



Effect of Stirrups on the Behavior of Semi-Precast Concrete Slabs

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Abstract

A semi-slab of precast concrete (or half-slab) is a structural system that consists of concrete at the bottom half of a slab and concrete cast in situ at the top. To avoid traditional formwork and minimize the bottom half of the slab, this section can function as formwork and reduce the thickness of precast slabs, which makes their transportation easy. The interface between precast and overtopping concrete is effective for the slab system's performance. To improve the half-slab floor system, it is needed to have a shear connector (stirrups). Therefore, to better understand the behavior of this slab system, six full-scale slab specimens (2×7.5 m) with different shapes of the stirrups and spacing between them were constructed for this study. One specimen was produced with no connections and served as a reference specimen, while the other employed stirrups to connect slab units. The tests found that the distribution and type of stirrups affect the structural performance of the semi-precast concrete slab. The maximum load capacity of slabs with rectangular or triangular connections was nearly more significant than reference slabs, reaching 136.11 and 86.11%, respectively. The maximum load increased by 81.4 % for rectangular connections and 54.9% for triangular connections when the distance between the connectors was reduced from 600 to 300 mm. Furthermore, stirrups in semi-precast slabs could improve the cracking behavior, stiffness, and ductility.

Keywords: Semi-Slabs; Precast Concrete; Site-in-place Concrete; Stirrups; Spacing.

1. Introduction

Precast and cast-in-place concrete are used in semi-precast or hybrid concrete construction (overtopped concrete). The bottom of the slab uses precast concrete and is closed using conventional concrete as a topping. The precast components' accuracy, speed, and high-quality finish can be combined with the economy and flexibility of cast in-site concrete units. This technique is beneficial for various reasons: reducing the use of wood material in formwork, facilitating transportation, and enabling safer and faster construction. The structural performance of semi-precast concrete demonstrates high cracks and deflection control due to the controlled factory environment in which the manufacturing process is conducted [1, 2].

The bond strength between semi-slab components is the main apprehension of it, where the concrete-concrete bonding was affected by numerous factors, such as roughness, initial moisture condition, and curing conditions [3]. So, an accurate surface treatment should be applied to develop adequate bonding for this slab type. Consequently, many studies indicated the bond capacity of concrete interfaces was distributed among the friction coefficient, dowel action, and cohesion behavior. For instance, Zilch and Reinecke [4] investigated the shear friction between high-strength precast units and normal-strength cast-in-situ concrete units. They indicated that the shear capacity of concrete interfaces is distributed among three mechanisms: friction coefficient, dowel action, and cohesion behavior. An additional study

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implemented by Santos et al. [5] studied the probability of computing the roughness of the substrate surface and comparing it with the bonding strength. Test results proved that roughness factors were linearly simultaneous with the interface bonding strength and the surfaces with higher average roughness values.

Additionally, Cavaco & Camara [6] investigated the performance of the concrete interface acquiesced to bending moment and shear. The study shows that loading transfer capacity decreased at the interfaces because of the cracks initiated, which decreased ductility but did not affect the strength of the specimens. An additional study by Sørensen et al. [7] studied the efficiency of using shear connections at the concrete interface for precast reinforced concrete shear walls. According to their results, the ductility is considerably enhanced using the shear connection. Cavaco et al. [8] tried to improve the ductility at the concrete-concrete interfaces by providing web reinforcement to limit the shear slippages. Moreover, Xia et al. [9] investigated a direct shear test on concrete interfaces, and they determined that adding reinforcement to concrete could increase the direct shear strength and change the performance from brittle to ductile.

However, little research can be found on the half-precast slabs; most studies focused on valuing their structural performance. Kim and Shim [10] studied the enactment of a pre-tensioned semi-precast slab system that used looping connections in the longitudinal direction. Kim and Shim [11] also examined the crack width of a half-precast slab system that uses looping connections between precast units. Asamoah et al. [12] examined the cost approximation of the structural by considering cast-in-site concrete and precast-concrete slabs and columns, respectively. The research points to out precast concrete units were more economical than cast-in-situ concrete units. Furthermore, Vakhouri [13] studied the effect of the length of reinforcement contiguous to the crack where the compatibility of strain between the steel and concrete is not maintained because of the bond breakdown and slip. Based on the results of case studies of the rail project, Pan et al. [14] proposed a "full-span precast launching method" as a new technique to develop the technology of construction bridges. Cho et al. [15] analyze the manufacturing process of the semi-precast concrete slabs by using a simulation method with actual data. Their results indicated that the construction productivity of this type of concrete is 1.7 times that of a customary slab.

Gowthami [16] investigated the variability of shear-connectors on one-way and two-way composite slabs and initiated that two-way slabs yielded a larger load associated with one-way slabs for a given shear-connector location. The author described that the diameter of bars has no attitude in the situation of one-way slab results but changes the load carrying capacity of a two-way slab. Also, Newell and Goggins [17] evaluated the performance of lattice-girder composite slabs systems during the manufacturing process and analyzed the key characteristics that influence their performance at both serviceability and the final limit state. The findings indicate that further optimization of this system is possible. Mohamed et al. [18] studied three slab surface treatment techniques (roughened, bonding agent, and shear keys) and discovered that surface treatment affected flexural behavior and that the slab system may behave monolithically under flexural action. They concluded that roughening the slab in a transverse direction is the most effective surface treatment method for this slab type. Zhang et al. [19] experimentally and analytically investigated the overall flexural strength of the lattice-girders composite slabs system with the monolithic connection. The authors concluded that this system meaningfully raises the stiffness of the slabs compared to the precast slabs without reinforcement passage of the interface. Kanchanadevi et al. [20] examined the bent-up rebar of precast-concrete embedded across cast-in-site concrete to create a new connection configuration of precast-concrete slab. As the angle of the bent-up rebar reduced from 90° to 60°, the failure modes of the slabs changed from connection failure to failure at the end section of the lap-splice rebar, improving the flexural strength.

During the development of semi-slab system, some research suggested using top chord of the steel bar truss (SBT), which filled with concrete, for instance, Liu et al. [21] compared the SBT-reinforced pre-stressed semi-slab and the precast bottom slab. The test results illustrated that the steel truss can meaningfully advance the load bearing capacity of the floor slab and the behavior of the bottom slab and the composite layer. The upper chord moment calculating formula has been recognized. Liu et al. [22] studied the influence of connections on flexural performance of semi-precast slabs having steel truss on the precast portion and used finite element analysis to reproduce the experiments. The results showed that the steel truss could reduce the brittle failure and change it to a ductile failure to improve the flexural strength of the slab.

2. Research Significance

The semi-precast system is a comparatively new manufacture system, and little information of semi-precast slab characteristics are known from previous research. From this point of view, the main goal of current study is to implement an experimental investigation to offer a more-needed understanding of the behavior of semi-precast slab. The behavior of the semi-precast slab was affected by the interface between the precast concrete component and the concrete overtopping component. Therefore, full-scale slab specimens using stirrups as shear connections with different shapes and distributions were prepared and tested under uniformly distributed loads. Figure1 shows the flow- chart of methodology.

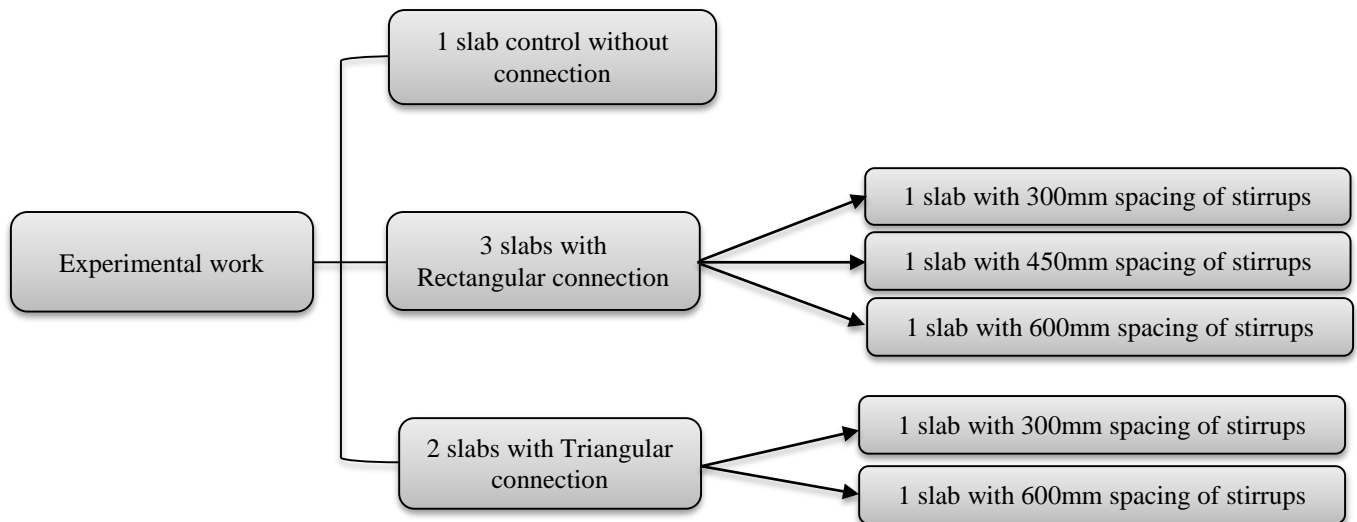


Figure 1. Flow chart of the research methodology

3. Experimental Program

3.1. Specimen Details

The experimental program included casting and testing six semi-precast concrete slabs (full-scale one-way slabs). All the specimens have the exact dimensions of 7500×2000 mm and 200 mm thickness, where the total thickness of slabs is divided between the precast concrete and the cast-in-site concrete. Figures 2 and 3 show the reinforcement details and the construction of the semi-precast slabs. Of these six specimens, one was without connectors to be used as a reference specimen, while the other specimens are full-scale slabs that have stirrups with different parameters, including shape (rectangular type (RT) or triangular type (TT)) and spacing (300, 450, or 600 mm) as indicated in Table 1. The cast of the slabs happened in two stages; the first unit of the concrete slab (precast concrete part) was cast and cured. After 14 days the first slab unit gained a strength and managed to reach to target compressive strength, the second unit of the slab (overlapped concrete) was casted and cured for 14 days also.

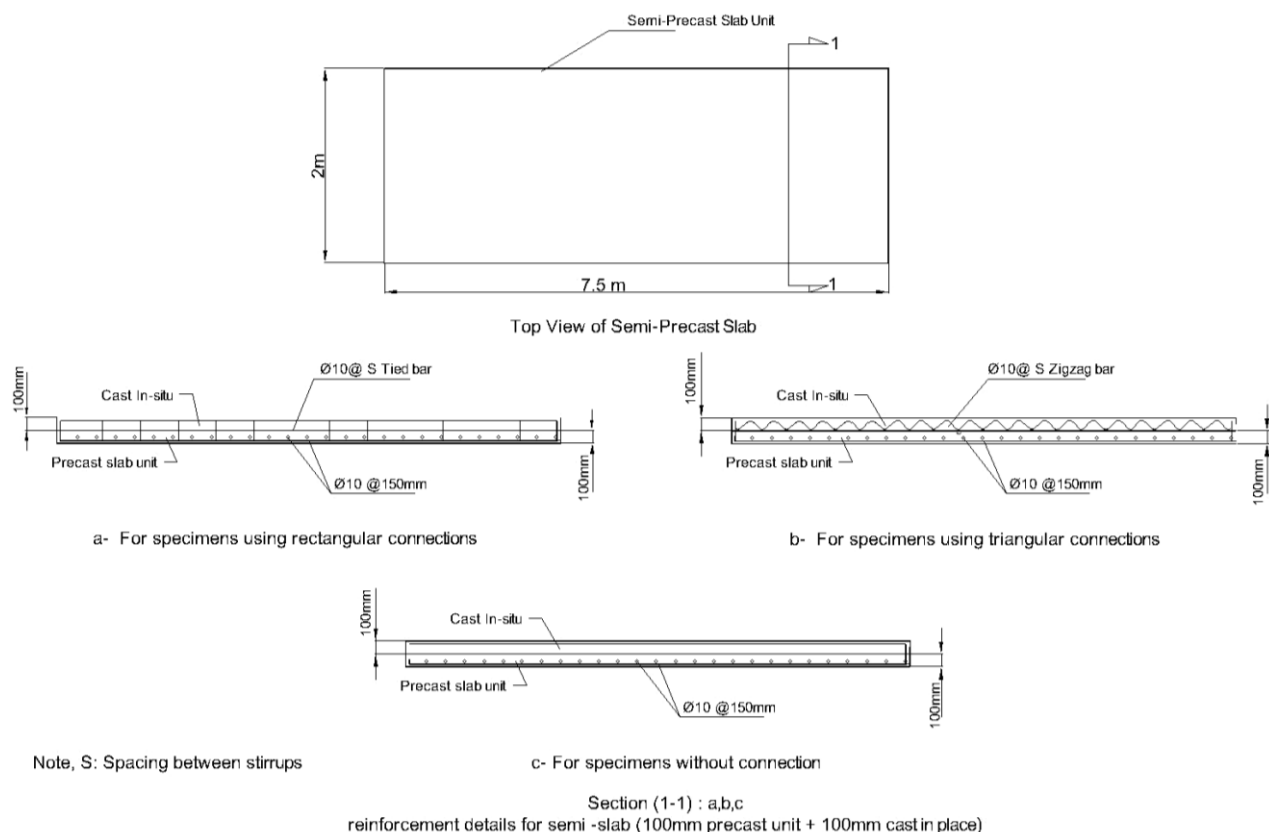


Figure 2. Dimensions and reinforcement details of specimens

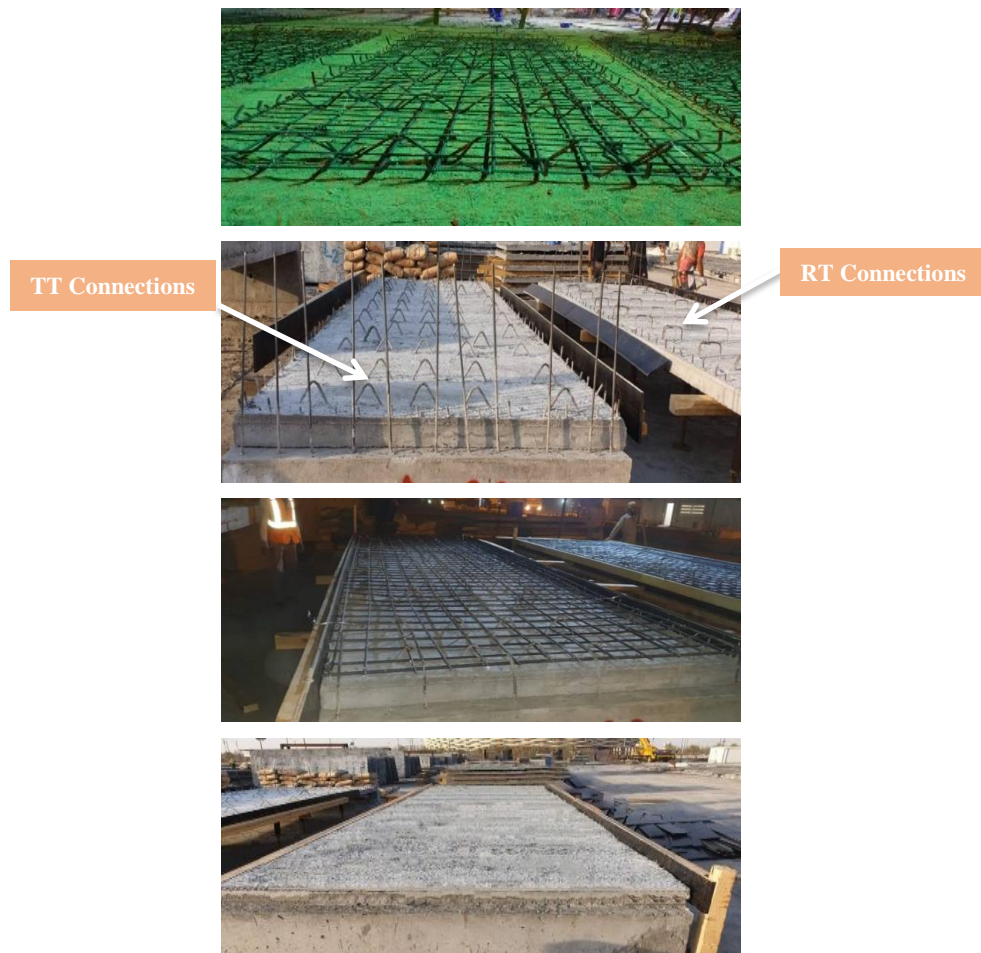


Figure 3. The manufacturing process of semi-precast slabs

Table 1. Details of the tested specimens

Code	Size mm ³	Precast concrete thickness (mm)	Cast-in-site thickness (mm)	The shape of Stirrups (connections)	Spacing of stirrups (S) (mm)
S1	7500×2000×200	100	100	Triangular	600
S2	7500×2000×200	100	100	Rectangular	600
S3	7500×2000×200	100	100	Rectangular	450
S4	7500×2000×200	100	100	Rectangular	300
S5	7500×2000×200	100	100	Triangular	300
S6	7500×2000×200	100	100	Without connection	---

3.2. Material Properties

Material properties were tested in accordance with BS EN 12390-7 [23] for concrete and ASTM A316-A370 [24] for steel. Each semi-slab was constructed using standard concrete for precast and cast in situ concrete. Concrete cubes test blocks with a side length of 150 mm are cured under the same circumstances throughout the manufacturing of each semi-slab. The axial compressive strengths f_{cu} of the cast-in-site and precast concrete are 37.6 and 41.2 Mpa, respectively. The yield and ultimate strengths of Ø10 steel bar are 485Mpa and 678Mpa, respectively.

3.3. Materials

Cement

Ordinary Portland cement (type I) manufactured by an Iraqi company is used in this study. The physical and chemical properties are shown in Tables 2 and 3.

Table 2. Components of cement

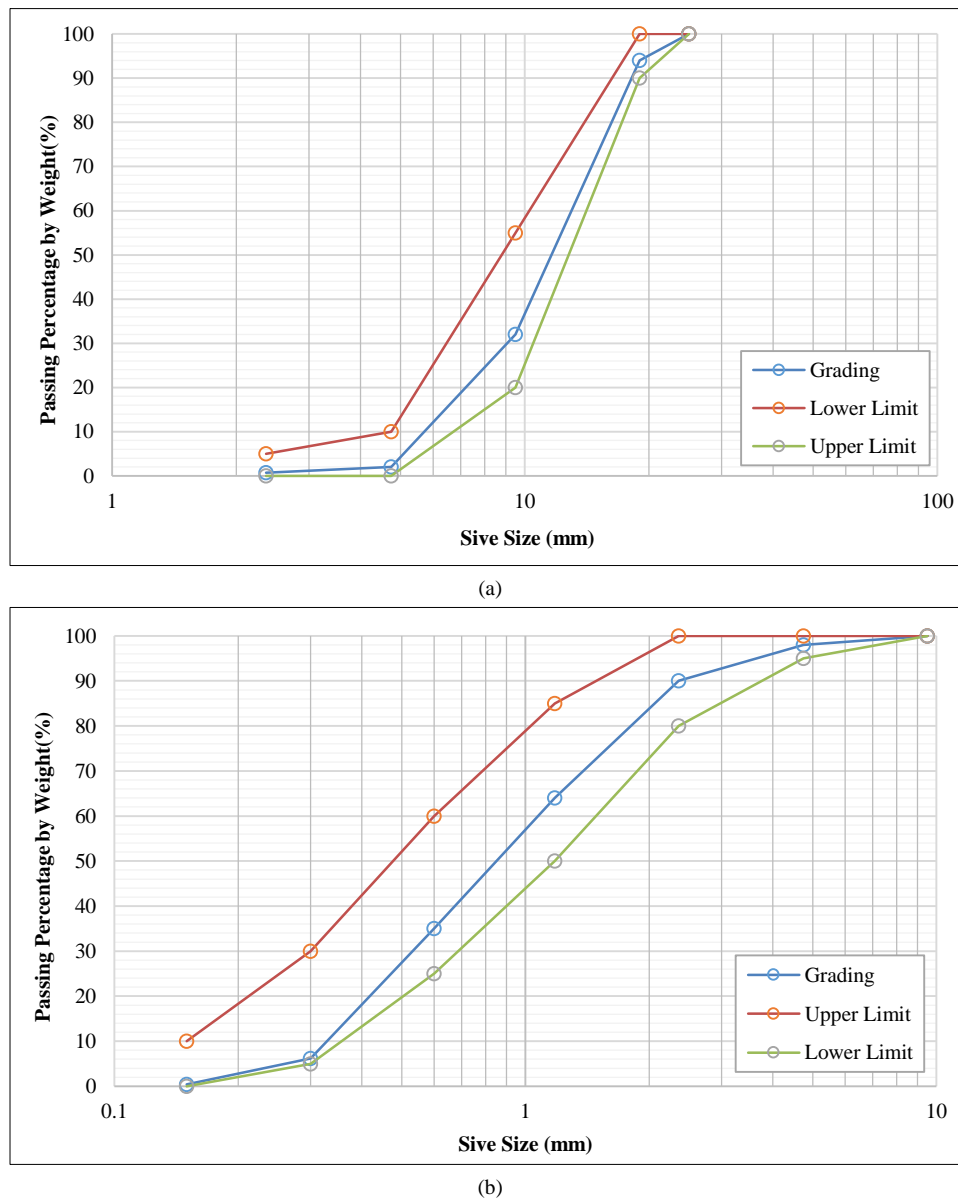
Chemical Components									Main Components				
SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃	Insoluble	LOI	C ₃ S	C ₂ S	C ₃ A	C ₄ AF
20.3	5.1	3.3	62.4	1.95	0.33	0.65	1.95	0.48	1.33	50.7	24.5	6.90	10.7

Table 3. Physical properties of cement

Property	Standard	Test Method	Unit	Result
Fineness	ASTM C204 [25]	Mesh 170	%	6.1%
		Blaine air permeability	(m ² /kg)	303
		Initial	min	131
Setting time	ASTM C191 [26]	Final	min	259
Compressive strength	ASTMC349 [27]	3 days	MPa	22.6
		7 days	MPa	27.5

Aggregate

Local crushed coarse and fine aggregate were provided from Iraq. The gradations for fine aggregate and coarse aggregate are displayed in Figure 4, which were tested according to ASTM C33/86 [28]. Table 4 shows the properties of aggregate, which were examined in accordance with ASTM C 128 [29].

**Figure 4. Aggregate grading: (a) Fine aggregate; (b) Coarse aggregate****Table 4. Physical properties of aggregate**

Type	Gravity(SSD)	Gravity	(Kg/m ³)	(Kg/m ³)	Content (%)	(%)
Coarse aggregate	2.49	2.53	1632	1451	-	0.87
Fine aggregate	2.67	2.76	1861	1712	0.24	1.65

3.4. Test Procedure

Testing was carried out after the cast-in-site concrete had aged for 28 days. As shown in Figure 5, all specimens were loaded with a consistent distribution of bagged cement weighing 50 kg per bag and accessible on-site. Two reinforced concrete beams support each specimen on two sides. The deflection and slip of the slabs along the span and the distribution of cracks were all measured. The deflection was measured using a dial gauge positioned in the middle of the slab. In addition, dial gauges were mounted horizontally on both slab ends to determine the relative interface slip.



Figure 5. Experimental loading of slab specimen

4. Discussion of Results

4.1. Cracking Behavior and Failure Mode

For all slabs, the flexural cracks appeared and propagated at different locations in the middle region of the slab. The cracks initially performed in the central area of the slab, as displayed in Figure 6. The cracks' length and width increased with the load until the failure occurred. The cracks on the bottom side of the specimen indicate that tensile stress was induced on the bottom surface of the slab. Flexural failure observed in most of the slabs, but there were two specimens (S1 and S6) where interface debonding failure was detected before flexural failure. The interface debonding between the semi-pre-casted slab and overtopped concrete layered was due to the few bond shear strength between their surfaces. However, for all the other tested slabs, the connections improved the slab interface bond shear strength compared to the slab without steel connectors (S6). So, it can be noticed that decreasing the spacing between triangular connectors in the S5 specimen improved the slab's behavior compared with the S1 specimen. This reveal that the type of failure depends on the spacing between connectors; therefore, to attain good composite behavior in this slab system, the interface bond connectors are very necessary. However, the failure of the slabs changed from debonding to flexural failure using the shear connectors. Rectangular stirrups avoided the debonding failure at the connection between the two slab components with small spacing. This is due to the fact that the horizontal component force of the connectors significantly strengthens the flexural resistance of the joint, while the vertical component force made the precast concrete units attach strongly with cast-in-site concrete.

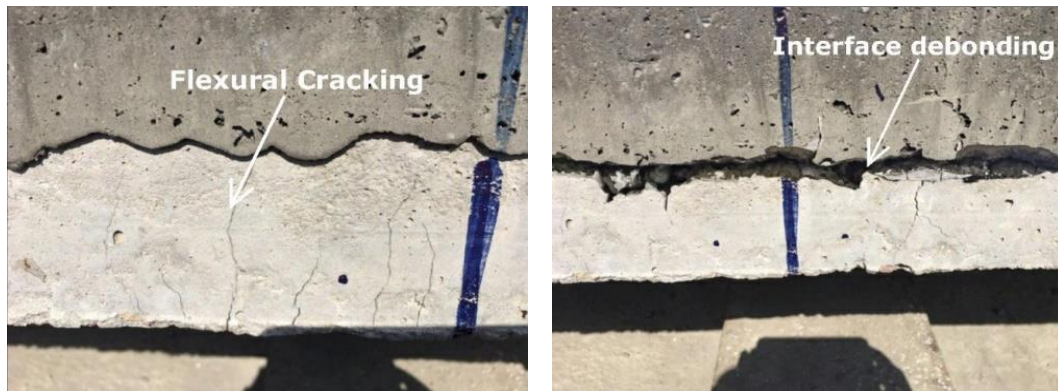


Figure 6. The typical failure mode of tested slabs

4.2. Load-Deflection Performance

The load-deflection curve for all specimens was linear up to the first cracking load, then the nonlinearity was detected until the failure load. From the results shown in Figures 7 and 8 and Table 5, it can be noticed that the presence of shear connectors led to an increase in the stiffness, cracking load, ultimate load, and the mid-span deflections at the same loading level corresponding to the control slab specimen (without connectors). As compared to S6, the ultimate load rose by about 55.56 %, 75.00 %, 91.67 %, 136.11 %, and 86.11 % for S1 through S5. However, the semi-precast slabs S1 and S6 have the lowest ultimate load value relative to other tested slabs due to the low shearing bond strength between the precast concrete unit and the cast-in-site concrete part. As a result, the interface connectors are required before the cast overtopping concrete part for the semi-precast slabs to improve bond strength, structural behavior, and ultimate load capacity.

Table 5. Cracking and maximum loads and their corresponding deflections of slabs

Slab	Cracking Load P_{cr} (Ton)	Ultimate Load P_u (Ton)	$\frac{P_{cr}}{P_u}$ %	Ultimate Load P_u (Ton)	$\frac{P_{u1}-P_{u2}}{P_{u5}}$ %	Cracking Deflection (mm)	Ultimate Deflection (mm)
S1	1.23	5.6	22.0	5.6	55.56	0.7	20.0
S2	1.56	6.3	24.8	6.3	75.00	0.78	24.1
S3	1.75	6.9	25.4	6.9	91.67	0.86	33.6
S4	1.85	8.5	21.8	8.5	136.11	0.94	34.3
S5	1.65	6.7	24.6	6.7	86.11	0.82	18.7
S6	0.84	3.6	23.3	3.6	-	0.42	16.6

* P_{u5} =Ultimate load for S6 slab; P_{u1} =Ultimate load for other slabs.

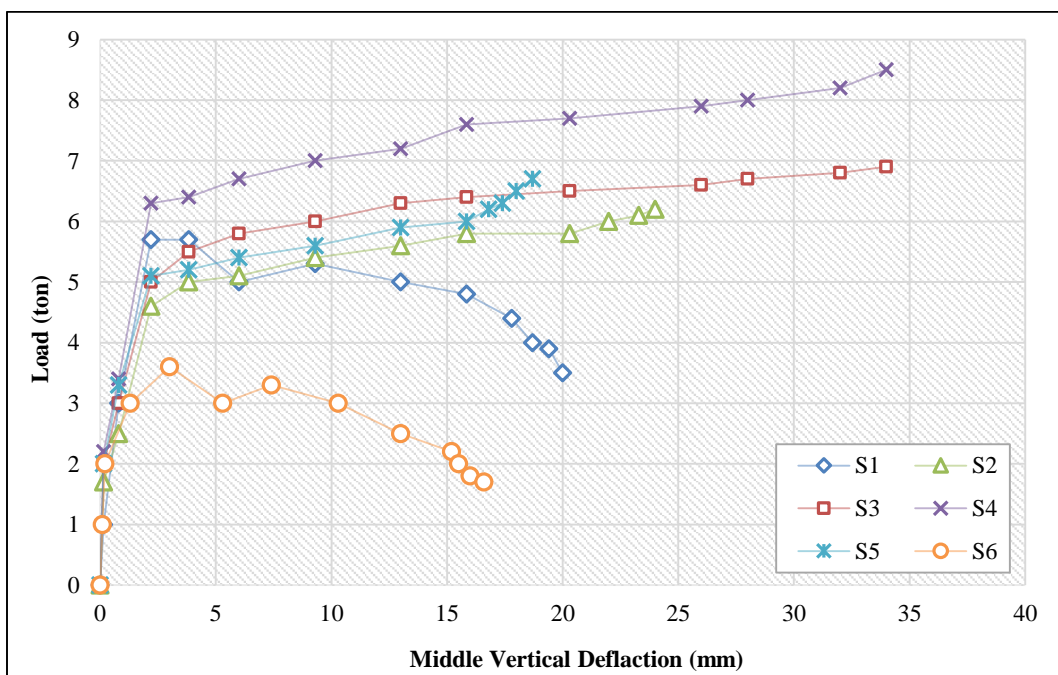


Figure 7. Load-mid deflection responses of all slabs

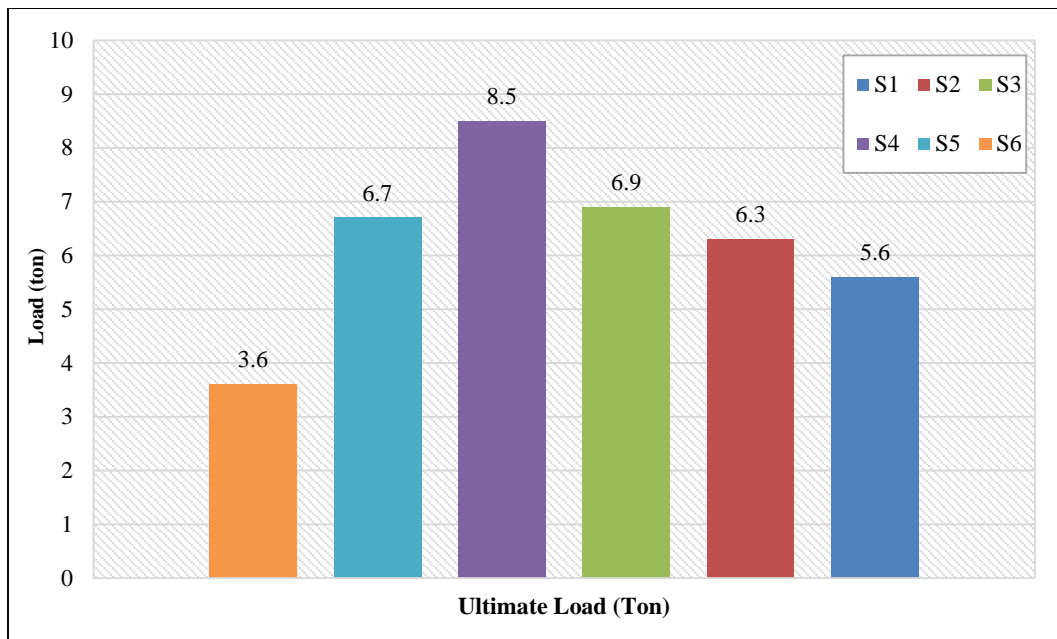


Figure 8. Ultimate load for tested slabs

Rectangular connections seem to have a higher ultimate load, rising between 20% and 50% above triangular connectors. Rectangular shear connections were more effective on semi-precast slab behavior than triangular ones. Compared with specimens without connections, the ultimate load rose by about 81.4% in slabs with RT connections and 54.9% in slabs with TT connections as the spacing was reduced from 600mm to 300mm. Therefore, it can be concluded that lowering stirrups spacing enhanced the ultimate load for slabs, and this is attributed to the addition of steel in the form of shear connectors, which leads to an increase in slab stiffness and bond strength between its units. Further good agreements between result of current study and previous studies were found that surface treatment methods have influenced on the flexural behavior of the slabs.

4.3. Interface Slip

As demonstrated in Figure 9, the interface slip is visible in the S6 and S1 specimens, but the interface slip in the other slabs was small. This behavior was acceptable with the failure mode detected in these slabs this consequence to bond strength provided by stirrups reinforcement.

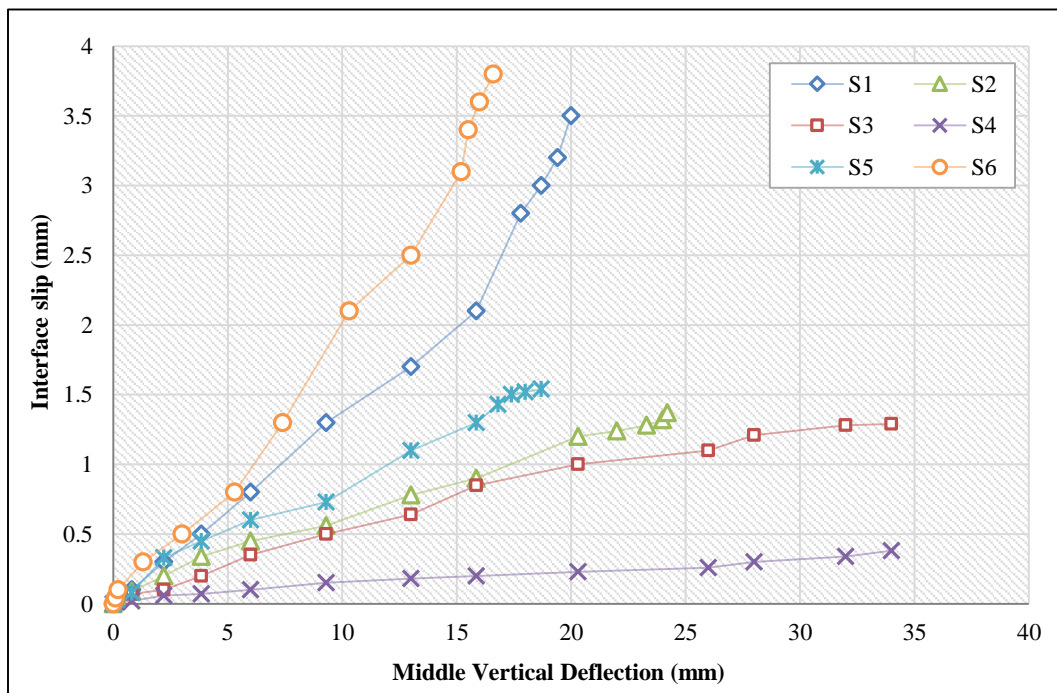


Figure 9. Slip-mid deflection responses for the slabs

4.4. Ductility

It is defined as the ability to sustain inelastic deformations without losing the strength capacity until failure. The present study assessed the ductility according to the vertical deflection at the maximum load divided by vertical deflection at the service load [23]. In reinforced concrete structures, structural ductility is critical to guarantee that sudden and brittle failure of structures is avoided. Significant deflection that occurs in ductile structures ensures sufficient prior warning of the impending failure of the structure [24]. It was noted that using stirrups as connectors in semi-slab system could increase the slab ductility. As shown in Table 6 and Figure 10, the specimens (S1, S2, S3, S4, and S5) with connectors between slab parts showed greater ductility factors of roughly 1.2%, 16.3 %, 44.2 %, 43.0 %, and 3.5%, respectively, than the reference specimen (S6). S3 and S4 exhibit higher ductility than all specimens because of the large number of stirrups that improve the bond strength between slab units.

Table 6. Ductility ratio of all tested specimens

Slab	Yielding Load (Ton)	Ultimate Load P_u (Ton)	Yielding Deflection Δ_y (mm)	Ultimate Deflection Δ_u (mm)	Ductility factor $\mu = \frac{\Delta_u}{\Delta_y}$	$\frac{\mu - \mu_s}{\mu_s} \%$
S1	4.1	5.6	2.3	20.0	8.7	1.2
S2	5.2	6.3	2.4	24.1	10.0	16.3
S3	5.6	6.9	2.7	33.6	12.4	44.2
S4	5.8	8.5	2.8	34.3	12.3	43.0
S5	5.2	6.7	2.1	18.7	8.9	3.5
S6	2.5	3.6	1.9	16.6	8.6	-

* μ_s = Ductility for S6 slab, μ_i = Ductility for other slabs

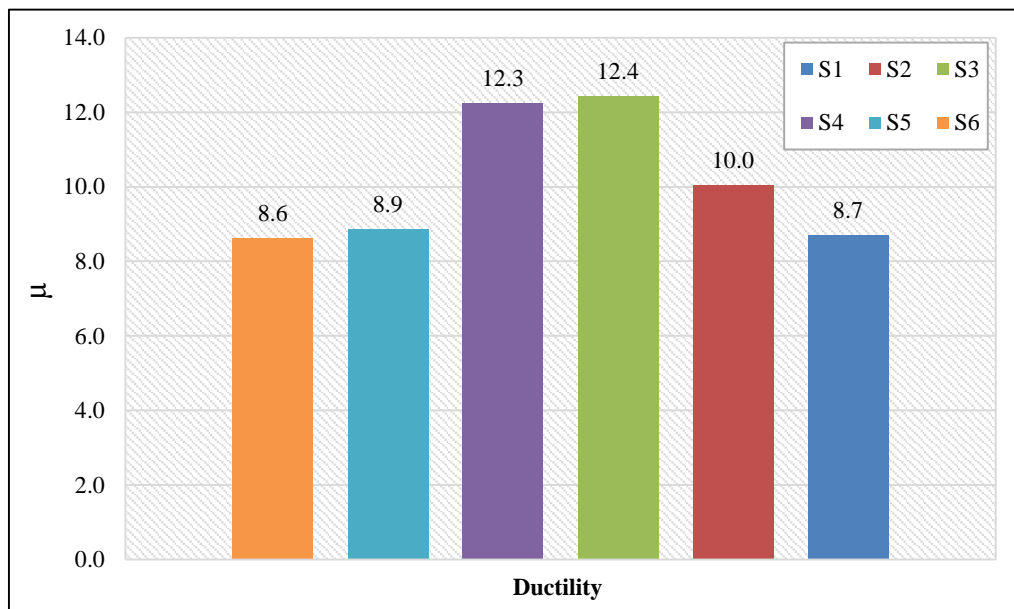


Figure 10. Ductility ratio of all tested specimens

4.5. Stiffness Criteria

It is the load needed to cause one unit of deformation in a member. The slope of the secant is drawn in the hysterical curve at loading at 75% of the ultimate load [25]. The stiffness of all slabs is presented in Table 7 and Figure 11. All slabs had increased elastic stiffness of 24.4, 29.6, 36.9, 62.8 %, and 55.1 % for S1, S2, S3, S4, and S5, respectively. This rise could be linked to the inclusion of steel connectors, which leads to an increase in the bond between the slab's parts.

Table 7. Stiffness of all tested specimens

Slab	0.75 P_u (Ton)	Deflection at 0.75 P_u (mm)	Stiffness K Ton/mm	$\frac{K_i - K_s}{K_s} \%$
S1	4.2	2.5	1.68	24.4
S2	4.7	2.7	1.75	29.6
S3	5.2	2.8	1.85	36.9
S4	6.4	2.9	2.20	62.8
S5	5.0	2.4	2.09	55.1
S6	2.7	2	1.35	-

* K_s = Stiffness for S6 slab, K_i = Stiffness for other slabs

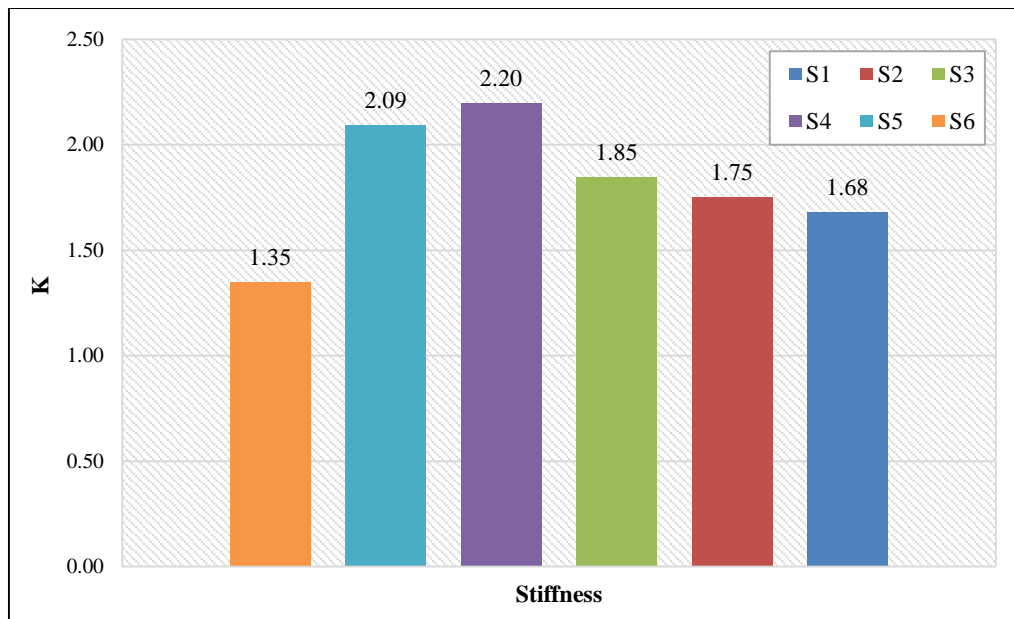


Figure 11. Stiffness of all tested specimens

5. Conclusion

The goal of this study is to perform an experimental investigation to understand the behavior of semi-precast slabs. The results found that semi-precast reinforced concrete slab systems could replace traditional in situ slab and heavy precast slab construction techniques. The bond strength between semi-slab components is the main concern of it, so to increase the bond strength, shear connectors like stirrups could be used between slab components. In general, the shear connectors can improve structural behavior, ductility, and stiffness of semi-precast slabs. Also, a flatter load-deflection curve shows a softer response using shear connectors. This is particularly true when there is a higher number of stirrups between precast concrete units and cast-in-site concrete units. However, semi-precast slabs with rectangular shear connectors exhibit advanced values of ultimate load-carrying capacity than triangular shear connectors. Where, the tests found that slabs with rectangular or triangular connectors have maximum load capacity more than reference slabs, reaching 136.11% and 86.11%, respectively, as compared with specimens without connectors. Additionally, the result found that higher number of stirrups can improve the structural behavior and the bond strength between slab parts. On the other hand, the failure mode of the slabs changed from debonding to flexural failure by using stirrups as shear connectors, especially those with a rectangular shape. However, as the distance between triangular shear connectors dropped to 300mm, the failure mode of specimens was altered from interface slip to flexural failure, and this significance to bond strength was provided by stirrup reinforcement. Further investigation is required to better understand the performance of the semi-slab system. The areas, which are to be of particular importance are two-way semi-slab, semi-slab with edge beam, thickness unite of slab, different sizes of slab, and theoretical study of semi-slabs.

6. Declarations

6.1. Author Contributions

Conceptualization, M.A., and K.A.M.M.; methodology, M.A., and K.A.M.M.; validation, M.A.; investigation, M.A.; resources, M.A.; data curation, M.A.; writing—original draft preparation, K.A.M.M.; writing—review and editing, K.A.M.M.; visualization, K.A.M.M.; supervision, K.A.M.M.; project administration, M.A.; funding acquisition, M.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in article.

6.3. Funding and Acknowledgements

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

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