ORIGINAL ARTICLE

Experimental investigation on rectangular reinforced concrete beam subjected to bi-axial shear and torsion

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Abstract

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This paper presents the experimental investigation on the failure mechanism and ultimate capacity of rectangular reinforced concrete beam under combined action of bi-axial shear accompanied with torsion through the test of four reinforced concrete members. The simple experimental set-up for a simply-supported beam under one point loading is introduced in this study by applying eccentric load to the tilted beam. This requires only one hydraulic jack to produce the complicated bi-axial shear and torsional loading. The main parameter is the magnitude of torsion induced to specimens which is relatively represented by the torsion-to-shear ratio. In addition, the influence of torsion on ultimate capacity of reinforced concrete with different ratio of two shears is investigated. From the experimental results, it is found that the increase in the magnitude of torsion about 69 percent drastically decreases bi-axial shear capacity as much as 12 to 39 percent according to the ratio of bi-axial shears. The experimental results are compared with the capacities calculated by the available interaction formula between uni-axial shear and torsion in the current design

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codes. The comparison indicates that the current design codes give quite conservative values of ultimate capacity.

Key words : reinforced concrete beams, bi-axial shear and torsion, ultimate capacity

บทคัดย่อ

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การศึกษาโดยการทดสอบคานคอนกรีตเสริมเหล็กภายใต้แรงเฉือนสองทิศทางกับแรงบิด

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บทความนี้เสนอการศึกษาเกี่ยวกับพฤติกรรมการวิบัติ และกำลังประลัยของคานคอนกรีตเสริมเหล็กรูปหน้าตัดสี่เหลี่ยมผืนผ้าภายใต้การกระทำร่วมระหว่างแรงเฉือนสองทิศทางและแรงบิดโดยการทดสอบคานคอนกรีตเสริมเหล็ก 4 ตัว ในการศึกษานี้ได้ใช้การทดสอบแบบง่ายโดยให้คานช่วงเดี่ยวแบบรองรับธรรมดาถูกกระทำด้วยแรงกระทำหนึ่งจุดและเยื้องศูนย์กับคานที่ถูกวางให้เอียง การทดสอบนี้ใช้เพียงหัวกดไฮโดรลิก 1 หัวในการทำให้เกิดแรงเฉือนและแรงบิดที่ซับซ้อนได้ ตัวแปรสำคัญคือขนาดของแรงบิดที่กระทำต่อคานทดสอบ ซึ่งถูกแสดงด้วยอัตราส่วนระหว่างแรงบิดต่อแรงเฉือน นอกจากนี้ได้ทำการตรวจสอบผลกระทบของแรงบิดต่อกำลังประลัยของคานคอนกรีตเสริมเหล็กภายใต้แรงเฉือนที่แตกต่างกันสองค่า จากผลการศึกษา พบว่าขนาดของแรงบิดที่เพิ่มขึ้นประมาณ 69 % ส่งผลทำให้ความสามารถรับแรงเฉือนสองทิศทางลดลงประมาณ 12 ถึง 39 % ตามอัตราส่วนของแรงเฉือนสองทิศทาง ผลการทดสอบได้ถูกนำไปเปรียบเทียบกับกำลังประลัยที่คำนวณได้จากสูตรความสัมพันธ์ระหว่างแรงเฉือนในแนวแกนและแรงบิดในมาตรฐานออกแบบในปัจจุบัน ผลการเปรียบเทียบแสดงให้เห็นว่ามาตรฐานออกแบบในปัจจุบันให้ค่ากำลังประลัยต่ำกว่าค่าที่ได้จากการทดสอบในการศึกษานี้เป็นอย่างมาก

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Reinforced concrete beam is practically subjected to multi-directional loading. With respect to the principal directions of 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. For example, in a bridge structure, eccentrically loaded box-girder bridges or multideck bridges are subjected to multi-directional forces, i.e. combined shear and torsion. In this case, the capacity of the member is decreased from the individual action of force and the relationship representing the declination of the ultimate load can be described by an interaction diagram.

One of the direct and typical methods of bi-axial shear test is to apply the shear loads in two directions as conducted by Yoshimura (1996). This type of test needs at least two hydraulic jacks, and hence the load controls are complicated when the two horizontal shear loads are proportionally increased. The result has led to the conclusion for the ultimate capacity of such member related to elliptic formula expressing the reduction of each other two uni-axial shear capacities. Hansapinyo, *et al* (2001) conducted the experimental studies on the behavior of rectangular reinforced concrete beams subjected to bi-axial shear. Due to the inclination between principal axis and line of application of load, the horizontal shear loads in two directions can be applied proportionally by one hydraulic jack. The experimental results show that the shear reinforcement capacity of rectangular reinforced concrete beam is less than the calculated value by using current design codes when the tilted angle increases. Rahal and Collins (1995) studied the behavior of reinforced concrete beam subjected to shear and torsion and proposed the three-dimensional truss model capable of analyzing rectangular reinforced and prestressed concrete sections subjected to combined loading pattern. It was found that calculated deformations and ultimate loads from the model are in good agreement with experimental results. Cocchi and Volpi (1996) present a method for the nonlinear analysis of reinforced concrete members subjected to combined torsion, bi-axial bending and axial loads based on an extension of the "diagonal compression field theory". Good agreement is found between theoretical and experimental results.

Review of the literature has shown the inadequacy of the investigation of capacity of reinforced concrete member under combination of bi-axial shear and torsion. According to current design codes, there is only a design formula for determining ultimate capacity of reinforced concrete beam subjected to uniaxial shear combined with torsional force. In other words, there are no codes or specifications associated with reinforced concrete members subjected to this kind of loading pattern.

This paper presents an experimental study regarding the behavior of rectangular reinforced concrete beam under combined bi-axial shear and torsion. Four reinforced concrete beams are tested by using a simple experimental set-up with only one hydraulic jack. Based on the experimental results, cracking behavior, load-deflection relationship, and failure mode of the test specimens are investigated, and the effect of torsion on bi-axial shear capacity is discussed.

Bi-axial shear and torsion test

The present study is intended to set up the simple and accurate test procedure to apply bi-axial shear and torsion to reinforced concrete beams with rectangular cross-section. In this test, only one hydraulic jack is used for a simply-supported beam under one point loading as shown in Figure 1. To achieve the combined loading between bi-axial shear and torsion, one stub at mid-span (loading point) and two stubs at the ends of span (support points) are used to create the condition of the tilted specimen subjected to the vertical load at the mid-span and torsional restraint at the support ends. These concrete stubs are cast at the same time as the specimen. The supporting condition of the beam is the modified-roller support, i.e. the translational components in *x* and *y* directions or deflection are restrained, and the rotational components about *x* and *y* directions or flexural slope is allowed while the rotational component about member axis or torsional angle is restrained. In order to create the condition of torsional restraint, support stubs of the beam specimen are clamped with the upper plate of the roller support device, while the lower plate of the device is clamped with the transfer column. It is noted that the roller support device used in this study is similar to that used in the practical bridge structure.

As shown in Figure 2, the vertical load P is applied in the inclined direction of the angle α with respect to the principal y-axis and applied at the point with eccentricity e from the shear center S, shear forces in two directions (P_x, P_y) and a torsional moment (T) can be applied to the beam simultaneously. With this kind of loading scheme, the ratio among shear forces in x and y direction P_x, P_y and torsional moment T can be changed in accordance with values of tilted angle α and eccentricity e.

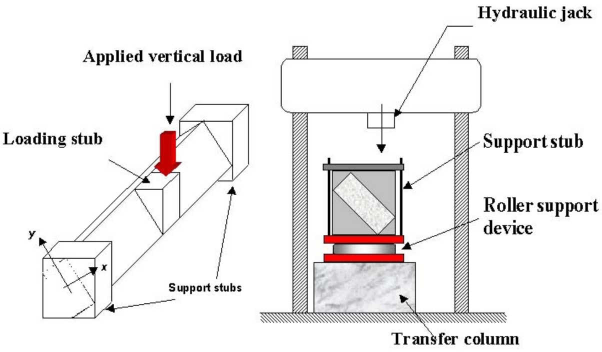


Figure 1. Simple test of bi-axial shear and torsion

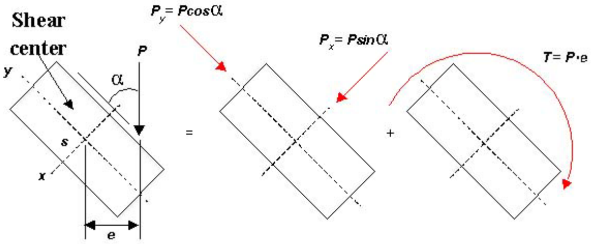


Figure 2. Components of applied loads

Table 1. Tilted angle and eccentricity of beam specimens

Series	Specimen	Eccentricity, *e* (mm)	Tilted angle, α (degree)
I	B45-I	147.8	45
I	B60-I	147.8	60
II	B45-II	250.0	45
II	B60-II	250.0	60

Details of specimens

Four specimens in the study are divided into two series in accordance with the ratio of applied shear and torsional force, i.e. eccentricity of vertical load (*e* in Figure 2). Series I consists of two specimens, identified as B45-I and B60-I and Series II consists of two specimens, B45-II, and B60-II. The number after B indicates the ratio of two shears applied in two principle directions of cross section, *x* and *y*, i.e. the magnitude of tilted angle (α in Figure 2). Eccentricity (*e* in Figure 2) was 147.8 mm for specimens in Series I, and 250 mm for specimens in Series II. Table 1 summarizes the two parameters of the present test, i.e. tilted angle (α) and eccentricity (*e*). Dimensions of all specimens are the same, but the dimension of the stubs in Figure 1 alters to allow for the changes in tilted angle and eccentricity of the applied load.

Dimension and reinforcement arrangement of all four specimens are 200 × 450 mm rectangular cross section as shown in Figure 3. Figure 4 shows the layout of the reinforcement of the specimen. The longitudinal steel reinforcement consists of seven 25-mm diameter deformed bars in each side of the specimens, totally fourteen bars. The transverse steel reinforcement or stirrup consists of 6-mm diameter closed stirrups spaced at 100 mm in the test span and 50 mm in the other span. The objective of this arrangement is to ensure that the failure region will fail in the test span, and measurement and observation can be concentrated on the test span. Strain gauges are attached on the longitudinal reinforcement bars and stirrup for measuring strain of each bar as shown in Figure 4. Table 2 shows the material properties of all specimens, i.e. concrete compressive strength and yield strength of reinforcement.

Test results

Crack patterns

In order to understand the crack patterns of the specimens subjected to bi-axial shear and torsion in the present test, comparison with the results of specimens subjected to bi-axial shear only from Hansapinyo *et al.* (2001) is made. Figure 5 shows failure crack pattern of the specimen subjected to bi-axial shear only (Hansapinyo *et al.*, 2001) and Figure 6 shows components of shear stresses which have the same direction in the longer faces A, C and in the shorter faces B, D, respectively.

Due to the shear stresses occurring on the four faces A, B, C, D, the diagonal cracks are formed on the longer faces A, C and the shorter

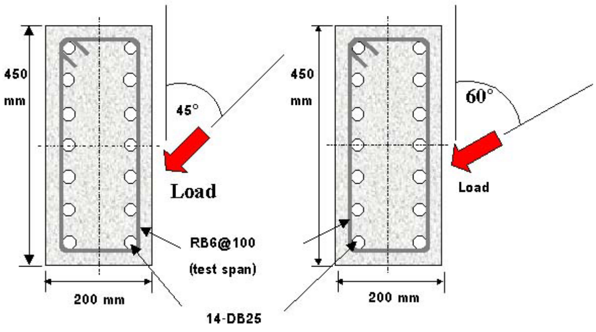


Figure 3. Cross-section of beam specimens

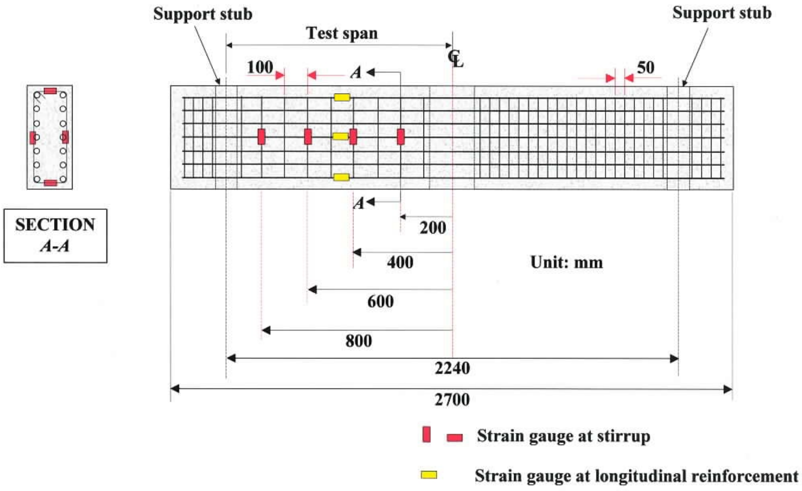


Figure 4. Details of reinforcement arrangement and position of the strain gauge

Table 2. Concrete compressive strength and yield strength of longitudinal reinforcement and stirrup of all specimens

Series	Specimen	Concrete compressive strength (MPa)	Yield strength of longitudinal reinforcement, DB25 (MPa)	Yield strength of stirrup, RB6 (MPa)
I	B45-I	29.3	439.5	372.8
I	B60-I	29.3	439.5	372.8
II	B45-II	37.8	484.9	372.8
II	B60-II	37.8	484.9	372.8

faces B, D with almost the same inclination angle as the case of the beams subjected to uni-axial shear in each direction parallel to the longer and shorter face, respectively.

In case of the specimen subjected to combined bi-axial shear and torsion in the current test, Figure 7 shows failure crack pattern of specimen B60-II (see Table 2). It is noted that failure crack patterns of other specimens B45-I, B60-I, B45-II are almost the same as in Figure 7. It can be seen that the inclination angles of diagonal cracks on two faces C and D are different from those in the case of the specimen subjected to bi-axial shear only. The comparison of inclination angle of diagonal cracks is clearly illustrated in Figure 8. The differences of inclination angle of diagonal cracks on faces C and D in Figure 8(b) can be explained by the opposite direction of shear stress due to the bi-axial shear and that due to torsion as shown in Figure 9. On the other hand, due to the same direction of shear stress due to bi-axial shear and that due to torsion on faces A and B in Figure 9, the similar inclination angle of diagonal cracks on faces A and B can be observed in Figure 8(a).

Ultimate capacity

The combined bi-axial shear and torsional capacities carried by concrete and stirrup are obtained by considering the load-stirrup strain relationship as shown in Figure 10 for specimen

B60-I. It is noted that for other specimens almost the same relationships as Figure 10 are observed. In Figure 10, the values of stirrup strain at different locations are shown, i.e. 200-mm, 400-mm, 600-mm, and 800-mm distance from the mid-span (see Figure 4). From the results, it can be seen that before diagonal cracking, strain in stirrup is relatively small, and hence only concrete carries the load. However, when the diagonal crack is initiated, the load is carried by both concrete and stirrup as can be seen by an increase in stirrup strain after diagonal cracking in Figure 10. The load carried by concrete is denoted by concrete contribution (P_c) and the load after diagonal crack is referred to stirrup contribution (P_s). As mentioned above, strain in stirrup is small before diagonal cracking, concrete contribution P_c is the load level where stirrup strain starts to increase. By assuming that concrete contribution P_c is constant even after diagonal cracking, stirrup contribution P_s is obtained by deducting the previous concrete contribution P_c from ultimate load, i.e. $P_s = P_u - P_c$. From the present test results of specimen B60-I, ultimate load P_u is 241.5 kN, concrete contribution P_c is 205.8 kN and stirrup contribution P_s is 35.7 kN ($P_u - P_c$). In Table 3, the values of P_c and P_s of all specimens are shown.

As shown in Table 3, concrete strength of the specimens in series I and II are different, i.e., 29.3 MPa for specimens in Series I and 37.8 MPa for specimens in Series II. In order to compare ultimate capacity among the four specimens in the two series, concrete contribution or diagonal cracking load P_c in Series II was adjusted.

According to ACI code for shear (1999), concrete compressive strength is taken into account for concrete contribution P_c by the term of $\sqrt{f'_c}$. Hence, the adjusted concrete contribution P'_c is obtained to be proportional to $\sqrt{f'_{c\,(series\,I)}}$ where $\sqrt{f'_{c\,(series\,I)}}$ is the value of concrete compressive strength of series I. The values of adjusted diagonal cracking load of specimens in series II are computed by the following equation,

$$P'_c = P_c \frac{\sqrt{f'_{c\,(series\,I)}}}{\sqrt{f'_{c\,(series\,II)}}} \qquad (1)$$

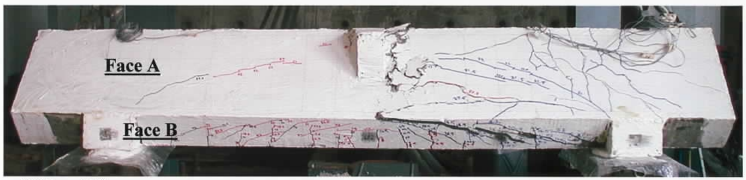
The ultimate capacity is also adjusted for the two series by taking summation between adjusted concrete contribution P'_c and stirrup contribution P_s.

For series I, the capacity of specimen B45-I is about 7 percent higher than that of specimen B60-I and for series II ultimate capacity of specimen B45-II is about 32 percent higher than that of B60-II. This might be due to different ratio of bi-axial shear load applied to each principal axis. In other words, for specimens with 60 degree tilted angle, larger load is applied in the direction of weak principal axis of the beam section, while smaller load is applied in the direction of strong principal axis. The ratio of the load in weak and strong principal direction is $\sqrt{3}\left(=\frac{\sin 60^{o}}{\cos 60^{o}}\right)$. On the other hand, the specimens with 45 degree tilted angle are subjected to the same load in both weak and strong principal directions.

For specimens with 45-degree tilted angle, the capacity of specimen B45-I is about 12 percent higher than that of specimen B45-II, and for specimens with 60-degree tilted angle, the capacity of specimen B60-I is about 39 percent higher than B60-II. In other words, when eccentricity or torsional moment is increased by 69 percent, the ultimate capacity is reduced about 12 percent and 39 percent in case of 45 and 60-degree tilted angle, respectively. This may be due to larger torsional moment leading to faster development of diagonal cracking. Hence, for the same tilted angle, the diagonal cracking load of the beam with larger torsional moment is lower and, consequently, the ultimate capacity decreases.

Comparison with Current design code

In most of current design codes, such as



(a) Front View

(b) Rear View

Figure 5. Failure crack pattern of the specimen subjected to bi-axial shear only (Hansapinyo *et al.*, 2001)

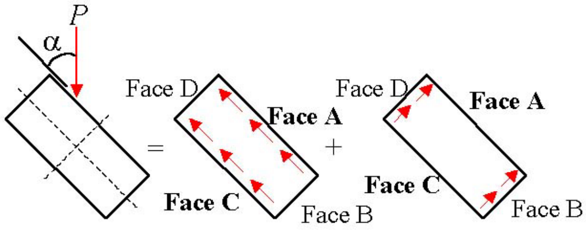
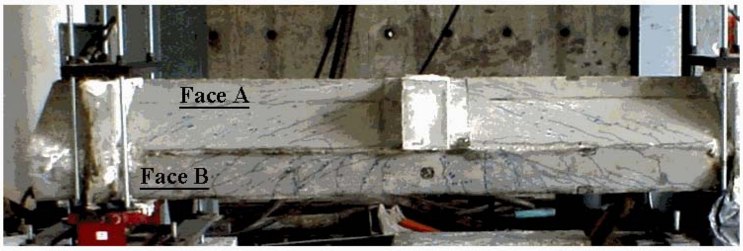


Figure 6. Components of shear stresses due to bi-axial shear only

ACI code 318-99 (1999), JSCE standard specification (1996), the interaction formula for uni-axial shear and torsion has been specified; however, there is none regarding the interaction for bi-axial shear and torsion. Hence, for comparison purpose, the calculation of shear capacity in the uni-axial direction is performed as shown in Figure 11. These two extreme cases of applied loads in the principal axes of beam section should cover the case of all tilted beam specimens in this study.



(a) Front View

(b) Rear View

Figure 7. Failure crack pattern of specimen subjected to combined bi-axial shear and torsion

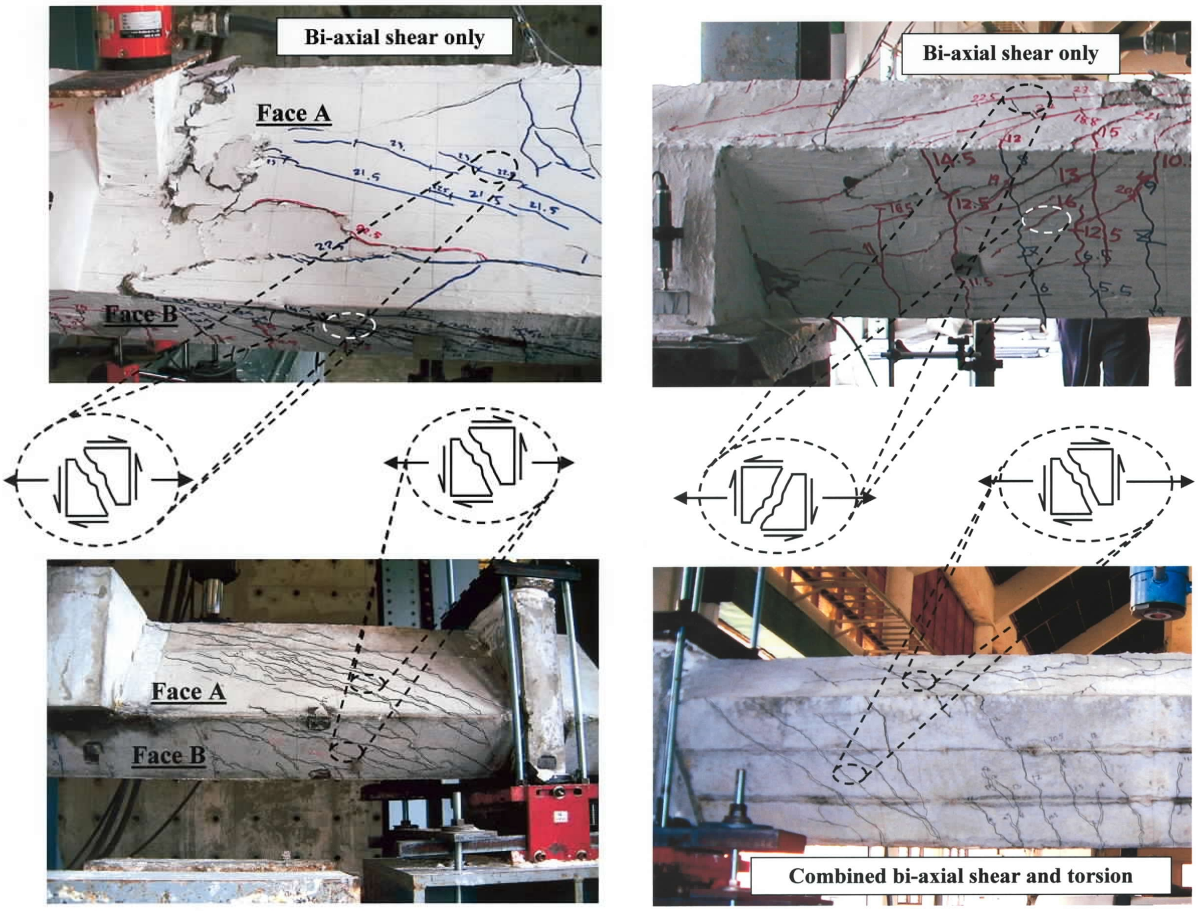


Figure 8 (a) Comparison on Faces A and B

Figure 8 (b) Comparison on Faces C and D

Figure 8. Comparison of inclination angle of diagonal cracks between specimen subjected to bi-axial shear only and combined bi-axial shear and torsion

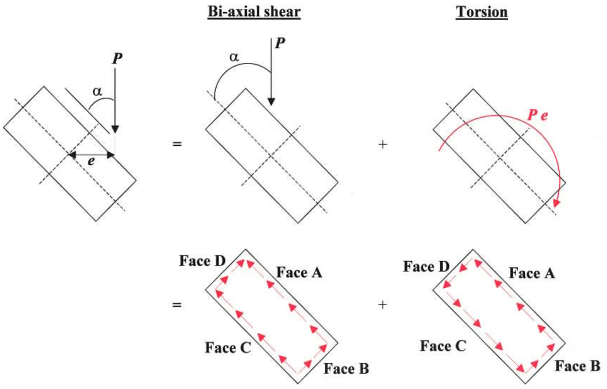


Figure 9. Components of shear stresses due to combined bi-axial shear and torsion

When the beam is subjected to uni-axial shear and torsion, ACI code (1999) provides the following relation:

$$\frac{\sum A_{v+t}}{s} = \left(\frac{V_u - V_c}{f_{yv}\,.d}\right) + 2\left(\frac{T_u}{2A_0 f_{yv}\cot\theta}\right) \qquad (2)$$

where

V_u : shear force due to load, N
T_u : torsional moment due to load, mm-N
V_c : shear strength contributed by concrete, N, expressed as follows:

$$V_c = \left(\sqrt{f_c'} + 120\rho_w \frac{V_u d}{M_u}\right)\frac{b_w d}{7} \qquad (3)$$

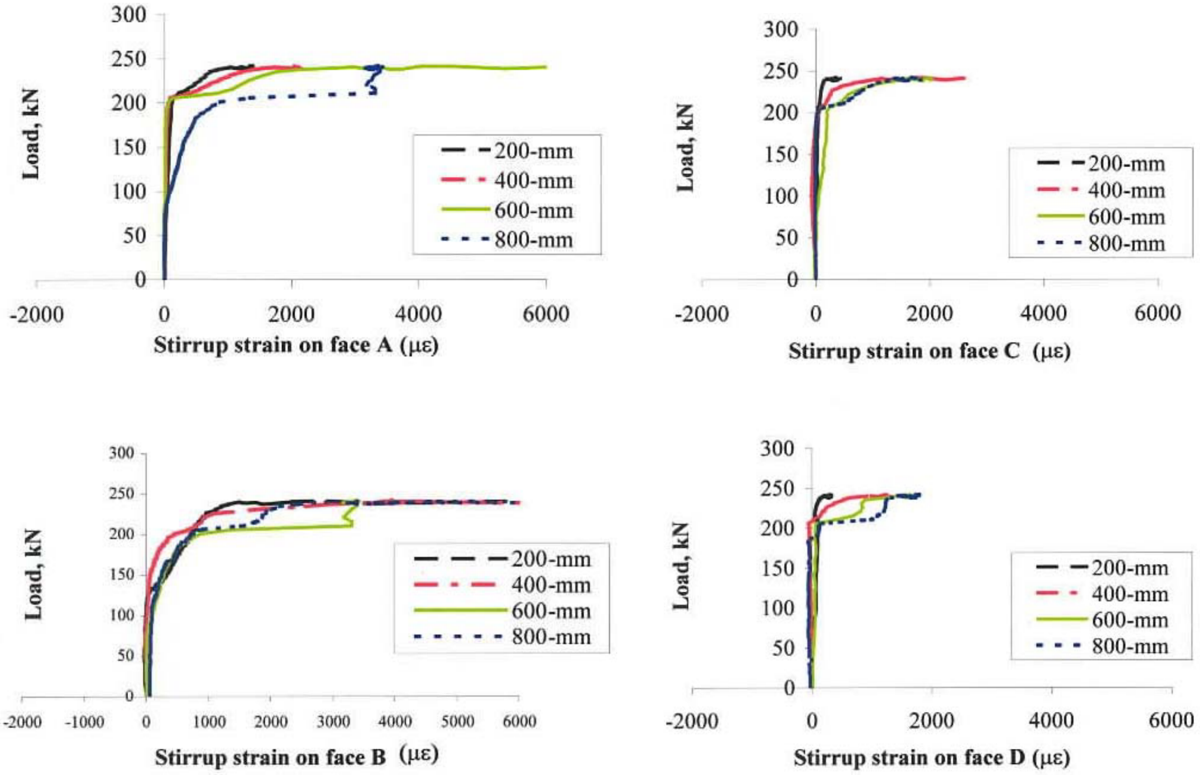


Figure 10. Load-stirrup strain relationship of specimen B60-I at various distances from mid-span

f'_c : concrete compressive strength, MPa

ρ_w : tension reinforcement ratio = $\frac{A_s}{b_w d}$

M_u : flexural moment due to load, mm-N

($\frac{M_u}{V_u}$ indicates shear span a , mm)

f_{yv} : yield strength of stirrup, MPa

b_w : web width, mm

d : distance from extreme compression fiber to centroid of tension reinforcement, mm

A_s : area of tension reinforcement, mm^2

θ : angle of compression diagonals in truss analogy for torsion

A_0 : gross area enclosed by shear flow path, mm^2 = $0.85A_{oh}$

A_{oh} : area enclosed by centerline of the outermost stirrups, mm^2

s : spacing of stirrup, mm

By substituting dimension and material properties of beam specimens, the ultimate load considering combined effect of shear and torsion can be obtained for both specimens as shown in Table 4. It is noted that according to cracking patterns at ultimate load in Figure 7, θ is taken as 30°.

According to JSCE standard specification (1996), the interaction formula for bi-axial shear and for uni-axial shear and torsion are provided. However, there is no interaction formula for bi-axial shear and torsion. Similar to the above discussion of ACI code, the two extreme cases in Figure 11 are also considered here. Based on JSCE standard specification, the interaction formula for uni-axial shear and torsion is given as

Table 3. Concrete compressive strength and ultimate capacity of test specimens

Series	Specimen	Concrete compressive strength (MPa)	Eccentricity, *e* (mm)	Diagonal cracking load, P_c (kN)	Adjusted diagonal cracking load, P_C' (kN)	Stirrup Contribution, $P_s = P_u - P_c$ (kN)	Adjusted Ultimate capacity, $P_U' = (P_C' + P_S)$ (kN)
I	B45-I	29.3	147.8	220.7	220.7	36.8	257.5
	B60-I	29.3	147.8	205.8	205.8	35.7	241.5
II	B45-II	37.8	250.0	167.1	147.1	82.4	229.5
	B60-II	37.8	250.0	152.5	134.3	39.0	173.3

$$\left(\frac{M_{td}}{M_{tyd}}\right)+\left[1-0.2\left(\frac{M_{tcd}}{M_{tyd}}\right)\right]\left(\frac{V_d}{V_{yd}}\right)=1.0 \qquad (4)$$

where

M_{td}: torsional moment due to load, mm-N

V_d: shear force due to load, N

V_{yd}: shear capacity of beam with stirrup when torsion is not applied, N, expressed as follows:

$$V_{yd} = V_{cd} + V_{sd}$$

V_{cd} : shear capacity contributed by concrete, N, expressed as follows:

$$V_{cd} = 0.2 \cdot \beta_d \cdot \beta_p \cdot \sqrt[3]{f_{cd}'} \cdot b_w \cdot d$$

$\beta_d = \sqrt[4]{1/d}$ (d: m), when $\beta_d > 1.5$, β_d is taken as 1.5

$\beta_p = \sqrt[3]{100 p_w}$, when $\beta_p > 1.5$, β_p is taken as 1.5

f_{cd}': compressive strength of concrete, N/mm^2

d : effective depth, mm

$$p_W = \frac{A_S}{b_w d}$$

A_s : area of reinforcing steel in tensile zone, mm^2

V_{sd}: shear capacity contributed by stirrup, N, expressed as follows:

$$V_{sd} = \frac{A_w f_{wyd} z}{s_s}$$

A_w : total amount area of stirrup over the interval s_s, mm^2

f_{wyd} : yield strength of stirrup, N/mm^2

$$z = \frac{d}{1.15}, \text{ mm}$$

s_s : spacing of stirrup, mm

M_{tcd} : torsional capacity of beam without stirrup when shear is not applied, mm-N, expressed as follows:

K_t : torsional constant, mm^3, expressed as follows:

$$K_t = \frac{b^2 d}{\left(3.1+\frac{1.8}{d/b}\right)\cdot\left(0.7+\frac{0.3}{d/b}\right)}$$

f_{td} : tensile strength of concrete, N/mm^2, expressed as $0.23 f_{cd}'^{\,2/3}$

b : width of beam

M_{tyd} : torsional capacity of beam with stirrup when shear is not applied, mm-N, expressed follows:

$$M_{tyd} = 2A_m \sqrt{q_w \cdot q_l}$$

A_m : effective area for torsion, mm^2, $A_m = b_o d_o$

b_o : length of the shorter side of stirrup, mm

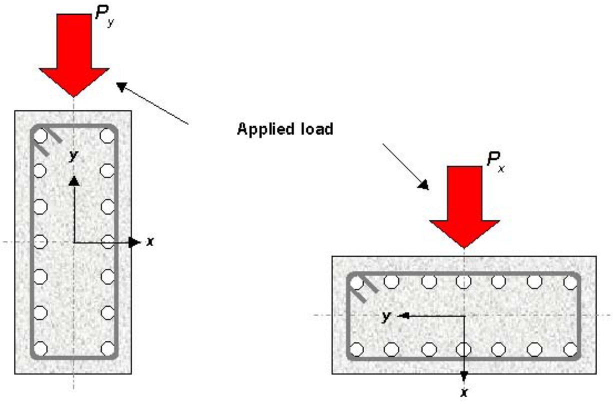


Figure 11. Two extreme cases for calculating shear capacity

d_o : length of the longer side of stirrup, mm

$q_w = A_{tw} \cdot f_{wyd} / s_s$

$q_l = \Sigma A_{tl} \cdot f_{ld} / u$

A_{tw}: area of a single leg of stirrup that works effectively as torsion reinforcement over the interval u , mm^2

ΣA_{tl}: total amount of the longitudinal reinforcement that works effectively as torsion reinforcement over the interval u , mm^2

u : length of the centerline of stirrup, mm, $u = 2(b_o + d_o)$

f_{ld}: yield strength of longitudinal reinforcement, N/mm^2

According to Table 4, the current design codes underestimate the ultimate loads of all specimens except the specimen B60-II of which the ultimate load is overestimated by JSCE specification in case of shear capacity the strong principal axis (*y*-direction). However, the difference between experimental and calculated results is practically small, about 8%. It should be noted that since in the present experiment the load is applied in the inclined direction, i.e. 45° and 60° with respect to y-axis, the ultimate capacity of beam specimens naturally falls in the two extreme cases of P_y and P_x. However, from results of comparison in Table 4, the current design codes give quite conservative values of ultimate capacity, i.e. about 1% - 40% lower than experimental values in case of P_y (strong principal axis). Therefore, in order to achieve more rational and economic design, the improvement of the current design codes regarding interaction of bi-axial shear and torsion is necessary.

Table 4. Comparison of ultimate capacity of beam specimens

Series	Specimen	ACI (kN)		JSCE (kN)		Experiment (kN)
		Case of P_x	Case of P_y	Case of P_x	Case of P_y	
I	B45-I	143.0 (55.5%)	184.8 (71.7%)	192.0 (74.5%)	240.2 (93.3%)	257.5
	B60-I	143.0 (59.2%)	184.8 (76.5%)	192.0 (79.5%)	240.2 (99.5%)	241.5
II	B45-II	133.0 (53.3%)	149.0 (59.7%)	174.6 (70.0%)	208.2 (83.4%)	249.5
	B60-II	133.0 (69.4%)	149.0 (77.7%)	174.6 (91.2%)	208.2 (108.7%)	191.5

Note: values in the parenthesis ( ) indicate ratio between calculated results and experimental results in percentage

Concluding remarks

The experimental investigation on the capacity of rectangular reinforced concrete beam with stirrups subjected to combined bi-axial shear and torsion by using simple test method was conducted. This method requires only one hydraulic jack to produce the complicated bi-axial shear and torsional loading by applying an eccentric load to the tilted simply-supported beam. Two main parameters in this study are eccentricity of the load which represents the magnitude of torsional moment, and tilted angle of specimens which represents the ratio of bi-axial shear. Experimental results indicate that all four specimens failed in the same mode, i.e. stirrup yielding after diagonal cracking which is caused by the combined effect of bi-axial shear and torsion. Cracking patterns of the beams can be explained by using the superposition of shear stresses in two directions and torsional stresses. It was found that the increase in the magnitude of torsion of about 69 percent results in a drastic decrease in bi-axial shear capacity, about 12 - 39 percent depending on ratio of bi-axial shears. The comparison of ultimate capacities from the experimental results with the calculated values by current design code, ACI and JSCE, indicates that the current design codes give quite conservative values of ultimate capacity.

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