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## ALTERNATIVE DESIGN APPROACH FOR THERMAL EFFECTS

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### ABSTRACT

Stresses resulting from thermal effects are self-relieving, which thermal forces and moments are greatly reduced or completely relieved with the progress of concrete cracking or reinforcement yielding. The dependence of thermal effects on concrete cracking and reinforcement yielding implies that thermal loads will be influenced by mechanical loads because conditions of concrete cracking and reinforcement yielding will be different for each mechanical load.

Various approaches have been used to account for thermal effects in design, but the design consideration for thermal effects has remain a challenge for structural engineers due to the nature of complexity for accurate assessment of thermal effects.

This paper provides an alternative design approach for thermal effects. Unlike the conventional approaches used in ACI 349 and ACI 359, where the main emphasis was given for estimating thermal loads and combining them with mechanical loads, the proposed design approach calculates thermal loads on the basis of design strengths. Design strengths are reduced by subtracting thermal loads and the remaining concrete design is to examine reduced design moments with mechanical moments. The proposed design approach provides more accurate, yet simple assessment of thermal effects on member design.

### INTRODUCTION

Thermal effects refer to response of a structure when the structure is exposed to varying temperature at its surface or temperature gradient through its cross section. Thermal effects generate deformations and internal forces and moments are secondary products which occur when constraints are provided against deformations. The amount of restrained thermal deformations is a function of imposed temperature distribution, details of a concrete section and restrained condition. In other words, the amount of restrained deformations, which can be presented in terms of strains and curvatures, is not affected by either concrete cracking or reinforcement yielding or mechanical loads.

The design approach for thermal effects given in ACI 349 (2006), ACI 349.1R (2007) and ACI 359 (2010) require estimating internal loads induced by temperature effects and combining them with mechanical loads. The challenge of this design approach is the dependence of thermal loads on mechanical loads. For an accurate estimate of thermal loads, they need to be calculated for each load combination as thermal loads may vary with mechanical loads.

In order to account the impact of concrete cracking and reinforcement yielding for mechanical and thermal loads, a nonlinear finite element analysis may be considered. However, it requires complex and iterative calculations. More realistic approach to account for concrete cracking is a hand-calculation method presented in ACI 349.1R. This hand calculation method calculates thermal moment using a set of formulas. Since thermal moments are calculated based on mechanical loads and thermal gradients, reasonable solutions can be obtained. However, the solution of this method is only valid when mechanical loads produce a cracked section and reinforcement does not yield. It is important to note that both nonlinear finite element analysis method and the hand calculation method calculate thermal loads by considering mechanical loads and thermal deformations, which makes possible accurate assessment of

thermal loads. However, thermal loads may have to be repeatedly calculated under different load combinations.

Another design approach is the use of an elastic finite element analysis method with a reduced modulus of  $0.50E_c$  for concrete in ACI 349.1R. A value of  $0.5E_c$  is recommended based on past practice, which accounts for various effects of cracking, creep and yielding. Estimated thermal loads are not dependent on mechanical loads due to the use of elastic analysis. This method is considered a simple and approximate approach but the rational of using the value of  $0.5E_c$  is often questioned.

Even though the hand calculation method and the elastic finite element analysis method with a reduced modulus of  $0.50E_c$  are convenient for calculating thermal moments, they have limited capability for accounting for cracking of concrete and yield of reinforcement and, thus, the optimum design is difficult to achieve. On the other hand, a nonlinear finite element analysis may provide accurate estimate of thermal loads, but is complex and computationally expensive. Moreover, thermal loads need to be evaluated for each load combination due to the dependency of thermal loads on mechanical loads.

This paper introduces an alternative design approach for thermal effects, which provides an elegant yet more economical solution for considering thermal effects on designing concrete structures.

## PROPOSED DESIGN APPROACH FOR THERMAL EFFECTS

Fig. 1(a) illustrates the effect of thermal gradient on a moment and curvature response. Thermally-induced moments vary with concrete cracking and reinforcement yielding. However, it is important to note that restrained thermal curvatures are constant unless changes of restrained conditions occur. Gurfinkel (1971) and Kohli and Gürbüz (1975) developed analytical tools to estimate thermal moments using a constant restrained thermal curvature. Gurfinkel (1971) also found that a thermal curvature induces smaller moment with the increase of mechanical moment. The same trend can be observed in Fig. 1(a).

Total moment,  $M_u$ , is the sum of mechanical and thermal moments. The total moment should be equal to or less than the design flexural strength,  $\phi M_n$ , in order to meet the strength requirements given in ACI 349. Considering that thermal moments reduce with the increase of mechanical moments, the thermal moment at which the total moment is equal to the design flexural strength,  $\phi M_n$ , will be the minimum thermal moment which satisfies the code strength requirement of  $\phi M_n \geq M_u$ . This minimum thermal moment is referred as design thermal moment,  $M_{th}'$ , in this paper. The use of design thermal moment enables to calculate a usable design flexural strength, which can be defined as design flexural strength minus (factored) design thermal moment ( $\phi M_n' = \phi M_n - M_{th}'$ ). As such, the remaining concrete design can be conducted using mechanical moments and usable design moments,  $\phi M_n'$ . Note that the design flexural strength,  $\phi M_n$ , will be replaced by  $M_{allow}$  in ACI 359, which are calculated based on allowable stress and strain limits.

Accordingly, a  $P$ - $M$  interaction curve for the design axial strength,  $\phi P_n$ , and the usable flexural strengths,  $\phi M_n'$ , can be determined, as illustrated in Fig. 1(b). Note that thermal effects are taken into account in  $P$ - $M$  interaction curve, which represents design strengths.

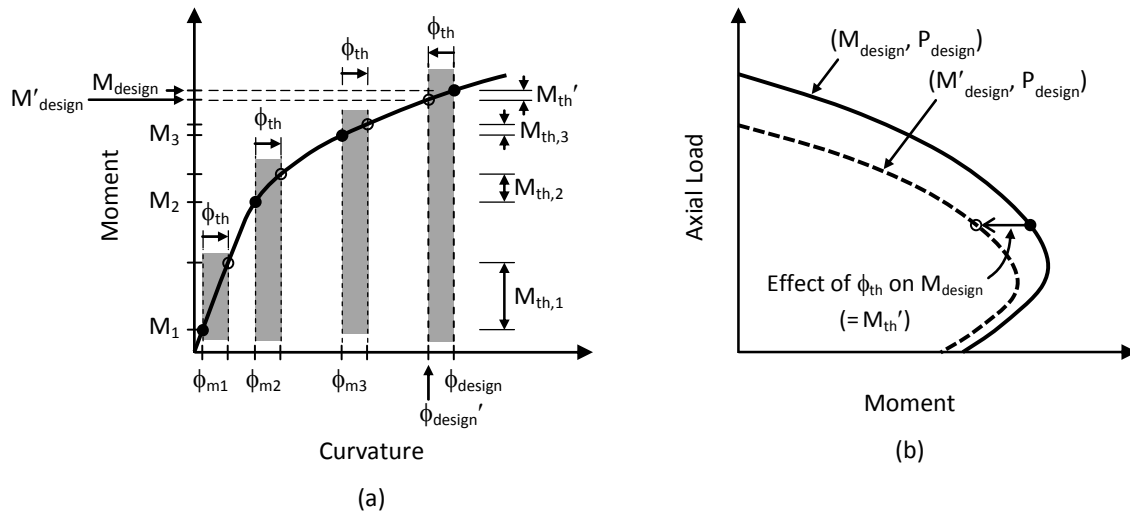


Figure 1. Effect of thermal curvature on moment-curvature response and on  $P$ - $M$  interaction curve

### Application of Proposed Design Approach in ACI 349

The proposed design approach can be applied to both ACI 349 and ACI 359. Thermal moments are calculated in the following steps:

- (1) Generate a moment-curvature response for a given axial load.
- (2) Calculate a design flexural strength,  $\phi M_n$ , and measure a corresponding curvature from the moment-curvature response.
- (3) Determine a design thermal moment,  $M_{th}'$ , from the design flexural strength,  $\phi M_n$  (see Fig. 1).
- (4) Repeat steps (1) through (3) by changing the axial load.

A moment-curvature response is calculated using a Hognestad's concrete model (1951) and bilinear stress-strain relationship for reinforcement in this study. A rectangular concrete section of 36 in. by 12 in. in Fig. 2 is used to illustrate the proposed design approach for thermal effects. This section is considered as a part of an axisymmetric structure with the specified compressive strength of concrete,  $f'_c$ , of 5 ksi and the specified yield strength of reinforcement,  $f_y$ , of 60 ksi. The structure is exposed to thermal gradient of  $\Delta T = 150^\circ\text{F}$  with hot on the interior face and cold on the exterior face. Positive moment is defined as one that produce tensile stress on the exterior face. Accordingly the applied thermal gradient generates a positive moment.

Fig. 3 shows the  $P$ - $M$  interaction curves for design strengths ( $\phi M_n$ ,  $\phi P_n$ ) and usable design strengths ( $\phi M_n'$ ,  $\phi P_n$ ) for mechanical loads. Note that the design strengths are reduced for thermal loads associated with the thermal gradient of  $\Delta T = 150^\circ\text{F}$  in the  $P$ - $M$  interaction curves for usable design strengths ( $\phi M_n'$ ,  $\phi P_n$ ). As such, when the mechanical loads within the usable design strengths are combined with thermal loads, the total mechanical plus thermal loads will not exceed the design strengths ( $\phi M_n$ ,  $\phi P_n$ ) given in ACI 349. The  $P$ - $M$  interaction curve for usable design strengths ( $\phi M_n'$ ,  $\phi P_n$ ) shows that negative flexural strengths increases due to the thermal gradient because positive thermal moments counteract against negative mechanical moments. However, Section E.3 of ACI 349 prohibits thermal loads from reducing mechanical loads. Therefore, mechanical loads should be located within the shaded area to satisfy both requirements for mechanical loads only and mechanical plus thermal loads.

In order to examine the validity of usable design strengths ( $\phi M_n$ ,  $\phi P_n$ ), thermal loads are calculated for actual mechanical loads, as shown in Fig. 4. The examined mechanical loads are widely distributed within the design interaction curve ( $\phi M_n$ ,  $\phi P_n$ ). Note that mechanical loads (2.4), (3.5), (4.6), (5.5), (6.4), (7.3) and (7.4) are located outside of the usable design strengths ( $\phi M_n'$ ,  $\phi P_n$ ). Therefore, when these mechanical loads are combined with thermal moments due to  $\Delta T = 150^\circ\text{F}$ , they are expected to exceed the design interaction curve ( $\phi M_n$ ,  $\phi P_n$ ). Fig. 5 presents the results of the total loads, which combine mechanical loads and thermal loads in the design interaction curve ( $\phi M_n$ ,  $\phi P_n$ ). This figure confirms that mechanical loads (2.4), (3.5), (4.6), (5.5), (6.4), (7.3) and (7.4) exceeds the design strengths when thermal moments due to  $\Delta T = 150^\circ\text{F}$  are combined. Thermal moments for each mechanical load are calculated using a moment-curvature response. Calculated thermal moments vary with mechanical axial loads and moments (see Fig. 4 and Fig. 5).

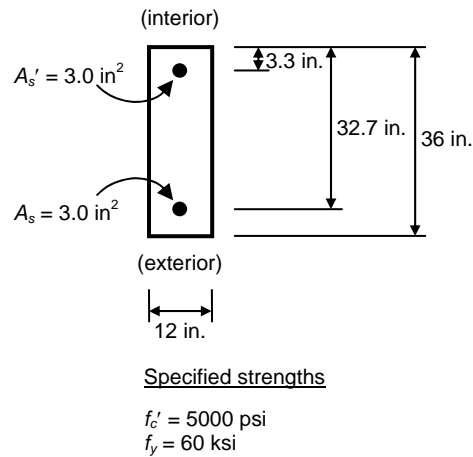


Figure 2. Section details

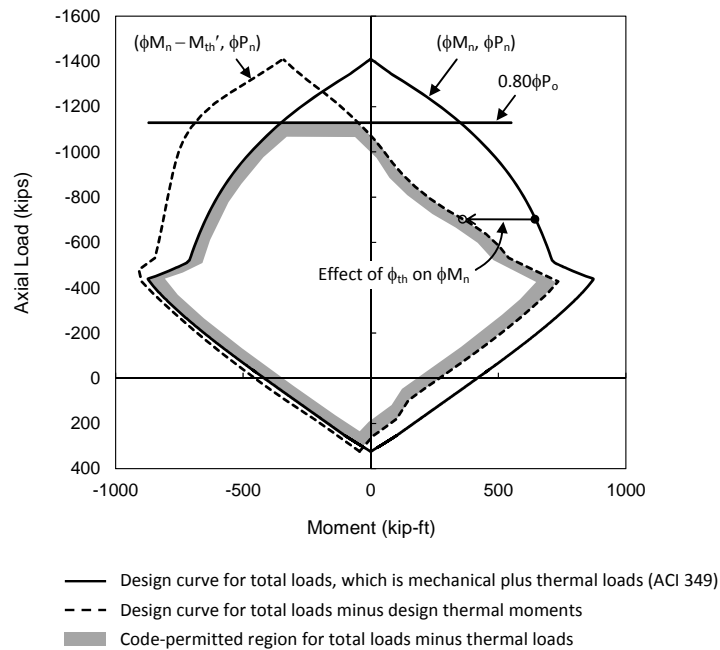


Figure 3. Effects of thermal gradient  $\Delta T = 150^\circ\text{F}$  on  $P$ - $M$  design curve: ACI 349

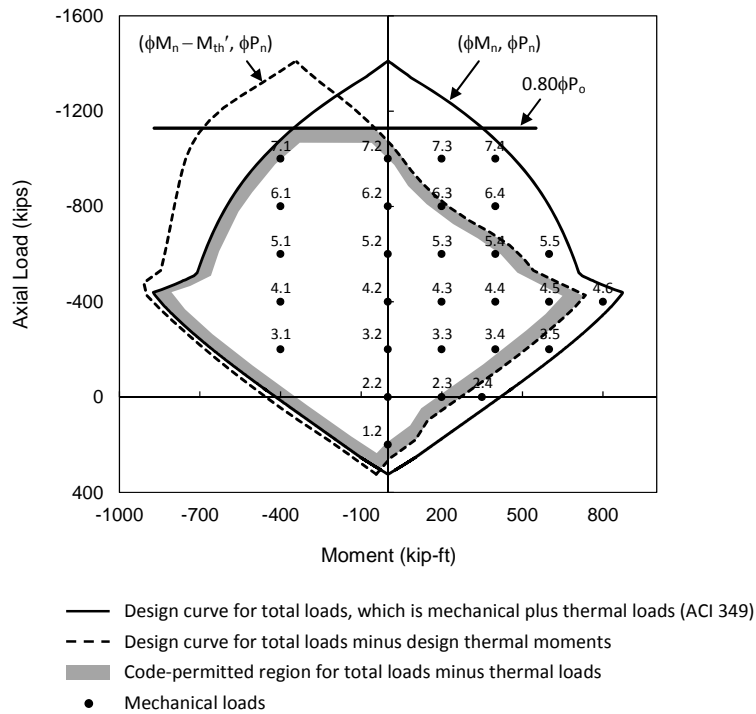


Figure 4. Mechanical loads on  $P$ - $M$  design curve: ACI 349

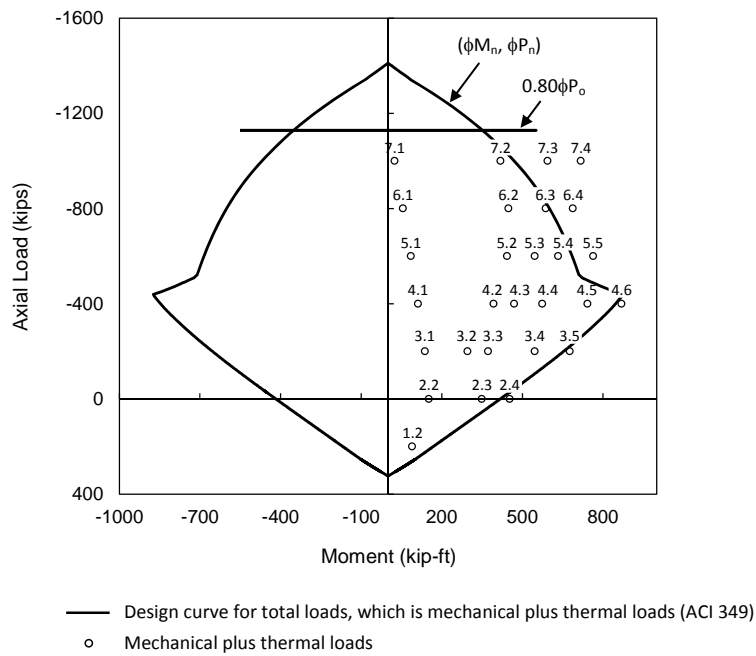


Figure 5. Mechanical plus thermal loads on  $P$ - $M$  design curve: ACI 349

### ***Application of Proposed Design Approach in ACI 359***

ACI 359 specified allowable stress and strain limits for members subjected to axial forces and moments. Different stress and strain limits are specified for different load category: (1) factored primary loads, (2) factored primary and secondary loads, (3) service primary loads, and (4) service primary and secondary loads. Primary loads are those which require equilibrating applied loads. Secondary loads are not required for equilibrating the applied loads. Examples of secondary loads are internal forces due to shrinkage and temperature changes. Therefore design strengths can be calculated for each load category.

Design strengths for factored loads are used to study thermal effect on  $P$ - $M$  interaction curve. Similar with ACI 349, a moment-curvature response is generated using a Hognestad's concrete model and bilinear stress-strain relationship for reinforcement. The stress in reinforcement is limited to  $0.9f_y$  per ACI 359. Design strengths for factored primary plus secondary loads are determined using allowable stress and strain limits of concrete and reinforcement from moment-curvature responses. The concrete section in Fig. 2 is evaluated for thermal gradient of  $\Delta T = 150^\circ\text{F}$ . Usable design strengths ( $M_{design}$ ,  $P_{design}$ ) are also calculated by reducing design strength for factored primary plus secondary loads by thermal loads associated with the thermal gradient of  $\Delta T = 150^\circ\text{F}$ .

The results are shown in Fig. 6. The shaded area represents the code permitted area to factored primary plus secondary loads minus thermal loads due to  $\Delta T = 150^\circ\text{F}$ . Design strengths for factored primary loads only can be also calculated using its allowable stress and strain limits. Comparison of the  $P$ - $M$  curves between the code permitted area to factored primary plus secondary loads minus thermal loads and the design strengths for factored primary loads only suggests that the concrete section is governed by the requirements for factored primary loads only. In other words, the thermal effect due to  $\Delta T = 150^\circ\text{F}$  does not control the design because the design strength increase due to the inclusion of secondary loads exceeds the thermal load demand. It is important to note that the allowable stress limit of  $0.9f_y$  for reinforcement is used in the bilinear stress-strain relationship per Paragraphs CC-3422 and CC-3511 of ACI 359. As a result, ACI 359 does not permit moment increases after the stress in reinforcement reaches  $0.9f_y$ , which is different from ACI 349.

In order to demonstrate the conclusion that the design of the concrete section in Fig. 2 is governed by factored primary loads only, mechanical loads are applied to the extent that they are just located at the design boundary, as shown in Fig. 7. Thermal loads are calculated for each mechanical load using moment-curvature response and added to the mechanical loads. The results are presented in Fig. 8. It can be observed that all mechanical plus thermal loads are within the design curve for factored primary plus secondary loads, which proves that thermal loads due to  $\Delta T = 150^\circ\text{F}$  do not control the section design per ACI 359.

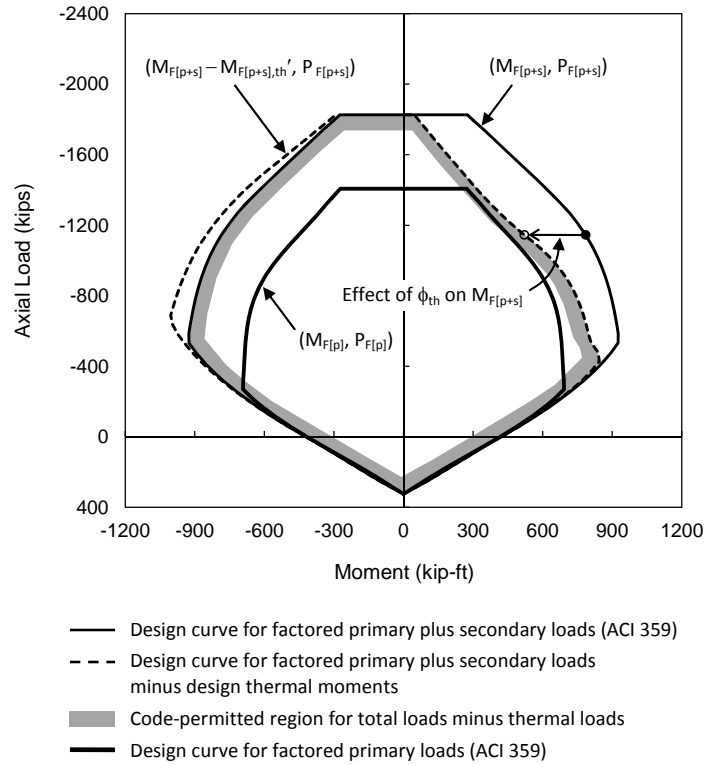


Figure 6. Effects of thermal gradient on  $P$ - $M$  design curve: ACI 359

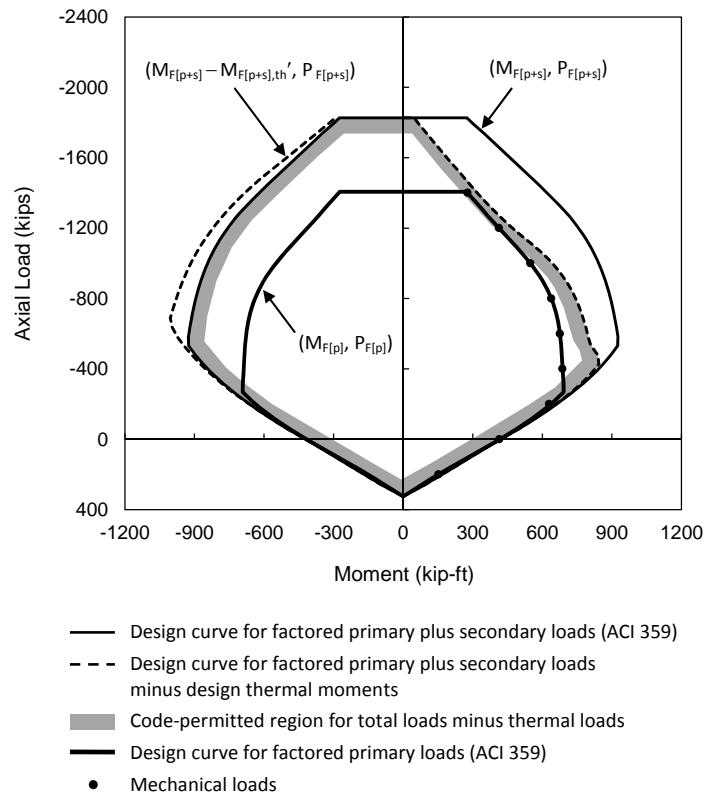


Figure 7. Mechanical loads on  $P$ - $M$  design curve for factored loads: ACI 359

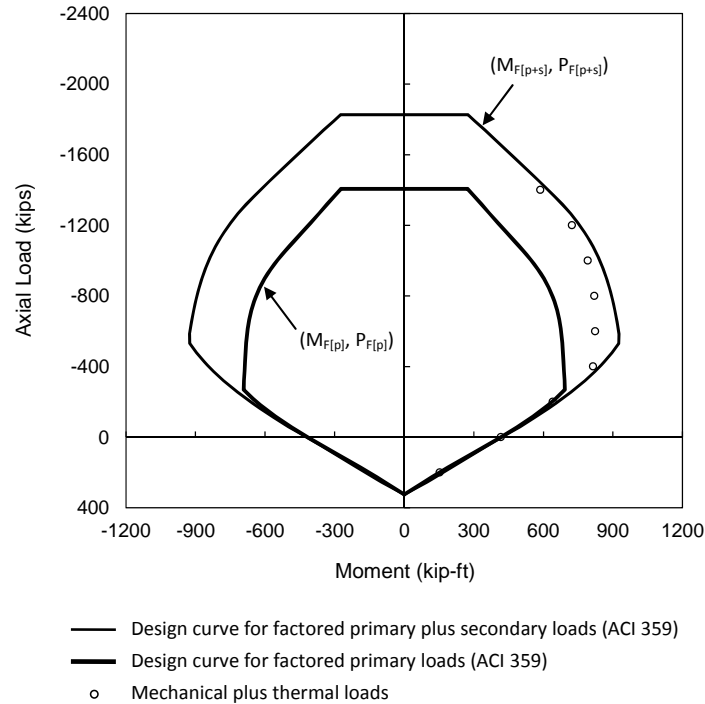


Figure 8. Mechanical plus thermal loads on  $P$ - $M$  design curve for factored loads: ACI 359

## CONCLUSION

A novel alternative design approach for thermal effects is proposed in this paper. Based on the fact that thermal moments reduce with the increase of mechanical moments, design thermal moments are calculated based on the design flexural strength,  $M_{design}$ . As such, the calculated design thermal moments will be the minimum thermal moment which satisfies the code strength requirement. Design strengths are reduced by the design thermal moments, which are defined as usable design strength. The remaining concrete design can be performed using mechanical moments and usable design moments. The validity of the proposed design approach for thermal effects is examined per ACI 349 and ACI 359.

Unlike the conventional methods for calculating thermal moments, the design thermal moment enables to account for cracking of concrete and yield of reinforcement and, thus, provides the minimum estimate of required thermal moment within each code context. Therefore, the proposed design approach provides a simple, elegant yet more economical solution for considering thermal effects on designing concrete structures.

## NOMENCLATURE

$A_g$	= gross area of concrete section
$A_s$	= area of longitudinal tension reinforcement
$A_s'$	= area of longitudinal compression reinforcement
$A_{st}$	= total area of longitudinal reinforcement
$f_c'$	= specified compressive strength of concrete



$f_y$	= specified yield strength of reinforcement
$M_{design}$	= design flexural strength
$M'_{design}$	= usable flexural strength, $M_{design} - M_{th}'$
$M_{F[p+s],th}'$	= design thermal moment at factored primary plus secondary loads
$M_{F[p]}$	= flexural strength for factored primary loads (ACI 359)
$M_{F[p+s]}$	= flexural strength for factored primary plus secondary loads (ACI 359)
$M_n$	= nominal flexural strength
$M_n'$	= usable flexural strength, $M_n - M_{th}'$
$M_{th}$	= moment due to temperature effects
$M_{th}'$	= design thermal moment
$M_u$	= factored total moment
$P_{design}$	= design axial strength
$P'_{design}$	= usable axial strength, $P_n - P_{th}'$
$P_{F[p]}$	= axial strength for factored primary loads (ACI 359)
$P_{F[p+s]}$	= axial strength for factored primary plus secondary loads (ACI 359)
$P_o$	= nominal axial strength at zero eccentricity, $0.85f'_c(A_g - A_{st}) + f_y A_{st}$
$\phi$	= strength reduction factor
$\phi_m$	= curvature due to mechanical loads
$\phi_{th}$	= curvature due to temperature effects
$\phi_{design}$	= curvature corresponding to design flexural strength
$\Delta T$	= temperature gradient
$\phi M_n$	= design flexural strength

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