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Structural performance of detachable precast composite column joints with mechanical metal plates

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ABSTRACT

The seismic performance of the novel precast concrete frame with mechanical joints using metal plates proposed to provide moment connections was estimated by the numerical analysis verified by experimental investigations. Nonlinear finite element analyses of mechanical column-to-column joints with metal filler plates under static loadings were performed to determine their failure modes and deformations in the column plates. Damages to the proposed novel mechanical connections for composite precast columns using metal plates that create a rigid joint were also elicited. This study also identified the material parameters of the damaged concrete using a plasticity model that were suitable for the prediction of the proposed precast columns. The calibrated dilation angle and concrete damage factor were validated by experimental investigations of the specimens subjected to cyclic loadings; the required stiffness of the column metal plates for rigid joints was identified. A comparison between numerical and experimental results showed that the calibrated FE models accurately predicted the joint behavior of the mechanical column-column joint. Recommendations were made for the practical and optimal design of the mechanical column connections based on the nonlinear behavior of the joints.

1. Introduction

1.1. Research background and objectives

Conventionally, sleeve connections are used for precast columns [1–4]. A cylindrical steel sleeve was used as a mechanical sleeve coupler for splicing reinforcing bars to provide full tension and compression for precast column connections. Fig. 1 shows a splice-sleeve into which reinforcing bars are inserted, meeting approximately at the center of the sleeve. The sleeve is then grouted with non-shrink high early strength mortar. In Fig. 1(a) [5] and Fig. 1(b) [6], the sleeves are embedded in the base of upper precast columns at the precast plant. Reinforcing bars are inserted halfway into the sleeves with the bars protruding from the lower precast columns. The precast columns are then connected by inserting the protruding bars from the end of lower precast columns into the sleeves of the upper columns. Proper grouted steel sleeves are used to ensure the continuity of the column longitudinal reinforcements [7,8]. The erection of precast columns proceeds after the grouted non-shrink high early strength mortar is cured, making the reinforcing bars continuous through the connection. Another traditional type of frame joint is cast-in-place with pour forms to form a moment connection to precast frames, as shown in Fig. 1(c) [9]. The joint concrete must be cured before further erection of precast frames proceeds. It is important to ensure that the vertical joints with only reinforcing re-bars support the full construction load and avoid bumping the precast members during frame erection.

In steel frames, bolted end plates were introduced to transfer both axial forces and moments exerted on two parts of a steel column connected with either end-plates or cover plates. Although bolted end plates are primarily designed to act as rigid connections, most of these connections fall into the semi-rigid category, implying that they fail to fully transfer moments and axial forces through interconnected parts. Additionally, their failure mechanisms are very complex since they depend on many parameters including plate thickness, bolt diameter, and bolt positioning. Numerous researchers investigated the structural performance of these connections to identify both loading capacities and failure modes.

Bahaari and Sherbourne [10] carried out an analytical investigation on the structural behavior of bolted end-plates in terms of both strength and stiffness. The calibrated FE models were able to predict the behavior of the tested specimens, and the results indicated that the main stresses in the end plate were compiled at the junction lines with a beam flange and web. Mashaly et al. [11] conducted a finite element analysis of beam-to-column joints subjected to cyclic loadings in order to present a simple 3D finite element model (FE) that can accurately predict the actual behavior of the tested joint. Good agreement between

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Nomenclature

ε_{c0}	strain corresponding to the maximum compressive stress of concrete
ε_c	concrete strain
f'_c	concrete cylinder strength in MPa
f_y	yield strength
f_u	ultimate strength
σ_c	concrete compressive stress
σ_{co}	maximum compressive stress of concrete
σ_{t0}	maximum tensile stress of concrete
E_c	modulus of elasticity of concrete
E_s	modulus of elasticity of steel and rebar
ε_t	tensile strain of concrete
ε_c	compressive strain of concrete
$\tilde{\varepsilon}_t^{pl}$	plastic strains of concrete in tension
$\tilde{\varepsilon}_c^{pl}$	plastic strains of concrete in compression
$\tilde{\varepsilon}_c^{el}$	elastic strain
$\tilde{\varepsilon}_c^{in}$	inelastic strain
$\tilde{\varepsilon}_t^{ck}$, $\tilde{\varepsilon}_c^{ck}$	cracking strains of concrete in tension and compression
d_t	concrete damage parameter in tension
d_c	concrete damage parameter in compression
ϵ	eccentricity
$\overline{p}$, $\overline{q}$	the plane in which plastic potential function is defined
$\mathbf{G}(\sigma)$	non-associated plastic flow potential, Druker-Prager formulation
ψ	dilation angle
K_c	the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian
$\frac{f_{bo}}{f_{c0}}$	ratio of initial equibiaxial compressive yield stress to initial compressive stress
	ultimate tensile strength
F_{nv}	nominal bolt shear strength (stress)
V_u	the required design shear demand
$V_{n,bolt}$	the design shear strength
ϕ	strength reduction factor (0.75)
A_b	area of bolt
L_{c1}	distance from edge of bolt hole to the edge of plate
L_{c2}	distance from edge of bolt hole to edge of adjacent hole
dt	bearing area (d bolt diameter, t thickness of the connected part)
R_n	nominal resistance (strength)
M_n	nominal moment capacity

the numerical results and experimental results was observed. More importantly, the authors concluded that FE models can provide a good view of full fields of stresses and strains that cannot be seen during experimental investigations. Further studies conducted for end-plate moment connections have provided a large database for the design of end-plates subjected to either monotonic or cyclic loadings [12–16]. Chen and Shi [17] introduced a novel ultra-large capacity end plate connection that can be used in steel structures involving heavy loads. A yield line model for the newly proposed joint was also presented. Their findings demonstrated that the moment resistance of the tested joints was influenced by both end plate thickness and bolt diameter, indicating that both are crucial parameters that dictate the behavior of bolted end plates.

1.2. Joint connection from the erection point of view

In previous study of the authors [18], the proposed mechanical joint illustrated in Fig. 2(a) [18], which is designed to transfer moments through the inter-connected components, was implemented for both precast steel-concrete composite frames and precast concrete frames. The precast members are connected by end-plates with metal filler plates that are designed to transfer moments through interconnected components. The joint of the proposed connection consists of two end-plates (lower and upper column plates), nuts, and high-strength bolts. In their study, nuts were incorporated to connect the threaded end of the vertical reinforcing bars at the rear part of end-plates, as illustrated in Fig. 2(b) [18] and (c). High-strength bolts designed based on a bearing-type connection were used to transfer moments through both lower and upper column plates. Full scale installation test of precast columns with mechanical joints fabricated with metal plates was demonstrated, exhibiting rapid assemblage similar to that of steel frames as shown in Fig. 2(d) [18]. The details of the erection test with mechanical joints for typical precast steel-concrete composite frames can be found in the previous study [18].

1.3. Significance of the study

In the previous study of the authors [19] and above, a novel mechanical joint using steel plates was introduced to reduce construction time by eliminating the time required to cure concrete at joints. The authors introduced brief results of experimental observation of the column connections with mechanical joints. This study, however, did not provided in-depth findings with comprehensive summary of the column to column connections with mechanical joints having metal filler plate. The nonlinear finite element analysis with parameter identification for the numerical investigation was absent. In this study, structural performance of detachable precast composite column joints with mechanical metal plates was explored in-depth with comprehensive numerical investigation. The numerical results were also calibrated and verified by test data for further application in precast industry. Precast steel-concrete composite frames are preferable over conventional precast concrete practices since they are less weight, achieving cost-efficient structural systems that offer rapid and facile erection. However, the application of the conventional precast joints required use of concrete cast, leading to failing to prove their efficiencies compared with the joints implemented in steel construction using bolted end plates. This study introduced a nonlinear finite element analysis of mechanical joints that consist of metal plates connecting two columns using high-strength plates and high-strength bolts. Subsequently, a nonlinear finite element analysis to study structural performance of the bolted column-to-column mechanical joints that consist of metal plates connecting the two columns using high-strength bolts was introduced. This study, then, identified the FEA (finite element analysis) parameters of the concrete damaged plasticity model including parameters suitable for the design of proposed precast columns jointed by metal plates. In addition, advanced techniques were discussed herein, including surface-to-surface contact properties, discretization and a constitutive relation for concrete with damage characteristics based on flow rule. The calibrated dilation angle and concrete damage factor were validated by experimental investigations of the specimens subjected to cyclic loadings; the required stiffness of the column metal plates for rigid joints was identified. A comparison made between numerical and experimental results showed that the calibrated FE models accurately predicted the joint behavior of the mechanical column-column joint.

The displaced nuts were reflected when the nuts penetrated into the adjacent column plate in the nonlinear inelastic finite model using a dilation angle of 30°. The FEA permitting nuts to penetrate into adjacent metal plates predicted the laminated column plates accurately.