Manual

Precast/Prestressed Concrete Institute

Design for Fire Resistance of Precast/Prestressed Concrete

Fire Subcommitee of
the PCI Building Code
Committee

INTERNATIONAL CODE COUNCIL

Third Edition

DESIGN FOR FIRE RESISTANCE OF PRECAST/PRESTRESSED CONCRETE

THIRD EDITION

PCI Manual MNL 124-11

Updated and Prepared by the
FIRE SUBCOMMITTEE
OF THE PCI BUILDING CODE COMMITTEE
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Based on the original work of
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COMMITTEE STATEMENT

The first edition of this manual was printed in 1977. At that time, calculated design for fire, which is the principal focus of the manual, was in its infancy. The first known introduction of calculated design was in 1942 by the Bureau of Standards, but it was seldom applied. It was not until several decades later that the model codes saw the value of this technology and began to look favorably at calculated design as a viable option to documenting fire ratings.

In the late 1960s, PCI forged ahead and, under the leadership of Armand Gustaferro, became the first industry to develop a procedure for calculated design. At that point "Gus," as he was called, had already spent much of his professional career managing the fire testing laboratory of the Portland Cement Association. He had written numerous publications on the subject of fire, served on domestic and international committees, and was world-renowned for his expertise. Sadly, Gus passed away in 2003, and it is only fitting that the members of the current PCI Fire Subcommittee, charged with updating the manual to its current status, dedicate their efforts and their finished work to this great pioneer. His brief biography follows.

Armand H. Gustaferro (1924–2003) was a world-renowned concrete technologist and authority on fire resistance issues. Gus (as he was known to his professional colleagues) was a nationally recognized expert on a variety of issues related to plain, reinforced, and prestressed concrete.

How to predict fire resistance ratings was an early and lingering problem in the prestressed concrete industry. In 1976, Gus wrote the *PCI Manual on Design for Fire Resistance of Precast Prestressed Concrete*. The manual allowed engineers to design for fire resistance without the need for conducting special tests on each product or structural assembly.

Also in 1976, Gus was recognized internationally for his contributions to the development of prestressed concrete, having received the FIP Medal from the Federation Internationale de la Precontrainte.

Gus obtained BS and MS degrees in civil engineering from Ohio State University (1946) and Yale University (1951), respectively. In 1987, Ohio State University conferred upon him the Distinguished Alumnus Award.

In 1954, he joined the Portland Cement Association (PCA) in its Chicago, Ill. office. From 1956 to 1959, he managed a precast/prestressed manufacturing plant for Vulcan Materials near Chicago.

Gus subsequently rejoined PCA in 1959 (this time in Skokie, Ill.), where he spent another ten years principally as manager of the fire research laboratory. It is here that he gained his worldwide reputation as an authority on the fire resistance of reinforced and prestressed concrete. Several of his publications became reference documents in national and regional building codes.

For the next 32 years, Gus was retained as a consultant by the Consulting Engineers Group (CEG) in the Chicago area. During his tenure, he investigated several hundred jobs dealing with concrete structures, quality control, and forensic issues including fire.

Gus was instrumental in organizing the technical committee structure of PCI during its formative years in the mid-1960s. He was PCI's second chair of the Technical Activities Committee. He also served as a professional member of the PCI Board of Directors, Fire Committee, and Durability Committee, as well as secretary of the ACI-ASCE Joint Committee on Prestressed Concrete.

In all, Gus authored approximately 60 technical papers, several of which have been published in the *PCI Journal*. In recognition of his outstanding contributions to PCI and the industry, in 1979 he was awarded the PCI Medal of Honor. He was also honored by the American Concrete Institute, American Society for Testing and Materials, and the World of Concrete.

Paraphrasing Kipling, "Gus could walk with kings and queens and yet could also hold the common touch." Whether Gus was talking to a judge as an expert witness in a courtroom or with a concrete worker using a trowel, both listeners knew instinctively that this was a man speaking the truth.

We shall all miss his wise counsel and gentle demeanor.

Biography adapted from *PCI Journal* article authored by George Nasser, September-October, 2003, p. 117

PREFACE

This manual has been used by designers for almost 30 years, and much of it has been reproduced or referenced in its entirety in the model building codes and the International Building Code. Since the 2nd printing in 1989, much has been experienced and learned, resulting in the need for updating the manual to its current status. Several parts have been rewritten to clarify the text and some new material has been added, but nothing has been changed that would affect the character of the manual.

The committee is pleased that soon after its initial publication, the International Conference of Building Officials issued an evaluation report (No. 3264) on the use of the manual. Similarly, the Building Officials and Code Administrators International issued Research Report No. 78-49 in 1979. The 1984 BOCA Basic/National Building Code and the 1987 BOCA National Building Code referenced the manual, permitting its use for determining the fire resistance ratings of precast, prestressed concrete. Today, the manual has the International Code Council Evaluation Service Report No. ESR-1997 and is referenced in the International Building Code.

It has been gratifying to the committee that the manual has gained such broad acceptance. This is evident through the thousands of copies that PCI has produced and distributed of each of the first two editions and their respective multiple printings.

The Fire Subcommittee (2005) of the PCI Building Code Committee for the third edition of this PCI manual is represented by producer and consultant members from throughout the U. S. It would be an oversight if acknowledgment were not given to those committee members who preceded us and so diligently pushed ahead to bring this work to fruition.

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TABLE OF CONTENTS

NOTATION

a = depth of equivalent rectangular stress block at nominal strength, in.

A = cross-sectional area of a member subjected to thrust, in.^{2} (Appendix C)

A_c = cross-sectional area of a concrete member, in.^{2}

A_s = area of reinforcing steel, in.^{2}

A_{ps} = area of prestressing steel, in.^{2}

b = width of compression zone (for use in flexural calculations), in.

b = width of a beam or joist at centroid of reinforcement (for use in estimating temperature during fire exposure), in.

c_1, c_2 = width of space between end of member and vertical face of restraining member, in. (Figure C.6)

d = distance between centroid of reinforcement and extreme compression fiber, in.

d_T = distance between line of action of thrust at the supports and extreme compression fiber, in. (Appendix C)

e = distance between line of action of thrust and the centroidal axis, in. (Appendix C)

E = modulus of elasticity of concrete, psi or ksi

f'_c = compressive strength of concrete, psi or ksi

f_{cb} = concrete fiber stress at bottom fiber, psi

f_{ps} = stress in prestressing steel in flexural member at nominal strength, ksi

f_{pu} = ultimate strength of prestressing steel, ksi
270 ksi used in all ensuing examples
250 ksi is also used by the industry

f_s = stress in hot-rolled steel, ksi

f_y = yield strength of hot-rolled steel, ksi

h = overall depth of flexural member, in.

h = unbraced height of column, in. (Appendix C)

H = height of wall, ft (Appendix C)

I = moment of inertia of cross section, in.^{4}

I_{cr} = moment of inertia of cracked cross section of flexural member, in.^{4}

k_h = coefficient of horizontal soil force, lb/ft^2

k_p = passive soil pressure, lb/ft^2

l = span length, ft or in.

l = heated length of a flexural member, in. (Appendix C)

M = service load bending moment; in general $M = M_d + M_l$ in which subscripts d and l indicate dead and live loads, kip-in. or kip-ft

M_n = nominal moment strength, kip-in. or kip-ft

M_T = moment due to thrust resulting from restraint of thermal expansion, kip-in. or kip-ft

M_u = factored moment at section, kip-in. or kip-ft

P_1, P_2, P_3 = concentrated loads applied to test specimen, kips (chapter 5)

P_p = passive soil force, lb or kip

R = fire endurance of a composite assembly as determined by the criteria for temperature rise of the unexposed surface, min (chapters 7 and 8)

R_1, R_2, R_n = fire endurance of one course of a composite assembly as determined by the criteria for temperature rise of the unexposed surface, min (chapters 7 and 8)

s = heated perimeter of a member, that is, the portion of the perimeter of a section of a member, normal to the direction of the thermal thrust, that is exposed to fire, in. (Appendix C)

s = rib spacing, in. (chapter 8)

t = thickness, in.

t_e = equivalent thickness, in. (section 8.3.2)

T = thermal thrust, lb or kip

u = distance from bottom of slab or beam to a point within the member, for example, the distance from the underside of a slab to the center of a prestressing strand, in.

$\bar{u}$ = effective u, for use with wide beams, in. (section 4.3)

u_s = distance from the side of a beam or joist to a point within the member, in.

w = uniformly distributed load on a flexural member, in general $w = w_d + w_l$ in which the subscripts d and l indicate dead and live loads, lb or kip per in. or per ft

x = distance along length of a flexural member from a support to a point in question, in. or ft

x_o = distance along length of a flexural member from support to point of zero moment, in. or ft (Figure 5.1)

x_1 = distance along length of a flexural member from support to point of maximum positive moment, in. or ft (Figure 5.1)

x_2 = distance along length of a flexural member between points of zero moment, in. or ft (Figure 5.6)

y_b = distance from centroidal axis of flexural member to extreme bottom fiber, in.

z = A/s, in. (Appendix C)

Z_b = section modulus of cross section with reference to bottom fiber = I/y_b, in.^{3}

γ = unit weight of soil, lb/ft^3

Δ = deflection, in.

Δl = increase in length due to thermal expansion, in. (Appendix C)

θ = temperature, °F

θ = subscript of property as affected by elevated temperature

θ_s = temperature of steel, °F

ρ_p = A_{ps}/bd

ϕ = capacity reduction factor from ACI 318; for flexure $\phi = 0.90$ or varies per Section 9.3 of ACI 318

ω = $A_s f_y / bdf'_c$

$\overline{\omega}_p$ = $A_{ps} f_{pu} / bdf'_c$

0, 1 = of reference specimens and member in question (Appendix C)

GLOSSARY OF TERMS

Built-up roofing – roof covering consisting of at least 3-ply, 15-lb type felt and not having in excess of 1.20 lb/ft^2 of hot-mopped asphalt without gravel surfacing.

Carbonate aggregate concrete – concrete made with aggregates consisting mainly of calcium or magnesium carbonate, such as limestone or dolomite.

Cellular concrete – a lightweight insulating concrete made by mixing a preformed foam with portland cement slurry and having a dry unit weight of about 30 lb/ft^3.

Cold-drawn steel – uncoated steel used in prestressing wire or strand. Does not include high-strength alloy steel bars used for post-tensioning tendons.

Critical temperature – the temperature at which the strength of the steel is the same as the stress in the steel.

End point criteria – the conditions of acceptance for an ASTM E119 fire test.

Fire endurance – a measure of the elapsed time during which a material or assembly continues to exhibit fire resistance under specified conditions of test and performance. As applied to elements of buildings, it shall be measured by the methods and to the criteria defined in ASTM E119 (defined in ASTM E176).

Fire rate – an insurance term indicating the annual premium per $100 of insurance.

Fire resistance – the property of a material or assembly to withstand fire or give protection from it. As applied to elements of buildings, it is characterized by the ability to confine a fire or to continue to perform a given structural function, or both (defined in ASTM E176).

Fire resistance rating (sometimes called **fire rating**, **fire resistance classification**, or **hourly rating**) – a legal term defined in building codes, usually based on fire endurances. Fire resistance ratings are assigned by building codes for various types of construction and occupancies and are usually given in half-hour increments.

Fire test – see **standard fire test**

Glass fiber board – fibrous glass roof insulation consisting of inorganic glass fibers formed into rigid boards using a binder. The board has a top surface faced with asphalt and kraft reinforced with fiber.

Gypsum wallboard, Type X – a mill-fabricated product made of a gypsum core containing special minerals and encased in a smooth, finished paper on the face side and liner paper on the back, and conforming to the requirements of ASTM C36.

Heat transmission end point – an acceptance criterion of ASTM E119 limiting the temperature rise of the unexposed surface temperature to an average of 250 °F or a maximum of 325 °F at any one point.

High-strength alloy steel bars – uncoated bars used for post-tensioning conforming to the requirements of ASTM A722.

Hot-rolled steel – uncoated steel used in reinforcing bars or structural steel members.

Intumescent mastic – a solvent-base, spray-applied coating that reacts to heat at about 300 °F by foaming to a multicellular structure having 10 to 15 times its initial thickness.

Isotherm – a line drawn on the cross section of a member connecting points of the same temperature.

Lightweight aggregate concrete – concrete made with aggregates of expanded clay, shale, slag, or slate or sintered fly ash, and weighing about 90 lb/ft^3 to 105 lb/ft^3.

Mineral board – a rigid, felted thermal insulation board consisting of either felted mineral fiber or cellular beads of expanded aggregate formed into flat rectangular units.

Normalweight concrete – any concrete made with natural aggregates, cement, and water having a unit weight above 120 lb/ft^3.

Perlite concrete – a lightweight, insulating concrete having a dry unit weight of about 30 lb/ft^3 made with perlite concrete aggregate. Perlite aggregate is produced from a volcanic rock that, when heated, expands to form a glass-like material of cellular structure.

Restrained assembly classification – the classification derived from fire tests of floors, roofs, or beams in accordance with acceptance criteria of ASTM E119.

Sand-lightweight concrete – concrete made with a combination of expanded clay, shale, slag, or slate or sintered fly ash and natural sand. Its unit weight is generally between 105 lb/ft^3 and 120 lb/ft^3.

Siliceous aggregate concrete – concrete made with normal weight aggregates consisting mainly of silica or compounds other than calcium or magnesium carbonate.

Spray-applied coatings, spray insulation – see **intumenscent mastic**, **sprayed mineral fiber**, or **vermiculite cementitious material**.

Sprayed mineral fiber – a blend of refined mineral fibers and inorganic binders. Water is added during the spraying operation, and the untamped unit weight is about 13 lb/ft^3.

Standard fire exposure – the time-temperature relationship defined by ASTM E119, and shown in Figure 1.1.

Standard fire test – the test prescribed by ASTM E119.

Steel temperature end point – the acceptance criterion of ASTM E119 defining the limiting steel temperatures for unrestrained assembly classifications based on the results of a fire test of a restrained specimen, that is, 1100 °F average or 1300 °F maximum for structural steel, 1100 °F average for reinforcing steel, and 800°F for cold-drawn prestressing steel. For restrained classifications of beams spaced more than 4 ft on centers, these limits must not be exceeded for the first half of the fire endurance period.

Structural end point – the acceptance criterion of ASTM E119 that states that the specimen shall sustain the applied load without collapse.

Unrestrained assembly classification – A classification derived from fire tests of floors, roofs, or beams in accordance with the acceptance criteria of ASTM E119. Such a classification is considered applicable in buildings when the conditions for a restrained assembly classification are not met.

Vermiculite cementitious material – a cementitious mill-mixed material to which water is added to form a mixture suitable for spraying. The mixture has a wet unit weight of about 55 lb/ft^3 to 60 lb/ft^3.

Vermiculite concrete – a lightweight insulating concrete made with vermiculite concrete aggregate, which is a laminated micaceous material produced by expanding the ore at high temperatures. When added to a portland cement slurry, the resulting concrete has a dry unit weight of about 30 lb/ft^3.

In the interest of life safety and property protection, building codes require that the resistance to fire be considered in the design of buildings. The degree of fire resistance required depends on the type of occupancy, the size of the building, its location (proximity to property lines and within established zones), and, in some cases, the amount and type of fire detection and extinguishing equipment available in the structure.

In addition to the life safety considerations, casualty insurance companies and owners are concerned about the damage that is inflicted upon the structure and its contents during a fire. Insurance rates are usually substantially lower for buildings with higher fire resistance ratings.

Fire resistance ratings have, in the past, been assigned to various building components on the basis of results of standard fire tests. Such tests leave much to be desired. In addition to being expensive and time-consuming, fire tests often yield results that are misleading. Because of these shortcomings, a considerable research effort has been expended to develop procedures and data for the rational design of structural members for fire resistance.

1.1 STANDARD FIRE TESTS OF BUILDING CONSTRUCTION AND MATERIALS

The fire-resistive properties of building components are measured and specified according to ASTM E119.[1.1] Fire endurance is defined as the period of resistance to the standard fire exposure that elapses before an end point is reached.

The standard fire exposure is defined by the time-temperature relationship of the fire shown in Figure 1.1, and is required by ASTM E119. This fire represents combustion of about 10 Ib of wood (with a heat potential of 8000 Btu/Ib) per ft^2 of exposed area per hour of test. Actually, the fuel consumed during a fire test depends on the furnace design and the heat capacity of the test assembly. For example, the amount of fuel consumed during a fire test of an exposed concrete floor specimen is likely to be 10% to 20% greater than that used during a test of a floor with an insulated ceiling, and considerably greater than for a combustible assembly. However, this fact is not recognized when assigning or specifying fire resistance ratings.

ASTM E119 specifies the minimum sizes of specimens to be exposed in fire tests. For floors and roofs, at least 180 ft^2 must be exposed to fire from beneath, and neither dimension can be less than 12 ft. For tests of walls, either load-bearing or non-load-bearing, the minimum specified area is 100 ft^2 with neither dimension less than 9 ft. The minimum length for columns is specified to be 9 ft, while for beams it is 12 ft.

During fire tests of floors, roofs, beams, load-bearing walls, and columns, the maximum permissible superimposed load as required or permitted by nationally recognized standards is applied. A load other than the maximum may be applied, but the results then apply only to the restricted load condition. The standard permits alternate tests of large steel beams and columns in which a superimposed load is not required, but the end point criteria are modified.

Floor and roof specimens are exposed to fire from beneath, beams from the bottoms and sides, walls from one side, and columns from all sides.

ASTM E119 distinguishes between restrained and unrestrained assemblies. Restrained in this case means that thermal expansion of the specimen is restricted

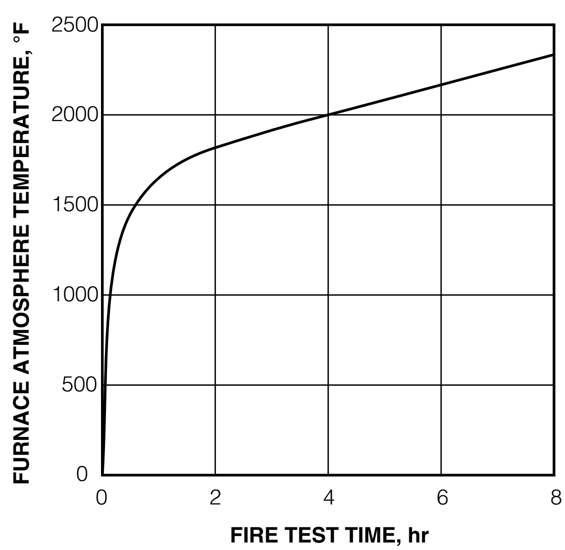

Figure 1.1 Standard time-temperature relationship of furnace atmosphere from ASTM E119.