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Experimental investigation of cementitious material-filled square thin-walled steel beams

M.F. Hassanein, O.F. Kharoob*, M.H. Taman

Department of Structural Engineering, Faculty of Engineering, Tanta University, Tanta, Egypt

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ABSTRACT

It was recently found that concrete-filled steel tubular (CFST) beams have some advantages in resisting forces compared to steel tubular beams. By using the CFST beams, the flexural capacity, stiffness, ductility and energy dissipation ability are improved due to the presence of the filled-in concrete. Currently, bending tests are performed on glass-fibre reinforced cementitious material-filled square steel tubular (GFCMFST) beams. For comparison, unreinforced cementitious material-filled square steel tubular (CMFST) beams with a higher compressive strength are also prepared and tested. Two shear span-to-depth ratios are considered in the tests. The tests showed that all beams have a significant yielding plateau, hence, exhibit adequate ductility. Furthermore, it was found that the first crack of the filling material took place for CMFST beams at lower load levels compared to the GFCMFST beams in spite having higher compressive strength. Also, it was found that the stresses of the CMFST beams were always greater than the corresponding values of GFCMFST beams in both the tensioned and the compressed zones. The experimental moment capacities were then compared with the available design methods. It is recommended to use the design strength as estimated following EC4. Comparisons between the experimental results of the initial and the serviceability-level section flexural stiffness and its corresponding values from literature and design specifications were also made. Among the different methods, the AIJ standard was found to give the most suitable results for the initial section flexural stiffness and the serviceability-level section flexural stiffness of the current composite beams.

1. Introduction

Steel-concrete composite beams are rather widespread as load bearing constituents in modern constructions. They combine the advantages of both steel and concrete; namely, the ductility, speed of construction, high capacity, high stiffness and acceptable cost (see for example Refs. [1–3]). Moreover, the surface of the beam is protected from impact and abrasion. Nevertheless, previous researches mainly focused on the behaviour of axially-loaded CFST columns (refer to Refs. [4–9]), while there are relatively few researches that dealt with the CFST beams under bending compared the to CFST columns. Fig. 1 provides the cross-section of a typical square CFST beam. Since the beam-to-column joints for square or rectangular CFST beams are much easier in fabrication and installation compared with those of circular beams, several investigations concentrated on the behaviour of square beams, as can be found in Refs. [1,2,10–14], though research on circular beams has also been considered of which Refs. [15–19] are just examples. Generally, it was found that these CFST beams have much higher strength compared with the bare steel tubular beams and the flexural stiffness of the composite beams enhances as well. Additionally, they exhibit a significant yielding plateau leading to a very ductile failure pattern. The typical failure mode of the CFST beams was found to take place by an outward folding of the outer steel tube in the compression side accompanied by a fracture of concrete in the tension side.

On the other hand, rapid advances were recently made in the development of high performance fibre reinforced cementitious materials. This progress is attributed to the developments in the fibre, matrix and process technology, besides the better understanding of the fundamental micromechanics governing the composite behaviour [20–25]. The primary reason for incorporating fibres into a cement matrix is their tensile strain-hardening after the first cracking. This increases the toughness and the tensile strength, as well as improves the cracking deformation characteristics of the resultant composite. This research presents cementitious matrix reinforced with glass fibre which has never been examined with the presented parameters and specimens' details. However, one of the most significant disadvantages of the ordinary fibre reinforced concrete is its low flow ability [22,24].

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* Corresponding author.
E-mail address: Omnia_m102010@yahoo.com (O.F. Kharoob).

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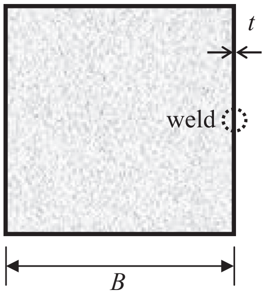

Fig. 1. Cross-section of square CFST beams.

Accordingly, to overcome such disadvantage, the current fibre reinforced cementitious materials were generated without using a coarse aggregate, making the resultant composite suitable for pouring, particularly in relatively small steel cross-sections. Through extensive research, it was established that adding glass fibres to concrete considerably improves the compressive strength of the material, the toughness by increasing the energy required for crack propagation, the impact strength, the tensile strength, the durability and the fire resistance [21–24]. The thermal expansion of the concrete reduces as a result of adding glass fibres.

It is worth pointing out that this study is a part of an ongoing research project conducted in the Department of Structural Engineering, Faculty of Engineering, Tanta University, Egypt and it focuses on investigating the behaviour of glass-fibre reinforced and unreinforced cementitious material-filled square steel columns under concentric and eccentric loadings. To successfully conduct this research project, cementitious material-filled square steel tubular beams should be tested for the use in the design of the eccentric loaded cementitious material-filled square steel columns. Hence, in this paper the behaviour of glass-fibre reinforced and unreinforced cementitious material-filled square steel tubular (GFCMFST and CMFST, respectively) beams are presented in detail, though their experimental strengths are used in the study of the eccentric columns [26]. To the authors' best knowledge, the flexural behaviours of the GFCMFST and CMFST beams have never been investigated, in spite of using polypropylene fibres in literature [27]. Full-scale experimental beams are prepared and tested up to failure. The experimental results are discussed and compared with current international design codes.

2. Experimental programme

2.1. Test specimens and instrumentations

In this experimental investigation, six composite beams (two CMFSTs and four GFCMFSTs) were tested. The main aim of the current study was to examine the effect of the added glass-fibre on both the behaviour and the cross-sectional capacity of the thin-walled beams. Two nominal compressive strengths of 60 and 55 MPa (with a difference of about 10%) were considered to the mixture using the fibre, while a higher compressive strength of 80 MPa was used in the ordinary mix (i.e. mix without fibre). Alternatively, as this is the first investigation that adds glass-fibre to the composite beams, the authors' initial decision was to conduct the experiments in identical pairs. However, after thorough discussions, it was decided, for each in-filled mix, to conduct two beams with different lengths (L); as can be seen in Table 1. This benefit gets from the well known fact that square cross-section beams do not fail by lateral-torsional buckling, but rather fail by their cross-sectional flexural capacities. So, these identical cross-sections (with different beam lengths) were used to check the accuracy of the loading cell and give the authors the confidence about the results. Therefore, two shear span-to-depth ratios of 5.5 and 7.0 were considered.

Commercially available cold-formed steel tubes with 100 mm depth were used. The ends of the tubes were cut to the required lengths. The nominal tube depth-to-wall thickness ratios of the beams were 50. Each tube was initially welded to a square end plate with a thickness of 18 mm. After filling the tubes with the cementitious material, the members were cured for at least seven days before another cover square plate was welded at the other end of each beam. In order to minimize the evaporated vapour from the cementitious materials, such treatment process was made by using a layer of waterproof material that is put at the wetted concrete surface. The measured dimensions of the cross-sections and the lengths of the specimens are shown in Table 1, using the nomenclature defined in Figs. 1 and 2. The specimens are labelled so that the span of the steel beam (in mm) and the type of infill material (i.e. glass-fibre reinforced (FC) and unreinforced (C) cementitious materials) with its strength can be identified from the label. For example, the label "B-1100-FC60" defines the beam with the span length of 1100 mm, which is filled with glass-fibre reinforced (FC) cementitious material with a nominal strength of 60 MPa. The specimens were simply supported, as can be seen in Fig. 2, on roller and hinged supports and the load was applied at mid-span by using a loading plate of 80 mm width. Fig. 2 gives also a general view of the instrumentations. Two displacement transducers (LVDT), located at mid-span, were used to measure the vertical deflections of the beams. For each specimen, the vertical displacement was obtained from the average readings of these two LVDTs. To measure the longitudinal strains on the outer surface of the steel mid-span cross-section, five strain gauges were used, as can be seen in Fig. 2.

Table 1
Details of the tested beams.

Specimen	L [mm]	B [mm]	t [mm]	f_c [MPa]
B-1100-C80	1100	99.5	1.82	77.5
B-1100-FC60	1100	99.5	1.82	61.2
B-1100-FC55	1100	101.7	1.85	55.4
B-1400-C80	1400	101.7	1.85	77.5
B-1400-FC60	1400	99.5	1.82	61.2
B-1400-FC55	1400	99.5	1.82	55.4

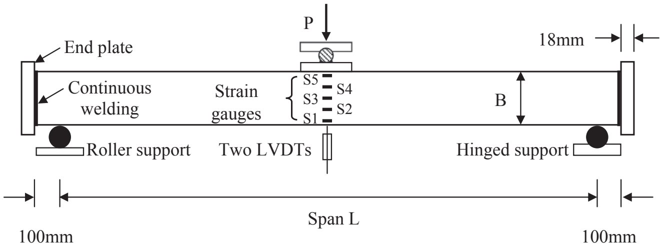

Fig. 2. Setup of beam specimens and locations of strain gauges and LVDTs.

2.2. Steel properties

The properties of the steel of the thin-walled tubes were determined by tensile coupon tests. The tensile coupon test specimens were taken from the centre of the longitudinal direction of the flat portion of the cross-section depth (away from the faces containing the longitudinal weld) from an untested specimen. The coupon dimensions conformed to the Australian Standard AS 1391 [28] for the tensile testing of metals and were tested in a displacement controlled testing machine using friction grips. A calibrated extensometer of 50 mm gauge length was used to measure the longitudinal strain, as shown in Fig. 3 which provides the tensile coupon tests before and after the testing. A data acquisition system was used to record the load and the readings of strain at regular intervals during the tests. It is worth pointing out that the load is singly applied in a fixed direction using a static loading rate. Hence, the results of the tensile coupon tests (Fig. 4) are static. Different