PERFORMANCE-BASED DESIGN OF CONCRETE STRUCTURES
― JSCE STANDARD SPECIFICATIONS FOR CONCRETE STRUCTURES ON STRUCTURAL PERFORMANCE VERIFICATION ―

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SUMMARY

The worldwide trend for structural design is shifting from the conventional prescriptive specified design format to the performance-based design format. The JSCE Standard Specifications for Concrete Structures started to embrace the performance-based design in 1995, which was almost completed in their 2002 versions. This paper outlines the present state of structural design of concrete structures focusing on the verification of safety and serviceability as per the JSCE Standard Specifications for Concrete Structures.

Keywords*: Performance-based design, concrete structure, JSCE Standard Specification; safety, serviceability, fatigue.*

INTRODUCTION

This paper briefly introduces the general procedures of structural design of reinforced concrete and prestressed concrete structures as per the JSCE Standard Specifications for Concrete Structures-2002, Structural Performance Verification. The Concrete Committee of JSCE has been actively conducting extensive research and investigation in Japan since its establishment in 1928. The committee considers the preparation and revision of the JSCE Standard Specifications for Concrete Structures as the most important task. The JSCE Standard Specifications are held in high regard by practicing engineers and have not only served as model codes for design, construction, and maintenance of concrete structures but also have been a major driving force in the development of new technologies.

Meeting the change in design format worldwide (ISO, 1998), the JSCE Standard Specifications were shifted from the specification-based format to performance-based format in 1995. The present version published in 2002 introduces many new concepts and methods for the first time in the world. This is a clear indication of the high level of competence and technology available in the country though various issues are still not completely understood and need further investigation. The JSCE Standard Specifications are nominated in ISO

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19338 (2003) as performance-based design codes deemed to satisfy the requirements in performance-based design standard.

In the JSCE Standard Specifications, the following three performance requirements are considered: safety, serviceability, and restorability. Since restorability can be taken particularly at the verification against earthquake actions, the restorability is referred to in the Standard Specifications-2002, Seismic Performance Verification. The general procedure for verifying mechanical performance of concrete structures is given in the JSCE Standard Specifications for Structural Performance Verification (hereinafter called “the Specification”). The performance of concrete structures varies over time due to environmental conditions and other factors. The examination on whether such change is in acceptable range is described in the JSCE Standard Specifications for Materials and Construction. Once the construction is completed, it is difficult to repair, strengthen, or renovate concrete structure; therefore, thorough investigation at the beginning stage of design, accurate prediction for possible problem in service life and future maintenance are of great importance. As recommended verification methods, those with the limit state design methodology are provided; ultimate limit states and fatigue limit state for safety and serviceability limit states.

Table 1 lists the table of contents of the Specification.

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SCOPE

Figure 1 gives a schematic representation of the various steps – design, construction planning, fabrication and erection, construction in practice, and maintenance – involved in the construction and management of concrete structures. At each stage, the work is carried out in a manner that all requirements specified in any upstream stage have to be satisfied.

The Specification provides the standard method of verification for safety and serviceability of structures in the design stage of all concrete structures, including those made with plain and reinforced concrete, prestressed concrete and steel-concrete composites, as well as the structural details as the prerequisite of verification. In cases where adequate structural performance can be confirmed using prototype experiments assuming design loads, scaled model experiments, or numerical analyses of which accuracy and applicability have been already ensured, the procedure for verification of structural performance as specified in the

Specification may not be followed.

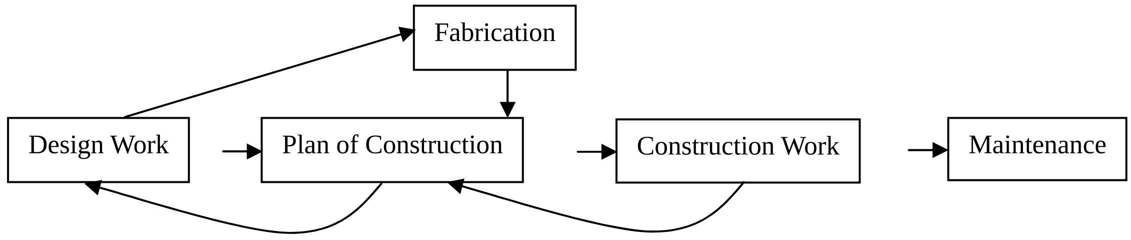

Figure 1 Flow of work

BASIS OF DESIGN

General

At the stage of design of the structure, the following issues are to be determined with due consideration of overall economy.

a) structural details including the shapes and sizes of members,
b) details of reinforcement,
c) specifications of concrete and reinforcement to be used,
d) construction method – cast-in-place or precast, and
e) maintenance method

Throughout the design life of the structure, appropriate steps are taken to ensure that the performance requirements are satisfied in respect to safety and serviceability. The other requirements such as environmental suitability, aesthetics, etc. may be taken into account. Verification methods for the structural characteristics are described in the Specification.

Design Life

For design of a structure, it is necessary to indicate the design life with wide consideration to the purpose of the structure, economically determined period over which the structure is required to be in service, environmental conditions in the neighborhood of the structure, and demanded durability of the structure. In general, the longer design life is specified, the higher durability and fatigue resistance performance will be required.

Prerequisite of Verification

The methods of performance verification described in the Specification are based on mechanics of structures and materials, which generally have some conditions such as deformational consistency of concrete and reinforcement and local states of stresses. Thus, general requirements for structural detailing are specified to realize these assumptions. Otherwise, accuracy of the verification reduces and scope for application is restricted.

For the verification of safety and serviceability of a structure, variation of performance over time during the design life of the structure should be considered. Therefore, it is necessary to assume safety margin by estimating possible deviation of member dimensions, accuracy of bar arrangement and varying mechanical properties of materials.

Principles of Verification

In principle, performance verification of a structure is carried out in such a way that limit states according to performance requirements of the structure are determined in regard to the entire structure or each constituent member during construction and design life, and that the structure or structural member with the structural details such as shape, size, bar arrangement is examined not to reach the limit state. The limit states are classified into the ultimate limit state, serviceability limit state, and fatigue limit state. The examination at the limit states should be carried out using the characteristic values of material strengths and loads and the safety factors.

As a principle of the Specification, performance requirements of a structure should be set clearly at first. Thereafter, an equivalent limit state corresponding to each requirement should be specified. When a structure or a part of it reaches a certain limit state, its serviceability may suddenly lose or it may even reach failure in some cases. Then, the structure cannot hold its function nor meet the requirements because of various defects. In such cases, performance verification of the structure may be done by examining the limit states. In setting a limit state, an index representing the state of a structure, member or material should be selected, and then a limit value set in accordance with the required performance. Verification is done by examining if a calculated response under given actions exceeds the limit values or not. The limit values should be set taking into account reliability of the analysis method and the model employed in calculating the response value. In the case that a total structural system is not simple, consisting of several structures, a process with a possibility that the structural system does not meet the requirements is selected. Required performance is set for each constituent structure, and thereafter, limit state may be set for each element in each structure.

The ultimate limit state is associated with the load carrying capacity of the structure or member. An examination for the failure of the member should be carried out by comparing the member force and its capacity by selecting appropriate cross sections. The serviceability limit state is associated with normal use or durability of the structure. The fatigue limit state is associated with the fatigue failure of the structure or member subjected to repeated loads. Although the fatigue limit state is somewhere included in the ultimate limit state, the Specification defines separately.

Safety Factors

Five partial safety factors are introduced including material factor, γ_m, load factor, γ_f, structural analysis factor, γ_a, member factor, γ_b, and structure factor, γ_i. Material factor, γ_m is determined considering the unfavorable deviations of material strengths from the characteristic values, the differences of material properties between test specimens and actual structures, effects of material properties on the specific limit states, and time dependent variations of material properties. Load factor, γ_f is determined considering unfavorable deviations of loads from the characteristic values, uncertainty in evaluation of loads, effect of nature of loads on the limit states, and variations of environmental actions. Structural analysis factor, γ_a is determined considering the uncertainty of computational accuracy in determination of member forces through structural analysis. Member factors, γ_b is determined considering the uncertainties in computation of capacities of members, seriousness of dimensional error of members, and the importance of members on the entire structure when the member reaches a certain limit state. The value of the member factor is determined corresponding to each equation for member capacities. Structural factor, γ_i is determined considering the importance of the structure, as determined by the social impact when the structure would reach the limit state.

The value of safety factors should be given for each limit state, and they are not necessarily the same for different limit states. Although each safety factor covers the uncertainty of individual event separately, the influence of each factor may be considered collectively. The standard values for safety factors that may be used when verifying durability and applying the inspection system in accordance with the JSCE Standard Specifications for Materials and Construction are listed in Table 2.

Table 2 Standard values for safety factors

	Material factor, γ_m		Member factor, γ_b	Structural analysis factor, γ_a	Load factor, γ_f	Structure factor, γ_i
	concrete, γ_c	steel, γ_s				
Ultimate limit state	1.3	1.0 or 1.05	1.1 ~ 1.3	1.0	1.0 ~ 1.2	1.0 ~ 1.2
Serviceability limit state	1.0	1.0	1.0	1.0	1.0	1.0
Fatigue limit state	1.3	1.05	1.1 ~ 1.1	1.0	1.0	1.0 ~ 1.1

DESIGN VALUE FOR MATERIALS

Quality of concrete or steel is represented by not only compressive or tensile strength but also other material properties such as other strengths, modulus of elasticity or deformation characteristics, thermal characteristics, durability and water tightness. The characteristic value for material strength, f_k is determined taking into account the variation in tested values, such that most of the tested values exceed this characteristic value. The design strength of material, f_d is obtained by dividing the characteristic value for material strength, f_k by a material factor, γ_m. When a specified value for material strength, f_n is determined independently from its characteristic value, the value of f_k is obtained by multiplying the specified value by a material modification factor, ρ_m.

Various types of concrete are used in concrete structures. Appropriate type and quality of the concrete are necessary to be applied for concrete used in structures or members, in consideration of its purpose for use, environmental condition, design life, construction condition and so on. Reinforcing bars, prestressing steel and rolled sections of structural steel used in composite steel-concrete construction are the different steels used in concrete structures. In accordance with needs in structural performance verification, quality of concrete is represented by not only compressive strength but also quantities for various material properties. Material properties can be classified into mechanical properties, such as strength and deformation characteristics, physical properties, chemical properties, and so on. Strength characteristics are expressed by strengths under static and fatigue loadings in compression, tension, bond, etc. Deformation characteristics are expressed by time-independent quantities such as modulus of elasticity and Poisson's ratio, and time-dependent quantities such as creep coefficient and shrinkage strain.

Durability of concrete is considered to be its resistance to time-dependent deterioration resulting from various actions, such as weather, intrusion of chemicals and erosion by chemicals. For the durability of reinforced concrete, resistance to corrosion of reinforcing steel over time is an additional concern. In regard to steel corrosion, durability performance verification has been carried out using the resistance to carbonation and chloride ion intrusion of concrete as indices.

Verification for safety of reinforced concrete may generally be carried out by assuming concrete to be a completely brittle material under tension. However, since performance verification for members, in which the occurrence and propagation of cracking governs, cannot be carried out in a rational manner, it may be necessary to take into consideration a fracture process zone at the crack tip where micro cracks accumulate. In a fracture process zone, which is located between the elastic zone having no cracks and the completely cracked portion, the transferred tensile stress decreases as the crack width; that is, the total width of minute cracks in the zone, increases. This is the so-called tension softening. A tension softening curve expresses the relationship between the transferred stress and the crack width, and the area below the curve corresponds to the fracture energy, which is equal to the energy required to form a unit area of completely opened crack. It is reported that by incorporating the tension softening properties in analysis, the fracture phenomenon in concrete associated with propagation of cracks can be understood, and the size effect in the apparent strength of members can be rationally explained.

An idealized curve given in Figure 2 may be used for the tension softening part. For tension softening properties of concrete, fracture energy, G_F (N/m) for normal concrete may be obtained using Equation 1.

$$G_F = 10(d_{max})^{1/3} f'^{1/3}_{ck} \quad (1)$$

where, d_{max}: maximum size of aggregate (mm)
f'_{ck}: characteristic compressive strength (N/mm^2)

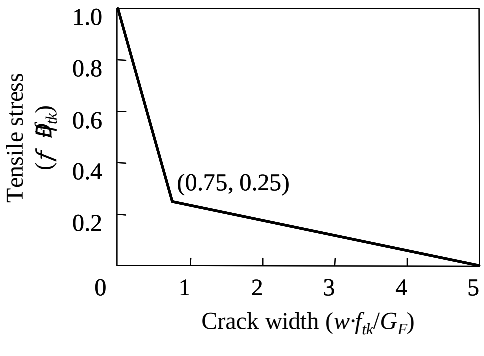

Figure 2 Tension softening curve

LOAD

Structures should be designed for appropriate combinations of loads likely to act during the construction stage and design life of the structure according to the limit states being considered. Design loads are obtained by multiplying a characteristic value of load by appropriate load factor. Combinations of design loads are determined according to the limit states as shown in Table 3.

Permanent loads act continuously on the structure of which variation is rare and in magnitude is negligible compared to the average magnitude. Dead load, load produced by prestressing, shrinkage and creep of concrete, earth pressure, and water pressure should, in principle, be considered as permanent loads. Variable load is the load that varies frequently or continuously and is such that the variations in the magnitude cannot be neglected compared to the average load. Load having varied value such as temperature, wind and snow is considered as variable loads. Accidental load rarely during the design life, but has serious consequences when it occurs. The accidental loads include earthquake, collision, the effect of strong wind, and so on.

Appropriate combinations of loads are selected from permanent load, main variable load, subsidiary variable load, and accidental load according to the limit states to be considered during construction and during the design life of the structure.

Table 3 Combinations of design loads

Limit state	Combination to be considered
Ultimate limit state	Permanent load + main variable load + subsidiary variable load
	Permanent load + accidental load + subsidiary variable load
Serviceability limit state	Permanent load + variable load
Fatigue limit state	Permanent load + variable load

STRUCTURAL ANALYSIS

Appropriate tools for analysis are used in consideration of factors such as the geometry of structures, support conditions, states of loads and the limit states to be examined. Appropriate structural analysis using reliable and accurate models is carried out by using these tools to calculate response values such as member forces, deflection and crack width under design loads. Structures may be analyzed assuming them to be made of simplified elements such as slabs, beams, frames, arches, shells and their combinations. Loads may be modeled in a manner to give equivalent loads to be on the safe side. In the process, load distributions may be simplified or dynamic loads may be replaced by static loads conservatively.

Member forces such as flexural moment, shear force, axial force and torsional moment corresponding to the limit states, are computed based on appropriate analytical theories. Moment of inertia for the member computed on the basis of the gross cross section, neglecting the presence of reinforcing bars, may be used for linear analysis of structures or to estimate the natural period of a structure. Linear analysis may be used for computing member forces for ultimate limit state and serviceability limit state.

STRUCTURAL PERFORMANCE VERIFICATION

Verification for Safety

General

Safety of structure is maintained as long as it or its members do not fail. In the case of a statically highly indeterminate structure, its safety may not be immediately lost even when some of the members reach the ultimate limit state and become incapable of carrying load. In cases where partial failure of members is permitted but the overall safety of the structure still needs to be maintained even after partial failure of some of the members, the nonlinear and the post-failure behavior of members should be appropriately taken into consideration at the time of safety verification as in seismic performance verification.

Basis of verification

It is to be verified that the concrete structure meets the required safety performance during its design life. Safety of a structure is verified by confirming that (a) the ultimate limit state for failure of cross section for any of the members, and, (b) the ultimate limit state for rigid body stability for the structure, is not reached.

Examination of the ultimate limit state for failure of cross section is carried out by confirming that Equation 2 is satisfied; that is, the value obtained by multiplying the ratio of design member force, S_d to design capacity of member cross section, R_d by structure factor γ_i is not greater than 1.0.

$$\gamma_i \, S_d \, / \, R_d \leq 1.0 \qquad (2)$$

The design capacity of cross section, R_d can be obtained from Equation 3, by dividing computed member capacity (considering its cross section, design strength of materials, f_d, etc.), $R(f_d)$ by member factor, γ_b.

$$R_d = R(f_d) \, / \, \gamma_b \qquad (3)$$

The design member force, S_d is obtained from Equation 4 as the sum of member forces, S, computed using the design loads, F_d multiplied by structural analysis factor, γ_a.

$$S_d = \Sigma \gamma_a \, S(F_d) \qquad (4)$$

Examination of ultimate limit states for displacement, deformation, formation of collapse mechanism and others, and, examination of the ultimate limit state of a member or structure using non-linear analysis without considering member forces, is carried out using methods whose applicability to the structure and accuracy have been previously established.

For design of members, generally, the ultimate limit state for failure of member cross-sections is examined for safety verification and other ultimate limit states are not taken into consideration so frequently. For members subjected to one of the member forces among flexural moment, axial load, shear force and torsional moment, verification of safety against failure of member cross sections is carried out as shown in Figure 3.

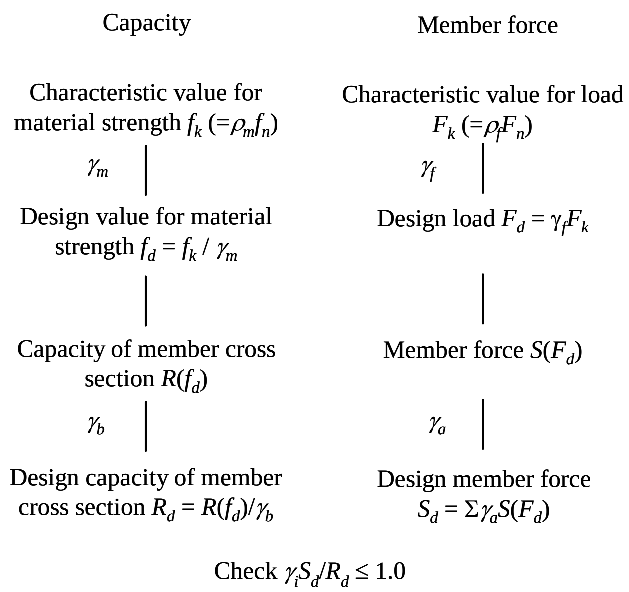

Figure 3 Check for ultimate limit state for failure of cross-section

Verification for Serviceability

General

Structures or members are required to preserve sufficient functions suitable for the purpose of their usage during their design life, such as comfort, water-tightness, appearance, durability during their design life, and others. The verification for serviceability of structure should, in principle, be carried out by ensuring that a concrete member or structure does not reach the serviceability limit state under the design load.

The Specification provides standard methods to verify serviceability of structures based on the assumption that they satisfy required durability and constructability specified in the JSCE Standard Specifications for Materials and Construction, and therefore, material deterioration during the design life is negligible. In case that the material degradation is inevitable, its influences are required to be considered in verification of structural performance by appropriate methods. The limit states of crack width from a viewpoint of durability of structures are presented.

Examination for cracking

Examination using appropriate methods is be carried out to ensure that cracking in concrete does not impair the function, durability, and appearance of the structure. Examination of cracks for durability should, in principle, be carried out by controlling the width of crack at the concrete surface to the extent that required performance of the structure is not impaired by corrosion of reinforcement due to chloride ingress or carbonation of concrete during design life under the given environmental conditions.

Performance of concrete in the concrete cover to protect reinforcement from corrosion due to chloride ingress is achieved by not only controlling crack width but also providing good quality of concrete. Based on this fact, examination of serviceability limit of cracks for durability should be made, in principle, by confirming both that crack width is smaller than the permissible width and that chloride concentration at reinforcement in concrete, predicted by the chloride transport analysis considering the effect of crack, does not exceed the threshold value for initiating corrosion during the design life. The principle of crack control is to keep the crack widths on the surface of concrete below the permissible crack width, which in turn depends on environmental conditions and concrete cover as shown in Figure 4.

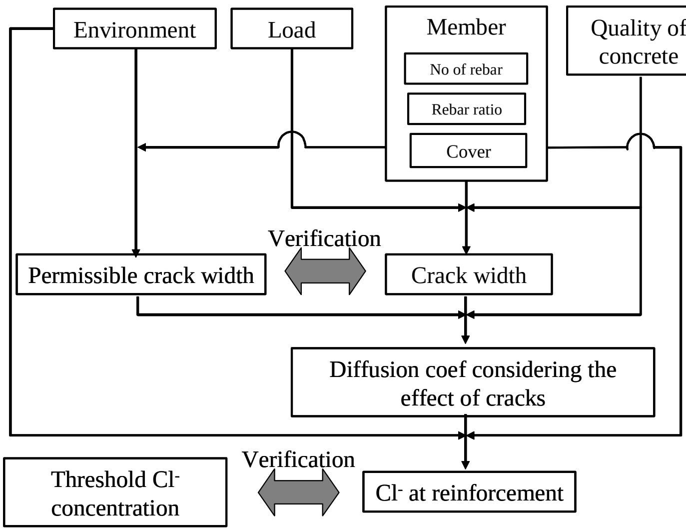

Figure 4 Link between structural performance and durability

Permissible crack width

The functions, importance, service life and purpose of use of structure, environmental and loading conditions of the structure, effects of axial loads, type and stress condition of the reinforcement, concrete cover, scatter in crack widths, etc. need to be taken into account in determining the permissible crack widths. In general, the permissible crack width for corrosion of reinforcement may be determined depending on the environmental conditions, concrete cover and type of reinforcement, as given in Table 4. However, the concrete cover c used there should not exceed 100 mm. Durability of concrete structures is greatly affected by corrosion of reinforcement. Depending upon the extent to which they affect the corrosion, environmental conditions have been classified into three categories as summarized in Table 5.

Corrosion of reinforcement in concrete does not depend only on crack width. Hence, the permissible crack widths indicated in this clause are minimum requirements to avoid risk of corrosion of reinforcement. For structures under "corrosive" or "severely corrosive" environments not only should the crack widths be kept to levels smaller than the permissible width, but also an examination for the concentration of chloride ions at the position of reinforcement should be carried out.

Table 4 Permissible crack width, w_a

	Environmental conditions for reinforcement corrosion		
	Normal	Corrosive	Severely corrosive
Deformed bars and plain bars	$0.005c$	$0.004c$	$0.0035c$
Prestressing steel	$0.004c$	---	---

Table 5 Classification of environmental conditions for reinforcement corrosion

Normal environment	Normal outdoor environment with ordinary conditions without any airborne salt, underground, etc.
Corrosive environment	1. In comparison to the normal environment, environment with more frequent cyclic drying and wetting, and underground environment below the level of underground water containing especially corrosive (or detrimental) substances, which may cause harmful corrosion of reinforcement. 2. Environment of marine structures submerged in seawater, or structures not exposed to severe marine environment, etc.
Severely corrosive environment	1. Environment in which reinforcement is subjected to detrimental influences considerably. 2. Environment of marine structures subjected to tides, splash, or exposed to severe ocean winds, etc.

Examination for flexural cracks

For structures without flexural cracks, examination of flexural cracks is not required in the examination of the serviceability limit state. However, in cases when there is a high risk of cracks, such as thermal cracks, which are not generally considered in the examination of the serviceability limit state, an examination using appropriate methods should be carried out to determine if such cracks may be potential causes for future problems. Examination for flexural cracks should be made, by ensuring that the crack width, w calculated using Equation 5 is not greater than the permissible crack width, w_a given in Table 4.

$$w = 1.1 k_1 k_2 k_3 \{4c + 0.7(c_s - \phi)\}\left[\frac{\sigma_{se}}{E_s}\left(\text{or } \frac{\sigma_{pe}}{E_p}\right) + \varepsilon'_{csd}\right] \quad (5)$$

where, k_1: a constant to take into account the effect of surface geometry of reinforcement on crack width. It may be taken to be 1.0 for deformed bars, 1.3 for plain bars and prestressing steel.

k_2: a constant to take into account the effect of concrete quality on crack width.

$$k_2 = \frac{15}{f'_c + 20} + 0.7 \quad (6)$$

f'_c: compressive strength of concrete (N/mm^2). In general, it may be taken to be equal to the design compressive strength.

k_3: a constant to take into account the effect of multiple layers of tensile reinforcement on crack width.

$$k_3 = \frac{5(n+2)}{7n+8} \quad (7)$$

n: number of the layers of tensile reinforcement.

c: concrete cover (mm).

c_s: center-to-center distance of tensile reinforcements (mm).

ϕ: diameter of tensile reinforcement (mm).

ε'_{csd}: compressive strain for evaluation of increment of crack width due to shrinkage and creep of concrete (150×10^{-6} in general concrete and 100×10^{-6} for high strength concrete)

$\sigma_{se(pe)}$: increment of stress of reinforcement (prestressing steel) from the state in which concrete stress at the portion of reinforcement is zero (N/mm^2).

$E_{s(p)}$: Young's modulus of reinforcement (prestressing bar)

Flexural cracking in reinforced and prestressed concrete is affected by various factors. According to the previous studies, the main factors are the types of reinforcement, increase of stress in reinforcement, concrete cover, effective cross sectional area of concrete, diameter of reinforcement, ratio of reinforcement, number of layers of reinforcement, surface geometry of reinforcement, quality of concrete, magnitude of prestress, and so on. Equation 5 has been formulated on the basis of the existing equations for prediction of crack width and results of recent studies.

Spacing of flexural cracks is affected by the bond between the reinforcement and the concrete. Coefficient k_1 is a constant to represent the effect of surface geometry of reinforcement, which is one of the bond factors affecting crack width. Coefficient k_2 is a constant to represent the effect of changes in bonding characteristics between the reinforcement and the concrete due to changes of concrete quality on crack width. It has been reported that concrete with little material segregation and having a dense pore structure, possesses not only high resistance to cracking but also reduces crack width due to good bonding. Coefficient k_3 is a constant to represent the effect of the reinforcement in the second and higher layers in members with multi layers of reinforcement on the surface crack width.

Examination for displacement and deformation

Displacements and deformations, in general, are related to maintaining functions and serviceability for safety and comfort with moving traffic, preventing damages due to excessive displacements and deformations, and maintaining esthetics of structures. Considering the purpose of use of a structure, enough stiffness and appropriate camber should be provided, and support need to be selected adequately. It is advisable to examine the influences of gasp kinks between members and expansions/shortenings of members if necessary. For structures resting directly on the ground, it is advisable to examine the serviceability limit state of vertical support using an appropriate method, in cases when such an examination is specially required.

There are two types of displacement and deformation. One is short-term displacement and deformation caused instantaneously at the time of application of load. The other is additional displacement and deformation caused by shrinkage and creep of concrete due to permanent loads. Long-term displacement and deformation are defined as the sum of the short-term and the additional displacement and deformation. In cases when precise computation of displacement and deformation are not required, displacement and deformation of cracked reinforced and cracked prestressed concrete members, may be computed using the moment of inertia of a gross cross section assuming no flexural crack. In computation of short-term or long-term displacement and deformation, for cases when reduction of stiffness due to flexural cracking and the influence of creep and shrinkage are taken into account, the effective flexural stiffness is used.

Verification of Fatigue Resistance

Examination for performance of a structure in fatigue is carried out when the ratio of variable loads to total loads is large, or the structure is subjected to a large number of loading cycles. Fatigue failure of a material in a structure will directly affect the safety of the structure. This specification provides the standard of verification of safety of a structure relating to fatigue failure of the material in the structure.

Safety of a beam under fatigue load is examined for flexural moment and shear force, while safety of a slab under fatigue load is examined for flexural moment and punching shear. For a column, examination of safety under fatigue loading is not required in general. However, when the applied flexural moment or axial tensile force is large, examination for fatigue is carried out in a manner similar to that for beams.

GENERAL STRUCTURAL DETAILS

The Specification covers the following as general structural details:

(1) concrete cover
(2) clear distance of reinforcement
(3) bend configurations of reinforcement
(4) development and splice of reinforcement
(5) beveling
(6) additional reinforcement for exposed surfaces
(7) additional reinforcement for concentrated reactions and for openings
(8) construction joints and expansion joints
(9) water-tight structures
(10) drainage and water proofing
(11) protection of concrete surface
(12) haunches

The descriptions in structural details sometimes contradict the spirit of performance-based design because almost all the statements are prescriptive specifications. Regarding the structural details, it can be understood that these are indispensable prerequisites for performance verification as per the Specification.

Several new mechanical devices have recently been invented for anchorage and splice in reinforcement. As for anchorage, the following methods are included: (a) bars such as high strength bars, ultra-large-diameter bars, and threaded bars, not stipulated in the present standards, that are embedded into concrete with sufficient development length, (b) embedment of bars having their ends made into a special shape, (c) use of special jigs such as steel plates, nuts or other hardware attached to the end of the bar, to transmit stresses to the concrete, or bar end anchorage connected with the steel frame by a weld or mechanically, and (d) by reinforcing the concrete around bars to increase the bond strength, and thereby shortening the required development length.

When one of these methods is used, the performance of embedment is verified depending on the type of the structure and members, the loading conditions, and other factors: (a) static strength, (b) resistance to repeated high stresses, (c) resistance to fatigue to high cycle, (d) reliability of execution and other conditions, and (e) other characteristics such as performance under low-temperature, etc. The examination for the performance of anchorages of reinforcement is generally carried out by the pullout test of reinforcement or the loading test using beam or column specimens.

There should be no harmful cracking in the anchorage zone under loads up to the levels corresponding the serviceability limit state in the steel reinforcement. The concrete around anchored reinforcement should not deform under loads up to levels corresponding to those that cause yielding in the reinforcement. The concrete around the anchored reinforcement should not fail under loads up to the levels corresponding to the breaking strength of the reinforcement. Under repetitive loading, the length of pullout of reinforcement, the width of cracks in the concrete anchorage zone, and looseness at the concrete/steel reinforcement interface should be within the specified limits. The required performance of reinforcement anchored in concrete varies depending on the purpose and the location of the anchorage. Thus, it is not reasonable to specify a single representative index for the performance.

PRESTRESSED CONCRETE

Use of prestressed concrete enables us to improve crack characteristics at the serviceability limit state and to reduce the required cross sectional area with use of high strength steel. As far as treatment of the prestressing force introduced to concrete members for the purpose of design calculations is concerned, it may, in general, be treated as a load in the consideration of the serviceability limit state. At the ultimate limit state, only the indeterminate force may be considered as the effect of the prestressing force is included in calculating the ultimate strength of the cross-section.

Prestressed concrete classified into general prestressed concrete (PC) and prestressed reinforced concrete (PRC) structures. In PC no cracking is allowed at the serviceability limit state, and the stress of tension-side fringe of concrete is controlled through introduction of prestressing forces. In PRC, cracking is allowed at the serviceability limit, and the crack width can be controlled by a suitable provision of deformed reinforcing bars and introduction of prestressing forces. However, the limit state of the stress of tension-side fringe is determined variously because of the circumstances, function or purpose of structure, or other reasons. In particular for PRC structure, the restraint of reinforcing bars by creep and shrinkage of concrete is considered. If required, a more rigorous analysis that also takes into account the effect of cracking may be performed, considerably widening the scope of application of such structure.

In recent year, many defects of prestressed concrete structures due to corrosion of prestressing steel have been reported. Since corrosion of prestressing steel reduces the safety or serviceability of prestressed concrete structure, it should not occur during the design life.

For post-tensioned structures, grouting is carried out for 2 reasons: one is to protect the prestressing tendon against corrosion, and the other is to establish a bond between the prestressing tendon and the surrounding concrete. Therefore, if grouting is incomplete, initiation of corrosion in the prestressing tendon, or concentration of cracks, or in the worst case, a much reduced failure strength due to breaking of the prestressing tendon, may be feared. As quality of grouting considerably affects occurrence of corrosion in prestressing tendons, it should be ensured that grout fills all the voids in the sheath.

DESIGN OF MEMBERS

The chapter of "Design of Members" specifies distinctive aspects of structural members. It covers beams including deep beams and corbels, columns, rigid frames, arches, planar members including slabs and footings, shell, wall, and precast concrete.

In this paper, among various specifications, the shear capacity of deep beam is particularly mentioned. Provision specifies a conservatively simplified equation for computation of the shear capacity of deep beams, in such a way that it gives the same value as obtained in the equation for the shear capacity of ordinary beam members. Since contribution of shear reinforcement is smaller than that of the slender beam, it was ignored for standing the safe side. However, given that the shear reinforcement is adequately provided, it has recently been revealed by the experiment that the contribution to the shear strength can be expected. Therefore, the shear reinforcement is taken into account to calculate the shear capacity of deep beam in the latest version of the Specification as presented in Equation 8.

$$V_{ydd} = V_{cdd} + \phi V_{sd} \qquad (8)$$

$$\phi = -0.17 + 0.3(a_v/d) + 0.33/p_{wb} \leq 1.0$$

Where,
V_{cdd}: design shear capacity without shear reinforcement
V_{sd}: design shear capacity of shear reinforcement
a_v: distance between edge of support and loaded point
d: effective depth of member at loaded point
p_{wb}: ratio of shear reinforcement (%)

STRUT-AND-TIE MODEL

General

The strut-and-tie model is a useful tool to estimate the resisting capacity of a structure and how the internal forces of a structure flow. The model was first introduced in the Specification. A reasonable, safe design can be achieved for structural members, such as beams, columns, or slabs, of which design and construction procedures have been well established by following the provisions mentioned earlier. On the other hand, ultimate structural capacity of members having abrupt changes in sections, corners of framed structures, and/or openings cannot be well examined by using the standard provisions. In such cases, it is desirable to perform proof experiments or nonlinear analyses with sufficient accuracy based on assumptions of geometry and material properties. However, if the resisting mechanism for the design load is predetermined, the design for determining the details of reinforcement and the properties of materials used can be accordingly carried out with the strut-and-tie model. Therefore, the strut-and-tie model may be applied to examine the ultimate limit state of structures having discontinuity regions in which the flow of internal forces changes significantly.

Description of the Model

In the strut-and-tie model, structures or members are discretely modeled into an assembly of one-dimensional struts and ties as well as nodes connecting these struts and ties (see example as shown in Figure 5). The ultimate capacity corresponding to the assumed flow of forces is calculated based on the static equilibrium conditions and the individual strength of the struts and ties. The tie is normally modeled on the basis of the resultant force from a layer of reinforcing steel. The strut represents the resultant of either a uniform compressive stress field or a fan-shaped compressive stress field. The node represents a certain amount of concrete volume, in which struts either intersect with ties or are deviated by ties.

Since the strut-and-tie model does not strictly consider the compatibility condition in deformation when deciding the location of struts and ties, it should be ensured that the compatibility of deformations is adequately maintained by providing sufficient deformation ability to the structural members. This ensures the transfer of forces according to the resisting mechanism assumed in the ultimate limit state. The Specification specifies strength of ties, strength of struts, and strength of nodes and anchorages of reinforcing bars.

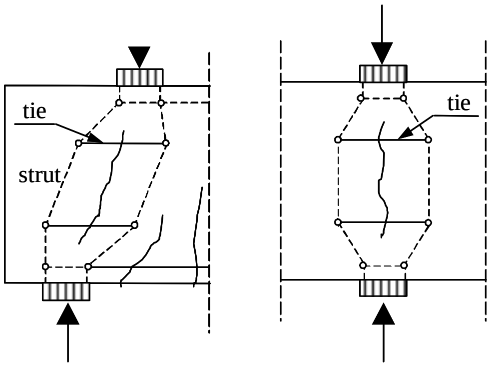

Figure 5 An example of strut-and-tie model

CONCLUDING REMARKS

The updating work on the Specification has just started. It becomes more important to modify the framework of design of concrete structures by linking structural performance aspects with durability aspects and environmental issues. We will be making best efforts to provide concrete engineers, designers, etc. with sufficient backgrounds of concrete structures as well as manuals for practical use.

REFERENCES

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