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Experimental Tests on Orthotropically RC Rectangular Slabs Having Various Restrained Edges and Subjected to Uniform Load

Hisham M.AL-Hassani* ,Husain M. Husain*

& Sarmad S. Abdul-Qader AL-Badri*

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Abstract

In this research, nine orthotropically reinforced concrete (RC**)** rectangular slabs having various boundary restraints at the edges are tested under uniformly distributed load. The main aim of these tests is to show that when some or all edges of a slab are restrained against rotation and horizontal translation the ultimate load carrying capacity of the slab will be enhanced greatly above that suggested by the simple Johansen 's yield line theory(1). For this purpose, a specially designed rig is constructed and used for providing slabs with various boundary restraints along their edges.

The results of tests, which are presented in the form of load-deflection curves plotted non-dimensionally, show that for restrained slabs the enhancement in load above Johansen 's load ranges between 50% and 100% depending on the number and positions of the slab restrained edges. These results are also used to examine the accuracy of a recently submitted elastic-plastic theoretical model(2).

Keywords: experimental test; orthotropic; reinforced concrete; slab

الفحوصات العملية للبلاطات الخرسانية المستطيلة الشكل والمسلحة تسليحاً مختلفاً في الأتجاهين المتعامدين وتمتلك حافات أسناد مختلفة ومسلط عليها حمل منتشر

الخلاصة

في هذا البحث تم فحص تسع بلاطات مستطيلة ومسلط عليها حمل منتشر وذات تسليح مختلف في الأتجاهين المتعامدين مع الأخذ بنظر الأعتبار تغير حالات الأسناد لنهايات البلاطة. الهدف الرئيسي من هذه الفحوصات هو لأظهار أن البلاطات الخرسانية المقيدة من الدوران والحركة الجانبية تعطي قوة تحمل أعلى من نظرية خط الخضوع المبسطة(1). لهذا الغرض تم أنشاء هيكل خاص يسمح بتغير حالات الأسناد لحافات البلاطة .

تم أظهارها النتائج المستحصلة من هذه الفحوصات على شكل علاقة بين الحمل و الهطول، أظهرت هذه النتائج بأن النسبة المؤية للزيادة في التحمل عن نظرية خط الخضوع يتراوح بمقدار 50% الى 100% بالأعتماد على عدد وموقع الحافات المقيدة للبلاطة. تم أستعمال النتائج العملية للمقارنة مع الطريقة النظرية للحل المرن - اللدن(2).

Notations

d	Effective depth of slab,
f_c'	Specified compressive strength of concrete by cylinder test (*MPa*) ,
f_y	Yield stress of steel reinforcement (*MPa*),
h	Overall depth of slab,
l_b	Long span of rectangular slab,
l_a	Short span of rectangular slab,
q	Uniformly distributed load per unit area,

* Building and Construction Department , University of Technology/Baghdad

q_J Ultimate uniformly distributed load per unit area given by Johansen's yield line theory,
w Vertical deflection at centre of slab, and
ρ Ratio of steel area to effective area of concrete = A_s / d ,

Introduction

The phenomenon of membrane action in RC slabs was mainly introduced by Ockleston[3] in his prototype test on a dental hospital building in Johannesburg, Powell[4] in his Ph.D thesis and Wood[5] in his famous book. They confirmed experimentally and analytically that when the edges of the slab are restrained against rotation and horizontal translation, membrane action will be developed in the slab which enables the slab to carry load far beyond that predicted by Johansen 's yield line theory. Many researchers, thereafter, such as Christiansen[6], Park [7,8], Sawczuk and Winnicki[9] , Maher[10] , Roberts [11] , Datta and Ramesh [12] , Desayi and Kulkarni [13] , Al-Hassani [14], Ouyang and Swaris[15], Rankin et. al.[16] and some others reported experimental ultimate loads of restrained slab models that were extraordinarily large. However, in the majority of these tests the slabs were considered to be either partially restrained against longitudinal expansion or fully restrained against rotation and lateral movement.

Since the present of restraining condition at some or all edges of a RC slab can affect its flexural performance, it is aimed from the present research to provide experimental data on the tests of RC rectangular slabs having the nine possible boundary condition cases shown in Figure (1).

Experimental Work

Nine concrete rectangular slabs having orthotropic reinforcement in the two directions and different boundary restraints were cast and tested under uniform load to obtain actual load-deflection curves for such slabs. All the slab models were rectangular of size 1100*750*25 *mm* but when placed over supports gave clear spans of 900*550 *mm*. A concrete mix of (1:1.75:2) with water/cement ratio of (0.52) was used in all slab models. The slab models were reinforced with 2.6 *mm* diameter smooth steel wires. Three specimens of these wires were tested under direct tension by using the tensile testing machine available in the laboratory of the Department of Minerals and Production Engineering in the University of Technology, (Photo 1). The test gave an average tensile yield stress of the three steel wires of 396 *MPa* and their idealized average stress-strain relationship is shown in Figure (2).

Details Of The Test Slabs.

Each test slab was orthotropically reinforced with 2.6 *mm* diameter steel wires in the two orthogonal directions. The steel wires were placed at the bottom face of the slab in the positive moment regions occurring at the slab central area and at the top face of the slab in the negative moment regions adjacent to fixed supports. Figure (3) shows the notations used for the steel ratios at different locations in the slab. The reinforcement running in the short direction of the slab had a 5 *mm* concrete cover. The ratio of steel reinforcement provided in the short span was (r_a^+ =0.36%) for positive moment region and (r_a^- =0.72%) for negative moment regions if present. In the long direction, the ratio of steel reinforcement was (r_b^+ =0.26%) for positive moment region and (r_b^- =0.52%) for negative moment regions if present. The details of the nine test slabs are shown in Table (1). It can be seen from this table that all steel ratios were carefully designed and computed to be larger than the minimum value for shrinkage and temperature required by ACI-05 code[17].

Casting And Curing.

Having constructed the specimen 's mould, the reinforcing steel wires were orthotropically arranged along the two orthogonal directions of the mould and carefully placed in position by using tying wires. In order to get a constant clear cover, small pieces of steel wires having 5 *mm* diameter were placed under the bottom layer of the reinforcement mesh. Photos (2) to (7) show the pattern of the reinforcement mesh used in some cases of the test slabs.

Mixing of materials was performed in accordance to ASTM C 192[18]. The procedure used involved first, adding all the aggregate into the mixer with half the quantity of water, mixing for a short time then adding the remaining ingredient of cement followed by the remaining water quantity. The components were then mixed for a period of five minutes. This procedure yielded a well mixed concrete.

To assess the compressive strength of concrete, three steel cylindrical moulds having 100 *mm* diameter and 200 *mm* height were used to cast the concrete control specimens according to ASTM C39-86[19].The three cylinders of control specimens were also oiled and prepared. Thus a system of a slab mould and three control cylinders were placed on a table vibrator. After the concrete had been mixed, casting was carefully performed. The vibrator was switched on for a small period till a perfect concrete compaction was achieved, and the slab surface was then carefully leveled.

After one day curing by means of wet jute sacks, the slab model and the three control concrete cylinders were stripped off their moulds and covered by wet jute sacks for 28 days before exposing to normal weather condition to get a surface dry condition then the slab and the control specimens were tested. The three control concrete cylinders were tested under direct axial compression to get the concrete compressive strength (f_c'). An average result of three specimens was adopted for each test as listed in Table (1).

The Testing Rig And The Restraining Requirements At The Slab Edges.

A slab to be tested was supported on a stiff rectangular frame fabricated from steel. Photo (8) shows a RC rectangular slab fixed along three edges while the fourth long edge is simply supported (slab case 8).

To achieve a fixed edge in a slab model (represented by end condition 1 in Figure 4), a steel channel was placed on the top face of the slab at that edge which was tightened firmly to the slab by using 12.7 *mm* diameter steel bolts. The number of steel bolts used to fix a long and a short edge in a slab model was 4 and 3 respectively (see Photo 8) and they were positioned such that one steel bolt was used at each corner of the slab to prevent it from any possible uplift during the slab loading process in additions to two more bolts in a long fixed edge and one "central" bolt in a short fixed edge. A steel plate was also used at each fixed edge which was tightened to the edge by using horizontal steel screws to prevent any possible lateral movement of that edge.

A simply supported edge in a slab model (represented by end condition 2 in Figure 4) was achieved by simply placing the slab over a steel plate connected to the testing frame through welding, and without using any vertical bolts or horizontal screws so that the edge was free to rotate and move horizontally.

System Of Loading And Testing Procedure.

Uniformly distributed load is the most common load encountered in practice. In the laboratory such load can be produced by using a large number of point loads applied through hydraulic jacks, for example *Wood*[5] used 16 point loads which were distributed uniformly over the entire surface of the slab to represent uniform loading, while *Johansen*[1] used

24 point loads to obtain uniformly distributed load (UDL). Alternatively hydrostatic or pneumatic pressure can be applied on a test slab as used by *Hayes*[20] , while *Sawczuk and Winnicki*[9] and *Park*[7,8] achieved UDL by applying water pressure to the bottom face of the slab. The uniform load can somehow be produced using sand as was adopted by *Al-Shadidi*[21] and *Hassan*[22].

In this research, the uniform load was furnished as follows

i) Using one layer of 50 mm diameter steel ball distributed uniformly over the entire surface of the slab which were held in position by using a steel box placed on the slab directly over the supports (as shown in Figure 5)

ii) More load was applied using small sacks of sand distributed uniformly over the layer of steel balls.

iii) In cases of restrained slabs, additional load was added on the slab using fragments of steel distributed over the sacks of sand.

It is to be noted that the steel box placed on the slab periphery was coated with a sheet of nylon to prevent any possible friction between the ingradients of the applied load and the inner surface of the steel box. This system of loading had caused the slab to fail in form of patterns which were satisfactory with the patterns adopted theoretically, as will be observed in the next articles.

A dial gauge of 50 *mm* maximum reading was used to measure the vertical deflection of the test slabs at centre for every increment of the applied loading. The procedure of loading and deflection measurement continued until excessive values of deflections were recorded indicating that the slab was on the verge of failure.

Results Of The Ultimate Loads And Load-Deflection Relationships Of The Test Slabs.

Table (2) contains the results of the experimental ultimate loads ($q_{u\,exp.}$) for the nine tested RC rectangular slabs together with their corresponding theoretical value ($q_{u\,theo.}$) obtained from the proposed elastic-plastic model by *Abdul-Qader*[2]. For more information, the values of *Johansen*'s[1] collapse loads (q_J) for these slabs are also listed in the table and the load ratios

$$\left(\frac{q_{u\,exp.}}{q_J}\right), \left(\frac{q_{u\,theo.}}{q_J}\right) \text{ and } \left(\frac{q_{u\,exp.}}{q_{u\,theo.}}\right)$$

for each test slab are calculated and shown for comparison. It can be seen that the proposed elastic-plastic model by *Abdul-Qader*[2] can predict the ultimate load of any orthotropic RC rectangular slab having certain restraining conditions at the edges with a reasonable accuracy.

The complete load-deflection behaviour of a generalized uniformly loaded orthotropic RC rectangular slab as predicted by *Abdul-Qader*[2] has also been examined. Figures (6) to (14) represent the theoretical and experimental load-deflection curves for the nine rectangular RC test slabs. In these figures, the horizontal straight line represents the value of *Johansen* 's[1] load. From these plots, the following conclusions may be drawn :

1- The load-deflection curves of the test slabs are found to be fairly comparable with the corresponding theoretical curves predicted by *Abdul-Qader*[2].

2- It is found that in all test slabs, there is a distinct reduction in the stiffness of the slab after initiation of cracking in the central region of the slab.

3- For an unrestrained RC slab (S_1), there is a continuous rise in the load-deflection curve beyond *Johansen* 's[1] load (post-yielding behaviour) which indicates that the slab can sustain higher load than *Johansen*'s[1] load at any large value of deflection.

4- For restrained RC slabs (S_2 to S_9), after the ultimate load has been reached the load decreases with further deflection owing to the reduction in the compressive membrane forces. With more deflection the membrane forces in the central region of the slab change from compression to tension. At this stage, because of the large stretch of the slab surface, the cracks in the central region penetrate the whole thickness of the concrete and yielding of steel spreads throughout the region enabling the load to be carried by the reinforcement acting as a tensile membrane. With further deflection, the slab shows a recovery of load enhancement and such increase in load continues until the reinforcement starts to fracture.

Photos (9) to (17) show the cracking pattern of the tested slabs.

Conclusions.

Based on the results of the present study, several conclusions may be drawn. These may be summarized as follows;

1- The analysis shows that orthotropically reinforced concrete rectangular slabs having variably restrained edges can sustain loads more than those predicted by Johansen's yield line theory.

2- The experimental ultimate load of the slab (q_u exp.) is found to be greatest for RC rectangular slabs having all edges restrained against rotation and horizontal translation (i.e fixed). As the number of the restrained edges of the slab decreases the enhancement in the slab load will also decrease. It is when all the edges of the slab are unrestrained (i.e simply supported) that the initial collapse load of the slab will be the simple yield line theory load.

3- The theoretical elastic-plastic model presented recently by *Abdul-Qader*(2) seems to compare reasonably with the experimental results of the present research.

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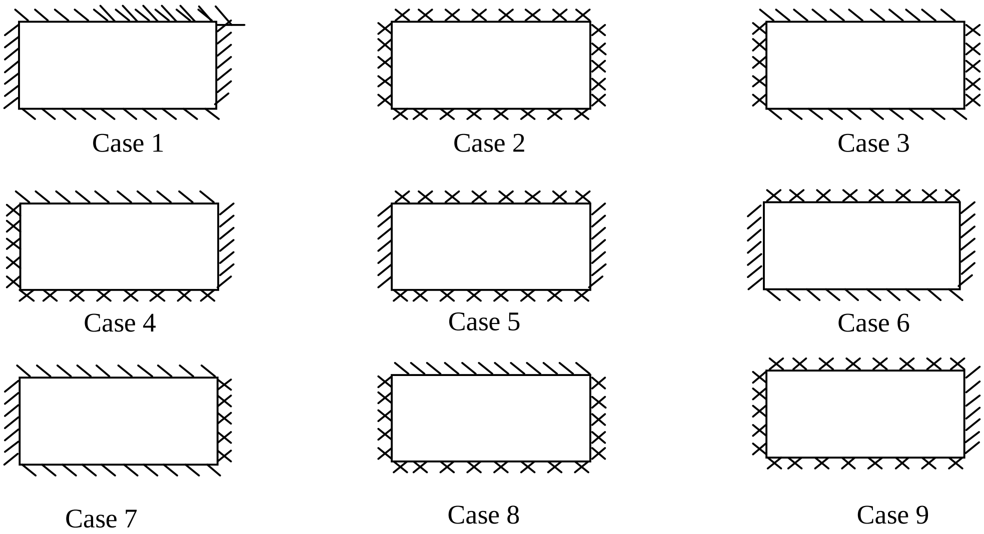
Table (1) Properties of the test slabs.

Slab No.	Support Condition	Dimensions (mm) $l_b * l_a * h$	f'_c MPa	f_y MPa	Percentage of steel reinforcement $(\rho\ \%)$					
					ρ_a^+	$\rho_{a_1}^-$	$\rho_{a_2}^-$	ρ_b^+	$\rho_{b_1}^-$	$\rho_{b_2}^-$
S_1	Case (1)	900*550*25	25.5	396	0.36	0	0	0.26	0	0
S_2	Case (2)	900*550*25	27.1	396	0.36	0.72	0.72	0.26	0.52	0.52
S_3	Case (3)	900*550*25	26.2	396	0.36	0	0	0.26	0.52	0.52
S_4	Case (4)	900*550*25	25.8	396	0.36	0	0.72	0.26	0.52	0
S_5	Case (5)	900*550*25	26.5	396	0.36	0.72	0.72	0.26	0	0
S_6	Case (6)	900*550*25	25.2	396	0.36	0.72	0	0.26	0	0
S_7	Case (7)	900*550*25	26.3	396	0.36	0	0	0.26	0	0.52
S_8	Case (8)	900*550*25	27.4	396	0.36	0	0.72	0.26	0.52	0.52
S_9	Case (9)	900*550*25	25.3	396	0.36	0.72	0.72	0.26	0.52	0

Table (2) Comparison between the experimental and theoretical ultimate loads of the restrained test slabs.

Slab No.	Support Condition	Experimental ultimate load $(q_{u\,exp.})$ kN/m^2	Theoretical ultimate load $(q_{u\,theo.})^{(2)}$ kN/m^2	$(q_J)^{(1)}$ kN/m^2	$\frac{q_{u\,exp}}{q_J}$	$\frac{q_{u\,theo}}{q_J}$	$\frac{q_{u\,exp.}}{q_{u\,theo}}$
S_2	Case (2)	75.52	95.67	50.35	1.50	1.9	0.79
S_3	Case (3)	45.95	51.57	25.53	1.80	2.02	0.89
S_4	Case (4)	60.29	70.02	31.4	1.92	2.23	0.86
S_5	Case (5)	67.3	78.70	39.35	1.71	2.00	0.86
S_6	Case (6)	49.09	53.94	26.97	1.82	2.00	0.91
S_7	Case (7)	38.39	39.02	20.98	1.83	1.86	0.98
S_8	Case (8)	63.4	77.07	36.7	1.73	2.10	0.82
S_9	Case (9)	72.1	91.99	44.44	1.62	2.07	0.78



simply supported or discontinuous edge

fixed (clamped) or continuous edge

Figure (1) The nine possible cases of two –way rectangular slabs supported at all edges.

Photo (1) The tensile testing machine belonging to the laboratory of the Department of Minerals and Production Engineering in the University of Technology which has been used in the present study.

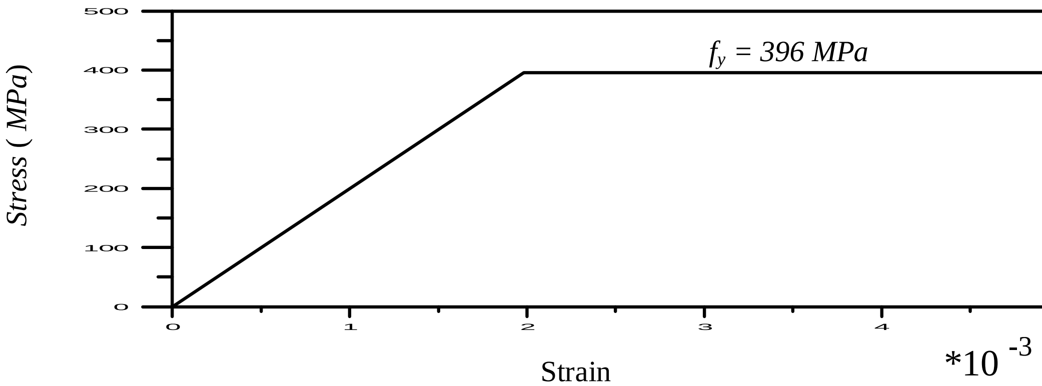


Figure (2) Idealized stress-strain relationship of 2.6 *mm* diameter steel wire.

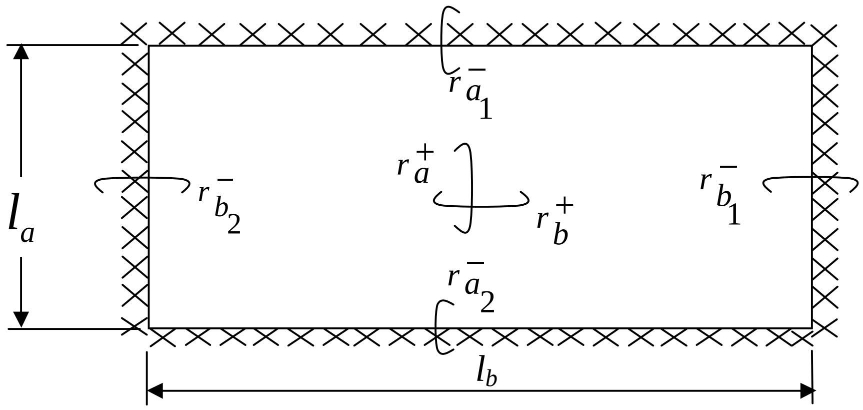


Figure (3) The notations used for the steel ratios at different locations in the slab.

Photo (2) Details of the reinforcement mesh of slab S_1 (case1).

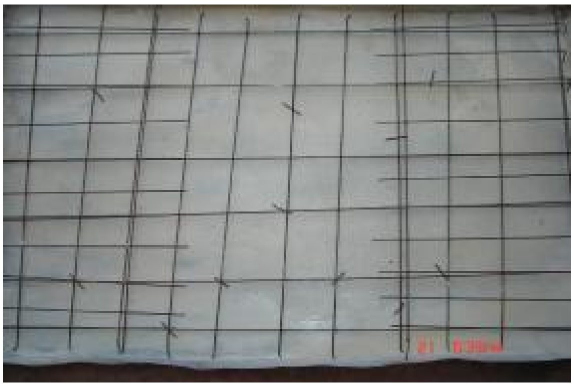


Photo (3) Details of the reinforcement mesh of slab S_3 (case3).

Photo (4) Details of the reinforcement mesh of slab S_4 (case 4).

Photo (5) Details of the reinforcement mesh of slab S_6 (case6).

Photo (6) Details of the reinforcement mesh of slab S_7 (case7).

Photo (7) Details of the reinforcement mesh of slab S_8 (case8).

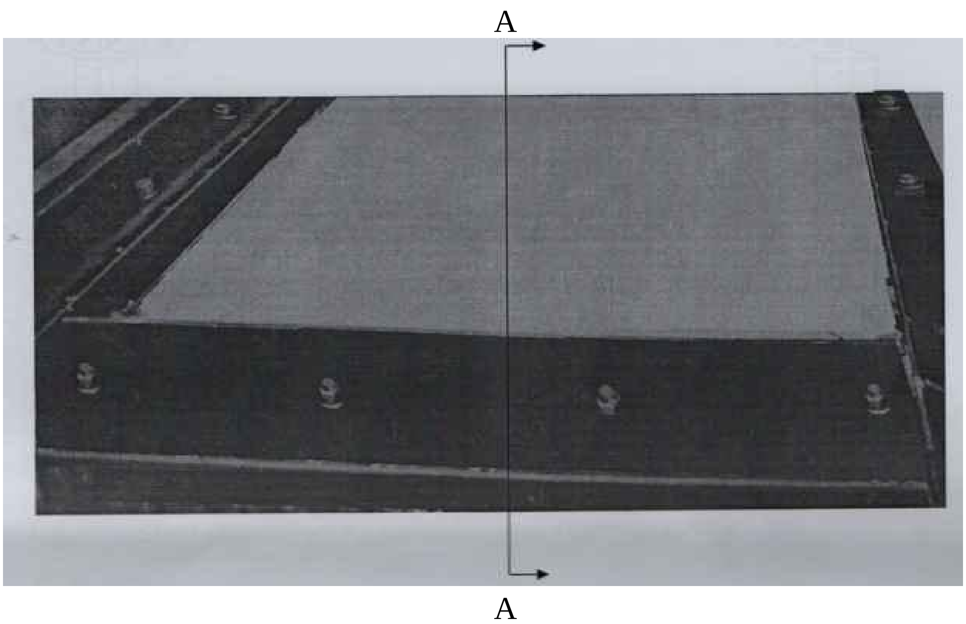
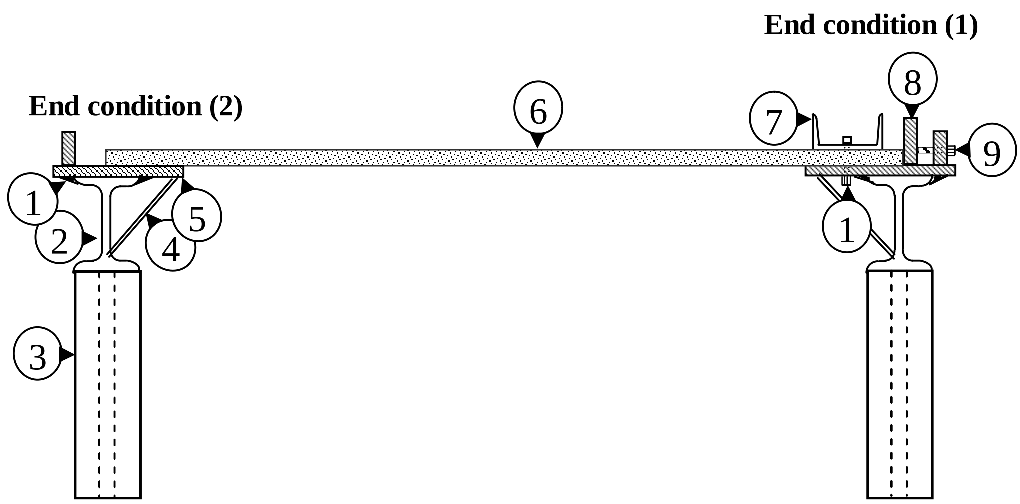


Photo (8) A RC rectangular slab fixed along three edges while the fourth long edge is simply supported (slab case 8) in the test frame prior to testing.
***The details of section A-A are given in Figure (4).**



(1) Welding.

Figure (4) Details of section (A-A).

(2) Rigid surrounding steel frame $(S\,4\times9.5)$

(3) Rigid steel column $(S\,4\times9.5)$

(4) Steel stiffeners (square section $10^{mm}\times10^{mm}$)

(5) Steel plate (type A) (cross section $150^{mm}\times10^{mm}$)

(6) Concrete slab model

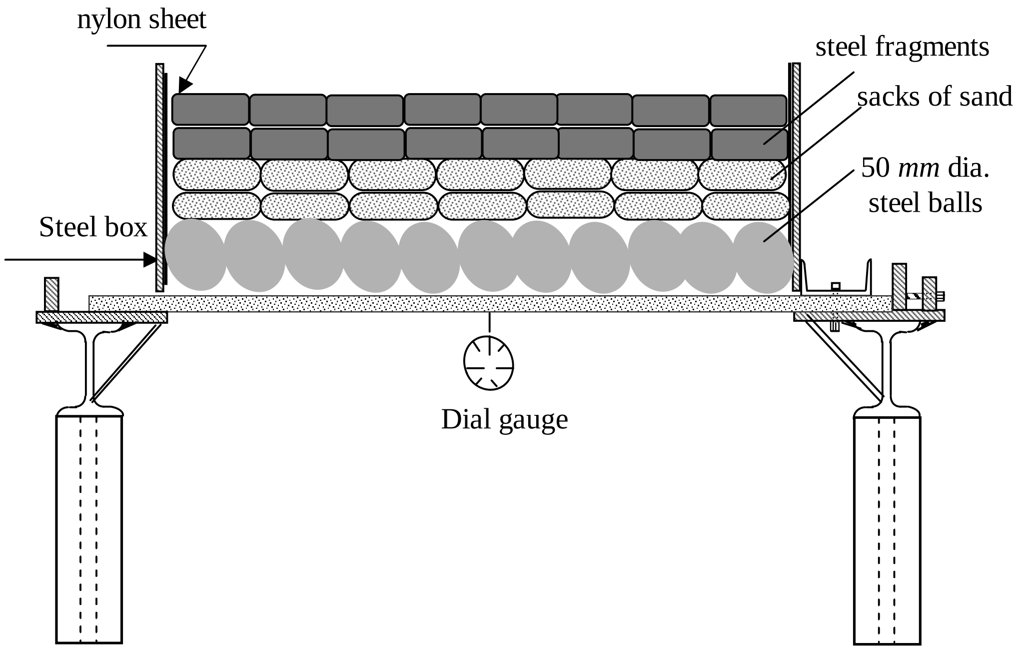
(7) Steel channel $(C\,3\times6)$

(8) Steel plate (type B) (cross section $60^{mm}\times10^{mm}$)

(9) 12.7 *mm* (1/2 in) diameter high-tensile screws at 100 *mm* center to center

(10) 12.7^{mm} (1/2 in) diameter bright steel bolts at 333^{mm} *c/c* in long direction and 325^{mm} *c/c* in short direction

<u>Note:</u> Steel plate (type A) is drilled along their short and long direction with holes of 15^{mm} diameter four holes in longer side and three holes in shorter side the benefit from these holes to connect slab with test frame by bolts when slab tests to give different boundary condition.



Details of sec. (A-A) during test.

Figure (5) The System of loading used to represent uniform load.

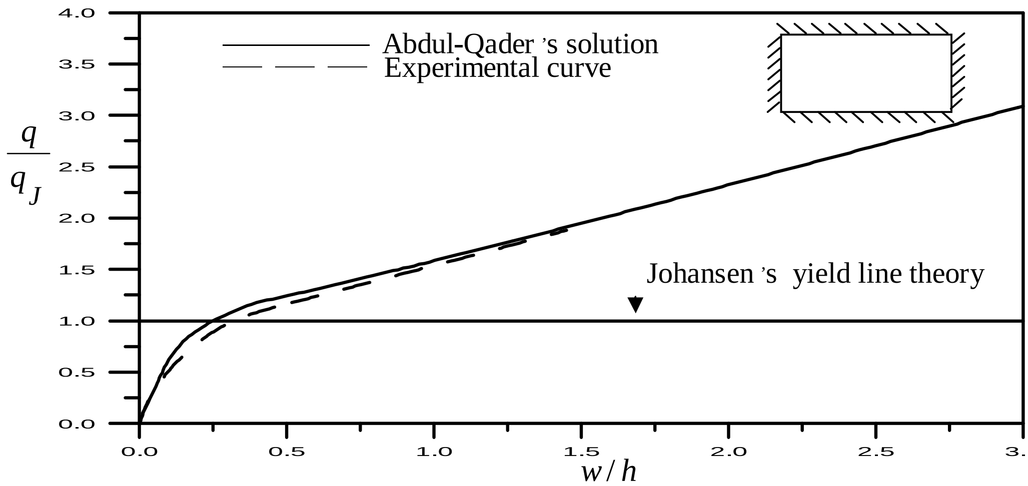


Figure (6) Theoretical and experimental load-deflection curve of an orthotropic RC rectangular slab simply supported at all edges (slab S_1).

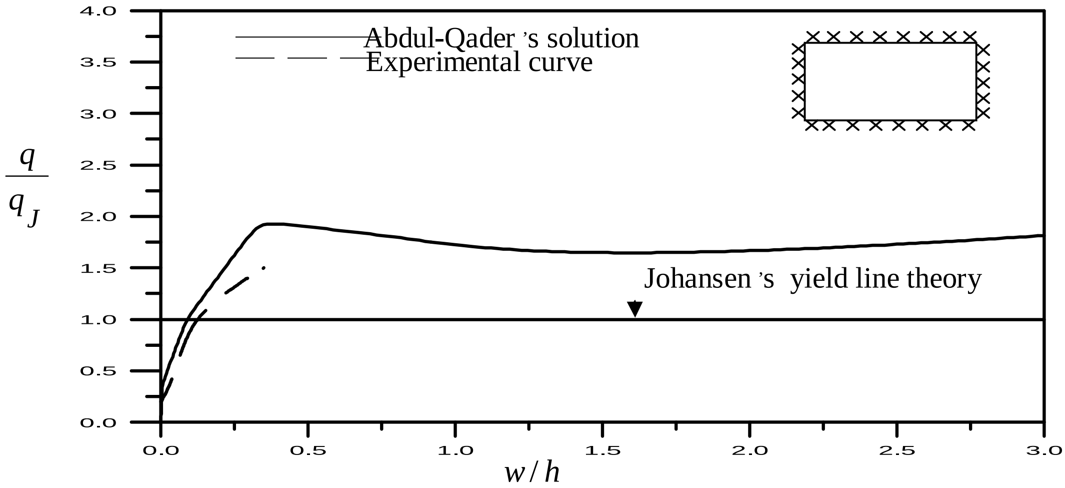


Figure (7) Theoretical and experimental load-deflection curve of an orthotropic RC rectangular slab fixed at all edges (slab S_2).

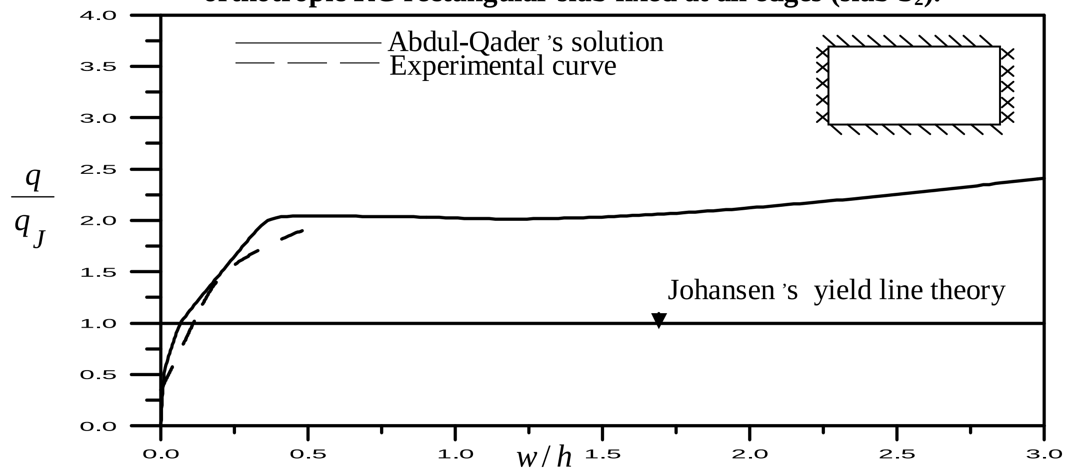


Figure (8) Theoretical and experimental load-deflection curve of an orthotropic RC rectangular slab fixed along the two short edges while the two long edges are simply supported (slab S_3).

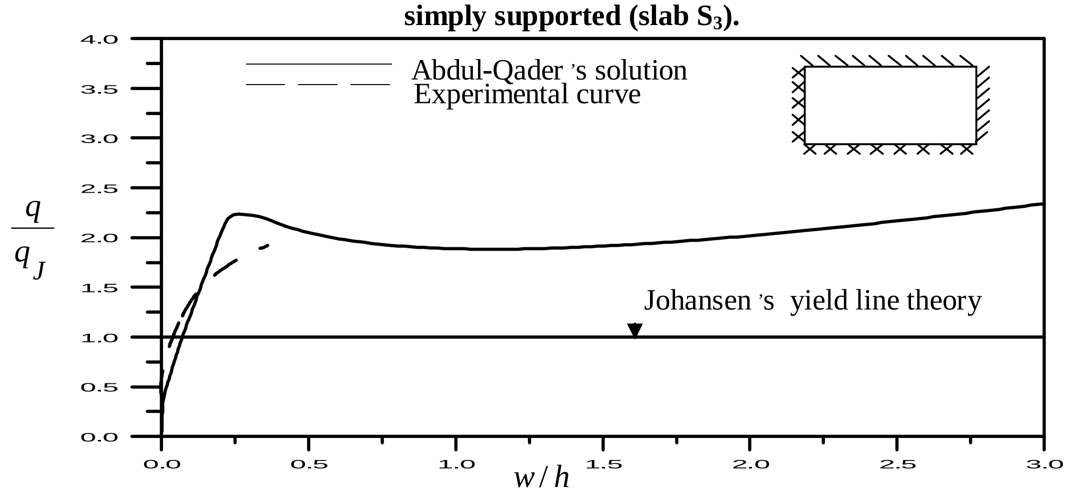


Figure (9) Theoretical and experimental load-deflection curve of an orthotropic RC rectangular slab fixed along two adjacent edges while the other two edges are simply supported (slab S_4).

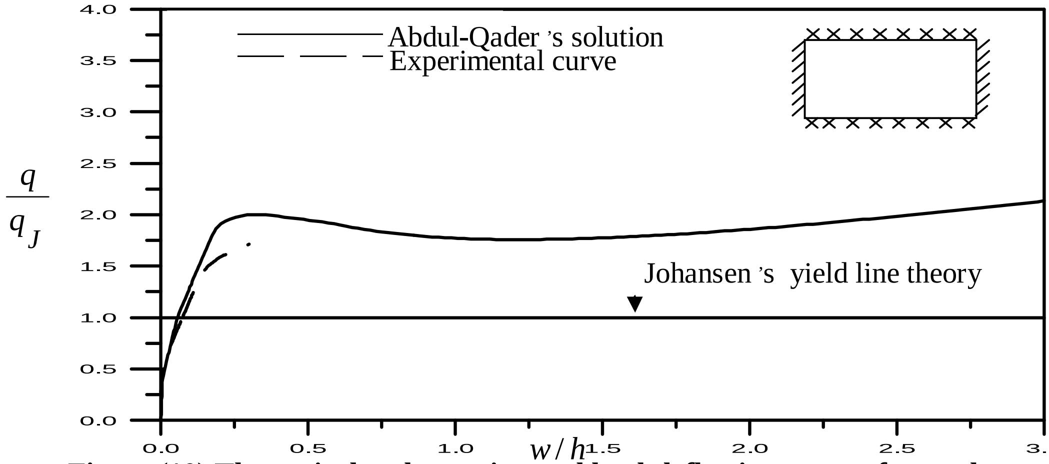


Figure (10) Theoretical and experimental load-deflection curve of an orthotropic RC rectangular slab fixed along the two long edges while the two short edges are simply supported (slab S_5).

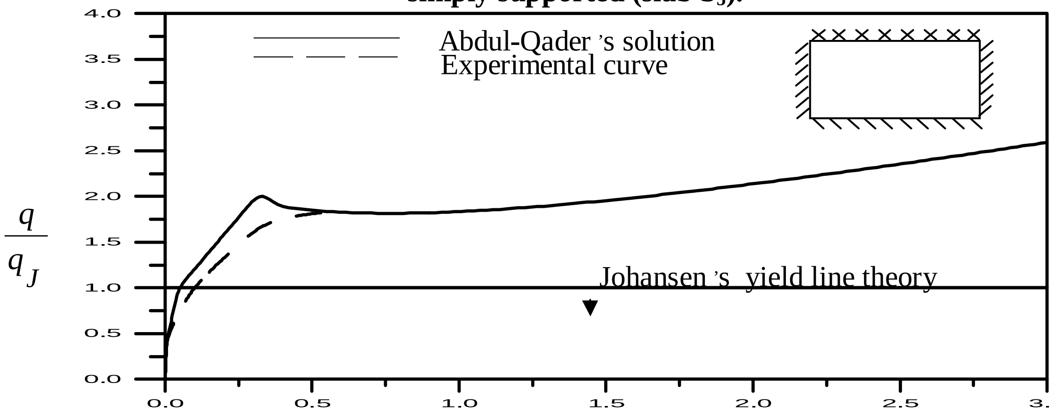


Figure (11) Theoretical and experimental load-deflection curve of an orthotropic RC rectangular slab fixed along one long edge while the remaining three edges are simply supported (slab S_6).

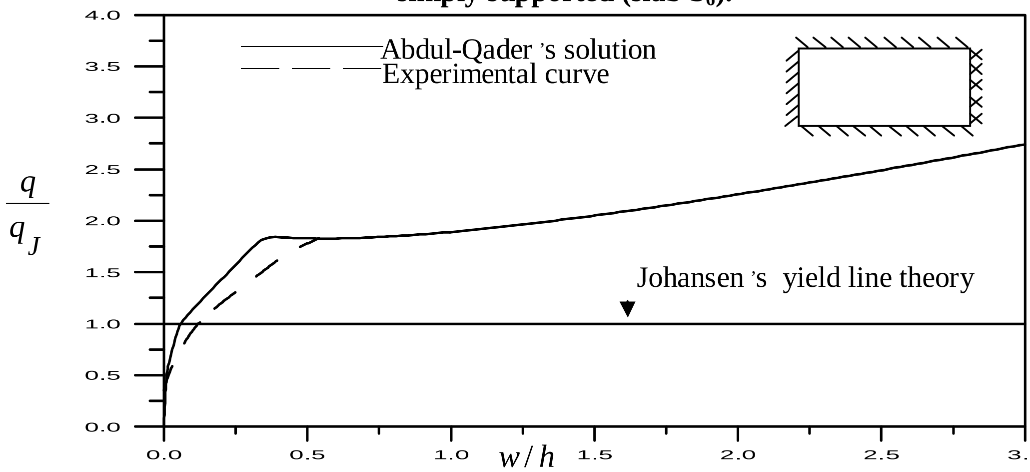


Figure (12) Theoretical and experimental load-deflection curve of an orthotropic RC rectangular slab fixed along one short edge while the remaining three edges are simply supported (slab S_7).

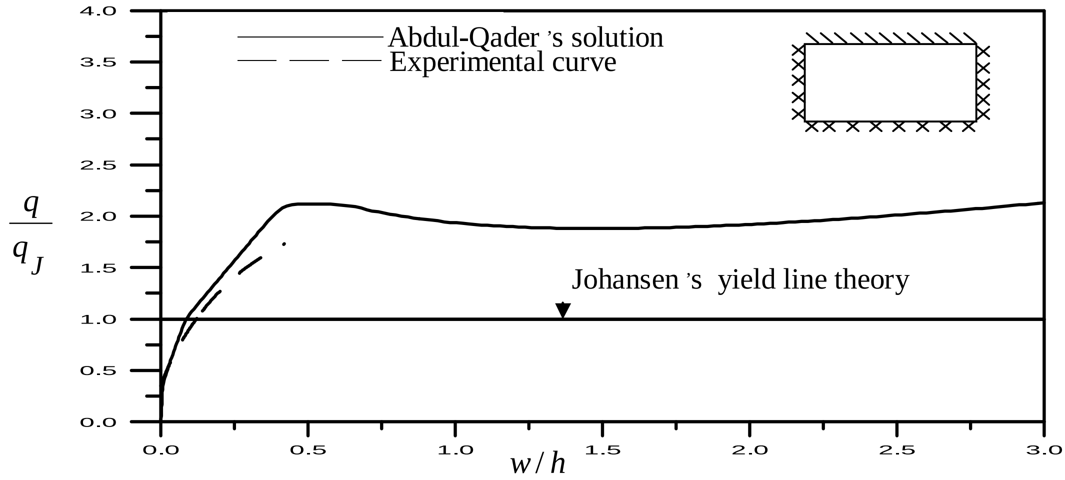


Figure (13) Theoretical and experimental load-deflection curve of an orthotropic RC rectangular slab simply supported along one long edge while the remaining three edges are fixed (slab S_8).

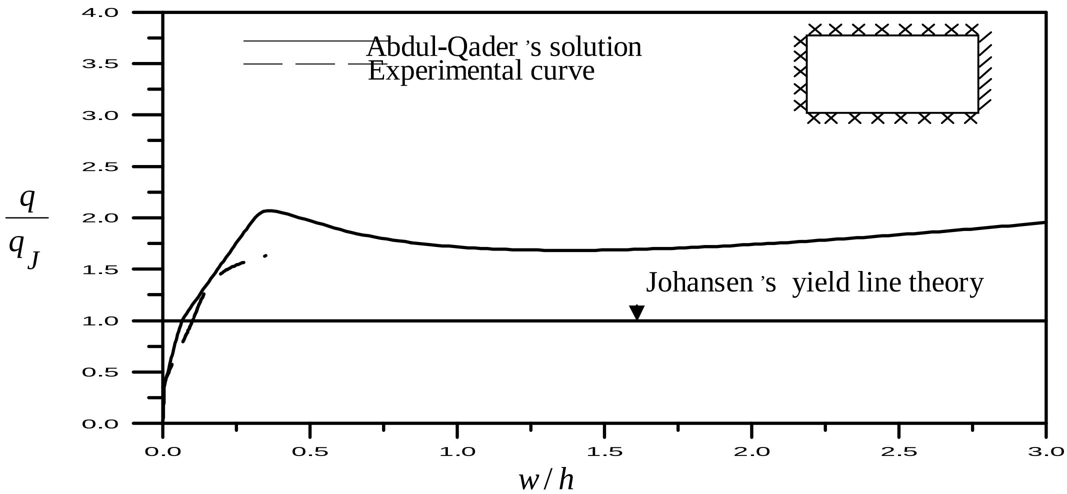


Figure (14) Theoretical and experimental load-deflection curve of an orthotropic RC rectangular slab simply supported along one short edge while the remaining three edges are fixed (slab S_9).

Photo (9) Yield line pattern for slab case (1)

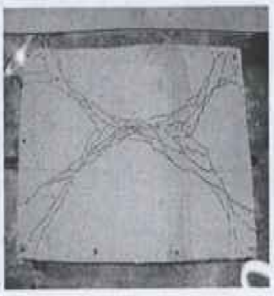


Photo (12) Yield line pattern for slab case (4)

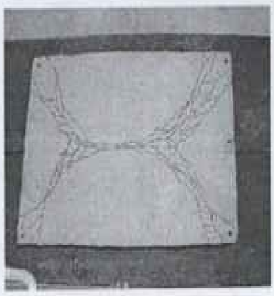


Photo (15) Yield line pattern for slab case (7)

Photo (10) Yield line pattern for slab case (2)

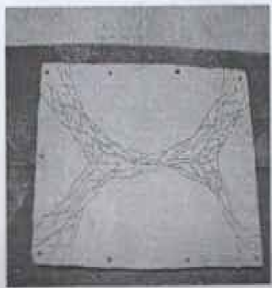


Photo (13) Yield line pattern for slab case (5)

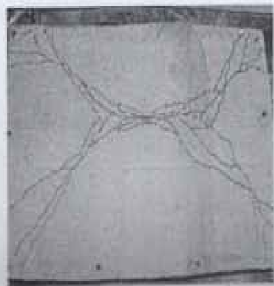


Photo (16) Yield line pattern for slab case (8)

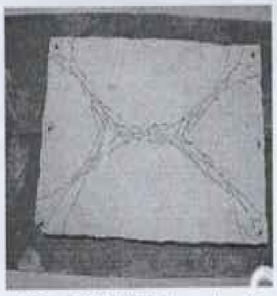


Photo (11) Yield line pattern for slab case (3)

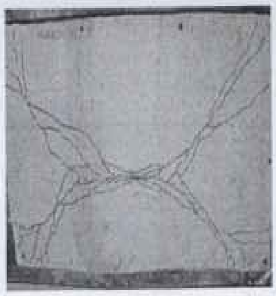


Photo (14) Yield line pattern for slab case (6)

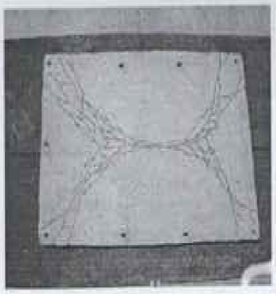


Photo (17) Yield line pattern for slab case (9)