Horizontal shear strength of fiber-reinforced composite deck slabs tested in the weak direction

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Abstract— In this research, six large-scale composited metal deck (CMD) slabs were constructed and tested in a cantilever diaphragm configuration to assess the viability of using discreet macro fibers as an alternative secondary reinforcement. Two common commercial steel deck types, Holorib and Ribdeck AL, with a reentrant and trapezoidal profile; respectively, were used in this study. Three types of secondary reinforcements were considered: (1) Conventional welded wire mesh of sizes A142 and A98; (2) synthetic macro-fibers at the dosages of 3 kg/m³ and 5.3 kg/m³; and (3) hooked-end steel fibers with a dosage of 15 kg/m³. All the slabs were tested in the weak configuration, a condition that practically exists between steel decks and primary steel beams. Test results showed that although fibers and WWM are theoretically used in CMDs to control cracks associated with shrinkage and temperature changes, they actually have a considerable effect on enhancing the horizontal shear capacity. Results indicated that when discreet synthetic macro fibers are used at the dosage of 5.35 kg/m³, an enhancement in the slab's horizontal shear capacity of up to 49% was achieved, suggesting that when the suitable dosage is used, discreet fibers can be a feasible secondary reinforcement for composite deck slabs.

Keywords— steel decking, composite slab, fiber-reinforced concrete, diaphragms, horizontal shear

I.   Introduction

In today's construction industry, the use of profiled steel sheeting together with a concrete infill has obtained a widespread acceptance. The advantage of the profiled steel sheet is twofold as it acts as a permanent formwork for the fresh concrete, and a tensile reinforcement once the hardened concrete. A welded wire fabric mesh (WWM) is usually used in CMDs to control shrinkage and temperature cracks and has theoretically no flexural role. Thus, for the last few decades, the flexural behavior of CMDs has been the main focus of research [1-4]. However, modern construction trends (supported by design guidelines such as ANSI/SDI C-2011 that permit the use of steel fiber as an alternative reinforcement for temperature and shrinkage in composite deck slabs [5]), made the use of fibers as secondary reinforcement in composite deck slabs a new acceptable practice.

Recent investigations on fiber-reinforced concrete (FRC) have demonstrated the ability of discrete fibers to enhance its residual strength, toughness, and ductility, which makes FRC an attractive material for a range of applications such as slabs on grade, tunnel lining, and composite decking [6,7].

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Tantamount, previous investigations on the flexural behavior of CMDs have proved the adequacy of fiber as an alternative secondary reinforcement to the traditional WWM [8, 9]. However, there are raising concerns among structural engineers over the horizontal shear capacity of CMDs when the traditional WWM is replaced with fibers.

The review of relevant literature reveals that the major factors affecting the horizontal shear capacity of CMDs include the profile and gauge of the deck; the orientation of deck corrugations; the strength and arrangement of shear connectors; the concrete topping; and the secondary reinforcement system.

Luttrell [10] investigated the effect of concrete topping on the diaphragm capacity of CMDs using trapezoidal steel profile with lightweight concrete topping and welded connections. He derived expressions correlating diaphragm strength to the number of diaphragm edge welds. Similarly, Davis and Fisher [11] carried out large-scale tests on CMDs using trapezoidal and reentrant decking profiles to established formulas for diaphragm capacity based on assumptions regarding the force distribution on the fastener pattern.

Easterling and Porter [12] tested 32 full-scale composite diaphragms and formulated analytical models to predict diaphragm capacity. However, since no secondary reinforcements were used, test results showed that at the post-peak phase, all diaphragms exhibited brittle inelastic behavior with increasing in-plane displacement. The effect of secondary reinforcement on horizontal shear strength of composite deck slabs has rarely been investigated. The present study is aimed to shed the light on the horizontal shear behavior of fiber-reinforced CMDs through an experimental program where the horizontal shear performance of fibrous composite deck slabs are compared to that of composite deck slabs reinforced with conventional WWM.

II.   Experimental Program

A.   Test Rig

A test rig was exclusively designed for this research and is shown in Fig. 1. It consists of a slab support and a reaction frame. The slab support consists of a reaction beam that provides the fixed-end condition of the cantilever diaphragm and rollers that support the free-end of the diaphragm and allow for free in-plane movement. The reaction beam is a built-up steel beam with its bottom flanges attached to the rigid floor of the laboratory. The reaction frame consists of a main built-up steel column to which a 500 kN actuator is attached. Three lateral braces were attached to the main column to enhance its lateral stability.
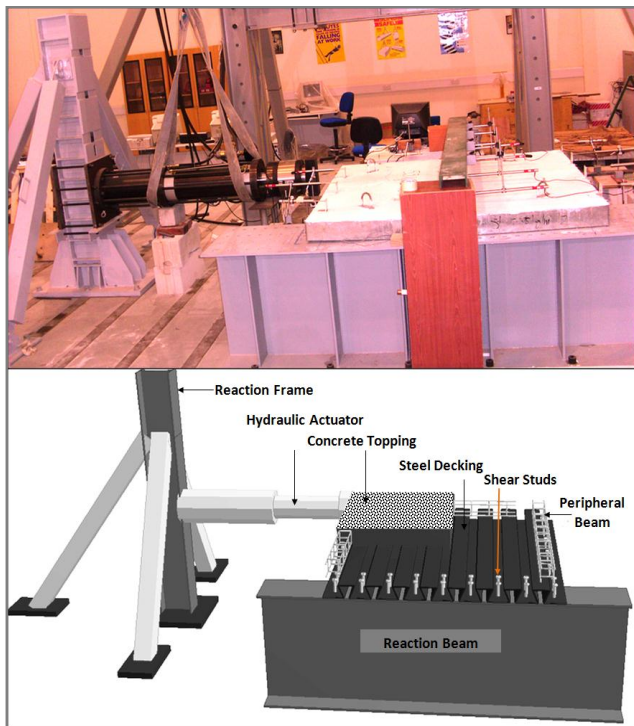
EN 10147-S350 GD+Z275-N-A-C, namely hot-dip galvanized, with minimum yield strength of 350 MPa [13].

5) Shear Connectors

This project used headed stud shear connectors with yield strength of 580 MPa, compliant with the requirements of BS EN ISO 898 [14].

C. Concrete Mixture

Four concrete mixes with targeted compressive strength of 40 MPa were used. The mixture properties are provided in Table 1. The maximum aggregate size used was 20 mm. The coarse aggregate used had a specific gravity of 3.10. The fine aggregates consist of natural washed sand and crushed stones with specific gravities of 2.62 and 2.50, respectively. The mix designs were adjusted in order to accommodate the addition of fibers by limiting the coarse to fine aggregate ratio to 55% of the total volume of aggregates as per ACI guidelines [15]. The concrete mixes were supplied from the ready mix plant in batches, and for each concrete batch, cube samples were prepared and tested according to BS 1881-101 and BS 1881-116, respectively [16,17].

TABLE I.   MIXTURE PROPORTIONS AND AVERAGE PROPERTIES OF CONCRETE

Material (kg/m³)	Concrete Mix Number			
	1	**2**	**3**	**4**
Cement OPC	380	380	380	380
20 mm Aggregate	630	630	630	630
10 mm Aggregate	440	440	440	440
Fine Aggregate	880	880	880	880
Free water, L	196	200	200	200
Super plasticizer, L	0.50	1.50	1.50	1.50
Water Cement Ratio	0.52	0.53	0.53	0.53
Coarse To Fine Aggregate Ratio (by Volume)	0.54	0.54	0.54	0.54
Synthetic Fiber	-	3.0	5.3	-
Steel Fiber	-	-	-	15.0
Average Cube Compressive Strength, MPa	46.8	41.9	45.8	43.6

Figure 1. Test Rig

B. Material Properties

1) Synthetic Fibers

The main components of the synthetic macro fiber used in this project are polypropylene and polyethylene (Fig. 2(a)). The fiber has geometry and mechanical properties that enhance dispersibility in the concrete mix. It is rectangular in shape with a nominal length of 40 mm; an average width of 1.4 mm; an average thickness of 0.105 mm; and an aspect ratio of 90. The fiber has a tensile strength of 620 MPa and a modulus of elasticity of 9.5 GPa.

2) Steel Fibers

The steel fiber used in this project consists of cold drawn wires with hooked ends (Fig. 2(b)). The wires are lumped in bundles by an adhesive that dissolves during the mixing process and ensures an easy mixing and homogeneous distribution. The fiber is 60 mm long, 0.9 mm in diameter and has an aspect ratio of 65. It has a tensile strength of 1000 MPa and a modulus of elasticity of 200 GPa.

3) Weld Wire Mesh (WWM)

Two common sizes of WWM (Fig. 2(c)) made of S500 steel (yield strength of 500 MPa) were used: A98 and A142 with steel bar diameter of 4 mm and 6 mm, respectively, and steel area in each direction equivalent to 98 mm²/m and 142 mm²/m, respectively.

4) Steel Decking

Two steel decking profiles were considered in this study: 1) a reentrant profile with a depth of 51 mm and a rib spacing of 150 mm, and 2) a trapezoidal profile with a depth of 60mm and a rib spacing of 300 mm (Fig. 3). The steel sheets are manufactured from a material meeting the specifications of BS
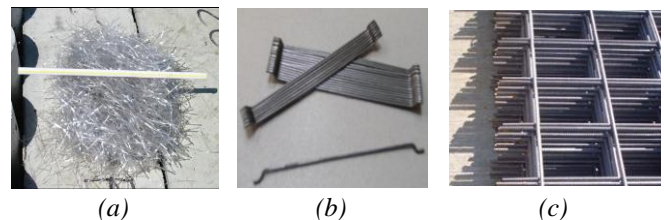

Figure 2. Secondary reinforcements: a) Synthetic fibers, b) Steel fibers, and c) WWF mesh

Figure 3. Decking profiles: a) Reentrant, b) Trapezoidal

D. *Test Specimens*

Six composite deck slabs with a cantilever diaphragm configuration were constructed and tested under in-plane monotonic load to failure. All slabs were 1800 mm x 1800 mm x 125 mm. Four slabs were constructed with a reentrant steel decking profile and two with a trapezoidal profile (Fig. 3). The slabs were attached to the reaction beam through two rows of 16 mm diameter shear connectors embedded into the concrete slab and bolted to the flange of the reaction beam. All slabs were tested in the weak direction which is defined as when the decking corrugations span parallel to the main beam. A small peripheral reinforced strip was used at the free edges of the slab to provide rigidity to the diaphragm, to circumvent local failure at the point of load application, and to force failure to occur within the slab (Fig. 4a). The effects of fibers (synthetic and steel) as well as that of the deck orientation were examined. All slabs were tested in the weak direction. The assortment of different reinforcement systems used for the different slabs is presented in Table 2.

E. *Instrumentation and Testing*

Test specimens were instrumented with embedded and external strain gages to monitor the strain in the concrete and in the steel deck at different stages of loading. Three embedment gages were placed at equal spacing along the diagonal of the specimen at the slab mid-height, and one gage was attached off-diagonal at a location where a potential flexural crack could occur (Fig. 4(b)). Also, surface mounted gages were attached in pairs but at different levels. The first was attached at the surface of the steel deck at the interface between the concrete topping and the steel deck, while the second was attached at the top surface of the concrete slab as shown (Fig. 4(b)).

A total of 12 linear variable differential transformers (LVDTs) were used to record the in-plane deformation of the slab: Four of them were placed at the slab corners, and eight were mounted at equal spacing along the slab edges and center lines. A data acquisition system was used to collect the strain and deformation data during all the stages of testing. The slabs were tested in displacement control mode with a displacement rate of 0.02mm/sec. The ultimate load carried by each slab, the load versus in-plane deflection response, and the load-strain response were recorded and used to evaluate the effect of different secondary reinforcement systems on the horizontal shear capacity of composite deck slabs.
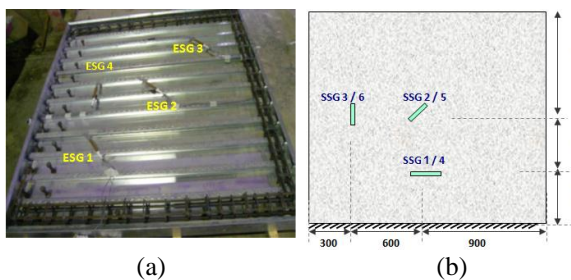

(a)   (b)

Figure 4. Arrangement of strain gages:
a) Embedded strain gages, b) Surface-mounted strain gages (SSG)

III. *Results and Discussions*

A. *Load-deflection results*

The load deflection response of slabs with reentrant profile is depicted in Fig. 5. Due to the slight variation in the concrete compressive strength between the different slabs, test results including the ultimate load were normalized to the concrete compressive strength for the control (unreinforced) specimen using a normalization factor proportional to the square root of the compressive strength. The load deflection curves illustrate that the control slab exhibited the lowest ultimate in-plane shear capacity (144 kN) followed by a substantial drop in the load carrying capacity and a rapid degradation in the post-peak strength. The slab reinforced with A142 mesh showed slightly improved ultimate and post-peak strengths relative to the control slab, but it also experienced some degradation in the post-peak load carrying capacity.

On the other hand, the slabs reinforced with synthetic macro-fibers (5.3 kg/m^3 and 3.0 kg/m^3) exhibited greater ultimate load and sustained the ultimate load for a wider range of deformation relative to the control slab. Additionally, they exhibited a smooth and stable post-peak behavior and thus showed superior performance to that with the conventional WWM in terms of strength and ductility.
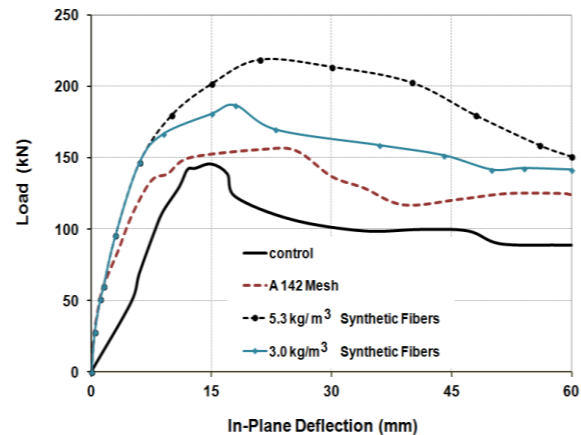

Figure 5. Load-deflection response for slabs with reentrant profile
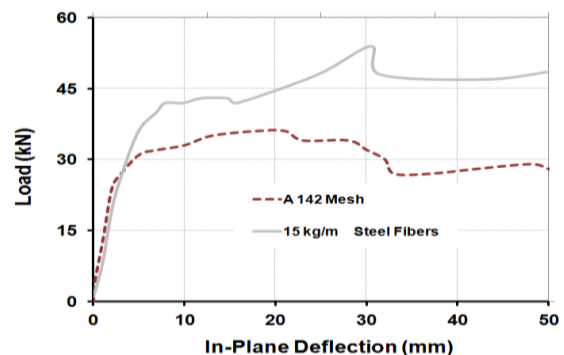

Figure 6. Load-deflection response for slabs with reentrant profile

The above results and observations are further confirmed by the load-deflection response of slabs with trapezoidal profile (Fig.6), although they exhibited much less diaphragm capacity compared to their counterparts with reentrant profile. Both slabs tested in the weak configuration (A 142 steel mesh and 15 kg/m^3 steel fibers) failed trough the formation of cracks at the thin concrete section above the deck flute, the reason for which the ultimate load reached is very low (36 kN, 55 kN). However, it can be seen that the fiber-reinforced specimen exhibited not only higher ultimate load, but also gradual strength degradation in the post peak phase.

B. *Ultimate In-plane Shear Capacity*

The load-deflection results presented in the previous section show that fibers and WWM (specifically when high dosages of fibers or large mesh sizes are used) can impart significant improvement to the ductility of the slabs relative to the control specimen. Furthermore, the ultimate horizontal shear capacity of the slab has been improved as reflected in the maximum sustained load. Table 2 presents the maximum horizontal shear sustained by the slabs as well as the percentage increase in the ultimate capacity of the slabs relative to the control specimen.

The results for slabs with trapezoidal profile show that the addition of A142 mesh and that of 3.0 kg/m^3 and 5.3 kg/m^3 of synthetic macro-fibers increased the ultimate in-plane strength of the diaphragm slab by 9 %, 38%, and 49%, respectively, suggesting that the tested synthetic macro fibers can provide significant horizontal shear resistance to composite deck slabs. This also reveals the viability of fibers an alternative secondary reinforcement in composite deck slabs.

TABLE II.   PERCENTAGE INCREASE IN ULTIMATE IN-PLANE SHEAR RELATIVE TO THE CONTROL SPECIMEN

Test	Label	Secondary Reinforcement	Concrete Mix	Normalized Ultimate Load	Increase in Ultimate Load (%)
1	C-R	Control	Mix 1	148	-
2	M_{142}–R	A142 mesh	Mix 1	161	9
3	$SN_{3.0}$–R	3.0 kg/m^3 Synthetic fibers	Mix 2	205	38
4	$SN_{5.3}$–R	5.3 kg/m^3 Synthetic fibers	Mix 3	221	49
5	M_{142}–T	A142 mesh	Mix 1	36	-
6	DR_{15}–T	15 kg/m^3 of Steel Fibers	Mix 4	55	-

C. *Load-strain responses*

The strain data were primarily used to explain the cracking pattern and to point out the difference in behavior between the different slabs. The effect of fibers on enhancing the horizontal shear capacity relative to the control specimen was significant and can be explained from the strain data measured by gages 2 and 3 depicted in Fig. 7(a) and Fig. 7(b), respectively. The load-strain results of Fig. 7(a) show that gage 2 measured relatively low tensile strain in the control

slab (up to a load level of around 20 kN), after which the gage did not measure further tensile strain until failure, which indicates that the control slab lost its integrity at a very small load level. Likewise, the tensile strain measured by gage 3 (Fig. 7(b)) for the control slab was also very minimal which also supports the results obtained from gage 2. On the contrary, gages 2 and 3 continued to capture tangible tensile strain in the slab with synthetic macro-fibers at the dosage rates of 5.3 kg/m^3 and 3.0 kg/m^3, until load levels as high as 170 kN and 230 kN, respectively were reached. These results suggest that synthetic macro-fibers have improved the integrity of the slabs.

D. *Cracking and Failure Mode*

Cracking pattern and sequence were carefully monitored and mapped during testing (Fig.8). Test Observations showed that slabs failed by developing horizontal shear cracks at the thin concrete section above the flute, but the severity of cracks at were dependent on the type of reinforcement used. The control slab (Fig. 8 (a)) was characterized by a single crack which subsequently widened up as the peak load was approached, and in the post-peak the control slab exhibited a rapid degradation associated with widening and propagation of the crack. Conversely, the FRC slabs and the slab with WWM developed multiple shear cracks before failure (Fig. 8 (b) and Fig. 8 (c)), with the occurrence of multiple cracking being a major factor in delaying the failure and increasing the load-carrying capacity and ductility. Moreover, the cracking pattern shows that fibers reduced splitting around the shear studs along the fixed edge of the diaphragm. This may be attributed to the fact that fibers improved the confinement stress around the studs and thus reduced splitting. This allowed for an effective transfer of load from the shear connectors to the reaction beam and consequently enhanced the overall performance and integrity of the diaphragm.
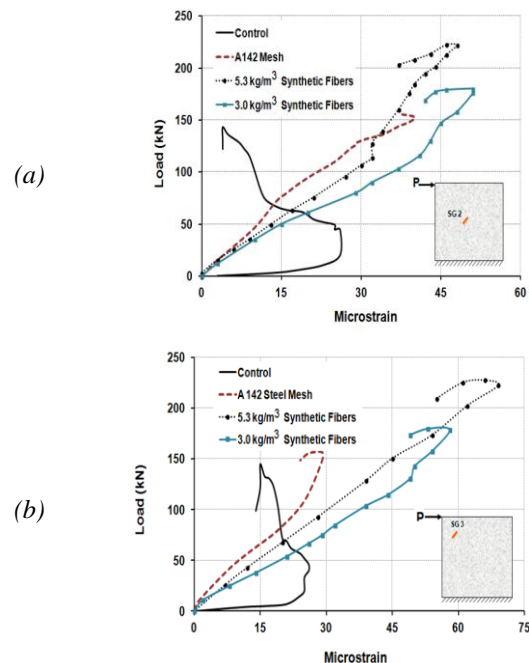

(a)

(b)

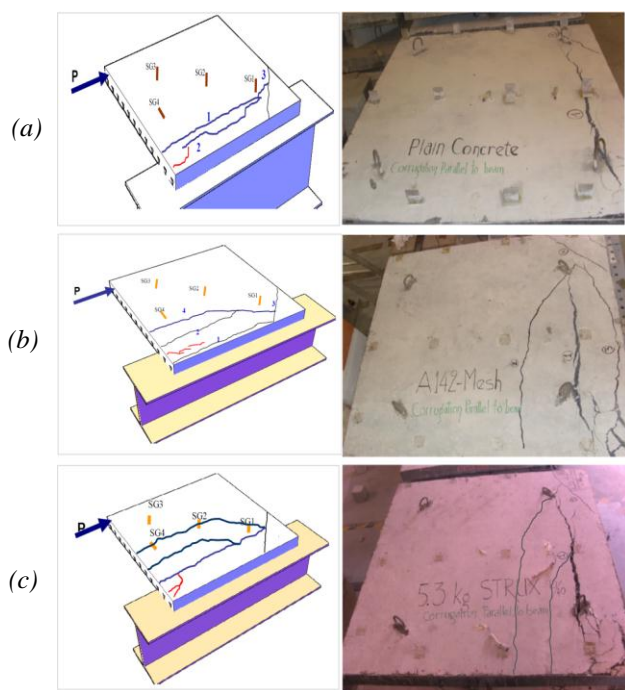*Figure 7. Strain data: a) gage 1, and b) gage 2*

Figure 8.Cracking pattern for: a) Control, b) $M_{142}-R$, c) $SN_{5.3}-R$

E. *Summary* and Conclusions

Six large-scale composite deck slabs were instrumented and tested in a cantilever diaphragm configuration under monotonic loading to investigate the horizontal shear behavior of FRC composite deck slabs. The effect of the type and quantity of the secondary reinforcement on the horizontal shear behavior of composite deck slabs when tested in the weak orientation was investigated. The secondary reinforcement tested in this study consists of: Conventional steel mesh (A142 and A98); synthetic macro fibers (dosages of 3.0 kg/m^3 and 5.3 kg/m^3 and hooked-end steel fibers with a dosage of 15.0 kg/m^3. Load-deflection responses and strains were measured and the cracking pattern was reported. All slabs exhibited the formation of cracks at the thin section above the flute deck where concrete section is minimal. The load deflection results showed that the addition of fibers and steel mesh increased the ultimate in-plane shear capacity and ductility of the slabs relative to the control. Results showed that the use of A 142 mesh resulted in 9% increase in the ultimate horizontal shear capacity while the additions of 3.0 kg/m^3 and 5.3 kg/m^3 of synthetic fibers increased the ultimate horizontal shear capacity of the slabs by 38%, 49%, respectively. Additionally, the slabs with steel mesh or fibers exhibited multiple shear cracking that contributed to the improved ductility and post-peak behavior of these slabs compared to the control slab which failed in a less ductile manner with a single and wide crack. In summary, the results of the load-defection response, the strain measurements, the ultimate shear capacity, and the cracking and failure mode all indicate the viability fibers as secondary reinforcement in composite slabs and that fibers impart significant enhancement to the in-plane shear capacity and ductility of composite deck

slabs comparable to that obtained using the traditional WWF mesh.

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