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Experimental behaviour of concrete-filled rectangular thin welded steel stubs (compression load case)

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ABSTRACT

In the present work, results of tests conducted on thin welded rectangular steel-concrete stubs are presented. The studied section was made of two cold steel plates with U shape and welded (with electric arc) to form a steel box. The cross section dimensions were: 100 × 70 × 2 mm. The main studied parameters were: the height (50, 100, 150, 200, 300, 400, 500 mm), the effect of the in filled concrete and its age, the discontinuous weld. The tests were carried out at 28 days and 3 years after the date of casting. All tests were achieved under axial compression in a 50 tf machine up to failure. A total of 21 stubs were tested, 8 were empty, 8 filled with concrete whose gravel was made of crushed crystallized slag tested at 28 days of casting and 8 composites as the previous but tested after 3 years. The aim of the study is to bring some light on the behaviour of such composite section. Also, to provide some evidence that the use of crushed slag could be integrated in the manufacturing of non-conventional concrete. All failure loads were predicted numerically and by using the Eurocodes EC3 and EC4 from test results it was confirmed that the length of empty stubs had a drastic effect on the load carrying capacity and the failure mode was rather a local buckling mode with steel sides deformed outwards and inwards. Both numerical EC3 predictions were higher and on the unsafe side when compared to experimental corresponding loads for empty steel samples. For composite stubs, the load carrying capacity increased significantly; the EC4 numerical load predictions were higher in the higher range 300–500 mm and lower in the higher range 50–200 mm. The failure mode of composite stubs was a local buckling mode with all steel sides deformed outwards. The experimental loads obtained after 3 years of casting were higher than the corresponding tested at 28 days. The load ratio (3 years/28 days) was found to be increasing linearly with the increase of the stubs height. More test results are needed to check the EC3 and EC4 validity.

1. Introduction

Hollow structural steel sections are often filled with concrete to form a composite column. Traditional concrete-filled steel columns employ the use of hot rolled steel sections filled with concrete. These columns have been used wide spread as they speed up construction by eliminating formwork and producing high load carrying [1]. This leads to using small steel wall thickness and thus to more economy. However, the major difficulty encountered is the local buckling of the steel wall especially in the case of stocky columns [2]. Very few experimental is done on built up cold formed welded steel sections filled with concrete or recycled materials [3] such as slag stone concrete designated here by SSC. The latter has been tested under direct compression and was used as a filling material to overcome the undesired effects of imperfections of built up

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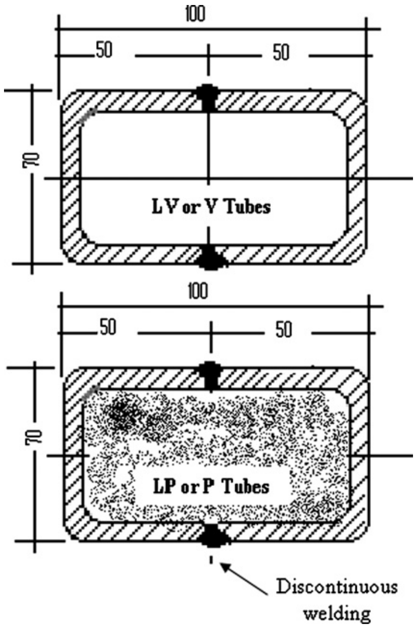

Fig. 1. Thin cold formed and welded steel cross section details.

Table 1
Slag stone concrete mix properties.

Cement content	350 kg/m^3
Water–cement ratio	0.50
Aggregate–cement ratio	2.0
10 cm crushed slag stones	700 kg/m^3
Sand	400 kg/m^3
Slump	70 mm
Compressive strength at 28 days	20 MPa
Compressive strength at 3 years	30 MPa
E_c	21 GPa

cold formed sections. The gain in strength was found to reach a value of up to 2 and decreased linearly with the stubs height [4]. More test results are needed to indicate what would be the effect of the age of SSC on the behaviour and the load carrying capacity. No evidence is available in the literature to confirm the benefit of SSC age. The present work is a contribution to understand the behaviour of SSC-filled cold formed thin short steel tubes subjected to axial compression.

2. Experimental program

To study the behaviour of SSC-filled cold formed steel tubes, 21 steel tubes were prepared. All specimens had the same cross section dimensions 100 × 70 × 2 mm (Fig. 1). The main parameters studied were the stub height and the age of SSC. Steel coupons were prepared to investigate the tensile yield steel strength. Six concrete cylinders were tested under direct compression: 3 at 28 days and 3 at 3 years. 8 empty steel with different height were tested under axial compression, 16 steel tubes were filled with concrete from the same batch. All concrete mix details are given in Table 1. 8 composite stubs were tested at 28 days and 8 were tested at 3 years. The stub height varied from 50 mm to 500 mm. The slag stone concrete mix propriety are presented in Table 1.

2.1. Materials and fabrication

The concrete mix proportioning is presented in Table 1. The natural crushed stones were substituted by crushed crystallized slag of 10 mm size brought from iron manufacture ELHADJAR-ALGERIA. The use of such artificial stone instead of natural stone would contribute to environment protection by recycling such industrial waste. The 28 days compression strength of SSC was 20 MPa and 30 MPa at 3 years of the date of casting. The Young's modulus of concrete at 28 days was 21 GPa and 35 GPa at 3 years. The steel yield strength was 300 MPa with a Young's modulus of 205 GPa. 16 steel tubes were cast vertically. During casting, concrete was vibrated externally by a shaking table for 2 to 3 min. All composite specimens were lefts in the curing room for a period of 28 days. Both, top and bottom faces of composite stubs were mechanically treated to remove surface irregularities and ensure that both steel and concrete are loaded during test.

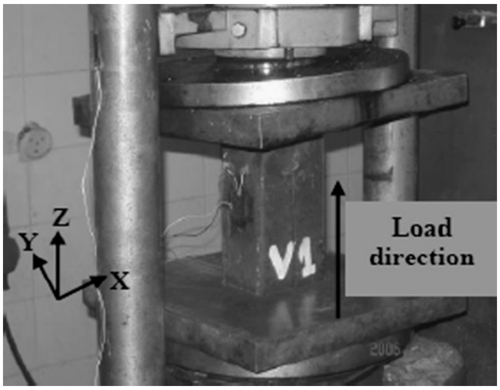

Fig. 2. View of test rig and sample v1 after test.

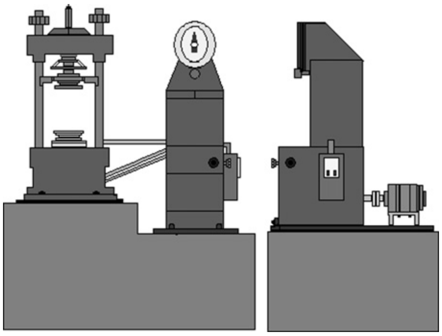

Fig. 3. Compressive machine.

2.2. Test rig and procedure

All specimens were tested in a 500 kN compressive machine, Figs. 2 and 3. Calibration of the test machine confirmed that the absolute accuracy was 0.5%. Special attention was given to verifying the correct position of the stubs before any loading. For the first load increment, a complete check of strains and load was carried out. The load was applied on the composite section (concrete and steel), the top metal plate is the fixed plate (all degrees of freedom were restrained except rotation belong X and Y axis), and the bottom metal plate is the moving plate (all degrees of freedom were restrained, except rotation belong X and Y axis and displacement at load direction "belong Z axis") as shown in Fig. 2.

Several loading, unloading and reloading cycles were performed at this stage. When the results were satisfactory, the loading then proceeded up to failure. Each specimen had two strain gages, one in the vertical position and the second in the horizontal position at the opposite side to record vertical and horizontal steel strains ε_v and ε_h respectively. All strain gages were placed at mid-height section. During tests, graphical monitoring of load-strain relationships was carried out to guide the running of experiment. The loading was performed up to failure. All data test results are gathered in Table 2.

3. Strength design codes

EC3 and EC4 are the most recently completed international standards in steel construction and composite construction, respectively. EC4 provided a simplified method of design for composite columns, which was based on the European buckling curves for the influence of instability and on cross section interaction curves determining the column section's resistance. EC4 covers concrete encased and partially encased steel sections and concrete-filled sections with or without reinforcement. Design procedure of the composite columns considers the second-order effects including imperfections and ensures that under the most unfavourable combinations of actions at the ultimate limit state, instability does not occur [5]. The plastic resistance to compression $N_{pl,Rd}$ of a composite cross section was calculated by adding the plastic resistance of its components:

$$N_{pl,Rd} = A_a f_y/\gamma_{Ma} + A_c(0.85 f_{ck}/\gamma_c) + A_s f_{sk}/\gamma_s \tag{1}$$

where A_a, A_c and A_s are the cross-sectional areas of structural steel, concrete and reinforcement respectively; f_y, f_{ck} and f_{sk} are respectively the yield stress of steel cross section, the strengths of concrete and the yield stress of steel reinforcement; γ_{Ma}, γ_c and γ_s are partial safety factors at the ultimate limit states.

Table 2
Results of empty steel and composite stubs.

Stub No.	$H \times B \times t$ (mm)	Steel A_s (mm^2)	Concrete A_c (mm^2)	Height L (mm)	Squash loads N_{sq} (kN)	Test loads (kN)	aEC3 loads (kN)	EC4 loads (kN)	Program loads (kN)
LV1	102 × 68 × 2.0	664	–	50.	199.	160.	173.2	–	213.
LV2	102 × 68 × 2.0	664	–	100.	199.	159.	173.2	–	208.
LV3	102 × 68 × 2.0	664	–	150.	199.	156.	173.2	–	204
V1	97 × 72 × 2.40	788.1	–	196.	236.4	150.	246.	–	201.
V2	99 × 69 × 2.50	815.	–	298.	244.5	144.	258.	–	194.
V3	97 × 71 × 2.30	751.6	–	390.	225.5	130.	212.	–	173.
V4	100 × 70 × 2.40	792.9	–	490.	237.9	120.	206.	–	160.
LP1/28	102 × 69 × 2.0	668.	6370.	50.	327.8	489.	–	273	493.
LP2/28	102 × 68 × 2.0	664.	6272.	100.	324.6	290.	–	270	306.
LP3/28	104 × 68 × 2.04	672.	6400.	150.	329.6	285.	–	274	278.
P1/28	102 × 70 × 2.10	704.7	6465.2	200.	313.	280.	–	265.	364.
P2/28	102 × 71 × 2.00	676.	6566.	300.	306.3	230.	–	252.	312.
P3/28	99 × 73 × 2.00	672	6555.	400.	305.	210.	–	253.	250.
P4/28	100 × 72 × 2.10	704.7	6495.2	500.	313.8	150.	–	268.	177.
LP1/3	102 × 70 × 2.0	672.	6468.	50.	395.6	548.	–	380.	538.
LP2/3	103 × 68 × 2.0	668.	6336.	100.	390.1	436.	–	364.3	424.
LP3/3	103 × 69 × 2.0	672.	6435.	150.	391.5	348.	–	368.3	328.
P1/3	99 × 72 × 2.40	797.7	6330.2	196.	339.1	347.	–	302.	394.
P2/3	100 × 71 × 2.50	830.	6270.	295.	347.8	344.	–	309.	335.
P3/3	97 × 68 × 2.30	742.4	5921.5	390.	316.1	349.	–	281.	260.
P4/3	98 × 70 × 2.30	751.6	6108.3	490.	321.8	264.	–	286.	182.

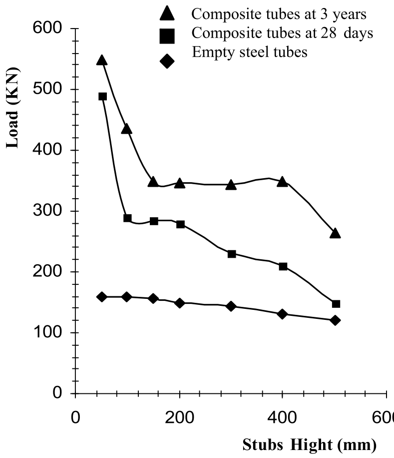

Fig. 4. Experimental failure loads.

According to EC3, the load carrying capacity for steel columns section is calculated by formula (2):

$$N_{b,Rd} = \chi \beta_A A_a f_Y / \gamma_{Ma} \tag{2}$$

where $\beta_A = 1$ for class sections 1, 2 and 3, and $\beta_A = A_{\text{effectif}}/A$ for class section 4, χ is a reduction coefficient of load carrying capacity in order to take into account the phenomenon of buckling [6].

4. Results of stub tests

A total of 21 rectangular stubs were tested in axial compression. The main parameters studied were the stub height and the age of SSC. Details of test specimens including EC3 and EC4 predictions are given in Table 2. The test program included 3 groups of specimens. The first group gathered the empty steel tubes LV1–V4, the second group was for composite stubs tested at age of 28 days LP1/28–P4/28 and the third group included composite stubs that were tested at age of 3 years LP1/3–P4/3.

Composite stubs were filled with an SSC from the same concrete batch. The results obtained from testing empty steel tubes that the main feature of thin walled steel tubes is the local buckling that took place in all samples with a small attenuation for longer steel stubs. Both, large and small sides buckled inwards and outwards respectively. The decrease in the steel tubes load carrying capacity with the stub height increase is well pictured in Fig. 4.

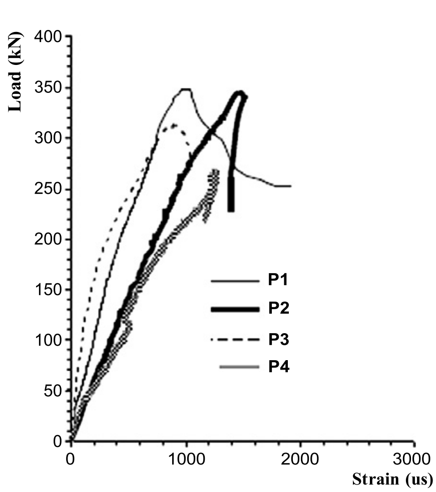

Fig. 5. Load–strain curve of P1, P2, P3, P4 columns at 3 years.

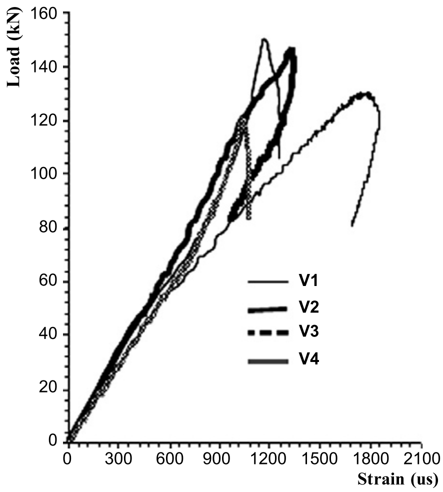

Fig. 6. Load–strain curve of V1, V2, V3, V4 columns.

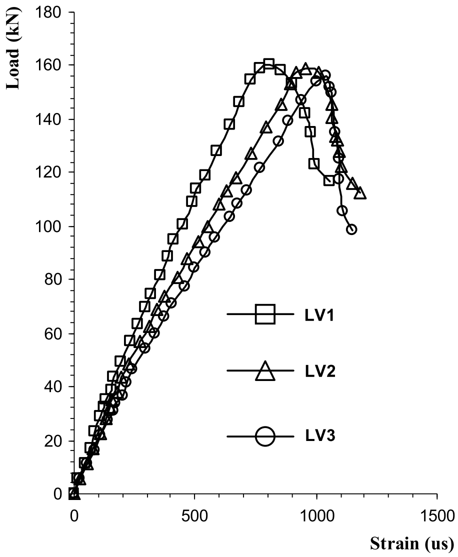

Fig. 7. Load–strain curve of LV1, LV2, LV3 columns.

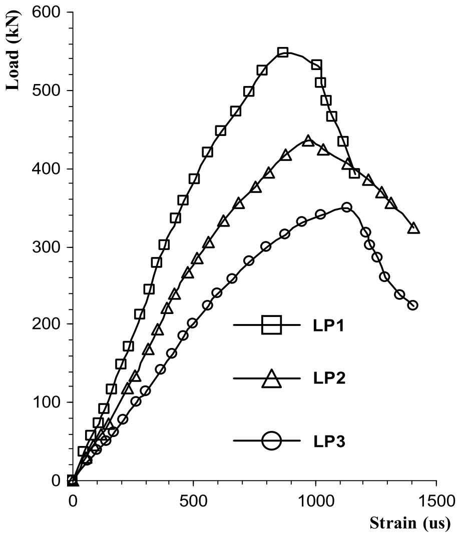

Fig. 8. Load–strain curve of LP1, LP2, LP3 at 3 years.

The test results of the second group conducted at 28 days of concrete casting date show the benefit of composite steel-concrete stubs. The load carrying capacity of composite 28 days samples is increased but with load decrease rate higher than the previous group. Both, large and small sides of the composite section buckled outwards significantly with attenuation for longer samples. The last group, tests were run after 3 years of concrete casting date. Results obtained from testing the third group are presented in Table 2 and Fig. 4.

The failure loads were higher when compared with the corresponding composite test obtained at 28 days. The 3 year load decreases rate is smaller than the corresponding at 28 days. The carrying capacity of tested empty steel tubes LV1 to V4 varied from 160 to 120 kN. The 28 days composite test varied from 489 to 150 kN for sample LP1/28 to P4/28. The highest test results correspond to composite stubs tested at 3 years LP1/3 to P4/3 which test loads varied from 548 to 264 kN. The test load ratio (filled/empty) at 28 days varies from 3.056 to 1.250 and from 3.425 to 2.2 for 3 year stubs. This expresses the advantage of filling cold formed and welded steel tubes with SSC (Figs. 5 to 8).

The composite test load ratio (3 years/28 days) is found to be varying linearly and increasing with the stubs height increase, Fig. 9, knowing the steel and composite test loads, the concrete load can be calculated by subtracting the test steel load. Hence, the steel and concrete average normal stresses can be calculated approximately. The considerable increases of the bearing capacity of the composite stubs after 3 years is due to the augmentation of resistance of concrete core after 3 years and the confinement of concrete by steel section (we must indicate here, in the composition of concrete, the

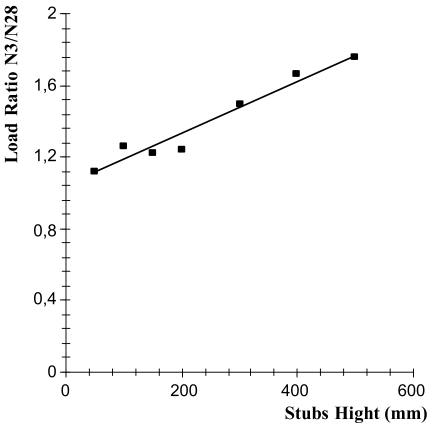

Fig. 9. Load ratio–stub height variation for composite stub.

Fig. 10. Local buckling mode at P1 to P4 columns after 3 years.

natural crushed stones are substituted by crushed crystallized slag of 10 mm size brought from iron manufacture ELHADJAR-ALGERIA, this slag comprises great percentage of iron what increases their resistance), Fig. 10 and Fig. 11.

Fig. 12 shows the stress ratio variation for both steel and concrete at 28 days and 3 years. This illustrates well the contribution of concrete age in improving the strength of composite stubs. It should be kept in mind that the 3 year concrete cylinder strength was 30 MPa, whereas the 28 days was 20 MPa, which represents 50% of concrete strength gain. The concrete stress ratio (f'_c/f_{c28}) varied from 3 to 0.92 for 28 days samples and from 1.6 to 3.44 for 3 year stubs.

Fig. 13 illustrates improvements in behaviour of SSC-filled steel tubes for the case V1 and P1/3 which both had 200 mm height. All composite stubs failed by a Local buckling mode with all cross section sides deformed outwards. The failure mode of composite specimens was by yielding of steel and partial crushing of SSC at both top and bottom ends. The removal of steel from tested composite stubs after test showed no sign of concrete cracking or crushing at the mid-height section. The composite squash load was computed on the basis of steel and SSC strength obtained from testing steel coupons and concrete cylinders in accordance with Eurocode EC4. The results of calculations are given in Table 2. The calculated average composite squash load varied from 327.8 kN to 313.8 kN for 28 days samples and from 395.6 kN to 321.8 kN for 3 year specimens.

For the purpose of compression, all ultimate loads for both empty and composite stubs were calculated in accordance with Eurocode EC3 and EC4. The EC3 loads were higher than test loads and on the unsafe side because the EC3 does not take into account this discontinuity of welding in the prediction of the load and that influences considerably at calculated prediction load using this design code. Although the steel samples were short, one would expect experimental loads to be close to the squash load.

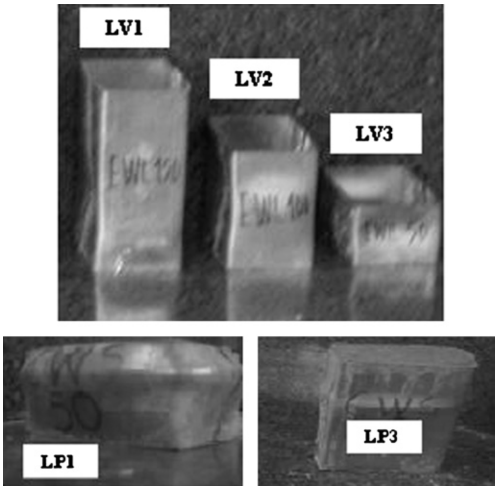

Fig. 11. Local buckling at LV1, LV2, LV3, LP1 and LP3 columns after 28 days.

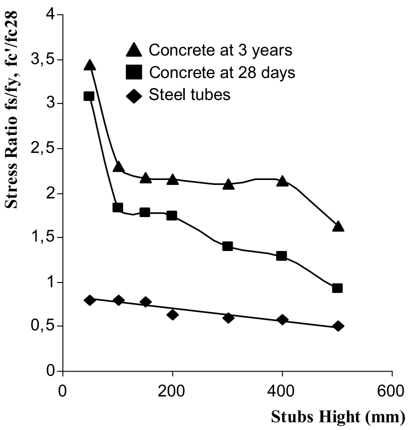

Fig. 12. Steel and concrete stress ratio–stub height variation for all tested tubes.

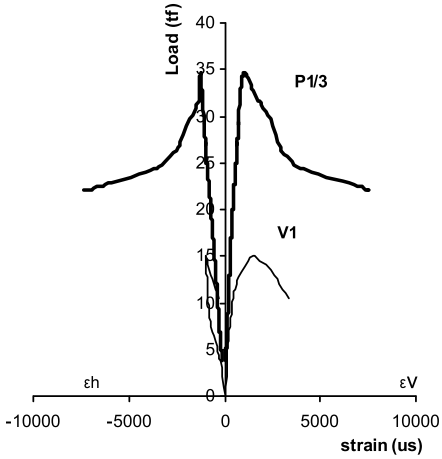

Fig. 13. Load–strain variation for samples V1 & P1/3.

This was not achieved; experimental empty steel tubes were lower as empty steel samples failed by a premature buckling mode. The prediction loads accordance with Eurocode EC4 for 28 days composite stubs were close to test loads, except for stubs P4/28 and LP1/28. Both test and predicted EC4 loads were good agreement for composite stubs tested at 3 years except LP1/3 and LP2/3; although the concrete strength used in generating the EC4 loads was the 28 days and not 3 year concrete strength. A computer program, described elsewhere was used to predict ultimate loads for both empty and composite stubs.

All results are gathered in Table 2; the numerically prediction loads were higher than test but lower than EC3 prediction in the case of empty steel tubes. For composite tubes, both numerical and test loads were in good agreement except for stubs P4/3 and P4/28. These discrepancies could be improved by recording all geometrical and mechanical imperfections from each sample before testing and implementing the recorded data in the program to simulate as close as possible the response of empty steel or composite stubs under axial loading. This was achieved in the course of the present work. In this study the effect of shrinkage is negligible. The steel wall was under axial as well as lateral pressure due to its interaction with the concrete core and was forced to undergo local buckling allowing lateral pressure to decrease at the section concerned. As loading continued further cracking sounds were heard and the on set of first local buckling was marked by a louder cracking sound. The location of the first buckle either local or global is indicated in Table 3.

5. Discussion

In the present work, the experimental results are given, it is shown that cold formed thin welded steel tubes subjected to axial compression are very sensitive to initial imperfections and affect drastically the behaviour and the load carrying capacity of empty steel samples. Although loads were applied axially, theoretically speaking, the stubs should remain straight up to failure. This was not the case, at the very beginning of tests; some overall bending took place as the loading plates

Table 3
Summary of test observations.

Stub No.	Load at start of first buckling (kN)	Distance from top to first local buckle (mm)	Failure test load (P) kN
LV1	113 (70% P)	24.4	160.
LV2	116 (73% P)	43.2	159.
LV3	106.1 (68% P)	87.8	156.
V1	105 (70% P)	56.7	150.
V2	95.1 (66% P)	76.6	144.
V3	92.1 (71% P)	84.3	130.
V4	84.5 (70% P)	112.5	120.
LP1/28	479.2 (98% P)	20.2	489.
LP2/28	281.3 (97% P)	46.3	290.
LP3/28	276.4 (95% P)	67.5	280.
P1/28	266. (97% P)	65.3	280.
P2/28	213.9 (97% P)	85.7	230.
P3/28	199.5 (95% P)	76.3	210.
P4/28	138. (93% P)	74.4	150.
LP1/3	542.5 (99% P)	17.4	548.
LP2/3	422.9 (97% P)	41.2	436.
LP3/3	330.6 (95% P)	55.4	348.
P1/3	336.6 (97% P)	53.6	347.
P2/3	333.8 (97% P)	63.7	344.
P3/3	335. (95% P)	108.8	349.
P4/3	245.5 (92% P)	75.6	264.

were seen to be rotating. This was followed by a combination of shear from stub–machine plate's contact and local bending in the buckling zone. The results of such complex equilibrium state produced a premature failure, leading to low test loads and far from the theoretical plastic load of empty steel tubes. The infill SSC improves the behaviour and increases the load carrying capacity at both ages 28 days and 3 years of the concrete casting date. Although 28 days composite stubs were short (L/B varying from 0.71 to 7.14) and consequently we were expecting test loads to reach the squash load predicted in accordance with Eurocode EC4.

However, test results show that failure loads of tested 28 days stubs were lower than the EC4 squash load varying from 150 to 489 kN, whereas the corresponding EC4 squash loads were in the range of 268 to 273 kN. By taking into account the effect of slenderness in computing the ultimate load in accordance with EC4, both test and EC4 loads were in good agreement for stubs LP2/28, LP3/28, P1/28 and P2/28 but EC4 predictions were higher on the unsafe side for stub P4/28 and lower in the case of stub LP1/28. At 3 years, the test loads were higher than the corresponding at 28 days, varying from 264 to 548 kN and close to squash load except for stubs P4/3 and LP1/3 whose test loads are respectively 264 kN and 548 kN, and the corresponding squash load is respectively 321.8 kN and 395.8 kN. The ultimate loads predicted by EC4 for 3 year stubs were conservative except for stub P4/3 witch test load is 264 kN and the EC4 load is 286 kN on the unsafe side. The test results obtained from testing composite stubs at age of 3 years illustrate the benefit of SSC age on the strength and stability. The age of SSC has a local buckling delaying effect allowing to composite stubs to reach loads close to their squash loads which was not recorded at 28 days samples where the slenderness effects drastically the load carrying capacity. It is believed by authors that with time the SSC gain more maturation and produces more composite stiffness and strength allowing undesired effects such as initial steel imperfections to be compensated.

6. Conclusion

Within the limits of the investigation reported above, it may be concluded that the ultimate loads of empty steel tubes are affected not only by the steel tubes height but also by the initial imperfections and are lower than numerical and EC3 predictions on the unsafe side. Filling steel tubes with a concrete that gravel was substituted by 10 mm crushed crystallized slag stone, increases the load carrying capacity at 28 days but with a significant drastically effect of slenderness. At 3 years, the concrete compressive strength is 30 MPa, which is 50% greater than the corresponding at 28 days. The behaviour of 3 year composite stubs is improved; the concrete age has a local buckling delaying effect allowing reaching higher load carrying capacity close to composite squash loads. More experimental data are needed to check the validity of both EC3 an EC4 predictions in the case of axially and eccentrically loaded empty steel and composite stubs using slag stone concrete as a filling material.

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