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Thermal analysis of reinforced concrete beams and frames

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Abstract It is known that changes in temperature may produce stresses in concrete structures of mainly the same order of magnitude as the dead and live loads in some cases. However, the stresses due to temperature are produced only when the thermal expansion or contraction is restrained. In this paper, the behavior of reinforced concrete beams and frames is studied under thermal loads, with the presence of dead and live loads, in order to examine the effect of temperature variation. The beams and frames are modeled properly by accounting for material nonlinearity, particularly cracking. Different temperature gradients, uniform, linear and nonlinear, are considered. The finite element method is employed for conducting the analysis utilizing the computer code ABAQUS.

The obtained results of the studied cases reveal that material modeling of reinforced concrete beams and frames plays a major role in how these structures react to temperature variation. Cracking contributes to the release of significant portion of temperature restrain and in some cases this restrain is almost eliminated. The response of beams and frames deviates significantly based on the temperature gradient, linear or nonlinear; hence, the nonlinear temperature gradient which is the realistic profile is important to implement in the analysis.

Introduction

Reinforced concrete structures are exposed to thermal loadings, whether through design or as a consequence of unavoidable conditions, heat of hydration, service function or fire. In some instances, such loadings represent the most critical loading condition and must be considered in the design of the structure [1]. Since the construction is carried out over a considerable period of time, the various elements of the structure are installed at different temperatures. The temperature changes causing displacements and stresses in a structure are different from those of installation/erection temperatures, over which the designer has minor, if any, control. There are many factors affecting temperature variations in buildings such as design temperature change which is the difference between the maximum temperature in summer or minimum temperature in winter and the construction temperature [2,3]. The second factor is the provision of temperature control [1,3]. The

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third factor is the statical system of the building, geometry, dimensions and the type of connection to foundation [1,3]. The last factor is the construction material of the building [1,3]. As a result of these factors, the values of temperature change and temperature gradient vary from one country to another. Therefore, codes in different countries give different gradients of temperature changes. A limited guidance is given to ordinary buildings that consist of beams, slabs and columns compared to the super-structures of bridges; codes give thermal gradients for bridge deck and its effect on the supporting elements.

If thermal strains are restrained in reinforced concrete elements, design codes require that the temperature effect be considered, although in many cases very limited guidance is given on how this can be achieved. Exposed concrete structures, e.g. bridges and roofs continuously lose and gain heat from solar radiation, convection and re-radiation to or from the surrounding environment. Analysis of heat flow in a body is generally a three-dimensional problem. However, for a concrete beam and frame or for a bridge cross-section, it may be sufficient to treat it as one- or two-dimensional problem [1,4,5]. The temperature at any instant is assumed constant over the structure length, but variable over the cross section [1,4,5].

Thermal stresses can be substantially reduced and the risk of damage caused by temperature can be eliminated by provision of expansion joints and sufficient well distributed reinforcement. Since expansion joints have many problems most design codes become interested in how to reduce the usage of expansion joints in buildings. This means that the thermal stresses must be calculated accurately and the structural elements are designed to carry the stresses from these thermal loads. The effect of temperature gradients and the effect of cracks as a result of tensile stresses obtained from dead and live loads must be taken into account when analyzing thermal stresses.

The main objective of this paper was to show the different effects of temperature variation on the behavior of reinforced concrete beams, multi-bay and multi-story frames under different temperature gradients which may be uniform, linear and nonlinear gradients, in the presence of gravity loads. The temperature is assumed to vary within the depth of beam or frame girder only and constant along the member span. This may be assumed as one dimensional problem and hence the obtained stresses due to temperature change are normal stresses. Frame columns resist the elongation of the girder due to temperature rise, so additional moments and additional axial forces are obtained in columns and girders, which means that the framing action influences the response of frames due to temperature variation.

The finite element method is utilized for the modeling and analysis of the beams and frames considered in this study, taking into account material nonlinearity.

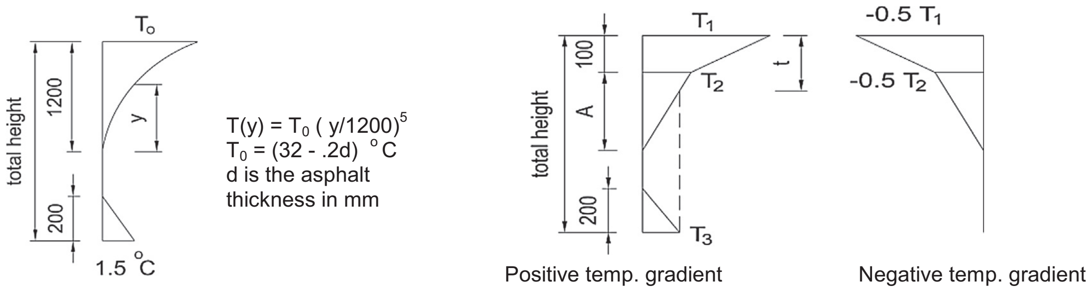
Thermal effect

Due to the poor thermal conductivity of concrete, diurnal temperature effects produce temperature gradients in concrete section; these gradients result in rotational distortions that produce stresses in the structure [3]. The temperature gradient that forms is governed by the heat flow through the body and is a function of the density (ρ), specific heat (c) and thermal conductivity of concrete (k). Various researches [6–8] and codes [2,3] give different thermal gradients that must be taken into account in thermal stress analysis. Some codes [2,3] and researches [8,9] take temperature gradients uniform over the cross section and other takes the gradient linear and nonlinear. Fig. 1 shows the different temperature gradients adopted by different codes. In this paper, uniform, linear and nonlinear temperature gradients are considered.

As a result of temperature variation there are two types of thermal stresses, the first is the primary thermal stress or self-equilibrating stress and the second is the continuity thermal stress.

Self-equilibrating stress

A change in temperature, which may be uniform or varies linearly over the cross-section of a statically determinate structure, such as simply supported beams, produces no stresses. When the temperature variation is nonlinear, the same beam will be subjected to stresses, because any fiber, being attached to other fibers, cannot exhibit free temperature expansion. Thermal stresses in the cross-section of a statically determinate structure will be referred to as self-equilibrating stresses. Fig. 2 shows the strain and stress distribution and the deflection of a simply supported beam, linear elastic homogenous uncracked beam, subjected to a rise of temperature which varies linearly or nonlinearly over the depth of the section. Two lines are shown for the strain distribution in the case of nonlinear



(a) Temperature gradient in New Zealand's Code for highway bridges[8,9]

(b) Temperature gradient in AASHTO[3], where T1, T2 and T3 are the temperature changes depending on building location

Figure 1 Temperature gradients in New Zealand's code and AASHTO.

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