THE ROLE OF MEMBRANE ACTION IN LOAD TEST

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ABSTRACT

Most of the structures subjected to load tests had successfully passed it, although some of them had failed in cube and core tests. It is believed that membrane action may be the most important factor that made them do so. In the present study, an attempt is made to study the effect of membrane action on load test results.

In this study, two space (3-D) model frames, nine panels (3×3), [consisted of rafts, columns, beams and slabs] were prepared for load test.

The results show the positive role of the membrane action especially with camber beams and slabs in successful passing of the load test. Also there is enhancement in the deflection behavior of camber members compared with straight members.

الخلاصة

معظم المنشآت التي يتم تعريضها لفحوص التحميل تجتاز الفحوص بنجاح، على الرغم من أنها فشلت في فحوص المكعبات واللباب. يتم الاعتقاد بأن الفعل الغشائي من الممكن هو العامل الأكثر أهمية الذي يجعلها تقوم بذلك. في الدراسة الحالية، المحاولة تمت لدراسة تأثير الفعل الغشائي على نتائج فحص التحميل.

في الدراسة الحالية، تم تهيئة نموذجين من الهياكل ثلاثية الأبعاد ذات التسعة فضاءات (3×3) [متكونة من أساس حصيري، أعمدة، عتبات وبلاطات].

بينت النتائج الدور الإيجابي للفعل الغشائي وخاصة مع وجود العتبات والبلاطات المقوسة (المحدبة) نحو الأعلى بالاجتياز الناجح لفحص التحميل. وكذلك هناك تحسن في التصرف نحو الإنحراف للأجزاء المقوسة بالمقارنة مع الأجزاء المستقيمة.

KEY WORDS

Load test, beams and slabs, membrane action, camber, deflection.

INTRODUCTION

If there is doubt concerning load-carrying capacity of a part or all of a structure, a strength evaluation shall be carried out. The National Center for Constructional Laboratories (NCCL) (Ministry, 2000) indicates that the types of tests applied for strength evaluation are (Collapse load test, Load test, Cores test, Pullout test, Ultrasonic Pulse velocity test and Rebound test).

Load test is used when there is inconsistency with code requirements (design, construction). There are two types (Ministry, 2000) of load tests:

1 – Collapse load test (Strength test).
2 – Load test (General performance test).

The phenomenon of membrane action in reinforced concrete was first considered by Westergaard and Slater (1921) who noticed a significant increase in the load carrying capacity of end restrained flat slab floor panels due to arching (i.e. development of horizontal thrust).

The concept of membrane action did not receive much attention until Professor Ockleston (1955) published in 1955 a paper concerning the results of full-scale load tests on three reinforced concrete slabs of Johannesburg.

Another experimental test, which was executed by the University of Illinois (Gamble, 1961), on a ¼ scale model of a nine panels (3×3) slab-beam floor . The failure load recorded on the interior panels was approximately twice the ultimate load predicted by the yield-line theory.

Hopkins and Park (1971) conducted tests on a ¼ -scale nine-panel reinforced concrete slab and beam floor which was designed with allowance for membrane action. They stated that "the doubt about the long-term behavior of the floor and the requirement that design loads must be high before membrane action can fully be exploited, limit the applicability of the membrane action design to relatively thick, heavily-loaded slabs with reliable lateral restraint".

So, membrane action is the development of a horizontal force in end-restrained structural members upon loading. It has the advantages of increasing moment and shear capacities of beams and slabs and reducing deflections in reinforced concrete structures.

All the above works, however, dealt only with straight (horizontal) slabs. But it has not been utilized in practice because of some drawbacks in its application. These drawbacks include long-term behavior of beams and slabs as shrinkage, creep and thermal contraction of concrete may lead to a decrease or loss of membrane action, slow development of membrane action at working load and the need for thick slabs and for reliable restraints.

Al-Rawi et al (1999) (Athuraia, 2004) showed that these drawbacks may be overcome by adopting camber.

The inclusion of shallow upward curvature (camber), to structural members, lend them (if laterally restrained) some beneficial properties of arches with the desired axial restraint force which results in a high load carrying capacity.

ACI code (2002) and Iraqi Building Code (1987) specify upper limits for maximum permissible deflection. The introduction of camber will of course waive away the possibility of exceeding these limits.

SCOPE OF RESEARCH

An attempt is made to study the effect of membrane action on load test results of two-way restrained slab [3×3] panels. The first model (S1) is consisted of straight beams and slabs, the second model (C1) is consisted of camber beams and slabs (the camber was in both directions) as shown in **Figs. (1) and (2)**. General information about structural members is given in APPENDIX (A).

In the present work, ACI code [9] procedure was followed. The total test load is to be as given in the following equation:

$$W_{TTL} = 0.85\ (1.4D + 1.7L) \qquad (1)$$

Measured maximum deflections shall satisfy one of the following conditions:

$$\Delta_{max} \le \frac{l^2_t}{20000h} \qquad \text{[ACI Eq. (20.1)]} \qquad (2)$$

$$\Delta_{r_{max}} \leq \frac{\Delta_{max}}{4} \quad \text{[ACI Eq. (20.2)]} \qquad (3)$$

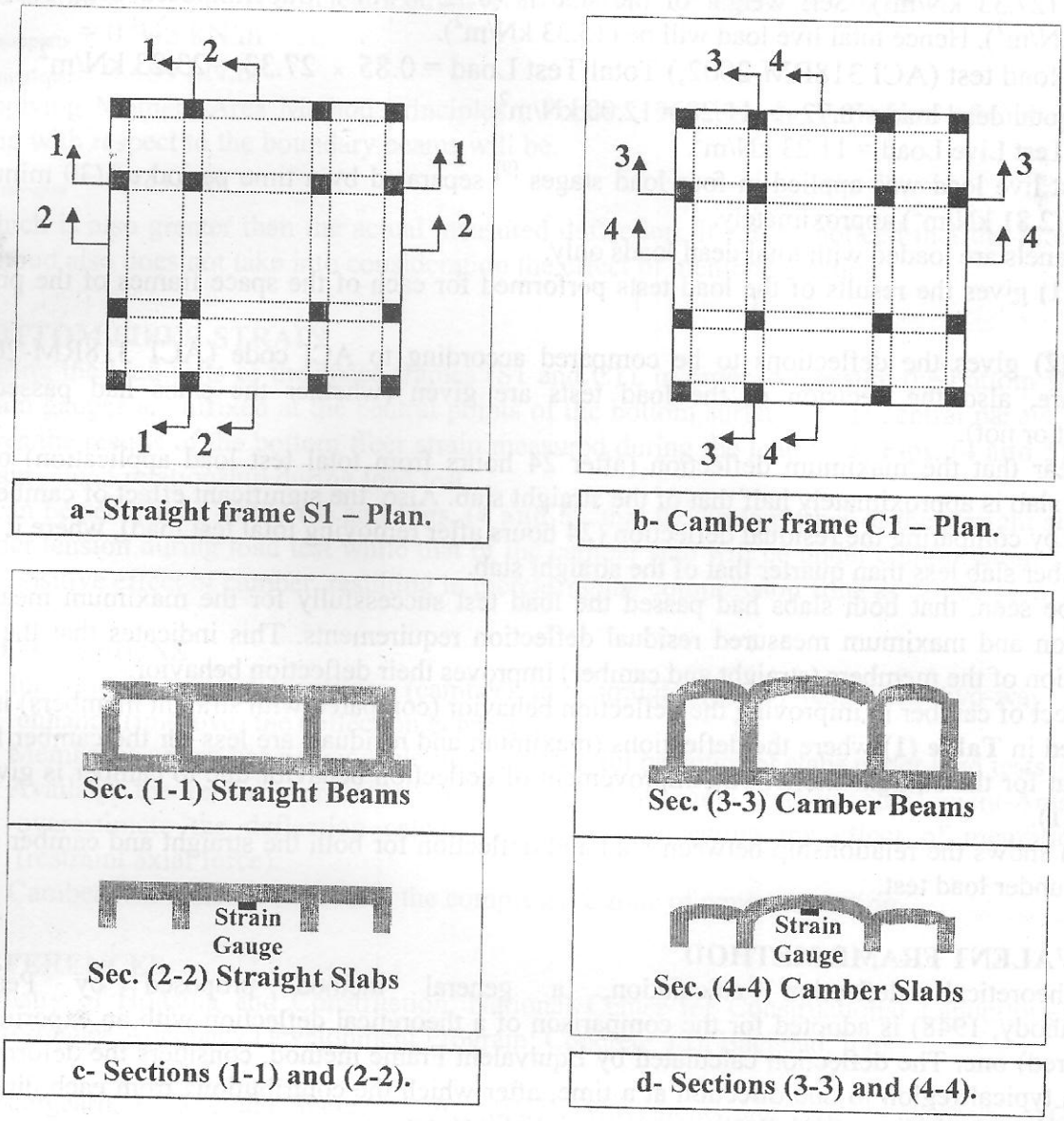

Fig. (1) Plans and sections of straight (S1) and camber (C1) model frames.

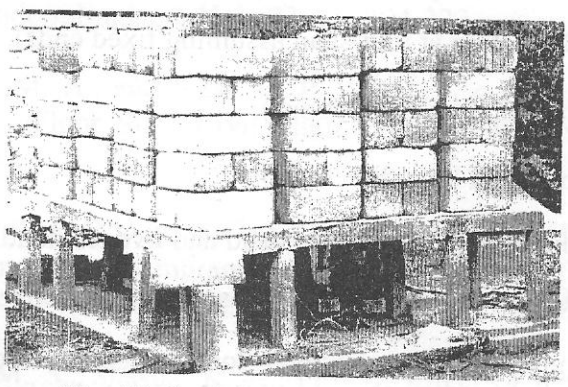

Fig. (2) Straight (S1) model frame.

LOAD TEST OF TWO-WAY SLABS

Structural analysis (Nilson, 1986) indicates that the ultimate load to be carried by the central panel will be (27.33 kN/m^2). Self weight of the slab is (0.72 kN/m^2). Superimposed dead load was (11.28 kN/m^2). Hence total live load will be (15.33 kN/m^2).

For the load test (ACI 318RM-2002,) Total Test Load = 0.85 × 27.33 = 23.23 kN/m^2.

Since: Total dead load = 0.72 + 11.28 = 12.00 kN/m^2.

Hence: Test Live Load = 11.23 kN/m^2.

This test live load was applied in four load stages [9] separated by a time period of (30 minutes), each of (2.81 kN/m^2) approximately.

Other panels are loaded with total dead loads only.

Table (1) gives the results of the load tests performed for each of the space frames of the present study.

Table (2) gives the deflections to be compared according to ACI code (ACI 318RM-2002,) procedure, also the decision of the load tests are given (whether the slabs had passed the load test or not).

It is clear that the maximum deflection (after 24 hours from total test load application) of the camber slab is approximately half that of the straight slab. Also, the significant effect of camber can be seen by comparing the residual deflection (24 hours after removing total test load), where it is for the camber slab less than quarter that of the straight slab.

It can be seen, that both slabs had passed the load test successfully for the maximum measured deflection and maximum measured residual deflection requirements. This indicates that the two-way action of the members (straight and camber) improves their deflection behavior.

The effect of camber in improving the deflection behavior (compared with straight members) is also indicated in **Table (1)** where the deflections (maximum and residual) are less for the camber frame than that for the straight frame. The improvement of deflection behavior due to camber is given in **Table (1)**.

Fig. (3) shows the relationship between load and deflection for both the straight and camber space frames under load test.

EQUIVALENT FRAME METHOD

For theoretical deflection calculation, a general method proposed by Peabody (D. Peabody, 1948) is adopted for the comparison of a theoretical deflection with an experimental (measured) one. The deflection calculated by Equivalent Frame method, considers the deformation of such typical region in one direction at a time, after which the contributions from each direction are added to obtain the total deflection at any point of interest.

Applying the Equivalent Frame method procedure (D. Peabody, 1948) (Arthur, 1975), to calculate deflections, the followings are predicted:

$(\Delta_i)_{ref} = \mathbf{0.414}mm$ (Deflection at mid-span assuming fixed ends).

$(\Delta_i)_{col.strip} = \mathbf{0.377}mm$ (short and long directions).

$(\Delta_i)_{mid.strip} = \mathbf{0.973}mm$ (short and long directions).

Hence, the final (total) immediate deflection due to dead and live test loads is:

$(\Delta_i)_{DL+LL} = \mathbf{0.377 + 0.973 = 1.35}mm$ > Maximum measured deflections.

It can be noticed that the Equivalent Frame method does not take into consideration the effect of membrane action (axial restraint force) to enhance the deflection behavior of flexural members.

MOMENT-AREA METHOD

Considering a strip of (1 m) width of the interior panel, then calculating moments at the supports and at mid-span using coefficient method (Nilson,1986), the moments will be:

$M_{supports}$ = 0.943 kN.m

$M_{mid\text{-}span}$= 0.469 kN.m

Applying Moment-Area Method principles (Popov, 1968) for the deflection of mid-span of the strip with respect to the boundary beams will be:

$\Delta_{mid-span} = 0.484mm$

Which is also greater than the actual measured deflection. It can be noticed that the Moment-Area method also does not take into consideration the effect of membrane action.

BOTTOM FIBER STRAIN

During the load tests of the space frames (S1 and C1), in order to measure the bottom fiber strain, strain gauges are affixed at the central points of the bottom surface of the central panels. **Table (3)** gives the results of the bottom fiber strain measured during the load tests. **Figs. (4 and 5)** show the strain – load relationship during load test.

It can be seen from **Table (4)** and **Figs. (4 and 5)**, that the bottom fiber of the straight slab will be under tension during load test while that of the camber slab will be under compression. This shows the positive effect of camber, resulting in increasing the compression zone as can be seen.

CONCLUSIONS

1- Introducing upward curvature (camber) into straight (plane) restrained two-way slabs will enhance (improve) the deflection behavior.
2- Membrane action has a major role in the successful behavior of slabs under load tests.
3- Available theoretical approaches (such as Equivalent Frame Method and Moment-Area Method) overestimate the deflection calculation due to neglecting the effect of membrane action (restraint axial force).
4- Camber will enhance (increase) the compressive zone of concrete section.

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NOTATION

W_{TTL} is the total test load.

D is the dead load.

L is the live load.

Δ_{max} is the maximum measured deflection.

$\Delta_{r_{max}}$ is the maximum measured residual deflection.

l_t is the span of member for load test and it is the smaller of :

(a) distance between centers of supports, and

(b) clear distance between supports plus thickness (h) of member.

Table (1) Load test results.

Time (hrs)	Load (kN/m^2)	Load Stage Number	Deflection of frame:(mm)		Enhancement of deflection due to camber (%) +++
			Straight	Camber	
			S1	C1	
0	12.00	---	0.000	0.000	-------
0	14.81	1	0.094	0.057	39.36
0.5	17.62	2	0.181	0.109	39.78
1.0	20.42	3	0.262	0.157	40.08
1.5	23.23	4	0.338	0.203	39.94
24 +	23.23	4	0.412	0.246	40.29
48 ++	12.00	---	0.005	0.001	80.00

+ after 24 hours from total test load application.

++ after 24 hours from total test load removal.

+++ Enhancement % = [S1 deflection – C1 deflection] / [S1 deflection]×100%

Table (2) Load test deflections: requirements and decision.

Space Frame	Maximum Allowable Deflection (mm)	Maximum Measured Deflection (mm)	Allowable Residual Deflection (mm)	Measured Residual Deflection (mm)	Decision of the Load Test
SF1	1.600 +	0.412	0.103 ++	0.005	Passed
SF2	1.600	0.246	0.062 +++	0.001	Passed

+ l_{t1}=1000 mm. L_{t2}=950+30=980 mm. Choose smaller one (l_t=980 mm)

hence: $(\Delta_{max})_{all} \le \frac{(980)^2}{20000(30)} \le 1.600mm.$

++, allowable residual deflection $(\Delta_{r\,max}) \le \frac{0.412}{4} \le 0.103mm.$

+++allowable residual deflection $(\Delta_{r\,max}) \le \frac{0.246}{4} \le 0.062mm.$

Table (3) Bottom fiber strain.

Load (kN/m^2)	S1 (straight)	C1 (camber)	Difference in strain at mid-span of mid-panel $\times 10^{-6}$ strain
	Bottom Fiber Strain at Mid-Span of Mid-Panel ($\times 10^{-6}$ strain)		
12.00	2130	-3600	5730
14.81	2145	-3635	5780
17.62	2148	-3640	5788
20.42	2189	-3700	5889
23.23	2204	-3730	5934
23.23	2224	-3760	5984
12.00	2202	-3725	5927

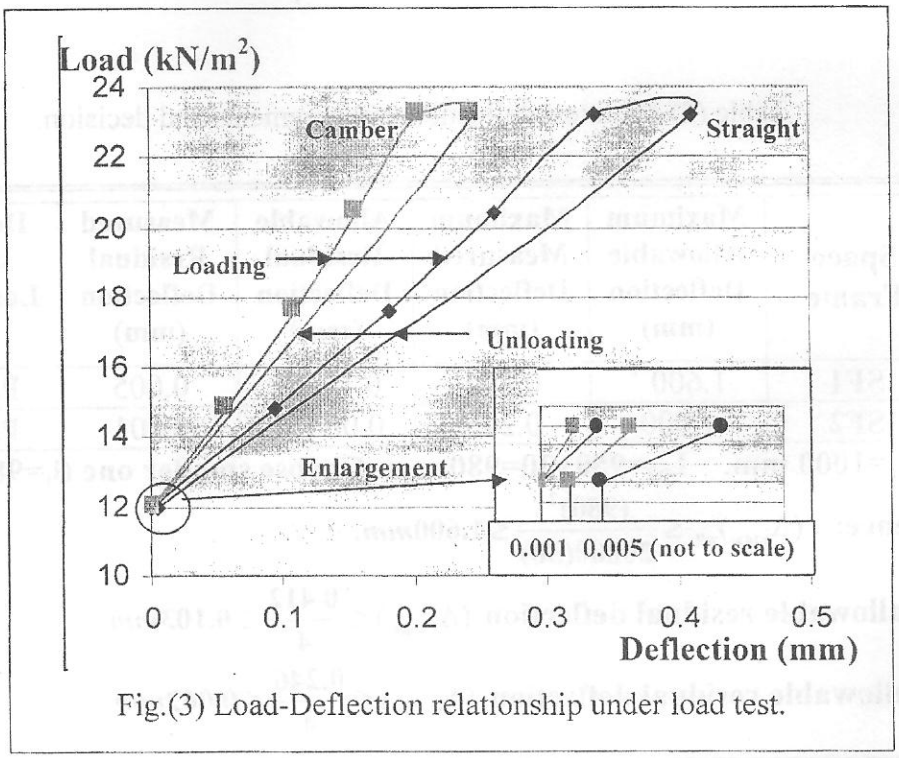

Fig.(3) Load-Deflection relationship under load test.

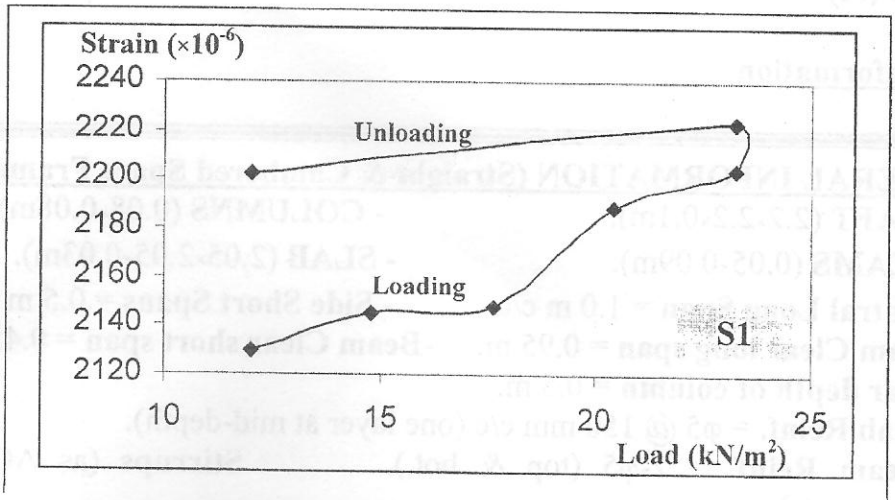

Fig. (4) Relation of bottom fiber strain and load.

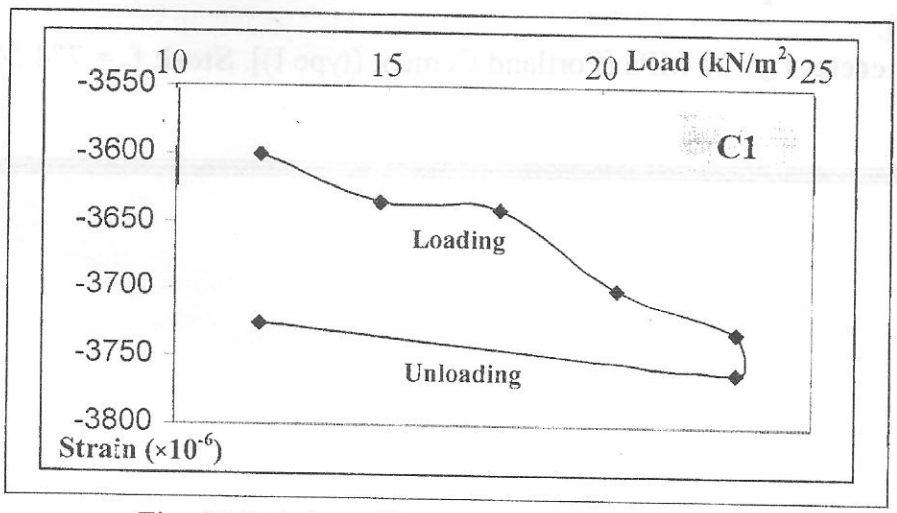

Fig. (5) Relation of bottom fiber strain and load.

APPENDIX (A)

Structural Information

GENERAL INFORMATION (Straight & Cambered Space Frames):

RAFT (2.2×2.2×0.1m). - **COLUMNS** (0.08×0.08m).

- **BEAMS** (0.05×0.09m). - **SLAB** (2.05×2.05×0.03m).

- **Central Long Span** = 1.0 m c/c. - **Side Short Spans** = 0.5 m c/c.

- **Beam Clear long span** = 0.95 m. -**Beam Clear short span** = 0.45 m.

- **Clear depth of column** = 0.5 m.

Slab Reinf. = φ5 @ 150 mm c/c (one layer at mid-depth).

Beam Reinf. = 2-φ5 (top & bot.). **Stirrups** (as ACI requirements).

Column Reinf. = 4-φ5 (Long. Reinf.). **Ties** (φ5 @ 80 mm).

Raft Reinf. = Two layers & Two Directions:

[at column region: 3 bars] , [at center region of long span: 1 bar].

- **Beam with upward curvature** = 4.6 %.

- **Slab with upward curvature** [2-directions] = 4.6% [the datum is the Beam].

- **Concrete**: f'_c= 21 MPa [Portland Cement (type I)]. **Steel**: f_y = 774 MPa.