IN-LB	Inch-Pound Units
SI	International System of Units

Reinforced Concrete Design for Thermal Effects on Nuclear Safety-Related Structures—Report

Reported by ACI Committee 349

ACI PRC-349.1-24

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This report presents a design-oriented approach for considering thermal effect on nuclear safety-related concrete structures. The approach presented in this report is intended to assist the licensed design professional in addressing the requirements of Appendix E of ACI CODE-349-13. Although this report is focused on the requirements of ACI CODE-349, the general behavior of structures under thermal effects and the significant issues to consider in design are broadly applicable in the design of other types of reinforced concrete members and structures. Three types of structures—frame structures, concrete wall structures, and axisymmetric structures—are addressed. For concrete wall structures, thermal and structural behaviors are discussed. Guidelines are provided for determining the required strengths for concrete walls subject to thermal loading combinations. 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: concrete walls; cracking (fracturing); frames; nuclear safety-related structures; shells; structural analysis; structural design; temperature; thermal effect; thermal gradient; thermal properties.

CONTENTS

ACI PRC-349.1-24 supersedes ACI 349.1-07 and was adopted and published in December 2024. This report was first published in 1980 and revised in 1991, 2007, and 2024.

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—General

This report presents a design-oriented approach for considering thermal effect on nuclear safety-related reinforced concrete structures. The approach is intended to assist the licensed design professional in addressing the requirements of Appendix E of ACI CODE-349-13. ACI CODE-349-13 Appendix E provides requirements for the design of concrete nuclear safety-related structures subjected to thermal effects. Thermal effects are defined as the exposure of a structure or component thereof to varying temperatures 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. Treatment of forces, moments, and stresses resulting from thermal restraints, as a function of type of structure, is contained in this report.

The Commentary to Appendix E, Section RE.1.2, of ACI CODE-349-13 instructs the licensed design professional 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.

2. Accident temperature transients can 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 in comparison to the capacity at operating temperatures.

The Commentary to Appendix E, Section RE.3.3, of ACI CODE-349-13 presents three approaches that consider thermal effects in conjunction with all mechanical loads acting on the structure.

The Commentary to Appendix E, Section RE.1.5, of ACI CODE-349-13 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 assessing thermal effects that are consistent with the abovementioned provisions. The goal is to present a design-oriented approach for determining the reduced thermal moments that result from cracking of the concrete structure. Thermal effects should also be considered for determining performance expectations under service loads. This report discusses conditions under which it can be shown that the thermal effects do not adversely affect the safe shutdown structural capacity (for example, the structural capacity of nuclear safety-related structures, enabling safe shutdown during an extreme or catastrophic scenario).

Behavior and general guidance are addressed in Chapter 1. Notation and definitions are addressed in Chapter 2. Frame structures are discussed in Chapter 3. Axisymmetric structures are described in Chapter 4 and concrete wall structures are covered in Chapter 5. 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. A frame is analyzed for mechanical and thermal loads using moment distribution (Section 3.5) and finite element method (FEM) (Section 3.6). For axisymmetric structures, an approach is described for regions away from discontinuities, and graphs of cracked section thermal moments are presented. For concrete wall structures (Chapter 5), a discussion is provided on thermal loads (Section 5.2) and structural behavior (Section 5.3). The chapter discusses how to determine required strength (Section 5.4). The methodology is illustrated by means of a finite element analysis example (Section 5.5) and a hand calculation (Section 5.6).

In this report, simplified analysis and design procedures are provided that satisfy the requirements of ACI CODE-349. In addition, the licensed design professional may use this report to determine the conditions where these procedures can replace those that are more complex and timeconsuming and, in cases of small thermal effects, avoid consideration altogether. Design examples and graphical presentation of cracked section thermal moments are used to explain how thermal effects interact with mechanical load effects and how these combined effects are influenced by concrete cracking. The potentially beneficial effect of reinforcement yielding, concrete creep and shrinkage, and the nonlinearity of concrete stress-strain is also covered in this report.

1.2—Definition of thermal effects

1.2.1 *Thermal effects on structural responses*—Thermal loads cause expansion or contraction of the components in a structural system. If the components are restrained, which is usually the case, stresses are induced. Note that there are three types of thermal effects that induce thermal loads:

(a) **Bulk temperature change:** A uniform temperature change over the entire structural component (or segments of the component).

(b) **Thermal gradient:** A temperature crossfall or thermal gradient 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.

(c) **Local thermal exposure:** Elevated temperature at a local area that significantly affects the stress distribution in the immediate area of exposure. For example, areas around operating equipment or hot piping or an abnormal event such as a pipe break.

Not included in the scope of this document is a consideration of thermal damage resulting from a fire event. This document is intended to be used within the temperature limitations presented in Appendix E.4 of ACI CODE-349-13.

Thermal effects will result in different states of stress and strain in structural components as a function of restraints. The analysis of thermal effects must distinguish between different types of thermal loads 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); or gradients formed when opposing faces of a structure are exposed to differing temperatures (for example, spent fuel pool) or cyclic gradients from plant startup and shutdown. Temperature change is manifested under one or more of the following transfer mechanisms:

(a) **Radiation:** The electromagnetic transfer of heat from a higher temperature source to a lower temperature surface of the concrete structure, such as from a radiator heating a room and the surrounding wall and floor structures.

(b) **Convection:** The transfer of heat usually by the movement of a liquid or gas across a surface, such as from environmental temperature changes in the air next to a concrete structure.

(c) **Conduction:** The transfer of heat through a solid, such as from a steam pipeline into the surrounding concrete at a penetration.

There are many instances where all three mechanisms are present, such as in the case of a fire acting on a structure. Radiation and convection from the flame itself transfers heat to the impinged structure. The surface of the flame radiates heat, which is absorbed by the concrete and reinforcing steel; finally, heat is transferred away from the flame-impinged area by means of conduction through the structure. The structure will also lose heat by means of convection and radiation.

Response of a structure to thermal effects depends on the nature of the temperature distribution, end constraints, material properties, and mechanical loads. A proper thermal stress analysis must take these parameters into account.

Stresses in the concrete and reinforcement occur due to restraint of thermal movement and these stresses are generally self-relieving, primarily in the form of concrete cracking. These thermal stresses are generally small, as most thermal exposures are within prescribed ACI CODE-349 temperature limits.

Thermal effects are considered under operating temperatures and accident temperatures. Operating thermal effects and duration are deemed long-term whereas the accident thermal effects are short-term. Accidental thermal effects are typically shorter than 7 days in duration. Ambient thermal effects typically have little effect on the ultimate strength of a concrete structure.

1.2.2 *General guidelines on consideration of thermal effects*—Stresses resulting from thermal effects are generally self-relieving—that is, thermal forces and moments may be greatly reduced or completely relieved once concrete cracks or reinforcement yields; as a result, thermal effects, for the temperature range within the scope of this document, are unlikely to reduce the strength of a section for mechanical loads.

For example, consider a fixed-end beam under combined transverse loads and thermal effects. The transverse loads will produce negative moments at the ends and positive moment at the center. Also assume that the transverse load is such that the negative moment reinforcement is near yield (for example, at 99% of yield). If the temperature is increased at the bottom of the beam, introducing a thermal gradient over its entire length, this gradient would cause additional negative moment. When the negative moments increase by 1%, the reinforcement would start yielding. The negative moments at the ends, however, cannot increase beyond 100% because the reinforcement is already yielded. Thus, it can be said that the thermal moments at the ends are relieved as soon as the reinforcement yields, yet the structure remains stable because the lateral load capacity does not change for flexure loading. Therefore, simplifying assumptions and approximations in analyses are acceptable. However, the stresses due to thermal loads may not be relieved for some demand types—for example, out-of-plane shear demands. Although it is not feasible to set definitive rules regarding these assumptions and approximations, some general guide-