# EXPERIMENTAL STUDY OF R.C. CORNER DETAILS

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## ABSTRACT

This investigation presents an experimental study of strength and behaviour of various types of reinforcement details in concrete corner subjected to bending moment tended to open the angle. Ten specimens with various arrangements of reinforcement in the corner region are tested to study the effect of reinforcement detail, corner strength, cracks type, cracking moment, cracks pattern, corner deflection and corner efficiency. The specimens are designed to represent an actual prototype of a portal frame corner. The compressive strength of concrete in the test varies from (37.1) to (43.6) MPa, and steel tension ratio in legs is constant at $\rho = 0.0081$ in all test specimens. The nominal dimensions of the tested corners are (1077.8 mm) in overall length, (600 mm) in height and (150mm) in thickness, the nominal width, and the effective depth for all corner's leg section is held constant at (150 mm) and (129 mm) respectively. All corners are supported to be hinged in one leg by two hooks and rolled in other leg, also all corners are loaded by steel frame where, it produces moment tends to open the angle. Concrete strains at three different loading stages are recorded for each tested corner; also load deflection curves were plotted. Throughout the test operation crack patterns were drawn and the mode of failure of the tested corners is identified, which is divided into two types (flexural and bearing) failure. It was found that reinforcement detailing in corners subjected to moment tends to open the corner has important effect on the strength and the mode of failure of the corner. Depending on the results of the current experimental work some details are recommended to be used in the field work.

**Keywords: Concrete, Corner, Reinforcement, Detail, Experimental Study**

# دراسة عملية لتفاصيل الوصلات الخرسانية المسلحة

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## الخلاصة:

يستعرض البحث الحالي دراسة عملية لمقاومة وتصرف أنواع متعددة من تفاصيل التسليح للأركان الخرسانية المعرضة لعزوم إنحناء تعمل على فتح الزاوية. تم فحص (10) نماذج لتفاصيل تسليح مختلفة في منطقة الأركان لدراسة تأثير تفاصيل التسليح، مقاومة الخرسانة، نوع التشققات، عزوم التشققات، أشكال التشققات، هطول الركن الخرساني وكفاءته. صممت النماذج

لكي تمثل وتحاكي أركان الهياكل الإنشائية. مقاومة إنضغاط الخرسانة في الفحوصات تراوحت بين (37,1 و 43,6 ميكاباسكال، نسبة حديد الشد في سيقان الأركان كانت ثابتة وتساوي($\rho = 0.0081$) لكل النماذج المفحوصة. أبعاد الأركان التي تم فحصها هي (1077,8ملم للطول، 600ملم للإرتفاع و 150ملم للسمك). تم الحفاظ على العرض والعمق الفعال ثابتاً لسيقان كل الأركان وبما يساوي (150ملم و 129ملم) على التوالي. أسندت جميع الأركان على شكل مفصلي في أحد السيقان بإستخدام عقفتين وأسندت الجهة الأخرى بمفصل متحرك. تم تحميل جميع الأركان بواسطة هيكل فولاذي يقوم بتوليد عزم يعمل على فتح الزاوية. تم تسجيل الإنفعالات في الخرسانة لثلاثة مراحل تحميل مختلفة ولكل ركن تم فحصه كما وتم رسم منحنيات الحمل والإزاحة. أثناء عملية الفحص تم رسم التشققات الحاصلة في الركن الخرساني وتحديد نوعية الفشل الحاصلة والتي كانت على نوعين (فشل إنحناء أو إرتكاز). لقد تبين بأن تفاصيل التسليح في الأركان الخرسانية المعرضة لعزوم انحناء تعمل على فتح الزاوية لها تأثير كبير على مقاومة ونوع الفشل الحاصل في الركن الخرساني. بالإعتماد على النتائج المستحصلة من البحث الحالي تم إختيار عدد من التفاصيل والتوصية بإعتمادها في المجال الحقلي.

## NOMENCLATURE

| | |
|---|---|
| $b_f$ | Width of compression face of member, (mm) |
| D | distance from extreme compression fiber to centroid of longitudinal tension reinforcement, (mm) |
| $f'_c$ | cylinder compressive strength of concrete, (MPa) |
| $f_y$ | specified yield strength of reinforcement, (MPa) |
| $M_{cr}$ | first cracking moment, (kN.m) |
| $(M_{cr})_R$ | first cracking moment of reference corner, (kN.m) |
| $M_u$ | factored moment at section, (kN.m) |
| $(M_u)_R$ | ultimate moment of reference corner, (kN.m) |
| $\Delta C$ | total deflection for corners specimens |
| $\Delta R$ | total deflection for reference corner |
| | steel reinforcement ratio |

## INTRODUCTION

In numerous structures, continuity between two adjacent members is necessary even though the members angle. The joint formed from this meeting usually refers to the "corner". The term "corner" in this investigation is used to describe a corner joint formed by the joining; at 90°, of the ends of two flexural members (Mayfield et. al, 1971). The terms "opening" and "closing" the corner are used to describe the increase and decrease of this right angle (Mayfield et. al, 1973), respectively. Concrete corners are found in wide variety of structures such as retaining walls, bridges and portal frame buildings. They are also common in the field of hydraulic structures, such as reservoirs, tanks, flumes and culverts. Various detailing systems have been in vogue from time to time and considerable efforts have been directed towards carrying out improvements in these detailing systems to achieve the desired structural behavior. In general, the failure of opening corners is invariably characterized by the low tensile strength of concrete resulting in the initiation of a splitting tensile crack originating at the reentrant corner and gradually moves out along the corner diagonal towards the exterior corner (Nilsson, 1973) and (Nilsson and Losberg, 1976).

## Dimensions of Tested Corners

The nominal dimensions of the tested corners is as shown in **Figure (1 - A)**. The cross section details are shown in **Figures (1 - B)** and **(1 - C)**. The inner and outer angle of corner is right angle ($90^o$). The corner pad is (70mm) in height and (70mm) in width.

## Reinforcement Details

The types of reinforcement details used in this work are, as shown in Figure (2) where,(C means corner and the number represents the type of detail).

Detail (C1) involves only simple $90^o$ bends in the main steel in corner region, detail (C2) involves vertical stirrup in corner region, detail (C3) involves two vertical stirrups in corner region, detail (C4) involves three vertical stirrups in corner region, detail (C5) involves horizontal stirrup in corner region, detail (C6) involves vertical and horizontal stirrup in corner region, detail (C7) involves two vertical and one horizontal stirrups in corner region, detail (C8) involves a $270^o$ bend in the tension steel (loop bar) in corner region, detail (C9) involves a $270^o$ bend in the tension steel (loop bar) with $45^o$ bend in compression steel in the corner region, detail (C10) involves a $270^o$ bend in the tension steel (loop bar) with $45^o$ bend in compression steel with vertical stirrup in corner region.

## Testing of Corners

All corner specimens are tested by using the universal testing machine (MFL system) under monotonic loads up to failure. According to the circumstances of this test, the specimen (concrete corner) is supported to be hinged at one leg and rolled in the other leg upon this apparatus, using two hooks in one side to achieve the hinged situation. The upper and lower parts of concrete corner are modified to make the applied loads act as a coupled situation on each side, this leads to open the corner at center, as shown in **Figures (3)** and **(4)**.

The distance between the two point loads is kept constant at (93 mm). The applied loads are concentrated by adjustment of steel frame that has two legs settled on the specimen's pad under hydraulic jack, as shown in **Figure (3)**. Thin wooden patches are inserted between the concrete and points of loads to provide even surface. The loads are applied in successive increments up to failure. At the end of each load increment, observations and measurements are recorded for the corner deflection, at the reinforcement angle strain gauge readings and crack development and propagation on the corners surfaces.

## Types of Cracks

In the current investigation two type of cracking are found, the first one is" Flexural Cracks" usually (in most specimens), these are the first to appear, starting in the middle of the legs and move to the corner base. In some corners, additional flexural cracks appear at high loads, in positions nearer to the corner region than the initial cracks appear at first. Generally, the first flexural cracks appear at small percentage of the measured ultimate loading, see **Figure (5)**, and continue to widen and extend until they reach the compression reinforcement when they either cease to extend or continue at a very much reduced rate but nevertheless continue to widen or extend after that. The second type is "Diagonals Cracks" these are the cracks which appear at the corner region, either at or parallel to the diagonal of corner crack, see **Figure (5)**. At least one diagonal crack appears in each corner. Generally, this crack starts approximately in half distance between the inner and outer angles of the specimen, and continues to widen and extends at both ends until it reaches the vicinity of the main reinforcement. It then ceases to extend, but continues to widen until failure.

## Cracking Moments

Flexural cracks and diagonal cracks both are noticed to appear at the different stages of loading. Since the flexural cracks are the first to appear; therefore, the word 'cracking moment' whenever it appears in this investigation will refer to the flexural cracking moment. Cracking moment is that moment at which the first visible surface crack is seen by the naked eye on the surfaces of the corner. Values of cracking moment are shown in **Table (1)**. The cracking moment is not high variable with different details.

**Table (1)** shows that the first visible crack moment of the corners vary from (33.3%) to (62%) of the experimental ultimate loads. For all tested corners, comparison will be performed with first cracking moment for reference corners $(M_{cr})_R$.

For corners cast with diagonals (vertical) stirrups in corner region (C2, C3 and C4), these diagonals stirrups increase the cracking moment where they produce the first crack about (19%, 61% and 47%) respectively compared with the ultimate load of reference corner (C1). This is due to the ability of the diagonals stirrups in arresting crack growth and crack widening in corner region (Strabo et. al., 1982) and (Shiohara, 2004). The effect of diagonal stirrups in increasing the cracking moment for corner (C3) is greater compared with (C2 and C4), due to the two vertical stirrups placed in corner region where that produces more bond force arresting crack growth and equals the force (push out force) that try to split the rectangular block of corner (Suparviriyakit and Pimanmas, 2007) .

For corners cast with diagonal (horizontal and vertical) stirrups in corner region (C5, C6 and C7), the maximum increase is (5%, 12% and 26%) for (C5, C6 and C7) respectively. These few advantages may be due to the low resistance of the horizontal stirrup for the spilt force in corner region and little bond force along the diagonal direction.

For corners with looped tension bar in corner region (C8, C9 and C10), high increase in first cracking moment occurs which, is due to the looped bar where it has a tension component across the diagonal crack and helps to provide force (push out force) equal to splitting force in corner region (Uma and Prasad, 2008) and (Lee et. al., 1977) and also that loop of the detail encloses a large part of the concrete in the corner (Balint and Taylor 1972). The maximum increase in first cracking moment is (54%, 33% and 33%) for (C8, C9 and C10) respectively.

As expected, corner specimens made with vertical stirrup exhibit large cracking moment compared with the other types of details. This enhancement is mainly due to the bond force in vertical stirrup arresting mechanism of crack propagation.

## Cracks Pattern

**Figure (6)** shows the crack patterns at failure for all corners tested under bending moment tending to open the angle. They also show the load that crack observed in it and the extent of the crack at that load. The patterns of the flexural cracks in the legs of the corner are similar for all the corners, as shown in **Figure (6)**. The first cracks to appear are the two cracks which are very close to the critical sections, one in each leg. These cracks extend and widen until they reach the compression zone of the section where they either terminate or change directions. While the loading processes continue, more flexural cracks appear and extend, in the same way along both legs. Diagonal crack patterns, unlike those of the flexural cracks, are different from corner to corner according to the type of detail. As shown in **Figure (6)**, in corners with details (C7, C8, C9and C10), then diagonal cracks are positioned close to the critical sections and nearly parallel to the flexural cracks, and in high percentage of load cracks appear near the outer angle of corner. That is because the looped tension bar in corner block arrests cracks in all directions. For corners with details (C2, C3, C4), the diagonal cracks appear in the middle distance between the inner and outer corner and perpendicular to vertical line between them, that is because the tension force that tries to split the rectangular block more than the bond force is created by vertical stirrups. For corners with details (C5 and C6), the diagonal crack starts from the inner angle of corner and extends to the legs, also in high percentage of load cracks appear near the outer angle of corner. The reference corner (C1) has random diagonal crack pattern where the cracks appear near the inner and outer angle and extend to perpendicular or parallel the leg section, because no stirrup exists in corner region due to poor bond force. The number of the diagonal cracks also differs as the detail is changed. Diagonal cracks usually appeared at loads higher than those of the flexural cracks.

## Concrete Strain

Measurements of concrete strain are taken on both legs and on the corner region. The collected data at 10, 30 and 50 kN are drawn in **Figure (7)**. Readings of this strain at different loading stages are plotted, against the depth of diagonal section. In these Figures, each case consists of three curves with different slopes. Each curve represents certain stage of loading. **Figure (7)** represent the strain along the diagonal where, in all ten specimens the strain has maximum value at the inner corner and it is tensile in nature as a result for that, the inner corner is subjected to high biaxial state of tensile stresses resulting in cracking at the inner corner along the diagonal. This necessitates reinforcement across the crack at the inner corner. Any reinforcement detailing without this steel will be deficient in controlling the inner corner cracking. In some portions of the corner, tensile stress value is higher than the tensile strength of concrete, this may cause cracking and pushing out of the concrete.

## Deflection

During the tests, the deflection readings are recorded at the inner angle of the corner, immediately after the application of the load. The load ─ deflection curves for the corners tested under bending moment tend to open the angle up to failure are shown in **Figure (8)**. In this figure, the curves in general consist of three parts each; however the curves for corners with detail (C1, C2, C4, C5, C6, and C7) consist of three parts, as shown. The first part, starts form zero load up to the formation of the first flexural cracks, is of relatively steeper slope which in turn means that the corners at this stage are of relatively higher flexural rigidity. The second part of the load-deflection curve extends from the point of the first yielding to the point at which yielding of all reinforcement takes place at any of the two critical sections or both. The third and final part of the load-deflection curve extends from the point of yielding at the critical section to failure of corner. This part is relatively linear and the corners at this stage have little rigidity in flexure. The load deflection curve for the corners with details (C8, C9 and C10) consists of one or two parts generally, where the load-deflection curve of corner with detail (C9) has one part starting from zero to failure point, this part is very steeper slope. That means the corner with that detail has higher flexural rigidity. For corners with details (C8, C9 and C10), the load ─ deflection curves consist of two parts, the first part starts from zero load point to first crack load point, that part is very steeper and very short. The second part is liner to the failure. From all the curves of load ─ deflection, it appears that for corners with different details, the slopes of all parts of the curves become steeper when the looped bars are used in corner region (C8, C9 and C10). The variation in the slope of the first part is very small as compared with those of the other parts. So this indicates that the effect of the formation of the concrete cracks on the rigidity of the corner decreases with the usage of the diagonal stirrups and looped bars in corner region.

The total deflection for tested corners is shown in **Table (2)**; this table shows the decrease in total deflection for most corners when compared with reference corner deflection. For corners cast with vertical stirrups in corner region (C2, C3 and C4), the maximum decrease in total deflection is (24%, 80% and 30%) respectively, compared with the total deflection of reference corner.

This is due to the ability of vertical stirrups in increasing the strength of corner, increasing the stiffness and decreasing the rotation in corner, as a result, the total deflection is decreases. For corners cast with horizontal stirrups (C6 and C7), the decrease is in total deflection (63% and 25%).

Corner (C5) has an increase in total deflection which is (33%), where this is not expected because the horizontal stirrups increase the strength of corner and also decrease the rotation in corner. This increase in total deflection is mainly caused by the lack of reinforcement in the region of the corner (Nilson et. al., 2004). For corners cast with looped bar (C8, C9 and C10), the decrease in total deflection is (76%, 85% and 49%) respectively, compared with the total deflection of reference corner, that is also because the increase in corner strength where the looped of detail encloses a large part of the concrete in the corner, as the corner is opened the loop tightens and restrains the concrete inside it.

## Mode of Failure

The mode of failure of the corners tested in this investigation, under bending moment tented to open the angle, could be divided in general into two types. The first one takes place in the legs of the corner mainly after crushing of the concrete at the inner angle, and extending of the flexural cracks near the critical sections, beyond tension reinforcement or in the middle of legs. This type of failure will be called, in this discussion as "Flexural Failure". Generally, this type of failure is found to occur at corners with details (C2, C3, C4, C8, C9 and C10). These corners fail with flexural failure because of the ability of looped bars and vertical stirrup to resist and arrest the cracks in corner region and increase the strength of corner region where this leads to the corner region stronger than legs, as result for that, the failure appears in the legs at first. The second type of failure occurs at the corner region in which complete destruction of the concrete in the corner region occurs. This type of failure is thought to be due to failure in the bearing of the concrete within the bends of the tension and compression bar, and; therefore, it will be called "Bearing Failure". This type of failure generally takes place at corners with details (C1, C5, C6 and C7). **Table (3)** shows the mode of failure for all corners.

## Ultimate Strength of Corners

When the applied load to corner tends to open the angle, the detailing of reinforcement has an important effect on strength of corner. **Table (4)** shows the ultimate strength of tested corners and also shows that detail (C1) is not usually considered adequate detail; it is inferior to many other details except detail (C5), but detail (C1) shows that stirrups near the corner are effective in increasing strength. Detail (C2) through (C7) attempts to improve the performance of detail (C1) by the use of diagonal stirrups (vertical and horizontal). The test results show that diagonal stirrups as positioned in detail (C2, C3 and C4) increase the strength where the increase in strength is (30%, 23% and 20%) respectively, compared with ultimate strength of reference corner (C1). When turned through $90^{o}$ (as in detail C5 and C6) it gives strength less than strength of reference corner. This increase in strength is mainly due to the presence of vertical stirrup and also the increase in the area of diagonal steel (Uma and Prasad, 2008) where, to ensure a good mechanical interaction between the main reinforcement and the stirrup it is necessary to violate the requirement of a minimum of (1.875 cm) concrete cover over the reinforcement. According to new styles of diagonal stirrups, as in details (C7) they give less advantages in strength about (3%), and less than details (C2, C3, and C4). In particular, results for details (C2, C3 and C4) are very satisfactory, detail (C2) is preferable to details (C3 and C4) because there is (one, two) stirrup which has less than detail (C3, C4) respectively and hence it would be cheaper and easier than details (C3, C4). The details (C8, C9 and C10) that have more high strength than detail (C1) (used in reference corner) about (60%, 90% and 83%) respectively, where that because the lapped tension steel tends to corner region and that leads to more bond force between the concrete and reinforcement and more steel area in corner region. These specimens (C8, C9, and C10) are expected to be the strongest corner due to the distribution of steel in the corner region; it is thought that the bond strength between the deformed bars and the concrete would be strong enough to prevent major slippage at an early stage. The thickness of the concrete cover measured from the plane of the loop has some influence on the strength of such corner. Obviously with a greater thickness, the splitting tendency of the loop would be somewhat restrained. The strength of a corner reinforced with the loop is also found to be dependent on the radius of the loop, a larger loop giving a stronger corner.

## Corners Efficiency

The efficiency of a corner is defined as a ratio of the strength of the corner from a test to the theoretical strength of the corner (Mayfield et. al., 1972). The results of corner opening by the moment show that the efficiency of corners (C8, C9 and C10) has been the higher than the others (see **Figure (9)** and **Table (5)**) (about 132%, 157.5% and 152%) because the main tension steel is protracted to most parts of corner region. That leads to more bond force between the concrete of corner region and the reinforcement; also the circular part of main steel resists the cracks in all directions. As a result, the strength is increased that leads to increase the efficiency. From the same figure it is shown that the efficiency of corners (C5, C6 and C7) is low (about 75%, 77.2% and 85.3%). This emphasizes of the weakness of these corners because of the little bond in corner block between the horizontal stirrup and concrete of corner block. Also, the main steel is not protracted to all corner regions. The corners (C2, C3 and C4) have a good efficiency compared with reference corner (C1) that is because the vertical stirrup produces good bond between the reinforcement and the concrete of corner region. Moreover, the vertical stirrups resist the diagonal cracks. The reference corner (C1) has lower efficiency and would be unsafe in design. The reason why that corner is weak is that; there is no steel across the diagonal direction to carry the tensile forces. From the results of test, it is found that the efficiency of all corners is good, see **Figure (9)** and it is obtained that the reinforcement detail is an important parameter for corner efficiency.

## CONCLUSIONS

The following conclusions are drawn only from the ten types of corner details studied in this investigation:

**1.** When the applied load is opening the corner, reinforcement detailing has important effects on strength, and its effects on cracking moment, cracking pattern, cracks type are obvious.

**2.** Details (C1, C5, C6 and C7) should be avoided, because they have efficiency less than (100%) and their joints fail before their legs (Bearing Failure).

**3.** Details (C8, C9 and C10) have high efficiency (more than 100%) and they are the strongest details but not favorite because they are difficult and high in cost.

**4.** Details (C2, C3 and C4) have acceptable efficiency (more than 100%), but detail (C2) seems to be the best choice because it would be cheaper and easier than details (C3 and C4), and also the diagonal stirrup in it does not need be placed with great accuracy and easy for compaction of the concrete in the congested corner zone.

**5.** The diagonal stirrups positioned in vertical direction (as in details C2, C3 and C4) definitely increase the strength and it is not necessary to bend or fix these stirrups to give a close tolerance, but that when turned through $90^o$ (as in details C5, C6 and C7) they give less advantage, detail (C7) is an exception to this, possibly because the two vertical stirrups in it.

**6.** The nature of load deflection curves for all specimens is similar where it consists of three parts except the specimens (C8, C9 and C10) which consists of two parts.

**7.** Ultimate moment carrying capacities, as observed in the test, are different with different details, where the detail (C9) has the highest magnitude (16.34 kN.m) and detail (C5) has the lowest magnitude (7.81 kN.m).

**8.** From the test results, reinforcement detailing for concrete corner subjected to bending moment opening the angle is suggested with:

  **(a)** Inclined steel or loop steel across the diagonal of the corner as in details (C2, and C9).
  **(b)** Stirrups near the inner angle of corner, as in detail (C1).

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Table (1) Cracking Moments for Tested Corners

| Corner No. | C1* | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $M_{cr}$ (kN.m) | 4.08 | 4.87 | 6.59 | 6.02 | 4.30 | 4.58 | 5.16 | 6.30 | 5.44 | 5.44 |
| $M_u$ (kN.m) | 8.60 | 11.18 | 10.61 | 10.32 | 7.81 | 8.03 | 8.89 | 13.76 | 16.34 | 15.77 |
| $M_{cr}/(M_{cr})_R$** | 1 | 1.19 | 1.61 | 1.47 | 1.05 | 1.12 | 1.26 | 1.54 | 1.33 | 1.33 |
| $M_{cr}/M_u$% | 47.4 | 43.5 | 62 | 58 | 55 | 57 | 58 | 45.8 | 33.3 | 34.5 |

* Reference corner

** $(M_{cr})_R$ is the first Crack moment for Reference corner = 4.08 kN.m

Table (2) Total Deflection for Tested Corners

| Corner No. | C1* | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Total deflection(mm) | 12.15 | 9.23 | 2.32 | 8.54 | 16.2 | 4.55 | 9.15 | 2.95 | 1.87 | 6.25 |
| $\Delta C/\Delta R$ | 1 | 0.76 | 0.2 | 0.7 | 1.33 | 0.37 | 0.75 | 0.24 | 0.15 | 0.51 |
| Mu | 8.60 | 11.18 | 10.61 | 10.32 | 7.81 | 8.03 | 8.89 | 13.76 | 16.34 | 15.77 |

* Reference corner
$\Delta C$ = Total deflection for corners specimens
$\Delta R$ = Total deflection for reference corner

Table (3), Mode of Failure for Tested Corners

| Corner No. | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Mode of failure | Bearing Failure | Flexural Failure | Flexural Failure | Flexural Failure | Bearing Failure | Bearing Failure | Bearing Failure | Flexural Failure | Flexural Failure | Flexural Failure |

Table (4), Ultimate Strength for Tested Corners

| Corner No. | C1* | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Ultimate Strength(kN.m) | 8.60 | 11.18 | 10.61 | 10.32 | 7.81 | 8.03 | 8.89 | 13.76 | 16.34 | 15.77 |
| $M_u / (M_u)_R$ | 1 | 1.3 | 1.23 | 1.2 | 0.91 | 0.93 | 1.03 | 1.6 | 1.9 | 1.83 |

* Reference corner
$M_u$ = Ultimate strength of tested corners
$(M_u)_R$ = Strength of reference corner = 8.6 kN.m

Table (5), Experimental Work Results

| Corner No. | Detail Type | Cracking | | | | Moment kN.m | | Efficiency $\frac{M_{test}}{M_{cal}}$ % | Mode of Failure | Cylinder Strength MPa |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Mcr | Crack Positio | Mu | Mcr/Mu % | M cal* | M test | | | |
| C1 | | 4.08 | Right Leg | 8.60 | 47.4 | 10.50 | 8.37 | 76.5 | Bearing Failure | 43.6 |
| C2 | | 4.87 | Right Leg | 11.18 | 43.5 | 10.50 | 11.18 | 106.5 | Flexural Failure | 43.6 |
| C3 | | 6.59 | Corner Region | 10.61 | 62 | 9.72 | 10.61 | 102 | Flexural Failure | 37.5 |
| C4 | | 4.30 | Corner Region | 10.32 | 58 | 9.72 | 10.32 | 99.36 | Flexural Failure | 37.5 |
| C5 | | 4.30 | Corner Region | 7.81 | 55 | 9.82 | 7.81 | 75 | Bearing Failure | 38.1 |
| C6 | | 4.58 | Corner Region | 8.03 | 57 | 9.82 | 8.03 | 77.2 | Bearing Failure | 38.1 |
| C7 | | 5.16 | Corner Region | 8.89 | 58 | 10.25 | 8.89 | 85.3 | Bearing Failure | 39 |
| C8 | | 6.30 | Right Leg | 13.76 | 45.8 | 10.25 | 13.76 | 132 | Flexural Failure | 39 |
| C9 | | 5.44 | Right Leg | 16.34 | 33.3 | 10.54 | 16.34 | 157.5 | Flexural Failure | 37.1 |
| C10 | | 5.44 | Left Leg | 15.77 | 34.5 | 10.54 | 15.77 | 152 | Flexural Failure | 37.1 |

$$^{*}\, M_{cal} = \rho\, f_y\, (1-0.59\rho\, \frac{f_y}{f_c'})\, b_f\, d^2$$

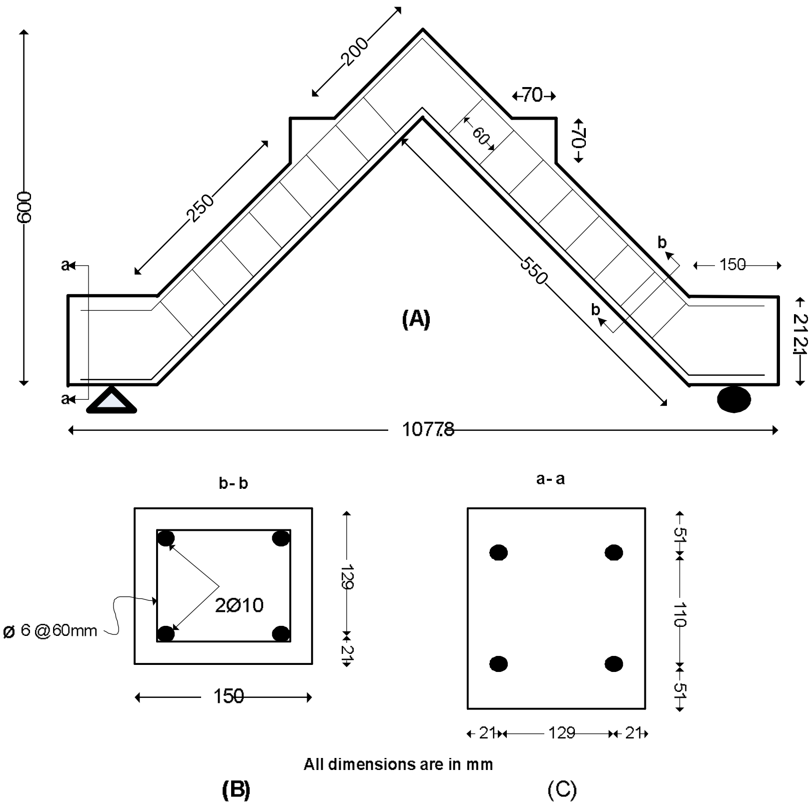

Figure (1), Details of Tested Corners: (A) Overall Dimensions (B) Leg Cross Section (C) Corner Base Cross Section

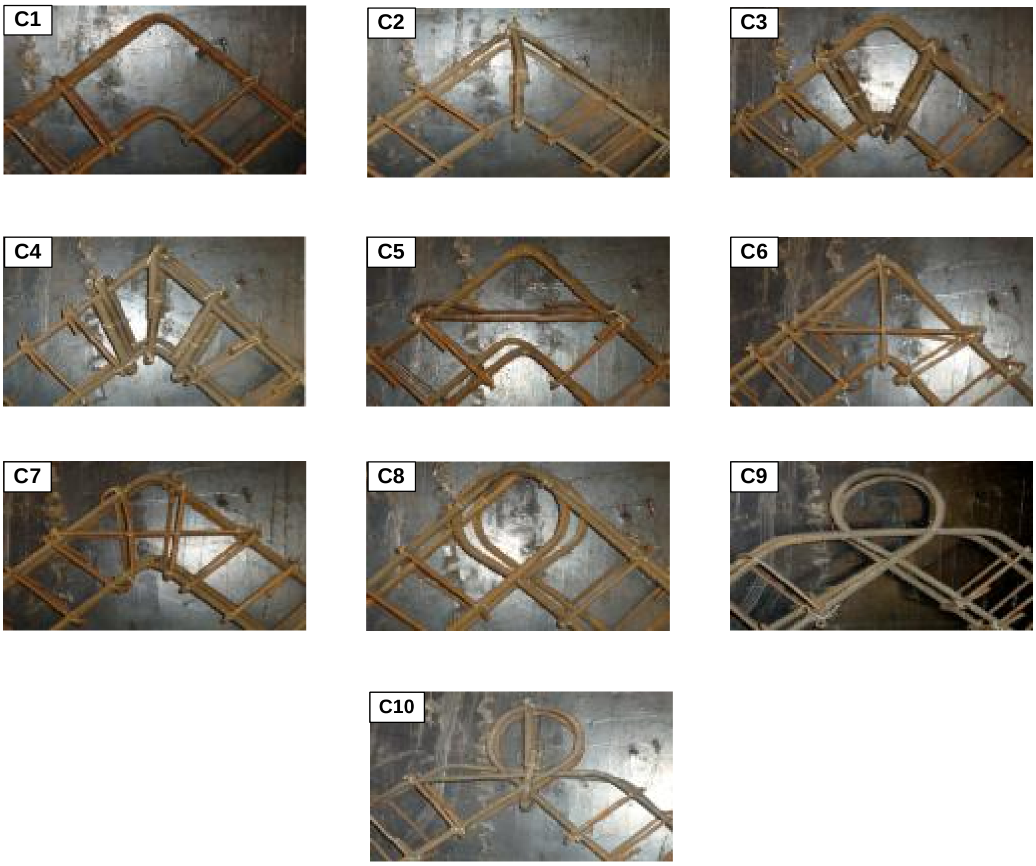

Figure (2) Reinforcement Details

Figure (3), Corner Set up

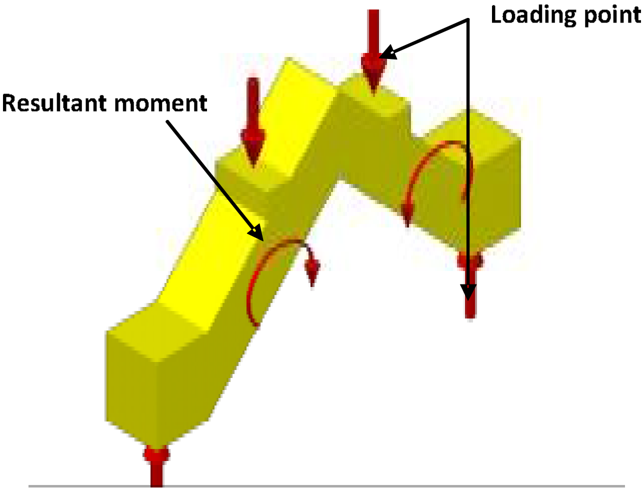

Figure (4), Corner Loading Arrangement

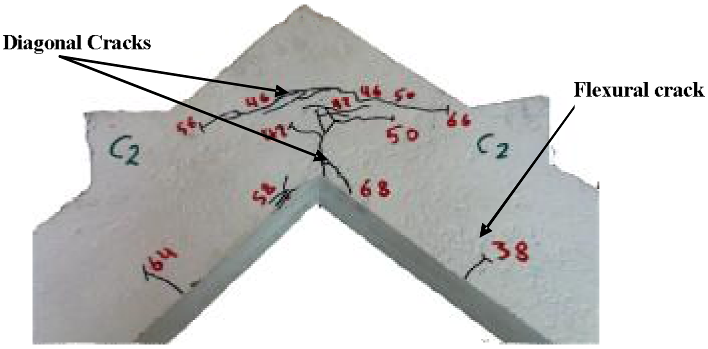

Figure (5), Cracks Pattern, Cracking Load, Cracks Type

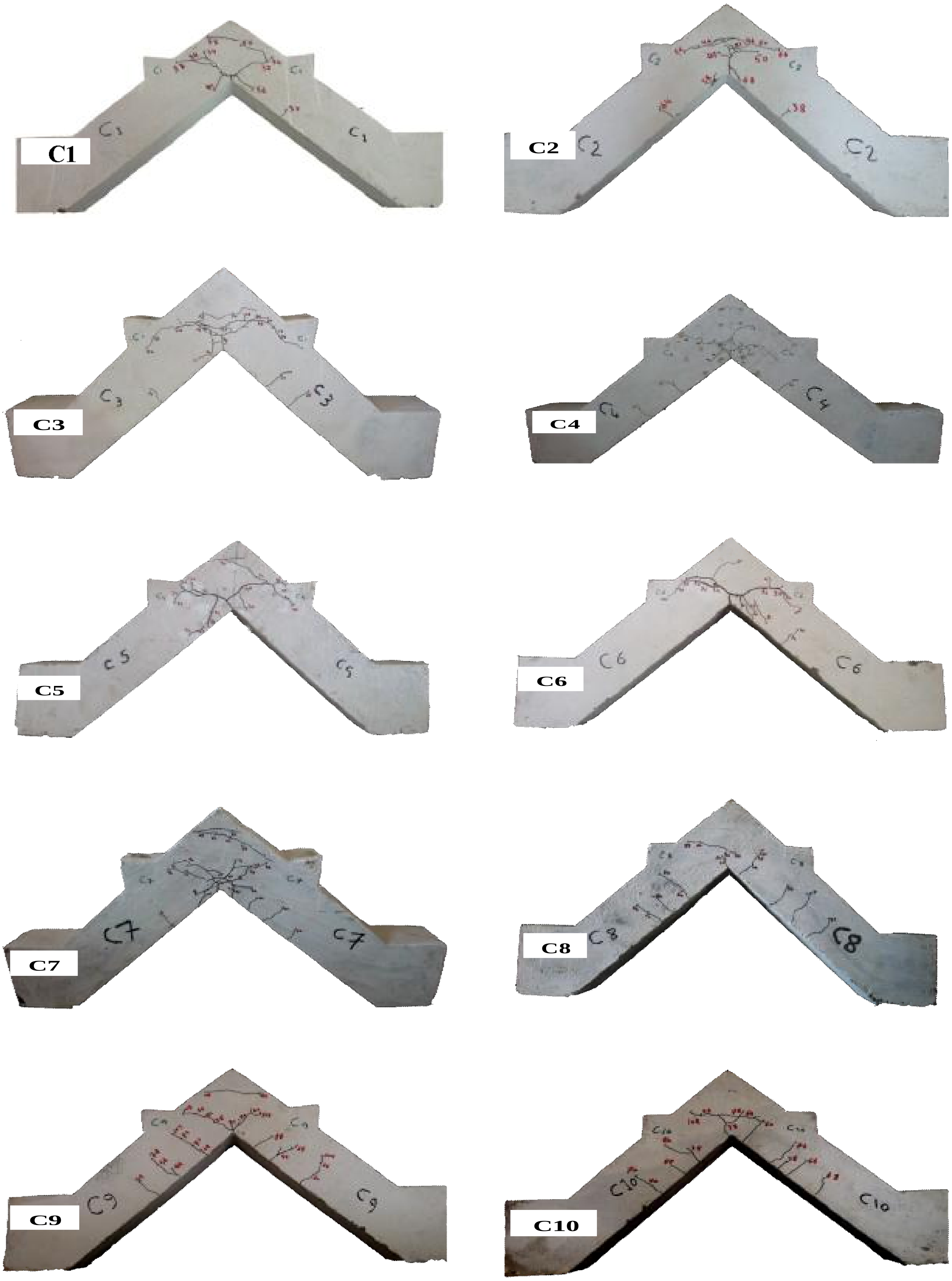

Figure (6), crack pattern at failure

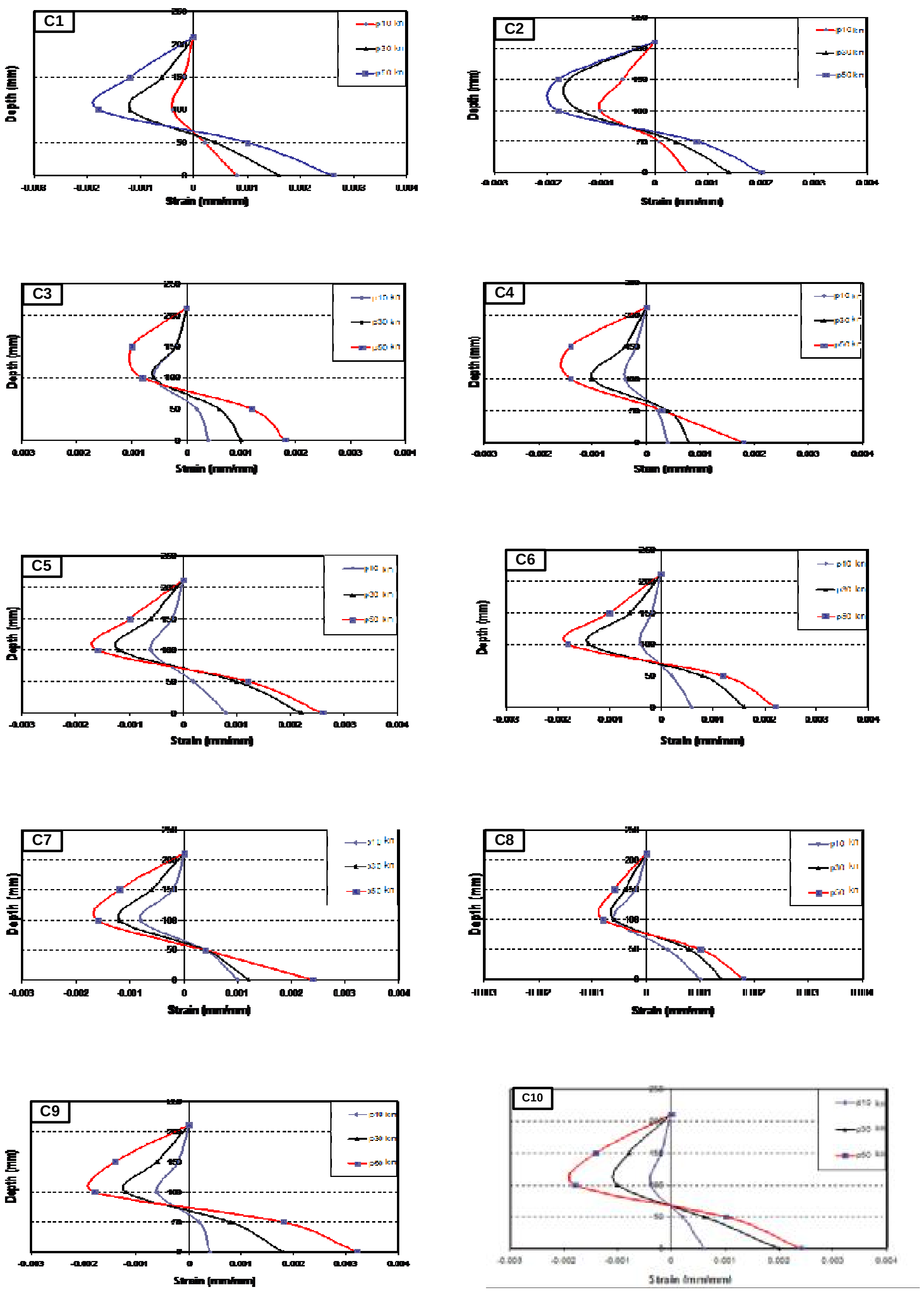

Figure (7), Concrete Strain Curves for all Corners

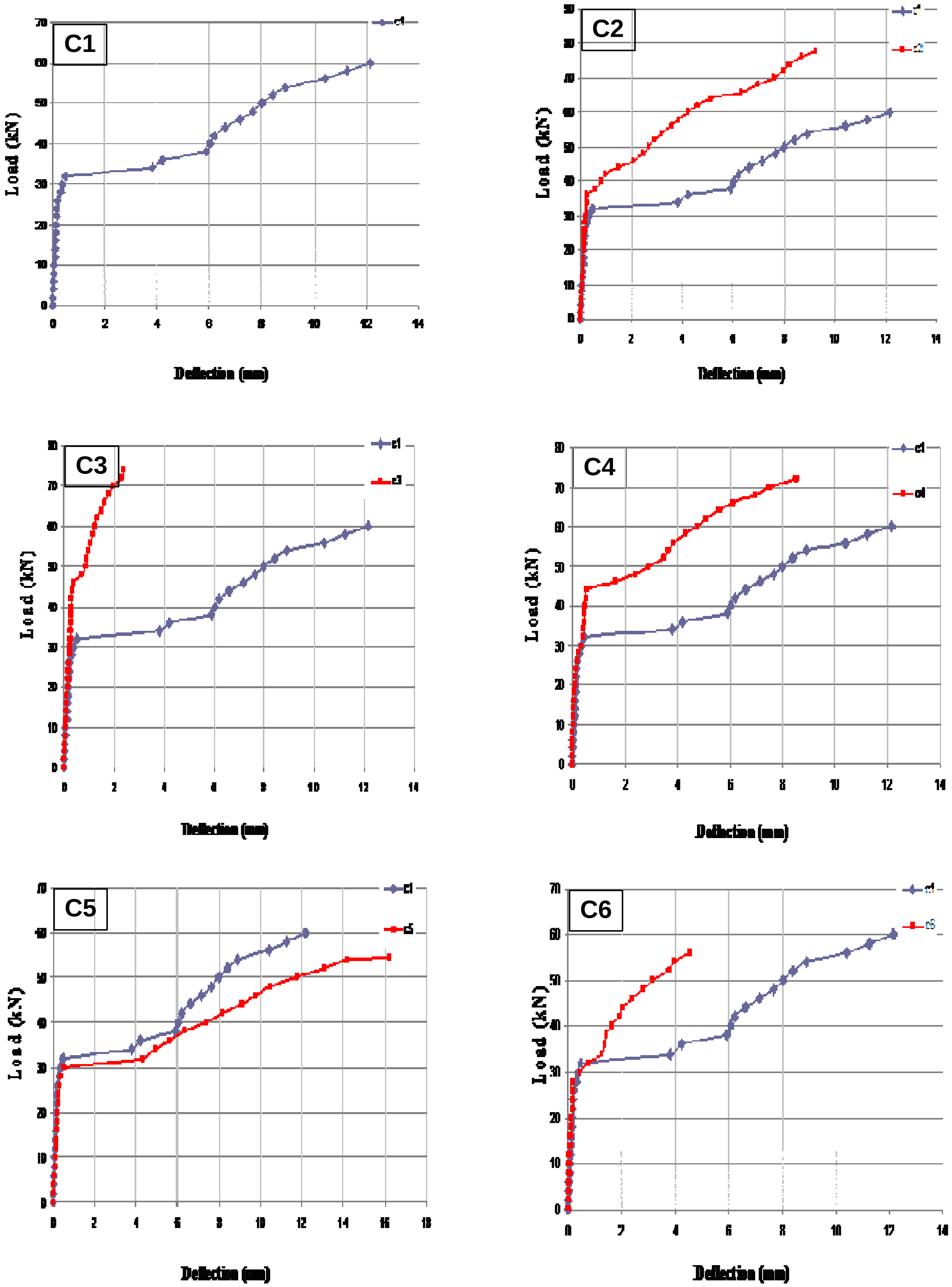

Figure (8), Load-Deflection curves for corners 1 to 6

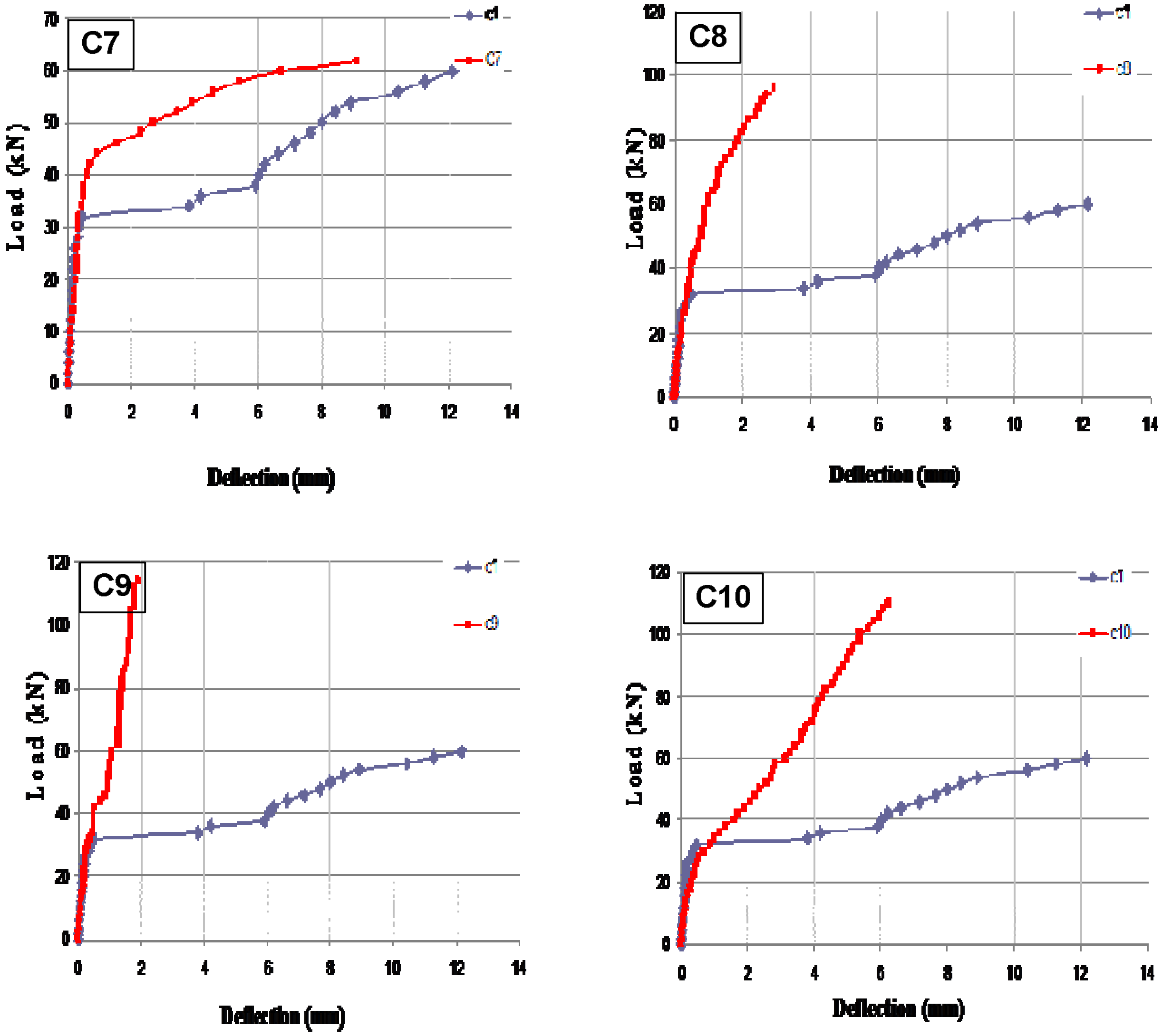

Figure (8), Load-Deflection curves for corners 7 to 10

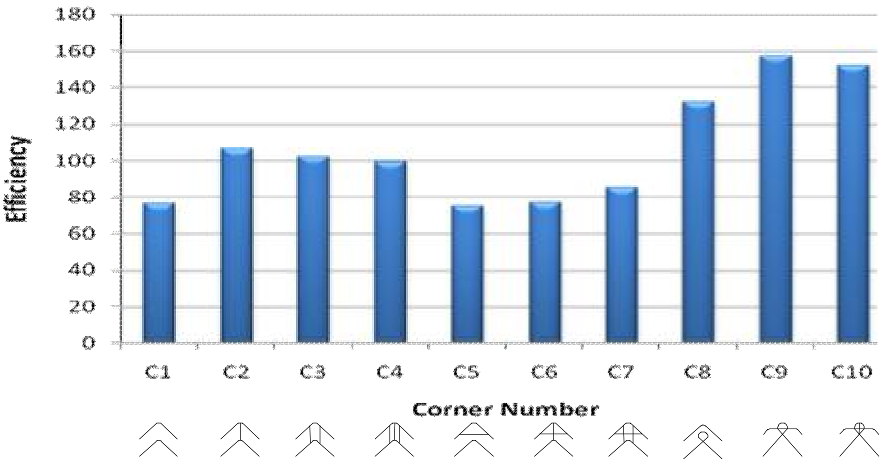

Figure (9), Corners Efficiency