Bi-axial shear capacity of the tilted solid reinforced concrete beam subject to point loading

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Abstract. This paper concerns the biaxial shear capacity of reinforced concrete beams utilizing the "simple test method". Applying the vertical shear force to the tilted beam. This loading condition simulated the response of the simply supported beams under biaxial shear applied corresponding to two main x and y axes. Three series of reinforced concrete beams have been tested. The main parameters of the present test are the tilting angle of the cross section simulating the ellipse formula of the JSCE recommendation to build reinforced concrete under biaxial shear, the shear reinforcement ratios from zero to 0.00377, 0.00502 and 0.00754, and three of ratios of longitudinal reinforcement were used (0.0276, 0.0426 and 0.0566). The ultimate capacity is discussed separately, based on the design approach using the ellipse interaction model, in terms of concrete contribution and shear reinforcement contribution (JSCE code 2010). By keeping the transverse steel ratio constant, it was found that the increase in the longitudinal ratio of reinforcement between 0.0276, to 0.0566 'respectively' increased the diagonal cracking load ($V_c$) by 22 % and 36.8 % and the ultimate load by 8 and 18 %.

Keywords: ultimate shear, visible crack, microcrack, tilted RC beams.

1. Introduction

The code provisions must sometimes be augmented by theoretical models from the literature by engineers designing sections subject to complex loading and the design issue is how to consider it safe enough to ensure that complex loading patterns prevent failure. Therefore, it is very important to understand the structural behavior under multi-directional loading conditions, such as biaxial shear. The member is subjected to biaxial loading with certain kinds of loading and frameworks, so the construction of such a reinforced concrete member should be carried out [1] and [2].

With respect to the principal directions of a beam section with negligible warping torsion, there are six components of internal force consisting of one axial force, two shear forces, two bending moments and one torsional moment. However, it is rare to find members subjected to one kind of loading pattern alone[3] and [4].

Since the prediction of shear strength cannot be verified exactly, the design question is how to determine whether the shear safety provided is adequate or not to ensure that shear failure is prevented [2]. A lot of past research has been done to achieve the goal of shear prediction for diagonal cracking load. However, the capability of the finite element programs to explain the phenomenon of crack shear[5]. The most reliable approach is the use of such a large amount of information from the results tested, leading statistically to an empirical formula that is applicable to the most recent design method.
Checking the evidence with different interpretations of the available data, which are partly based on logical reasoning.

2. Objectives of study
The main contributions of this paper are aimed at:

1. Conduct experimental tests for studying the load-bearing capacity and behaviors of eight rectangular reinforced concrete beams subject to biaxial shearing.
2. Examine the influence of principal parameters on the attitude of the biaxial shear. Such parameters include tilting angle, transverse and longitudinal reinforcement ratio.
3. The present experimental results are compared to capabilities that are determined by the available formula of interaction in the design code of the JSCE and the ACI design code through the importation of the same formula of interaction from the design code of the JSCE.

3. Reinforced concrete members subjected to biaxial shear
Previous studies have verified the difference in behavior in the biaxial and uniaxial loading of a reinforced concrete element. However, most of them focused on bending behavior. In 1996, Yoshimura [6] experimented on a reinforced concrete element that was subjected to multi-directional loads, i.e. axial compression with two lateral loads. Samples have been constructed in such a way that shear causes failure as shown in Figure 1. The results of the experiment showed that the ultimate shear capacity in X direction was associated with the shear capacity in Y direction using the elliptical formula, see Figure 2.

![Figure 1. Short RC column (biaxial shear test) [6].](image1)

![Figure 2. Ultimate capacity of RC member under multi-direct loading [6].](image2)

In 2003, Hansapinyo, et al [7] and [8] Error! Reference source not found. Using a simple test method, the ultimate biaxial shear capacity for concrete and shear reinforcement was measured separately under biaxial shear loading, where 13 square and rectangular reinforced concrete beams were evaluated for ultimate performance. The test includes 3 square reinforced concrete beams with a variety of the angles, i.e. 0°, 20°, 45° in order to validate the simplified biaxial shear test, the standardized biaxial shear capacity obtained from the simplified test and the Yoshimura interaction diagram[7] as depicted in Figure 3. The agreement between both test results and ellipse function, which has been utilized in the existing JSCE code design practices may be observed. This agreement provided for verifying the simplified bi-axial shear test.
Figure 3. Verification of results of the simplified diagram interaction test method in jsce code [8].

In 2003, Chaisomphob et al [9] examined four reinforced concrete beams with a rectangular section to explore the mechanism and final capacity of these beams under the combined action of torsion-accompanied bi-axial shear. Experimental findings have shown that the increase in torsional magnitude by around 69% has dramatically reduced the efficiency of bi-axial shears by approximately 12 to 39% depending on the ratio of the two shears. Experimental results were compared to that capacity that has been calculated in the current design codes (ACI and JSCE codes) using the available formula for interaction between uni-axial shear and torsion. The analysis showed that the new design codes offered reasonably conservative values for the ultimate capability.

Experimental studies have shown that the use of steel fibers in the concrete, using appropriate amounts, enhances the shear resistance, and Owing to the rise in tensile strength, the development and growth of cracks are delayed and the distance between fibers is decreased compared to that of stirrups [10] and [11].

4. JSCE design code for bi-axial shear
JSCE Code of Design addresses the decreased capacity when there is orthogonal shear force. It is also considered that the presence of two shears reduces the uniaxial shear capacity of each other, sometimes referred to as the reduction of bi-axial shear loading as the "Interaction Formula" [12]. This interaction can be shown in Figure 4.
5. Specimen description and position of dial gages
The beams tested were 1300mm long with a rectangular cross section of 150mm×250 mm and fitted into a concrete stub with a width of 150 mm and a triangular shape from the side with two identical legs as shown in Figure 5.

The biaxial shear capacity test consisted of 8 specimens primarily designed for investigating the impact of tilting angle, the shear reinforcement ratio and the ratio of the longitudinal reinforcement. The details of these beams have been shown in Table 1 and shown in Error! Reference source not found. and Error! Reference source not found.
Table 1. Details of specimen

| Group Designation                        | Beam Designation | $\beta$ degree | $\rho_w$  | $\rho_v$  |
|-----------------------------------------|------------------|----------------|-----------|-----------|
| Beams Reference                         | B-0-R            | 0              | 0.0276    | 0.00377   |
| With Various Tilting Angle              | B-45-R           | 45             | 0.0276    | 0.00377   |
|                                         | B-90-R           | 90             | 0.0276    | 0.00377   |
| Beams Loaded at $\beta = 45^\circ$     | B-45-WS          | 45             | 0.0276    | 0   |
| With different transverse reinforcement ratio | B-45-S2        | 45             | 0.0276    | 0.00502   |
|                                         | B-45-S3          | 45             | 0.0276    | 0.00754   |
| Beams with Different Longitudinal Reinforcement Loaded at $\beta = 45^\circ$ | B-45-L2         | 45             | 0.0426    | 0.00377   |
|                                         | B-45-L3          | 45             | 0.0566    | 0.00377   |

During testing, the deflection measurement was taken at several points. Five dial gages having (0.01mm) sensitivity were used; two were in vertical direction under different faces of the beams at beams center; one was in horizontal direction also at the center of the beams; and the rest two dial gages positioned vertical to the beams the first was at the quarter span of the beam and the other was near the support. As shown in Figure 8 and Figure 9.

Figure 5. Overview of test specimen.

Figure 6. Typical arrangement of steel reinforcement beam

Figure 7. Typical arrangement of steel reinforcement beam (side view)
6. Mix Design
In accordance with the recommendations of ACI 211-05[13], a concrete mixture of 1:1.5:2.5 and w/c ratio of 0.45 was made after 28 days for all of the specimens tested with nominal cylinder compressive strength (31 MPa) and $f_{cu}=41$ MPa.

7. Results and discussion
The increase in load resulted in the creation of a number of flexural cracks during the shearing cycle, and then extended the previously developed flexural cracks longer and wider. The latter induced flexural crack occurred at different degrees, due to the magnitude of the shear stress at different parts, in the direction of the member axis. As the load increased further, diagonal cracks, which were successively formed within the span of the previous flexural cracks, emerged. Due to the cracking nature described above, the concept in this study is that when the flexure crack is horizontally inclined at an angle of 35 to 45°, it is defined as diagonal crack[14].
The appearance of cracks in beams of reinforced concrete with a tilted angle results in cracks appearing in different configurations. Due to the direction of loading cracks formed on 4 sides are special. As a result, as shown in Figure 10, the definition of four beam faces is used to describe the propagation of inclined beams by cracking.

![Figure 10. Definitions of beam faces](image)

7.1. Load-Deflection
The distinct phase of the beam response to the load can be demonstrated by the relationship between the load-deflection and the different tilt angles and the reinforcement resulting in different load-deflection curves.

In this study, comparisons between vertical and lateral displacement were made at two mid-span points, as shown in Figure 11 through Figure 16 for the first mid-span point (C-side) where vertical and lateral deflection were very close to each other. This was due to a tilting angle of 45 degrees at which (sine) and (cosine) were equal.

For both beams, the second midspan point vertical deflection values (face B) reflected approximately half of the first point deflection values, either vertical or lateral. It means the load has been transferred to the shear center of the beams.

![Figure 11. Load-mid-span deflection in horizontal and vertical direction](image)

a. load-deflection curve  
b. Crack Pattern of Specimen B-45-R
Figure 12. Load-mid-span deflection in the vertical and horizontal directions

Figure 13. Load-mid-span deflection in horizontal and vertical direction
Figure 14. Load-mid-span deflection in horizontal and vertical direction

Figure 15. Load-mid-span deflection in horizontal and vertical direction
Figure 16. Load-mid-span deflection in the vertical and horizontal directions

Since the stiffness of the member is much greater when loaded in the direction of y than in the direction of x, the diagram slope is reduced from the largest specimen stiffness (B-0-R) to the smallest (B-90-R), corresponding to the increase in tilting. It is also observed that the specimen (B-90-R) had a relatively small elastic area, as shown in Figure 17.

Figure 17. Load-midspan deflection in vertical direction

Figure 11 through Figure 17 show linear relationships up to the first crack after which the deflection increases until the failure associated with an increase in the number of cracks. Table 2 shows the deflection at failure for each beam that was tested at the beam's first midpoint (C-side). These figures and the table indicate that when the transverse steel ratio was increased the average deflection increased. Increase in the longitudinal steel ratio also increased maximum deflection. It can also be shown that the minimum deflection was found in beams (B-0-R) and (B-90-R), because the stiffness of the element is much greater when subjected to vertical loading only, because of the direction of loading the load deflection curves were also different for these two beams from other beams.
Table 2. The deflection at failure and ultimate load (kN)

| Beam Name | Ultimate Load (kN) | Maximum Deflection (mm) |
|-----------|-------------------|-------------------------|
| B-0-R     | 180               | 10.1                    |
| B-45-R    | 149               | 23.4                    |
| B-45WS    | 103               | 17.6                    |
| B-90-R    | 128               | 8.5                     |
| B-45-S2   | 165               | 24.9                    |
| B-45-S3   | 204               | 41.6                    |
| B-45-L2   | 161               | 13.6                    |
| B-45-L3   | 176               | 27.8                    |

7.1.1. Effect of transverse steel ratio.
Beams B-42-S2, B-45-R, B-45-WS, and B-44-S-3 with a ratio of transverse steel of ‘respectively’ 0.00502, 0.00377, 0, and 0.007540. In those beams, longitudinal steel ratio has been maintained constant at $\rho_w = 0.0276$. It noted the following:

- Figure 18 shows the shear strength versus the deflection of beyond the creation of the main diagonal cracking, where the shear-reinforced beams behave rigidly compared to those reinforced with less web reinforcement according to Munikrishna, et al [15]. This means shear reinforcement does not have a major effect on the beam's stiffness before the diagonal cracks are formed but instead after large diagonal cracks are created, the enhanced influence of shear reinforcement on beam stiffness continues to dominate by increasing web reinforcement.

![Deflection with different $\rho_v$](image)

Figure 18. Load-vertical midspan deflection with different transverse steel ratio

Table 3 shows the effect of variance on $(Vu)$ and $(Vs)$ of those beams in the transverse reinforcement ratio.
Table 3. Effect of the variance of the ratio of transverse reinforcement on ultimate load and contribution of shear reinforcements

| Beam Designations | Transverse ratio $\rho_v$ | $V_n$ kN | Increase Percentage (%) | $V_s$ kN | Increase Percentage (%) |
|-------------------|---------------------------|----------|-------------------------|----------|-------------------------|
| B-45-WS           | 0                         | 50.50    | ---                     | 32.50    | 47.70                   |
| B-45-S2           | 0.005020                  | 82.50    | 63                      | 22       | ---                     |
| B-45-R            | 0.003770                  | 74.50    | 47.50                   | 52       | 1360                    |
| B-45-S3           | 0.007540                  | 102      | 101                     | 52       | 1360                    |

Table 3 reveals that when the ratio of transverse steel increases from 0 to 0.003770, 0.005020 and 0.007540, the value of the ultimate load increases by 'respectively' 47.50%, 63.0%, and 101.0%. Therefore, as the ratio of the transverse steel has been increased from 0.003770 to 0.005020 and 0.007540, the role of the shear reinforcement has been increased 'respectively' by 47.70% and 136%.

In addition to that, with the increase in the ratio of transverse steel from 0.003770 to 0.005020 and 0.007540, the (Experimental / calculated) ratio has been increased 'respectively' by 10.90% and 18.20% for calculation of ACI and increased 'respectively' by 10.60% and 18.60% both for calculation of JSCE, as can be seen in Table 4. The reason for such increase can be a result of little spacing between the stirrups that resulted in making them working together more than the reference beam B-45R.

Figure 18 & Table 3 Show that the ultimate load as well as the $V_s$ are increased with the ratio of shear reinforcement ($\rho_v$) increasing. Results have shown that the behaviors of those stirrup-reinforced beams up to the diagonal cracking point is generally similar to that of stirrup-free beams. None-the-less, beyond that point, after inclined crack crossing shear reinforcement, the force has been transferred then from one of the planes to a different one via the stirrups’ action. Which is why, adding stirrups helps the beam to re-distribute internal forces through inclined cracks and limit the expansion of inclined crack and tie Longitudinal reinforcement in its place by enclosing the center of the concrete beam to increase or at least sustain forces that are carried by dowel action and aggregate interlock [16].

7.1.2. Effect of longitudinal reinforcement ratio.
Beams B-45-R, B-45-L2 and B-45-L3 which of longitudinal steel ratio ranged from 0.0276, 0.0426 to 0.0566, respectively. The transverse steel ratio that has been held constants at $\rho_v$ equals 0.00377 in these beams. Results reveal:

- **Figure 19** shows the load applied against the beam deflections. As expected, the deflection decreases with increasing $\rho_v$ at the same load level. Which is a result of the fact that any increase in $\rho_v$ increases crack control and prevents flexural cracks from widening further and therefore reduces beam deflection at the same load level.
- **Table 5** Displays the effects of the longitudinal reinforcement ratio variance on ($V_n$) and ($V_s$) of those beams.
Figure 19. Load-vertical midspan deflection with different longitudinal steel

Table 5. Effect on ultimate load and concrete contribution of variance in longitudinal steel reinforcement ratio

| Beam Designation | Longitudinal Ratio $\rho_w$ | $V_u$ kN | Percent of Increase (%) | $V_c$ kN | Percent of Increase (%) |
|------------------|-----------------------------|----------|-------------------------|----------|-------------------------|
| B-45-R           | 0.0276                      | 74.5     | ----                    | 47.5     | ----                    |
| B-45-L2          | 0.0426                      | 80.5     | 8                       | 58       | 22                      |
| B-45-L3          | 0.0566                      | 88       | 18                      | 65       | 36.8                    |

Table 5 it shows that by changing the longitudinal steel ratio from 0.0241 to 0.03703 and 0.0489, the diagonal cracking load ($V_c$) is raised by 22% and 36.8%, respectively. While the ratio of longitudinal steel is increased from 0.0241 to 0.03703 and 0.0489, the ultimate load has been increased by ‘respectively’ 8% and 18%.

Figure 18 and Table 5 indicate that both the diagonal cracking load and the ultimate load increase with an increase in longitudinal reinforcement ratio. The increase in the longitudinal steel ratio contributes to an increase in the dowel capacity of the member through the increase in dowel region and thus reducing the tensile stress caused by the surrounding concrete. The increase in the longitudinal steel ratio also increases the aggregate interlocking capacity.

7.2. Biaxial Shear Capacity

For comparing biaxial shear capacity from the experimental results with ACI-318M-11 results equations, the same elliptical function of JSCE (2010) has been utilized for the estimation of the ability from the uniaxial shear capacity in x direction and y direction determined by the equations ACI-318M-11[17].

(B-45-R), (B-45-WS) average concrete shear capacity ($V_c$) is (50 %) and(81 %) higher than JSCE and ACI codes figures, respectively. The efficacy of the concrete contribution for the calculation of ACI-318-2011 was higher in the range (64-116%) and (43-50 %) for calculating the JSCE 2007.

The contrast for shear reinforcement capacity part ($V_s$) shows that the elliptical formula utilized to calculate ACI or JSCE code overestimates the shear reinforcement capacity of all of the beams measured at 45° (-40)(-30 %) and (-25)(-11 %) respectively for the ACI and JSCE codes, as can be seen in the ACI and JSCE codes Table 6.

As regards ultimate load ($V_u$), in other words, the amount of concrete and reinforcement capacity, the existing design methods of ACI and JSCE are conservative for the concrete contribution ($V_c$), but the
calculation using the existing ellipse formula is not conservative for the shear reinforcement contribution ($V_s$).

**Table 6. Capacity of tested specimens**

| Beam Name | Calculation (by JSCE Code) Kn | Calculation (by ACI Code) Kn | Experimental Kn | Exp./Cal. By JSCE code | Exp./Cal. By ACI code |
|-----------|------------------------------|-------------------------------|-----------------|-----------------------|----------------------|
| B-0-R     | 68.77                        | 31.7                         | 37.7            | 57.14                 | 23.48                | 33.66                | 90               | 45 | 45          | 1.3 | 1.4 | 1.19 | 1.57 | 1.91 | 1.33 |
| B-45-R    | 63.38                        | 34.24                        | 29.14           | 49.4                  | 21.74                | 27.66                | 74.5             | 47.5 | 22          | 1.17 | 1.5 | 0.75 | 1.5  | 2.4  | 0.79 |
| B-45-WS   | 34.24                        | 34.24                        | ___             | 21.74                 | 21.74                | ___                  | 50.5             | 50.5 | ___         | 1.5  | 1.5 | ___  | 2.4  | 2.4  | ___ |
| B-09-R    | 54.61                        | 34.56                        | 20.04           | 38.87                 | 19.85                | 19.01                | 64               | 40   | 24          | 1.17 | 1.15 | 1.2  | 1.6  | 2.2  | 1.26 |
| B-45-S2   | 73.84                        | 34.98                        | 38.85           | 59.32                 | 22.45                | 36.86                | 82.5             | 50   | 32.5        | 1.11 | 1.43 | 0.83 | 1.39 | 2.2  | 0.88 |
| B-45-S3   | 92.528                      | 34.24                        | 58.28           | 78.1                  | 22.805               | 55.3                 | 102              | 50   | 52          | 1.1  | 1.46 | 0.89 | 1.3  | 2.19 | 0.94 |
| B-45-L2   | 69.326                      | 40.26                        | 29.66           | 49.8                  | 22.31                | 27.48                | 80.5             | 58   | 22.5        | 1.16 | 1.44 | 0.77 | 1.61 | 2.6  | 0.81 |
| B-45-L3   | 79.28                       | 44.5                         | 28.78           | 49.83                 | 22.51                | 27.32                | 88               | 65   | 23          | 1.2  | 1.46 | 0.8  | 1.76 | 2.88 | 0.84 |

* $V_u - V_c$

** Range $(7_{20})$ $(43_{50})$ $(25_{30})$ $(30_{76})$ $(119_{21})$ $(188_{6})$

** subjected to bi-axial shear with shear reinforcement only

8. Conclusions

According to the concrete contribution and the shear reinforcement contribution, the ultimate shear capacity of this study is discussed separately, according to the current design methodology utilizing the Ellipse Interaction Model (JSCE Code 2010). From the experimental results of examined RC beams, the set of the conclusions below may be obtained.

1. Using ACI and JSCE code calculations, the comparison of the ultimate capacity levels from the experimental results with measured values from elliptic equation shows that these codes give very conservative ultimate capacity values in the range of (-2 - 21) % and (10 - 20)% respectively of the experiments, fluctuating between the test results.

2. The elliptical formula under-estimates the concrete portion capacity for both the ACI and JSCE designs (64-116 %) and (43-50 %), respectively.

3. For shear enhancement contribution, the calculations with the use of an elliptical formula overestimates the shear enhancement component by (-40) (-30) % and (-25) (-11) % respectively for JSCE and ACI codes.

4. Experimental results have revealed, therefore, a flaw in the existing elliptical model.

5. As the transverse steel ratio increases from 0 to 0.003770, 0.005020 and 0.007540, the value of the ultimate load is increased 'respectively' by 47.50%, 63% and 101%.

6. Even though the ratio of transverse steel has been increased from 0.003770 to 0.005020 & 0.007540, the shear reinforcement role increases 'respectively' by 47.70 % & 136%. Through the increase in the ratio of transverse steel, the (experimental / measured based on the ACI-318 M-11) ratio was also increased by 10.9. % and 18.2%, respectively.

7. By keeping the transverse steel ratio constant, the increase in longitudinal ratio of reinforcement from 0.0276 to 0.0426 and 0.0566 was found to increase the diagonal cracking load ($V_c$) by 22% and 36.8% 'respectively' and ultimate load increased by 8 and 18%, respectively.
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