Proceedings Paper:

Ahmed, I and Tsavdaridis, KD orcid.org/0000-0001-8349-3979 (2019) Prefabricated Composite Flooring Systems with Normal and Lightweight Concretes. In: Special Issue: Proceedings of Nordic Steel 2019. NSCC 2019, 18-20 Sep 2019, Copenhagen, Denmark. Ernst und Sohn , pp. 257-263.

https://doi.org/10.1002/cepa.1053

NORDIC STEEL 2019
The 14th Nordic Steel Construction Conference,
September 18–20, 2019, Copenhagen, Denmark

Prefabricated Composite Flooring Systems with Normal and Lightweight Concretes

I.M. Ahmed[a] and K.D. Tsavdaridis[b]*

[a] PhD Candidate, School of Civil Engineering, University of Leeds, UK
[b] Associate Professor of Structural Engineering, School of Civil Eng., University of Leeds, UK
**Corresponding Author and Presenter*: k.tsavdaridis@leeds.ac.uk

ABSTRACT

The use of lightweight concrete in structural applications for the sustainable design of composite slabs require the revision of today's flooring systems and the development of more efficient shear connectors. This paper studies a novel prefabricated and shallow steel-concrete composite flooring system which is consisted of two main structural components: two C-channel steel beams and a partially encased concrete floor. The concrete floor, which is in the form of T-ribbed slab sections, was constructed using three types of concrete (reinforced normal concrete, reinforced lightweight aggregate concrete, and reinforced ultra-lightweight aggregate concrete), and the steel edge beams which partially encase the floor slab and provide clear and straight finish edges. This paper includes the work of 2 full-scale push-out tests aimed at investigating the longitudinal shear behaviour of the new shear connection system (made of shear studs and steel dowels) when the normal concrete is replaced by lightweight and ultra-lightweight concrete.

Keywords: prefabricated slabs; flooring system; innovative shear connection; push-out test; lightweight aggregate concrete.

1 INTRODUCTION

Structures such as high-rise buildings benefit from prefabricated and lightweight shallow flooring systems since the weight and the number of erection (installation) lifts are significant factors. This led to the wide use of the hollow core precast floors and Cofradal floors. However, the span and width of these flooring systems with a depth of 250mm are up to 8.0m for Cofradal floor and 9.5m for hollow core precast units with a width of 1.2m (1,2). It has become clear that the industry is looking for increased spans with the lowest possible structural depth and weight of the flooring system to meet architectural and functional requirements as well as to reduce the number of columns and foundations leading to a lighter and more sustainable construction with reduced time and costs. For that reason, different types of flooring systems with the use of new lightweight materials have been recently developed (3-7).
This paper presents a series of push-out tests conducted for a new prefabricated and shallow steel-concrete composite flooring system, aka PUSS. It investigates the behaviour and properties of the shear transfer mechanism, which forms by steel dowel and web-welded shear studs.

2 NEW PREFABRICATED SHALLOW FLOORING SYSTEM

Conventional prefabricated lightweight shallow flooring systems can span up to 8m while hollow core precast units can span up to 9.5m (1, 2 & 4). PUSS, a recently developed fully Prefabricated Ultra-Shallow flooring System consists of T-ribbed slab sections constructed using reinforced lightweight aggregate concrete, and two C-channel steel edge beams which encapsulate the floor slab in the middle while providing clean and straight finish edges, as shown in *Fig. 1* (4-7).

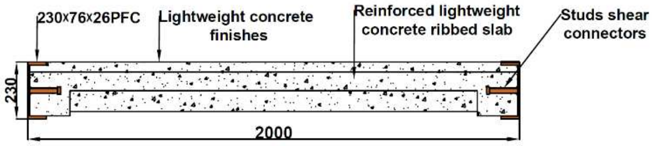

Fig. 1 : Schematic drawing of a cross-section of the new flooring system (4-7)

The floor slab width is 2m inclusive of the width of the steel edge with a finished depth of 230mm. The new flooring system is designed to span up to 11m with 230mm depth. The total weight of the floor is reduced by having voids running from one side to the other side of the T-ribbed slab. The proposed flooring system reduces the weight and the number of erection (installation) lifts by using lighter elements (lightweight concrete and steel members) and the wider possible units, as well as reduces the extent of site works by pre-off site fabrication by examining the material cost against the fabrication and site erection costs being proportionally in the order of 35% and 65%, respectively.
PUSS exercises the sustainability approach in the selection of its components using sustainable materials such as lightweight aggregate concrete (Lytag aggregate) and thin-walled steel sections. An analytical Life cycle Assessment (LCA) for the proposed flooring system was developed and compared with another prefabricated flooring system (4-7). From the study, it was found that the proposed flooring system reduces the embodied energy and embodied carbon by about 17.94 % and 9.33% respectively.
As the proposed flooring system is being cast in the shop, the steel dowels pass from one side to another side along the width of the flooring system and are connected to the steel beams. Such shear studs and steel dowels form a unique mechanism for transferring longitudinal shear forces along the flooring system. The aim of this research is to investigate the shear capacity and slip behaviour of this new shear transfer mechanism by conducting experimental push-out tests.

3 AIM AND OBJECTIVES

The aim is to investigate the performance of this unique shear transfer system (steel dowels and web-welded studs) with two types of concrete (normal and ultra-lightweight concrete).
The objectives of this research study are listed as follows:

- Design the specimens to fit a new type of push-out tests for steel-concrete prefabricated slabs;
- Design the push-out testing apparatus that can reflect the desired loading condition and is in compliance with the specifications of the Eurocode 4 (EN 1994-1-1:2004) (8);
- Analyse the characteristic behaviour of the shear connectors from the load-slip curves;
- Examine the test results to further propose a design approach for the shear behaviour.

4 EXPERIMENTAL WORK

Two push-out specimens were examined herein. All material and specimen tests are conducted in the Heavy Structures Laboratory of the University of Leeds.

4.1 Test specimen and measurement devices

A 230x75x26 PFC C-channel steel section was used. Two dowels (spanning across the width) and two shear studs (one on each channel) were welded to the beam webs, as shown in *Fig. 2*. Two types of concrete were examined herein: normal concrete and ultra-lightweight concrete.

Fig. 2: The steel section with the shear connectors (4)

One identical hydraulic jack was used to apply a load, with a capacity of 1000kN. Load levels were measured using a load cell. To measure the longitudinal slip, six dial gauges were placed on both sides of the slab near the position of the shear connectors. Two digital dial gauges were positioned on both sides of the slab measuring the separations in the horizontal direction, as depicted in *Fig. 3*.

Fig. 3: Set up and instrumentations of the push-out tests (4)

Prior to the tests, the specimens were bedded in using a steel plate, which resulted in even contact with the reaction plate. An incremental monotonic load was applied; the duration of the push-out tests was around 2 hours with a load rate of 0.5kN/sec, to satisfy with the requirement of not less than 15 minutes duration as specified in the Eurocode 4 (8). Brief descriptions, numbering, and dimensions of the specimens are summarized in *Table 1*.

Table 1. Brief descriptions and numbering of the specimens

Test group	Concrete type	Specimen No.	Slab width (mm)	Slab depth (mm)**	Total length of specimen (mm)
T1*	Normal (NC)	T1-NC	2000	230	1653
	Ultra-Lightweight (ULWC)	T1-ULWC	2000	230	1653

T1* dowels with web-welded stud shear connector

4.2 Casting the shallow flooring system

Two push-out test specimens were cast using Lafarge Blue Circle OPC CEM-I 42.5 N conforming to BS EN197: Part 1(9). Two types of materials were used in the present study: (1) normal weight concrete (NWC), (2) ultra-lightweight concrete (ULWC). NWC was manufactured from coarse aggregate (gravel), natural sand, Portland cement, and water. Coarse aggregates with a maximum size of 10mm and natural sand were used as fine aggregates, respectively. Densities for gravel and natural sand were 1600 and 1800kg/m^3, respectively. The density of the normal concrete was 2325kg/m^3

with a compressive strength of 30MPa at 28 days. The ULWC was produced by expanded clay coarse aggregates of size 8mm, expanded clay fine aggregates of size 4mm cement, and water with a 28-day compressive strength of about 16MPa. Twenty-four hours (±4 h) later, the specimens were de-moulded and left to air-cure in a storage room covered in sheeting for (30-60) days. The storage room's temperature was 19–23°C at 50–60% relative humidity. Vibrators were used to ensure that the concrete was well compacted.

4.3 Test procedure

After a preloading stage, the load was applied in steps at a low displacement rate. Concrete crack patterns were recorded throughout the tests. Initially, the beams were loaded with approximately 10kN and the dial gauges zeroed.
The tests were performed not only until the maximum load was reached, but also until a sufficient branch of the descending post-failure load-slip curve was recorded. The general test-procedure is summarised in the following four steps: (i) preloading, (ii) monotonic loading and (iii) unloading.

4.4 Load–slip relationships

The load-slip curves obtained from the push-out tests represent the characteristic behaviour of the shear connectors. Load-slip curves of specimens of each test group are shown in *Fig. 4*. The failure load of every shear connector has also been captured.

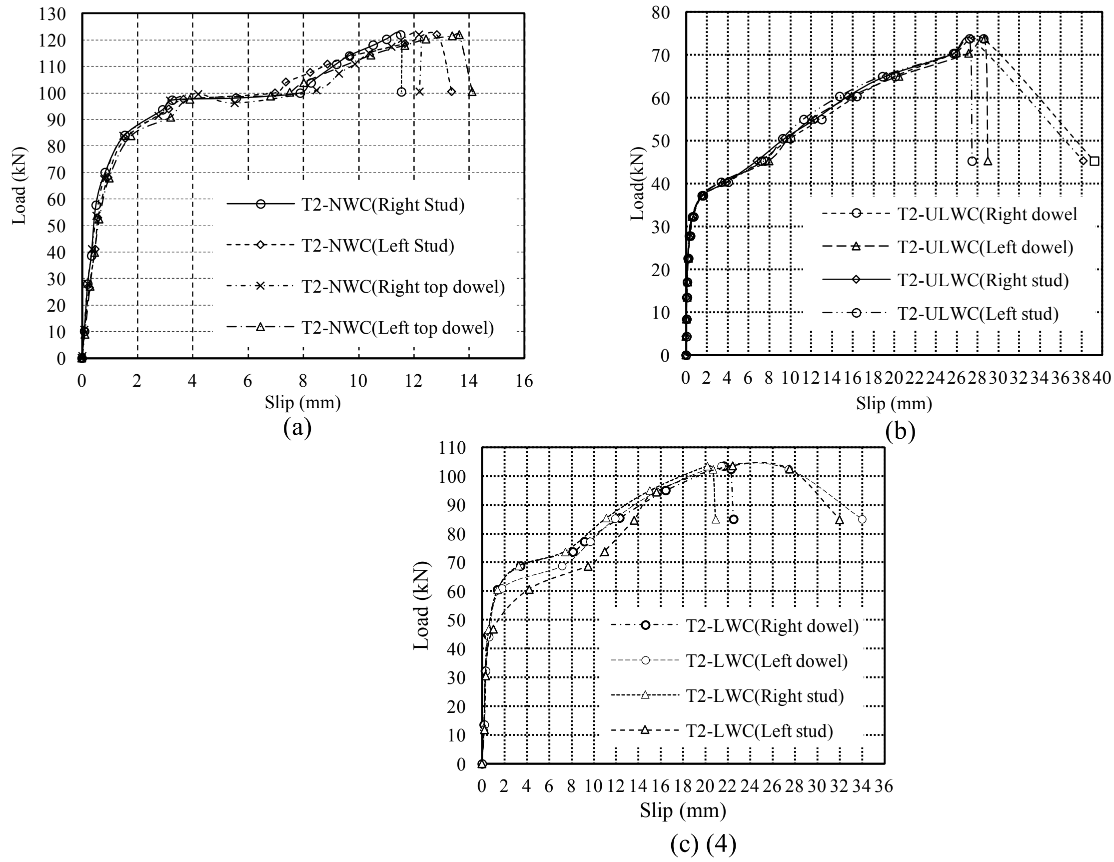

Fig. 4: Load-slip curves of (a) specimen T1-NWC, (b) specimen T1-ULWC and (c) specimen T1-LWC

A uniform behaviour of the steel dowels at both sides of the specimen was observed by the specimen T2-NWC. Up to the level of 65kN, which is the 53.3% of the ultimate load capacity of the shear connector, a linear behaviour was observed. At around 98kN, the plastic deformation of the shear connectors took place. The post-failure plastic deformation started at a load of 105kN while the dowels on the left-hand side of the specimen showed some post-failure strength with extensive slip.

This was due to resisting the vertical movement of the steel section by the steel dowels. The ultimate load capacity of the shear connector is 121.9kN.
For the specimen with ultra-lightweight concrete, up to the level of 32kN, which is the 43.3% of the ultimate load capacity of the shear connector, a linear behaviour was observed. The plastic deformation of the shear connectors started at load around 42kN. The post-failure plastic deformation started at a load of 50kN with large slips compared with the specimen T2-NWC.
The specimens with lightweight concrete, T2-LWC (4) & T2-ULWC, demonstrated additional ductility comparing with the specimen made of normal weight concrete, T2-NWC.

4.5 Results Evaluation

The properties of the shear connectors were evaluated from the results of the push-out tests, and are summarised in Table 3 and 4. The concrete strength of the specimens is listed in *Table 2*.

Table 2. Concrete strength of the specimens

Specimen No.	Compressive Strength (MPa)	Tensile Strength (MPa)
NWC	37.3	2.45
ULWC	20.0	1.38

- The ultimate shear capacity, P_u, of every shear connector was obtained by dividing the ultimate load of the specimen by the number of the shear connectors.
- The slip capacity of the shear connector, δ_u, was the slip value at the load level dropped by 10% below the ultimate load EC4 (8). Where the shear connectors have no plastic deformation after the maximum load is reached, the slip capacity is the slip value at the maximum load level.
- Characteristic slip capacity, δ_{uk}, is the slip capacity reduced by 10%. If it is greater than 6mm, the shear connector is classified as ductile (8). The load-slip curve of the shear connector should demonstrate plastic deformation after the maximum load is reached.
- The stiffness of the shear connector, K, was the linear stiffness of the load-slip curves.
- The criterion of tie-resistance check is that the transverse separations at 80% of the ultimate load should be less than half of the slip at that load level EC4 (8).

Table 3. Result evaluations of the shear connectors of the specimens

Specimen No.	Ultimate shear capacity, P_u, (kN)	Shear Connectors	Slip capacity, δ_u (mm)	Characteristic slip capacity, δuk, (mm)	Stiffness, K, (kN/mm)	Ductility classification (pass/fail)	Tie resistance check (pass/fail)
T1-NC	121.9	Right dowel	12.18	10.96	10.0	pass	pass
	121.9	Right stud	11.52	10.36	10.58	pass	pass
	121.9	Left dowel	13.64	12.27	8.93	pass	fail
	121.9	Left stud	12.83	11.55	9.50	pass	fail
T1-ULWC	73.83	Right dowel	31.90	28.71	2.31	pass	pass
	73.83	Right stud	30.70	27.63	2.40	pass	pass
	73.83	Left dowel	29.00	26.10	2.54	pass	pass
	73.83	Left stud	27.30	24.57	2.70	pass	pass

The results of test group T1 showed that the shear-resisting capacity of the shear connector increased with the increase of the concrete strength. The failure load of the specimen with higher strength of concrete (T1-NWC) was higher than that of the specimen with lower strength of concrete (T1-ULWC), respectively. This comparison was based on the same type of shear connectors.
The slip of the dowels and shear studs were significant at the ultimate load, between 11-13mm for T1-NWC specimen, and between 27-32mm of T1-ULWC specimen. However, the slip stiffness of the dowels and shear studs among the two specimens was somewhat different. It was demonstrated

that the slip stiffness was influenced by the concrete strength. The separations at the ultimate loads were 5mm for T1-NWC specimen and 8.25mm for T1-ULWC specimen, respectively.

4.6 Failure mechanism

The failure of T2-NWC specimen was near the top dowels' position around the rib in both sides at approximately 600kN. The cracks continued towards the position of the dowel connectors in the vicinity of the ribs. Then the concrete near the studs' position started cracking at approximately 620kN. These cracks continued towards the position of the shear studs. Then the concrete near the bottom dowels' position started cracking at a load of approximately 640kN. The cracking noise was initially heard at the end of the elastic deformations and it was then intensified during the plastic deformations. A sudden "bang" failure took place at the end of the test, as the top and bottom dowels and the shear stud on the left-hand side were sheared off, as shown in *Fig. 5*.
The failure of T1-ULWC specimen started with concrete cracking near the top dowels' position in the vicinity of the rib in both sides at approximately 261kN. These cracks continued towards the position of the shear studs. Then the concrete near the bottom dowels' position started cracking at approximately 300kN. The cracking noise was initially heard at the end of the elastic deformations, and it was then intensified during the plastic deformations. A sudden "bang" took place at the end of the test, as the top and bottom dowels and the shear stud on the left-hand side were sheared off, as shown in *Fig. 6*.

Fig. 5: Failure profile of concrete of specimen T1-NWC (4)

Fig. 6: Failure profile of concrete of specimen T1-ULWC

5 SUMMARY

The shear transferring mechanism of a novel prefabricated shallow steel-concrete composite flooring system, PUSS, is examined in this paper. The components of the proposed flooring system were selected according to a comparative LCA study with another prefabricated flooring system (5-7). The study demonstrated a reduction in the embodied energy and embodied carbon by about 17.94% and 9.33% respectively when compared with the Cofradal slab. Two full-scale push-out tests were carried out to study the shear connectors in terms of the shear capacity and slip behaviour.
The test results are assessed and the following conclusions can be reached:
(1) Consistent behaviour is demonstrated by the new shear connection system with plastic deformations occurring before and after the ultimate load.
(2) Both dowels and web-welded shear studs demonstrated a ductile behaviour.
(3) The shear capacity of the connectors increases with the increasing of concrete strength.
(4) The steel dowels (mainly) together with the web-welded shear studs connection system increase the shear resistance and the slip capacity of the shear connection.

Acknowledgments

The authors would like to acknowledge Lytag for their kind contribution in providing the material for the conduction of the full experimental campaign.

REFERENCES

1. Precast Concrete Flooring, BISON Precast Ltd., August 2007.

2. ArcelorMittal Construction Benelux: Arval COFRADAL200®.

3. Yan, J.B., Liew, J.R., Sohel, K.M.A. and Zhang, M.H. 2014. Push-out tests on J-hook connectors in steel–concrete–steel sandwich structure. Materials and Structures, 47(10), pp. 1693-1714.

4. Ahmed, I., Tsavdaridis, K.D. and Neysari, F. 2018. Push-Out Shear Tests for a Novel Pre-fabricated Shallow Steel-Concrete Composite Flooring System. The 12th International Conference on Advances in Steel-Concrete Composite Structures (ASCCS 2018). 27-29 June 2018, Valencia, Spain.

5. Ahmed, I., Tsavdaridis, K. and Neysari, F. 2017. A New breed of sustainable ultra-lightweight and ultra-shallow steel-concrete composite flooring system: life cycle assessment of materials. CESARE'17 International Conference of Coordinating Engineering for Sustainability and Resilience, Dead Sea, Jordan 3-8 May 2017.

6. Ahmed, I. and Tsavdaridis K.D. 2017. A New Breed of Sustainable Ultra-lightweight and Ultra-Shallow Steel-Concrete Composite Flooring System: LCA. In: Proceedings. Postgraduate Research Conference, Faculty of Engineering, 30-31 Mar 2017, Leeds, UK. The University of Leeds.

7. Ahmed, I.M. and Tsavdaridis, K.D. 2018. Life Cycle Assessment (LCA) and Cost (LCC) Studies of Lightweight Composite Flooring Systems. Journal of Building Engineering, 20, pp.624-633.

8. EN 1994-1-1: Eurocode 4: Design of composite steel and concrete structures, part 1-1: general rules and rules for buildings. European Committee for Standardization: 2004.

9. BS EN197: Part 1: 2000. Cement. Composition, specifications and conformity criteria for common cements. BSI; 2000.