WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2022.141877

ARCHIVES OF CIVIL ENGINEERING

Vol. LXVIII ISSUE 3 2022

pp. 125–137

Research paper

Bond between steel and SCC in completely concrete encased HEA 160 I-section columns

Magdalena Szadkowska[1], **Elżbieta Szmigiera**[2]

Abstract: The paper presents research results of bond tests in completely concrete encased steel I-section columns made of self-compacting concrete (SCC). The results of push-out tests obtained by elements made of SCC were compared with those elements, which were made of vibrated concrete. The influence of selected factors on resistance to the vertical shear was considered in this study. The analysis of research results shows that the resistance to the vertical shear between steel I-section and SCC concrete depends on distance between stirrups and concrete age. Shrinkage has important influence on interfacial bond forces. The test results were compared with a recommendations given in the Design code – Eurocode 4. This standard can be used only for composite elements made of lightweight and vibrated concrete. In the case of completely concrete encased I-section composite columns the shear resistance after 28 days and after concrete shrinkage was higher than design resistance strength given in the standard. This means that the design value of the shear strength given in the standard should be verified and checked, if it can be applied to elements made of SCC concrete. Further tests should be carried out to determine the value of shear resistance for such elements.

Keywords: I-section, composite, columns, self-compacting, concrete, bond

---

[1] MSc., Eng., Warsaw University of Technology, Faculty of Civil Engineering, Al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: m.szadkowska@il.pw.edu.pl, ORCID: 0000-0001-5840-6239

[2] Prof. DSc., PhD., Eng., Warsaw University of Technology, Faculty of Civil Engineering, Al. Armii Ludowej 16, 00-637 Warsaw, Poland, e-mail: e.szmigiera@il.pw.edu.pl, ORCID: 0000-0001-9084-2372

1. Introduction

Completely concrete encased I-section columns are one of the basic types of composite columns widely used in construction. Due to such features as: high bearing capacity, stiffness and ductility, they gained popularity and are used in bridge piers, buildings located in areas with seismic danger as well as hydrotechnical constructions.

Cross-sections consists of completely concrete encased I-section are commonly used in subsea tunnels in China. The construction of subsea tunnels were built due to increased traffic demand and economic development of China. With the development of technology for the construction of subsea tunnels, their number has also increased. Most of the tunnels in China, such as: Xiamen Xiang, Quingdao Jiaozhou Bay, Hong Kong–Zhuhai–Macao, were made using the drilling and blasting method. The composite cladding consists of a primary support and secondary lining. The basic support consists of shotcrete, a steel arch frame, steel mesh and rock bolts. The steel arch frame is most often made of steel I-section reinforced concrete (SRC-steel reinforced concrete). Because of electrochemical action caused by the chloride ions invasion, steel profiles rust despite being covered with shotcrete. Steel profile corrosion significantly affects the adhesion between steel I-section and shotcrete and reduces the load-bearing capacity of the entire support system. Therefore, in the world literature can be found research papers in which the tests of bond between concrete and corroded steel I-section are described. Wang M. et al. [1] conducted push-out tests of completely concrete encased I-sections with various degrees of corrosion. As it turned out, with the increase of the corrosion coefficient of the steel profile, the value of force at which loss of adhesion occurs, decreased. With the corrosion coefficient above 12%, a significant acceleration in the loss of adhesion forces between steel and concrete was observed. Zhang Y. et al. [2] conducted push-out tests of completely concrete encased corroded I-section columns. They found that as the corrosion coefficient increased from 0% to 21.54% the dissipated energy coefficient increased from 19% to 40% and the elastic energy coefficient gradually decreased from 81% to 60%. This shows that greater degree of corrosion of steel I-section leads to more serious internal damage. Xue J. et al. presented in [3, 4] research results of cyclic bond behaviour between H-shaped steel and recycled concrete. The test results show that envelope curves, which arose as a result of cyclic reversed loading, can be divided into four stages: minimal slip stage, slip development stage, falling stage and residual stage. The energy dissipation mainly occurs in two last stages. What is more, the bond stress received in elements under cyclic reversed loading is lower about 40÷50%, than bond stress received in elements under monotonic push-out load.

There are also many research papers about steel I-section columns used in bridge piers. Columns with such a cross-section are widely used in bridge structures in the United States due to the relatively high load capacity in relation to the small cross-section. Changing weather conditions expose these structures to a cyclically wet and dry environment. This leads to the destruction of the steel profile surface and its corrosion, which reduces load-bearing capacity of the element and may lead to its collapse. One of the easiest methods of repairing a corroded steel column and improving its load-bearing capacity, is to completely encase it in concrete. In order to transfer loads from the steel profile to the concrete, it is necessary to provide a proper adhesion in the interface between both materials. The tests of completely concrete encased corroded I-profiles made of various types of concrete with a different heights of the interface between steel and concrete were carried out by Abdulazeez M.M. et al. [5]. They noticed that with the increase in the compressive strength of concrete, the value of the force at which the loss of adhesion between steel and concrete occurs also increase. The same relationship was observed by Qu X. et al. [6] and the authors of this paper [7] in the push-out tests of concrete filled steel tubes. Moreover, conducted by Abdulazeez M.M. et al. [5] analysis shows that the value of the bond forces increases with the increase in the length of the interface between steel and concrete. Interesting conclusions were also reached by Wang X. et al. [8], who tested the adhesion between steel and concrete in completely concrete encased I-section columns. As it turned out, one of the key factors influencing the bond between the steel profile and concrete is the thickness of concrete cover. According to them, the bond strength increases with the increase of the thickness of the steel profile cover. It can be caused by the enhancement of the confinement effect of the concrete. When the concrete cover thickness increased from 90 mm to 140 mm, the initial bond stress, the ultimate bond stress and the residual bond stress increased by 36.9%, 28.0% and 50.9%, respectively. Meanwhile, when comparing the results obtained by elements with a 90 mm and 170 mm concrete cover, an increase in initial bond stress, ultimate bond stress and residual bond stress was observed by 76.9%, 46.6% and 97.2%, respectively.

Because of the earthquakes in China (Wenchuan) and Japan (Fukushima), which destroyed thousands of buildings, a lot of concrete debris appeared. It was the reason to look for methods of managing and recycling this waste. Therefore, scientists were conducting research on the use of recycled aggregate in concrete in various types of elements, including composite columns. Research on the bond between steel and recycled aggregate concrete in completely concrete encased I-section columns was conducted by Zheng H. et al. [9], Liu C. et al in [10, 11] and Bai G. et al. [12]. They noticed that as the concrete cover thickness decreased, the value of the bond stress decreased too. They also observed the influence of the number of steel stirrups in the column cross-section on the interaction between steel profile and concrete. The bond stress increase with the increase of the transverse reinforcement coefficient. According to Zheng H. et al. [9] the bond forces between steel and recycled aggregate concrete increase with the increase of the recycled aggregate content factor. Liu C. et al. [10, 11] came to the opposite conclusions, in their opinion, the bond forces decrease with the increase of the concrete aggregate content coefficient.

Chen L. et al. [13] carried out push-out tests of completely concrete encased I-sections with a checkered steel plate. During the tests, they were analysing the influence of checkered plate height, its position in the cross-section and transverse reinforcement coefficient on the adhesion between steel profile and concrete. The research shows that the placement of the checkered plates between steel profile and concrete can improve the bond stress at the interface. At the same time, it was found that the bond forces increase with the increase of height of checkered plate and stirrups coefficient. Additionally, it was observed that placing the checkered plate on the outside surface of the flange of the steel I-section positively influences the increase of bond strength. Moreover, it has been found that placing checkered plate on the inside surface of the flange of I-section gave less beneficial effect than placing on the outside surface. The least beneficial effect was achieved by placing the checkered plate at the web of the steel I-section.

Interesting information can also be found in the publication of Pecce M. and Ceroni F. [14], who investigated the bond between concrete and partially concrete encased I-section. According to the authors, the compressive strength of concrete affects the bond stress. Elements whose profiles were covered with oil showed a reduction of the bond forces in the interface between steel and concrete by about 50%. Simultaneously, a reduction of the bond forces by about 10÷20% was observed due to the placement of longitudinal reinforcement and stirrups in the cross-section on both sides of the web.

The simplification of the technology of making composite columns by using self-compacting concrete (SCC) instead of vibrated concrete, induced the authors of this paper to conduct research on bond between steel and SCC concrete in composite columns. Research on the impact of using SCC concrete to fill the space between double I-section HEA 160 composite columns was carried out by Szmigiera E. and Woyciechowski P. in [15] and Szmigiera E. in [16]. The analysis of the test results showed that the use of SCC concrete instead of vibrated concrete does not affect the load-bearing capacity of the column, as well as the bond in the interface between steel and concrete. These conclusions led to further work on the adhesion between steel and SCC concrete. For this purpose, push-out tests of tubular steel columns filled with SCC concrete were carried out. The research results are presented in [7, 17] Szadkowska M., Szmigiera E. and in [18] Grzeszykowski B. et al. The conducted analysis show that when determining the shear resistance in the interface between steel and concrete, not only the type of the cross-section as it is specified in Design code-Eurocode 4 [19] should be taken into account, but also its geometry, thickness of the steel profile, concrete compressive strength, as well as shrinkage of the concrete.

This paper presents the results of push-out tests of completely concrete encased I-section columns with the use of SCC concrete and vibrated concrete. The research showed the influence of such factors as the spacing of transverse reinforcement and the age of concrete on the value of bond forces in the interface between steel I-section and SCC concrete.

2. Research program

The tests were carried out in the Laboratory of the Institute of Civil Engineering at the Warsaw University of Technology, in two stages: in the first – the elements were tested 28 days after concreting, while in the second – after about 8 months, after testing the concrete shrinkage. In the first and second stage, 9 elements were examined, among which three characteristic types of cross-sections can be distinguished. The cross-sections of tested specimens differed in the type of concrete mix and the number of stirrups. During the research, the tests determining the strength characteristic of concrete, such as: compressive strength, average concrete tensile strength, concrete elasticity modulus and the concrete shrinkage were also carried out. Mean value of compressive and tensile strength of concrete was tested on cubic samples 150 × 150 × 150 mm. Mean values of cylindrical compressive strength and secant modulus of concrete were measured on cylindrical samples with diameter of 150 mm and height of 300 mm. The shrinkage of concrete was measured on cuboid samples with dimensions 100 × 100 × 500 mm.

2.1. Research methodology

The tests were carried out on elements with a square cross-section of 25 × 25 cm, composed of a completely concrete encased steel I-section (HEA 160) made of steel grade S355. The steel profile was encased in SCC and vibrated concrete. The cross-section also includes 4 longitudinal rods with a diameter of 8 mm, one in each corner and transverse reinforcement with a diameter of 6 mm. The reinforcement was made of B500SP steel grade. Depending on the type of element, two stirrups with a spacing of 160 mm or three stirrups with a spacing of 100 mm were placed in the cross-section. The interface area in all specimens were the same 226 561.94 mm^2 and it did not constitute a variable parameter in the research. Height of all types of the members was 250 mm. In the experiment, it was investigated the effect of the type of concrete mix (vibrated concrete or SCC), stirrup spacing and concrete age on the bond between steel and concrete. Figure 1 shows the types of cross-section of elements.

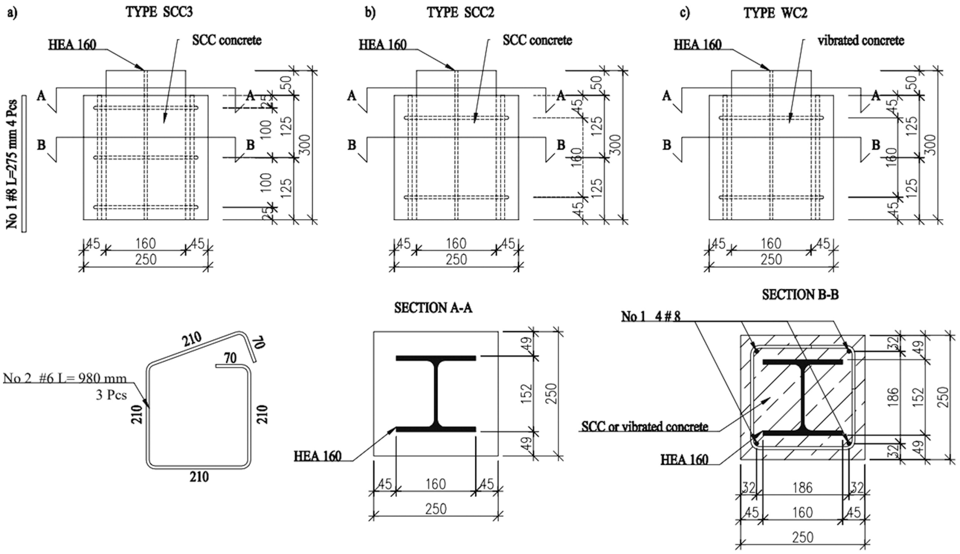

Fig. 1. Cross-sections of tested columns: a) made of SCC concrete with 3 stirrups, b) made of SCC concrete with 2 stirrups c) made of vibrated concrete with 2 stirrups

The designation of the tested elements and their characteristics are shown in the Table 1.

Table 2 and 3 summarize the mechanical properties of the concrete mix used to make elements after 28 days and 8 months, respectively.

The tests were carried out in the EU1000h hydraulic press, Fig. 2. The elements were placed in a hydraulic press, and the axial force was applied to the steel I-section which protruded above the upper edge of the concrete section. In order to transfer the shear stress from the steel I-section to the concrete only by bond forces, a 30 mm thick steel plate, with a hole in a shape of HEA 160, was installed in the lower part of the specimen. This allowed free movement of the steel profile.

Table 1. Types of tested elements

Notation of series	Cross-section type	Type of concrete mix
1	2	3
SCC2	encased H-profile, main reinforcement: 4 $\varphi 8$ and stirrups: 2 $\varphi 6$	self-compacting concrete
SCC3	encased H-profile, main reinforcement: 4 $\varphi 8$ and stirrups: 3 $\varphi 6$	
VC2	encased H-profile, main reinforcement: 4 $\varphi 8$ and stirrups: 2 $\varphi 6$	vibrated concrete

Table 2. Strength properties of concrete after 28 days

Notation of series	Mean value of cubic compressive strength of concrete $f_{c,\text{cube}}$ [MPa]	Mean value of cylindrical compressive strength of concrete $f_{c,\text{cyl}}$ [MPa]	Mean value of tensile strength of concrete f_t [MPa]	Mean value of secant modulus E_{cm} [GPa]
1	2	3	4	5
SCC2	56.5	46.73	3.40	33.3
SCC3				
VC2	52.56	45.20	3.19	35.2

Table 3. Strength properties of concrete after 8 months

Notation of series	Mean value of cubic compressive strength of concrete $f_{c,\text{cube}}$ [MPa]	Mean value of cylindrical compressive strength of concrete $f_{c,\text{cyl}}$ [MPa]	Mean value of secant modulus E_{cm} [GPa]
1	2	3	4
SCC2	63.28	54.63	33.98
SCC3			
VC2	60.35	52.40	36.88

During push – out tests, measurements of the axial force, the slip between steel and concrete on the upper edge of the specimen and the deformations of the concrete in the middle of the height and width of each of the four walls were made. Slip measurements between steel profile and concrete were made using inductive sensors, which were placed on the upper surface of the concrete. The handle holding the sensor in the right position was attached to the steel profile HEA 160. The scheme of the test stand and the arrangement of inductive sensors is shown in Fig. 3.

Fig. 2. The test stand and the supporting steel plate with an H-shaped opening

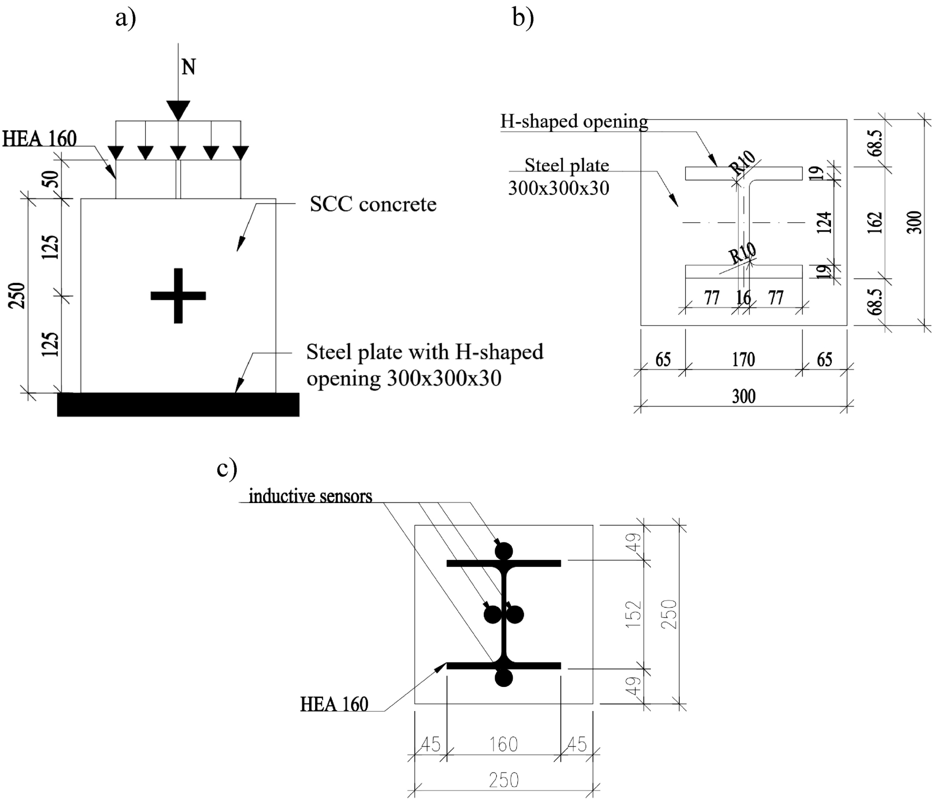

Fig. 3. The scheme of: a) test stand, b) H-shaped opening in the steel plate, c) the arrangement of inductive sensors

3. Analysis of test results

On the basis of the obtained test results, the analysis of longitudinal force – slip diagrams, as well as bond stress and maximum axial force values received in the push-out tests were analysed.

3.1. Analysis of axial force – slip diagrams

Figures 4 and 5 show axial force – slip relationship in elements tested after 28 days and after 8 months from the moment of concreting specimens, respectively.

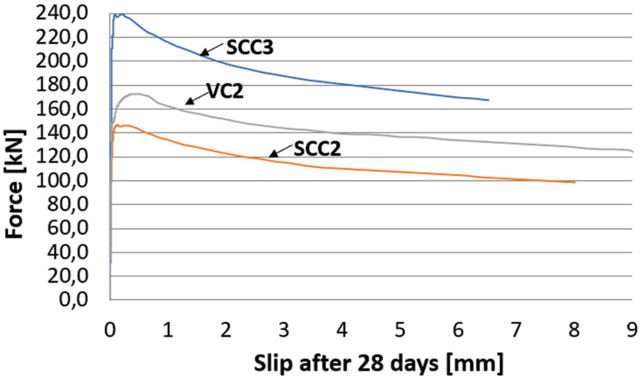

Fig. 4. Axial force – slip relationship in elements tested after 28 days

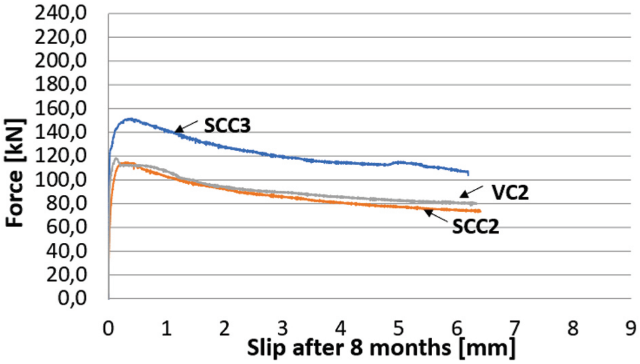

Fig. 5. Axial force – slip relationship in elements tested after 8 months

By analyzing the graphs in Figures 4 and 5, it can be observe the effect of shrinkage on the adhesion between the steel profile and SCC concrete. In the elements tested after 8 months, a large increase in the slip occurs at a lower value of the axial force. The ultimate force at which it is expected the loss of adhesion occurs, is lower in elements tested after 8 months.

Figures 4 and 5 show the effect of the number and spacing of stirrups on the bond forces between steel profile and concrete. In the case of elements with three stirrups (SCC3), a higher value of the ultimate axial force in the push-out tests was obtained than in the case of elements with two stirrups (SCC2 and VC2). It is caused by the concrete confinement effect which is greater in the case of specimens with denser stirrup spacing.

Focusing on the elements with two stirrups, it can be seen that the type of concrete mix did not have a significant influence on bond forces in the interface between steel profile and concrete, especially in the case of columns tested after 8 months. VC2 elements, which were tested after 28 days, obtained a higher value of the ultimate force than the SCC2 elements. However, when considering the shrinkage effect, the ultimate force for both VC2 and SCC2 was nearly equal.

3.2. Analysis of average bond stress

The bond stress analysis was carried out on the basis of the recommendations included in the Design code – Eurocode 4 [19]. According to the standard, it is necessary to provide the transfer of longitudinal shear stress in the interface between steel and concrete, in regions of load introduction and when moments are applied at the ends of the column and when loads occur locally along its length. In axially loaded columns, it is necessary to provide the transfer of shear forces only in the regions of load introduction. In areas where design shear strength τ_{Rd} is exceeded in the interface between steel and concrete, special shear connectors should be used. The values of the design shear resistance τ_{Rd} according to the standard [19] are given in Table 4. It should be noted that the research tests described in this paper concern composite steel-concrete elements made of SCC concrete, while the recommendations included in Eurocode 4 refer to elements made of vibrated concrete.

Table 4. Design shear strengths τ_{Rd} according to EC4 (2004)

Type of cross section	τ_{Rd} [N/mm^2]
Completely concrete encased steel sections	0.30
Concrete filled circular hollow sections	0.55
Concrete filled rectangular hollow sections	0.40
Flanges of partially encased sections	0.20
Webs of partially encased sections	0.00

On the basis of the obtained test results, the values of maximum push-out forces and average bond stress were analysed and compared with the recommendations given in the standard [19].

Assuming that at the maximum force $N = N_u$, the distribution of vertical shear stress is constant at the all height of element H, the average bond stress can be determined from the formula:

$$\tau_u = \frac{N_u}{\rho H} \tag{3.1}$$

where: N_u – maximum load received from push-out tests, ρ – a perimeter of the concrete in contact with the steel tube, H – the height of the interface between steel and concrete.

Table 5 summarizes the values of the ultimate bond stress calculated according to Eq. (3.1) obtained from the tests with the appropriate design shear strength τ_{Rd}, defined in the standard Eurocode 4. In order to be able to compare the shear strength obtained by tested elements with the values given in the standard, the values of average bond stress τ_u received in the research were divided by the value of the partial coefficient $\gamma_{vs} = 1.25$. Looking at the values in table 4, we are not sure whether they were determined taking into account the influence of such factors as concrete shrinkage and the number of stirrups and longitudinal reinforcement in the cross-section on the resistance to the vertical shear in the interface between steel and concrete. However, in the conducted studies, such an effect was observed. The analysis of the research results given in Table 5 shows that the shear strength in the interface between steel and concrete in all elements tested after 28 days and after 8 months was higher than the design shear strength in the standard table. SCC3 elements (with three stirrups) obtained a higher shear resistance between steel and concrete than SCC2 and VC2 elements (with two stirrups). Comparing the elements tested after 28 days with the two stirrups SCC2 and VC2, it can be observed that the SCC2 elements achieved a lower resistance to the vertical shear in the interface than the VC2. However, this relation was reversed in the case of elements tested after 8 months. This time the SCC2 elements obtained a higher shear resistance in the interface than the VC2 elements. In case of elements SCC3 and VC2 the shear strength decrease after 8 months was 37% and 32% respectively, while in elements SCC2 only 13%. The concrete shrinkage seems to reduce the confinement effect.

Table 5. The values of the maximum bond stress obtained before and after the concrete shrinkage tests together with the corresponding standard values

Notation of series	Results after 28 days		Results after 8 months		Percentage change in shear strength	Designed shear strength according to EC4
	N_u	$\tau_{md} = \dfrac{N_u}{A_{c-s} \cdot \gamma_{vs}}$	N_u	$\tau_{md} = \dfrac{N_u}{A_{c-s} \cdot \gamma_{vs}}$		τ_{Rd}
[–]	[kN]	[N/mm^2]	[kN]	[N/mm^2]	[%]	[N/mm^2]
SCC3	245	0.86	152	0.54	37%	0.3
SCC2	156	0.55	135	0.48	13%	0.3
VC2	174	0.62	119	0.42	32%	0.3

According to the standard recommendations, the resistance to the vertical shear in the interface between steel and concrete in composite columns depends only on the shape of the cross-section. However, the values of shear resistance obtained from the tests show that they are influenced by factors such as the number of transverse and longitudinal reinforcement, and the age of the concrete. The reason for higher shear resistance obtained in the tests than values of designed shear strength given in EC4 can be the intensification of confinement effect in concrete as a result of the number of stirrups and their denser spacing.

4. Conclusions

On the basis of the conducted analysis of own research results on the bond between steel and self-compacting concrete, the following conclusions can be made:

- The bond forces between steel and self-compacting concrete are influenced not only by the shape of cross-section, but also by the number of transverse and longitudinal reinforcement and concrete age.
- Concrete shrinkage has a significant influence on the resistance to the vertical shear in the interface between steel and SCC in completely concrete encased I-section composite columns.

The value of resistance strength decrease with the increase of concrete age.

- The denser stirrup spacing has a beneficial effect on the bond forces in the interface between steel and self-compacting concrete in completely concrete encased I-section composite columns. Bond forces increase with the decrease of distance between stirrups in the cross-section.
- The value of shear resistance in the interface between steel and SCC in completely concrete encased I-section composite columns is higher than design resistance strength given in the standard, regardless of the age of concrete at the time of the test.

As it follows from previous bond tests of CFST columns filled with SCC concrete, which were conducted by the authors of this paper, the value of resistance to the vertical shear decrease almost twice time in elements tested after concrete shrinkage. What's more the resistance to the vertical shear after concrete shrinkage in CFST columns was lower than design resistance strength given in the standard. As we can see, in two different types of cross-sections of composite columns we received various values of shear resistance strength in comparison to the standard recommendations. In the case of completely concrete encased I-section composite columns the shear resistance after concrete shrinkage was higher than design resistance strength given in the standard but in the case of CFST columns value of shear resistance strength after concrete shrinkage was lower than in the standard. This means that the design value of the shear strength given in the standard cannot be directly applied to elements made of SCC concrete and further tests should be carried out to determine the value of shear resistance for such elements.

References

[1] M. Wang, Y. Zhang, L. Yu, Y. Dong, Y. Tian, G. Zhou, "Experimental study on bond-slip behavior between corroded I-shaped steel and concrete in subsea tunnel", *Materials*, 2019, vol. 12, no. 18, art. ID 2863, DOI: 10.3390/ma12182863.

[2] Y. Zhang, M. Wang, L. Yu, X. Guo, Z. Wang, Y. Jiang, "Bond-slip behavior between corroded I-shaped steel and concrete in subsea tunnel", *Engineering Failure Analysis,* 2021, vol. 120, art. ID 105061, DOI: 10.1016/j.engfailanal.2020.105061.

[3] J. Xue, H. Li, R. Ren, X. Zhang, "The bond behavior of steel reinforced recycled concrete under cyclic reversed load", *Engineering Stuctures*, 2021, vol. 248, art. ID 113238, DOI: 10.1016/j.engstruct.2021.113238.

[4] X. Zhang, J. Xue, R. Ren, "Bond capacity between H-shaped steel and recycled concrete under cyclic loading", *The Structural Design of Tall and Special Buildings*, 2021, vol. 30, no. 16, DOI: 10.1002/tal.1890.

[5] M.M. Abdulazeez, B. Shrestha, E. Gomaa, A. Ramadan, M.A. ElGawady, "Bond behaviour of steel H-pile bridge columns encased in concrete jackets", presented at *Conference Transportation Research Board,* December, Washington DC, 2018.

[6] X. Qu, Z. Chen, D. Nethercot, L. Gardner, M. Theofanous, "Push-out tests and bond strength of rectangular CFST columns", *Steel and Composite Structures*, 2015, vol. 19, no. 1, pp. 21–41, DOI: 10.12989/scs.2015.19.1.021.

[7] M. Szadkowska, E. Szmigiera, "Bond between steel and self-compacting concrete in composite tube columns", *Archives of Civil Engineering*, 2017, vol. 63, no. 2, DOI: 10.1515/ace-2017-0021.

[8] X. Wang, Y. Liu, F. Yang, Y. Lu, X. Li, "Effect of concrete cover on the bond-slip behavior between steel section and concrete in SRC structutres", *Construction and Building Materials*, 2019, vol. 229, art. ID 116855, DOI: 10.1016/j.conbuildmat.2019.116855.

[9] H. Zheng, Z. Chen, J. Xu, "Bond behavior of H-shaped steel embedded in recycled aggregate concrete under push-out loads", *International Journal of Steel Structures*, 2016, vol. 16, no. 2, pp. 347–360, DOI: 10.1007/s13296-016-6008-y.

[10] C. Liu, Z. Lv, G. Bai, Y. Yin, "Experiment study on bond slip behaviour between section steel and RAC in SRRC structures", *Construction and Building Materials*, 2018, vol. 175, pp. 104–114, DOI: 10.1016/j.conbuildmat.2018.04.120.

[11] C. Liu, L. Xing, H. Liu, Z. Quan, G. Fu, J. Wu, Z. Lv, C. Zhu, "Numerical study of bond slip between section steel and recycled aggregate concrete with full replacement ratio", *Applied Sciences*, 2020, vol. 10, no. 3, DOI: 10.3390/app10030887.

[12] G. Bai, J. Ma, B. Liu, X. Chen, "Study on the interfacial bond slip constitutive relations of I-section steel and fully recycled aggregate concrete", *Construction and Building Materials*, 2020, vol. 238, art. ID 117688, pp. 1–13, DOI: 10.1016/j.conbuildmat.2019.117688.

[13] L. Chen, S. Wang, C. Yin, S. Li, "Experimental study on constitutive relationship between checkered steel and concrete", *Construction and Building Materials*, 2019, vol. 210, pp. 483–498, DOI: 10.1016/j.conbuildmat.2019.03.164.

[14] M. Pecce, F. Ceroni, "Bond tests of partially encased composite columns", *Advanced Steel Construction*, 2010, vol. 6, no. 4, pp. 1001–1018.

[15] E. Szmigiera, P. Woyciechowski, "Influence of the compaction method on the bond between steel and concrete in composite columns", *Periodica Polytechnica – Civil Engineering*, 2013, vol. 57, no. 2, pp. 129–137, DOI: 10.3311/ppci.7169.

[16] E. Szmigiera, "Verbund zwischen Stahl und Selbstverdichtendem Beton in Verbundstützen", *Stahlbau*, 2012, vol. 81, no. 8, pp. 616–620, DOI: 10.1002/stab.201201591.

[17] M. Szadkowska, E. Szmigiera, "Analysis of shrinkage influence on bond in CFST elements filled with SCC", *Journal of Constructional Steel Research*, 2021, vol. 184, art. ID 106824, DOI: 10.1016/j.jcsr.2021.106824.

[18] B. Grzeszykowski, M. Szadkowska, E. Szmigiera, "Analysis of stress in steel and concrete in CFST push-out test samples", *Civil and Environmental Engineering Reports*, 2017, vol. 26, no. 3, pp. 145–159, DOI: 10.1515/ceer-2017-0042.

[19] *EN 1994-1-1 Eurocode 4 – Design of composite steel and concrete structures – Part 1–1: General rules and rules for buildings* European Committee of Standardization, Brussels, Belgium, 2004.

Przyczepność między stalą i betonem SCC w słupach zespolonych o przekroju złożonym z obetonowanego dwuteownika HEA 160

Słowa kluczowe: przekrój dwuteowy, zespolony, słup, samozagęszczalny, beton, przyczepność

Streszczenie:

Stalowo–betonowe słupy o przekroju złożonym z obetonowanego dwuteownika stanowią jeden z podstawowych typów słupów zespolonych szeroko stosowanych w budownictwie. Dzięki takim cechom jak: wysoka nośność, sztywność czy też ciągliwość, zyskały na popularności i znalazły zastosowanie jako podpory w obiektach mostowych, konstrukcjach hydrotechnicznych, a także w różnego rodzaju budynkach posadowionych na terenach zagrożonych sejsmicznie. Przekroje złożone z obetonowanego dwuteownika są powszechnie stosowane, np. w podmorskich tunelach Chin. Jednocześnie istotnym zagadnieniem rozważanym w wielu publikacjach jest możliwość wzmocnienia stalowych, skorodowanych słupów, stanowiących podpory mostów w Stanach Zjednoczonych, poprzez ich obetonowanie. W tego typu konstrukcjach, których przekroje są często gęsto zbrojone, a przestrzeń między deskowaniem i stalowym kształtownikiem nieduża, zasadnym wydaje się użycie betonu samozagęszczalengo (SCC z ang. *Self-Compacting Concrete*). Dlatego Autorki artykuły podjęły się zbadania przyczepności między stalą i betonem samozagęszczalnym w zespolonych słupach o przekroju złożonym z obetonowanego dwuteownika HEA 160. W niniejszym artykule przedstawiono wyniki badań przyczepności między stalą i betonem samozagęszczalnym (SCC), elementów zł ożonych z obetonowanego dwuteownika HEA 160 i porównano je z wynikami uzyskanymi przez elementy wykonane z betonu wibrowanego. W pracy przedstawiono również wpływ wybranych czynników na nośność na ścinanie w płaszczyźnie zespolenia. Analiza wyników badań pokazała, że rozstaw zbrojenia poprzecznego oraz wiek i rodzaj betonu wpływają na nośność na ścinanie w płaszczyźnie zespolenia. Jednocześnie wyniki badań obliczeniowej nośności na ścinanie w płaszczyźnie zespolenia zestawiono z wartościami granicznymi podanymi w normie Eurokod 4. Jak wynika z przeprowadzonej analizy, wszystkie badane elementy uzyskały wyższą wartość naprężeń ścinających w płaszczyźnie zespolenia niż wartość podana w tablicy normowej EC4, zarówno po 28 dniach jak i po badaniu skurczu betonu. Zgodnie z zaleceniami określonymi w normie PN-EN 1994-1-1-2008, wartość obliczeniowych naprężeń ścinających zależy jedynie od rodzaju przekroju elementów ściskanych. Należy podkreślić, że zalecenia normowe dotyczą jedynie elementów wykonanych z betonu zwykłego, ale wydaje się, że nawet w tym przypadku warunki klasyfikacji granicznej nośności na ścinanie τ_{Rd} wydają się być niewystarczające. W związku z tym wydaje się, że powinny zostać przeprowadzone kolejne badania w celu określenia obliczeniowej nośności na ścinanie dla elementów wykonanych z betonu SCC.

Received: 12.10. 2021, Revised: 25.01. 2022