Reinforced Concrete Design for Thermal Effects on Nuclear Power Plant Structures

Reported by ACI Committee 349

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This report presents a design-oriented approach for considering thermal effect on reinforced concrete structures. Although the approach is intended to conform to the general provisions of Appendix E of ACI 349, it is not restricted to nuclear power plant structures. The general behavior of structures under thermal effects is discussed together with the significant issues to consider in reinforcement design. Two types of structures—frames and axisymmetric shells—are addressed. For frame structures, a rationale is described for determining the extent of component cracking that can be assumed for purposes of obtaining the cracked structure thermal forces and moments. Stiffness coefficients and carryover factors are presented in graphical form as a function of the extent of component cracking along its length and the reinforcement ratio. Fixed-end thermal moments for cracked components are expressed in terms of these factors for: 1) a temperature gradient across the depth of the component; and 2) end displacements due to a uniform temperature change along the axes of adjacent components. For the axisymmetric shells, normalized cracked section thermal moments are presented in graphical form. These moments are normalized with respect to the cross-sectional dimensions and the temperature gradient across the section. The normalized moments are presented as a function of the internal axial forces and moments acting on the section and the reinforcement ratio. Use of the graphical information is illustrated by examples.

Keywords: cracking (fracturing); frames; nuclear power plants; shells; structural analysis; structural design; temperature; thermal effect; thermal gradient; thermal properties.

CONTENTS

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CHAPTER 1—INTRODUCTION

1.1—General

ACI 349, Appendix E, provides general considerations in designing reinforced concrete structures for nuclear power plants subject to thermal effects. Thermal effects are defined to be the exposure of a structure or component thereof to varying temperature at its surface or temperature gradient through its cross section; the resulting response of the exposed structure is a function of its age and moisture content, temperature extreme(s), duration of exposure, and degree of restraint. The terms "force," "moment," and "stress" apply and are used in this report where a structure is restrained against thermally induced movements. Further treatment of these forces, moments, and stresses are contained in this report as a function of type of structure.

The Commentary to Appendix E, Section RE.1.2, of ACI 349-06 (ACI Committee 349 2006) instructs the designer to consider the following:

1. Linear thermal strain causes stress only under conditions of restraint, and a portion of such stress may be self-relieving. Mechanisms for relief are: cracking, yielding, relaxation, creep, and other time-dependent deformations; and

2. Accident temperature transients may be of such short duration that the resulting temperature distributions and corresponding stress changes are not significant. Therefore, these temperature transients may not adversely affect the safe shutdown capacity of the plant.

The Commentary to Appendix E, Section RE.3.3, of ACI 349-06 addresses three approaches that consider thermal effects in conjunction with all mechanical loads acting on the structure. One approach is to consider the structure uncracked under the mechanical loads and cracked under the thermal effects. The results of two such analyses are then combined.

The Commentary to Appendix E also contains a method of treating temperature distributions across a cracked section. In this method, an equivalent linear temperature distribution is obtained from the temperature distribution, which can generally be nonlinear. The linear temperature distribution is then separated into a pure gradient ΔT and into the difference between the mean and base (stress-free) temperatures $T_m - T_b$.

This report discusses approaches for making an assessment of thermal effects that are consistent with the aforementioned provisions. The goal is to present a designer-oriented approach for determining the reduced thermal moments that result from cracking of the concrete structure. Thermal effects should be considered in design for serviceability. The report discusses conditions under which it can be shown that the thermal effects do not adversely affect the safe shutdown capacity of the plant. Behavior and general guidance is addressed in Chapter 1. Chapter 2 addresses notation and definitions. Chapter 3 addresses frame structures, and Chapter 4 deals with axisymmetric structures. For frame structures, general criteria are given in Sections 3.2 (Section cracking) and 3.3 (Component cracking). The criteria are then formulated for the moment distribution method of structural analysis in Section 3.4. Cracked component fixed-end moments, stiffness coefficients, and carryover factors are derived and presented in graphical form. For axisymmetric structures, an approach is described for regions away from discontinuities, and graphs of cracked section thermal moments are presented.

This report is intended to propose simplifications that may be used for structural assessments. It will permit exclusion of thermal cases with small effect and a reduction of thermal effects for a large class of thermal cases without resorting to sophisticated and complex solutions (Appendix E, 349-06). Also, as a result of the report discussion, the design examples, and graphical presentation of cracked section thermal moments, it is hoped that a designer will better understand how thermal effects are influenced by the presence of other loads and the resulting concrete response, primarily in the form of cracking, although reinforcement yielding, concrete creep, nonlinear concrete stress-strain, and shrinkage are also very significant in mitigating thermal effects in concrete structures.

1.2—Thermal effects and structural responses

Thermal effects cause expansion or contraction of the components in a structural system. If the components are restrained, which is usually the case, stresses are induced. It is sufficient to note that there are three types of thermal effects:

1. Bulk temperature change. In this case, the entire structural component (or segments of the component) is subject to a uniform temperature change;

2. Thermal gradient. A temperature crossfall or thermal gradient is caused by different thermal conditions on two faces of a structure, such as two sides of a wall or the top and bottom of a beam; and

3. Local thermal exposure. Elevated temperature at a local surface caused by an external source such as operating equipment or piping or an abnormal event such as a fire.

Thermal effects will result in different states of stress and strain in structural components as a function of restraints. The analysis for thermal effects must distinguish between different types of thermal effects and properly characterize the structural response accordingly (for example, the degree of fixity of end and boundary restraints, component stiffness, influence of cracking, and concrete and reinforcing steel strain).

Thermal effects can arise from many sources including, but not limited to, process fluid transport; proximity to hot gasses, steam, or water passage (for example, reactor vessel or steam piping from reactor building to turbine); fire; or gradients formed when opposing faces of a structure are