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Structural response of thin-walled circular steel tubular columns filled with demolished concrete lumps and fresh concrete

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HIGHLIGHTS

- The performance of circular steel tubular columns filled with DCLs and FC is addressed.
- The effect of random distribution of DCLS on the column strength is clarified.
- Simplified design method is suggested in light of an enlarged experimental database.
- Coarsely-crushed DCLs have a potential to be reused directly as structural materials.

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ABSTRACT

A straightforward use of coarsely-crushed demolished concrete lumps (DCLs) mixing with fresh concrete (FC) has recently been suggested by the authors and co-investigators, with a desire to provide another option for recycling concrete waste. Due to their being free of strong, costly crushing, the DCLs termed herein are characterized by larger size than conventional recycled aggregates. Bearing in mind this salient feature, the proposed recycling approach is easy to follow: a pre-determined percentage of DCLs, along with FC of complementary amount, can be placed in layers into a hollow steel tube, thereby forming a new structural member named *steel tubular column filled with DCLs and FC*. Field practice has demonstrated constructability of the proposed columns, as well as their advantages of being low-impact and cost-effective.

In this research, several aspects pertaining to the structural response of said columns under concentric and eccentric loadings are addressed. An experimental program was first carried out, which comprised 24 intermediately slender thin-walled circular steel tubular columns filled with DCLs and FC, accompanied by 12 reference columns filled with FC alone. Primary test variables were the replacement ratio of FC by DCLs, the eccentricity of loading, and the thickness of steel wall. It was observed that, despite a noticeable reduction on ultimate strength, the overall structural performance of the proposed columns was not dramatically compromised, even though as much as 40% of FC was replaced by DCLs. Subsequently, a three-dimensional finite-element model is developed, attempting to understand the effect of random spatial distribution of DCLs on the ultimate strength of the columns, with the aid of Monte Carlo simulation technique. Stochastic simulations indicate that heterogeneous locations of DCLs lead to variations in the ultimate resistance, but such effect is generally limited in a probabilistic sense. This implies that when designing the columns concerned, a homogenization-based estimate of the resulting compressive strength of concrete infill may be reasonable and adequate, irrespective of the locations of DCLs. To examine this, lastly, a code-based design discussion is made, involving comparisons between analytical predictions using design provisions and experimental results of 111 pertinent column tests. A unified, simplified and more robust recommendation for determining the axial and axial-flexural capacities of the proposed columns is accordingly suggested, relying upon a strength-reduction factor of 0.9.

1. Introduction

Over the past years, developing suitable techniques for concrete recycling has gained greater momentum than ever before. This is

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directly driven by several factors, such as the expanding extraction of natural aggregate for new construction; the continued generation of concrete waste amounting annually to millions of tons (notably, around 200 million tons per year in China [1]); the increasing footprint of landfills coupled with high landfill costs; and the growing concerns over construction sustainability. Among the techniques prompted, recycled aggregate concrete (RAC) is considered environmentally beneficial and having positive prospects [1,2].

Manufactured by crushing and sieving concrete debris to replace natural aggregates, RAC is usually characterized by its higher porosity and water absorption, lower strength and stiffness, as well as larger creep and shrinkage than its natural aggregate concrete (NAC) counterpart. The inferiority associated with RAC is mainly caused by the residual mortar adhered to the recycled aggregates [3–5]. Nevertheless, on the mechanical properties of RAC, as of today opinions are not consensual and test data essentially scattered [6]. Equal or higher compressive strength of RAC in comparison with its NAC counterpart has been achieved by some treatments such as adjusting the mix proportions [7].

To promote the use of RAC as structural concrete, considerable research has been conducted on concrete members made with recycled aggregate (including slabs [8,9], beams [10–12], columns [13,14], beam-column joints [15], moment frames [16–18], and shear walls [19]). Steel–concrete composite members incorporating RAC have also been proposed and tested, including RAC filled steel tubular members [20–22] and steel reinforced RAC members [23]. No overwhelming evidence has been found that RAC should be excluded from use in structural concrete.

Notwithstanding those extensive research endeavors, RAC has been largely limited to non-structural applications. The reasons hampering wide use of RAC are multifold; one may be that manufacturing quality RAC is often costly and time-consuming, rendering it less energy-saving and/or less economical in actual practice. For the limited use of RAC as structural concrete, the replacement ratio of virgin aggregate is generally low [24].

Against this background, a new eco-friendly method of recycling demolition concrete has been suggested by the authors and co-workers [25], with intent to provide another option for recycling concrete waste. In this proposal, old concrete only needs to be coarsely crushed into large pieces (referred to as demolished concrete lumps or DCLs) for direct mixing with fresh concrete (FC) during casting. Both the aggregates and the mortar from old concrete can be recycled, and the fresh concrete serves as the "binder" for the old concrete. This recycling method has at least two advantages over the traditional method of recycling concrete as aggregates [26]: (1) the recycling process is substantially simplified as crushing to smaller pieces and sieving are avoided; (2) an increased recycling ratio can be achieved. In addition, thanks to the coarse crushing, larger surface asperities are achieved in DCLs, possibly improving the interlock capacity between DCLs and FC.

To examine the proposed idea, the authors' research group has conducted a series of experimental studies on structural members made of DCLs and FC, including bending or shear tests on concrete beams cast with DCLs and FC [27–29], axial or lateral cyclic loading tests on steel tubes filled with DCLs and FC [30–34], the size effect of concrete cubes or cylinders made of DCLs and FC [35,36], and an investigation into the possible use of normal-strength DCLs in high-strength concretes [37]. More recently, Teng et al. [26] has recognized this concrete recycling method and extended it to FRP confining tubes containing DCLs. They demonstrated that substantial confinement provided by the FRP tube (4- or 6-ply) could eliminate (or at least minimize) the weakness induced by the inclusion of DCLs.

In addition to conducting the laboratory campaigns, the authors have cooperated with some design companies and contractors, aiming to put this recycling method into real construction. Fig. 1 shows the concept and pilot applications of directly using DCLs in composite construction. The DCLs and FC are expected to function cooperatively in structural composite elements such as slabs, beams (U-shaped), or columns (tubed), as conceived and depicted in Fig. 1a. This composite system is currently being implemented in a build-out project. In Fig. 1b–d, various implementation scenarios are also shown. The experience has demonstrated that the on-site casting was not difficult (or at least not as initially envisioned); undesirable problems such as obstruction or long waiting due to the inclusion of DCLs did not occurred, as long as the slump of FC, the replacement ratio, and the size of DCLs were properly chosen (e.g., the slump of FC greater than 120 mm; the replacement ratio lower than 33%; and the ratio between the maximum size of DCLs and the diameter/width of the column less than 0.3 (in Fig. 1b–c the ratio of 0.5 was used due to the lower replacement ratio)).

Obviously, much more research is needed before this new recycling technique can be widely accepted. Along this line of consideration, the presented research intends to address the structural performance of the circular steel tubular columns filled with DCLs and FC, which may be one of the most easy-to-implement members containing DCLs proposed by the authors. It is noteworthy that previous works [30–32] on such columns concentrated mostly on the axial behavior of stub specimens. However, particular concerns might be raised when more complex situations, such as eccentric loadings or slenderness effects, are taken into consideration. This is simply because the casting is likely to become difficult as the height of the columns increases. More importantly, the locations of DCLs in concrete infill are actually random; if the compression zone at critical section of eccentrically loaded slender columns is occupied by the DCLs of low-strength, the response and ultimate capacity of the columns may be appreciably degraded. In other words, the question is whether the uncertainty about the effect of random spatial distribution of DCLs is a critical issue? In fact, there are generally two sources of heterogeneity in the columns concerned: one is the microscopic heterogeneity originated from flaws and micro-cracks at interfaces between DCLs and FC; the other is the macroscopic (or structural) heterogeneity attributable directly to the random distribution of DCLs with different strength to FC. Aside from the former heterogeneity, the latter inhomogeneity – caused by "randomly distributed strength" effect – also needs to be properly understood, which is one of the motivations behind the present study.

As explained above, the current authors think that the structural inhomogeneity induced by the large size of DCLs with relatively lower strength than that of FC may constitute the main cause of the potential inferiority associated with the proposed columns. This brings about a certain degree of uncertainty in determining the strength of the proposed columns. Such uncertainty may be addressed by some statistical evaluations, such as conducting Monte Carlo simulations and analyzing an experimental database. In view of the above remarks, this paper therefore has a threefold objective: (a) to continue to contribute to the experimental database of the thin-walled circular steel tubular columns filled with DCLs and FC; (b) to reach a further understanding of the impact of heterogeneous distribution of DCLs on the ultimate resistance of the columns by numerical modeling; and (c) to provide more robust design recommendation for determining the ultimate capacity in light of an enlarged test database.

2. Experimental program

2.1. Specimen design

In total, 36 column specimens were fabricated and tested [38], out of which 24 were filled with DCLs and FC, and 12 filled with FC

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