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Geometrically and materially nonlinear creep behaviour of reinforced concrete columns

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ABSTRACT

A mathematical model is developed, which considers creep at the nonlinear range of stresses, shrinkage, aging, cracking, and the geometric nonlinearity in reinforced concrete columns. Creep is modelled through the modified principle of superposition that is based on the use of a stress-dependent compliance function. The governing equations are solved through numerical integration in time and the multiple-shooting method for the solution in space. An iterative procedure is used for convergence at each time step. A numerical study is conducted, which reveals the importance of considering the combined geometric and material nonlinear effects in the creep analysis of concrete columns.

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1. Introduction

Reinforced concrete (RC) columns are subjected to eccentric vertical compression forces in general, and their failure is sudden and drastic, which can be a result of buckling, material failure, or a combination of both due to the interaction between the material and geometric nonlinearities. However, in most cases, a considerable portion of the total load acting on RC columns can be classified as sustained compression load. When this load is combined with the normal construction inaccuracies and load eccentricities, the column undergoes increasing out-of-plane deflection with time due to creep. This may consequently lead to loss of stability (creep buckling) under a sustained load that is significantly smaller than the short-term load carrying capacity. However, creep may not necessarily lead to buckling failure, but it may lead to premature creep rupture failures of the concrete or may reduce the residual strength of the column due to the increased internal stresses and strains with time.

In most cases RC columns are subjected to low levels of serviceability sustained stresses where sophisticated linear creep models in compression can be used to predict the structural response. Many theoretical and experimental studies can be found in the literature regarding the creep behaviour of concrete at low level of stresses (less than 30% the compressive strength, f_{cm}), where the creep strain is linearly proportional to the applied stress [4,22,36]. The creep strains (ε_{creep}) in these cases can be described by means of a stress-independent creep coefficient $\varphi(t, t_0)$ that describes the ratio between the creep strain at time t and the instantaneous strain (ε_{ins}) at time t_0, as shown in Fig. 1, which shows a typical stress (σ) versus strain (ε) curve of concrete. However, in some cases, the level of sustained stresses (locally or globally) can exceed the linear limit. In such cases where the stress levels are above 30% of the compressive strength, not only the instantaneous strain becomes nonlinear with respect to the applied stress, but also the creep strain and the creep coefficient, and they both increase with the increase in the applied load level. A study by Rossi et al. [40] showed that the main physical reason for this phenomenon is attributed to cracking evolution, i.e., creation of microcracks and/or the propagation of macrocracks.

One of the simplest ways to account for nonlinear creep in structural design and analysis is based on the use of the instantaneous nonlinear stress–strain relation of concrete along with a stress-dependent creep coefficient or a stress-dependent compliance function as shown in Fig. 1 ([7,9,14,18,20,25]). For stresses that are greater than around 80% of the compressive strength, nonlinear stress-dependent creep still controls the response but with potential creep rupture failures with time once the total strain exceeds a certain limit defined through a creep rupture envelop as shown in Fig. 1 [20,37,43]. Therefore, knowledge

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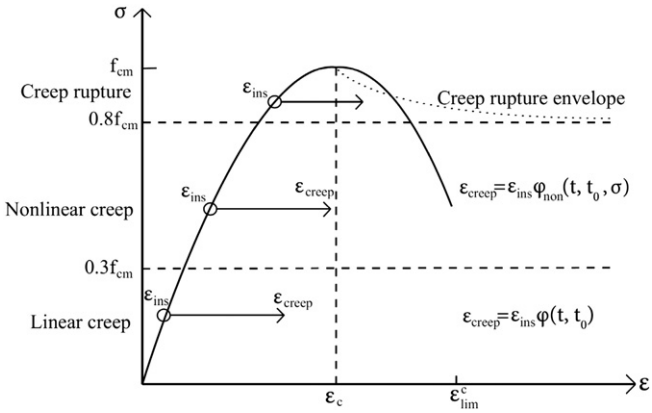

Fig. 1. Stress–strain curve of concrete.

regarding the nonlinear creep behaviour of concrete and its influence on the load carrying capacity of RC columns is essential for a more reliable prediction of their long-term time-dependent response.

A number of studies have been devoted to investigate the linear creep and shrinkage effects in RC columns ([10,23,30,31,41]). These studies considered the geometrically nonlinear effects, but they were limited to compressive stress levels that are relatively low, i.e., less than 30% the compressive strength of concrete that are within the linear range of the stress–strain curve (Fig. 1). Gilbert [23] presented an iterative step-by-step procedure for the nonlinear analysis of slender RC columns under sustained eccentric loading. The time dependent creep and shrinkage effects were included using the age adjusted effective modulus method for the analysis of critical cross sections including the effects of cracking. Samra [41] developed a simple approach to predict creep deformations in RC columns at service loads. The model accounts for age effects, concrete mix composition, and dependence of creep on member size and humidity. The model was compared to laboratory test data, as well as to creep strain measurements taken from existing structures in Chicago.

A finite element step-by step analysis was performed by Kawano and Warner [30], which accounted for the geometric nonlinearity. The method was found to effectively describe the time dependent behaviour including non-uniform shrinkage and creep buckling of slender columns. However there was no consideration of stress applications in the nonlinear range. Bradford et al. [11] incorporated a step by step analysis into a layered nonlinear finite element method, for the analysis of general RC structures. The method accounted for the geometric nonlinearities, including the effects of creep, shrinkage and aging of the concrete. The method was used in Bradford [10] for the analysis of RC columns. However it does not account for the material nonlinearity in compression, and did not consider cracking of the concrete.

A simple numerical model that accounts for the geometric nonlinearity and the cracking of concrete using a layered approach was developed by Kwak and Kim [31] for the creep analysis of slender RC columns. The results were compared to experimental data from Drysdale and Huggins [17]. The study found that high strength concrete is less effective in slender columns than in short columns due to the significant decrease in the load carrying capacity as a result of the pronounced geometrically nonlinear effects. Following this study, a simple regression formula for the design of slender RC columns was proposed in Kwak and Kim [32]. Huang and Hamed [29] developed a nonlinear theoretical model that is based on a rheological generalized Maxwell chain modelling of the creep of concrete in high-strength concrete panels. The model is applicable for RC columns under low stress levels as it accounts for the geometric nonlinearity, cracking, and tension stiffening, but does not account for nonlinear creep at high stress levels.

On the other hand, only few studies have considered the creep response of RC columns including the effects of the geometric nonlinearity of the structure, and the material nonlinearity of concrete that appears at compressive stresses greater than 30% of its compressive strength. Mauch and Holley [34] presented a simplified model that is based on a number of approximations that may not provide a reliable description of the structural behaviour. These include the linearized mathematical modelling of the geometric nonlinearity, and the modelling of concrete using a basic Maxwell model with a single spring and dashpot, which does not provide a good representation of concrete behaviour. Bažant and Tsubaki [8] modelled the nonlinear creep of RC columns using a previously developed constitutive model by Bažant and Kim [6]. The model accounts for the increase of creep at high compressive stress (flow) and also the decrease of creep for subsequent load increments (adaption) caused by low sustained compressive stress. While the analysis showed a reasonable comparison to test data, the creep function was expressed as a function of time only and did not consider the magnification caused by the nonlinear material behaviour at high stress levels. In addition, the endochronic model adopted in Bažant and Kim [6] actually involves a relatively large number of parameters that are not easy to obtain, making it too complex to use for the analysis and design of RC structures. Furthermore, cracking, shrinkage and aging effects were not considered.

Claeson and Gylltoft [16] performed tests on normal and high strength concrete columns. An analysis was performed using a moment-curvature curve approach and a cross-sectional analysis considering creep, based on the CEB-FIP model (1990) and a modified curve by Han [28] for high strength concrete. The nonlinear creep effects were accounted for by multiplying the creep coefficient by a magnification factor. The model showed partial agreement with test data. However, shrinkage effects were disregarded and the second order effects were taken into account by assuming a sine curve deflection shape, which can be inaccurate when cracks develop or when the compressive stresses reach the nonlinear range at some locations. In addition, the influence of the variable stress history, which is important in slender RC columns due to the geometric nonlinearity, was not considered through a time-stepping analysis, and the final stage of the column was assumed to be reached in one time step. Therefore, a more refined model is needed for a more reliable prediction of the structural behaviour.

In the design of RC columns, the effect of creep is included using simplified methods (see for example ACI318 [2] and AS3600 [3]). The approach adopted in these design standards is based on reducing the stiffness required for calculating the buckling load of the column by a factor of $1/(1+\beta)$, where β is the ratio between the sustained and the total loads. Bearing in mind that different concretes creep differently in time, and the fact that the creep properties are not accounted for because the influence of creep is only introduced through the load ratio (β), it can be seen that the existing design standards may lead to inaccurate estimation of the member strength. The interaction between creep, cracking, and material nonlinearity are also not considered.

It can be seen that the existing numerical models do not comprehensively account for the combined effects of nonlinear creep, shrinkage, aging, geometric nonlinearity, and cracking. Here, these effects are considered through the development of an incremental nonlinear numerical model that is based on a step-by-step time analysis. Through the time stepping procedure, the model is capable of describing the time-dependent change of the internal stresses, the incremental cracking and material softening, and the increase of the deformations with time. In previous studies conducted by the first author [24,25], a full nonlinear viscoelastic model that is based on the modified principle of superposition [33] was developed for the nonlinear creep analysis of RC beams. The model accounted for nonlinear creep, shrinkage, aging, and yielding of the steel reinforcement, through an incremental time-stepping analysis. This model depends on a fewer number of parameters than other models in the literature developed for describing the nonlinear viscoelastic behaviour of concrete (see for example Bažant

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