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Original Research Article

Load-carrying capacity of axially loaded concrete-filled steel tubular columns made of thin tubes

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ABSTRACT

An experimental investigation was conducted on 30 CFST columns. An influence of the following factors on load-carrying capacity of the investigated columns was analyzed: the column slenderness ($\lambda_1 = 42$, $\lambda_2 = 27$ and $\lambda_3 = 15$), the tube thickness (the reinforcement ratio was equal to 4% or 6%), the way of applying the load to CFST columns (through the concrete core or through the entire cross-section), the bond strength between a steel tube and a concrete core.

The results of the experimental investigation let the author derive a practical method of determining load-bearing capacity of CFST columns. The Eurocode 4 provisions regulating composite steel and concrete structures design impose the minimum share of a steel tube in the cross-sectional area of a CFST column. This minimum share is the prerequisite for the Eurocode 4 to be applicable. It ranges from 0.5% to 6%. As the experimental research presented in the paper indicate, the CFST columns of such low reinforcement ratios can be also effective in carrying loads. The proposed method is a second order analysis based on stiffness, similarly as the calculation procedure for the ordinary reinforced concrete columns which is used in Eurocode 2. The experimental results prove the author's suggestion to be correct.

1. Introduction

Concrete-steel composite columns have numerous advantages and are an interesting alternative for columns made of steel or reinforced concrete. Compared to steel structures, composite structures are distinguished by high fire resistance and, because of their mass, are less sensitive to vibrations. Compared to reinforced concrete columns composite columns, especially CFSTs (Concrete Filled Steel Tubes) are able to resist higher load in a post-critical region. Moreover, the destruction mechanism of the CFSTs is not so immediate. Their behaviour before destruction is plastic, ductile, which is valuable for construction safety. For that reason CFST columns are widely used for civil engineering structures in the countries of high seismic activity (e.g. Japan, the United States, China).

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CFST members have a lot of other advantages, which make them popular also in the European countries. CFST columns are comfortable in realization since they do not require any formwork and additional internal reinforcement. It makes the construction process faster. Moreover, CFST columns are easy to adapt to prefabrication and to form simple standardized connections with beams and other columns. They show also a high impact resistance, which is important for bridge supports. Eventually, building facades with adopted CFST columns are of high aesthetic value. The CFST columns were intensively experimentally tested in recent years. Ahmadi et al. [1] specify 18 important experimental research programs for CFSTs conducted worldwide in the recent 50 years. Design of CFST columns was standardized in Europe 25 years ago [2].

Concrete-filled steel tubular cross-sections are extensively used for the main girders of the arch bridges. Shrestha et al. [3] report that more than 230 CFST arch bridges had been built in China before 2007. Liu et al. [4] report that more than 300 CFST arch bridges and 40 bridges spanning over 200 m were constructed in China over the last 20 years. This effective technology was used in China for the first time in 1990s and since then the technique has been developed and has become popular. When the arch is closed after assembling hollow steel units concrete is pumped into these tubes from the bottom up. Depending on the length of the span and the width of the bridge, different arrangements of CFSTs in the cross-section of an arch girder are used. Common configurations include dumbbells with two tubes closely connected and a tight cluster of tubes known as 'multiple contiguous'. The separate tubes are connected to each other along the arch by means of other (smaller) CFSTs.

Multiple thin-walled steel tubes are often used as the main girders of the Chinese arch bridges. Table 1 shows the geometrical data of the selected bridges [5]. The share of a steel tube in the cross-sectional area of the presented CFST arches is between 4.9% and 6.6% which is close to the share analyzed in the paper (4% and 6%).

The main objective of the work is to propose a practical method of calculating CFST columns made of thin-walled tubes. Calculating of such columns is often impossible according to Eurocode 4 [6], as its provisions impose the minimum share of a steel tube in the cross-sectional area of a CFST column. Experimental research on 30 CFST columns was carried out. An influence of some factors on load-carrying capacity of the investigated columns was analyzed. The most important factor was the bond strength between a steel tube and a concrete core.

2. Previous research

2.1. *Determining load-carrying capacity of CFSTs according to Eurocodes*

Calculation of load-carrying capacity of the CFST columns designed in Europe should be made according to Eurocode 4 [6]. However, not every CFST column can be calculated using that standard. Eurocode 4 imposes the upper and lower limits of the load-carrying capacity share of a steel tube in the total cross-section load-carrying capacity of a CFST column. The steel contribution should be between 20% and 90%. The columns with too low steel contribution should be actually calculated according to Eurocode 2 [7] dedicated to the concrete structures design. That group of CFST columns is distinguished by a thin steel tube, i.e. using an analogy to reinforced concrete structures – by a low reinforcement ratio. For instance, for a tube made of steel S275 and a concrete core C30/37, the group will include all the CFST columns with the reinforcement ratio less than 1.8%. Taking into consideration all steel and concrete classes authorized by the European standards the minimum reinforcement ratio required to meet Eurocode 4 criteria ranges from 0.5% to 6%. There are similar reinforcement ratios typical for the reinforced concrete columns: the lowest reinforcement ratio approved by Eurocode 2 is 0.2%, whereas the highest is 4%.

In spite of the huge difference between the load-carrying capacity calculation methods according to Eurocode 2 and Eurocode 4, the author decided to compare the capacities of CFST columns determined in line with both standards. In the existing, very comprehensive literature on the CFST columns design the author has not found any suggestions of utilizing concrete structures design standards to determine load-carrying capacity of the CFST columns with low reinforcement ratio. Meanwhile, there is an analogy in the work of the CFST columns with low reinforcement ratio and the confined reinforced concrete columns: in both cases a concrete core of a column works in triaxial compression.

The presented analysis takes into consideration solely the columns with the low (according to Eurocode 4) reinforcement ratio ranged from 4% to 6%. The calculated values of

Table 1 – Geometrical data of the selected Chinese arch bridges made of thin-walled CFSTs.

No.	Bridge name	Span [m]	Tubes configuration (number of CFSTs in the cross-section of the arch girder)	Tube internal diameter [mm]	Tube wall thickness [mm]	Share of a steel tube in the cross-sectional area [%]
1	Wang-Cang	115.0	Dumbbell (2)	780	10	4.9
2	Fo-Chen	110.0	Dumbbell (2)	972	14	5.5
3	Gao-Ming	100.0	Dumbbell (2)	730	10	5.3
4	Mo-Zi-Wan	120.0	Dumbbell (2)	776	12	5.9
5	Da-Du	140.0	Cluster (4)	534	8	5.7
6	An-Yang	135.0	Cluster (4)	696	12	6.6
7	San-Shan	200.0	Cluster (4)	730	10	5.3

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