Plain Concrete Tunnel Lining—Design Concepts

REINHARD GNILSEN

Discussed in this paper are domestic and foreign concepts for the design of plain concrete tunnel lining. Comparisons are made in terms of the respective design capacity assumed by the concepts. A new concept, tailored to U.S. tunnel design practice, which builds on an advanced approach to defining the capacity of plain concrete tunnel lining, is developed. The first concept is the standard approach incorporated in the Deutsches Institute für Normung (DIN) building code (DIN 1045). This concept is built on strength design criteria similar to those considered in American Concrete Institute (ACI) Code 318, Strength Design. The applicability of this design concept to unreinforced concrete tunnel lining has been proven extensively during the last decade. Partial cracking of the concrete, a characteristic of strength design, is restricted by the code to the extent that stability and safety requirements are observed. The second concept discussed is incorporated in the ACI Code 318.1, Building Code Requirements for Structural Plain Concrete. In contrast to DIN 1045, the ACI code is based on working stress provisions, which thus precludes cracking of the concrete. A comparison of the permissible lining forces of the two concepts is presented. A new Combined Design Concept, based on discussions of ACI 318.1 and DIN 1045, is developed. This concept is specifically tailored to the design of underground lining and incorporates U.S. design practices. ACI Building Codes 318 and 318.1 are used for reference.

The concept used in the design of a tunnel lining should reflect boundary conditions associated with the shape of the tunnel and the construction concept used. Traditionally, tunnel shapes and load assumptions, linked to construction methods, often required a lining that could withstand bending moments. In these cases, consideration of axial forces in the lining is most often of minor design importance. However, research shows that axial thrust, rather than bending, should be the primary factor when competitive lining is required.

The promotion of axial liner thrust has proven effective. This concept has been verified through model studies performed by various authors and confirmed through theoretical analysis. An arched tunnel geometry and a highly flexible lining are shown to be the crucial factors in the design of economic structures. If these criteria are satisfied, axial thrust in the lining, rather than bending, will govern design requirements, provided that adequate construction concepts are implemented. Reinforcement or use of a thicker liner, otherwise required to accommodate bending moment, can frequently be omitted.

Consequently, a design concept is required that is tailored to thin, unreinforced, arched tunnel lining. To account for the specific boundary conditions of tunnel linings, it is necessary

Law/Geoconsult International, Inc., 1140 Hammond Drive, Suite 5250-E, Atlanta, Ga. 30328.

that this design concept differ significantly from the existing American Concrete Institute (ACI) Building Code for Plain Concrete. Like many existing building codes, the ACI code is primarily tailored for surface structures.

The Deutsches Institut für Normung (DIN) and the ACI codes for unreinforced concrete design are discussed in this paper, and a new design concept is developed and proposed for use in U.S. tunnel design. Nevertheless, critical evaluation by potential users will be crucial to further development of the concept to enhance meeting practical design requirements.

Basically, the proposed concept is applicable to concrete linings regardless of whether the concrete is cast in place, precast, or pneumatically applied. However, some characteristics of precast or pneumatically applied concrete (shotcrete) are not specifically dealt with here. These are primarily the handling and installation requirements of precast elements and the plastic behavior of green shotcrete when subjected to early loading from the ground. The corresponding relief of stress concentrations represents safety reserves in addition to those discussed in this paper.

Also, it should be noted that this discussion is of the sizing of the lining only. Other important factors of the design process—load assumptions, selection of a calculation model, and the like—are not dealt with.

Unreinforced linings of underground structures have been constructed throughout history. Examples are numerous, ranging from ancient tunnels to today's linings of underground structures for water, conveyance, and sewage. Also, conditions similar to those of unreinforced linings prevail in segmental (hinged) precast linings. However, it was not until the introduction of the New Austrian Tunneling Method (NATM) that the use of unreinforced cast-in-place concrete liners became standard practice for highway and transit structures.

First applications of NATM for highway tunnels, including the use of unreinforced concrete lining, date back to the early 1960s. Lined unreinforced tunnels in Austria, Switzerland, and Japan were the basis for research on and experience with this innovative lining concept.

Economic considerations and experience gained abroad prompted other countries to review their traditional design standards. In the Federal Republic of Germany, for instance, extensive use of NATM for subway systems called for the development of an analytical approach to unreinforced tunnel lining. This resulted in the definition of a new design standard, incorporated in the German building code (DIN 1045) (1).

Effective January 1984, the DIN code for unreinforced concrete was incorporated in the general provisions for the design

and construction of tunnels within the German railway network (e.g., high-speed rail line, Hannover to Würzburg). This step is significant given the exceptionally large dimensions of the tunnels involved.

The need for a U.S. standard approach was encountered during preparation of the NATM designs for the Mount Lebanon Tunnel, Stage 1, Light Rail Transit System, Pittsburgh, Pennsylvania, and the Wheaton Station and tunnels of the Glenmont Route of the Washington, D.C., subway system. The design concept developed here was first used for the design of these sections. It offers cost-effectiveness and meets the conventional safety requirements of the U.S. standards. The author is confident that the concept represents an important step forward in the evolution of American tunnel design.

DESIGN ACCORDING TO THE GERMAN STANDARD (DIN 1045)

For the design of both reinforced and unreinforced structural members, only the strength concept is specified in DIN 1045 (1). The working stress model is used only to check deformation behavior under service load. Thrust capacity of the tunnel lining is defined using simplified analytical tools. The equations used are contained in Manual 220 (2) that accompanies the DIN Code.

Ultimate Thrust in the Lining

The ultimate thrust capacity of unreinforced concrete is expressed (2, 3) as

$$P_e = (A_g) (\beta_r) (1 - 2\, e/h) \tag{1a}$$

$$P_0 = (A_g) (\beta_r) \tag{1b}$$

where

P_e = ultimate thrust at given (computed) eccentricity,
P_0 = ultimate thrust at zero eccentricity,
e = M/P eccentricity of thrust resultant in the lining,
A_g = (b) (h) area of the overall liner cross section,
b = unit width of the lining,
h = overall thickness of the lining, and
β_r = design strength for concrete specified in DIN 1045, Table 12.

β_{wn} is minimum strength value of any test series performed on cubes (DIN 1045, Table 1).

$$\beta_r = (0.85) (0.80) (\beta_{wn}) = 0.7\, \beta_{wn} \tag{2}$$

β_r values account for the reductions of prism strength from cube strength and fatigue effects (4). Equation 2 is valid for β_r up to 17.5 MN/m^2 (2,536 psi). For higher-strength concrete, an additional reduction of β_{wn} is required.

Thrust capacity (P_e in Equation 1) is analyzed in Figure 1 according to the effect of different design assumptions. P_e-values are indicated as percentages of P_0 ($e/h = 0$).
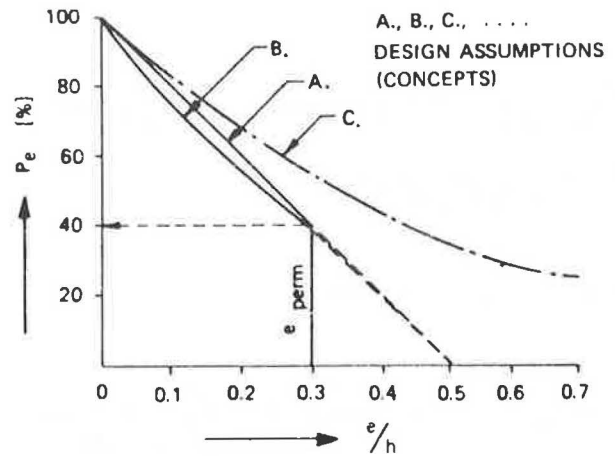

FIGURE 1 Thrust capacity of unreinforced lining according to different design assumptions.

Concept A is simplified design stress distribution according to Figure 2, bottom, and considered for Equation 1.

Concept B is parabolic stress distribution according to Figure 2, bottom, used in the strength design for reinforced concrete components (DIN 1045).

In Concepts A and B, the eccentricity input parameter (e) is conservatively based on discounting the effect of concrete tension cracking:

$$e = e_l = e_{n\,.\,l} \quad \text{(see Figure 2, bottom)}$$

where e_l is the eccentricity of liner thrust resulting from linear elastic calculations and $e_{n\,.\,l}$ is the eccentricity of liner thrust after partial cracking (nonlinear behavior) of the lining.

Concept C is stress distribution according to Concept B. In addition, a decrease of thrust eccentricity due to nonlinear behavior (cracking) is considered (5): $e_l > e_{n\,.\,l}$ (see Figure 2).

Figure 1 shows that the conservative design assumptions (A and B) lead to similar results and thus justify the simplified assumption (A) for determining lining capacity.

Restriction on Thrust Eccentricity and Crack Depth

According to DIN 1045 cracking from service loads must not exceed the centroid of the concrete section. This is to be achieved by limiting the thrust resultant's eccentricity (e) to 0.3 h. In comparison, the parabolic stress distribution in Figure 2, bottom, corresponds to an eccentricity of 0.294 h (1, 4). The difference between the two eccentricity values is considered negligible.

This relationship between the eccentricity of the thrust resultant and crack depth applies to ultimate compression only (parabolic stress distribution, Figure 2, bottom). Working stress considerations (linear triangular stress distribution, Figure 2, top) lead to a smaller crack depth (x). The eccentricity value (e) used in Equation 1 usually relates to working stress characteristics. Therefore the design approach of DIN 1045, Equation 1 linked to ultimate stress assumptions, is conservative and eliminates the requirement to check the crack depth at working stress level.
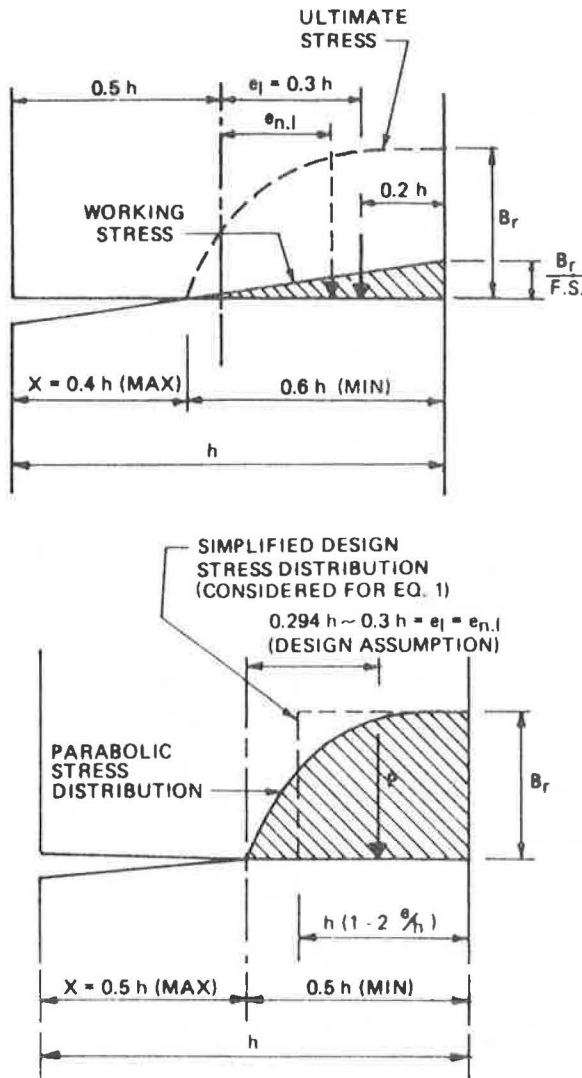
FIGURE 2 Different design assumptions at permissible eccentricity $e = 0.3\ h$: working stress design assumption and transition to ultimate stress level (*top*) and ultimate stress design assumption of DIN 1045 (*bottom*).

Safety Considerations

To account for irregularities in the structure, load uncertainties, and computational inaccuracies, a factor of safety (*FS*) is considered in arriving at a permissible thrust value:

$$P_{\text{perm}} = P_e/FS \qquad (3a)$$

$$P_{\text{perm}} = P_0/FS \qquad (3b)$$

where *FS* is 2.5, as specified for unreinforced concrete components in DIN 1045.

DESIGN ACCORDING TO ACI 318.1

Unreinforced concrete members are covered by the Building Code Requirements for Structural Plain Concrete (ACI 318.1)

(6). Like most local codes, the ACI code has been developed primarily to address requirements of aboveground structures not underground structures. Consequently, working stress criteria only are provided for the design of unreinforced concrete members.

Working Stress Criteria

The principles of the working stress design concept are observed in ACI 318.1. Thus a linear elastic stress distribution in the lining is assumed. Both compression and tensile stresses must not exceed permissible values. Corresponding thrust limitations can be derived from stress restrictions in Section 6.3.6 of ACI 318.1 and Section 7.8 of ACI 322-72 (7):

$$(f_{au}/f_{ciu}) + [f_{bu(c)}/f_{cu}] \leq 1 \qquad (4)$$

with respect to limitations on compression and

$$f_{bu(t)} - f_{au} \leq f_{tu} \qquad (5)$$

with regard to the permissible tensile stress of the concrete where

$$f_{au} = \text{compression due to axial thrust,}$$
$$f_{bu(t)} = \text{tension due to bending, and}$$
$$f_{bu(c)} = \text{compression due to bending.}$$

Safety Considerations

The index (u) indicates that thrust and bending, factored by U, are considered for Equations 4 and 5. U is load factor according to ACI 318. All permissible stress values are governed by Section 6.2 of the code:

$$f_{cu} = \text{permissible bending compression,}$$
$$f_{ciu} = \text{permissible axial compression, and}$$
$$f_{tu} = \text{permissible bending tension.}$$

The permissible stress (f_{perm}), induced by service load (P_n) equals (f_n) (ϕ)/U. Therefore the factored permissible stresses as used in Equations 4 and 5 [i.e., induced by the factored load (P_u)] equal (f_n) (ϕ). f_n is nominal strength and ϕ is 0.65, strength reduction factor, according to ACI 318.1.

Permissible Thrust in the Lining

Permissible thrust values (P_{perm}), considering compression limits, can then be derived from Equation 4:

$$[(P_u/A_g)/f_{ciu}] + [P_u\,(e/S)/f_{cu}] \leq 1 \qquad (6a)$$

where S is $bh^2/6$, section modulus. By transformation,

$$P_{\text{perm}} = (f_{ciu})\,(f_{cu})/[(f_{cu}/A_g) + e\,(f_{ciu}/S)]\ U \qquad (6b)$$

Permissible thrust values with respect to tensile capacity can be derived from Equation 5:

$$(P_u \, e/S) - (P_u/A_g) \le f_{tu} \tag{7a}$$

and by transformation,

$$P_{perm} = f_{tu}/[(e/S) - (1/A_g)] \; U \tag{7b}$$

Equations 6b and 7b require the factored permissible stress values $[(f_n) \, \phi]$ contained in ACI 318.1, Section 6.2, and ACI 322-72, Table 7.1. The nominal strength values included in these parameters are broken out. Nominal strength (f_n) according to ACI 318.1 for flexure is

$$f_{cn} = f_c' \quad \text{(compression)} \tag{8}$$

$$f_{tn} = 5(f_c')^{1/2} \quad \text{(tension)} \tag{9}$$

For axial compression it is

$$f_{cin} = 0.6 \, f_c' \tag{10}$$

Instead of using Equations 6b and 7b, P_{perm} can be calculated using these nominal strength values:

$$P_{perm} = (0.6 \, f_c') \, (f_c') \, (0.65/[(f_c'/A_g) + e(0.6 \, f_c'/S)] \; U \tag{11}$$

substituting Equation 6b and

$$P_{perm} = [5(f_c')^{1/2}] \, 0.65/[(e/S) - (1/A_g)] \; U \tag{12}$$

substituting Equation 7b.

COMPARISON OF DIN 1045 AND ACI 318.1

Comparison of the two codes evaluates the impact of different design assumptions. Both concepts are expected to lead to structurally sound underground linings. However, the degree of conservatism implicit in the design assumptions varies, and this potentially affects the economy of the underground structure. The same factor of safety, $FS = 2.50$, is used for either concept to eliminate the effect of explicitly imposed safety margins. According to ACI 318.1,

$$f_{perm} = f_n \, (\phi/U) \tag{13a}$$

where ϕ is 0.65 (6) and U is 1.63, leading to $FS = 2.5$.

The value of 1.63 represents average load conditions; compared with the full range of U from 1.4 to 1.7,

$$f_{perm} = (0.65/1.63) \, f_n = 0.40 \, f_n \tag{13b}$$

According to DIN 1045,

$$f_{perm} = \beta r/2.5$$
$$\beta r = 0.56 \, \beta_{ws} \; (8)$$
$$f_c' = 0.85 \, \beta_{ws} \tag{14a}$$

$\beta_{ws} = f_w$ = cube strength, averaged from a test series according to DIN 1045.

By substitution,

$$f_{perm} = 0.66 \, f_c'/2.5 = 0.26 \, f_c' \tag{14b}$$
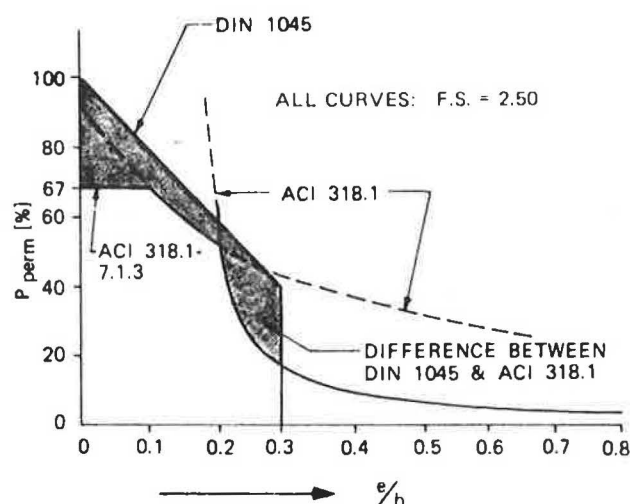

FIGURE 3 Comparison of permissible thrust according to ACI 318.1 and DIN 1045.

Permissible thrust values given in Table 1 and shown in Figure 3 are determined from Equations 1 and 3, and 11 and 12, respectively. Values are indicated as percentages of P_{perm} at zero thrust eccentricity determined according to DIN 1045.

Plain concrete provisions according to ACI 318.1 lead to a considerably smaller design capacity than do those calculated according to DIN 1045. This reflects the tensile stress limitations and the observation of a minimum eccentricity value specified in the ACI code. However, it must be noted that many local codes developed from DIN 1045 call for consideration of a minimum "unavoidable" eccentricity as well.

DEVELOPMENT OF THE COMBINED DESIGN CONCEPT

General

According to the Guidelines for Tunnel Lining Design of the Underground Technology Research Council (9), "structural codes should be used cautiously" because "most codes have been written for above-ground structures on the basis of assumptions that do not consider ground lining interaction." The guidelines further state: "Blind application of structural design codes is likely to produce limits on the capacity of linings that are not warranted in light of the substantial contributions from the ground and the important influence of construction methods on both the capacity and cost of linings." Similar statements have been made by other authors and organizations (5, 10, 11).

Careful evaluation of the applicability of existing structural codes to the design of tunnel liners was necessary. Comparison of the German and the U.S. standards for unreinforced concrete design indicates that the strength model used in DIN 1045 allows greater use of the lining capacity than do the ACI 318.1 working stress criteria. It is widely acknowledged that the strength criteria can represent a sound basis for the design of unreinforced concrete tunnel lining. Nevertheless, it is understandable that use of foreign codes (i.e., the German DIN code) is severely limited in the United States. Therefore a new concept needed to be developed to better reflect typical U.S. situations.

TABLE 1 PERMISSIBLE THRUST VALUES

ECCENTRICITY	ACI 318.1			DIN 1045
e/h	EQ. 11	EQ. 12	EQ. 11, 12	EQ. 1, 3
0	(92) %	— %	(92) %	100 %
0.1 *	67	—	67	80
0.2	53	64	53	60
0.3	43	16	16	40
0.4	37	9	9	(20)
0.5	32	6.5	6.5	(0)
0.6	28	4.9	4.9	—
0.7	25	4.0	4.0	—
0.8	23	3.3	3.3	—

* MINIMUM ECCENTRICITY ACCORDING TO ACI 318.1/SECTION 7.1.3

This design concept uses design parameters and safety definitions incorporated in ACI 318 (*12*). In addition, elements of the German standard are used, thus making use of a proven tool for applying strength criteria to unreinforced concrete design.

Figure 4 shows the sources used in developing the design approach. Elements of two codes are combined to arrive at the Combined Design Concept. Their applicability is subject to the extent of concrete cracking that corresponds to the eccentricity of the thrust resultant. For eccentricities up to a limit defined later, a strength design concept, referred to as Modified Strength Design, is used. For eccentricities that exceed the defined limit, a working stress concept is applied to the uncracked lining portion, thus averting further cracking of the concrete lining.
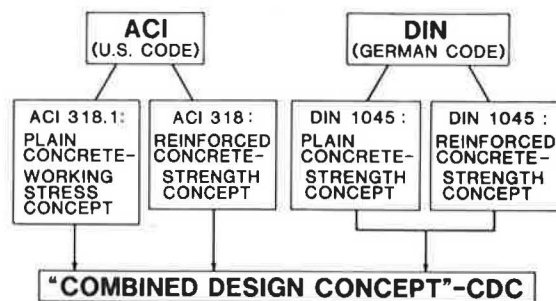

FIGURE 4 Derivation of the Combined Design Concept.

Modified Strength Design Based on ACI 318 and the German Standard

A liner's capability to sustain nonlinear behavior induced by an eccentric thrust is best modeled by the strength design approach. This is also indicated by the Alternate Design provisions in ACI 318 (*6, 12*) in which it is stressed that "the straight line theory [as it is used in the working stress method of ACI 318.1] applies only to design members in flexure without axial load." Such load conditions do not typically occur in arched structures.

The Modified Strength Design concept developed here follows the strength design concept (ACI 318) in the design assumptions made for stress and strain in the concrete. Deviating from ACI 318, however, the developed design concept considers the potential of tunnel liners to render reinforcement (*5, 10, 11*) unnecessary.

According to DIN 1045 and ACI 318, a simplified rectangular compression stress figure is recommended for design purposes unless test results call for other distributions. Simplified rectangular stress figures are derived differently in the design concepts shown in Figure 5. DIN 1045 and the Modified Strength Design define smaller ultimate compression stress blocks than are granted by ACI 318 (Figure 5, right). Corresponding ultimate strain assumptions are shown in Figure 5, left. The correlation between these ultimate stress-strain assumptions and working stress conditions has been shown in Figure 2. The effect on the conservatism implicit in the design assumptions is analyzed as follows.

According to ACI 318,

$$c = 3 \ [(h/2) - e] \tag{15a}$$

$$a = 0.85c = 2.55 \ [(h/2) - e] \tag{15b}$$

According to DIN 1045 and the Modified Strength Design,

$$\bar{a} = 2.0 \ [(h/2) - e] \tag{15c}$$

where $\bar{a}$ is the depth of the rectangular design stress block according to DIN 1045 and the Modified Strength Design.

The conservatism in the Modified Strength Design compared with ACI 318 regarding the width of the design stress block is expressed by

$$a/\bar{a} = 2.55/2.0 = 1.28$$

In the Modified Strength Design, ultimate thrust capacity is written as

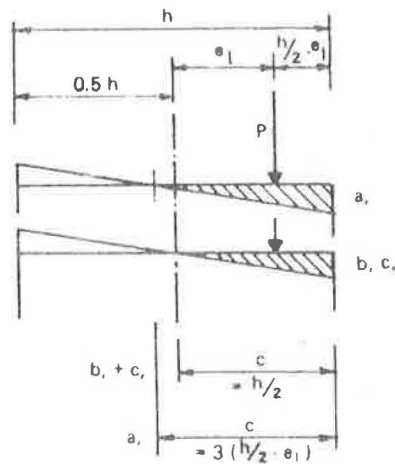$$P_e = (b) \ (h) \ (0.85 \ f_c') \ [1 - (2 \ e/h)] \tag{16a}$$

for $e > 0.1 \ h$ and as

$$P_0 = 0.8 \ (h) \ (b) \ (0.85 \ f_c') \tag{16b}$$

for $e \leq 0.1 \ h$

Because these equations are based on tension cracking, their validity is limited to reaching a permissible crack width as specified later.
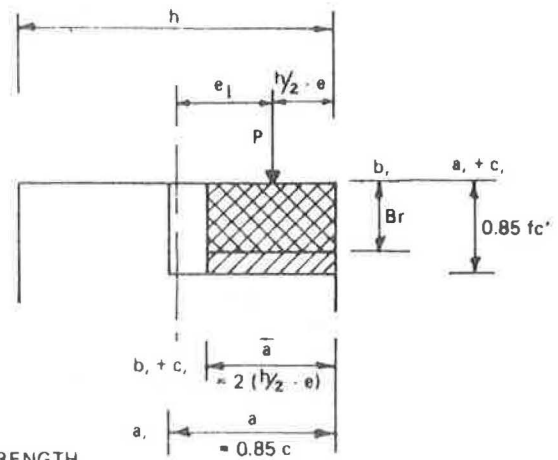
FIGURE 5 Design parameters for strength design concepts: strain design assumption (*left*) and ultimate stress design block (*right*).

Crack Restrictions

Distortion is controlled by limiting thrust eccentricity (e), to $e = 0.30$ of the liner thickness (h). In the ultimate stress design, such eccentricity corresponds to cracking to the centroid of the cross section. In comparison, stresses from service loads lead to smaller crack depths (Figure 2, top).

Design Based on ACI 318.1 Beyond Maximum Permissible Cracking

Crack restrictions limit the use of the strength design method to a maximum eccentricity of 0.3 h. However, greater eccentricities will not cause further cracking as long as tension stresses in the uncracked liner portion remain within the elastic range. A pertinent design approach is provided by the working stress method of ACI 318.1. Observation of the permissible concrete tension (Equations 9 and 13) yields the permissible values of liner thrust at given eccentricities.

Figure 6 shows a linear stress distribution as induced by service load (P_n) at the critical eccentricity ($e = 0.3\ h$). A comparison with ultimate stress conditions is shown in Figure 2. The depth of the compressed liner portion ($\bar{h}_{compr}$) is

$$\bar{h}_{compr} = 3 \times (0.2\ h) = 0.6\ h \tag{17}$$

When the concrete's tensile strength is considered, an even larger uncracked liner depth ($\bar{h}$) is actually provided. It is governed by the provision of ACI 318.1 that the thrust (P_n) must not cause tensile stresses that exceed permissible values (6). From Equation 7b it generally follows that

$$P_{perm} = f_{t\ perm}/[(e/S) - (1/A_g)] \tag{18}$$

and

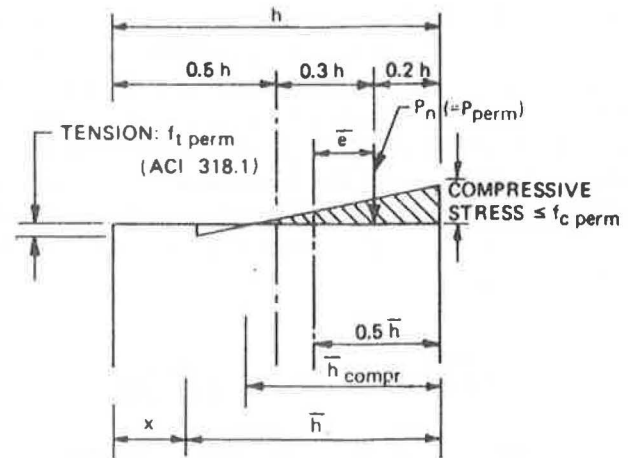$$P_{perm} = f_{t\ perm}/[(\bar{e}/\bar{S}) - (1/\bar{A}_g)] \tag{19}$$

FIGURE 6 Cracking of the lining at the strength design limit, $e = 0.3\ h$.

where

$\bar{A}_g =$ $b\bar{h}$, uncracked portion of the lining pertinent to thrust eccentricity $e = 0.3\ h$;

$\bar{h} =$ uncracked depth of the lining pertinent to $e = 0.3\ h$;

$\bar{S} =$ $b\bar{h}^2/6$, section modulus of the uncracked lining portion; and

$f_{t\ perm} =$ $5(f_c')^{1/2}\ (\phi/U)$, according to Equations 9 and 13.

Uncracked lining depth ($\bar{h}$), is determined by iteration from Equation 20 developed from Equation 19 after substitution and transformation. It was demonstrated earlier that the uncracked depth of the cross section is greater than 0.6 h. For most cases, a value of approximately 0.65 h will result from the iteration. The value of P_{perm} considered in Equation 20 pertains to $e = 0.3\ h$ and is calculated according to Equation 16a with the additional consideration of a safety factor (FS).

$$[2 - 1.2\ (h/\bar{h})]/b\bar{h} = f_{t\ perm}/P_{perm} \tag{20}$$

The thrust eccentricity ($\bar{e}$) can then be expressed by $\bar{h}$:

$$\bar{e} = [0.5\,\bar{h} - (0.5\,h - e)] \tag{21}$$

P_{perm} for $e > 0.3\,h$ is calculated using Equations 19–21:

$$P_{\text{perm}} = [5(f_c')^{1/2}]\,0.65/[(\bar{e}/\bar{S}) - (1/b\bar{h})]\,U \tag{22}$$

Equation 22 is reflected in Figure 7. The graph shows how P_{perm} increases with a decreasing thrust eccentricity $(\bar{e})$.
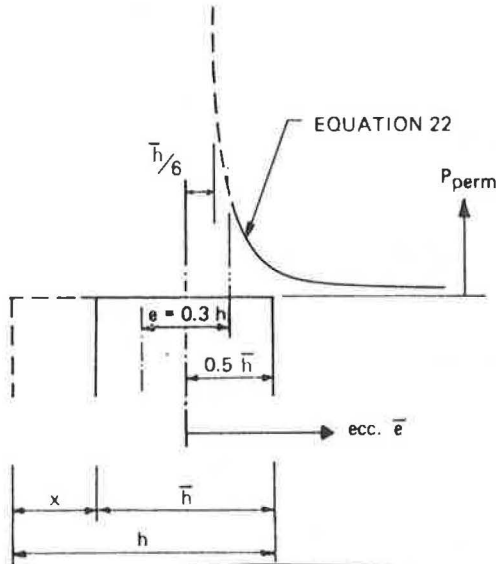

FIGURE 7 Permissible thrust versus eccentricity, $e > 0.3\,h$.

Safety Considerations

In accordance with ACI building code requirements for both reinforced and unreinforced concrete, a permissible thrust value must include an explicit safety factor that is related to the ultimate design capacity of the liner. Load uncertainties are hereby accounted for by a factor (U). Reduction of the ultimate design strength by ϕ accounts for imperfections of the structure and computational inaccuracies. A compound safety factor can thus be written:

$$FS = U/\phi \tag{23}$$

Explicit and implicit safety components are analyzed elsewhere (8). They are considered in determining the factors U and ϕ to be used in the proposed liner design concept. The evaluation suggests that a conservative approach will be taken by meeting the safety factor provisions of ACI 318.1 ($\phi = 0.65$ and $U = 1.4$ to 1.7). These parameters provide a compound safety factor of from 2.15 to 2.62 according to Equation 23.

Comparison of Design Concepts

The graph shown in Figure 8 reflects the computation of permissible thrust values given in Table 2. Although Table 2 covers the full range of load factors (1.4 through 1.7), $U = 1.63$ is based on the graphic display.

For the Combined Design Concept ($\phi = 0.65$) the factor $U = 1.63$ corresponds to $FS = 1.63/0.65 = 2.5$. Values in Table 2 are indicated as percentages of P_{perm} at zero eccentricity determined according to DIN 1045. Values in parentheses relate to
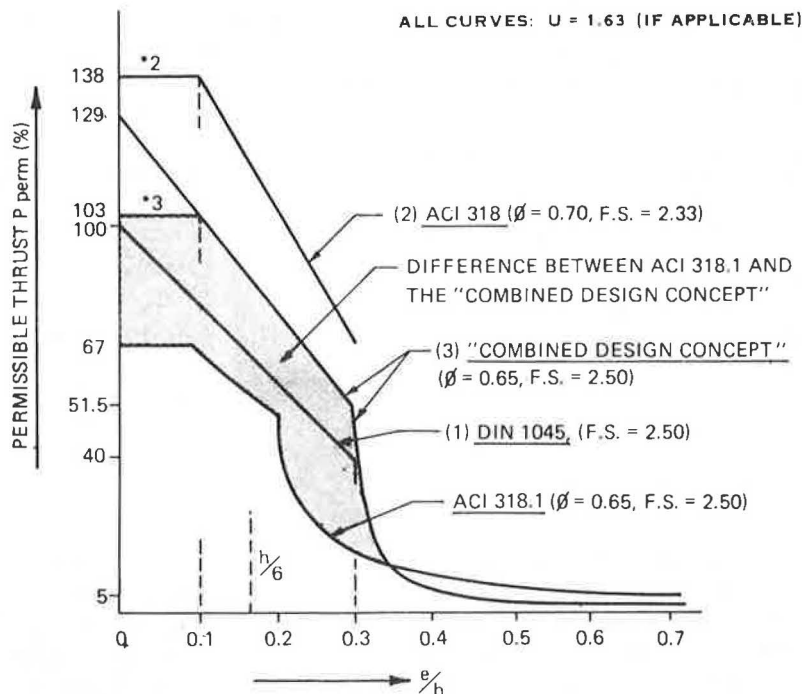

FIGURE 8 Comparison of permissible thrust according to ACI 318 ("Strength Design"), DIN 1045, ACI 318.1, and the Combined Design Concept.

TABLE 2 DESIGN FACTORS

| Reference to Figure 8 | | Thrust Eccentricity | Design Criteria | | | | | Permissible Thrust |
| | | | Design Safety | | | Ultimate Design Strength | Width of Stress Figure | |
Design Concept	Notes	e/h	$\emptyset$	U	F S	% of R_r	[(h/2) - e]	%
(1) DIN 1045		0.0	—	—	2.50	100	2.00	100
		0.3			2.50	100	2.00	40
(2) ACI 318	*2	0.0	0.70	1.4 (1.7)	2.00 (2.43)	129	2.00	161 (132)
		0.3	0.70			129	2.55	82 (68)
(3) "Modified Strength Design"	*3	0.0	0.65	1.4 (1.7)	2.15 (2.62)	129	1.60	120 (99)
	*1	0.3	0.65			129	2.00	60 (49)

Note: *1, equivalent to modified strength design for eccentricity $e \geq 0.3\ h$. *2, $e_{min} = 0.11\ h$, according to the strength design parameter used [see Figure 5, and refer to equation 15b in which $a = 2.55 (0.5\ h - e)$]; $a_{max} = 2.55 (0.5\ h - 0.11\ h) = h$. *3, $e_{min} = 0.10\ h$; according at ACI 318.1, Section 7.1.3.

the maximum load factor ($U = 1.7$), and other values relate to minimum safety factors permitted by the codes. For a comparison with P_{perm} according to ACI 318.1 refer to Figure 3.

Figure 8 indicates permissible thrust values subjected to the design parameters (Figure 5) and safety factors used. The Combined Design Concept (i.e., the Modified Strength Design for eccentricities smaller than $0.3\ h$) yields similar results for concentric thrust but allows higher permissible values for eccentric thrust in the lining than does DIN 1045.

A prime purpose of combining two distinctly different concepts in the Combined Design Concept was to extend the applicability of unreinforced concrete design. In particular, the combined concept allows for eccentricities greater than the strength design limit (cracking to one-half of the lining depth; $e_{max} = 0.3\ h$), if the liner thrust is small enough to satisfy working stress criteria imposed on the uncracked portion of the lining depth. This provision can be crucial to permitting use of unreinforced concrete where load cases generate low thrust values that increase the eccentricity of the thrust resultant (e.g., dead weight).

Figure 8 also makes it possible to evaluate the impact of using the working stress design according to ACI 318.1 over different eccentricity ranges. P_{perm} is evaluated for eccentricities greater than $0.3\ h$. It shows that ACI 318.1 yields slightly more conservative results if used only for $e > 0.3\ h$ (Figure 7 and Equation 22). In contrast, the curve describing Equation 12 is based on the unlimited use of ACI 318.1 (i.e., for all eccentricities). This results in a higher P_{perm} for $e > 0.33\ h$.

Summary of the Combined Design Concept

The permissible liner thrust according to the design concept developed in this paper is shown in Figure 9. The eccentricity (e) of the compression resultant corresponds to a linear elastic stress distribution and is indicated as a variable input parameter. Permissible thrust values are given as percentages of the permissible thrust at zero eccentricity.

Figure 9 is designed from Equations 16a, 16b, 22, and 23 and is valid regardless of specific design data if restrictions on
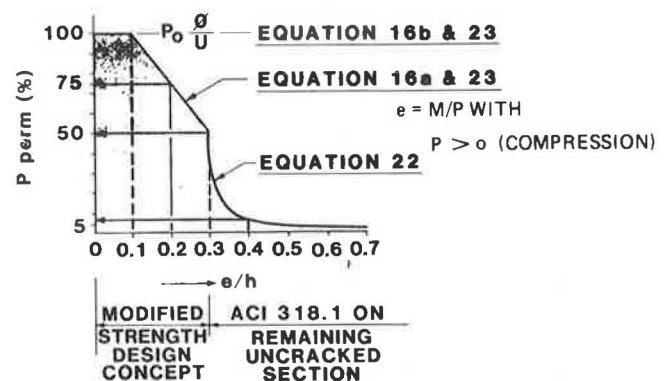

FIGURE 9 Design chart for permissible liner thrust.

compression stress constitute the criterion for P_{perm}. This is the case for eccentricities of up to $0.3\ h$. For eccentricities greater than $0.3\ h$, permissible tension stresses govern P_{perm}. According to ACI 318 and DIN 1045, permissible tension stress induced by service loads is related to compression strength characteristics by a nonlinear correlation law. As a result, limits on compression and tension, respectively, diverge with increasing concrete strength. The graph in Figure 9 is based on a concrete strength frequently used for tunnel lining design ($f_c' = 3,500$ psi). Therefore, for most cases, Figure 9 can be used as a design tool, which makes it possible to avoid analytical calculations. Also, deviations from other concrete strengths are negligible for most practical purposes.

NOTATION

a = depth of rectangular design stress block according to ACI 318;

$\bar{a}$ = depth of rectangular design stress block according to DIN 1045 and the Modified Strength Design method;

A_g = gross area of overall section;

$\bar{A}_g$ = gross area of uncracked section portion after partial cracking;

b = width of compression face of lining (unit width);

c = distance from extreme compression fiber to neutral axis, design assumption;

e = eccentricity of thrust in the lining, general;

e_l = eccentricity of liner thrust resulting from linear elastic calculations (service load condition);

$e_{n.l}$ = eccentricity of liner thrust after partial cracking (nonlinear lining behavior);

$\overline{e}$ = eccentricity of liner thrust measured from the centroid of the uncracked liner portion after partial cracking of the unreinforced structure;

f_c' = compressive strength of concrete specified in ACI 318;

f_w = average cube strength of a series according to ACI 318;

f_u = compressive stress in concrete induced by P_u, general;

f_{au} = compression stress induced by P_u at zero eccentricity;

$f_{bu(t)}$ = concrete tension stress induced by M_u;

$f_{bu(c)}$ = compression stress induced by M_u;

$f_{c\,perm}$ = permissible compressive stress in concrete, general;

f_{cu} = $f_{cn}\,\phi$, permissible compression stress in concrete subjected to M_u;

f_{ciu} = $f_{cin}\,\phi$, permissible compression stress in concrete subjected to P_u at $e = 0$;

f_{tu} = $f_{tn}\,\phi$, permissible tension stress in concrete subjected to M_u;

f_n = nominal concrete strength, general;

f_{cin} = nominal concrete compression strength subject to P at $e = 0$ according to ACI 318.1;

f_{tn} = nominal concrete tension strength subject to M according to ACI 318.1;

f_{cn} = nominal concrete compression strength subject to M according to ACI 318.1;

$f_{t\,perm}$ = permissible concrete tension stress induced by P_n;

FS = factor of safety;

h = overall thickness of lining;

$\overline{h}$ = minimum thickness of an uncracked lining portion;

M = bending moment, general = $P\,(e)$;

M_u = factured moment = $P_u\,(e)$;

P = axial load, general;

P_n = nominal axial load (= service load);

P_u = factured axial load;

P_c = concrete compressive force induced by P_u;

P_0 = ultimate thrust at zero eccentricity;

P_e = ultimate thrust at given eccentricity;

P_{perm} = permissible P_n;

S = section modulus of overall section;

$\overline{S}$ = section modulus of uncracked section portion;

U = load factor;

x = depth of cracked section portion;

β_{ws} = f_w, average cube strength of a series according to DIN 1045;

β_{wn} = Minimum value of any cube strength test series according to DIN 1045;

β_r = Design strength for concrete according to DIN 1045; and

ϕ = strength reduction factor.

ACKNOWLEDGMENT

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