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# Finite element modelling approach for precast reinforced concrete beam-to-column connections under cyclic loading

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ABSTRACT

In this paper, a finite element modelling approach is developed for the analysis of the cyclic behavior of precast beam-to-column connections. In particular, the modelling takes into account the compression-softening of concrete, the bond-slip effect in the critical regions and the representation of the post-cast concrete interface. A newly developed softened damage-plasticity model, which can reproduce the typical cyclic behavior of reinforced concrete, is adopted for concrete. Meanwhile, to reflect the significant bond-slip effect between concrete and reinforcement bars, the M-P stress-strain model is modified to account for the slippage by assuming the bar strain is the sum of the bar deformation and the slip, while the anchorage slip is theoretically derived and validated through benchmarking the pull-out tests. Additionally, a concrete layer between the precast concrete and the cast-in-situ concrete is incorporated to reflect the features of the interface. The proposed numerical modelling approach is validated through simulation of both interior and exterior precast beam-to-column connection tests. The validated models are subsequently employed to investigate the influences of key factors such as the compression-softening and the bond-slip effect on the analysis of the cyclic behavior of the precast beam-to-column connections. Results demonstrate that the proposed model is capable of reproducing the typical behavior of precast beam-to-column connections and can serve as an effective tool for the seismic performance analysis and investigation of design parameters of precast connections.

## 1. Introduction

Precast concrete structures are widely used in industrial and residual buildings around the world including the United State, Japan, New Zealand and China, and they have various advantages compared with the traditional cast-in-situ concrete structures, including the product quality, construction speed, less manual labor, low environmental pollution, and so on [1]. Among different kinds of precast concrete structure systems at present, frame structures are particularly suitable for precast concrete industry since the beam and column components are very convenient for standardization, prefabrication and assembling. For example, in the past 5 years precast frame systems have been applied in more than 1 million $m^2$ buildings in China. In precast concrete frame structures, the beam-to-column connections are the crucial part as they affect not only the overall performance of the structures but also the cost and construction efficiency. Therefore, it is of great interest in studying the design methodologies, detailing, and analysis models of the precast concrete beam-to-column connections.

Most of the past investigations into the seismic performance of precast beam-to-column connections have been conducted using reversal cyclic loading tests on large size specimens, e.g., the work by Park and Bull [2], Alcocer et al. [3], Im et al. [4], Xue and Yang [5], Kulkarni and Li [6], Li and Kulkarni [7], Cai et al. [8], Chen et al. [9], Guan et al. [1], etc. Through physical experiments, direct comparisons have been made between the various precast beam-to-column connections and their conventional monolithic counterparts in terms of the strength, ductility and energy dissipation capacities. However, experimental studies are usually costly and time consuming, and can be restricted by the test facilities and space [10]. Furthermore, the behavior of the beam-to-column connection is very complex and several parameters (e.g., axial load ratio, reinforcing details, concrete strength, etc.) have significant influences on its seismic performance; it is impractical to fully investigate all parameters through a limited number of experiments [11]. Therefore, numerical simulation has become a much needed means for the quantification of the influence of the

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underlying parameters, as well as further development of the design methodologies.

Generally, two kinds of numerical models are developed for precast beam-to-column connections. Models of the first kind are the macro-level joint models. These models [12,13] usually use fiber elements to simulate the beams and columns, while additional rotational springs are introduced to the joint region to represent the bar slippage and the shear distortion of the joint panel, which are especially important for precast concrete structures due to the inevitable differences between the pre- and post-cast concrete. Yu and Tan [14] also proposed a new component-based joint model for precast concrete structures with an emphasis on the bond-slip behavior of longitudinal bars under large tension. Obviously, such a macro-level approach is simple and computationally efficient, thus is widely adopted for seismic analysis of precast beam-to-column connections. However, the calibration of the model parameters is usually difficult. Moreover, the macro-level joint models are suited mainly for analysis of whole or part of a frame structure, but cannot be used effectively for the investigation of the behavior within a joint or connection itself.

Models of the second kind are continuum-based finite element models, usually in a three-dimensional (3D) domain. These models are more elaborate and can provide detailed responses of the local region as compared with the macro models. Kulkarni et al. [15] and Li et al. [16] proposed a finite element model for precast hybrid-steel concrete connections under cyclic loading based on DIANA software, where two-dimensional (2D) plane stress elements were used for concrete and steel plates. The hysteretic curves of the connection were obtained and the influences of some critical design parameters were studied. Kaya and Arslan [17] used ANSYS to model post-tensioned precast beam-to-column connections under different stress levels; however, only monotonic behavior was obtained. Hawileh et al. [10] developed a detailed 3D finite element model for precast hybrid beam-to-column connections subjected to cyclic loads, and surface-to-surface contact between the beam and column faces were considered in the model. Bahrami et al. [18] numerically analyzed seismic performance of two new precast beam-to-column connections using ABAQUS software, covering the lateral resistance, ductility and energy dissipation of the connections. However, the analysis was also limited to monotonic loading.

It is fair to state that 3D finite element modelling represents the current trend in the numerical analysis of precast beam-to-column connections, due apparently to its presumed ability in describing the complex connection behavior in a realistic manner. However, there has been a lack of detailed discussion on the methodology and specific modelling techniques for precast beam-to-column connections, especially under reversal cyclic loading. This may be caused by the challenges in devising an adequate multi-axial concrete model with good computational stability under cyclic loading. Further, though widely realized of its significance, there has been a lack of efficient ways to represent the bar slippage (or bond-slip effect) in the critical regions, as well as the precast and cast-in-situ concrete interface, in a detailed FE model for the precast connections.

In light of the above-mentioned background, this paper aims at developing a rational procedure for the 3D finite element modelling of precast beam-to-column connections, with a particular emphasis on the cyclic behavior. A newly developed softened damage-plasticity model, which is numerically stable and reflects the typical cyclic behavior of reinforced concrete, is adopted for modelling of concrete. Meanwhile, to reflect the significant bond-slip effect between concrete and reinforcement bars at the joint core and plastic hinge regions of the precast connection assembly, the Menegotto-Pinto (M-P) stress-strain model is modified to account for the slip deformation. The modification to the M-P bar model is established on the basis of equivalent overall slip over the development length (anchorage slip) by adopting a modified bar strain to represent the sum of the bar deformation and the slip, while the anchorage slip is theoretically derived and validated through benchmarking the pull-out tests. An additional post-cast interface is set in the finite element modelling of the precast beam-to-column connections. The developed finite element model is validated through comparisons with the experimental results of several interior and exterior connections in terms of hysteretic load-displacement curves, stiffness degradation, energy dissipation, etc. Finally, the influences of the key factors, including the compression-softening, bond-slip effect, and the pre- and post-cast concrete interface on the cyclic performance of the precast beam-to-column connection are investigated.

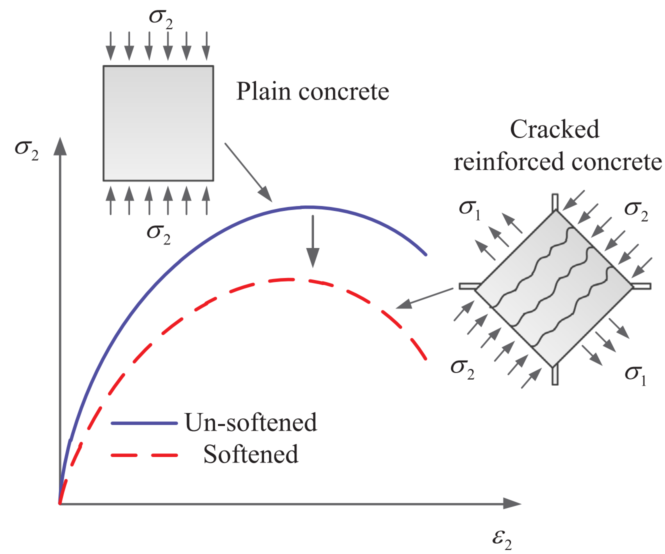


**Fig. 1.** Compression-softening effect of reinforced concrete.

## 2. Concrete damage-plasticity model with compression-softening

To model the typical cyclic behavior of the precast beam-to-column connections, a newly developed softened damage-plasticity model [19,20] is adopted for concrete. This concrete model accounts for the compression-softening effect (Fig. 1) [21,22] and is proven to be numerically robust for cyclic loading. The detailed derivation of the model can be seen in Refs. [19,20]. Here it is briefly introduced.

Based on this model, the constitutive relation of concrete material is expressed as

$$\boldsymbol{\sigma} = (\mathbb{I}-\mathbb{D}^s):\mathbb{E}_0:(\boldsymbol{\epsilon}-\boldsymbol{\epsilon}^p) \tag{1}$$

where $\boldsymbol{\sigma}$ is the Cauchy stress tensor; $\mathbb{I}$ is the unit tensor; $\mathbb{E}_0$ is the fourth-order elastic modulus tensor; $\boldsymbol{\epsilon}$ is the total strain tensor; $\boldsymbol{\epsilon}^e$ and $\boldsymbol{\epsilon}^p$ are the elastic and plastic components of the strain tensor, respectively; $\mathbb{D}^s$ is the fourth-order damage tensor with compression-softening, which is given by

$$\begin{cases} \mathbb{D}^s = d^+\mathbb{P}^+ + d^{s-}\mathbb{P}^- \\ d^{s-} = 1-\beta(1-d^-) \end{cases} \tag{2}$$

in which $\mathbb{P}^+$ and $\mathbb{P}^-$ are the projection tensors; $d^+$ and $d^-$ are the two damage variables representing the corresponding tensile and compressive behaviors of concrete; $\beta$ is the softening coefficient.

The damage evolution is controlled by the energy release rates $Y^{\pm}$ [23–25], which be further simplified into energy equivalent strains $\bar{\epsilon}^{eq\pm}$ to represent the multi-dimensional damage evolution through uniaxial damage functions [26], i.e.,

$$\begin{cases} \bar{\epsilon}^{eq+} = \sqrt{\dfrac{2Y^+}{E_0}} \\ \bar{\epsilon}^{eq-} = \dfrac{1}{E_0(1-\alpha)}\sqrt{\dfrac{Y^-}{b_0}} \end{cases} \tag{3}$$

where $E_0$ is the initial elastic modulus; $b_0$ and $\alpha$ are the material parameters [23].