FLEXURAL BEHAVIOUR OF PREFABRICATED ULTRA-SHALLOW COMPOSITE (PUSS®) SLABS WITH HORIZONTALLY ORIENTED SHEAR CONNECTORS

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1. ABSTRACT

This paper presents the experimental results of flexural tests on a recently developed steel-concrete composite flooring system. The flooring system is composed from prefabricated ultra-shallow slab units (aka PUSS) that consist of T-ribbed concrete floors partially encased within and connected to two C-channel steel edge beams with novel horizontally oriented shear connections. The results of two static four-point bending tests are presented in this experimental study. This study investigates the effects of replacing normal weight concrete with lightweight concrete on the flexural behaviour of PUSS and performance of the shear connections under bending. The two 4m span test specimens are constructed using two types of concrete, which are reinforced normal weight concrete (NWC) and reinforced lightweight aggregates concrete (LWC). Both specimens implement the unique shear connection system composed of horizontally oriented steel dowels with horizontally oriented web-welded shears studs (dowels with WWSS). The failure mechanism of the slabs and the contribution of the concrete type and the shear connection system to the flexural behaviour of PUSS units are examined. The study concludes that replacing NWC with LWC with similar strength does not affect the flexural behaviour of PUSS in terms of slabs capacity, ductility and failure mechanism. However, LWC provides lower initial stiffness and results in larger size of cracks with increasing loads in comparison to NWC.

2. INTRODUCTION

Over the previous decades, Steel-Concrete Composite (SCC) structural elements had a huge contribution to the development of the construction industry since they helped in using materials efficiently and reducing construction cost, which made SCC a central subject for research.

Composite flooring is one of the SCC structural elements that had remarkable evolution over time and participated in rising the quality of flooring systems and comfortability as well as construction methods. With SCC floorings, it became possible to reach faster construction, have larger uninterrupted floor areas, and integrate floors thickness within the depth of the composite beams which led to reducing the overall depth of floors and accordingly reducing the height of the buildings. Therefore, such kind of systems became widespread in the construction sector. The current trend is towards the development of longer spans and lighter flooring systems (using shallower sections and lighter materials). Therefore, various slim floor systems have been developed, such as Slimfor, Slimdek, composite slim-floor beams (CoSFB) and ultra-shallow floor beams (USFB) [1-4].

3. PREFABRICATED ULTRA-SHALLOW SLABS (PUSS®)

Prefabricated ultra-shallow slab (PUSS®) is a recently developed SCC flooring system that was first introduced in 2017 and it is the subject of research in this paper.
The standard PUSS units have a width of 2m and a 230mm depth. PUSS is composed of ribbed reinforced concrete slab encased within two parallel flange C-channel steel beams and connected to them with one of three novel shear connection systems, either (1) horizontally oriented web welded shear studs (WWSS), (2) horizontal steel dowels welded to the webs, or (3) a combination of both shear connection systems (WWSS with dowels) [5]. Fig. 1 presents a detailed schematic drawing of a typical section of a PUSS unit with second shear connection system (WWSS with dowels).

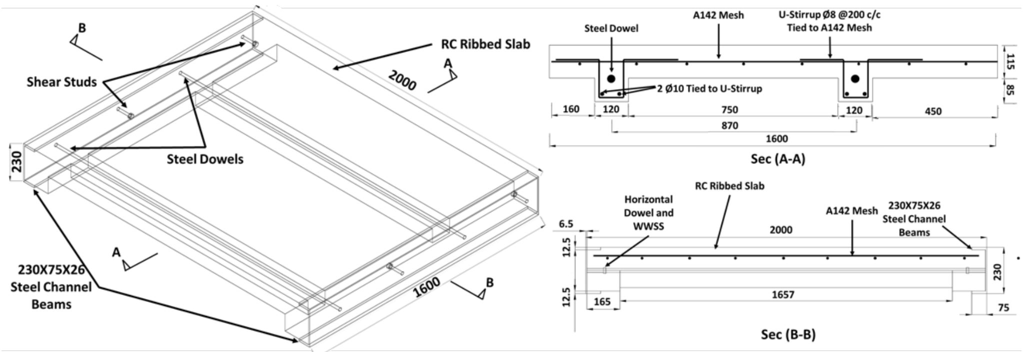

Fig. 1: Schematic Drawing of Typical 1.6m Segment of a PUSS Flooring Unit with Steel Dowel and WWSS Shear Connection System [6]

Previous research on this flooring system demonstrated potential in developing high strength sustainable lightweight slim floors. One of its main advantages is its light weight, because of its shape (regular voids running between concrete ribs) as well as the use of lightweight concretes. Cumulatively, this leads to wholly lighter weight buildings with less material consumption. The voids underneath the ribbed slab are beneficial for the passage of building services and placing fittings or acoustic insulation materials to the ceilings especially when combined with the use of perforated beams (where PUSS units sit on). As a result, lower height buildings or more floors can be constructed within the same height can be achieved [5]. On another aspect, previously conducted Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) studies showed many advantages of PUSS in comparison to the widely used hollow core precast (HCU) and the Cofradal slabs. These studies indicated that the use PUSS causes a substantial reduction in energy consumption, Global Warming Potential (GWP), cost and time in comparison to the other two

aforementioned prefabricated slabs. One significant reason for these results is the fact that PUSS is prefabricated offsite in a well-controlled worksite which reduces the errors and materials waste. In addition, the wider 2m units and the use of lightweight materials reduces the number of lifts required for slab installation, and that decreases the overall construction time, transportation cost and energy consumption [7].
The behaviour of shear connection systems implemented in PUSS was examined under direct shear force by performing experimental push-out tests as well as carrying out FEA parametric studies. Two shear connection systems were under investigation, which are the WWSS system and the steel dowels with WWSS system, with three different concrete types; namely normal weight concrete (NWC), lightweight aggregate concrete (with Lytag aggregates) (LWC), and ultra-lightweight aggregate concrete (with Leca aggregates) (ULWC) [8]. The analysis of the results of the experimental work and FEA parametric study produced a formula for calculating the shear resistance of the shear connection systems (Eq. 1) [8].

$$P_{sd} = 1.873(f_{ck} d a_r)^{0.835} \leq 0.8 f_u A_s \quad (1)$$

Where:
P_{sd} : shear resistance of shear stud or dowel
f_{ck} : cylinder compressive strength of concrete
d : diameter of stud or dowel
a_r : distance from first stud or dowel to top of concrete
f_u : ultimate tensile strength of the material of the stud or dowel which should not be greater than 500N/mm^2
A_s : cross-sectional area of the shear connector

4. OBJECTIVES AND SCOPE OF THE STUDY

The objective of this experimental work is to investigate the flexural behaviour of PUSS units with two types of concrete (normal and lightweight concrete) and the shear transfer mechanism of the unique shear connectors system composed of dowels with WWSS under bending. This study includes:

- Designing 4-point bending test rig that reflects the anticipated loading conditions in accordance with the specifications of Eurocode 4 (BS EN 1994-1-1, 2004) [9] and to fit the available space in the Heavy Structures Laboratory (George Earle Laboratory) at the University of Leeds, UK.
- Designing test specimens to fit in the testing apparatus.
- Analysing the flexural behaviour of PUSS units and the performance of the shear connectors from the load-deflection curves, strains in steel sections and concrete, cracks development and end-slip curves.
- Examining the test results to study the effects of changing concrete type and to propose further parameters to be included in future tests and FEA parametric study.

5. EXPERIMENTAL WORK

5.1. Test Specimens

Test specimens were initially designed to represent the actual sizes of the slabs in the construction practice which are designed to be of 2m wide (a fixed dimension that takes into consideration the transportation means in British cities). Lab space restrictions led to reducing both the dimensions of test specimens. The redesigned specimens are kept within practical real life structures dimensions with 1.1m width and 4.4m length (4m clear span). Two 230x75x26 PFC C-channel steel section are used as edge beams of each specimen. Shear connection system is composed of three steel dowels of Ø20mm (spanning across the width) welded to the web posts of each beam at 3 of the concrete slabs rib locations. In addition, two shear studs of Ø16mm are welded horizontally to the web posts of each beam at the remaining two rib locations, as shown in Fig. 2. Two types of concretes are examined, normal concrete and lightweight concrete with Lytag aggregates. The dimensions and differences between the test specimens are presented in Table 1. Eq. 1 was used to determine the size and number of shear connectors required to achieve full shear connection in the composite slabs.

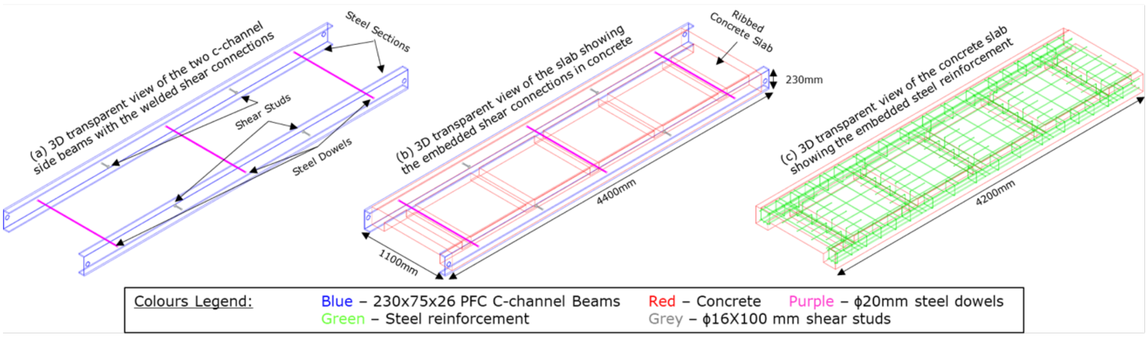

Fig. 2: 3D View of the Details of Test Specimens

Name	Concrete Type	Size (WxDxL)	Steel Beam	Shear Connectors
NWC-230-SD	NWC	1.1m x 230mm x 4.4m (span 4m)	230x75x26 PFC	3 x 20mm Ø Steel Dowels with 4 x 16mm Ø WWSS
LWC-230-SD	LWC with Lytag			

Table 1: Specimen Test Matrix

5.2. Specimens Preparation

The shuttering and formwork fabrication for concrete ribbed slabs and steelwork (steel reinforcements bending and welding shear connectors) were carried out by SC4 ltd. (a steel fabrication company in the UK). In addition, 50mm diameter holes were drilled at the two ends of the side steel beams to provide lifting points for the slabs.

Fig. 3: (a), (b) Prepared Specimen before Casting Concrete (c) Casted Specimen

Ready-mix concretes conforming to BS EN197: Part 1 [10] were casted at the worksite of SC4 and vibrators were used to ensure proper compaction (Fig. 3). Concrete class for both NWC and LWC was 20/25, with a maximum aggregate size of 14mm and around 110mm slump. Tests on the concrete cubes and cylinders samples showed that the density of NWC was 2230kg/m^3 with a compressive strength of 22.4MPa on the test day. LWC on the other hand (which was manufactured using Lytag lightweight aggregates) had a density of 1560kg/m^3 and a compressive strength of 21.6MPa on the test day. Slabs were kept at the worksite for 30-50 days for curing in an average temperature of about 15°C before moving them to the University of Leeds to attach strain gauges and testing.

5.3. Test Setup and Loading Protocol

The four-point bending tests are carried out in accordance with the specifications of Eurocode 4 (BS EN 1994-1-1, 2004) [9]. Test specimens are simply supported near the two ends of their lengths with an overhang of 100mm at both ends (200mm included extended steel beams). Two equal concentrated line loads are applied 1m apart symmetrically on the middle part of the specimens using a hydraulic jack and spreader beams. Loading apparatus are attached to reaction frame as shown in Fig. 4.

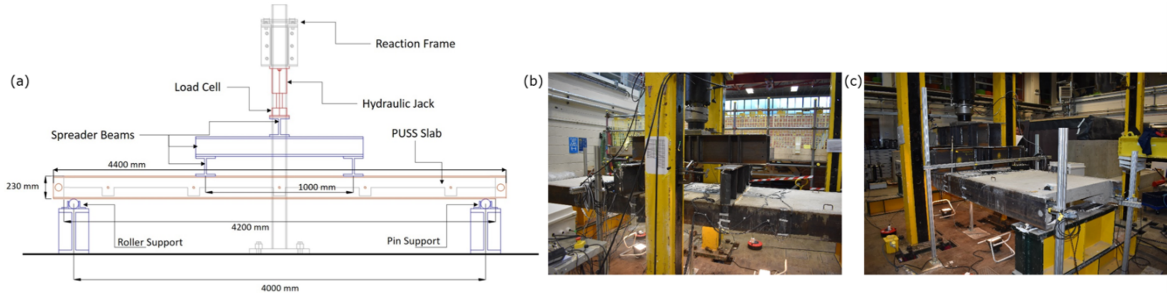

Fig. 4: (a) Side View Sketch of the Test Setup for 4m Span PUSS (b) & (c) Test Setup

The static monotonic loading starts by applying three preloading incremental loading cycles in the elastic region before the specimens are tested up to the maximum expansion of the hydraulic jack as presented in Table 2. To evaluate the flexural behaviour in the post-elastic range properly, the 4-point bending tests are displacement controlled, with sufficiently small displacement rate (1mm/minute) to capture every damage in the specimen and to avoid dynamic impacts. Each test takes at least 3 hours to conduct.

Loading Cycles	***Aimed Displacement***	***Displacement (mm)***
1st Cycle	0.5 x SLS Max allowed deflection	≈ 4mm
2nd Cycle	1 x SLS Max allowed deflection	≈ 8mm
3rd Cycle	1.5 x SLS Max allowed deflection	≈ 12mm
Final Push	Maximum expansion of the hydraulic jack	≈ 170mm
*Maximum allowable SLS deflection = span/360 =4000/360 = 11.1mm		

Table 2: Loading Cycles

5.4. Instrumentation

A reaction frame of capacity higher than 1000kN (100ton) is used for the tests with 1000kN hydraulic jack to apply the load (Fig. 4). To monitor the development of cracks with the load/ deflection increments, a total of 8 cameras are placed around the test setup to capture the cracks propagation. In addition, each specimen is calibrated to measure the strain, displacement and end-slip at various locations. The general instrumentation layout for the test setup is shown in Fig. 5. Each specimen has a total of twenty-three 5mm strain gauges, seven 60mm strain gauges, four 5mm Rosettes strain gauges and ten LVDTs placed over it. The instruments are linked to a data logger machine which is connected to a computer to record all the readings at different load levels.

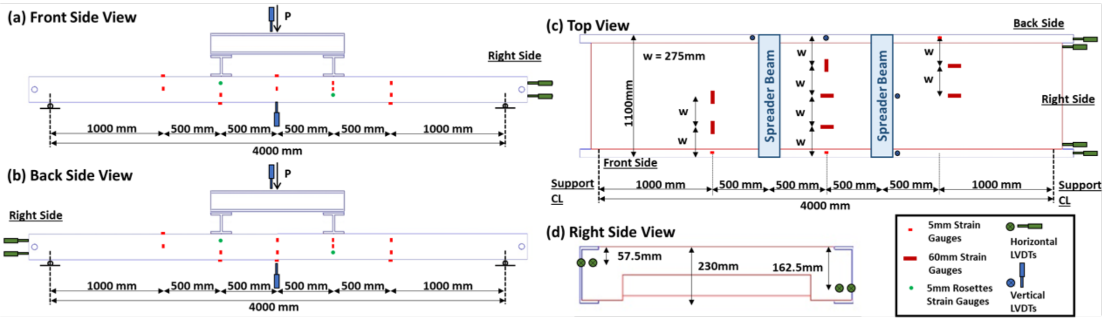

Fig. 5: Strain Gauges, Rosettes Strain Gauges and LVDTs Layout

6. RESULTS EVALUATION

A summary of the results obtained from two 4-point bending tests on PUSS units is presented herein.

6.1. Maximum Moment vs. Mid-span Deflection

Tests are terminated when the actuator reached its maximum expansion. At this stage, in both tests, load reaches plateau and continuing the tests would not get further load increment. At the end of the tests, no total collapse is reached but several of the measured strains in steel exceed yielding and long deep cracks are observed in concrete's bottom surface. In all cases, the mid-span deflection exceeds 180mm (about L/22), which is significantly higher than the serviceability limit and specimens are considered to have failed in all practical purposes. Fig. 6 shows the relation between maximum moments in slabs (applied Load x 1.5/2) and mid-span deflection and Table 3 compares the load values of both specimens at different stages during the tests.

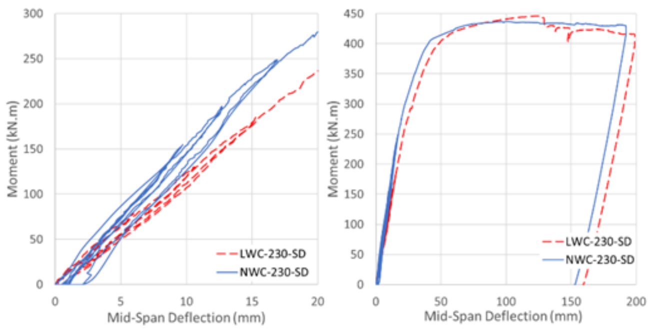

Fig. 6: Relationship between Moment and Mid-Span Deflections

Overall, both specimens show similar behaviour during the tests. However, taking a closer look to the first 3 loading cycles and the moment deflection curves in elastic region, as predicted, the LWC specimen appears to be less stiff due to lower modulus of elasticity of LWC in comparison to NWC. After that, they behave in an identical manner during the early stage of plateau until larger cracks start to appear in the LWC specimen and thus loses part of its strength at around 125mm of deflection. It is noted from the diagram that the LWC specimen reached a bit higher load capacity compared to the NWC specimen before it loses part of its strength, and this is expected since both concretes have almost equal strength, but the LWC is lighter which reduces the dead load of the slab and allows it to gain more live load (test load). Finally, comparing the maximum moment reached in both tests to the calculated maximum moment capacity using block stress method (Table 3) demonstrates that each specimen reaches about 6-10% higher than the expected capacity. This can be due to some uneven material/ strength distribution in the specimen which is not counted for in the calculation. Nevertheless, this also indicates that block stress method is slightly conservative in predicting the moment capacities of PUSS units.

Hydraulic Jack Opening (mm)	NWC-230-SD	LWC-230-SD
4mm 1st Loading Cycle: Load (kN)	119.4	77.7
8mm 2nd Loading Cycle: Load (kN)	216.5	130.3
12mm 3rd Loading Cycle: Load (kN)	296.5	196.7
20mm: Load (kN)	414.0	315.0
40mm: Load (kN)	551.0	495.0
Maximum Load (kN)	582.9	594.9
Moment at Maximum Load, i.e. Moment Capacity (kN.m)	437.2	446.2
Expected Maximum Moment Capacity (Calculated using block stress method) (kN.m)	409.3	408.7

Table 3: Comparison of Load values at Specific Stages of the tests

6.2. Strain in Steel Sections

Fig. 7 (a) & (b) display the strains measured in steel sections at the top and bottom flanges as well as the web at multiple distances from the mid-span and during different stages of the tests. Strains are presented from the stage of mid-elastic region, the beginning of the plateau, and in the mid-plateau for each specimen. Strain gauges are placed at multiple spots with some being at symmetric locations, hence, some of the readings presented in the figure are the averaged from more than one reading. Since it was not possible to place strain gauges below the load spreader beams directly, the strains at the top flange at loading points are estimated by assuming that strains vary linearly through the section. It is observed that both steel sections have similar strain development during the tests.

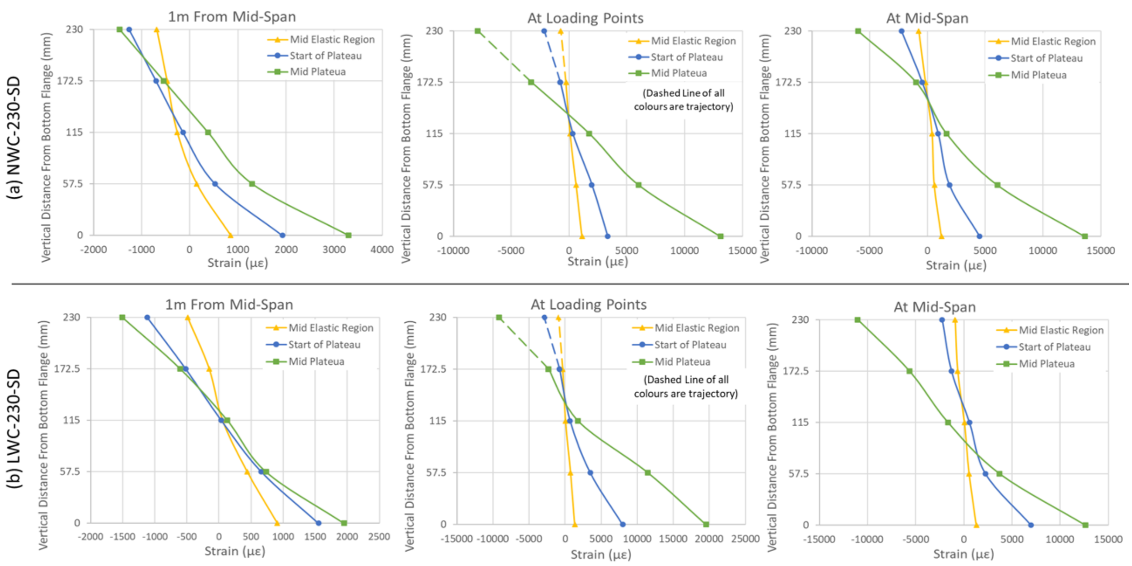

Fig. 7: Strains Measured in Steel Section at Different Locations Stages of Tests

By having a look at the graphs for strains measured at 1m from mid-span (0.5m away from loading points), it can be derived that yielding (about 2100 με) is not reached at any point on the section up to reaching mid-plateau with the exception that in NWC specimen this strain is exceeded in the bottom flange at the end of the test. On the other hand, at the loading points, the flanges begin yielding before reaching the plateau with higher strain readings recorded in LWC specimen. Afterwards, strains significantly increase in the plateau region, leaving substantial local bending in the section after the end of the test. Finally, it can be noticed that at mid-span, measured strains are close to those recorded at loading points in both tests. This is mainly due to the constant moment between the two loading points.

6.3. Cracks Development and Failure Mechanism

At around 350kN load some initial horizontal line cracks started to appear at the bottom surface of the concrete directly below the loading points. With load increasing, these cracks start to widen and grow gradually in length and depth. Also, similar cracks started to appear in the region around the previously developed cracks, but they are all mainly horizontal ones. Fig. 8 (a) & (b) captures the cracks below the loading points at the end of both tests. The horizontal cracks at the end of the two tests indicate flexural failure of the specimens without signs of shear failure. However, the larger and wider spread of cracks in the LWC specimen explain the sudden drop of its capacity at around the mid-plateau stage as previously discussed. The larger development of cracks in the LWC specimen is expected due to its lower stiffness in comparison to the NWC specimen, however the fact that they have similar strength resulted in reaching similar load capacities.

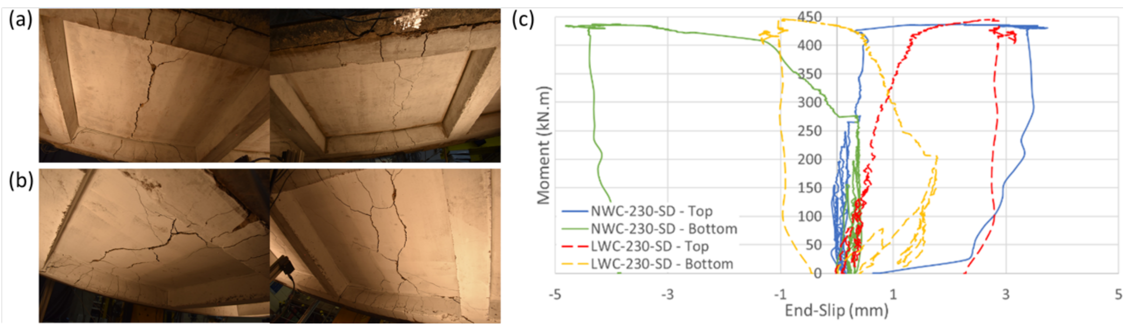

Fig. 8: (a) Horizontal Cracks at the end of the Test below Loading Points in NWC-230-SD and (b) in LWC-230-SD. (c) Relationship between Moment and End-Slip

6.4. End-Slip

Fig. 8 (c) captures the relationship between moment and end-slip between concrete and steel sections at top and bottom flanges of each of the test specimens. In both cases, the end-slips are less than 1mm during the elastic region loading phase of the test, and then they increase rapidly during the plateau phase. However, the maximum end-slip at each location is between 3 to 5mm which is lower than the 6mm value specified by Eurocode 4 [9] for ductile shear connector behaviour. This illustrates a brittle behaviour of the shear connectors in bending despite the fact that the applied shear connection system was tested to be ductile under direct shear tests [7]. In addition, this demonstrates that the PUSS steel-concrete composite shear connection system allows it to behave as a single rigid body under bending, especially if full shear connection is provided alike in the tested specimens. Because of that, none of the connectors failed in shear during the test, if that was the case, additional slippage would be measured and more ductility could be gained.

7. CONCLUDING REMARKS

This paper presented the initial results of a group of flexural tests on PUSS. From the results, the following points are concluded:

- In general, LWC and NWC specimens perform similarly in bending and can reach similar capacities if similar concrete strengths are used. However, the lower stiffness of lightweight concrete, results in larger cracks and some loss of strength during tests.
- The use of lightweight concrete reduces the initial stiffness of PUSS in bending but can also achieve a bit higher load capacities in comparison to normal weight concrete due to its lighter weight which reduces the dead load on slabs.
- The slabs behave in a brittle manner, achieving end-slips less than 6mm at deflections exceeding span/22 due to the use of more shear connectors than the required to reach full shear connection, which makes the whole composite system to behave as a single rigid body and this proves the effectiveness of the novel shear connection system.
- Test loading procedure with the dimensions of the test specimens resulted in flexural failure of the slabs. However, changing some of the test parameters (such as reducing span or increasing slab's depth) might change the failure mechanism.

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ΚΑΜΜΠΤΙΚΗ ΣΥΜΠΕΡΙΦΟΡΑ ΠΡΟΚΑΤΑΣΚΕΥΑΣΜΕΝΩΝ ΣΥΜΜΙΚΤΩΝ ΠΛΑΚΩΝ (PUSS®) ΠΟΛΥ ΜΙΚΡΟΥ ΠΑΧΟΥΣ ΜΕ ΟΡΙΖΟΝΤΙΑ ΠΡΟΣΑΝΑΤΟΛΙΣΜΕΝΟΥΣ ΔΙΑΤΜΗΤΙΚΟΥΣ ΣΥΝΔΕΣΜΟΥΣ

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ΣΥΝΟΨΗ

Αυτή η εργασία παρουσιάζει τα πειραματικά αποτελέσματα δοκιμών κάμψης σε ένα πρόσφατα αναπτυγμένο σύστημα σύμμικτης πλάκας από χάλυβα και σκυρόδεμα. Το νέο σύστημα (που ονομάζεται PUSS) αποτελείται από προκατασκευασμένες πλάκες σκυροδέματος με ραβδώσεις μερικώς εγκιβωτισμένες και συνδεδεμένες με δύο δοκούς από χάλυβα τύπου C. Η σύνδεση έγινε με νέες οριζόντια προσανατολισμένους διατμητικούς συνδέσμους. Τα αποτελέσματα δύο πειραματικών δοκιμών κάμψης παρουσιάζονται σε αυτήν την πειραματική μελέτη. Αυτή η μελέτη διερευνά συγκεκριμένα τις επιπτώσεις της αντικατάστασης σκυροδέματος κανονικού βάρους με ελαφρό σκυρόδεμα στην καμπτική συμπεριφορά του PUSS και στην απόδοση των νέων διατμητικών συνδέσεων υπό κάμψη. Τα δύο δοκίμια ανοίγματος 4 μέτρων κατασκευάστηκαν με χρήση δύο τύπων σκυροδέματος, το οπλισμένο σκυρόδεμα κανονικού βάρους (NWC) και το οπλισμένο ελαφρύ σκυρόδεμα (LWC). Και τα δύο δείγματα εφαρμόζουν το νέο σύστημα σύνδεσης διάτμησης που αποτελείται από οριζόντια προσανατολισμένους χαλύβδινους πείρους με οριζόντια προσανατολισμένους συγκολλημένους διατμητικούς συνδέσμους. Εξετάζεται ο μηχανισμός αστοχίας των πλακών και η συμβολή του τύπου σκυροδέματος όπως και του συστήματος διατμητικής σύνδεσης στην καμπτική συμπεριφορά των πλακών PUSS. Η μελέτη καταλήγει στο συμπέρασμα ότι η αντικατάσταση του NWC με LWC με παρόμοια αντοχή δεν επηρεάζει την καμπτική συμπεριφορά της πλάκας PUSS όσον αφορά την αντοχή των πλακών, την ολκιμότητα και τον μηχανισμό αστοχίας. Ωστόσο, το LWC παρέχει χαμηλότερη αρχική δυσκαμψία και οδηγεί σε μεγαλύτερο αριθμό ρωγμών σε σύγκριση με το NWC.