload factors. CP 114 suggests the same values of load factors for dead load and imposed (live) load, while ACI 318-63 permits different factors for dead load, imposed load, and wind load in various combinations. The ultimate strength of the member section is determined taking into account the non-linear compressive stress distribution in concrete, which exists before a member fails.

In both of these methods, the forces and moments acting on individual members are calculated from elastic analysis of idealized structure.

Elastic analysis combined with permissible stress approach gives a realistic represntation of conditions in members and the structure at working loads. However, permissible stress method can give no information in respect of the strength capacity and the actual factor of safety of a member or that of a structure as a whole.

Load factor or ultimate strength methods give accurate prediction of strength capacities and the actual factor of safety against failure of members. However, these methods give little information about the service load behaviour of the members. With the development of high strength materials that may provide depths of sections less than those used in the past, it is important to give attention to condition (deflection, crack widths) at service loads.

OBJECT OF STRUCTURAL DESIGN

The permissible stress and ultimate strength methods have served their purpose over the years. However, the engineers have always realized the shortcomings of these methods and been on the outlook for improvements in the process of design.

The purpose of design may be stated as the provision of a safe and economical structure complying with the clients requirements (Ref 7). In other words the process of design should ensure a balance between total cost of the structure and an acceptable probability of the structure becoming unserviceable during its life. Limit state design is based on this philosophy. It recognizes the need to provide a safe and efficient structure at an economical price. Simultaneously, it gives clear idea of actual factors of safety used to take into account elements of uncertainty and ignorance.

The idea of limit state design was formulated in Russia in 1930's and has been the basis of Russian code for reinforced concrete structures since 1955 (Ref. 8). In 1963, it formed the basis of Recommendations for an International Code of Practice for Reinforced Concrete, published by the European Concrete Committee (CEB) (Ref. 9). Investigations in United Kingdom and Australia have shown that the adoption of such design methods could permit savings of upto 40 percent in the cost of bridges (Ref. 10).

The new British Code of Practice CP 110 for structural concrete is also based on limit state philosophy. The new ACI Standard ACI 318-71 does not mention the term limit state design specifically, but its provisions are based on the same approach.

PHILOSOPHY OF LIMIT STATE DESIGN

Limit state design takes account of the variations and uncertainties that may occur in the design and construction of structures. Some of the important items of variation and uncertainty are listed in Table 1. Different safety factors are provided for those variations in design and construction. Safety and serviceability are expressed in terms of the probability that the structure will not become unfit for its intended purpose during its life. Limit state or unfitness for use may arise in various ways, the principal ones being as follows (Ref. 12) :

(*i*) Ultimate limit states : the usual collapse limit states including collapse due to fire, explosive pressure etc.,

(*ii*) Serviceability limit state : local damage and deflection limit states, durability, viberation, fire penetration and heat transmission etc.

Limits states of collapse may be defined as occurring when a part or the whole of the structure fails under extreme loads. It may be due to rupture of one or more critical sections, loss of overall stability or buckling owing to elastic or plastic instability.

Limit states due to local damage may occur, when cracking or spalling of concrete impairs the appearance or usefulness of the structure or adversely affects finishes, partitions etc. For example, a check on the limit state of crack width may be necessary in water retaining structures or structures situated in severe environments. Similarly, it may be necessary to check the limit state of crack formation in compression to ensure that no initial microcracking, which could be harmful to the durability of the member, is produced at any stage of construction in zones subject to high compressive stresses.

Limit states of deflection or deformation may be defined as occurring when it becomes excessive to impair the appearance or usefulness of the structure and may cause discomfort to users.

In certain cases limit states of other effects such as viberation, fatigue, impact, durability of fire damage may also have to be considered. For example, the limit states design of bridges requires the investigation of limit states of viberation and fatigue in addition to collapse, cracking and deflection (Ref. 10). Similarly, the consideration of limit states of impact resistance is essential for structures which may be subjected to impact, explosions or earthquakes.

The usual approach is to design the structure on the basis of limit states for collapse and then check that the criteria governing remaining limit states are satisfied.

The limit state af collapse under extreme loads is investigated by ultimate strength theory of reinforced concrete, while the limit states of deflection and local damage both utilize the elastic theory (Ref. 12).

SAFETY PROVISIONS IN CP 110

In CP 110, safety of reinforced concrete structures is achieved by considering all possible uncertainties and variations in loads and materials strength and other sources of error listed in Table 1. A semiprobabilistic approach is used for determination of the structural safety.

The main parameter for the strength of a material is the "characteristic strength σ_k" with a 95 percent reliability, that is probability of obtaining a lower strength should be 5 percent or less.

The "design strength σ^*" is then determined by dividing the characteristic strength σ_k by a partial safety factor γ_m (strength reduction factor).

Thus $\sigma^* = \sigma_k/\gamma_m$

The code specifies different values of γ_m for steel and concrete for different limit states (Table 2). γ_m for steel takes account of the difference between assumed cross-sectional areas of steel and actual as affected by rolling tolerances or bad storage condition causing corrosion. The safety factor γ_m for concrete takes care of the difference between the strength of the test specimen and the strength in actual structure which is influenced by accidental errors in cement or water content, by poor compaction or inadequate curing.

A lesser value of γ_m is used for steel than for concrete, since a better quality control is used in the manufacture of steel and therefore less variations in its strength are possible.

The "design load W**" for which a structure is proportioned is determined by multiplying the "characteristic load W_k" by a partial safety factor γ_1 (load factor).

At present sufficient data is not available to define W_k for all types of loading. CP 110 recommends the use of working loads given in British Standard CP 3 for the characteristic loads.

The safety factor γ_1 takes account of the sources of error related to design of structures (Table 1). Different values of γ_1 are recommended for live load, dead load and wind load in various combinations and for different limit states (Table 2). A greater factor is recommended for live load than for dead load, since dead load can be determined with reasonable accuracy whereas live load is often more uncertain and subject to change during the life of a structure.

SAFETY PROVISIONS IN ACI 318-71

Safety provisions in ACI 318-71 correspond closely with those of CP 110. The margin of safety is provided in two ways. First the applied loads are multiplied by load factors to take account of excess load effects and simplified assumptions in structural analysis. Secondly, the theoretical capacity of the structnral members is reduced by capacity reduction factors ϕ. Table 3 gives the values of load factors and capacity reduction factors for collapse load analysis. To check the servive-ability requirements, the code specifies load factors and strength reduction factors equal to unity.

Tables 2 and 3 show that the values of load factors for various load combinations given in ACI 318-71 lie close to those of CP 110.

The strength reduction factor ϕ provides for the strength variations, workmanship and dimensions as well as the degree of ductility, the importance of the member and the accuracy with which the strength of the member can be evaluated.

Columns have lower ϕ factors than beams, since a beam may not support as large a loaded area as a column. Further, the failure of a column can be sudden and catastrophic, while a beam failure normally is preceded by cracking and increased deflection.

Spirally reinforced concrete columns are more ductile than non-spirally reinforced concrete columns, the ϕ factor for the former is greater than for the later. Bearing at 0.70 is also consistant with the value for the nonspirally reinforced columns (Ref. 11).

The value of 0.85 assigned for shear and torsion recognizes the need to guard againt "brittle failure" and therefore has a value lower than the 0.90. recommended for bending. Bending in concrete is so seldom a determining factor that a value that is reasonnble and not too conservative was selected at 0.65 (Ref. 11).

CONCLUSIONS

1. Limit state method is a rational approach for accurate, safe and economical design of reinforced concrete structures. It is therefore suggested that this approach may be adopted in Pakistan.

2. The design method is based on investigating different limit states and providing an acceptable probability so that the structure does not reach a limit state throughout its useful life.

3. By assigning different safety factors, limit states design takes account of the variations and uncertainties likely to occur in the design construction of structures.

4. CP 110 and ACI 318-71 introduce two safety factors ; one applied to loads and the other to the material strength. The main reason for adopting two safety factors instead of one "global" factor is to enable the uncertainties in assessing loads and their influence on the structure to be considered separately in design from the uncertainties associated with the performance of the materials of construction. It will also be easier to incorporate amendments to the codes as new knowledge becomes available with regard to variations in loads and strengths.

5. The safety provisions of CP 110 and ACI 318-71 closely relate to each other.

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TABLE 1 — SOURCES OF ERROR (Ref. 11)

Design related	Construction related
Actual loads varying from assumed.	Actual layout varying from plans.
Future loads exceeding assumption.	Size of members "as built" varying from drawings.
Approximations in analytical methods.	Number, size and placement of bars differing from those called for.
Unrecognized continuities, restraints, plastic regions, etc.	Field addition of holes, inserts, pipes, conduits, etc.
Imprecisions in taking dimensions from priliminary plans.	Actual strength of materials lower than specified.
Use of oversize members for standardization.	How well do tests of materials measure strength of structure ?
Imprecise calculation, rounding off etc.	Damage to materials or members during construction, heat, rain, freezing.
Possible three-dimensional action of completed structure as compared with planar assumption.	Abuse of building during construction, overloading, impact, etc.
Failure to include some possible loadings.	Inclusion of sawdust, debris, etc., in concrete.
(Gross Errors)	(Gross Errors)

TABLE 2 — SAFETY FACTORS OF CP 110

Limit states and load combination	Partial safety factors		
	Load factors (γ_1)	Strength reduction factors (γ_m) Steel	Concrete
Collapse			
I Dead and imposed	$1.4\ W_d + 1.6\ W_i$	1.5	1.5
II Dead and wind*	$0.9\ W_d + 1.4\ W_w$	,,	,,
III Dead, imposed and wind	$1.2\ W_d + 1.2\ W_i + 1.2\ W_w$	,,	,,
Deflection			
I Dead and imposed	$1.0(W_d + W)_i)$	1.0	1.0
II Dead and wind	$1.0(W_d + W_w)$	,,	2
III Dead, imposed and wind	$1.0\ W_d + 0.8(W_i + W_w)$	,,	,,
Local Damage	As for deflection	1.0	1.3

*** A critical stability condition may result if, on the selected parts of the structure, the dead load is increased to 1.4 W_d; in these circumstances higher figure for dead load should be adopted.**

TABLE 3 — SAFETY FACTORS OF ACI 318-71

Load factors	Capacity reduction factors (ϕ)	
1 Dead and imposd (live) $U = 1.4\ W_d + 1.7\ W_i$	Bending, without axial tension	0.90
II Dead and wind $U = 0.9\ W_d + 1.3\ W_w$	Axial compression with or without bending	
	Spirally rainforced	0.75
	Otherwise reinforced	0.70
III Dead, imposed wind $U = 0.75(1.4W_d + 1.7W_i + 1.7\ W_w)$	Shear and torsion	0.85
	Bearing on concrete	0.70
	Bending in plain concrete	0.65