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Numerical and parametric studies on steel-elastic concrete composite structures

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ABSTRACT

This paper provided an overview on the developments of the steel-elastic concrete composite (SECC) structures. 16 push-out tests and six beam tests were reported to demonstrate the ultimate strength behaviour of the SECC structure from the component level to the structure level. Three-dimensional finite element models (FEMs) have been developed to simulate the ultimate strength behaviour of the SECC structures. The developed FEMs considered the nonlinear mechanical properties of the elastic concrete and steels in the structure, geometric nonlinearities, and complex interactions among the headed studs, I-beam, and concrete slabs. Extensive validations of the numerical analyses against the reported 16 push-out tests and six beam tests proved that the developed FEMs offered reasonable simulations on the ultimate strength behaviour of the SECC structure from component level to the structural level in terms of ultimate resistances, load-slip (or deflection) behaviours, and failure modes. A subsequent parametric study was carried out to investigate the influences of the rubber content in the elastic concrete and strength of the I-beam on the ultimate strength behaviour of the SECC beams. Finally, step-by-step FE analysis procedures on the SECC structures were recommended based on these numerical studies and validations.

1. Introduction

Elastic concrete, i.e., concrete with addition of tire rubber, exhibits improvements on its crack and fatigue resistance. The added rubber particles in elastic concrete were usually recycled from the crushed waste rubber (e.g., automobile tires) that could reduce the environmental pollution, result in green constructions, and reduce carbon dioxide emission. The elastic concrete was initially developed for the road pavement in 1990s [1]. Pilot research by Eldin and Senouci [2] showed that the concrete with tire chips and crumb rubber exhibited lower strength but more ductile behaviour under compression than that of concrete without rubber. Continued works by Topcu and Toutanji [3,4] also proved that the elastic concrete with tire rubber improved its toughness [3,4]. Further tests [5,6] also showed that elastic concrete with crushed rubbers exhibited reductions in the flexural tensile strength, but increased its fracture strain. The three-point bending tests under fatigue loading by Feng et al. [7] proved that the fatigue resistance of the elastic concrete was significantly improved. Including the improved fracture toughness, deformability and fatigue resistance, the elastic concrete also exhibits advantages of superior acoustical behaviours, aging and wearing resistance over conventional normal weight concrete. This type of relative new material has been extensively used as the pavements for roads and bridges, parking lots, and sport court. More recently, it has been used in the steel-concrete composite structures, i.e., steel-elastic concrete composite (SECC) structures.

SECC structure typically consists of a concrete slab connected to the underneath I-beams through the cohesive materials (e.g., epoxy) or headed shear studs. This type of structure combines the advantages of concrete compression and steel tension, and has been widely used in the residential and commercial buildings, bridges, and multi-story factories. In steel-concrete composite structures, the strengths of the concrete and shear connectors are important to the ultimate load carrying capacity of the structure. Kim et al. [8] experimentally studied the influence of the degree of the composite action on the ultimate loading carrying capacity of the steel-concrete composite beam, and found that this influence was quite limited. Experiments carried out by Nie et al. [9] also showed that partial composite steel-concrete composite beams could also be used in the continuous steel-composite beams if proper measures were taken. More recently, the steel-concrete composite beam with elastic concrete has been developed for engineering constructions [10–13]. Preliminary experimental studies showed that using the elastic

Abbreviations: CDM, continuum damage model; CDP, concrete damage plasticity; COV, coefficient of variation; FE, finite element; FEA, finite element analysis; FEM, finite element model; HSS, headed shear stud connector; SECC, steel-elastic concrete composite structure.

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Nomenclature

D_c, D_t	compressive and tensile damage ratios of concrete, respectively
E_0	initial elastic modulus of concrete
E_s	elastic modulus of the steel
H	height of the I-beam in the SECC composite beam
K_e	experimental elastic stiffness in the load-central deflection curves of the SECC beam
$K_{e,FE}$	numerical elastic stiffness in the load-central deflection curves of the SECC beam
P	resistance of the SECC composite beam
$P_{u,FE}$	ultimate resistance of SECC structure predicted by the finite element analysis
$P_{u,t}$	experimental ultimate resistance of SECC structure
S_1, S_2	spacing of the connectors in mid-span and side span as shown in Fig. 3
T	thickness of the concrete slab as shown in Fig. 3
W	width of the I-beam as shown in Fig. 3
a	with of the flange of the concrete slab as shown in Fig. 3
f_c	compressive stress at the softening region in the stress-strain curve
f_{ck}	compressive stress at the softening region in the stress-strain curve
f_{yr}, f_{ur}	yield and ultimate strength of the reinforcement in the concrete slab
f_{yI}, f_{uI}	yield and ultimate strength of the I-beam
n_s	quantity of the headed studs in half span of the SECC beams
δ_f	central deflection of the steel-elastic concrete composite beam
ε_c	compressive strain of the concrete
ε_{ck}	compressive strain of the concrete corresponding to f_{ck}
ε_c^{In}, ε_t^{In}	inelastic compressive or tensile strain of the concrete
$\overline{\varepsilon}_c^{In}$, $\overline{\varepsilon}_t^{In}$	inelastic compressive and tensile strain against the maximum strain in the stress-strain curves
ε_c^{pl}, ε_t^{pl}	true compressive or tensile plastic strain of the concrete
ρ	rubber content by volume of the elastic concrete
σ_c, σ_t	uniaxial tensile compressive or tensile stress of concrete
σ_y, σ_u	yield and ultimate strength of the headed studs
Δ	interfacial slip between the I-beam and concrete slab in the push-out test
υ	Poisson's ratio

concrete improved the fatigue resistance of the steel-concrete composite beams, which becomes more essential to the bridges with steel-concrete composite decks.

Since the SECC structures have been developed for civil constructions, their structural behaviours need to be well understood. Push-out tests were widely carried out to obtain the shear-slip behaviour of the headed shear studs in steel-concrete composite structures. Extensive experimental works on shear strength behaviour of the headed studs in different normal and lightweight concrete have been reported by Viest et al. [14], Ollgaard et al. [15], Lam et al. [16], and Tahir et al. [17]. Yan et al. [18] have reported 102 push-out tests on specimens with J-hook types of connectors. Xie et al. [19] reported 24 push-out tests on laser welded bar connectors used in the Bi-steel type of steel-concrete composite structure. However, these experimental studies focused on the shear strength behaviour of the connectors mainly embedded in normal- or light-weight concrete. The information on the shear strength of stud connectors in elastic concrete is still quite limited. In addition, specifications on shear strength of the headed studs in most of the design codes, e.g., Eurocode 4 and ANSI/AISC, are empirical that were developed through regression analysis on the push-out tests. Thus, the design recommendations in Eurocode 4 and ANSI/AISC need to be checked on the predictions on shear resistance of connectors in steel-elastic concrete composite structure. From this point of view, the push-out tests on headed studs embedded in elastic concrete are still required and of importance to the development of design equations on the strength of the SECC structures.

The full scale tests on strength behaviour of the headed studs and beams tend to be costing and could not offer the thorough understanding on the structural behaviour of the SECC structures. Finite element (FE) simulation usually offers the alternative to analyse the structural behaviours of the steel-concrete composite structures. FE models that detailed simulate the connectors in push-out tests have been reported by Nguyen et al. [20], Pavlović et al. [21], Lam and Ellobody [22], Guezouli et al. [23], and Yan et al. [24]. However, it was found that the detailed simulation on the headed stud connectors as well as on the concrete surrounding the connectors would lead to a large quantity of element in FE modelling (FEM). Therefore, simplifications of the headed stud in the steel-concrete composite structures become popular in the last two decades. Spring element or cohesive material was used in the FEM instead of connectors through assigning experimental shear-slip behaviours to the spring or cohesive materials [24–27]. Zhao and Li [25] developed a 3D FE model for the steel-concrete composite beam by simplifying the shear connectors with cohesive material. Song et al. [26] used spring element to simulate the headed studs used in the steel-concrete composite structures under fire hazard. Though this simplified method could efficiently improve the computing efficiency, the spring element used in the FEM just adopted the shear-slip behaviour of the stud from the push-out tests. However, previous studies showed that the shear and tensile resistance of the stud connector would compensate each other, and this shear-tension interaction strength of the headed stud connectors could not be precisely simulated that would compromise the accuracy of the FE simulation [27]. Thus, it is necessary to develop a FEM with detailed simulation of the headed stud connectors for the steel-concrete composite structure, especially for SECC beams.

This paper aimed to develop the three-dimensional nonlinear finite element model (FEM) for SECC beams. Firstly, the paper briefly introduced the developments of steel-elastic concrete composite beams. The push-out tests and four-point bending tests on the SECC beams [10–13] were then introduced that were used to experimentally study the structural behaviour of SECC structure on the component level to the structural level, respectively. Then, the FEMs were developed for the push-out tests and SECC beams in four-point bending tests. The accuracies of these developed FEMs were validated against these reported push-out and beam tests. Parametric studies were also carried out to investigate the influences of the rubber content and steel strength of the I-beam on ultimate strength behaviour of SECC beams. Finally, FE analysis procedures for the SECC structures were recommended.

2. Experimental studies on the steel-elastic concrete composite structure

Sixteen push-out tests and six quasi-static tests were carried out on component specimens with headed studs and SECC beams, respectively. Elastic concrete with different volume fraction of crumb rubber were used in all the 24 specimens.

2.1. Materials

The elastic concrete used in this test program consists of ordinary Portland cement (P.O. 42.5) [see Fig. 1(a)], water, granite coarse aggregate [see Fig. 1(b)], fine aggregate [natural sand, see Fig. 1(c)], and rubber particles as shown in Fig. 1(d). The crushed granite stone type of coarse aggregate with particle diameter of 5– 25 mm was used in the mixture. The maximum particle diameter and fineness modulus for