Investigations on mechanically fastened FRP-strengthened concrete slabs

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ABSTRACT: This investigation studies the feasibility of using the mechanically fastened (MF) FRP system for strengthening two-way concrete slabs in flexure. The slabs are simply supported on all four sides and measure 2600 x 2600 x 120 mm. Different strengthening patterns are used with different spacings between fasteners. Also, the conventional bonded strengthening technique is used for the sake of comparison. The mechanically fastened system is found to be a valid alternative to the bonded system resulting in a rapid, economic, and effective system. The gained increase in the ultimate capacities of MF FRP-strengthened slabs range between 30 to 70% over that of the unstrengthened specimen. In addition, finite element models are presented for MF FRP-strengthened concrete slabs. The numerical predictions are compared with experimental data, and very good agreement is obtained.

1 INTRODUCTION

A new strengthening technique has recently been introduced based on mechanically fastening (MF) FRP strips to the concrete, without any bonding, by means of closely spaced powder actuated fasteners. This technique utilizes off-the-shelf tools to attach pultruded FRP strips to the concrete. This technique has many advantages such as a rapid installation using simple hand tools; no special labor skills are needed, and no surface preparation is required (Bank, 2004). With this technique, the attached FRP strips must have a high bearing strength as well as high longitudinal strength. The commonly used fasteners in this technique are embedded into the concrete using a powder actuated fastening gun. Initial surface cracking and concrete spalling usually occurs during the fastener driving (Lamanna et al., 2004a). To overcome these problems, another fastener type is introduced in this study. The installation of this fastener is based on screwing into the concrete instead of shooting.

A few researchers have examined the feasibility of this technique for the external strengthening of reinforced concrete beams. Beams strengthened with this technique have been tested, and the results compared with those when the conventional bonding method was used. In one of these investigations it was observed that the gain in strength for the MF technique was 70% of that gained from the conventionally bonded counterpart (Lamanna et al. 2001). In another investigation, it was concluded that, using the MF method, it was possible to achieve a failure mode similar to that of a standard reinforced concrete beam (Lamanna et al. 2004a; Galati et al. 2007). Also, it was found that using this strengthening technique can increase the load capacity by up to 60% (Bank et al. 2003). When using this technique on T-beams, it was found that strip separation was the primary failure mode for all the beams after they had experienced very high deformations (Lamanna et al. 2004b). In addition, several case studies were also performed to address the analysis, design, installation, and testing for old deficient bridges. The MF-FRP system has thus proved to be an advantageous solution for the strengthening of major damaged areas of bridges (Borowicz et al. 2004; Lopez et al. 2005; Rizzo et al. 2005).

This study introduces a new application of using the MF technique for the flexural strengthening of two-way concrete slabs. Different FRP configurations are considered and different spacings between fasteners are examined. Also, a comparison is reported between the MF system and the bonded system. In addition, numerical implementations have been conducted to model the response of the MF FRP-strengthened slabs. The comparisons between the numerical predictions and the test results show very good agreement in terms of the ultimate carrying capacities, failure modes, and load–deflection relationships.

2 EXPERIMENTAL PROGRAM

2.1 *Materials*

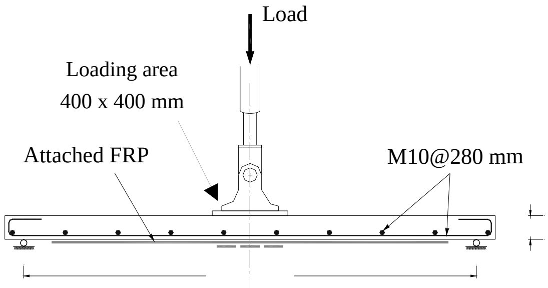
The concrete mix was designed for an average target cylinder compressive strength of 35 MPa after 28 days. The average actual cylinder compressive strengths for the tested slabs are given in Table 1. Normal deformed bars, of size M10 (Grade 400), were used for all of the reinforcing steel in the slab constructions. The average yield strength and modulus of elasticity were 325.4 MPa and 255.9 GPa, respectively. A special hybrid (carbon and glass) FRP composite (SAF-STRIP®) was used in this investigation. This type of FRP product is characterized by its high bearing strength as well as high tensile strength. The average modulus of elasticity and tensile strength were found to be 71.72 GPa and 1002.4 MPa, respectively. A screwed fastener was used in this study to fix the FRPs to the concrete. The screwed fasteners had a 37 mm shank length and a 4.76 mm shank diameter; 16 mm neoprene backed washers were used with each fastener.

2.2 *Test specimens and test setup*

Five full-scale reinforced concrete slabs were tested to assess the performance of using the MF FRP composite as an external strengthening technique (Elsayed 2008). The slab dimensions were 2600 x 2600 x 120 mm simply supported on all four sides with a span length of 2400 mm. The slabs were subjected to central loading, as shown in Fig. 1, and designed to fail in flexure. Special precautions were taken to prevent the up-lift movement of the slab corners by a set of steel plates and rods fixing the slab to the supporting frame at each corner. One layer of steel reinforcement was used in tension with a reinforcement ratio of 0.47%. One slab was left unstrengthened to serve as a control and another slab was strengthened with the bonded FRP system. The MF system was used to strengthen the remaining slabs. Two different schemes were used for the strengthening. For both schemes, six FRP strips were used with dimensions of 2000 x 100 x 3.2 mm. The different configurations of the strengthening schemes are summarized in Table 1. For the MF system, holes were predrilled to a depth of 45 mm inside the concrete with a diameter of 3.97 mm, as recommended by the manufacturer. Afterwards, the fasteners were screwed inside the concrete. For the bonded system, the concrete surface was first ground and blasted. A two-component epoxy paste adhesive (Sikadur 30) was used. The tensile strength and modulus of elasticity of the adhesive were 24.8 MPa and 4.5 GPa, respectively.

Table 1. Slab configurations

Designation	$f_c^{'}$ MPa	Strengthening technique	Strengthening scheme	No. of fasteners	Fastener spacing (mm)	FRP strip spacing (mm)
SW-Ctrl	37.3	n/a	n/a	n/a	n/a	n/a
SW-F-MS-100	39.8	mechanically fastened	middle strips	105	100	100
SW-F-MS-50	41.4			240	50	100
SW-F-SS-50	42.2		separated strips	240	50	500
SW-B-MS	46.3	bonded	middle strips	n/a	n/a	100



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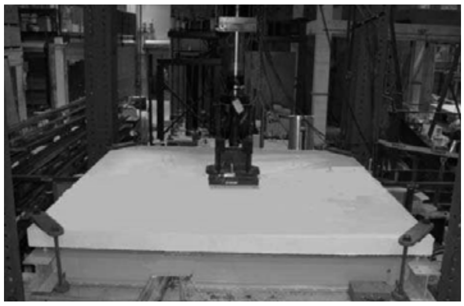


(b)

Figure 1. (a) Principal sketch of the tested specimen, (b) Test setup

3 TEST RESULTS AND DISCUSSION

Load versus deflection curves for the tested specimens are plotted in Fig. 2(a). The deflection was measured at the center point underneath the slab. Table 2 summarizes the cracking, yielding, and ultimate load capacities along with the observed modes of failure.

The control specimen, SW-Ctrl, was tested to obtain the capacity of the unstrengthened slab and also to obtain a basis for comparison with the strengthened specimens. The SW-Ctrl slab yielded at 86.6 kN and failed at an ultimate load of 135.6 kN. A 56% increase in the post-yield stiffness of the control slab is attributed to strain hardening of the steel reinforcement and progressive continuous movement of the neutral axis. The first cracks initiated at the center of the slab and propagated diagonally towards the corners at a load of 54.5 kN. The pattern of the tensile cracks eventually formed a pattern of yield lines, which resembled what is generally referred to as a yield fan pattern. The failure was identified by a leveling-off of the load–deflection curve, after sufficient yield cracks had formed, to cause flexural collapse.

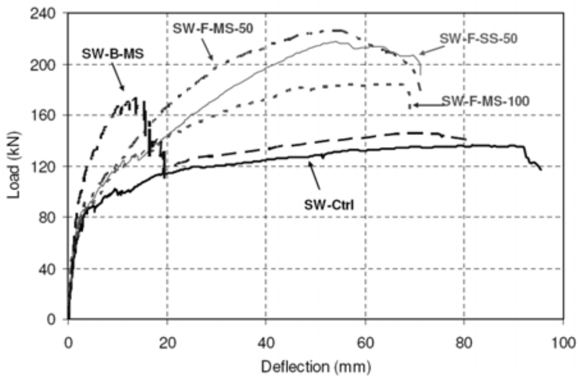
For the bonded FRP-strengthened slab, the behavior of this specimen was very stiff compared to that of the control specimen. This specimen showed an increase of 28% in the load capacity over the control specimen. The failure was initiated by sudden debonding of the FRP strips off the concrete and a subsequent dramatic drop in the load capacity. The debonding initiated at the mid-span and then propagated rapidly towards the FRP plate end.

For the Specimen SW-F-MS-100, the cracking behavior was very similar to that of the control specimen. The yield and ultimate load were 92.0 kN and 184.3 kN, respectively. The strengthened slab showed an increase of 6% in the yield strength and 35.9% in the ultimate capacity over the control slab. In addition to the improved capacity, the specimen SW-F-MS-100 showed a significant ductile behavior.

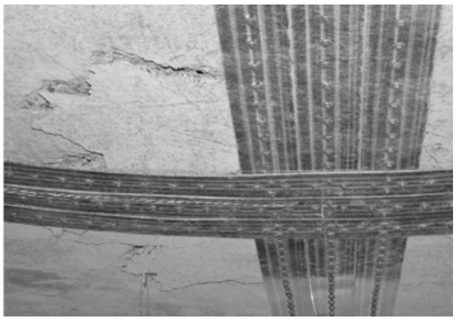
For Specimen SW-F-MS-50, remarkably, compared to Specimen SW-F-MS-100, the increase of load capacity was almost double that of the control specimen, as can be seen in Fig. 2(a). The yield strength increase was 30.9% while the ultimate strength increase was 66.9% over the corresponding values of the control specimen. At the end of the test, the FRP strips and the fasteners were still well-fastened to the concrete, as shown in Fig. 2(b).

Another strengthening scheme was used for Specimen SW-F-SS-50. The general behavior and the ultimate failure mode of specimens SW-F-MS-50 and SW-F-SS-50 were very similar; however, the specimen SW-F-SS-50 exhibited a slightly less stiffness and ultimate load capacity, as shown in Fig. 2(a). This may be attributed to the strengthening scheme where the FRPs, unlike the case of the slab SW-F-MS-50, were distributed away from the maximum moment and crack concentration region. The ultimate strength increased by 60.5% over that of SW-Ctrl.

In general, The MF-FRP strengthened specimens exhibited a lower stiffness than the bonded specimens due to the fact that the MF system, unlike the bonded system, allows for relative displacement to take place between the FRP strip and the concrete surface.



(a)



(b)

Figure 2. (a) Load–deflection relationships, (b) Specimen SW-F-MS-50 after test.

Table 2. Test results for the slab specimens.

Specimen	Crack load (kN)	Yield load (kN)	Max. load (kN)	% increase in capacity	Failure mode
SW-Ctrl	54.5	86.6	135.6	n/a	Flexural failure
SW-F-MS-100	58.0	92.0	184.3	35.9	
SW-F-MS-50	48.3	113.4	226.3	66.9	
SW-F-SS-50	55.8	109.1	217.7	60.5	
SW-B-MS	65.0	124.2	173.6	28.0	FRP debonding

4 NUMERICAL ANALYSIS

4.1 *Material models for concrete, steel and FRP*

The numerical analysis is carried out using the finite element software package ADINA (2004a). A hypoelastic model is used to describe the nonlinear stress–strain relationship for the concrete (ADINA, 2004b). A compressive uniaxial nonlinear relationship is used until the maximum concrete characteristic strength $f_c^{'}$ is reached, beyond which the behavior softens until concrete crushing occurs. The ultimate uniaxial compressive stress, σ_u, is taken as $0.85 f_c^{'}$ and the ultimate uniaxial compressive strain, ε_u, is taken as 0.0035. Poisson's ratio for the concrete, ν, is taken as 0.18. The smeared crack approach is employed to describe the behavior of the cracked concrete. The steel reinforcement is modeled as a bilinear elastic-plastic material. The FRPs are simulated as orthotropic linear elastic materials until failure. Based on the experimental tests, the Young's modulus of the shell element was taken as 71.7 GPa and 7.3 GPa in the longitudinal and in the transverse directions, respectively.

4.2 *FRP/concrete interface*

In this study special emphasis was taken to properly account for the FRP/concrete interface. Based on the experimental responses obtained by Elsayed (2008), an analytical model was established to describe the MF FRP/concrete interface, as shown in Fig. 3(a). This model is referred to as a bearing–slip model. In this model, the mechanical behavior of the FRP/concrete interface is modeled as a relationship between the local bearing stress in the FRP, σ, and the relative displacement, *S*, between the FRP strip and the concrete. More details can be found in Elsayed (2008).

4.3 *Geometrical modeling*

The 3D finite element mesh used for the FRP-strengthened slabs is depicted in Fig. 3(b). To represent the concrete, 8-node 3D brick elements are used with three degrees of freedom at each node. The steel reinforcement is modeled using two-node truss elements with three translational degrees of freedom at each node. Four-node thin shell elements with three degrees of freedom at each node are used for the FRP laminates. Truss elements are employed to represent the FRP/concrete interface. Each element has two nodes, each with three degrees of freedom. A stress–strain relationship for the response of the truss elements in the horizontal directions was developed based on the interface model described above (Elsayed 2008).

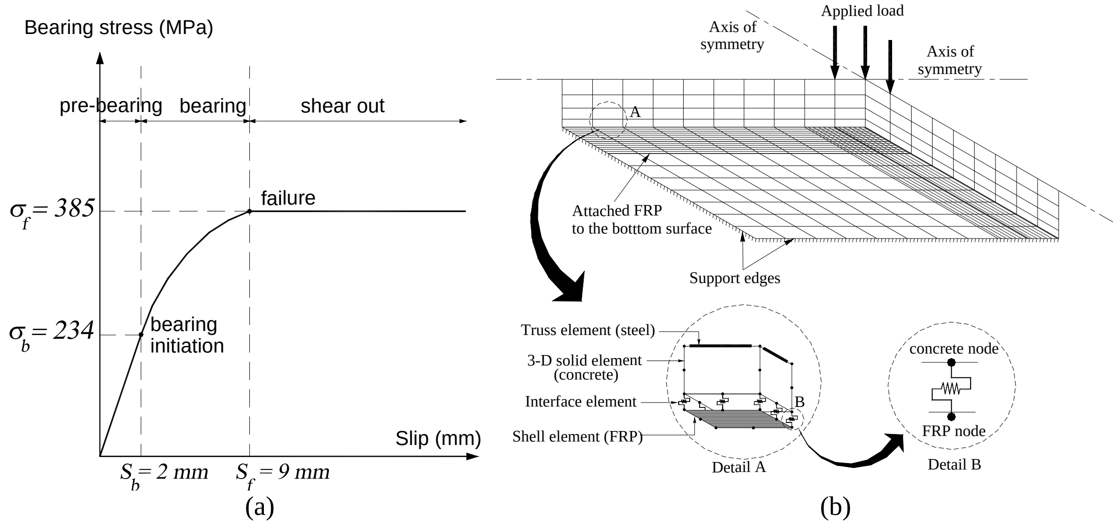


Figure 3. (a) Bearing–slip model, (b) Geometrical model.

4.4 *Numerical results*

Numerical predictions are now compared to the experimental data for the MF FRP-strengthened slabs. Comparisons are presented in terms of load–deflection relationships and modes of failure. In Table 3, the predicted maximum load capacities and the corresponding deflections are summarized. The comparison shows a reasonably good agreement between the numerical predictions and test results. The average accuracy (numerical-to-experimental ultimate load ratios) and corresponding standard deviation are 1.043 and 0.1, respectively. The main difference between the observed behavior and the numerical analysis is found in the post-yield stage and at the beginning of the nonlinear behavior. This difference is believed to be a consequence of the boundary conditions and the inability of the model to properly account for the crack propagation. Figure 4 shows the predicted and the experimental load–deflection curves for representative specimens SW-Ctrl and SW-F-MS-100.

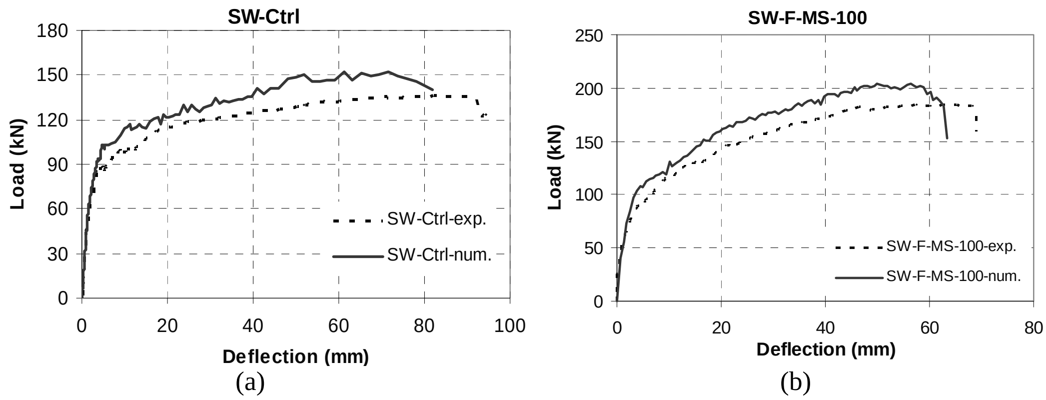


Figure 4. Comparison between numerical and experimental load–deflection relationship for (a) Specimen SW-Ctrl and (b) Specimen SW-F-MS-100.

Table 3. Comparison between numerical and experimental results.

Specimen	Experimental		Numerical		P_{num}/P_{exp}
	P_{max} (kN)	Defl. (mm)	P_{max} (kN)	Defl. (mm)	
SW-Ctrl	135.6	91.1	152.4	71.4	1.12
SW-F-MS-100	184.3	65.2	204.9	56.4	1.11
SW-F-MS-50	226.3	54.6	209.2	52.3	0.92
SW-F-SS-50	217.7	54.0	203.1	53.1	0.93

5 CONCLUSION

It has been shown experimentally in this research that reinforced concrete slabs can be strengthened effectively in flexure with mechanically fastened FRP strips. A comparison between the bonded and the mechanically fastened techniques was carried out. Further advantages, in terms of ultimate strength and gained ductility, were achieved through using the MF FRP technique. Increases in the yield and ultimate load of about 30% and 66%, respectively, were observed over the corresponding control specimen. In addition, finite element analyses were carried out to simulate the behavior of the MF FRP strengthened concrete slabs with special emphasis on the interfacial behavior between the concrete and the MF FRPs. The comparisons between the numerical predictions and the test results showed a very good agreement in terms of the ultimate carrying capacities, failure modes, and load–deflection relationships.

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