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Applications of ultra-lightweight cement composite in flat slabs and double skin composite structures

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HIGHLIGHTS

- Develop ultra lightweight cement composite (ULCC) for offshore and onshore structures.
- Develop double skin composite (DSC) elements for Arctic offshore structures with ULCC.
- Report tests on flat slabs with ULCC under localized ice loads.
- Report tests on DSC plates and shells under localized ice loads.
- Develop design equations on strengths of flat slabs and DSC plates and shells.

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ABSTRACT

Ultra-lightweight cement composite (ULCC) has been developed for building and offshore constructions. This paper aims to apply the ULCC in the flat slabs of commercial buildings and double-skin-composite (DSC) ice-resistant walls in the Arctic offshore structures. After developing the structural concepts, quasi-static tests were performed on ULCC flat slabs, DSC slabs, and DSC shells to investigate their ultimate strength behaviors under concentrated loads. General behaviors of these specimens were reported, and the influences of flexural reinforcing ratio (or steel content), volume fraction of the fibers in ULCC, and depth of cross section on ultimate strength behaviors were studied and analyzed. A design approach with a series of equations was developed to predict the ultimate resistances of the reinforced flat slabs, DSC slabs and shells with ULCC. This design approach incorporated influences of fiber content, the resistance contributed by top steel skin, the influence of the curvature on the size of the punching cone in DSC shells, and the modifications on the punching shear resistance by the stud connectors in DSC structure. The accuracy of the design approach is checked against the reported 15 tests. Design recommendations were given for the flat slabs and DSC structures with ULCC.

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1. Introduction

There are three general ways to produce the lightweight concrete, i.e., using lightweight aggregates (voids are mainly in the aggregates), producing cellular or foam concrete (voids are in the cement paste), and using no fines in concrete [fine aggregates (i.e. sands) are removed and voids are mainly among the coarse aggregates]. The civil constructions with requirement of low permeability usually produce the lightweight concrete by using lightweight aggregates, e.g., expanded shale, expanded clay, and sintered fly ash [1–3]. Ultra-lightweight cement composite (ULCC) with compressive strength up to 65 MPa and a low density less than 1500 kg/m^3 has been recently developed by using the lightweight cenospheres as the main aggregates in the cement paste [4–9]. The cenospheres have a low density ranging from 600 kg/m^3 to 900 kg/m^3 due to their hollow structure in the

Abbreviations: COV, coefficient of variation; DSC, double skin composite; LVDT, linear variable displacement transducer; PVA, polyvinyl alcohol; ULCC, ultra-lightweight cement composite.

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Nomenclature

E_{ck}	Initial elastic modulus of concrete
E_s	Elastic modulus of the steel
$K_e = P_e/\delta_e$	Elastic stiffness of SCS sandwich plate
L_p	The perimeter of the punching cone
L_a	The perimeter of the square loading area
P_e	Elastic limit resistance of the SCS sandwich plate under service loading state
P_1, P_2	First and second peak resistances of the DSC structures that correspond to punching shear failure of the concrete core and top steel skin, respectively
R	Radius of the inner shell in DSC shells
S	Spacing of the reinforcement or shear connectors
T	Tensile resistance of the stud connectors in DSC structure
V_c	Punching shear resistance contributed by ULCC core
$V_{c,R}$	Punching shear resistance of ULCC core calculated by the recommended model
V_s	Punching shear resistance contributed by the stud connectors in DSC structure
V_{Ts}	Punching shear resistance contributed by top steel skin
a, b	Length and width of the patch loading
b_0	Critical perimeter for the determination of punching shear resistance locating 0.5 h_e away from the loading edge
d_c	Diameter of the stud connector
f_{ck}	Compressive strength of the ULCC
$f_t, f_{t,a}, f_{t,r}$	Tensile strength, predicted tensile strengths by ACI and the developed model of the ULCC, respectively
f_y, f_u	Yield and ultimate strength of the steel skin
h_a, h_b	Depth of the punching cone along the arch and width direction, respectively
h_c	Thickness of the concrete core in SCS sandwich plate
h_t	The depth of the DSC structure, and $h_e = h_c + (t_t + t_c)$
h_{ef}	The effective height of the connector
h_{ef}	The effective height of the connector
l_a, l_b	Length of punching cone in arch and width direction of DSC structure, respectively
$v_{c,A}$	Punching shear strength specified in ACI 318 [29]
$v_{c,R}$	Punching shear strength of the ULCC
δ_e	central deflection of the SCS sandwich plate under load P_e
γ_v	Reduction factor that accounts the failure of the punching cone and equals 0.5
ρ_P	Volume fraction of PVA fibers in ULCC
ρ_{fl}	Flexural reinforcing ratio in reinforced concrete slabs
σ_y, σ_u	Yield and ultimate strength of the stud connectors

particles that promises the low density of the ULCC [5]. ULCC exhibits high specific strengths compared with normal weight concrete with the same strength, e.g., the strength-to-density ratio for ULCC is 47 kPa/(kg/m^3) compared with this ratio of 27 kPa/(kg/m^3) for normal weight concrete with density of 2400 kg/m^3 and compressive strength of 65 MPa [4]. Including the high specific strengths, the ULCC also exhibits advantages of high freeze and thaw resistance, lower water permeability [8], and low thermal conductivity that is essential to develop the energy efficient building [9]. With these advantages, the ULCC could be used in versatile applications in civil and offshore constructions, e.g., bridge deck [see Fig. 1(a)], double skin composite slabs [see Fig. 1(b)], offshore deck, steel-concrete composite slabs [see Fig. 1(c)], flat slabs in commercial and residential buildings [see Fig. 1(d)], and Arctic offshore structures [10].

Double skin composite (DSC) structure [see Fig. 1(b)], consisting of a concrete core sandwiched by two layers of external steel skin, is a relatively new type of innovative construction and becomes popular in recent three decades [11–17]. The DSC structures have been used as the beams, columns, beam–columns, walls, and slabs. Due to the high specific strengths and high freeze and thaw resistance, more recently, the ULCC has been used in the DSC walls and shells to develop the gravity-based-conical Arctic offshore structure for oil and gas explorations as shown in Fig. 2 [10,17–19]. From the ice impact tests as shown in Fig. 2(c) [19], these conical Arctic offshore structure failed the impacting ice creatures in flexural bending rather than crushing that significantly alleviated the ice-contact pressure at the interacting surface. Previous studies also pointed out that the ice-contact pressure was not evenly distributed and there existed some localized high pressure zones (HPZs) [20] with high value of more than 15 MPa. Therefore, punching shear resistance of the DSC walls under these localized patch loads becomes the main consideration for design purpose. The structural behavior of the DSC ice-resistant walls under horizontal concentrated loading can be treated as the DSC slabs or shells under vertical concentrated loading in the buildings. Therefore, it is of interest to experimentally study the ultimate strength behavior of them under concentrated loads to advance the understanding on the structural performance of this type of structure. These test data will be further used to support developing design protocols in engineering guidelines that are not available in current provisions for such composite structures.

Due to the high specific strengths, the ULCC also shows competitive applications in reinforced flat slabs with supported columns as shown in Fig. 1(d). This flat slab system can be used in building and factory constructions, which shows advantages of easy construction, high cost-efficiency ratio, and providing architectonical flexibility. Compared with the flat slabs made of normal weight concrete with the same strength, ULCC flat slabs save the self-weight by 40% that significantly reduce the size of the column and the cost of foundation. For the flat slab system, the supporting column produces high shear stress concentration on the slab-column connection. Moreover, the punching shear failure occurred in the column-slab conjunction has caused several dramatic collapse in the world and may trigger the progressive collapse of the building that caused damage of property and human casualties. Thus, the punching shear failure becomes the main concern, and it is meaningful to experimentally study the structural performance of the ULCC flat slabs under concentrated loading.

Since the ULCC has been developed for the double skin composite structures and reinforced flat slabs, the major difference between them is that the DSC structures employ the top and bottom steel skins. The difference of the structural behavior between the RC slab and SCS sandwich structure has so far not been pointed out, discussed and recognized. Therefore, it will be meaningful to recognize their differences in the structural performance, and these comparisons of the structural performances, including the load transferring mechanism, failure modes, and ultimate resistances, will provide useful information to develop the design approach on predicting their ultimate resistances. Moreover, previous reported experimental studies were mainly carried out on reinforced flat slabs [21–25] or DSC slabs [26] with normal weight

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