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**Autor:** Wakabayashi, Minoru

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# IV

## Special Problems

Problèmes spéciaux

Spezielle Probleme

MINORU WAKABAYASHI
Professor
Disaster Prevention Research Institute
Kyoto University
Kyoto, Japan

### 1. LOADS

In the design of buildings and bridges, consideration must be given to dead and live loads, wind load, earthquake load, to the effects of temperature and to others as is discussed in the introductory report for Theme III.

An earthquake may be defined as an irregular vibration of the ground with a certain duration time and a unique feature of the earthquake load lies in the fact that it is related to the nature of the ground motion and structure.

If ground motion is well defined, it is only necessary to investigate the dynamic response in order to evaluate the safety of the structure. In the analysis of elastic-plastic response, careful consideration should be paid not only to strength but also to the deformability of the structure in order to insure its safety against the earthquake. For example, a frame with high strength and small deformability, as shown by the load-deflection curve A in Fig. 1, is not necessarily safer than a structure with low strength and large deformability, as shown by curve B. From the view point of design, a larger design load should be chosen for a structure with small deformability than for a ductile one. This design concept should be applied to the design of a reinforced concrete column which shows a very brittle failure when triggered by compression failure of concrete under axial thrust, and by shear failure, even though its behaviour is ductile when flexural failure occurs by yielding of the reinforcing bars.

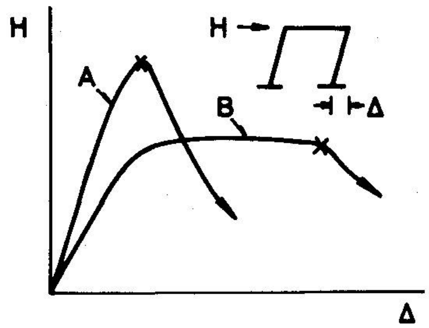

Fig. 1 Deformability of a Frame

### 2. CLIMATIC INFLUENCES

One of the most important climatic influences is temperature change. Factors of importance include 1) daily change and yearly change of temperature, 2) temperature change due to direct sunlight, and 3) temperature change due to heat sources such as room heating systems. The significance of the temperature effect depends on the amplitude of the temperature change. Reference (1) is a state-of-the-art report on thermal loadings.

It is often necessary to introduce expansion joints and/or control joints in buildings with large floor areas and in open-air structures, in order to minimize temperature effects. In Ref. (1), proper design and detailing for the structural floors, columns and partitions for temperature deformations and stresses are discussed.

The temperature inside a high rise office building and an apartment house is kept constant through the year by the air-conditioning system. When the inside of the building is covered by the curtain wall and the structural frame is not exposed to the air, only an expansion of the outer wall occurs. Therefore, if the joint of the outer wall allows free expansion or shrinkage, there should be no problem. However, there are many tall buildings in which the outer columns are exposed to the air. In such cases, columns tend to expand, shrink or bow, and stresses are generated in the columns themselves and in connected members.

Where periodic changes occur in the temperature of the air to which columns or walls of a building are exposed, for example as daily changes, a difference in the temperature phase and an attenuation of the temperature amplitude occur at some distance inside from the exposing surface, due to a kind of temperature inertia. Reference (2) analyses such phenomena, and indicates a method for determining an equivalent steady state daily temperature. The values determined by this method are conservative when used to compute the stresses in a column due to expansion, and are slightly liberal when used to compute bowing stresses. By the relaxation method or graphical solution, isotherms and temperature gradients inside the column can be determined when the steady state temperature, to which a part of the column is exposed, and a constant temperature inside, are given. The relaxation method requires a tedious computation, while the graphical solution is simple. Details of the latter are discussed in Ref. (2).

From the temperature distribution inside the column, the thermal stress distribution is determined for several boundary conditions of the column. Bowing action of columns is actually restrained in tall buildings by adjacent members, and tension stresses are generated on the low temperature side of columns. Also the expansion of outer columns is restrained by adjacent beams and claddings. In Ref. (3), an iterative method and simplified method are introduced for the frame analysis. It is clear from the analyses that the relative deflection decreases with an increase in the number of stories if free expansion is allowed, and that the expansion of the outer columns becomes less and the shear force in beams increases as the slab system, including beams, become stiffer.

When the expansion of columns, the transmission of the loads and bowing stresses are determined, it then becomes necessary to combine these thermal stresses with stresses generated by the vertical loads and horizontal loads. The combined system to be considered in allowable stress design, and the load factors to be taken in ultimate strength design, are discussed in Ref. (3). However, from a practical point of view, it seems to the author that the temperature would not affect much on the ultimate strength of reinforced concrete structures. In Ref. (4), results are given of field observations on existing tall buildings which were affected by temperature.

## 3. INFLUENCE OF FIRE

The fire resistance of column members is commonly judged by fire tests. The standard temperature-time curves in tests specified in each country are similar. Test methods should ensure that the highest allowable temperature for the steel material be not exceeded when the column is heated without load, or that the load be sustained during the fire test.

When the outer surface of a column is heated, the temperature distribution in the column cross section is determined according to the size of the cross section and the heat diffusivity of the material composing the column. Therefore, when the temperature at the column surface and the allowable temperature in the steel are given, the necessary thickness of the covering concrete can be determined.

Investigations into the fire resistance of axially loaded columns with large cross sections were undertaken long ago. However, column cross sections have tended to become smaller because of the recent development and use of high strength concrete. Research into the fire resistance of such columns has been recently carried out(5, 6, 7).

The fire resistance of an axially loaded column is related to the cross sectional area, thickness of concrete covering of the steel bars, aggregates, reinforcement ratio, the strength of concrete and the yield stress of a steel bar. The strength of the column at high temperature can be computed by superposing the contribution of the steel reinforcement on that of the concrete. As a practical matter, the treatment of the centrically loaded column needs less consideration than that of the column subjected to combined axial compression and bending, since the concrete inside the steel reinforcement provides adequate resistance to the axial compression, even when the steel bars are softened due to heat. When the heat effect is applied to a column subjected to combined compression and bending, a decrease in load carrying capacity is to be expected because of the decrease of the yield stress of the tensile steel bars as well as of the strength of the compressive concrete. However, experimental data for this case are few.

The expansion of floor slabs is rather large because of the small heat absorbing capacity of the slabs, and this causes shear and bending in columns. Such states of stress are also generated by the expansion of beams. Since the columns in a framed structure are rigidly connected to the beams, the state of stress generated in the columns by the heat effect becomes complex due to the restraining effect of the beams on the columns. It is necessary to consider the effects of the restraining members on the fire resistance of the columns. However, there has been very little research carried out(8).

From time to time, explosive spalling can be observed in the initial stage of a fire and sometimes causes critical loss of cross section and bearing capacity. This phenomenon more frequently occurs in the prestressed concrete and the precast concrete thin members. From available test results(9, 10, 11), it can be seen that spalling is most likely to occur in a prestressed concrete member under the following conditions: 1) the early time of the fire test, 2) the sudden heating, 3) large prestress, 4) small cross section and 5) the corner portion of the column. When large stresses are generated by the combined effect of temperature, the restraint of the attached member and the axial load, the spalling is seen even in some ordinary reinforced concrete members(12).

Covering to protect the sudden heating and aggregates with a small expansion coefficient may be effective in preventing spalling. The mechanism of spalling has not yet been perfectly clarified.

## 4. CORROSION AND DURABILITY

Reinforced concrete members and prestressed concrete members are subjected to different kinds of corrosion problems according to the environmental conditions.

The worst environment to cause corrosion of the concrete is air and/or water containing chemicals. Inorganic acids cause severe corrosion, while the effect of organic acids and salts is not very severe. To protect the concrete from corrosion, it is necessary to use very dense concrete with anti-corrosion cement. When the chemical action is expected to be severe, the surface of the concrete should be treated chemically, or be covered by anti-corrosion materials. Air-entrainment is effective in the case of the corrosion of concrete exposed to freeze-thaw cycles in the field and in sea water(13).

Even when concrete is placed in a normal environment, corrosion damage is accelerated in the concrete by the following reasons: unsound aggregates; reactive aggregates; cement containing unusual percentages of chemicals, and acids or sulphates in the mixing water.

The adequate alkalinity of the concrete prevents the corrosion of the steel reinforcing bars. However, too thin a cover allows the neutrality to proceed from the surface of the concrete to the steel, with subsequent corrosion of the steel. The chloric ion contained in the air or in water spray can initiate the corrosion of steel used in off-shore structures and structures close to seashore.

Cracks allow carbonation penetration and provide a route for oxygen to the surface of the steel. Cracks should be thus avoided from the view point of steel corrosion. However, cracks are generally not as important in the corrosion mechanism as commonly believed.

In order to increase the durability of concrete and steel, the following considerations are important: 1) careful choice of materials, such as cement, aggregates and steel; 2) use of mixes with high cement factors and low water-cement ratios; 3) use of concrete with entrained air; 4) casting of very dense concrete with smooth surfaces; 5) providing a sufficient thickness of the covering concrete around the reinforcing bars(14).

It may be interesting to discuss the investigation of corrosion damage on columns in existing structures, the continuous observation of the corrosion phenomena in the long duration, the experiments, the relation between the results of aging tests and the real corrosion, and protection methods. And it may be also interesting to discuss how to balance the requirements for large confinement area to secure ductility of a column and for providing a sufficient thickness of the covering concrete to secure the durability and the bond strength of the main reinforcement.

## 5. INTERACTION BETWEEN AXIAL THRUST, BENDING AND SHEAR

Shearing failure of columns is scarcely to be observed in areas where earthquakes do not occur. Evidence of shearing failure of columns has been available for many years, and photographs taken in studies of earthquake damage, such as for the 1923 Kanto Earthquake, show damage on columns which have failed in shear. However, the importance of shearing failure in columns has been only recently recognized. A great deal of attention has been paid to shear failure of columns following the 1968 Tokachi-Oki Earthquake in which many reinforced concrete structures were destroyed(Fig. 2). Column failure was confirmed to be the most important problem in reinforced concrete structures in areas exposed to the danger of earthquake, when in the 1971 San Fernando Earthquake in California column damage by shear was again observed.

A great deal of experimental and theoretical research on the behavior of reinforced concrete beams subjected to shear has been reported. However, experimental and theoretical studies of the shearing failure of a reinforced concrete member subjected to axial thrust and bending are very scarce. Although test results for a reinforced concrete columns as shown in Fig. 3(a) were reported at an early time(Ref. 15), little attention has subsequently been given to the problem. In Refs. (16) and (17), tests were reported for the reinforced concrete columns shown in Fig. 3(b), which were carried out as a part of an experimental series on steel reinforced concrete structure. A series of parametric tests of reinforced concrete using the same loading system as shown in Fig. 3(b) was reported in Ref. (18), and an experimental formula was proposed for estimating the shear strength of reinforced concrete columns. At nearly the same time, tests shown in Fig. 3(b) and (c) were reported in

**Fig. 2 Shear Failure in a Column**

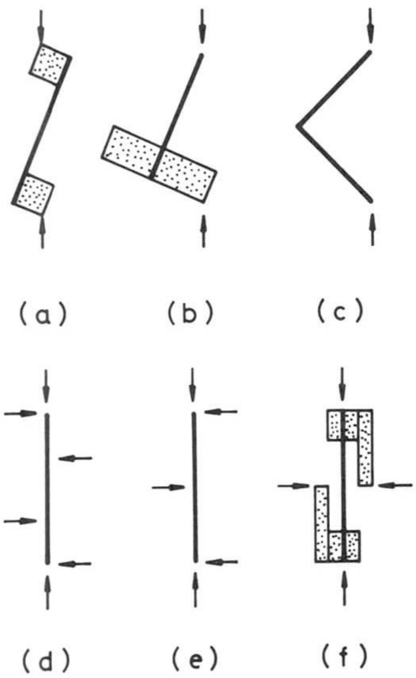


Fig. 3 Testing Methods of a Column

Refs. (19) and (20), respectively, and semi-theoretical formulas for estimating the shear cracking strength and maximum shear strength were proposed in both references.

The behavior of reinforced concrete columns subjected to a constant axial load and monotonic and alternately repeated shear was investigated under the parametric testing program, a loading system shown in Fig. 3(d) being used(21). In Ref. (22), test results for reinforced concrete columns under monotonic shear load, applied as in Fig. 3(d), were reported, and experimental load-deflection relationships up to the maximum strength were compared with theoretical results derived by the finite element method. An empirical formula for determining the shear cracking strength of the column was derived from test results(23) which were obtained using the test set up shown in Fig. 3(e). Ref. (24) discusses the effect of stirrups on the strength of the reinforced concrete column subjected to the loads shown in Fig. 3(d) and (e). Series of parametric tests of reinforced concrete columns subjected to a constant axial load and repeated shear as shown in Fig. 3(f) were carried out, and test results were reported in Refs. (25) and (26).

Since the 1968 Tokachi-Oki Earthquake, the number of experimental studies on the shear failure of reinforced concrete columns has increased rapidly in Japan. Experimental investigations of the behavior of reinforced and steel-reinforced concrete columns are now being carried out in Japan as a part of a national project(27).

The elastic-plastic behavior of a column failing in shear under the application of a constant axial force P and monotonically increasing shear force V and bending moment M are affected by the value of P, height-to-depth ratio, amount of stirrups and main reinforcements. The solid line in Fig. 4(a) shows a relationship between the shear force V and deflection Δ of a column subjected to a constant axial force and monotonically increasing shear. At point A, the shear crack appears. After the maximum strength is achieved at point B, the sustained load on the column rapidly decreases and point C is reached. In the case where the axial load is not applied, the load-deflection curve is given by dashed line in Fig. 4(a). It is observed from the two curves that the shear cracking load and the maximum strength both increase in the presence of the axial load, but that the slope of the unloading curve becomes steeper than in the case of zero axial load. Fig. 4(b) shows that the maximum strength increases and that the ductility of the column

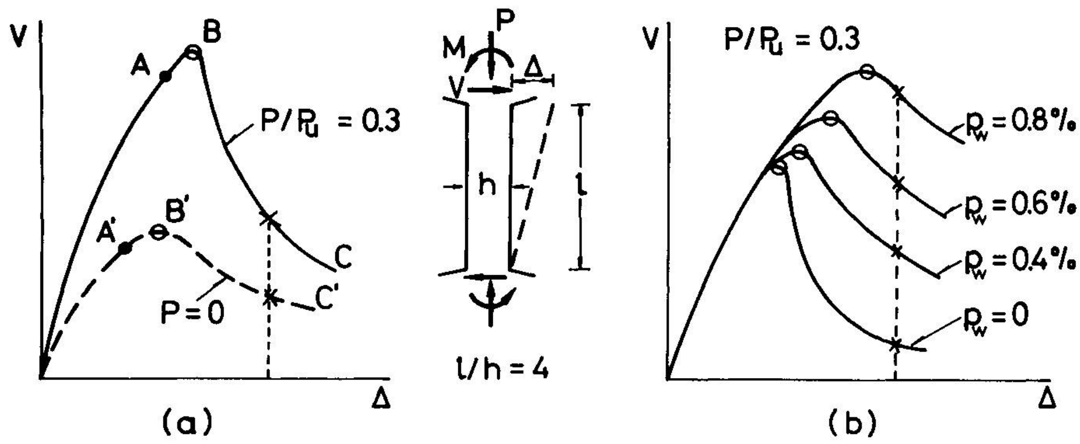


Fig. 4 Load-Deflection Relations of a Column

is improved as the amount of stirrups increases. In Figs. 4, Pu and $p_w$ denote ultimate compressive strength of a column and web reinforcement ratio, respectively.

A sample load-deflection curve of a column under a constant axial load and repeated shear, as might occur in an earthquake, is shown in Fig. 5(25). It is observed that the strength of the column decreases as the loading cycle increases after the attainment of the maximum strength. The hysteresis loop shows an S-shaped slip type loop. It is necessary to know the load-deflection relationship to study the real behavior of the column or an overall structure under earthquake loading. However, the theoretical estimation of the load-deflection relation has not yet been attempted.

Another problem is that the shear strength of a column may be affected by the scale of the specimen as is indicated in case of beam tests(28). In case of a column, full scale tests are more difficult than beam tests because of applying large axial forces.

Some formulas to give the shear cracking strength of the column have been proposed, which are derived from the principal stress at the location at which the diagonal crack is expected to be initiated(19, 23, 29). The formula for the cracking strength of a prestressed concrete beam may to some extent be applicable to the column. In order to compute the maximum shear strength of the column, the empirical formula derived from parametric test results(18, 29) and the formula derived from the semi-theoretical formula for beams by taking the axial force effect into consideration(19, 30) have been proposed.

The interaction among P, M and V which defines the maximum strength of the reinforced concrete column may be represented by a surface as shown in Fig. 6. When V is equal to zero, the interaction between P and M is merely determined by the strengths of columns subjected to axial compression and bending, which are already clarified, if the secondary effect by the axial force is neglected. When M is equal to zero, the P-V curve represents the strength of a column with zero length subjected to the axial compression and shear, and may be closely connected to the failure theory of concrete. M-V interaction of the column under constant P can be generated by the column strengths corresponding to the flexural failure, diagonal tension failure and shear compression failure, as shown in Ref. (19). However, the general interaction to determine column strength has not yet been fully established, and experimental investigations cover only a part of M-P-V interaction surface.

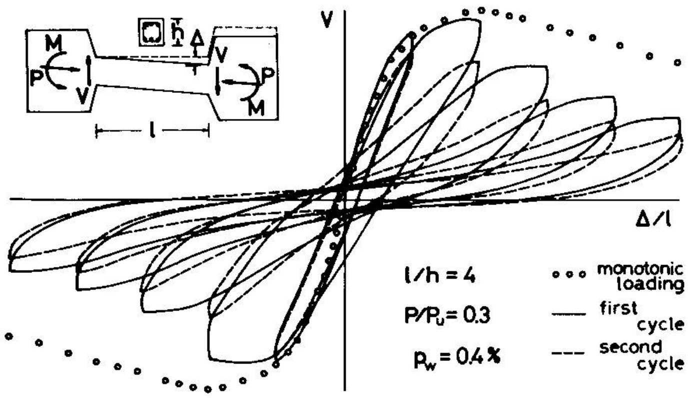


Fig. 5 Hysteretic Load-Deflection Relation of a Column

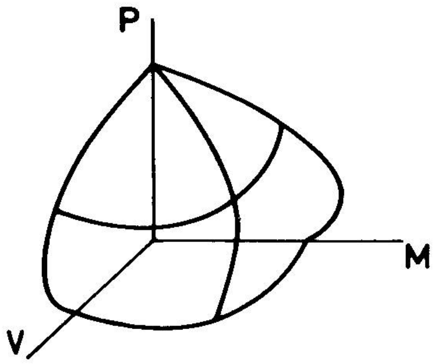


Fig. 6 M-P-V Interaction of a Column

Most of the practical design formula are derived from recent research developments, and are written in simplified form. For example, ACI Standard and Commentary use the experimental studies described in Ref. (19) and (20), and specify the design formula which takes the axial force effect into account (31, 32), and SEAOC Specification on the seismic design is seen in Appendix of ACI Standard. SEAOC Specification requires the web reinforcement in the column to prevent the shear failure of the column occurring earlier than the flexural failure of the column or adjacent beams. AIJ Specification follows this design concept(33).

The following design recomendations for a column subjected to a large shear force as in an earthquake could be derived by summarizing the above discussions.

1) A column should primarily be designed to prevent the shear failure of the column occurring earlier than the flexural failure of the column or adjacent beams.
2) When shear failure of some columns involved in a frame cannot be avoided, that is, the design philosophy deseribed in 1) is not usable, necessary web reinforcement should be determined based on the shear strength of those columns at sway deflections(marked with crosses in Figs. 4(a) and (b)), at which other columns failing in flexure would acieve their maximum flexural strengths.
3) When shear failure of the most of columns involved in a frame could not be avoided, a design should be made for a factored earthquake load, based on the maximum shear strengths of columns(marked with circles in Figs. 4(a) and (b)).

## 6. PRESTRESSING OF COMPRESSION MEMBERS

Although prestressing is usually applied to flexural members, it is sometimes used in beam-columns in frames and in compression members with nearly centric loading. Application of the prestress on a compression member can also be seen in a pile or a pole of a power transmission tower(34, 35). Many experimental and theoretical researches have been carried out on reinforced concrete members in compression. However, the behavior of a prestressed concrete member in compression is a rather recent subject(36-43), and results of several studies have been used to develop the PCI specification, which appears to be the only specification available to date(44).

The strength of a very stubby column under a centrically applied compression entirely depends on the material failure. Therefore, it is obviously predicted that the application of the prestress on a such column reduces the strength. This prediction has been verified by experimental results. The PCI specification includes column with a slenderness ratio of less than 30 in the category of a stubby column, and gives an allowable strength formula derived from the ultimate strength of the column. Interaction between the axial thrust and bending for a short prestressed concrete beam-column is obtained in a manner similar to that for a reinforced concrete beam-column(44, 45).

The strength of a prestressed concrete member with medium or large slenderness ratio under centric compression or compression with a small eccentricity is controlled by buckling. Prestress works beneficially on the strength of a slender compression member or on a member under compression with a large eccentricity(36, 37, 40, 41).

Methods have been reported to obtain the strength of a prestressed concrete member under centric or eccentric compression from the stress-strain relationships assumed for concrete and steel taking the effect of the prestress into account, and theoretical results have been compared with experimental ones. In these theoretical works, the deflected shape of the column is assumed to be defined by a cosine curve, or numerical integration of a differential equation is adopted. The reason for descrepancies between theoretical and experimental results lies in the change of the stress-strain relationship which is seen in the increase of the initial modulus of elasticity and the decrease of the strain at failure of concrete due to prestress. Although these phenomena have been considered in some reports, theories have not yet been fully developed(36, 40). Little research has been carried out on the post-buckling behavior of a column, which is one of the important factors in determining the behavior of an overall frame(41). Research on the elastic-plastic instability of a beam-column subjected to single or double curvature bending and of a subassemblage is scarcely to be found. Research is also necessary on the effect of creep and shrinkage on the strength of a slender prestressed concrete column under sustained load(42), as pointed out for a slender reinforced concrete column.

According to the PCI specification, the strength of prestressed concrete column with slenderness ratios of 30 to 100 is obtained by dividing the strength of a stub column by a reduction factor R which is a linear function of the slenderness ratio. This method is based on the results of the research reported in Ref. (37). The strength of a long column with slenderness ratio of more than 100 is given by the secant formula.

Since the energy absorption of a frame under the repeated horizontal load generated by the earthquake is important, it is necessary to investigate the hysteretic behavior of a prestressed concrete column or of a frame involving a prestressed concrete column, which differs from the behavior of an ordinary reinforced concrete member or frame(46).

## 7. SPLICES

A various experimental investigations have been carried out on lapped splices which are the most frequently used jointing method for reinforcing bars. When the lapping length is not enough, necessary column strength could not achieved, as pointed out in Ref. (47). Necessary lapping length has been experimentally determined and is shown in design specifications. Splices produced by arc welding and pressure welding have worked well in practice, and are described in the design and construction specifications. Because of the frequent use of high-tensile reinforcing bars with large cross section, several kinds of mechanical splices have recently been developed in order to simplify the field work.

One mechanical splice consists of a threaded coupler. In order to prevent a decrease in strength of the reinforcing bar due to the loss of the cross section at the thread, several methods are considered; these include the use of upset threads, treating the threaded portion with high frequency tempering, and pressure welding a threaded high-tensile steel piece to an end of the reinforcing bar by frictional heat. The Dywidag method developed in Germany provides a neat solution by using the ribs of a deformed bar as threads. Another mechanical splice is obtained by the Pressmuffenstoss method, developed in Germany, which applied pressure on a sleeve covering the reinforcing bars.

Cadweld method developed in U. S. A. is a combined mechanical and metallurgical method. Several new trial can be seen among metallurgical methods, such as enclosed arc welding method, thermit welding method and semi-automatic welding method.

Workability and reliability of splices used in compression members may be interesting subjects to be discussed.

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## SUMMARY

Special problems involved in the design and safety of reinforced concrete compression members are indicated, such as: earthquake load, climatic influences, influence of fire, corrosion and durability of concrete and steel reinforcements, axial thrust-bending-shear interactions, prestressing and splices. Experimental and theoretical investigations on these problems are introduced, and necessary design considerations are discussed. Also, interesting subjects of discussion in the symposium are pointed out.

## RESUME

Les problèmes spéciaux relatifs au dimensionnement et à la sécurité de pièces comprimées en béton armé sont traités dans ce rapport, en particulier: charges dues aux tremblements de terre, influences climatiques, feu, corrosion et durabilité du béton et des armatures, interaction force axiale-flexion-cisaillement, précontrainte et chocs. Les recherches théoriques et expérimentales sont mentionnées et des considérations nécessaires au dimensionnement sont présentées. Les thèmes intéressants de discussion lors du colloque sont mentionnés spécialement.

## ZUSAMMENFASSUNG

Die bei der Bemessung von Stahlbeton-Druckgliedern auftretenden und deren Sicherheit beeinträchtigenden besonderen Einflüsse werden behandelt und zwar im speziellen: Erdbebenbelastung, klimatische Einflüsse, Feuer, Korrosion und Dauerhaftigkeit von Beton und Bewehrung, Normalkraft-Biegung-Schub-Interaktion, Vorspannung und Stösse. Die sich diesen Fragen in versuchstechnischer oder theoretischer Hinsicht zuwendenden Untersuchungen werden angegeben und die notwendigen Ueberlegungen für die Bemessung diskutiert. Die für eine Diskussion am Symposium besonders interessanten Themen werden speziell erwähnt.

## NOTATIONS

To facilitate discussions and understanding, the following notations should be used in all contributions for the Symposium:

$A$ = Area

$A_c$ = gross area of concrete section

$A_s$ = area of tension reinforcement

$A'_s$ = area of compression reinforcement

$b$ = width of rectangular section

$d$ = depth from extreme compression fibre to centroid of tension reinforcement

$D$ = Dead load

$e$ = eccentricity

$e_a$ = additional eccentricity

$e_c$ = eccentricity due to creep

$e_s$ = eccentricity of sustained load

$E_c$ = modulus of elasticity of concrete

$E_s$ = modulus of elasticity of steel

$f'_c$ = 28 day compression strength of a 6 by 12 in. (15 by 30 cm) concrete test cylinder

$h$ = overall depth of a concrete section

$H$ = lateral load

$I$ = moment of inertia

$I_g$ = moment of inertia of gross (uncracked) concrete section ignoring the reinforcement

$I_s$ = moment of inertia of reinforcement

$k$ = effective length factor

$K$ = curvature = $(\epsilon_1 - \epsilon_2)/h$

$l$ = length of a column

$L$ = live load

$m_j$ = mean of j

$M$ = moment

$M_a$ = additional moment

$M_o$ = moment capacity of cross section

$M_{ox}$ = uniaxial moment capacity of column cross section about x axis

$M_1$ = smaller of the two column end moments, positive if column is bent in single curvature

$M_2$ = larger of the two column end moments, always positive

$p_t$ = total reinforcement ratio = $(A_s + A_s')/A_c$

$p$ = tension reinforcement ratio = $A_s/A_c$

$p'$ = compression reinforcement ratio = $A_s'/A_c$

$P$ = axial load

$P_{cr}$ = critical load

$P_E$ = Euler buckling load

$P_o$ = capacity of column cross-section under pure axial load

$P_\phi$ = constant sustained load

$r$ = radius of gyration of section

$R$ = Resistance

$S$ = Shear force

$t$ = time

$T$ = Temperature

$v_j$ = coefficient of variation of j

$x, y$ = Axes in cross-section

$z$ = Axis along member

$\gamma$ = Safety factor

$\Delta$ = lateral deflection of a column or storey

$\epsilon$ = strain

$\epsilon_c$ = concrete strain

$\epsilon_{cu}$ = failure strain of concrete

$\epsilon_k$ = creep strain of concrete

$\epsilon_{sh}$ = shrinkage strain in concrete

$\epsilon_s$ = steel strain in tension reinforcement

$\epsilon_s'$ = steel strain in compression reinforcement

$\epsilon_y$ = yield strain of reinforcement

$\epsilon_1, \epsilon_2$ = extreme strains in cross-section

$\phi$ = creep coefficient

$\lambda$ = load factor

$\rho$ = resistance reduction factor

$\sigma$ = stress

$\sigma_y$ = yield strength of steel

$\sigma_j$ = standard deviation of j

In what concerns unities, the International System, especially N (Newton) or kN for forces and cm or m for lengths should be used.

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