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Effectiveness of concrete confinement in thick-walled circular Concrete-Filled Steel Tubular columns

Efektywność skrępowania betonu w grubościennych słupach typu Concrete-Filled Steel Tube o przekroju kołowym

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Abstract. In the limit state of the CFST columns, the core concrete strength increases due to its confinement. This positive effect depends on many factors. One of the most important is the ring stiffness of the steel tube. Its impact on the effectiveness of increasing the core concrete strength was experimentally tested on a group of 48 thick-walled CFST columns. It has been shown that an excessive increase in the tube thickness does not translate into an increase in its relative load capacity. On the contrary, it is decreasing. A much better use of the core concrete confinement can be achieved by using thin-walled tubes rather than thick-walled ones.

Keywords: columns; experimental investigation; confined concrete; CFST; effectiveness.

Streszczenie. W słupach typu CFST w stanie granicznym dochodzi do zwiększenia wytrzymałości betonu rdzenia na skutek jego skrępowania. Zaistnienie tego zjawiska zależy od wielu czynników. Jednym z najważniejszych z nich jest sztywność obwodowa płaszcza stalowego. Jej wpływ na efektywność wzrostu wytrzymałości betonu rdzenia przebadano eksperymentalnie na grupie 48 grubościennych słupów CFST. Wykazano, że nadmierne zwiększanie grubości płaszcza słupa CFST nie przekłada się na wzrost jego nośności sprowadzonej. Jest wręcz przeciwnie: następuje jej spadek. Znacznie lepsze wykorzystanie pozytywnego wpływu skrępowania betonu rdzenia można osiągnąć z zastosowaniem rur cienkościennych niż grubościennych.

Słowa kluczowe: słupy; badania eksperymentalne; beton skrępowany; CFST; efektywność.

CFT *(Concrete-Filled Tube)* structures have been an appealing choice for many years because the concrete filling of the closed cross-section does not require formwork. In addition, support structures of this type are considered to be aesthetically pleasing (photograph). They are mostly used in columns. The tube, with a circular or rectangular (especially square) cross-section, are made of steel or *Fiber-Reinforced Polymer* (FRP). When steel is used, the abbreviation CFT is changed to CFST, the letter S standing for the word steel, and when FRP is used, it is changed to CFFT. A concrete core trapped in a steel or polymer tube, under the conditions listed below, operates in a state of triaxial compression. Known as concrete confinement, this state leads to an increase in the strength of the core concrete and an eventual increase in the load-carrying capacity of the CFT column. The created spatial state of stress in the core concrete and its effect on the increased concrete strength of CFST columns depends on a number of factors, most importantly:

1) adequate circumferential stiffness of the jacket (i.e. tube) – one that is too thin, in addition to having a low modulus of elasticity, will not resist the lateral deformation of the core concrete (see Figure 1);

An example of CFST columns application: composite steel and concrete bridge over the A93 highway between Hof and Regensburg in Germany
Przykład zastosowania słupów CFST w konstrukcji zespolonego stalowo-betonowego obiektu mostowego nad autostradą A93 między Hof i Ratyzboną w Niemczech

2) the resultant compressive force located as close as possible to the section's centre of gravity or at least inside its core – large eccentricities reduce or even eliminate the confining effect of the concrete;

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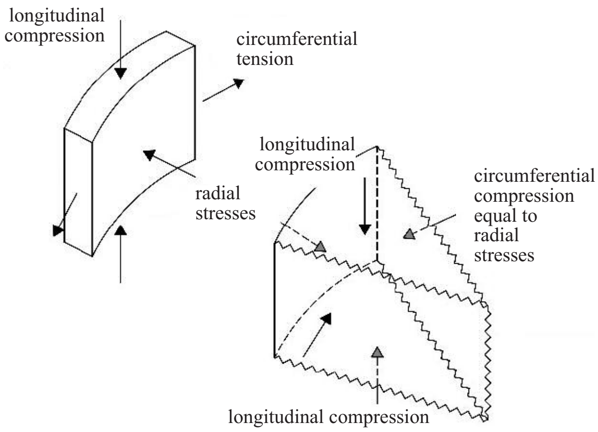

Fig. 1. State of stresses in a CFT column
Rys. 1. Idea pracy słupów typu CFT

3) low column slenderness – high column slenderness causes second-order effects which leads to an increase in the force eccentricity;

4) the shape of the tube cross-section should be close to circular, which allows for rotationally symmetric triaxial compression conditions in the column core – a circular cross-section is best.

The authors set as the objective of this study to test the extent to which the above-mentioned factors affect the load-carrying capacity increase of the concrete core of the CFST column. Testing all four factors on a limited number of test elements would be difficult, and therefore the second and fourth factors played no rolein the developed experimental test programme of forty-eight columns. Excluding unintended eccentricities, all columns were axially compressed and all had a circular cross-section but differed by the circumferential stiffness of the tube and column slenderness.

Concrete confinement coefficient as a measure of effectiveness of increasing core concrete strength in CFST columns

Of the two factors which determine confinement effectiveness, the authors first tested the circumferential stiffness of the jacket. This term needs to be clarified as it is not used usually for concrete core confinement of CFT columns. In order to define the circumferential stiffness, Fig. 1 and Fig. 2 show the principle for creating a spatial state of compressive stress in CFST columns as a result of the confinement of the core concrete by the steel jacket. The confinement of the transverse deformations in the core concrete results in the creation of transverse (radial) stresses in the concrete. These leads to an increased compressive strength of the core concrete in the longitudinal direction. Fig. 2 illustrates half of the cross-section of a CFST column divided into the outer shell and the concrete core. The stress value is, by analogy with the compressed gas filling the pipeline, the same around the perimeter of the concrete core and in the cross-section drawn rectilinearly through the geometric centre of the column (Fig. 2b). When analysed in the elastic phase, i.e. before plastic stress f_y is reached in the steel, the relationship between the radial pressure on the internal surface of the shell σ_2 and the balancing circumferential forces in the shell can be written:

$$\sigma_2 \cdot d_{core}/2 = \sigma_s \cdot t = E_s \cdot \varepsilon_s \cdot t \qquad (1)$$

where:

ε_s and $\sigma_s \leq f_y$ – are respectively the circum ferential strains and stresses in the steel tube wall induced by the action of thrust;

σ_2 and E_s, t – are the elastic modulus of steel and the wall thickness of the tube, respectively.

The term *circumferential stiffness* is commonly used in the theory and practice of underground non-pressure pipelines laid with thermoplastic [1] or thermosetting [2] pipes. It is defined as the resistance of a pipe to a change in its cross-sectional diameter due to an external load, most commonly une-

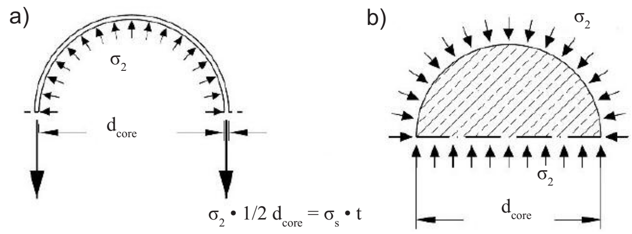

Fig. 2. Stress equilibrium in the cross-section of the CFST column: a) steel tube; b) concrete core
Rys. 2. Równowaga naprężeń w przekroju poprzecznym słupa CFST: a) płaszcz stalowy; b) rdzeń betonowy

ven soil pressure, causing bending of the pipe's cross-section. For CFST columns, the nature of the load is different. The loading on the tube results from a rotationally symmetrical concrete pressure causing the tube to elongate in the circumferential direction. This elongatingis accompanied by an increase in the circumference and cross-sectional diameter of the jacket. This weakens the restraining effect of the jacket on the confined concrete core. For this reason, the authors introduced the concept of *tube circumferential stiffness* as the resistance posed by the tube cross-section against the elongation of its perimeter due to radial thrust acting perpendicular to the inner surface of the tube. The increase in circumference and diameter of the cross-sectionis clearly related to the tube circumferential strain ε_s. From the relationship (1) the tube circumferential strain ε_s can be determined:

$$\varepsilon_s = \frac{\sigma_2}{\dfrac{E_s \cdot t}{\dfrac{d_{core}}{2}}} = \frac{\sigma_2}{S} \qquad (2)$$

where:

S is the *tube circumferential stiffness* as defined by the authors:

$$S = \frac{E_s \cdot t}{\dfrac{d_{core}}{2}} = \frac{2 \cdot E_s \cdot t}{d_{core}} \qquad (3)$$

As can be seen, besides the elastic modulus, the stiffness thus defined depends on geometrical quantities; it increases as the wall thickness of the tube increases and its diameter decreases. Tubes with high circumferential stiffness(large thickness and small diameter) will more effectively create a spatial state of stress in the concrete core than tubes with low circumferential stiffness. In our opinion, the tube circumferential stiffness, as defined by the authors, makes analysis of the effectiveness of the tube in creating the spatial state of stress in concrete in CFST columns easier than tensile stiffness $E_s \cdot A$ does.

The presented mechanical model of the increase in the core concrete strength is commonly used in the design of CFT columns. Namely, the model is applicable in standards for the design of concrete structures [3] and composite steel-concrete structures[4]. The concrete confinement phenomenon discussed in this paper occurs in reinforced concrete confined columns [5], hence it is reasonable to consider in literature the design standard [3]. This standard determines the increased compressive concrete strength f_{cc} (e.g. in the reinforced concrete confined column core) from the relation:

$$f_{cc} = f_c(1{,}0 + 5{,}0\ \sigma_2/f_c) \text{ for } \sigma_2 \leq 0{,}05 \cdot f_c \tag{4}$$

$$f_{cc} = f_c(1{,}125 + 2{,}5\ \sigma_2/f_c) \text{ for } \sigma_2 > 0{,}05 \cdot f_c \tag{5}$$

The numerical value of the transverse stress σ_2 of the column tube against its core, denoted as radial stresses in Figure 1, can be determined by the reasoning shown graphically in Figure 2.

Assuming steel yielding at the ultimate limit state, the equilibrium condition for forces and stresses in this particular section can be written as follows:

$$\sigma_2 \cdot d_{core} = 2 \cdot f_y \cdot t \tag{6}$$

where: f_y – is the circumferential tensile strength of the tube steel.
From the above condition we can write:

$$\sigma_2 = \frac{2 \cdot f_y \cdot t}{d_{core}} \tag{7}$$

After inserting the determined relation for σ_2 into formulae (4) and (5), the result is:

$$f_{cc} = f_c\left(1{,}0 + 10{,}0\frac{t \cdot f_y}{d_{core} \cdot f_c}\right) \quad \text{dla} \quad \sigma_2 \leq 0{,}05 \cdot f_c \tag{8}$$

$$f_{cc} = f_c\left(1{,}125 + 5{,}0\frac{t \cdot f_y}{d_{core} \cdot f_c}\right) \quad \text{dla} \quad \sigma_2 > 0{,}05 \cdot f_c \tag{9}$$

The relations derived in this way hardly differ from those given in the second of these standards, namely for the design of composite structures [4]:

$$f_{cc} = f_c[1{,}0 + \eta_{c0}(t \cdot f_y/(D \cdot f_c))] \tag{10}$$

where:
D is the outer diameter of the CFST column;
η_{c0} is a dimensionless factor that increases the strength of the concrete according to further more complex relationships given in the standard.

In view of the demonstrated unified computational approach to determining the strength increase of confined concrete, the quotient σ_2/f_c can be assumed to be the sought-after measure of the effectiveness of CFST column core confinement. As can be seen from equations (4) and (5), this is the only parameter that affects the increase in core concrete strength expressed by the quotient f_{cc}/f_c. The parameter σ_2/f_c hereinafter referred to as the concrete core confinement coefficient will be denoted by the symbol φ. This coefficient can be expressed according to relation (7) by the formula:

$$\varphi = \frac{\sigma_2}{f_c} = \frac{2 \cdot f_y \cdot t}{f_c \cdot d_{core}} \tag{11}$$

By applying the proposed coefficient φ, assuming a simplification $D = d_{core}$, the standard relationship (10) can be written as:

$$f_{cc} = f_c[1{,}0 + \eta_{c0}\ (\varphi/2)] \tag{12}$$

The coefficient φ, although not used in design norms, is sometimes used by researchers studying on confined concrete. For example, in the work [6] and in the widely cited work [7] the authors used the coefficient φ without giving it a symbol to compare the effectiveness of concrete confinement by steel jacketing and FRP jacketing.

However, the coefficient φ proposed here is not an ideal solution as a measure of CFST column effectiveness of core confinement. It does not take into account the effect of the increase in the diameter of the column jacket due to the Poisson phenomenon taking place in the jacket. More on this problem is written by the authors in [8]. The coefficient φ also does not take into account any shrinkage of the concrete of the column core, which adversely affects concrete confinement. Furthermore, circumferential stresses in the steel tube do not always reach thesteel yield strength f_y. This is especially the case with thick-walled tubes. Despite these limitations, the authors considered the arguments cited in this chapter to be sufficient and decided to choose the coefficient φ as a measure of CFST column core confinement effectiveness.

Analysis of the influence of the concrete confinement coefficient on the increase of the load capacity of the CFST column

The authors analysed this impact using their own experimental study on forty-eight CFST columns [8]. The outer diameter of all the columns tested was 168.3 mm. The thickness of the steel tube for half of the columnswas 5 mm and for the other half 10 mm. In terms of height, the columns were also divided into two equal groups – 800 mm and 2200 mm. Similarly, one half of the columns tested were made of concrete with an average cylindrical strength of $f_{cm} \approx 30$ MPa and the other half with a strength of $f_{cm} \approx 60$ MPa. One more parameter for the tests was the way in which the load was applied to the column. Half of the columns were loaded by the concrete core only, while the other half were loaded simultaneously by the core and the steel tube via a wider steel plate. The test programme was designed so that the listed test parameters were evenly represented (table). More informationon the test programme, realisation and results of the experimental tests (including the experimental capacities of the columns) are given in the paper [8]. All the columns analysed were tested by the same research team in the same laboratory. The load was controlled by displacement. The columns were supported articulated on both sides, and the compressive force was applied axially.

Overview of the experimental research programme of 48 columns
Poglądowe przedstawienie programu badań eksperymentalnych 48 słupów

Group of co-lumns	Column slenderness λ [-]/height L_0 [mm]	Tube wall thickness t [mm] /Reinforcement ratio ρ [%]	The load applied to the column by:	Average cylin-drical strength of concrete f_{cm} [MPa]	Number of items tested
1	19,0 / 800	5 / 11,5	core	≈ 30	3
2				≈ 60	3
3			entire section	≈ 30	3
4				≈ 60	3
5		10 / 22,4	core	≈ 30	3
6				≈ 60	3
7			entire section	≈ 30	3
8				≈ 60	3
9	52,3 / 2200	5 / 11,5	core	≈ 30	3
10				≈ 60	3
11			entire section	≈ 30	3
12				≈ 60	3
13		10 / 22,4	core	≈ 30	3
14				≈ 60	3
15			entire section	≈ 30	3
16				≈ 60	3
				Total:	48

The ratio of the actual column load capacity N_{column} to the theoretical load capacity $N_{cross\text{-}section}$ of its cross-section on the assumption of its full yielding at the point of failure was taken as a measure η of the increase in capacity of CFST columns:

$$\eta = N_{column}/N_{cross\text{-}section} \tag{13}$$

It was assumed that the increase in the load capacity of the CFST column was caused by an increase in the strength of the core concrete due to the triaxial compressive stress state of the core. The parameter η will be hereinafter referred to as theconcrete confinement effectiveness factor. The capacities of the individual columns were determined experimentally:

$$N_{column} = N_{exp.} \tag{14}$$

On the basis of material experimental investigations accompanying the column tests, the authors determined the theoretical cross-sectional capacity of the analysed CFST columns (on the assumption of its yielding) as the sum of the theoretical capacity of the steel tube and the concrete core:

$$N_{cross\text{-}section} = N_{tube} + N_{core} = f_y \cdot A_{tube} + f_c \cdot A_c \tag{15}$$

The symbols A used above denote the cross-sectional areas of the two components of the CFST column section. The compression strength of the tubes f_y is taken as their tensile strength. This strength and the compressive strength of the concrete core f_c were measured on material specimens – the tube and the concrete filling it, respectively. Tube steel specimens for the tensile tests were prepared as paddle-shaped, milled from strip specimens, which in turn were cut from steel tubes. The tube specimens were delivered to the laboratory for the sole purpose of determining the mechanical parameters of the steel and were not used for testing the CFST columns. The measured tensile strength of the tube steel ranged between 300 and 380 MPa. The strength of the concrete, on the other hand, was measured on standard cylinders with a diameter of 150 mm and a height of 300 mm. The exact measured strength of the concrete varied between 28.8 and 38.7 MPa for the weaker concrete (f_{cm} ≈ 30 MPa) and between 49.4 and 68.4 MPa for the stronger concrete (f_{cm} ≈ 60 MPa).

The considered concrete confinement effectiveness factor η is often referred to as effective load capacity of the column [8]. Fig. 3 shows the relationship between the effectiveload capacity of the CFST columns and the concrete confinement coefficient (η – φ). The individual points on the graph symbolise individual test members (columns), while the straight lines are the trends determined for the two groups of columns listed in the table. As can be seen from Fig. 3, in the group of forty-eight CFST columns tested, their slenderness (λ = L/i = 4L/D) was of primary importance for the effective load capacity. Slender columns (diagonal crosses in the diagram) have significantly reduced effective load capacities than stubby columns (marked with pluses) with similar values for the concrete confinement coefficient, which was to be expected. Increased slenderness results in decreased bearing capacity of all columns; in the case of CFST columns, this decrease is greater due to the adverse influence of second-order effects on the confinement of the core concrete.

The maximum observed increase in the load capacity N_{column} of the column in relation to the load capacity of its cross-section $N_{cross\text{-}section}$ was about 15%. Approximately half of the columns tested showed some increase, while the other half showed a decrease due to second-order effects. For slenderness λ = 52,3, increases were recorded sporadically and did not exceed 10%.

Analysis of the results illustrated in Fig. 3 leads to an observation less obvious than the effect of slenderness that the confinement effectiveness factor η (effective load capacity) decreases as the confinement coefficient φ increases. The monotonicity of the two trend lines shows that they are decreasing functions. In confined columns, an increase in spiral reinforcement leads to increased column capacity due to an increase in the strength of the core concrete due to its triaxial state of

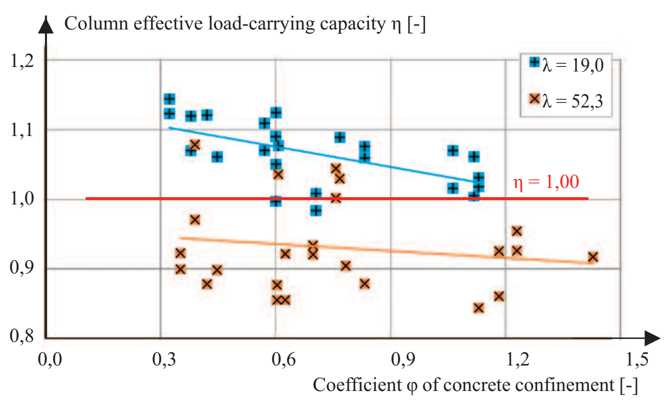

Fig. 3. Relationship between the effective load capacity η of CFST columns and their slenderness λ and the coefficient φ of concrete confinement (which is a measure of the circumferential stiffness of the steel tube) for 48 experimentally tested columns
Rys. 3. Zależność między nośnością sprowadzoną η słupów CFST a ich smukłością λ oraz współczynnikiem φ skrępowania betonu (będącym miarą sztywności obwodowej płaszcza stalowego) w przypadku 48 słupów przebadanych eksperymentalnie

compressive stress. In the case of CFST columns, an increase in the confinement coefficient φ should also lead to an increase in radial compressive stresses in the concrete core and, therefore, to an increase in the concrete strength. This should translate into an increase in the load carrying capacity of the CFST column. In CFST columns, however, the situation is fundamentally different to that in the confined columns, in which the spiral reinforcement (winding) only affects the creation of radial stresses without transmitting the longitudinal force. In CFST columns, the steel jacket which is equivalent to the spiral reinforcement also participates in the transmission of the compression force of the column, reducing the force absorbed by the concrete core. This results in a reduction of the vertical stresses in the concrete core and thus in the radial stresses as a result of the steel jacket reducing the radial deformation of the concrete. As can be seen from equation (11), the concrete confinement coefficient φ increases with the thickness of the steel jacket. On the one hand, with an increase in the value of this coefficient, the radial stresses in the concrete core should increase, but on the other hand, a greater thickness of the steel jacket leads to a decrease in the proportion of force transmitted through the concrete core and thus to a decrease in the radial stresses. The effect of an increase in the confinement coefficient φ on the increase in the strength of the core concrete is therefore not at all clear, and from the graph shown in Fig. 3 it is even unfavourable.

In the case of the stubby columns, except for two specimens there was always an increase in the column load capacity in relation to the cross-section load capacity. This demonstrates the beneficial effect of confinement on the increase in strength and therefore in the bearing capacity of the core concrete. As noted earlier, the increase in the effective load bearing capacity caused by increased concrete core load bearing capacity diminishes with an increase in the confinement coefficient φ. This trend is observed for slender columns too. The effective load capacity η of the columns are predominantly less than 1.0, which is due to the detrimental effect of slenderness and the associated second order effects.

The presented conclusions are based on the analysis of experimental tests on thick-walled CFST columns. In the case of thin-walled CFST columns, the use of the concrete confinement coefficient φ to assess the effectiveness of the core concrete confinement may be justified. To get an idea of how much variation can occur in the thickness of the CFST column tube, a parameter that is simple in definition, the reinforcement ratio ρ, can be used. This parameter is the ratio of the cross-sectional area of the tube steel to the cross-sectional area of the concrete core: $\rho = A_{tube}/A_c$. In the case of the columns analysed in this study, the reinforcement ratio ρ was 11.5% for the tube thickness t = 5 mm and 22.4% for t =10 mm. In contrast, in our experimental investigations described in our other papers, conducted on 30 CFST columns of similar slenderness and diameter to the investigations described in this paper, the reinforcementratio was significantly lower, ranging from 4% to 6%. A preliminary analysis of the relationship (η – φ) for this group of thin-walled CFST columns gives results confirming the favourable influence of the concrete confinement coefficient φ on the confinement effectiveness factor η.

Summary

In a comparative analysis of forty-eight thick-walled CFST columns tested experimentally, it was found that there was a confining effect on the concrete of their core. The resulting increase in the load capacity of the column was not significant, amounting to a maximum of 10 – 20%. The analysis provided the following conclusions:

- The significant influence of the column slenderness on the effectiveness of their concrete core confinement was confirmed. The confinement effect is significantly lower in the case of slender columns.
- The confinement coefficient φ determined by the equation (11) is not a measure of the actual confinement of the concrete core resulting in an increase in its compressive strength due to the spatial state of stress. It is possible that this coefficient is suitable for estimating the effect of confinement in thin-walled CFST columns, i.e. those in which the reinforcement ratio ρ is at most a few per cent.
- Significantly increasing the tube thickness in CFST columns results in an obvious increase in the load bearing capacity of the column, mainly as a result of increasing the cross-sectional area of the tube, but this does not entail an increase in the radial stresses in the concrete core and thus does not translate into its increased load carrying capacity. On the contrary, the radial stresses in the concrete core decrease as the cross-sectional area of the steel tube increases, because the proportion of the normal force carried by the concrete core decreases while the proportion of the force in the steel tube increases. As a result, there is a decrease in the effective load capacity η (the value of the confinement effectiveness factor).
- A much better use of the positive effect of the spatial state of stress in the concrete core can be achieved with thin-walled tubes than with thick-walled tubes.

CFST columns have a number of advantages over reinforced concrete columns including high post-critical load capacity and lower labour costs, but no significant increase in load capacity can be attributed to them as a result of utilising the spatial state of stress in the concrete core.

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