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Non-linear finite element analysis of reinforced concrete beams with temperature differentials

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ABSTRACT

Nonlinear finite element modelling is initially conducted to simulate simply supported reinforced concrete beams with temperature differentials over their depth ($\Delta T = 30\,^\circ\mathrm{C}$) that were tested at room (15 °C) and low temperature (−25 °C) during the experimental phase of this research program. Three-dimensional finite element models of the beams are developed to account for the geometry, material, loading, boundary conditions, and temperature profile. Then, the results of the nonlinear finite element analysis (NLFEA) are verified against the corresponding experimental results in terms of cracking loads, yield loads, ultimate loads, displacements, and cracking patterns. The validated NLFEA models are then extended to explore the response of the same beams with uniform temperature profiles as well as similar statically indeterminate reinforced concrete beams with and without temperature differentials. The numerical results show that the models are capable of predicting the ultimate strength of the beams at both room and low temperature. Additionally, the results show that indeterminacy (fixed-ends) substantially increases the ultimate strength of the reinforced concrete beams (up to 110%). The NLFEA results also show that low temperature (down to −40 °C) increases the strength of the beams without stirrups and decreases the number of the cracks on those beams even when temperature differentials are present. On the other hand, the strength and cracking pattern of the beams with stirrups are not affected when exposed to temperatures as low as −40 °C.

1. Introduction

Bridges are predominant elements in surface transportation networks. For instance, over 55 million cars and 10 million trucks crossed the Canada-US border in 2011 [1], and a significant percentage of these vehicles passed over bridges to reach their destination. However, many bridges in the US and Canada built during the post World War II construction boom are deficient, mainly due to environmental degradation and increased legal loads [2]. Many of these aging bridges are located in northern US states and Canada with severe environmental conditions such as significant and continual temperature fluctuations and prolonged freezing seasons that cause the bridges to be subjected to frequent freeze-thaw cycles and lengthy freezing periods.

Nevertheless, most previous research focused on the effect of low temperature on concrete as a material [3–6] rather than on structural performance of reinforced concrete members. However, limited research was conducted on the seismic behaviour of reinforced concrete at low temperature [7–10]. Furthermore, to the best knowledge of the authors of this paper, none of the developed finite element models accounts for temperature effects on the static behaviour of conventionally reinforced concrete members.

Genikomsou and Polak [11] studied the punching shear behaviour of slabs without shear reinforcement by conducting a nonlinear finite element analysis (NLFEA) on three-dimensional models of five concrete slab-column connections that were subjected to either static loading or pseudo seismic horizontal loading. To simulate the behaviour of the concrete, the concrete damage plasticity model was incorporated as the constitutive model with the secant modulus of elasticity of the concrete determined using the Hognestad parabola. The numerical results showed that the contribution of the tensile behaviour of the concrete to the response of the slabs was significant because of the absence of shear reinforcement.

Liang et al. [12] conducted a numerical study on the flexural and shear strengths of simply supported composite beams that were tested by Chapman and Balakrishnan [13]. A three-dimensional finite element model using a smeared cracking constitutive model was adopted, and reinforcing bars in the concrete slabs were modelled as smeared layers in the shell elements. To define stress-strain relationship of the steel section and the concrete in compression, a bilinear stress-strain curve with strain

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Nomenclature

A	cross-sectional area	T	temperature
b_c	constant factor	ε	flow potential eccentricity
b_t	constant factor	ε_c	strain values
D	diameter	ε_c^{pl}	compressive plastic strain
d	elastic stiffness degradation (single scalar variable)	ε_{eng}	engineering strain
d_c	uniaxial compressive damage variable	ε_0	strain at ultimate stress
d_t	uniaxial tensile damage variable	ε_t^{pl}	tensile plastic strain
E_c	modulus of elasticity of concrete	ε_{true}	true strain
f'_c	28-day compressive strength of concrete	μ	viscosity parameter representing the relaxation time of the viscoplastic system
f_{b0}	initial biaxial compressive yield stress	ν	Poisson's ratio
f_c	value of the stresses as function of the strains ε_c	σ_c	compressive stress
f_{c0}	initial uniaxial compressive yield stress	σ_{eng}	engineering stress
f_t	tensile strength of concrete	σ_t	tensile stress
f_{ult}	Ultimate Strength	σ_{true}	true stress
f_y	Yield Strength	ψ	dilation angle
K_c	the strength ratio of concrete under biaxial compression to triaxial compression		
s_c	compressive stiffness recovery		
s_t	tensile stiffness recovery		

hardening and the equation proposed by Carriera and Chu [14] were used, respectively. The numerical results were in good agreement with the experimental results, i.e. the initial stiffness of the composite beam and the ultimate load predicted through the numerical analysis were approximately 100% and 95% of the corresponding experimental values, respectively, and the same mode of failure, i.e. crushing of the top concrete slab at midspan, was predicted by the NLFEA.

Alih and Khelil [15] developed stress-strain relationships for cold and hot austenitic (inoxydable) steels for numerical modelling of stainless-steel reinforcement and reinforced concrete members. To model the concrete, a smeared cracking constitutive model with tension stiffening was adopted. To validate the FEA, the predicted strains in the reinforcing steel were compared to the readings of corresponding strain gauges in experiment. The FEA results predicted slightly higher strains, but the strain distribution predicted by the FEA was generally in good agreement with the strain gauge readings. The difference between the FEA and the experimental results was attributed to the tension stiffening model used in the modelling in which some parameters (i.e., density of the reinforcement, the actual concrete-steel bond, the size of the concrete aggregate compared to the diameter of the reinforcement) were not taken into account.

Yu et al. [16] developed a modified plastic damage model within the theoretical framework of the concrete damage plasticity constitutive model, and verified the modified constitutive model with the results of the tests in which concrete was subjected to different stress states, i.e., actively confined concrete, concrete under biaxial compression, FRP confined concrete in circular and square sections, and Hybrid FRP-concrete-steel double-skin tubular columns (Hybrid DSTCs).

Comparison of the results of the finite element models incorporating the modified concrete damage plasticity against the experimental results showed that the FEA results were in good agreement with the test results in terms of axial and hoop stress-strain behaviour.

DeRosa et al. [17] studied the static behaviour of four large-scale reinforced concrete beams at −20 °C and room temperature. Two beams were loaded and tested at room temperature while the other two beams were exposed to a temperature of −20 °C during the sustained and the following loading stages. The results of that study suggested that the cracks in the two low-temperature beams closed up after the 48-h constant load period, and that the percentage increases in crack widths close to the failure load were smaller than those in similar beams tested at room temperature. In addition, the failure load for the beam tested at −20 °C was approximately 20% higher than its counterpart at room temperature. This study concluded that temperature had an impact on crack widths at ultimate loads, and that cracks in reinforced concrete specimens decreased in size at lower temperatures, which could potentially increase the overall shear capacity of the member during colder times of the year.

To fill the gap in numerical study of temperature effects on the static behaviour of reinforced concrete members, this paper presents a numerical model for reinforced concrete beams with and without thermal gradients at room and low temperature. Specifically, the results obtained in the experimental phase of this research program by Mirzazadeh et al. [18] as well as the results of the experimental study conducted by DeRosa et al. [19] are used to validate the three-dimensional finite element models respectively with and without temperature differentials at room and low temperature. Subsequently, the models are extended to determine the cracking pattern and the ultimate strength of similar statically indeterminate beams subjected to temperature differentials at a range of other temperatures between −40 °C and +40 °C.

2. Experimental program

2.1. Material tests

To determine the compressive and tensile strength of the concrete, compressive and splitting tensile tests were conducted on concrete cylinders (150 mm × 300 mm). To determine the yield and ultimate strengths of 20 M (D = 19.5 mm) and 10 M (D = 11.3 mm) reinforcing steel bars that were respectively used as tension, compression, and shear reinforcement in the beams, uniaxial tensile tests were performed on samples of the hot rolled bars. The strength values of the concrete and the bars from the material tests are given in Table 2 and elsewhere [18].

Fig. 1 shows the tested engineering stress–strain curves (σ_{eng}-ε_{eng}) for the reinforcing bars as well as the corresponding stress–strain curves based on true stress (σ_{true}) and true strain (ε_{true}) that were calculated using Eqs. (1) and (2) [20]: