ESTIMATING PRESTRESS LOSSES

by Paul Zia, H. Kent Preston, Norman L. Scott, and Edwin B. Workman

Equations for estimating prestress losses due to various causes are presented for pretensioned and post-tensioned members with bonded and unbonded tendons. The equations are intended for practical design applications under normal design conditions as discussed in the commentary. Using the equations, sample computations are carried out for typical prestressed concrete beams selected from the literature. The comparison of the results shows fairly good agreement.

Keywords: beams (supports); creep properties; friction; post-tensioning; **prestressed concrete;** prestressing steels; **prestress loss;** pretensioning; shrinkage; stress relaxation; unbonded prestressing.

Prepared as a part of the work of, and sponsored by, ACI-ASCE Committee 423, Prestressed Concrete.

Introduction

The prestressing force in a prestressed concrete member continuously decreases with time. The factors which contribute to the loss of prestress are well known and they are clearly specified in the current Code.[1] The Code provisions for prestress losses (ACI 318-77, Section 18.6) are written both in performance language and in specific how-to-do-it procedures for losses due to friction. Without detailed analyses, design engineers are permitted to use lump sum loss values as suggested by the Code Commentary.[2] These lump sum loss values were originally proposed by the U.S. Bureau of Public Roads[4] and by the ACI-ASCE Committee 323.[3] Experiences have shown, however, that these lump sum values may not be adequate for some design conditions.

More recently, design recommendations have been developed by others[5,6,7,8,9,10,14] to implement the performance requirements of Section 18.6. Most procedures are relatively complex and convey the impression of an exactness that may not actually exist. The authors, members of ACI-ASCE Committee 423, prepared this report as a means of obtaining reasonably accurate values for the various code-defined sources of loss. A similar procedure was developed and adopted for use in bridge design.[11] It should be noted that the procedures described below are not intended for special structures such as water tanks.

Computation of Losses

Elastic Shortening of Concrete (ES)

For members with bonded tendons,

$$ES = K_{es} E_s \frac{f_{cir}}{E_{ci}} \qquad (1)$$

in which

K_{es} = 1.0 for pretensioned members

K_{es} = 0.5 for post-tensioned members when tendons are tensioned in sequential order to the same tension. With other post-tensioning procedures, the value for K_{es} may vary from 0 to 0.5.

$$f_{cir} = K_{cir} f_{cpi} - f_g \qquad (2)$$

in which K_{cir} = 1.0 for post-tensioned members
K_{cir} = 0.9 for pretensioned members.

For members with unbonded tendons,

$$ES = K_{es} E_s \frac{f_{cpa}}{E_{ci}} \qquad (1A)$$

in which f_{cpa} = average compressive stress in the concrete along the member length at the center of gravity of the tendons immediately after the prestress has been applied to the concrete.

Creep of Concrete (CR)

For members with bonded tendons,

$$CR = K_{cr} \frac{E_s}{E_c} (f_{cir} - f_{cds}) \qquad (3)$$

in which

K_{cr} = 2.0 for pretensioned members
K_{cr} = 1.6 for post-tensioned members

For members made of sand lightweight concrete the foregoing values of K_{cr} should be reduced by 20 percent.

For members with unbonded tendons,

$$CR = K_{cr} \frac{E_s}{E_c} f_{cpa} \tag{3A}$$

Shrinkage of Concrete (SH)

$$SH = 8.2 \times 10^{-6} K_{sh} E_s \left(1 - 0.06 \frac{V}{S}\right)(100 - RH) \tag{4}$$

in which

K_{sh} = 1.0 for pretensioned members

or

K_{sh} is taken from Table 1 for post-tensioned members.

TABLE 1 — Values of K_{sh} for post-tensioned members

Time after end of moist curing to application of prestress, days	1	3	5	7	10	20	30	60
K_{sh}	0.92	0.85	0.80	0.77	0.73	0.64	0.58	0.45

Relaxation of Tendons (RE)

$$RE = [K_{re} - J(SH + CR + ES)]\, C \tag{5}$$

in which the values of K_{re}, J and C are taken from Tables 2 and 3.

TABLE 2 — Values of K_{re} and J

Type of tendon*	K_{re}	J
270 Grade stress-relieved strand or wire	20,000	0.15
250 Grade stress-relieved strand or wire	18,500	0.14
240 or 235 Grade stress-relieved wire	17,600	0.13
270 Grade low-relaxation strand	5,000	0.040
250 Grade low-relaxation wire	4,630	0.037
240 or 235 Grade low-relaxation wire	4,400	0.035
145 or 160 Grade stress-relieved bar	6,000	0.05

*In accordance with ASTM A416-74, ASTM A421-76, or ASTM A722-75

TABLE 3 — Values of C

f_{pi}/f_{pu}	Stress relieved strand or wire	Stress-relieved bar or low relaxation strand or wire
0.80		1.28
0.79		1.22
0.78		1.16
0.77		1.11
0.76		1.05
0.75	1.45	1.00
0.74	1.36	0.95
0.73	1.27	0.90
0.72	1.18	0.85
0.71	1.09	0.80
0.70	1.00	0.75
0.69	0.94	0.70
0.68	0.89	0.66
0.67	0.83	0.61
0.66	0.78	0.57
0.65	0.73	0.53
0.64	0.68	0.49
0.63	0.63	0.45
0.62	0.58	0.41
0.61	0.53	0.37
0.60	0.49	0.33

Friction

Computation of friction losses is covered in Section 18.6.2 of ACI 318-77[1] and its Commentary.[2] When the tendon is tensioned, the friction losses computed can be checked with reasonable accuracy by comparing the measured elongation and the prestressing force applied by the tensioning jack.

Commentary

Determination of loss of prestress in accordance with Section 18.6.1 of ACI 318-77 usually involves complicated and laborious procedures because the rate of loss due to one factor, such as relaxation of tendons, is continually altered by changes in stress due to other factors such as shrinkage and creep of concrete. Rate of creep is, in turn, altered by the change in tendon stress. Many of these factors are further dependent upon such uncertainties as material properties, time of loading, method of curing of concrete, environmental conditions, and construction details.

The equations presented are intended for a reasonable estimate of loss of prestress from the various sources. They are applicable for prestressed members of normal designs with an extreme fiber compressive stress in the precompressed tensile zone under the full dead load condition ranging from 350 psi (2.41 MPa) to 1750 psi (12.1 MPa) using a minimum concrete cyclinder strength f_c' of 4000 psi (27.6 MPa) and a unit weight of concrete of at least 115 pcf (1842.3 kg/m^3). For unusual design conditions, a more detailed procedure should be considered.[8]

Actual losses, greater or smaller than the estimated values, have little effect on the design strength of a flexural member with bonded tendons unless the final tendon stress after losses is less than 0.5 f_{pu}. However, they affect service load behavior, such as deflection and camber, connections, or cracking load. Over-estimation of prestress losses can be almost as detrimental as under-estimation, since the former can result in excessive camber and horizontal movement.

Careful consideration of losses may be required for simply supported, slender members which may be sensitive to small changes in deflections. For example, shallow beams supporting flat roofs may be subject to ponding if sensitive to deflection.

Elastic Shortening of Concrete

Prestress loss due to elastic shortening of concrete is directly proportional to the concrete strain at the center of gravity of prestressing force immediately after transfer. For example, for members of simple span,

$$f_{cir} = K_{cir} f_{cpi} - f_g$$

$$= K_{cir}\left(\frac{P_{pi}}{A_c} + \frac{P_{pi}e^2}{I_c}\right) - \frac{M_G e}{I_c}$$

The different values for the coefficients K_{es} and K_{cir} account for the difference in the order of transfer. In applying Equation (2), the transformed section of a member may be used in lieu of the gross concrete section.

Creep of Concrete

Part of the initial compressive strain induced in the concrete immediately after transfer is reduced by the tensile strain resulting from the superimposed permanent dead load. Loss of prestress due to creep of concrete is therefore proportional to the net permanent compressive strain in the concrete.

For prestressed members made of sand lightweight concrete, there is a significantly larger amount of loss due to elastic shortening of concrete because of its lower modulus of elasticity, resulting in an overall reduction in loss due to creep. This effect is accounted for by a 20 percent reduction of the creep coefficient. For members made of all lightweight concrete, special consideration should be given to the properties of the particular lightweight aggregate used.

Unbonded Tendons

Since an unbonded tendon can slide within its duct, for most flexural members it does not undergo the same stress induced strain changes as the concrete surrounding it. For this reason, the average compressive stress, f_{cpa}, in the concrete is suggested for use in evaluating prestress losses due to elastic shortening and creep of concrete. This procedure relates the elastic shortening and creep of concrete prestress losses for unbonded tendons to the average member strain, rather than the strain at the point of maximum moment. The somewhat higher residual tensile stress in an unbonded tendon logically results in somewhat higher loss due to steel relaxation.

Shrinkage of Concrete

Shrinkage strain developed in a concrete member is influenced, among other factors, by its volume/surface ratio and the ambient relative humidity. Thus, the effective shrinkage strain ε_{sh} is obtained by multiplying the basic ultimate shrinkage strain ε_{sh} of concrete, taken as 550×10^{-6}, by the factors $(1 - 0.06\ V/S)$ and $(1.5 - 0.015RH)$. Thus

$$\varepsilon_{sh} = 550 \times 10^{-6}\left(1 - 0.06\frac{V}{S}\right)\left(1.5 - 0.015RH\right)$$

$$= 8.2 \times 10^{-6}\left(1 - 0.06\frac{V}{S}\right)\left(100 - RH\right)$$

The loss of prestress due to shrinkage is therefore the product of the effective shrinkage ε_{sh} and the modulus of elasticity of prestressing steel. The factor K_{sh} accounts for the reduction in shrinkage due to increased curing period.

It should be noted that for some lightweight concrete, the basic ultimate shrinkage strain ε_{sh} may be greater than the value used here. In addition, the following tabulated correction factors for the effect of the ambient relative humidity may be used in lieu of the expression $(1.5 - 0.015\ RH)$:

Ave. Ambient RH (%)	Correction Factor
40	1.43
50	1.29
60	1.14
70	1.00
80	0.86
90	0.43
100	0.00

Relaxation of Tendons

Relaxation of a prestressing tendon depends upon the stress level in the tendon. Basic relaxation values K_{re} for the different kinds of steel are shown in Table 2. However, because of other prestress losses, there is a continual reduction of the tendon stress, thus causing a reduction in relaxation. The reduction in tendon stress due to elastic shortening of concrete occurs instantaneously. On the other hand, the reduction due to creep and shrinkage takes place in a prolonged period of time. The factor J in Equation (5) is specified to approximate these effects.

Maximum Loss

The total amount of prestress loss due to elastic shortening, creep, shrinkage, and relaxation need not be more than the values given below if the tendon stress immediately after anchoring does not exceed 0.83 f_{py}:

Type of strand	Maximum Loss psi (MPa) Normal Concrete	Lightweight Concrete
Stress relieved strand	50,000 (345)	55,000 (380)
Low-relaxation strand	40,000 (276)	45,000 (311)

Seating Loss at Anchorage

Many types of anchorage require that the anchoring device "set" from 1/8 in. (3.2 mm) to ¼ in. (6.4 mm) in order to transfer force from the tendon to the concrete. The actual seating loss varies with field technique and anchor type. As the seating loss is small, it is not practicable to measure it with accuracy; therefore it is important to recognize the effects of maximum and minimum values of seating loss. Usually long tendons with curvature will be unaffected by seating loss, since the required tendon elongation generally necessitates stressing to the maximum initial value to overcome friction. For short tendons, however, the elongation corresponding to the range of stress of 70 percent to 80 percent of the ultimate is too small to nullify seating loss, and attempts to obtain the necessary elongation would require exceeding the 80 percent limit with possible rupture of the tendon. Thus, the

TABLE 4 — Beam data from reference 6

Beam No.	Beam section	Deck width x thickness & weight	Transfer at (days)	Cast deck (days)	No. of strands ϕ ½ in.	Initial stress f_{pi} (ksi)	f_{cir} (psi)	f_{cds} (psi)	*RH* %	*V/S* (in.)
HG1	AASHTO-III	No Deck	2½	—	20	189	1411	0	80	4.06
HG2	AASHTO-III	96x8-800	1	90	22	189	1622	765	80	4.06
HG3	AASHTO-III	60x5-310	2½	90	22	189	1596	297	50	4.06
HG4	AASHTO-III	96x8-800	7	90	24	189	1721	761	80	4.06
HG5	8 ft Single Tee	96x2-200	2½	90	12	189	1125	695	80	2.07
HG6	8 ft Double Tee	96x2-200	2½	90	24	189	1600	696	80	1.87
HG7	54 in. I-Beam	60x5-310	2½	90	30	189	1554	309	80	3.60
HG8	8 ft Single Tee	96x2-200	2½	90	12	205*	1469	695	80	2.07
HG9	AASHTO-III	96x8-800	2½	90	24	205*	2020	761	80	4.06
HG10	54 in. I-Beam	96x8-800	2½	90	30	205*	1646	796	80	3.60

*Low relaxation strand

$E_s = 28 \times 10^6$ psi, $E_{ci} = 3.5 \times 10^6$ psi and $E_c = 4.2 \times 10^6$ psi

TABLE 5 — Comparison of loss values based on proposed procedure with theoretical results obtained by Hernandez and Gamble (H & G)

Beam No.	Method	*ES* (psi)	*CR* (psi)	*SH* (psi)	*RE* (psi)	Total (psi)
HG1	Proposed	11288	18813	3473	14964	48538
	H & G	9057	17656	3836	18699	49219
HG2	Proposed	12976	11427	3473	15819	43695
	H & G	10364	15327	3836	18085	47614
HG3	Proposed	12768	17320	8683	14184	52955
	H & G	10202	25840	7195	16743	59981
HG4	Proposed	13768	12800	3473	15494	45535
	H & G	10965	11793	3836	19370	45966
HG5	Proposed	9000	5733	4022	17187	35942
	H & G	8170	9374	5348	18949	41842
HG6	Proposed	12800	12053	4077	15661	44591
	H & G	11264	16069	5348	16840	49522
HG7	Proposed	12432	16600	3600	15105	47737
	H & G	9984	17285	3723	18414	49408
HG8	Proposed	11752	10320	4022	4154	30248
	H & G	10295	16192	5348	4558	36393
HG9	Proposed	16160	16787	3473	3720	40140
	H & G	12816	19780	3835	4564	40996
HG10	Proposed	13168	11333	3600	4070	32171
	H & G	10552	15154	3835	4368	33910

seating loss in short tendons should be deducted from the prestress that is applied to the tendon by the tensioning jack.

Restraining Effect of Adjoining Elements

Loss of prestress to adjoining elements of the structure must be properly evaluated. If a member is in contact with or attached to another member during the post-tensioning operation, there can be a transfer of prestressing force from one member to the other.

After the structure is complete, there will be volume changes due to creep and shrinkage of concrete and to variations of temperature. If the member can not move freely to accommodate these volume changes, there will be a transfer of prestressing force from the prestressed member to the restraining member and a resultant loss of prestress in the prestressed member.

Sample Computations

In order to assess whether the proposed equations are appropriate for estimating prestress losses, the following sample computations have been prepared for typical prestressed beams selected from the test program reported by Hernandez and Gamble.[6] The pertinent data regarding the beams are summarized in Table 4. With the procedures described herein, the computed prestress loss values are compared with the theoretical values obtained by Hernandez and Gamble as shown in Table 5. It should be noted that the theoretical predictions made by Hernandez and Gamble were based on their revised rate of creep method treated as a step-by-step numerical integration procedure with short time intervals. The unit creep and shrinkage strains versus time relationships were based on the 1970 CEB recommendations[13] which were found to be comparable to the field data obtained in their study. It can be seen that the comparisons show fairly good agreement.

Additional sample computations have been carried out on selected double T beams listed in the PCI *Design Handbook*. The double T beam properties are summarized in Table 6. The results are shown in Table 7. It is interesting to note that for those slender beams (i.e., Z2 and S2) with very small superimposed permanent load and under fairly low humidity, the total loss of prestress would be quite significant. With more superimposed permanent load and/or higher humidity, the total prestress loss value is reduced. (Compare S1a and S1b with S1, or S2a and S2b with S2, or S3a with S3.) Comparison of S3a with S4 also shows that the total prestress loss value is somewhat increased for the beam made of lightweight concrete.

TABLE 7 — Results of sample computations for pretensioned beams from PCI *Design Handbook*

Beam No.	*ES* (psi)	*CR* (psi)	*SH* (psi)	*RE* (psi)	Total (psi)
Z1	6896	5693	6268	17171	36028
Z2	16064	19613	10653	13051	59381
Z3	3784	5400	5340	17821	32345
S1	4352	7253	10681	16657	38943
S1a	4352	4880	10681	17013	36926
S1b	4352	4880	5341	17814	32387
S2	16280	27133	10447	11921	65781
S2a	16280	18933	10447	13151	58811
S2b	16280	18933	5224	13934	54371
S3	2816	4693	5224	18090	30823
S3a	2816	3061	5224	18335	29436
S4	5622	5486	5224	17550	33882

$E_s = 28 \times 10^6$ psi

For normal wt. concrete:	$E_{ci} = 3.5 \times 10^6$ psi	$E_c = 4.2 \times$
For light wt. concrete:	$E_{ci} = 2.5 \times 10^6$ psi	$E_c = 3.1 \times 1$

TABLE 6 — Beam data from PCI *Design Handbook* for sample computations

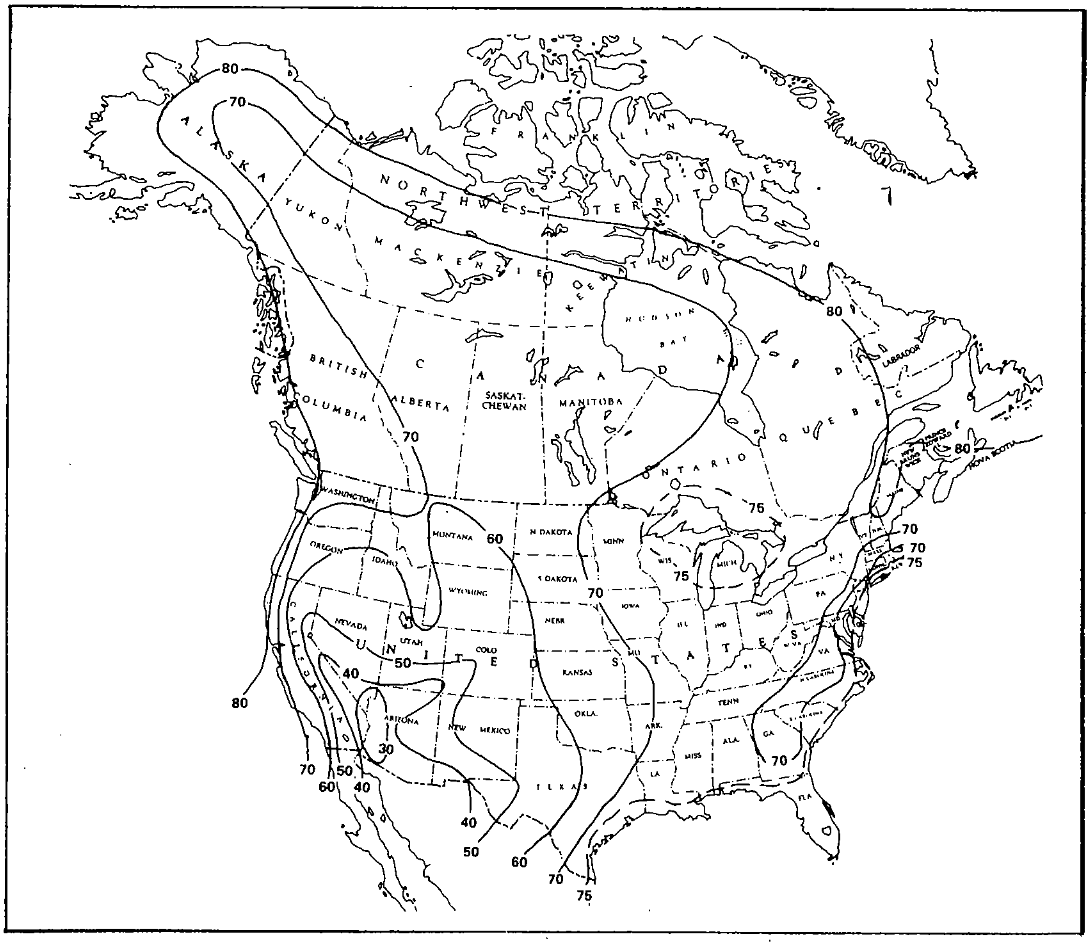
Beam No.	Beam Sec.	Span (ft)	Initial prestress P_{pi} (kips)	Initial stress f_{pi} (ksi)	Ecc. e (in.)	D. L. (lbs/ft)	Superimposed assumed permanent load (lbs/ft)	f_{cir} (psi)	f_{cds} (psi)	*RH* (%)	*V/S* (in.)
Z1	8DT24	62	230.6	189	14.15	418	112	862	435	70	1.5
Z2	4DT14	50	173.9	189	7.34	188	56	2008	537	50	1.2
Z3	8DT12	28	115.7	189	4.13	299	40	473	68	75	1.16
S1	8DT12	26	115.7	189	4.13	299	0	544	0	50	1.16
S1a	8DT12	26	115.7	189	4.13	299	120	544	178	50	1.16
S1b	8DT12	26	115.7	189	4.13	299	120	544	178	75	1.16
S2	8DT24	72	404.8	189	13.65	418	0	2035	0	50	1.5
S2a	8DT24	72	404.8	189	13.65	418	120	2035	615	50	1.5
S2b	8DT24	72	404.8	189	13.65	418	120	2035	615	75	1.5
S3	8DT24	42	115.7	189	12.15	418	0	352	0	75	1.5
S3a	8DT24	42	115.7	189	12.15	418	80	352	122.4	75	1.5
S4	8LDT24	42	115.7	189	12.15	320	80	502	122.4	75	1.5

Conclusions

Simple equations for estimating losses of prestress have been proposed which would enable the designer to estimate the various types of prestress loss rather than a lump sum value. It is believed that these equations, intended for practical design applications, would provide fairly realistic values for normal design conditions. For unusual design situations and special structures, more detailed and complex numerical analysis should be used.

Notation

A_c = area of gross concrete section at the cross section considered
A_{ps} = total area of prestressing tendons
CR = stress loss due to creep of concrete
C = a factor used in Eq. (5), see Table 3
e = eccentricity of center of gravity of tendons with respect to center of gravity of concrete at the cross section considered
E_{ci} = modulus of elasticity of concrete at time prestress is applied
E_c = modulus of elasticity of concrete at 28 days
E_s = modulus of elasticity of prestressing tendons. Usually 28,000,000 psi
ES = stress loss due to elastic shortening of concrete
f_{cds} = stress in concrete at center of gravity of tendons due to all superimposed permanent dead loads that are applied to the member after it has been prestressed
f_{cir} = net compressive stress in concrete at center of gravity of tendons immediately after the prestress has been applied to the concrete. See Eq. (2)
f_{cpa} = average compressive stress in the concrete along the member length at the center of gravity of the tendons immediately after the prestress has been applied to the concrete
f_{cpi} = stress in concrete at center of gravity of tendons due to P_{pi}
f_g = stress in concrete at center of gravity of tendons due to weight of structure at time prestress is applied
f_{pi} = stress in tendon due to P_{pi}, $f_{pi} = P_{pi}/A_{ps}$
f_{pu} = ultimate strength of prestressing tendon, psi
I_c = moment of inertia of gross concrete section at the cross section considered
J = a factor used in Eq. (5), See Table 2
K_{cir} = a factor used in Eq. (2)
K_{cr} = a factor used in Eq. (3)
K_{es} = a factor used in Eq. (1)
K_{re} = a factor used in Eq. (5). See Table 2.



Annual average ambient relative humidity

M_G = bending moment due to dead weight of member being prestressed and to any other permanent loads in place at time of prestressing
P_{pi} = prestressing force in tendons at critical location on span after reduction for losses due to friction and seating loss at anchorages but before reduction for *ES, CR, SH,* and *RE.*
RE = stress loss due to relaxation of tendons
RH = average relative humidity surrounding the concrete member. See annual average ambient relative humidity map appended.
SH = stress loss due to shrinkage of concrete
V/S = volume to surface ratio. Usually taken as gross cross-sectional area of concrete member divided by its perimeter.

1 in. = 25.4 mm
1 ft = .3048 m
1 psi = .0069 MPa
1 ksi = 70.31 kgf/cm^2

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Received January 25, 1979, and reviewed under Institute publication policies.

FACI ***Paul Zia*** *is professor and head of the Department of Civil Engineering, North Carolina State University at Raleigh. He has been an active member and chairman of many ACI committees including TAC and ACI-ASCE Committee 423, Prestressed Concrete, and is currently an ACI director and chairman of ACI-ASCE Committee 445, Shear and Torsion. He has authored numerous papers and received many awards.*

FACI ***Norman L. Scott*** *is president of the Consulting Engineers Group, Inc., Glenview, Ill. He is currently chairman of the ACI Institute and Industry Committee and is past chairman of ACI-ASCE Committee 423, Prestressed Concrete.*

ACI member ***H. Kent Preston*** *is a senior consultant with Wiss, Janney, Elstner and Associates, Inc., and is consultant to Florida Wire and Cable Company. He is a member of ACI-ASCE Committee 423, Prestressed Concrete. Since 1950 he has authored and coauthored numerous publications in various professional journals and three textbooks on the subject of prestressed concrete.*

Edwin B. Workman *is owner of Edworkman, S. E. Structural Engineer, Inc., Canoga Park, Calif. He has been an ACI member since 1970 and is a member of ACI-ASCE Committee 423, Prestressed Concrete.*