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Strengthening of Reinforced Concrete Slabs Subjected to Flexural Stresses Using External Layers to Act as Sandwich Slabs

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Abstract
Concrete sandwich panel is an innovative approach of construction that can be used for slabs or walls. Sandwich reinforced concrete slab consist of sheets or plates fixed on the top and bottom surfaces of a reinforced concrete core. An experimental program was conducted consists of eight one-way reinforced concrete slabs. One of them was a reinforced concrete slab to serve as a reference slab, three slabs were strengthened from the bottom surface (tension side) and four slabs were strengthened from both the top and bottom surfaces to act as sandwich reinforced concrete slabs. Different types of sheets or plates such as aluminum, steel, carbon fiber reinforced polymers CFRP, aluminum reinforced with CFRP were used as external layers.
The results showed that the strengthening either from the bottom surface or from the bottom and top surfaces enhanced the flexural capacity of the reinforced concrete slabs, leading to the formation of diagonal shear cracks and the slabs were failed due to shear stresses. To get the full flexural capacity of the strengthened and the sandwich slabs, the reinforced concrete slabs should have high shear strength due to the concrete cross section and the shear reinforcements. The use of the steel plates enhanced the ultimate load of the strengthened slabs from the tension surface to be 114% higher than the reference slab, while the use of the aluminum plates resulted in 50% increase for the value of the ultimate load. Strengthening with aluminum plate and CFRP resulted in 80 % increase for the value of the ultimate load. The values of the ultimate loads for the sandwich slabs was increased from 30% to 104% when compared to the value of the ultimate load of the reference slab. The use of the steel plates or the aluminum plates for the sandwich reinforced concrete slab resulted in 104 % and 72% increase for the values of the ultimate loads, respectively. The presence of both the aluminum plates and the CFRP sheets for a sandwich slab resulted in 93 % increase in the value of the ultimate load. The values of the deflection for the sandwich slabs and the strengthened slabs from the tension side were less than the values of deflection of the reference slab. Compared to the reference slab, the values of the ductility energy index for the strengthened slabs from the tension side were increased from 15% to 39%, and the value of the ductility energy index for the sandwich slabs were increased from 8% to 42%.
Keywords: *Concrete sandwich panel (CSP), Aluminum plates, Steel plates, CFRP sheets, Flexural Strength.*

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I. Introduction

Concrete sandwich panel (CSP) consist of a central reinforced concrete core covered with external layers. Despite several studies and developments in CSP over the past 30 years, CSP has not yet gained widespread usage. The two face-plates with the concrete core act as permanent formwork during construction providing impermeable skins, which are highly suited for marine and offshore applications, the plate surfaces can be readily protected, inspected and tested so that the integrity of the structure can be assured throughout its service life [1,2]

Composites are a prevalent field between researchers in civil engineering due to their excellent characteristics. Among the different types of composites in industry, sandwich elements are the key source of research due to their thermal comfort, energy efficiency, reliability, fire resistance, fast and easy construction [3]. Using reinforcement on both sides increases the elements' weight and size as it requires a sufficient clear cover to prevent corrosion. It is necessary to take this as a major point of consideration in developing thin sandwich elements with improved structural and thermal performance [4]. The precast concrete institute committee (PCI - March–April and May–June 1997) describes the types of sandwich panels such as, composite sandwich panels, non-composite sandwich panels and partially sandwich panels [5]. A novel type of reinforcement other than steel reinforcement is required to reduce the size of the layers of the sandwich elements leading to thin construction [6].

In order to increase the ratio of strength to weight of the structures and increase energy absorption, in recent years, the combination of concrete with steel face-plates has been considered by researchers. In this combination a concrete piece can be mounted on a steel face-plate using a sufficient number of shear connectors [7]. Concrete core can be sandwiched between two steel faceplates, which known as a steel-concrete-steel (SCS) sandwich. These are made of a concrete core between two steel face-plates connected using adhesive materials and mechanical shear connectors [8, 9]. SCS sandwich slabs show better performance in terms of stiffness, strength, and fire resistance compared to the ordinary reinforced concrete slabs. The main advantages of SCS include the steel face-plates play an important role to increase the flexural behavior and construction efficiency, the steel plates increase the impact resistance of concrete slab. According to the previous researches, steel-concrete-steel slabs have excellent structural performance in terms of static, impact, and blast strength [10,11,12,13]. Sandwich panels can be used in different projects, including residential buildings, schools, office buildings, low-temperature environments-controlled atmospheres, warehouses, industrial buildings, justice facilities, hospitals, submerged tube tunnels, building core walls, offshore structures and bridge decks, etc. [14,15,16,17].

R. A. S. Mohamed et al (2013) [18] studied the structural behavior of strengthened R.C. beams using externally bonded steel plates, steel angels, steel Channels or Carbon fiber reinforced polymers Sheets. Test results showed that, the beam strengthened with CFRP laminate recorded a slightly higher failure load than the beam strengthened with steel plate. While the beam strengthened with steel plate recorded a higher cracking load and less deflection. Yasser R. Tawfic et al (2021) [19] conducted experimental and theoretical studies to determine the flexural behavior of steel plate-reinforced concrete composite beams have different variables including the thickness of the steel plates, the concrete compressive strength, the number of shear connectors, and the use of epoxy resin. Test results revealed that using epoxy adhesive and mechanical anchors lead to increase the load bearing capacity and the efficiency of the composite beams due to the increase of the bond strength between the steel plates and the reinforced concrete beams.

The combination of the concrete elements and the aluminum plates strengthened with carbon fiber reinforced polymers using epoxy resins is found to be highly useful for the rehabilitation of concrete and masonry structures. The aluminum plates provide optimal solution for providing building durability and extending the serviceability period of masonry structures [20, 21]. Aluminum flexibility significantly contributes to material malleability on any kind of surface Lamination is performed easily and the two materials combine without difficulty. Aluminum sandwich composite (ASC) laminates were selected due to their availability and high performance in real-time applications. Aluminum sandwich composite laminates are used in structural and building [22,23,24]

The main objective of this research is to evaluate the flexural behavior of the strengthened reinforced concrete slabs using external layers to act as sandwich reinforced concrete slabs. Different types of external layers were used such as steel, aluminum, CFRP and aluminum reinforced with CFRP fixed on the bottom or fixed on both the top and bottom surfaces of a reinforced concrete core using shear connectors and epoxy resin.

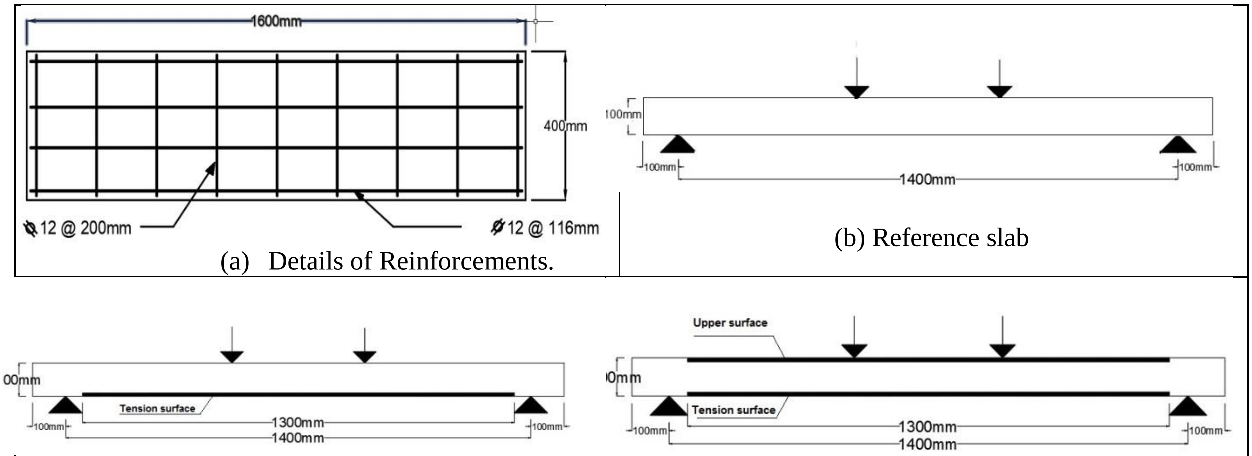
II. Experimental Program

The experimental program consists of eight simply supported one-way reinforced concrete slabs as shown in table (1). The dimensions of all specimens were 400×1600×100 mm with clear span 1400 mm as shown in figure (1). Specimen (s1) without any exterior layers to serve as a reference specimen. Three slabs were strengthened from the tension surface and four slabs were strengthened from the tension and compression surfaces to act as sandwich reinforced concrete slabs. The strengthening layers were from steel, aluminum, carbon fiber reinforced polymers CFRP or aluminum strengthened with CFRP. The external layers were fixed using epoxy resin and ten shear connectors as shown in figure (2). The Concrete compressive strength at 28 days age was 250 kg/cm^2 for all slabs and all specimens were tested under two-point static load.

Table (1): Details of the Experimental Program.

Slab	Lower restoration		upper restoration	
	Type of layer	Plate Thickness (mm)	Type of layer	Plate Thickness (mm)
S1	–	–	–	–
S2	Steel	2	–	–
S3	Alum.	2	–	–
S4	Alum. + CFRP	2	–	–

S5	Steel	2	Steel	2
S6	Alum.	2	Alum.	2
S7	CFRP	0.13	CFRP	0.13
S8	Alum. + CFRP	3	Alum. + CFRP	3



(a) Details of Reinforcements.

(b) Reference slab

b) Slabs strengthened from tension side

c) Sandwich slabs

Figure1: Details of tested specimens

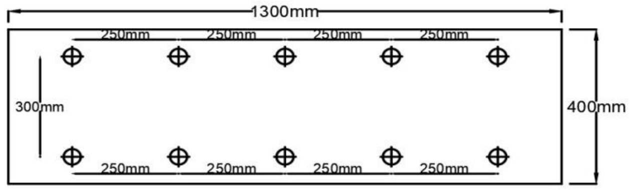


Figure 2: Details of shear connectors.

2.1 Materials

2.1.1. Cement

Ordinary Portland cement [CEM I 42.5N] was used to cast all the slabs. The surface area, the specific gravity and 28-day compressive strength of the cement were 3250 cm^2 gm^{-1}, 3.15 and 48 MPa, respectively

2.1.2. Fine and Coarse Aggregate

The fine and coarse aggregate were supplied from local quarries in Minia Governorate. The fine sand was natural siliceous sand with specific gravity 2.66. The maximum nominal size, specific gravity and volume weight of the gravel were 20 mm, 2.64 and 1.66 t/m^3, respectively.

2.1.3 Epoxy resin

Kemapoxy 165 adhesive mortar is a pre-filled medium viscosity and solvent-free, two components of modified epoxy resin with an adequate hardening system. The density was 1.95 ± 0.02 kg/l, the compressive strength was 800 kg/cm^2 and the adhesive strength on concrete was 103 kg/cm^2.

2.1.4 Steel reinforcements

High tensile steel (diameter 12 mm) was used as tensile reinforcements. The yield strength was 450 MPa, ultimate strength was 607 MPa and the percentage of elongation was 20 %.

2.1.5 Steel plates

The Steel plates were 2 mm thickness, the yield strength, the ultimate strength and the percentage of elongation were 360 MPa, 440 MPa and 10%, respectively.

2.1.6 Aluminum plates

The yield strength and the ultimate strength of the aluminum plates were 118 MPa and 124 MPa, respectively.

2.1.7 Fiber Reinforced Polymer (FRP)

Carbon fiber reinforced polymers had thickness 0.13 mm, modulus of fiber 230 GPa and ultimate tensile strength of 3500 MPa was used for the tested slabs.

2.2 Concrete mix design

The concrete mix design strength for all the tested reinforced concrete slabs were 250 kg/cm^2, the cement content was 350 kg/m^3 and the water cement ratio was 0.55. The details of concrete compositions are shown in Table (2).

2.4 Preparations of Reinforced Concrete Slabs

For all the tested slabs cleaning and roughing the surface of the reinforced concrete slabs was required for the installation of the external layer as shown in figure (3-a). In case of slabs strengthened using CFRP, the surfaces of the slabs were saturated with epoxy resin to install the CFRP sheets with the concrete slab as shown in figure (3-b). In case of slabs strengthened using aluminum or steel plates, ten holes (with diameter 2 mm larger than the diameter of the anchors) were drilled for the fixation of the anchors, dust was removed by using air blower and the surfaces of the slabs were saturated with epoxy resin to fix the plate on the surface of the concrete, then the anchors were installed as shown in figure (3-c). In case of slabs strengthened using aluminum reinforced with CFRP sheets, the surface of the slab was saturated with epoxy resin to install the CFRP sheet. After hardening, ten holes were drilled and the surface was re-saturated with epoxy resin to install the aluminum plate using ten anchors as shown in figure (3-d).

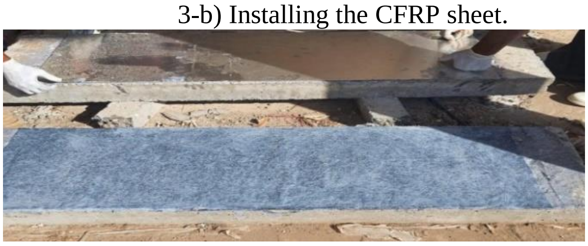
Table (2): Mix proportions of specimens tested.

Mix	Amount of constituent materials/m^3				
	Cement (kg)	Water (liter)	w/c ratio	Sand (kg)	Gravel (kg)
1	350	190	0.55	750	1100

3-a) Roughing the surface.

3-b) Installing the CFRP sheet.

3-c) Fixing the plates.



3-d) Aluminum reinforced with CFRP sheets.

Figure 3: Strengthening the reinforced concrete slabs.

2.4 Test procedures and Measurements

The slabs were tested under two-point static load using (1000 kN) capacity universal testing machine, as shown in Figure (4). Dial gauge of (0.01mm) and LVDT were used to determine the deflection at mid-span. Electrical strain gauges were fixed at the center of steel reinforcements and external plates or sheets to measure the strain. A pie gauge was fixed at the center of the span to measure the cracks width. The electrical resistance strain gauges, pie gauges, and displacement measurements were connected to a data logger.

Figure 4: Universal testing machine.

III. Test results and discussion

3-1 patterns of cracks and modes of failure

At 28 days, the slabs were tested under two-point static loads. When the slab was loaded, the cracks were formed and propagated until the failure occurred. The cracks were drawn, and the modes of failure were determined.

The reinforced concrete reference slab S**1** was free from crack at early stages. Increasing the loads, the first visible crack was observed at the maximum moment zone at a load of 1.8 ton. Afterwards, more cracks were formed, extended upwards and widened, leading to a flexural type of failure as shown in Figure (5)**.**

Slabs strengthened at the lower tension side (S2 , S3 , S4) were loaded and the first visible crack was occurred in the critical moment zone at a higher value of load compared to the value of cracking load of the reference slab. Increasing the load, the cracks were extended and widened and new crack was formed at the end of the strengthening layer. Then the crack at the end of the strengthening layer was extended in a diagonal direction and widened leading to a shear type of failure as shown in Figure (6).

The sandwich reinforced concrete slabs (S5, S6, S7, S8) showed similar patterns of cracks to the reinforced concrete slabs strengthened from the tension side. However, the formation of the inclined crack was accompanied with the occurrence of local buckling at the aluminum plate at the compression zone. Debonding at the ends of the upper layer was observed as shown in Figure (7).

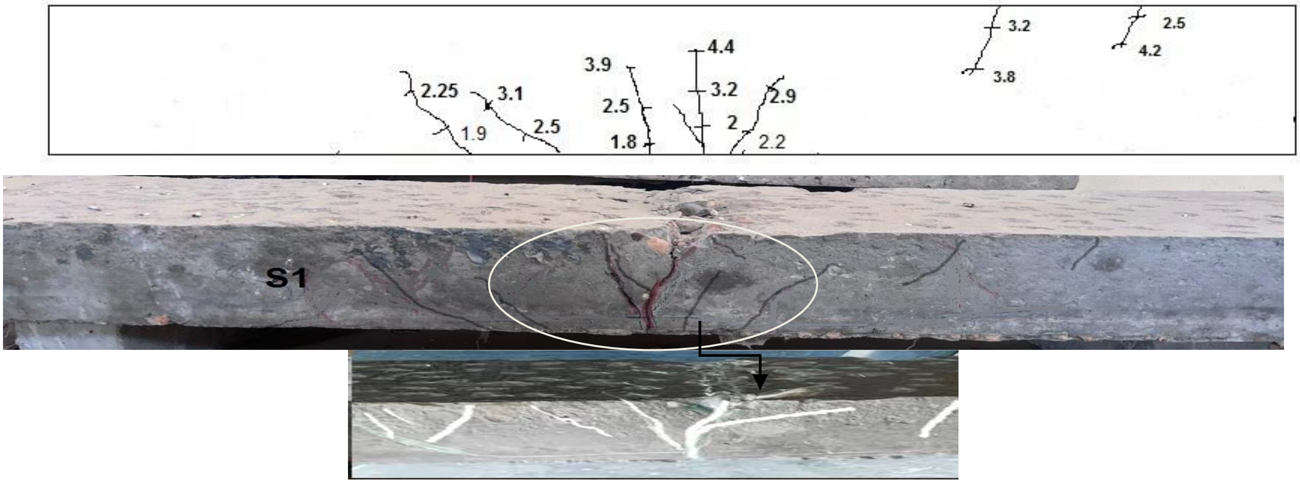
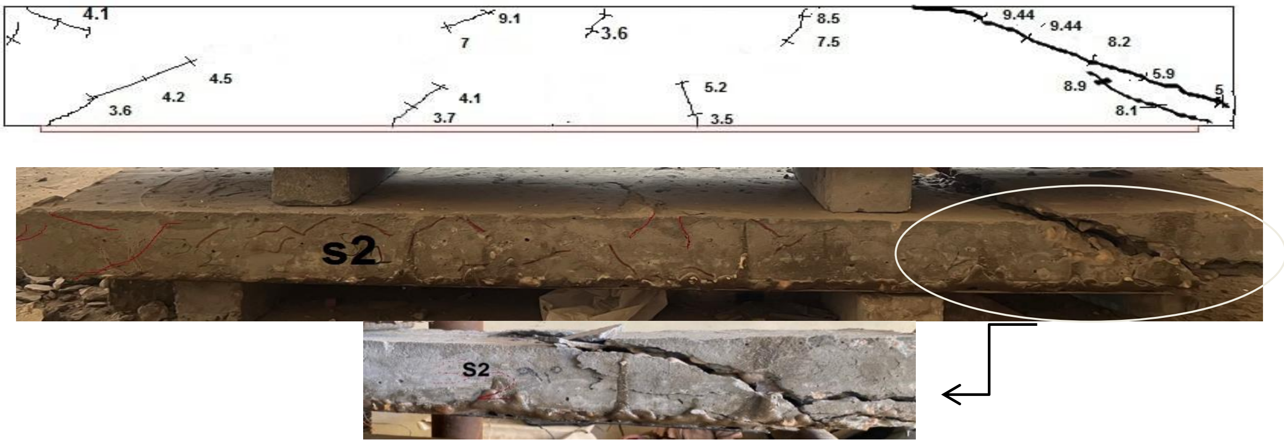
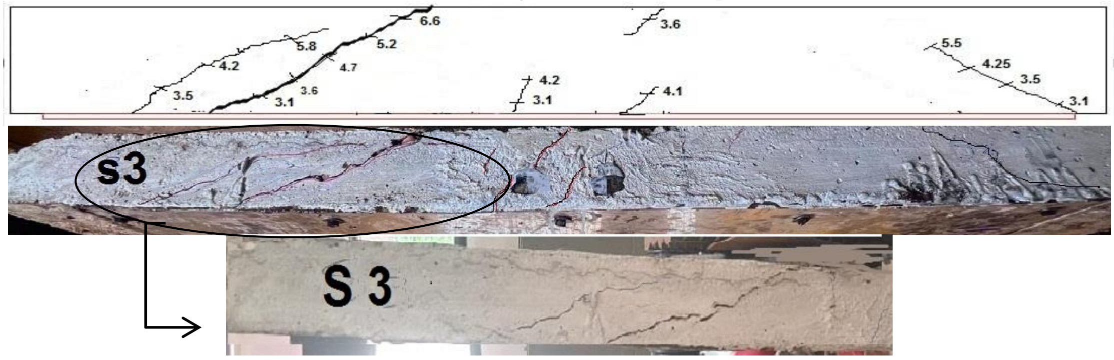


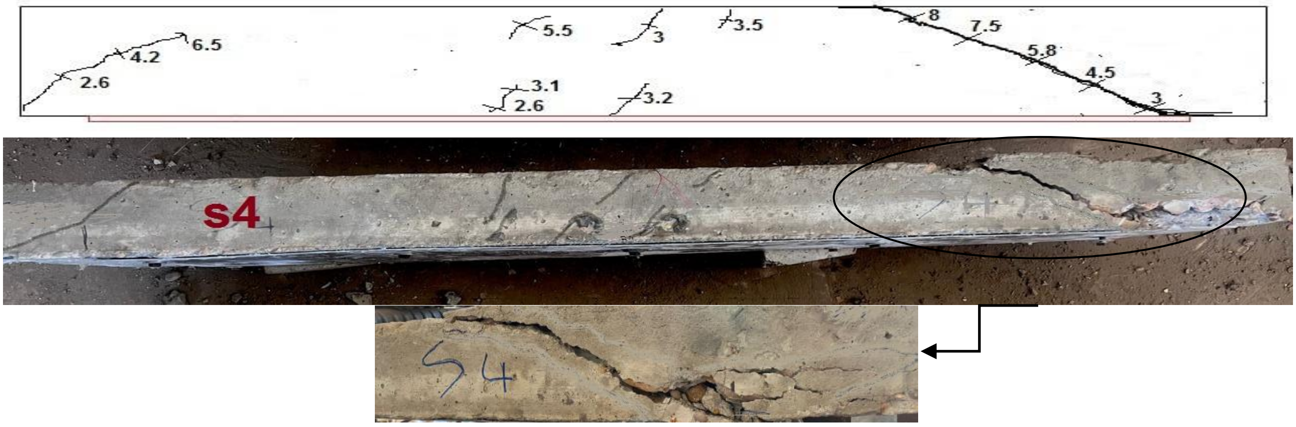
Figure 5: Pattern of cracks of the reference slab.



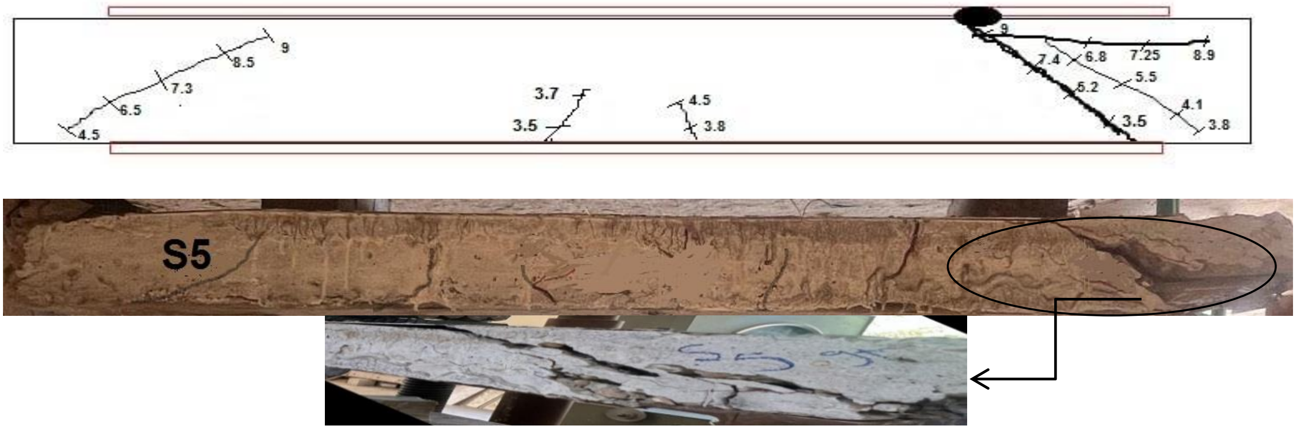
(a): Pattern of cracks of the slab strengthened with steel plate at the bottom surface.



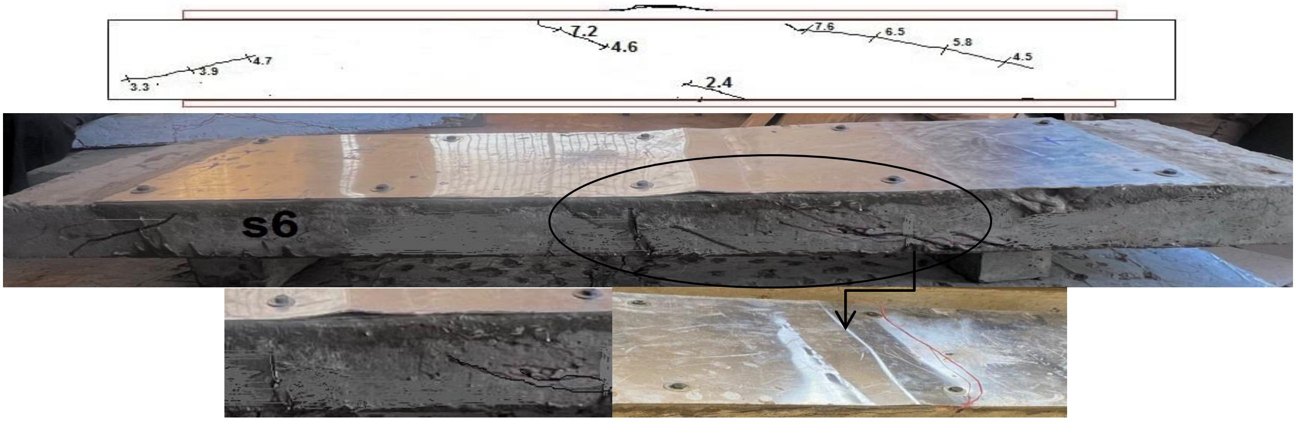
(b): Pattern of cracks of the slab strengthened with aluminum plate at the bottom surface.



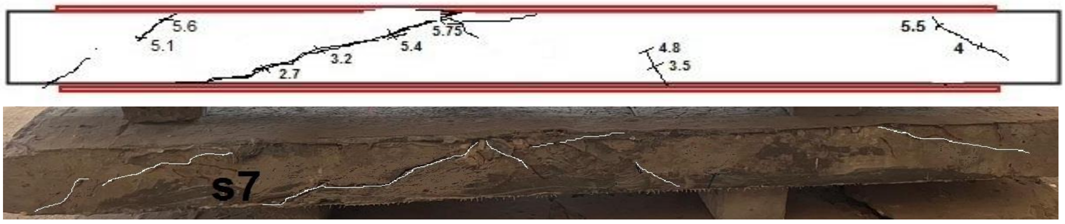
(c): Pattern of cracks of the slab strengthened with steel plate at the bottom surface.
Figure 6: Pattern of cracks of the slab strengthened at the bottom surface.



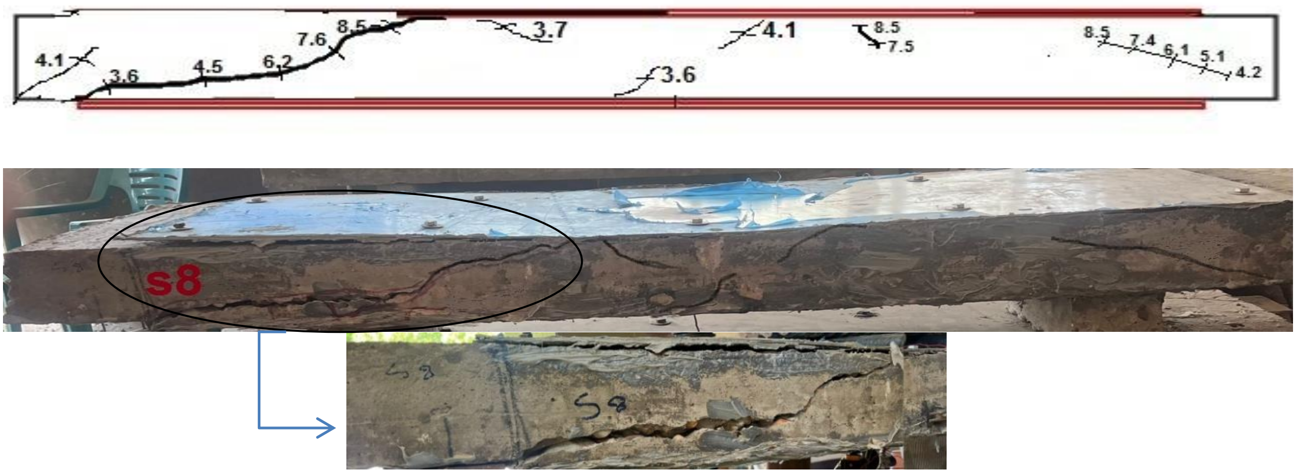
(a): Pattern of cracks of the slab strengthened with steel plates at the top and bottom surfaces.



(b): Pattern of cracks of the slab strengthened with aluminum plates at the top and bottom surfaces.



(c): Pattern of cracks of the slab strengthened with CFRP sheets at the top and bottom surfaces**.**



(g): Pattern of cracks of the slab strengthened with Aluminum-CFRP at the top and bottom surfaces. Figure 7: Patterns of cracks of the sandwich reinforced concrete slabs.

3.2 Cracking and ultimate loads

Figure (8) shows the cracking loads of the reference slab, strengthened slabs from tension side, and sandwich slabs. The values of cracking loads for the strengthened slabs at the tension surface were found to be up to 94% higher than the reference slab. Similarly, the value of cracking loads for the sandwich slabs were up to 100% higher than the reference slab. By reinforcing the slabs with steel or aluminum strengthened with CFRP at the bottom surface or both top and bottom surfaces, the formation of cracks was delayed, resulting in higher value of cracking loads.

The ultimate loads of all the tested reinforced concrete slabs are shown in figure (9). Compared to the reference slab, the values of the ultimate loads for the strengthened slabs at the tension surface was increased from 50% to 114%, and the values of the ultimate loads for the sandwich slabs was increased from 30% to 104%. The reference slab was failed due to flexural stresses. However, the slabs strengthening from the lower tension surface and the sandwich slabs showed high flexural strength leading the slabs to fail due to a shear type of failure.

The ultimate load of the slab S2, strengthened using steel plate fixed to the bottom surface, was 114% higher the the value of the ultimate load of the reference slab. Strengthening the RC slab with aluminum plate at the bottom surface of slab S3, resulted in 50 % increase for the value of the ultimate load. The strength of the steel plates resulted in higher values of ultimate loads than the aluminum plates. Slab S4, strengthen with aluminum plate and CFRP from the bottom surface, resulted in 80 % increase for the value of the ultimate load.

Compared to the reference slab, the sandwich reinforced concrete slab S5, strengthened with steel plates from the top and bottom surfaces, resulted in 104 % increase for the value of the ultimate load. The sandwich slab S6, strengthened with aluminum plates at the top and bottom surfaces, showed 72% higher values of the ultimate load. The presence of aluminum plates and CFRP for the sandwich slab S8 resulted in 93 % increase in the value of the ultimate loads. However, the use of CFRP for the sandwich slab S7 from the top and bottom surfaces, showed 30% higher values of the ultimate load.

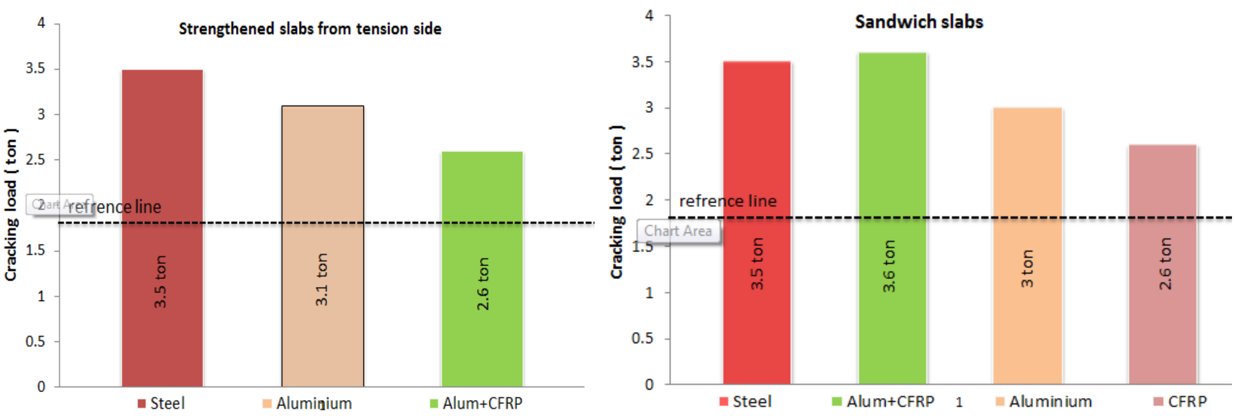


Figure 8 The values of the cracking loads for the tested slabs

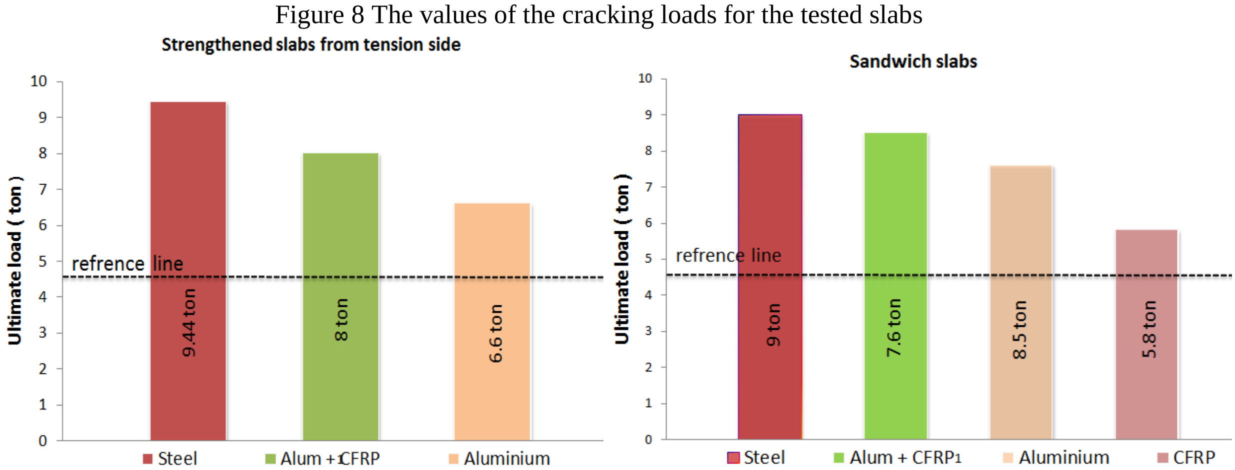


Figure 9 The values of the ultimate loads for the test slabs

3.3 Deflection characteristics.

Figures (10 to 14**)** show the load–midspan deflection curve for the experimental test slabs. At a certain value of load, it can be seen that the values of the deflection for the sandwich slabs and the strengthened slabs from the tension side were less than the values of deflection of the reference slab. The sandwich and the strengthened slabs have higher stiffness than the reference one. Figures (10 and 11) show that the strength and stiffness of the RC slabs strengthened with steel plates either from the bottom or the bottom and the top surfaces are higher than those of slabs strengthened with the aluminum plates or the CFRP sheets. The deflection at failure load for the slabs strengthened with aluminum plates or CFRP sheets was found to higher than the deflection of the slabs strengthened with steel plates. Figures (12 to 14) show that the load-deflection curves of the slabs strengthened from the lower tension surface and the sandwich slabs were almost similar, which could be attributed to the shear type of failure.

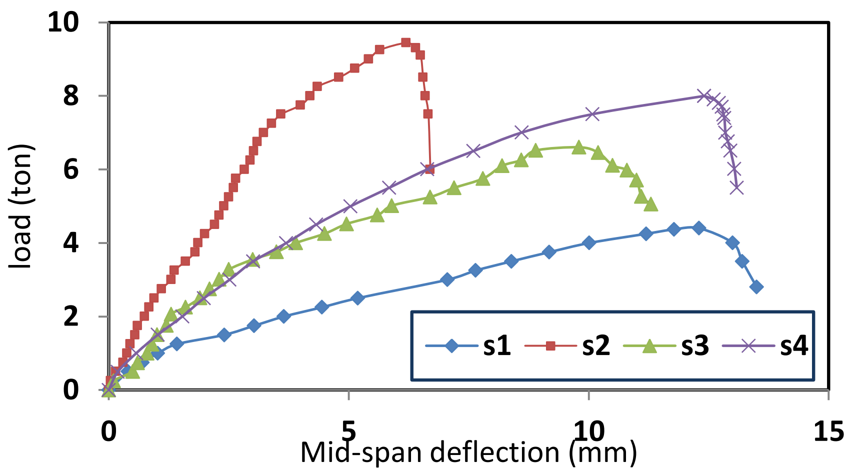


Figure 10: Load–Deflection relationship for the reference and strengthened slabs.

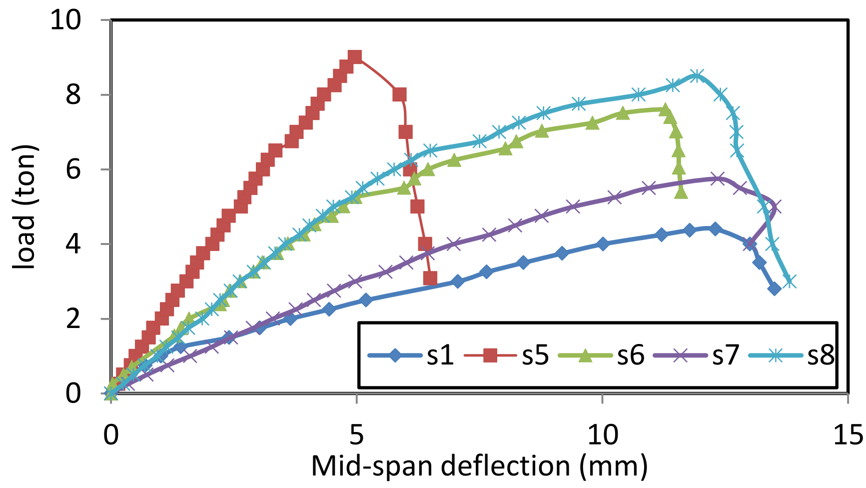


Figure 11: Load–Deflection relationship for the reference and the sandwich slabs.

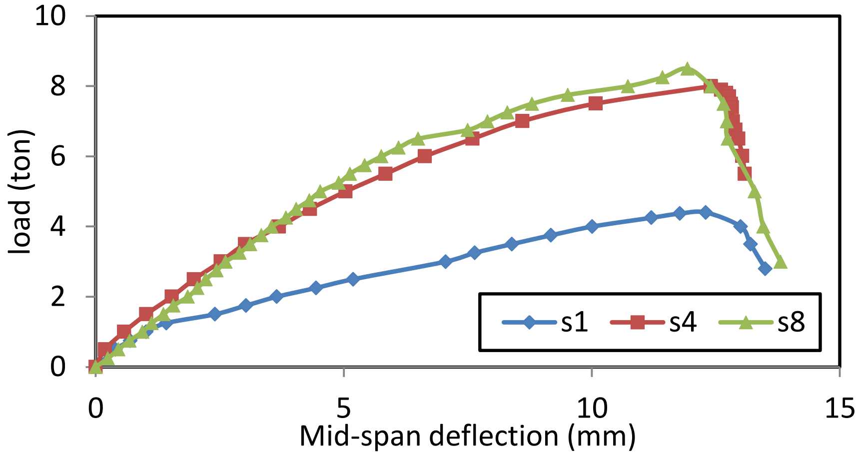


Figure 12: Effect of using aluminum plates reinforced with CFRP sheets on Load-Deflection relationship.

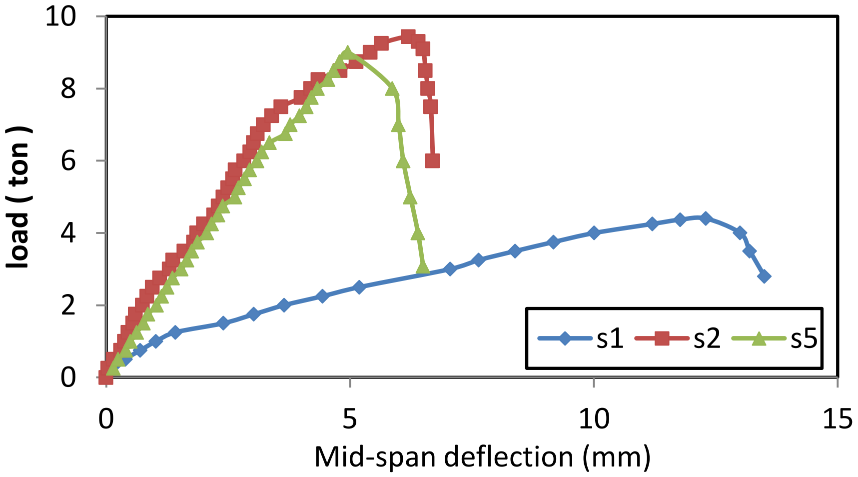


Figure 13 Effect of using steel plates as external layer on the load-deflection relationship.

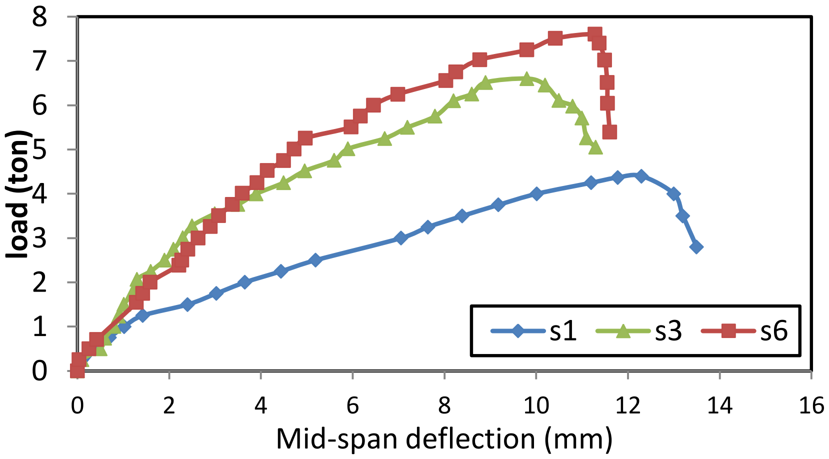


Figure 14 Effect of using aluminum plates as external layer on the load-deflection relationship.

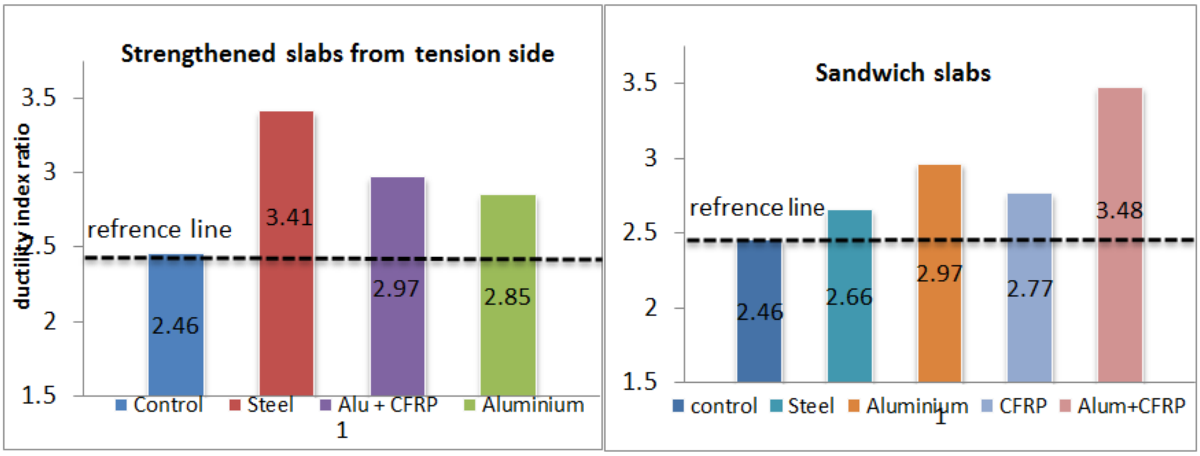


Figure 15 the ductility energy index of the slabs.

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3.4 Ductility

The ductility of the experimental tested reinforced concrete slabs was defined in terms of the energy absorption. The energy absorption was detected by the area under the load deflection curve. The ductility energy index is the ratio of the total energy absorption up to the failure load and the energy absorption up to 75% of the maximum load [25]. Compared with the reference slab, the values of the ductility energy index for the strengthened slabs from the tension side were increased from 15% to 39%, and the value of the ductility energy index for the sandwich slabs were increased from 8% to 42% as shown in Figure (15). High values of ductility energy index were recorded for the slabs strengthened with steel plates from lower surface and for the slabs strengthened using aluminum reinforced with CFRP from lower and upper surfaces. These values could be predicted to be higher, in case of slabs were not failed due to shear stresses.

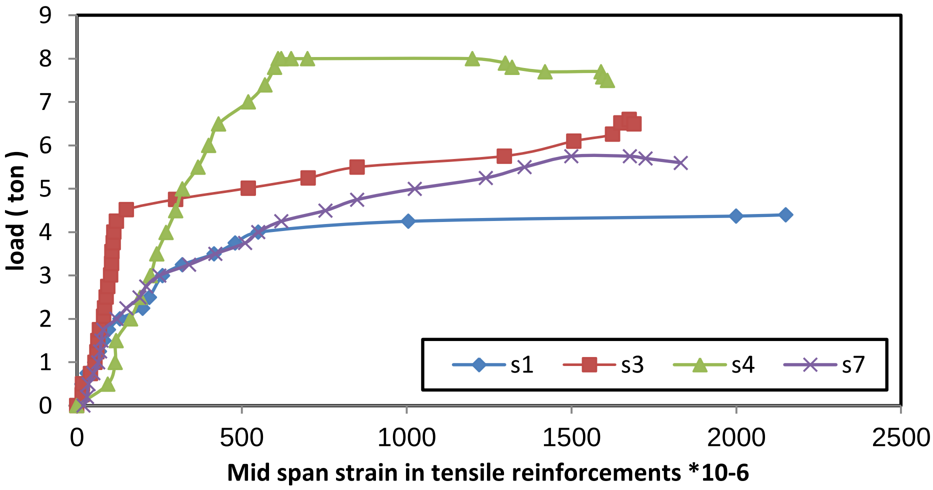

Figure (16): Load–strain relationship of the steel reinforcement

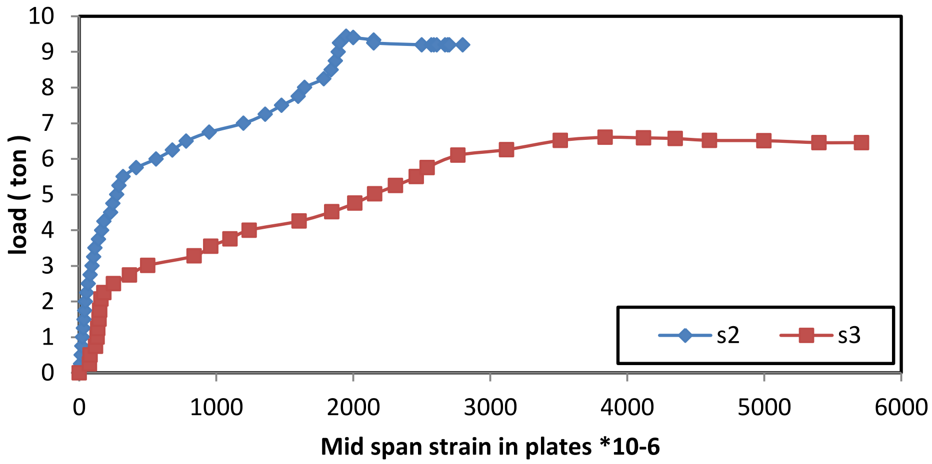

Figure 17: Load–strain relationship of the steel and aluminum plates

3.5 Strain in plates and tensile steel bars:

Figure (16) shows the strain in the steel bars for the reference slab S1, slabs S3 and S4, which were strengthened from the bottom, and the sandwich slab S7. For the control slab, only the tensile steel bars reached the yield strength, while the slabs that were reinforced from the bottom or the sandwich slabs did not reach the yield strength. The strain in the plates of slabs S2 and S3 reached the yield strength as shown in Figure (17).

IV. Conclusions

1- Strengthening either from the bottom surface or from the bottom and top surfaces enhanced the flexural capacity of the reinforced concrete slabs, leading to the formation of diagonal shear cracks and the slabs were failed due to shear stresses. To get the full flexural capacity of the strengthened and the sandwich slabs, the reinforced concrete slabs should have high shear strength due to the concrete cross section and the shear reinforcements.

2- Compared to the reference slab, the values of the ultimate loads for the strengthened slabs at the tension surface was increased from 50% to 114%. The use of the steel plates enhanced the ultimate load of the strengthened slabs from the tension surface to be 114% higher than the reference slab, while the use of the aluminum plates resulted in 50% increase for the value of the ultimate load. Strengthening with aluminum plate and CFRP resulted in 80 % increase for the value of the ultimate load.

3- The values of the ultimate loads for the sandwich slabs was increased from 30% to 104% when compared to the value of the ultimate load of the reference slab. The use of the steel plates or the aluminum plates for the sandwich reinforced concrete slab resulted in 104 % and 72% increase for the values of the ultimate loads, respectively. The presence of both the aluminum plates and the CFRP sheets for a sandwich slab resulted in 93 % increase in the value of the ultimate load.

4- The values of the deflection for the sandwich slabs and the strengthened slabs from the tension side were less than the values of deflection of the reference slab. The sandwich and the strengthened slabs have higher stiffness than the reference one.

5- Compared to the reference slab, the values of the ductility energy index for the strengthened slabs from the tension side were increased from 15% to 39%, and the value of the ductility energy index for the sandwich slabs were increased from 8% to 42%.

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