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Behavior of Reinforced Concrete at Elevated Temperatures

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By George N. Freskakis, M. ASCE

KEY WORDS: Concrete properties; reinforcing steel properties; elevated temperatures; sectional behavior; compressive strength; modulus of elasticity; thermal expansion; stress-strain relationships; strain limits.

ABSTRACT: A study is presented concerning the behavior of reinforced concrete sections at elevated temperatures. Material properties of concrete and reinforcing steel are discussed. Behavior studies are made by means of moment-curvature-axial force relationships. Particular attention is given to the load carrying capacity, thermal forces and moments, and deformation capacity. The effects on these properties of variations in the strength properties, the temperature level and distribution, the amount of reinforcing steel, and limiting values of strains are considered.

BEHAVIOR OF REINFORCED CONCRETE AT ELEVATED TEMPERATURES

By George N. Freskakis[1], M. ASCE

INTRODUCTION

The behavior of reinforced concrete sections at elevated temperatures is a subject of great interest in the design of nuclear plant facilities and particularly LMFBR plants where structures can be exposed to severe temperature conditions from potential liquid metal spills. The nonlinearities in material properties, the variation of properties with temperature, tensile cracking, and creep effects in the case of sustained temperatures, affect the build-up of thermal forces as well as the load carrying capacity and the deformation capacity or ductility of structural members. Despite the analytical difficulties in accounting for the material behavior of concrete it is essential, when severe temperatures are considered, to include realistic behavior in order to avoid undue and impractical conservatism in the design. This paper presents a study on the material properties, and the behavior characteristics of reinforced concrete sections at elevated temperatures which are essential for a basic understanding of overall structural behavior and the formulation of methods and criteria for structural analysis.

Material properties at elevated temperatures summarized here cover the strength properties and the coefficient of thermal expansion for concrete and reinforcing steel. In the case of concrete the strength properties are

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based on an extensive study of these properties (6) while the coefficient of thermal expansion is based on rather limited data for the purpose of studying structural behavior. For reinforcing steel the properties are based on accepted relationships for steels.

The behavior of reinforced concrete sections is examined by means of moment-curvature-axial force relationships which account for both the effect of temperature on the material properties and the mechanical effects induced by the tendency for thermal expansion. Of particular interest are the load carrying capacity, the thermal forces, and the deformation capacity. The effects on these properties of variations in the strength properties with temperature, the temperature level and distribution across a section, the amount of reinforcing steel, and limiting values of compressive strains are considered. The effect of creep which becomes significant at sustained elevated temperatures is not in the scope of this paper.

MATERIAL PROPERTIES AT ELEVATED TEMPERATURES

Strength Properties of Concrete

It is well known that the compressive strength and the modulus of elasticity of concrete decrease with exposure to elevated temperature. The magnitude and variation of the reduction in these properties with temperature, however, is influenced by a multitude of factors resulting in a wide scatter of experimental results. An extensive study of these properties, presented in Reference (6), considered the various factors and established relationships for two general types of test conditions, "cold" and "hot" testing. In "cold" testing the test specimens are heated gradually to a specified temperature, are allowed to remain or heat soak at that temperature for a period of time, then are allowed to cool to ambient and are tested. In "hot" testing the specimens are heated gradually to the specified temperature, are allowed to heat soak and are tested while at that temperature. Hot testing conditions are more appropriate for structures under thermal gradients and for this reason the relationships corresponding to these conditions were adopted, from Reference (6), for these behavior studies. The upper and lower bound relationships for strength and the modulus of elasticity are shown in Figure 1 and the stress-strain temperature curves in Figures 2 and 3. It should be noted that the stress-strain curves are shown to extend to strain limits much higher than allowed by the present codes and were used in this form to study sectional behavior. The effect of strain limits is discussed in this paper.

Thermal Expansion of Concrete

The thermal expansion of concrete depends on a number of factors including mix proportions, moisture content, age, and the rate of heating. The most important factor, however, is the mineral composition and structure of the aggregate. Concrete mixtures with high quartz content have the highest coefficients of thermal expansion while those containing little or no quartz, such as limestone concrete have the lowest coefficients.

The coefficient of thermal expansion for concrete varies with temperature and generally increases at higher temperatures. Test results of this property at elevated temperatures are limited for temperatures below 300°F and rather scarce above. Some of the results found in literature for the average coefficient of thermal expansion, α, are shown in Figure 4 together with a general relationship established from these data. The proposed relationship for α starts out with a value equal to that specified in the code [(4)] for normal temperature then follows the trend of the experimental which show a linear increase with temperature above 300^{O}F.

Properties of Reinforcing Steel

Stress-strain curves for reinforcing steel at normal temperatures exhibit an initial elastic portion up to the yield point, a plastic range where strain increases at a constant or nearly constant stress, and a strain-hardening range where strain increases with stress. A relationship at normal temperature has been developed for Grade 60 bars using the results reported in Reference (1) together with the ASTM Specification (A615) for yield stress and tensile strength.

There is a lack of information on the properties of reinforcing bars at elevated temperatures, however, for the purpose of this study it is assumed that reinforcing bars exhibit the same behavior described in Reference (3) for structural steels, i.e., the tensile and yield strength generally decrease and the modulus of elasticity also drops with increasing temperature. The σ-ε curves for reinforcing steel at elevated temperatures, shown in Figure 5, were obtained from the curve at normal temperature by adjusting the yield value, modulus of elasticity and tensile strength, according to the reductions indicated in Reference (3) for low alloy steels. It should be pointed out that since the steel strength is not affected significantly in the range of interest in this study, small deviations from the actual strength do not affect the basic behavior of reinforced concrete sections.

The average coefficient of thermal expansion, α, for reinforcing steel may be assumed the same as that recommended in the AISC Specification[8] for structural steels. This relationship is given by the following equation:

$$\alpha = (6.1 + 0.0019\ T) \times 10^{-6}$$

Where T is the temperature in question.

SECTIONAL RESPONSE AT ELEVATED TEMPERATURES

Moment Curvature Relationships

The behavior of concrete sections and the influence of various factors on the behavior can be best represented by relationships between moment, curvature, and axial force. In order to develop such relationships for the case of elevated temperatures it is important to consider both the effect of temperature on the material properties and the mechanical effects induced by the tendency for expansion.

The effect of elevated temperatures on the material properties was discussed in the previous sections. In order to explain the mechanical effects, consider Section A-A of the beam in Figure 6 which is under some nonlinear temperature gradient. The section tends to expand to the shape $\alpha\Delta T$ but due to internal restraints remains plane and assumes the position B-B. If the rotation of the beam, and hence of the cross section, is totally prevented, but axial expansion is allowed, the final position of the section will be at A'-A' while if both rotation and translation are prevented the section will remain in its original position A-A. In any case the offsets between the free thermal expansion line $\alpha\Delta T$ and the final line represent mechanical strains and hence stresses. The thermal axial force, P_t, and moment, M_t, may be obtained by summing up the stresses, σ, and the moments of the stresses over the entire cross section.

Moment curvature force relationships for sections under thermal gradients may be obtained by methods similar to those when the temperature is not involved, i.e. select a curvature ϕ and calculate the forces and moments corresponding to different positions of the section. For the purpose of this study a computer program was developed that uses the following numerical procedure to develop the moment-curvature relationship corresponding to a given axial force.

a. The section is divided into a discrete number of elements and the thermal strain of each element, i, is calculated as $(\varepsilon_t)_i = \alpha_i \Delta T_i$

b. A plane section is passed at a curvature ϕ and strains ε_f. The mechanical strains are calculated as

$$\varepsilon_i = (\varepsilon_f)_i - (\varepsilon_t)_i = (\varepsilon_f)_i - \alpha_i \Delta T_i$$

c. Stresses at the centroid of each element are calculated from the temperature dependent σ-ε relationships and the corresponding force and moment are obtained from the summations

$$P = \sum_{i=1}^{n} \sigma_i \; A_i$$

$$M = \sum_{i=1}^{n} \sigma_i \; Y_i \; A_i$$

where Y_i is the distance of element i from the centroidal axis of the section.

d. The value of P is compared with the force under consideration and if different the section is moved to a new position maintaining the same ϕ and the process is repeated until convergence.

e. A new curvature is selected and steps c and d are repeated.

A typical moment-curvature diagram for a section under a thermal gradient is shown in Figure 7 for a particular value of axial force, P. The intersept of the diagram with the horizontal, ϕ, axis represents the rotation that would take place if there were no rotational restraints. The intersept of the diagram and the vertical, M, axis represents the thermal moment of the section when it is restrained against rotation, i.e., the fixed end thermal moment which will be simply referred to as "thermal moment". The peak moment represents the moment capacity of the section corresponding to the particular axial force P. The difference between the moment capacity and the thermal moment will be referred to as the "net moment (or bending) capacity" and is of particular interest since it represents a margin of safety or the moment capacity available for other loads or forces.

Axial forces may be due to loads other than thermal or they may be thermal forces resulting from axial restraints. A thermal force may vary from zero when a member is free to grow axially to a value corresponding to full axial restraint. The thermal force corresponding to full axial restraint will be referred to as the "full fixity force" and is of particular interest because it often represents an upper bound of the axial load.

General Characteristics

In order to study the behavior of reinforced concrete sections at elevated temperatures a 48" x 12" section (Figure 8) with f'_c = 4000 psi was selected, which may typically represent a strip of wall or floor in a structure. In a case that is used as a base to determine the effects of various factors, the section has one percent of Grade 60 reinforcing steel distributed equally at the two sides. Moment-curvature axial force relationships were obtained at normal temperature and for the thermal gradients of Figure 9(b) which have temperatures of 300^{o}F, 500^{o}F, and 800^{o}F at the face of the section and will be referred to by these temperatures. The gradients of Figures 9(a) and 9(c) were also used extensively to ensure that any conclusions drawn from results using the type II gradients are applicable to other temperature distributions as well. The stress-strain relationships used in this base case are those in Figure 1 which correspond to lower bound relationships for strength and elasticity. The tensile strength of concrete was neglected in the calculations.

Moment-curvature-axial-force diagrams for normal temperature are shown in Figure 10 and for the 300^{O}F type II thermal gradient in Figure 11. Both sets of curves show the same general behavior characteristics i.e. an increase in bending capacity at low values of the compressive force and a decrease at higher values, a loss of ductility with axial force, and higher stiffness in the presence of axial forces. The presence of a compressive force increases the thermal moment since it prevents or reduces the cracking of the section, however, at high compressive forces the thermal moment decreases due to the loss of stiffness of the section resulting from plastic strains. An increase in deformation capacity or ductility is observed at elevated temperatures.

Temperature Level and Distribution

In considering thermal effects both the temperature level and the distribution of temperature across the thickness of a section are important parameters. The level of temperature relates to the changes in material properties and the level of thermal stresses, while the shape relates to the distribution of stresses and hence to the resultant bending and axial forces. In this study, temperature level is defined as the temperature at the hot face of the section, and distributions are grouped into three basic types that cover the range from short to long durations of heat exposure (Figure 9).

The effect of the temperature level on the behavior is illustrated in Figure 12 for the case of the thermal gradient Type II. The higher temperature level results in greater loss of bending capacity in the presence of axial forces but has practically no effect in the case of pure bending where the capacity is governed by the reinforcing steel. As the thermal moment increases with the temperature level the net bending capacity decreases rapidly at higher temperatures. The stiffness EI, measured by the slope of the M-ϕ curves, is practically not affected by the level of temperature in the case of P = 0 but drops sharply in the presence of axial forces.

The different types of temperature distributions resulted in the same general behavior discussed earlier except that in the case of steady state gradients (Type III) there was a drop in the ductility. The severity, in terms of the net bending capacity, of different thermal gradients is illustrated in Figure 13. As expected, case (a) which represents a short duration of heat exposure is the least severe, however, the results on the other cases are not easily predictable. Of the two cases using a Type III distribtuion, case (c) with the steeper gradient, is more severe for specific values of axial compression but becomes less severe when conditions of full fixity are considered. In general the net bending capacity increases with axial compression in the region of the interaction diagram governed by tension and decreases in the region governed by compression and this should be taken into account in assessing different gradients.

In view of the results in Figures 12 and 13 it is worth noting that in terms of bending and axial force capacity reinforced concrete sections can be designed to sustain severe temperature gradients with levels of temperature much higher than allowed by the present codes.

Upper and Lower Bound Strength Relationships

In the behavior of concrete sections subject to thermal gradients, the compressive strength (f'_c) and the modulus of elasticity (E) have opposite effects; the compressive strength influences the load carrying capacity while the elasticity relates to the forces developed by various restraints. For this reason, the thermal response of sections at elevated temperatures may be bracketed by using the two sets of stress-strain-temperature curves shown in Figures 1 and 2, one of which is based on lower bound and the other on upper bound relationships for compressive strength and elasticity.

Some typical M-Ø-P curves corresponding to the 300°F Type II temperature gradient and the upper and lower bound σ-ε relationships are shown in Figure 14. These curves show that when the axial compression force is zero, the two sets of relationships result in almost the same bending capacities but for higher compressive forces the upper bound relationships result in much higher capacities. Thermal moments corresponding to the upper bound relationships are always higher and increase or decrease with the compressive force in a manner similar to the capacity.

In order to establish which set of relationship results in the most severe response with respect to the net bending capacity, extensive results were obtained in this study for all the thermal gradients shown in Figure 9 and using 1% and 2% of reinforcing steel. In summary, the following behavior was noted:

- In all cases, the upper bound relationships resulted in lower net moment capacities in the case of free axial expansion (P=0), however, the difference from the values corresponding to the lower bound relations is generally small (< 10%) except at temperature levels of 500^{o}F and above.

- In the case of the Type I gradients representing short duration of heat exposure the net moment capacity corresponding to a specific axial force was always lower for the upper bound relationships. The difference in values from the two sets of relationships was generally small particularly in the region of the interaction diagram governed by tension (<10%).

- For the gradients representing long duration of heat exposure, Types II and III, the net moment capacity corresponding to a specific axial force was lower (by less than 10-15% except for temperatures of 500^{o} and above) for the upper bound relationships in the region of the interaction diagram governed by tension, and significantly lower for the lower bound relationships in the region governed by compression except in the case of the 800^{o} gradient (Figure 15).

- The upper bound relationships always result in higher compressive forces than the lower bound relationships when axial expansion is restrained. These higher compressive forces increase the net moment capacity in the region of the interaction diagram governed by tension and decrease it in the region governed by compression thus reducing the difference between the values of net bending capacity obtained by the two sets of relationships.

- In the extreme case of full axial fixity the two sets of relationships generally resulted in almost identical values of net bending capacities (Figure 15). Exceptions were noted at low temperature levels (Type II, $T_1 = 150^0F$, $T_2 = 70^0F$) where the lower bound relationships resulted in the worse response, and in the case of the 800^0F Type II gradient where the upper bound relationships resulted in the worse response.

Based on the above observations it may be concluded that either set of relationships may result in a more severe response depending on the type of thermal gradient, the level of temperature, and the nature of the axial force i.e. whether it is a thermal and hence variable force or a specific force. The lower bound relationships generally result in values of the net bending capacity which are either lower (sometimes considerably lower), than the corresponding values from the upper bound relationships or higher by a small percentage ($\leq$ 10%) and may be used for most thermal stress calculations. The upper bound relationships, however, should be considered in the case of high temperature levels (500^0F and above) and in the case of short duration of heat exposure.

Effect of Reinforcing Steel

Reinforcing steel affects significantly the behavior of reinforced concrete sections at elevated temperatures and proper selection of the amount and its placement in the structure are essential in achieving an optimum design. Results that show the effect of the amount of reinforcing steel on the sectional properties at elevated temperatures are shown in Figure 16. As expected, an increase in the amount of reinforcing steel resulted in higher thermal moments and bending capacities. The net bending capacity shows a substantial increase as the amount of reinforcing steel increased from 1% to 2%. This improvement, however, sometimes diminishes at conditions of full axial fixity due to the build-up of higher compressive forces that may tend to decrease the bending capacity.

Proper distribution and placement of the reinforcing steel in a section are important in order to avoid excessive amounts that do not particularly contribute to the overall capabilities of a section. This is illustrated in Figure 16 where the amount of steel near the hot face (compression steel) is reduced to one half the amount without affecting significantly the net bending capacity of the section, which in fact increased at P=0.

Strain Limits

It is well known that the stress-strain curve for concrete descends beyond the point of maximum stress and material failure occurs at some lower stress level. At normal temperature, the ACI 318-77 Code recommends that the maximum usable strain be limited to 0.003 in/in or approximately 50 percent higher than the value corresponding to maximum stress while Reference 6 examines the behavior at elevated temperatures and recommends that the limit for unconfined concrete be extended to at least 0.004 in/in at temperatures of 500^{o}F and above.

Typical behavior curves presented so far in this study were obtained using the stress-strain relationships for concrete shown in Figures 2 and 3 without imposing any limit on the strains. The effect of strain limits has been considered separately using maximum strain values of 0.003 and 0.004 in/in and typical results shown in Figures 16 and 17, for the 300^{o}F and the 500^{o}F thermal gradients respectively, indicate that when strain limits are imposed the rotational ductility drops sharply as the temperature level increases. The curves for the 300^{o}F gradient show that for compressive forces up to values much higher than that corresponding to full axial restraint (600k) there is little or no change in the maximum bending capacity and the primary effect of the strain limits considered, is to reduce the ductility of the section. In the case of the 500^{o}F thermal gradient, the results show that in the range up to full fixity (1080k), a strain limit of 0.004 in/in has little or no effect on the bending capacity, however, the strain limit of 0.003 in/in results in capacity reductions up to almost 20 percent. For the 800^{o}F thermal gradient significant reductions in capacity occur with both the 0.004 and the 0.003 in/in strain limits. Reduction in the strength and ductility are significantly lower in the case of the upper bound relationship.

Tensile Strength of Concrete

The tensile strength of concrete is a very significant factor in thermal calculations involving small increase in the temperature above the reference level. However, when thermal gradients result in large strains, such as those considered in this study, the tensile strength of the concrete has no significant effect on either the thermal moment or the capacity and may be neglected without significant error.

SUMMARY AND CONCLUSIONS

A study has been presented concerning the behavior of reinforced concrete of elevated temperatures. In the first part of the paper, the structural properties of the component material, specifically the strength properties and the coefficient of thermal expansion, are reviewed and relationships are established for the behavior studies. In the second part of the paper, the characteristics of reinforced concrete sections are examined by means of moment-curvature-axial force relationships and the effect of various factors is assessed.

Of particular interest in the study are the effects of different strength elasticity relationships, the temperature level and distribution across the section, the reinforcing steel, strain limits, and the tensile strength of the concrete on the load carrying capacity and the ductility of sections. The results may be summarized as follows:

- The effect of elevated temperatures is to decrease the section capacity when axial forces are present, and with the build-up of thermal forces decrease significantly the net carrying capacity.

- In terms of bending and axial force capacity, reinforced concrete sections can be designed to sustain severe temperature gradients with levels of temperature much higher than allowed by the present codes.

- A comparison of results on the net moment capacity based on the upper bound and lower bound strength and elasticity relationships indicates that either set of relationships may govern the design depending on the level and distribution of temperature across the section, and the nature of the axial compression, i.e., whether it is a thermal and hence variable force or a specific force. The lower bound relationships are generally more appropriate for thermal stress calculations but the upper bound relationships should be considered for high temperature levels (500^{o}F and above) and in the case of short duration of heat exposure.

- The addition of reinforcing steel improves the net capacity of sections. Proper placement of the steel, however, is important and can result in significant reduction of the amount required.

- When strain limits are imposed, increases in the temperature level result in significant reductions in rotational ductility.

- For temperatures of 300^{o}F and perhaps up to about 400^{o}F, using limiting strains as low as 0.003 does not result in any significant loss of strength. Above these temperatures, there is a significant loss of strength in the presence of compressive forces.

- The tensile strength of the concrete is important in the calculation of thermal forces at low elevated temperatures but is insignificant in the case of severe temperatures as the ones considered in this study.

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NOTATION

The following symbols are used in this paper:

E = modulus of elasticity

f'_c = compressive strength of concrete

I = moment of inertia

M = moment

M_t = thermal moment

P = axial force

P_t = thermal axial force

T = temperature

T_1 = heated face temperature

T_2 = non-heated face temperature

α = coefficient of thermal expansion

ΔT = change in temperature

$\varepsilon, \varepsilon_f$ = strain

ε_t = thermal strain

σ = stress

ϕ = curvature

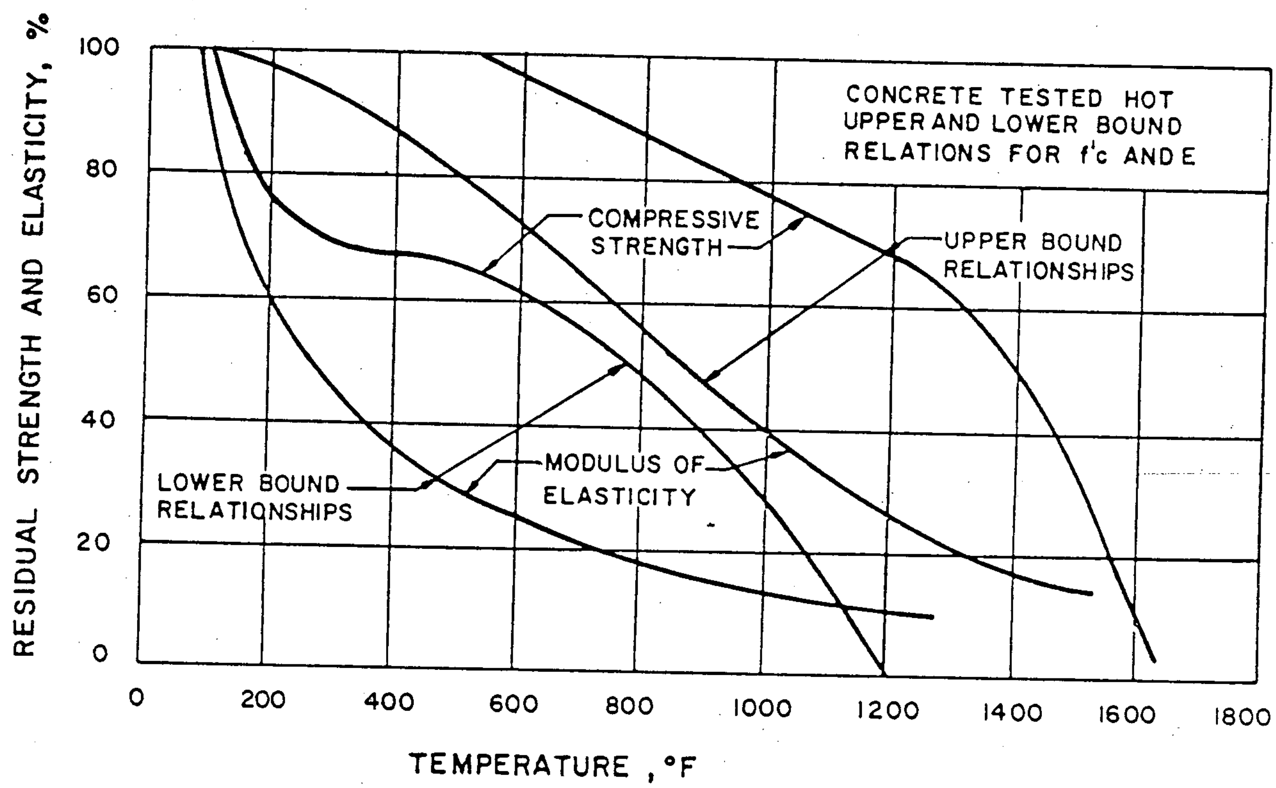

FIG. I UPPER AND LOWER BOUND RELATIONSHIPS FOR COMPRESSIVE STRENGTH AND MODULUS OF ELASTICITY (From Ref.6)

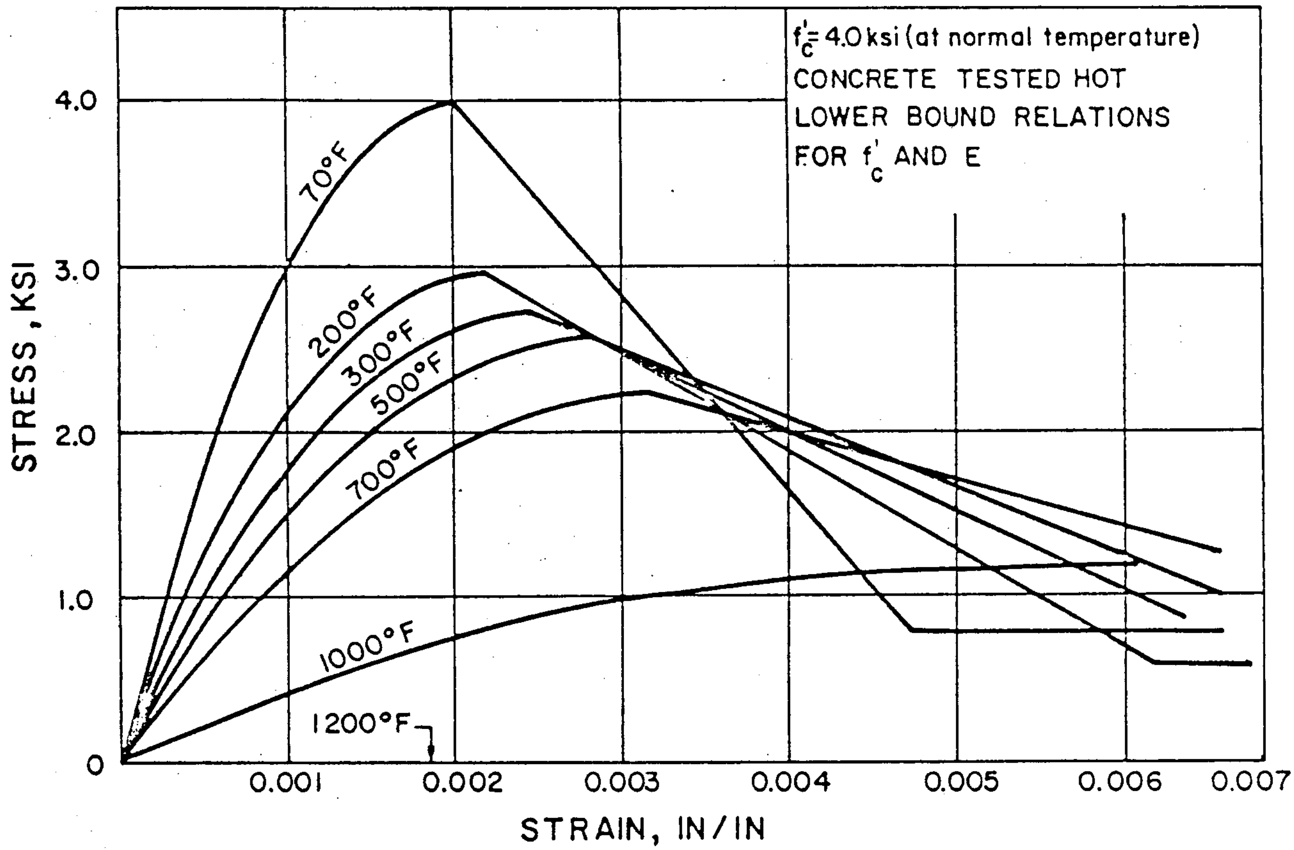

FIG. 2 STRESS-STRAIN RELATIONSHIPS FOR CONCRETE (L.B.)

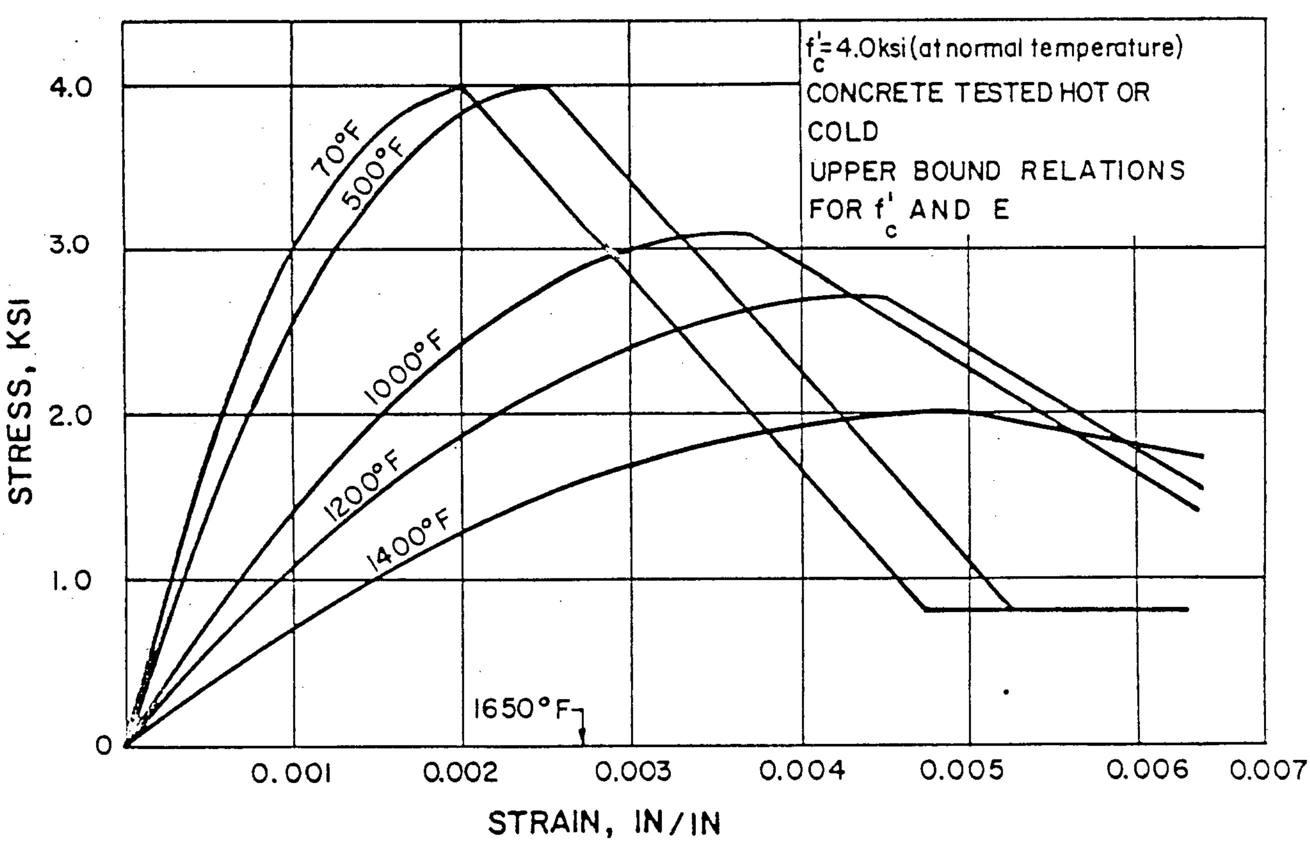

FIG. 3 STRESS-STRAIN RELATIONSHIPS FOR CONCRET (U.B.)

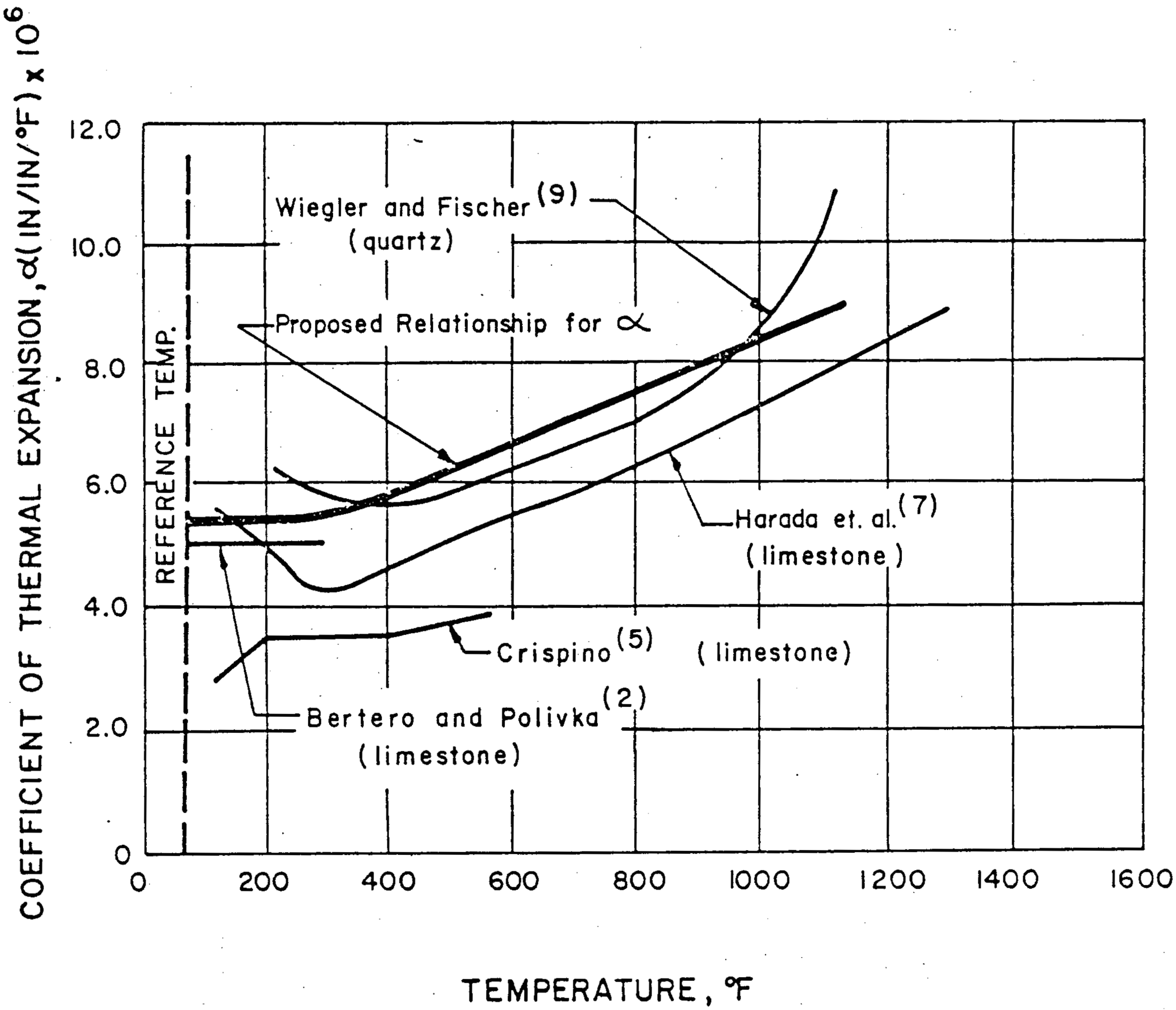

FIG.4 — VARIATION OF THE COEFFICIENT OF THERMAL EXPANSION FOR CONCRETE WITH TEMPERATURE

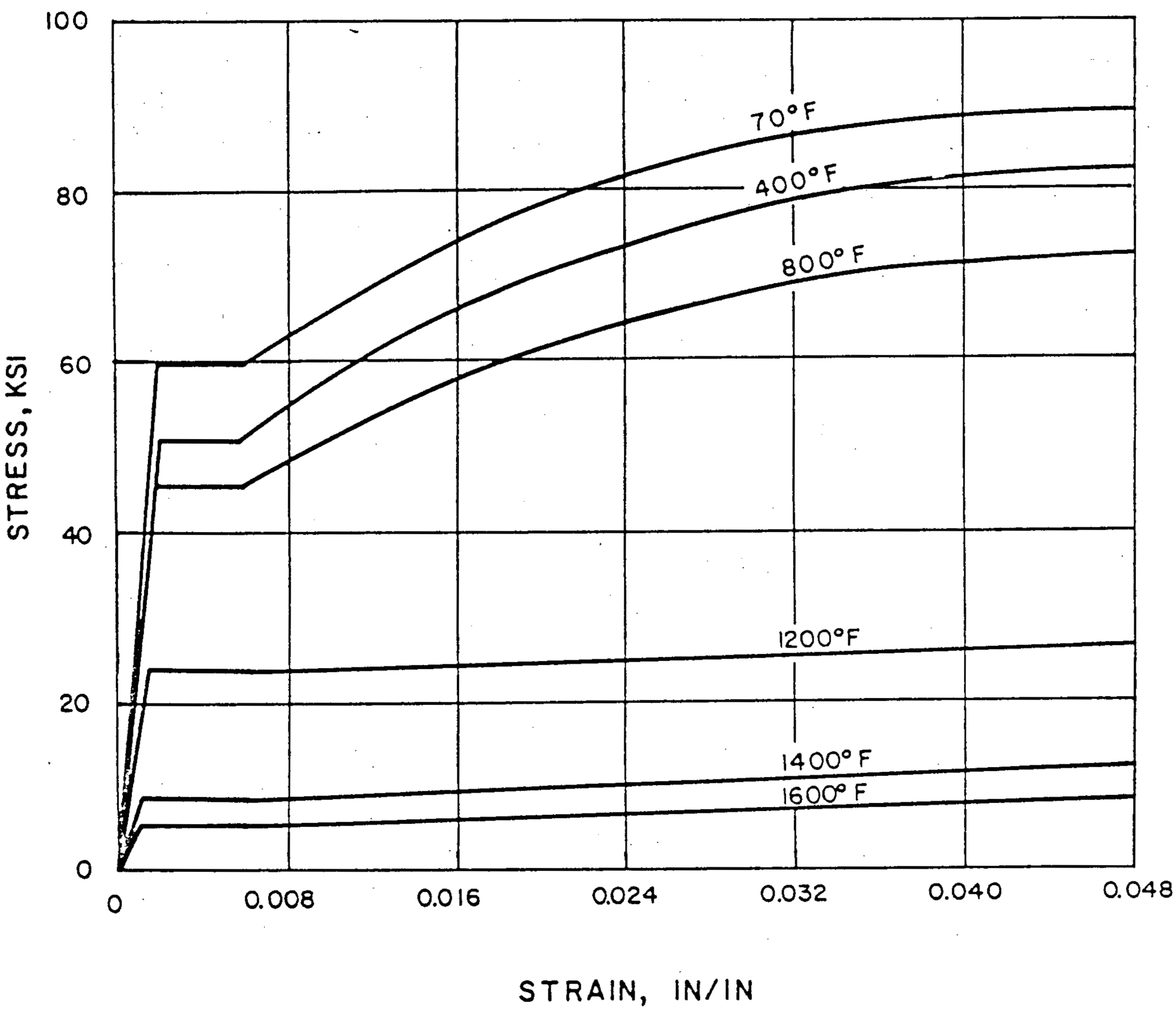

FIG. 5 STRESS-STRAIN RELATIONSHIPS FOR REINFORCING STEEL BARS

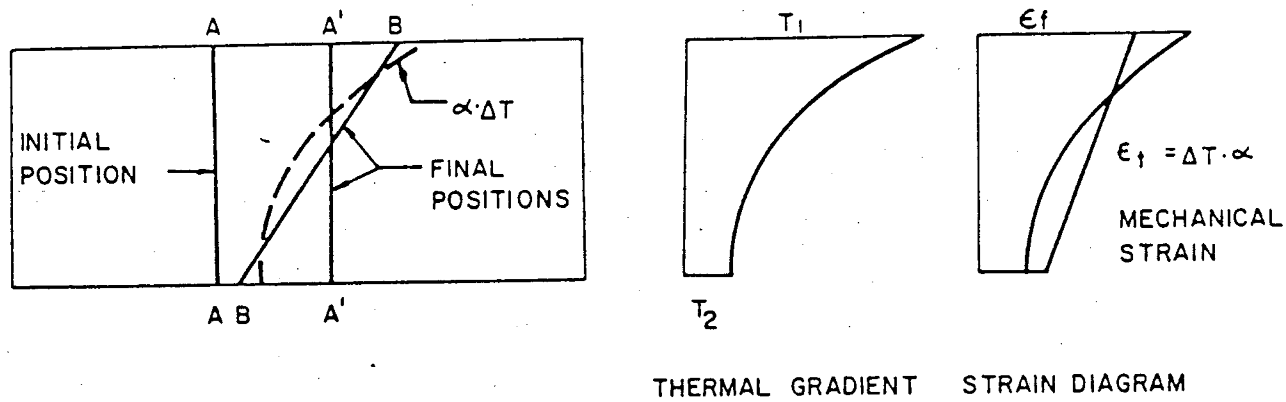

FIG. 6 - BEAM WITH THERMAL GRADIENT

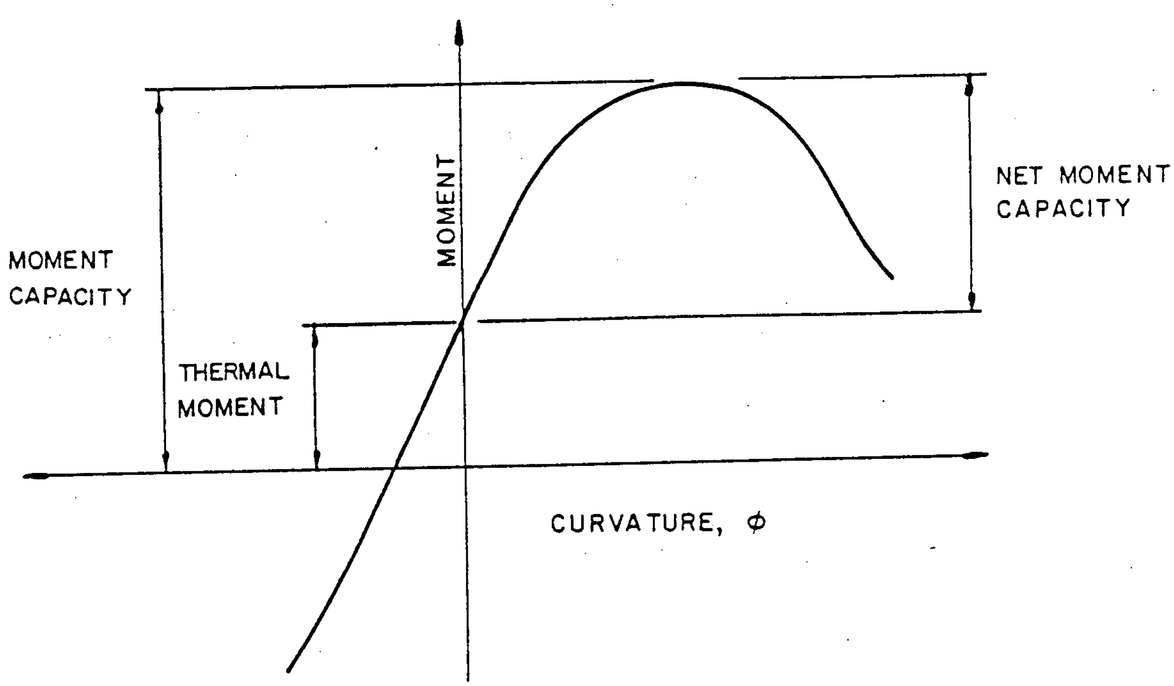

FIG. 7 - TYPICAL MOMENT-CURVATURE (M-ϕ) DIAGRAM
FOR SECTION UNDER A THERMAL GRADIENT

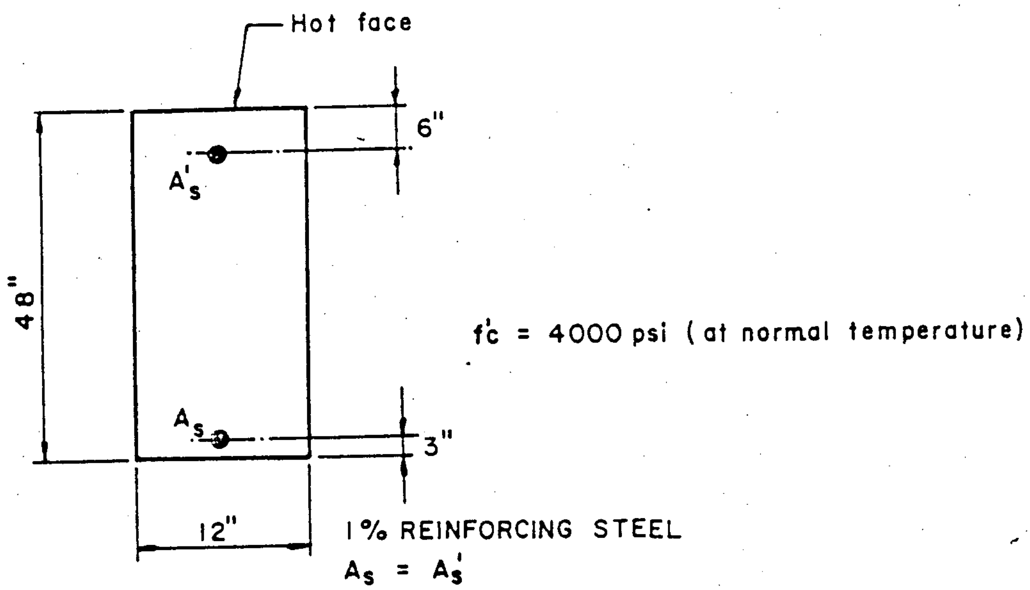

FIG. 8 SECTION PROPERTIES

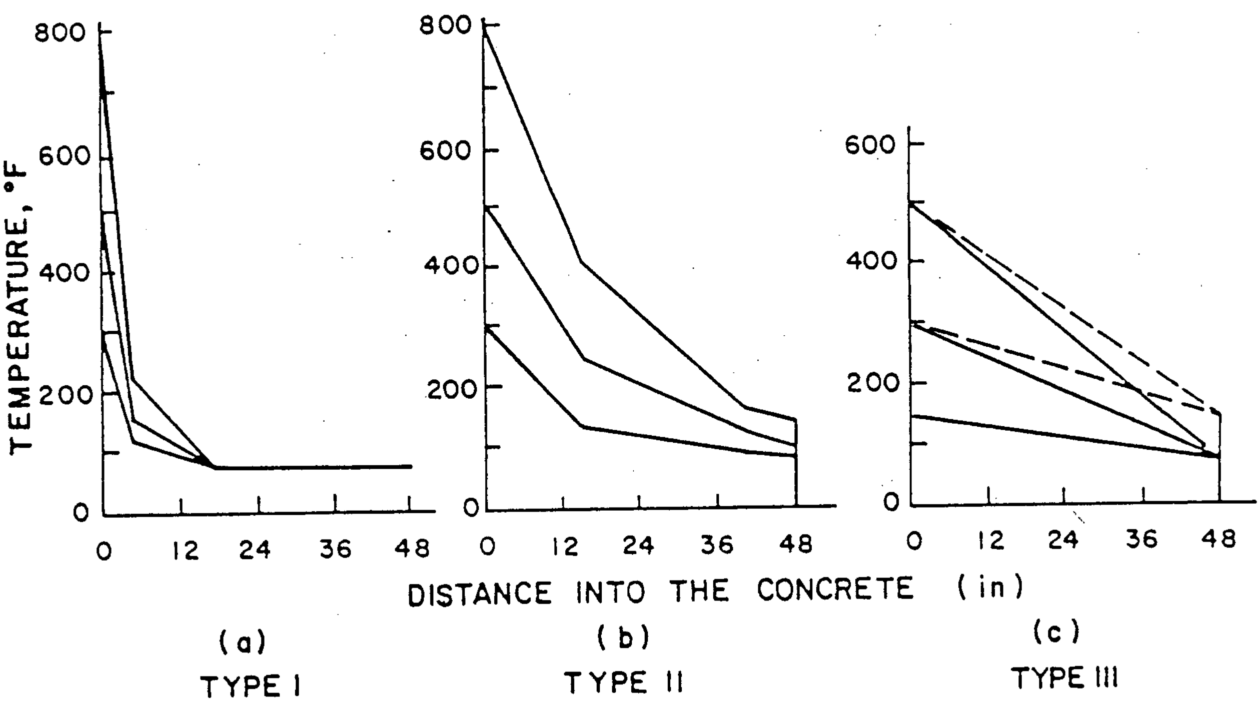

FIG. 9 THERMAL GRADIENTS

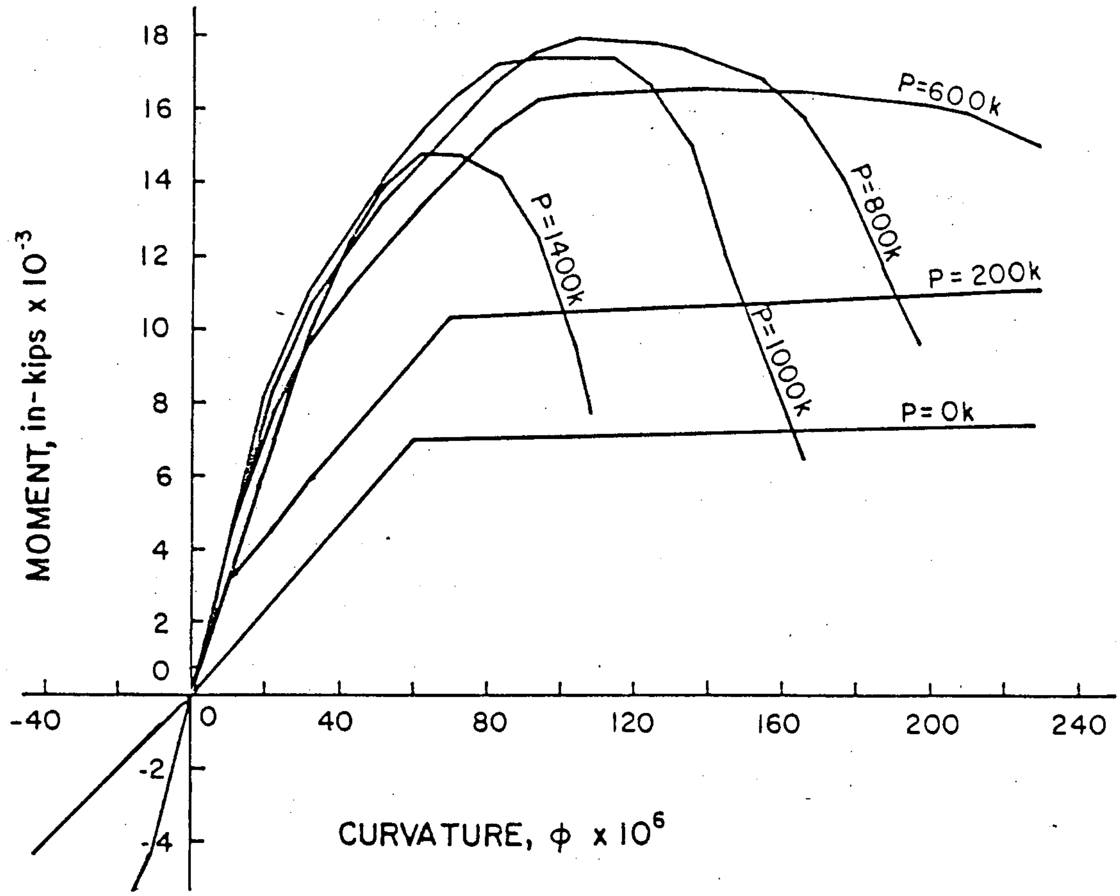

FIG. 10 M-Φ-P RELATIONSHIPS-NORMAL TEMPERATURE

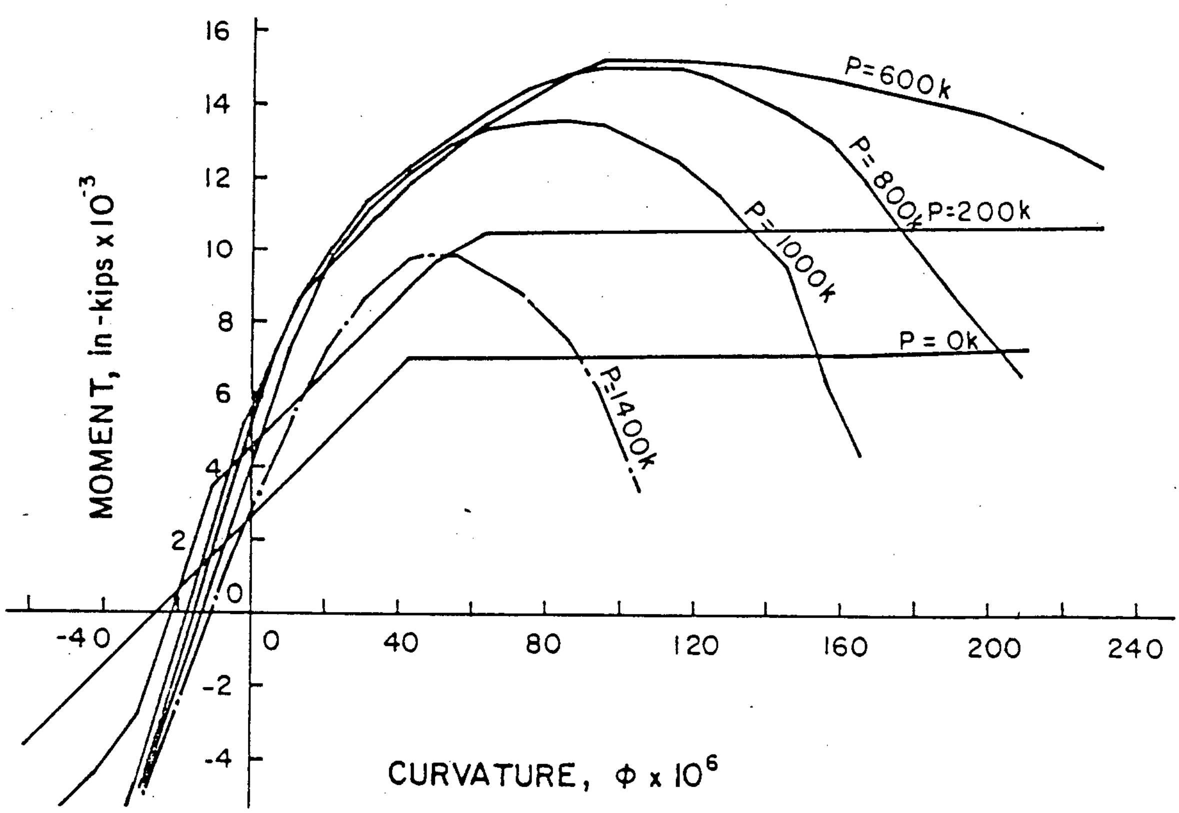

FIG.11 M-Φ-P RELATIONSHIPS - T_1 = 300° F, TYPE II
(Based on L.B. Relationships)

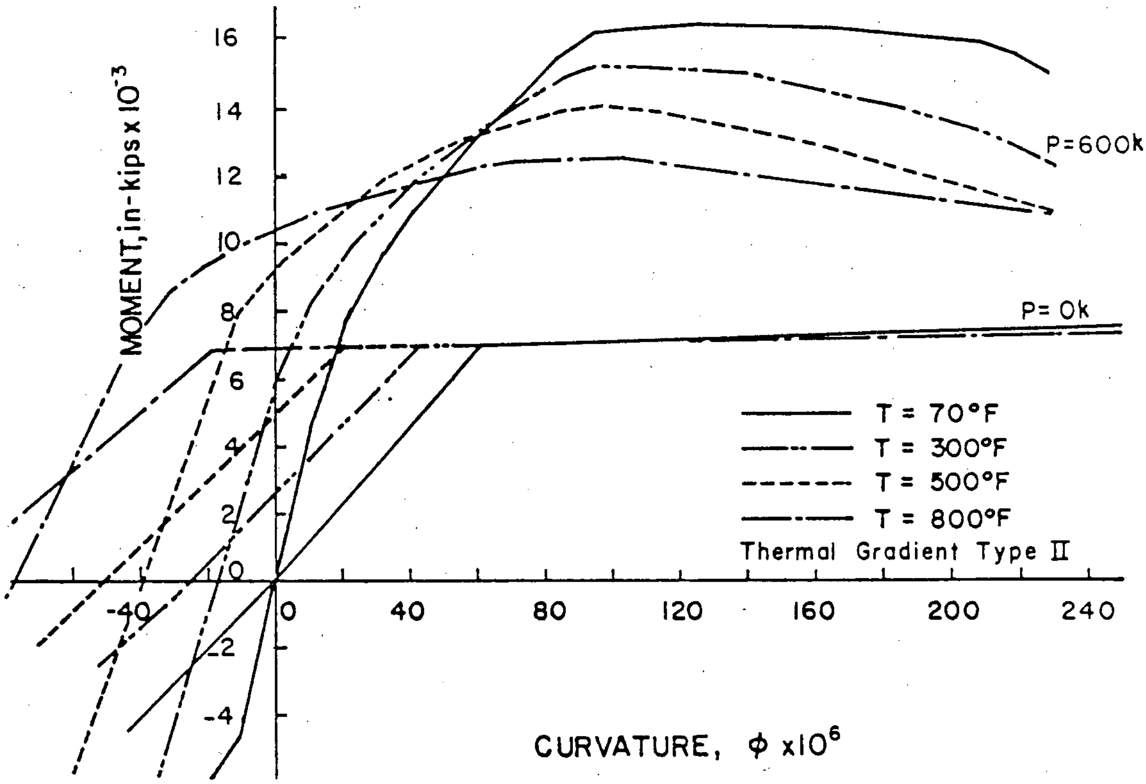

FIG. 12 - EFFECT OF TEMPERATURE LEVEL ON BEHAVIOR
(Based on L.B. Relationships)

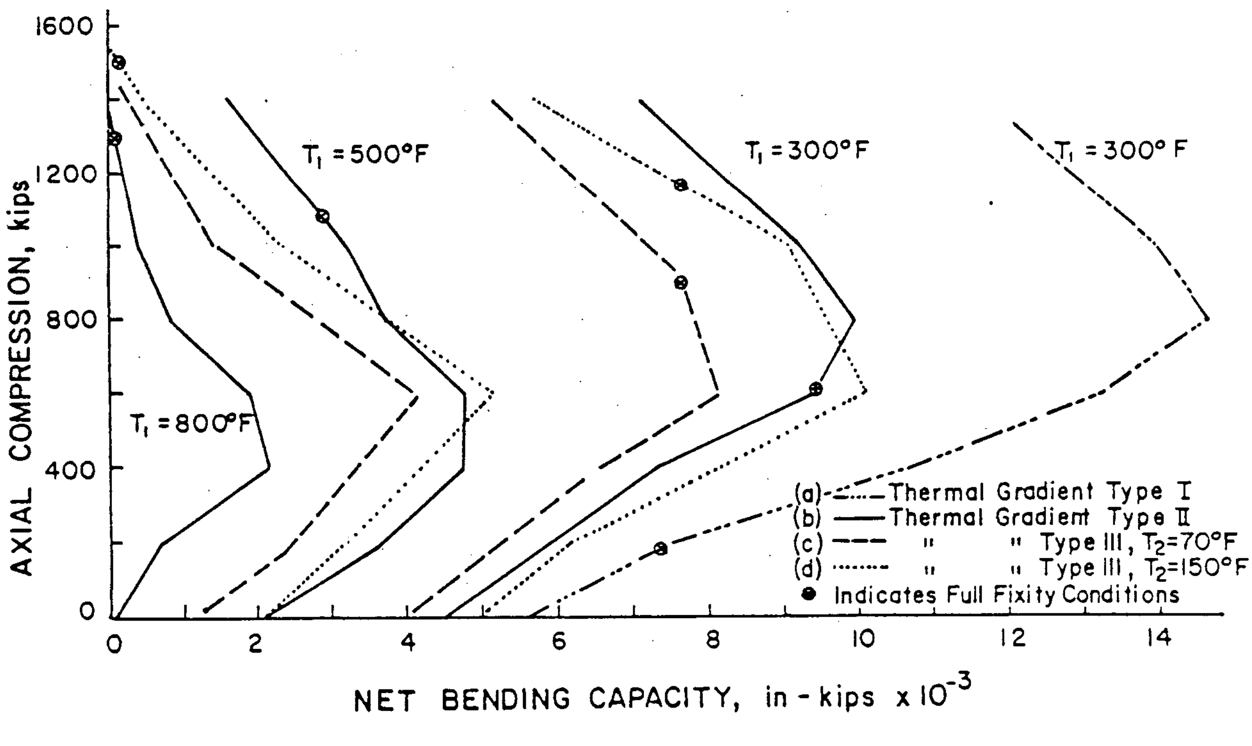

FIG. 13 EFFECT OF TEMPERATURE DISTRIBUTION ON NET BENDING CAPACITY

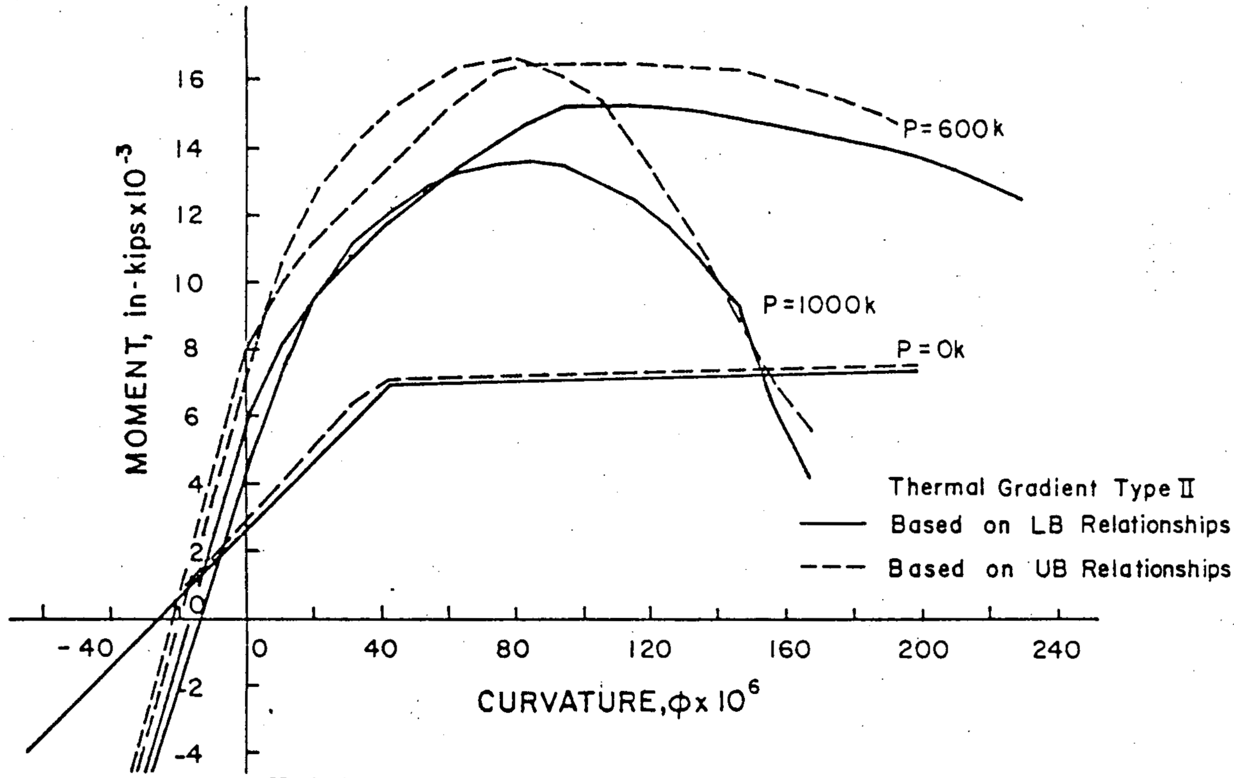

FIG. 14 M-ϕ-P DIAGRAMS BASED ON UB AND LB STRENGTH RELATIONSHIPS

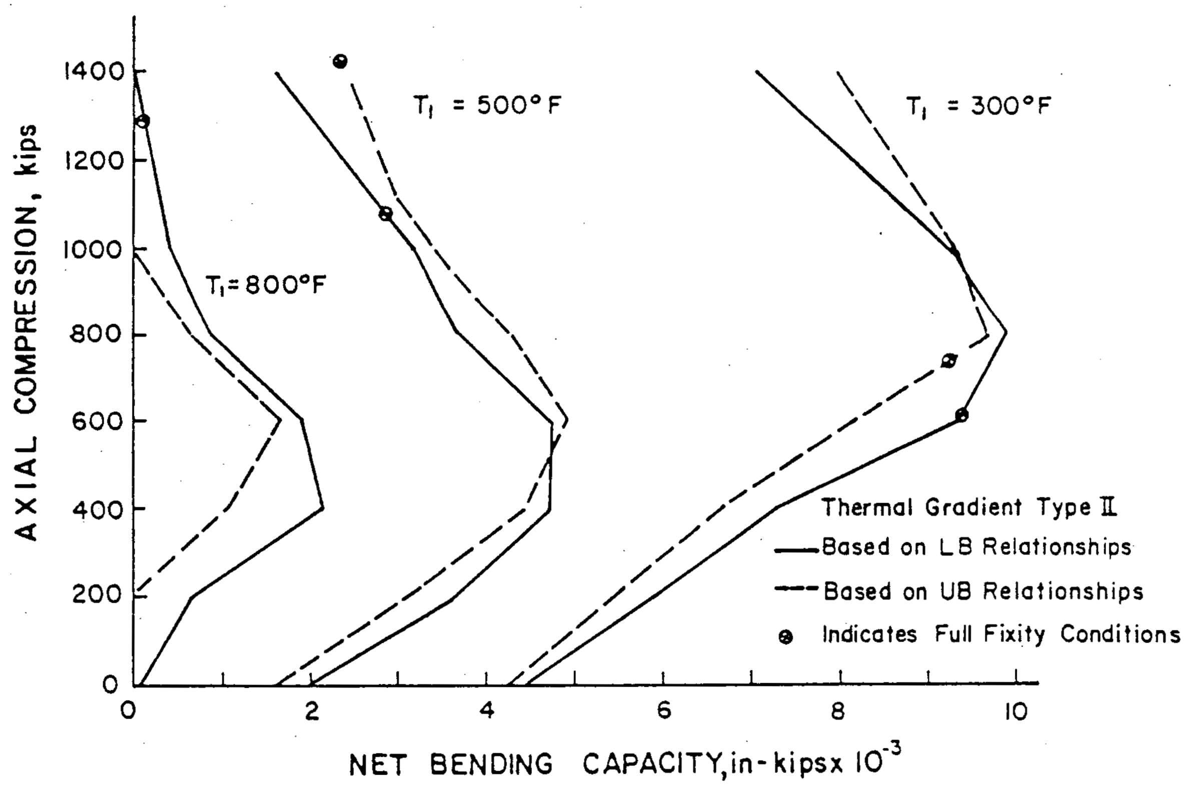

FIG. 15 NET BENDING CAPACITY BASED ON UB AND LB STRENGTH RELATIONSHIPS

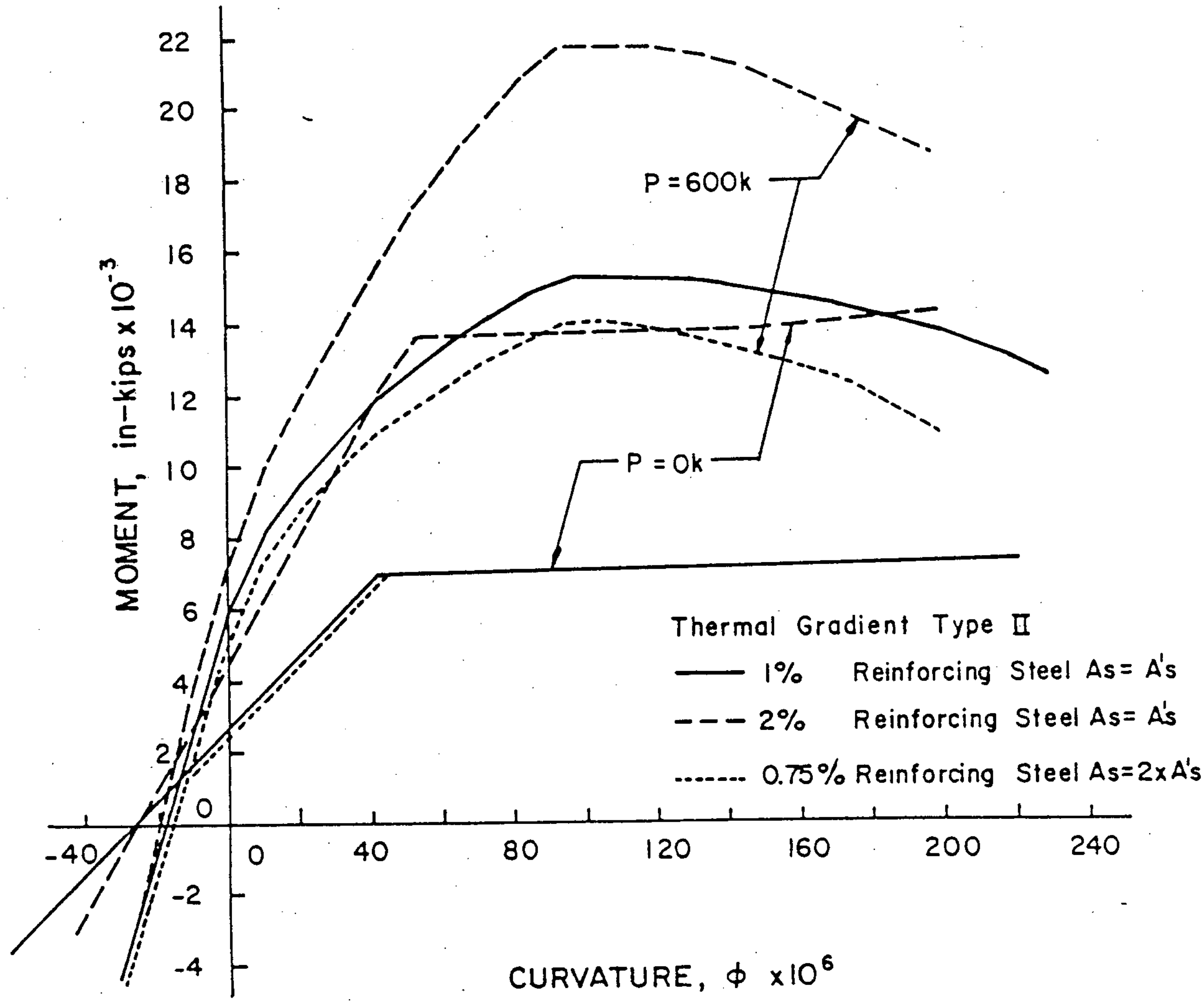

FIG. 16 EFFECT OF REINFORCING STEEL ON BEHAVIOR
(Based on L.B. Relationships)

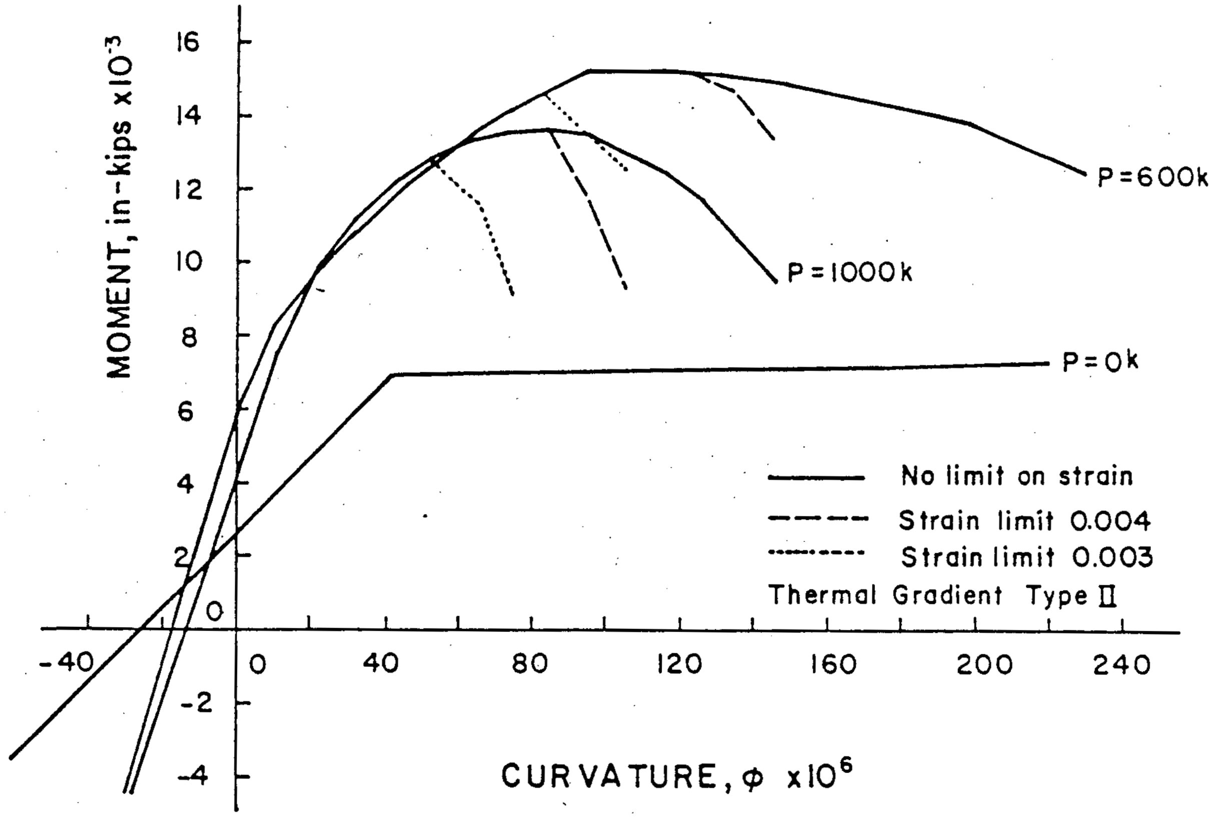

FIG. 17 EFFECT OF STRAIN LIMITS ON BEHAVIOR $T_1 = 300°F$
(Based on L.B. Relationships)

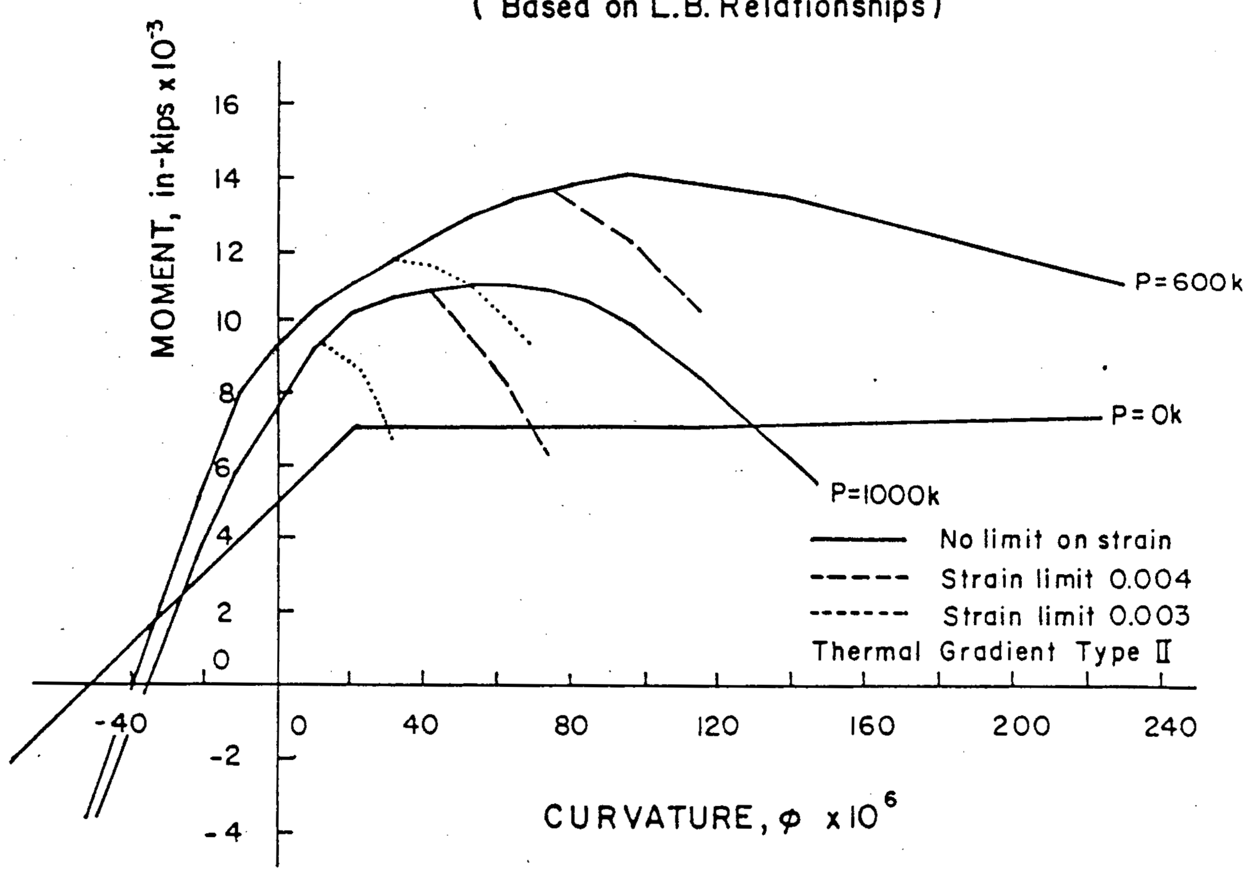

FIG. 18 EFFECT OF STRAIN LIMITS ON BEHAVIOR $T_1 = 500°F$
(Based on L.B. Relationships)