Test of Reinforced Concrete Deep Beams Subjected to Concentric Bi-Axial Loading

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Abstract

Prediction of the shear capacity of reinforced concrete members subjected to complicated loading is the subject of much interest in the ultimate state evaluation. This paper deals with the experimental investigation that aims to explain cracking behavior and the strength of reinforced concrete deep beams subjected to bi-axial loading. In the study, two series of reinforced concrete beams (one is deep beam and the other is slender beam) were tested under bi-axial loading. Based on the test results, comparisons between the two series of the test results are made in terms of cracking pattern and strength associated with ellipse formula which is currently used in JSCE specification for design of reinforced concrete members subjected to bi-axial shear. The experimental results have shown that the calculation of bi-axial shear capacity of reinforced concrete deep beams should be made into two formulae due to apparently different between slender and deep beams behavior.

1. Introduction

In practice, reinforced concrete deep beams are very common structural components used in tall buildings, foundations and offshore structures. The beams are often used to carry loads for a large span of space. Additionally, they are sometimes used for load distributions such as transferring girders, pile caps, and foundation walls. Corresponding to its dimension, a reinforced concrete beam is defined as a deep beam when the ratio of shear-to-depth is small, implying that the load carrying mechanism is described by a strut and tie action. At present, there have been plenty of definitions of deep beam in accordance with various design formulae. For example, Joint ASCE-ACI Task Committee 426 [1] define beams with shear span-to-effective depth ratio less than 2.5 as deep beams. CEB-FIP [2] treats simply supported and continuous beams as deep beams when their shear span-to-depth ratios are less than 2 and 2.5, respectively. ACI specification [3] expresses beams with a clear span-to-depth ratio not exceeding 5 for deep beam. However, the latest published one [4] defined deep beam as a beam with a clear span not exceeding four times the overall depth, or a region of beams loaded with concentrated loads within twice the beam depth or D-region.

Regarding the capacity, reinforced concrete deep beams are usually governed by shear. There have been a hundred of researches carried out to explore and establish an equation to predict shear capacity ([5], [6], [7]). However, so far, there is no agreed procedure to predict the shear strength of reinforced concrete deep beams in accordance with their complex mechanism.

Occasionally, the aforementioned structures composed of deep beams may be subjected to the load acting inclined to the plane of symmetry. This leads to two orthogonal loads acting simultaneously in which hereinafter is called bi-axial loading. Yoshimura [8] has carried out a test consisting of reinforced concrete members subjected to bi-axial loading associated with a constant longitudinal force. All members are square reinforced concrete columns and defined in the range of slender member. The strength of

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reinforced concrete members obtained from the tests agree well with the calculated ones by using ellipse function, which is currently adopted in JSCE design specification. The test of rectangular reinforced concrete slender beams subjected to bi-axial shear has been done by Hansapinyo et al [9]. Nevertheless, the prediction of ultimate bi-axial shear capacity of deep beams is still questionable.

This study aims to investigate the cracking behavior and strength of reinforced concrete deep beams under bi-axial shears by conducting experimental works. All specimens are classified into 2 series: slender beams and deep beams. In the test, a bi-axial load is applied to beam specimens by using only one hydraulic jack. Finally, discussions are made by comparing the test results of the two series of the beams in terms of cracking behavior and strength associated with an ellipse formula.

2. Design of reinforced concrete beams subjected to bi-axial shear

Most of international design codes provide a shear formula predicting uni-axial shear capacity. Among them, the JSCE design code [10] mentions the reduction of the capacity when the other orthogonal shear force exists. It is also considered that the acting of two shears simultaneously reduces each other uni-axial shear capacity possessed in each principal direction. Fig. 1 shows the relationship of the reduction of uni-axial shear capacity when the other orthogonal shear exists. The calculation for bi-axial shear capacity is started by calculating uni-axial shear capacities in x and y directions, for which x and y are the directions of major axes, as represented by circles in the figure. Substituting the uni-axial shear capacities into the interaction formula, as shown in Fig.1, the ellipse curve is drawn and shear capacities in any directions can be obtained. Unless the magnitude of applied external shear $|S_R|$ is larger than the absolute resultant shear capacity $|V_R|$, the appropriate designed member can be achieved.

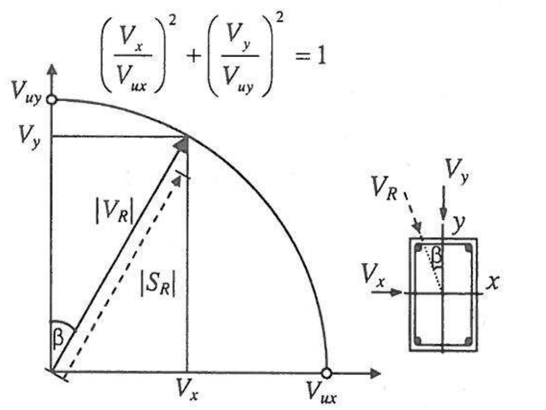


Fig.1 Bi-axial shear interaction formula ([10])

3. Test of Reinforced concrete deep beams subjected to bi-axial shear

In this study, tests of bi-axial shear of reinforced concrete deep beams were conducted by using a simplified test method. Only one hydraulic jack is used to produce the concentric bi-axial load to the simply-supported beams with an angle of tilting provided. In order to create the condition of the tilted beam specimen subjected to vertical load, the beam specimens are attached with the so-called loading stub at the mid-span and the so-called support stubs at both ends of the beam, as illustrated in Fig. 2.

The vertical load P is applied in the direction with tilt angle β from y axis, and hence two forces acting in the directions of x and y axes can be applied to the beam simultaneously, as shown in Fig. 3. The ratio between two forces in x and y directions (P_x, P_y) can be changed in accordance with values of the tilted angle β between the principal y axis and the line of load P.

4. Specimens details

According to their dimensions, the test specimens are classified into 2 series. With the definition of a deep beam by Joint ASCE-ACI Task Committee 426 [1], shear span-to-depth ratios in principal x and y axes of specimens in series I are defined in a slender beam range. For specimens in series II, the ratios in principal x axis is large while that in y axis is small and respectively defined as a slender beam range and a deep beam range. Table 1 shows dimensions and tilt angles of specimens

In order to investigate bi-axial shear behavior of reinforced concrete deep beam, four specimens were tested with different tilted angle i.e. 0, 25, 45 and 90 degrees (in Fig. 2). As seen in Table 1, the number after B (Beam specimen) indicates the magnitude of the tilted angle. Specimens B0_I, B0_II and B90_I, B90_II were tested under uni-axial loading which are considered as reference beams. According to their dimension, B0_II is classified as deep beam while B90_II is classified as slender beam ([1], [2]).

The compressive strength of concrete for the specimens series I and II are 32 and 21.4 MPa. For reinforcement arrangement of specimens in both series, deformed bars with diameter of 25 mm and round bars with diameter of 6 mm. are used for longitudinal reinforcement and stirrups, respectively. Yield strength of longitudinal reinforcement (DB25) is 440 MPa while that of shear reinforcement (RB6) is 370 MPa. It is noted that in a test span which contains less stirrups than those in the other span of the beam, all specimens were designed to fail in shear mode. Details of reinforcement arrangement and sectional dimension are shown in Fig. 4.

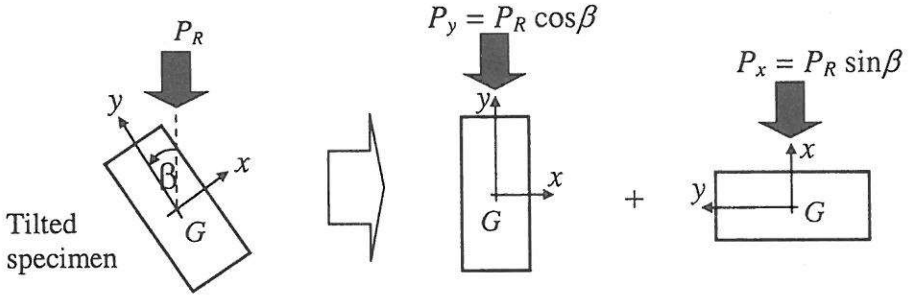


Fig. 2 Simplified test method for bi-axial shear test

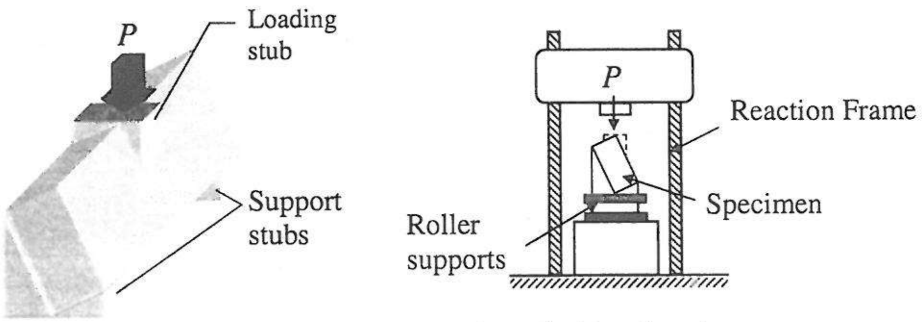
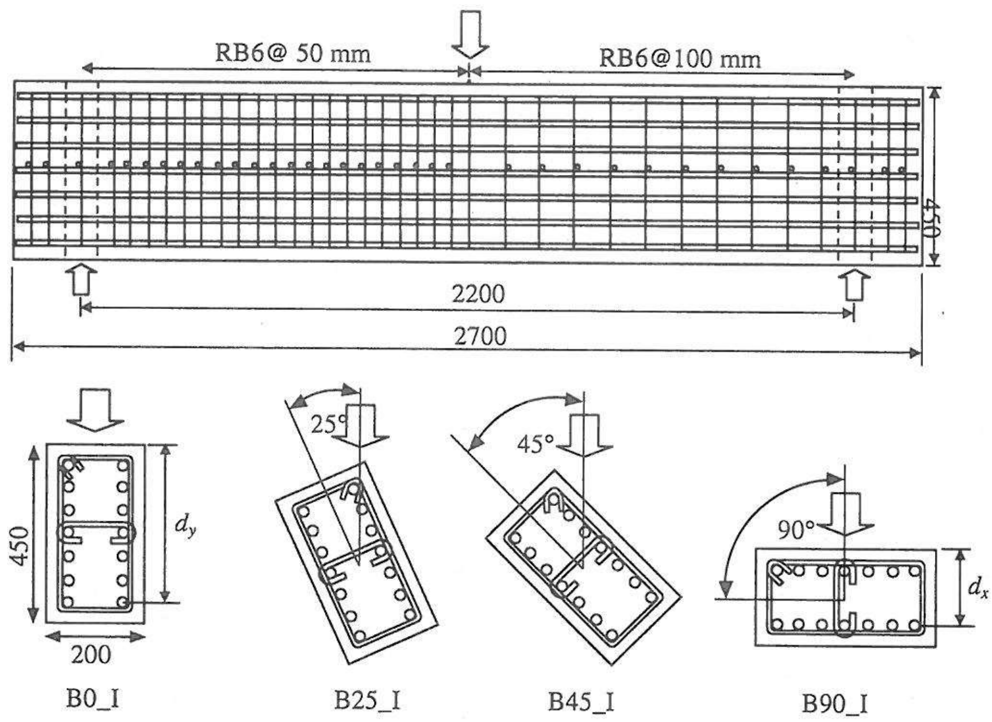


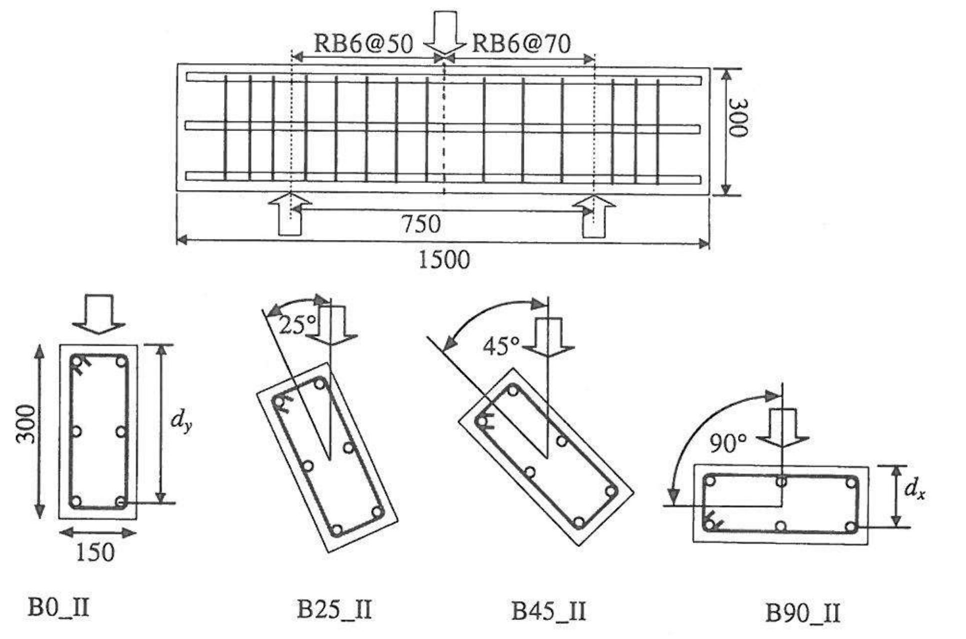
Fig. 3 Components of applied load

Table 1 Dimensions and tilt angle of specimens

Series	Specimen	Section $h_x \times h_y$ (mm×mm)	y-depth (see Fig.4) d_y (mm)	x-depth (see Fig.4) d_x (mm)	Tilt angle β (Degree)	Shear span a (mm)	Shear span-to-depth ratio (y) $(a/d)_y$	Shear span-to-depth ratio (x) $(a/d)_x$
I	1. B0_I	200×450	410	160	0	1,100	2.68	6.87
	2. B25_I	200×450	410	160	25	1,100	2.68	6.87
	3. B45_I	200×450	410	160	45	1,100	2.68	6.87
	4. B90_I	200×450	410	160	90	1,100	2.68	6.87
II	5. B0_II	150×300	260	110	0	375	1.44	3.41
	6. B25_II	150×300	260	110	25	375	1.44	3.41
	7. B45_II	150×300	260	110	45	375	1.44	3.41
	8. B90_II	150×300	260	110	90	375	1.44	3.41



(a) Specimens in series I [11]



(b) Specimens in series II

Note: Longitudinal steel: DB25
Stirrup steel: RB6
Unit in mm.

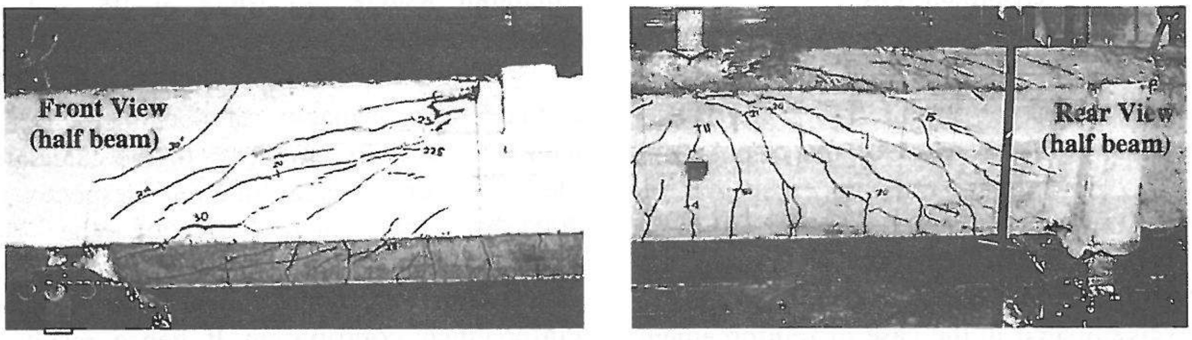
Fig. 4 Dimension and reinforcement arrangement of specimens

5. Tests results

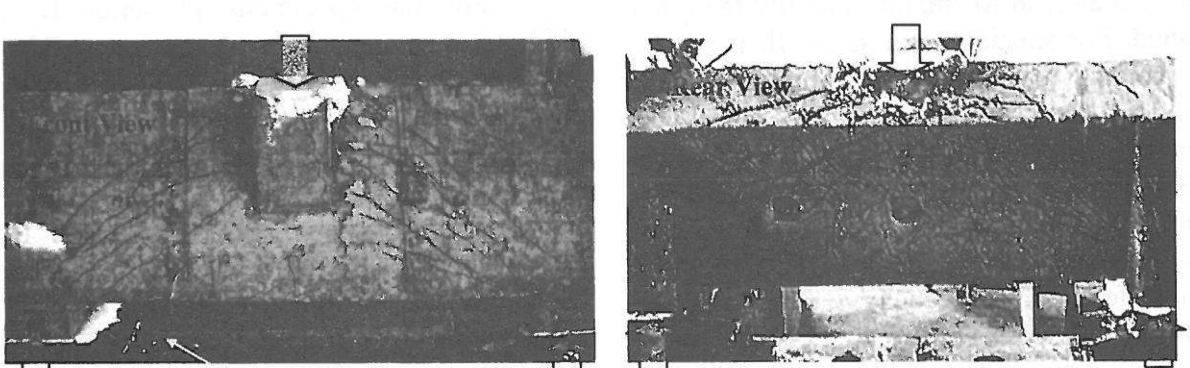
5.1 Crack pattern

For all specimens, the first generated crack was the flexural crack near or at mid-span where is the section of the maximum moment. With additional load intensity, the crack widened and was propagated upwards. At the diagonal shear strength, the diagonal crack started to appear in the web. For specimens in series I, the diagonal crack width was large, causing yielding of the crossed stirrups. For specimen B90_I, the propagation of the crack was not as fast as those that occurred in a typical manner. Nevertheless, the shear tests performed by Kani [12] have indicated the independency of the shear capacity with respect to beam width.

For specimens series II, at the ultimate load of specimens B0_II and B25_II, the compression failure around the loading point apparently occurred, while diagonal tension cracks have been observed in specimens B45_II and B90_II. Fig.5 showed different crack patterns of specimens B25_I and B25_II. These were both inclined at 25 degrees with respect to vertical loading direction. The diagonal crack of specimen B25_I is wider compared to that of B25_II which contains crushing cracks near the load stub.



(a) B25_I



(b) B25_II

Fig. 5 Crack configuration of specimens B25_I and B25_II

5.2 Shear capacity

Ultimate capacities (V_u) of specimens in series I are separated into concrete contribution (V_c) and shear reinforcement contribution (V_s). Based on the fact that the slender beam which has a moderate shear span-to-depth ratio will fail suddenly after appearing of diagonal crack, the concrete contribution is defined as the shear force corresponding to diagonal cracking load. In the test, it is recognized at the commencement of straining of stirrups (Ozcebe, et al [13]). Fig.6 shows shear-stirrup strain relationship of specimen B25_I at the section x=60 from midspan.

For series I, all specimens failed in diagonal tension mode. Regarding the ultimate

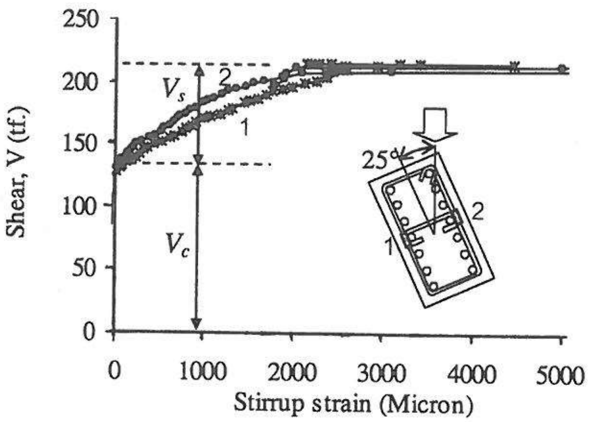


Fig.6 Shear-stirrup strain relationship of specimen B25_I

capacity, the test results of B25_I and B45_I are 0.97 and 1.06 percent of the calculations used as the ellipse function, respectively. However, with the separated concrete and shear reinforcement capacities, the calculations are underestimated in the case of concrete capacity and overestimated in the case of reinforcement capacity. The overestimation of reinforcement capacity may lead to smaller ductility than that expected. For specimens in series II, it can be seen that the behavior of specimen B25_II is similar to that of specimen B0_II, where the ultimate bi-axial shear capacities are 416.9 kN and 394.6 kN, respectively. Failure mode is the crushing of concrete strut near loading stub. For specimens B45_II and B90_II, there is a small difference in the behavior between the specimens in which the ultimate bi-axial shear capacities are 259.7 kN and 265.1 kN, respectively. The failure mode of these two beams is due to a diagonal tension failure. Table 2 shows ultimate capacity of the test specimens associated with the calculated ones using the ellipse formula. Moreover, they are graphically shown in Fig.7. It is noted that the ultimate capacity of the specimens in series II can not be separated into concrete contribution and shear reinforcement contribution due to the failure mode that occurs when crushing concrete. Hence, the total ultimate load is calculated and compared with the test results.

6. Concluding remarks

In order to investigate the ultimate capacity of reinforced concrete deep beams subjected to bi-axial shear, the experimental study has carried out two series of the bi-axial shear tests comprising of four beams each. According to their dimensions (in major direction), series I is classified as a slender beam and the other series as a deep beam. In this test, to induce bi-axial loading, tilting an angle about specimen axis is given to each specimen. In each series, two beams are considered as reference beams tested under uni-axial loading, one tilted at the 0 degree, the other one is tilted at 90 degrees. The two remaining beams are tilted at 25 and 45 degrees, respectively.

Based on the experimental results, the ultimate shear capacity of specimens B25_I and B45_I are 0.97 and 1.06 of the calculated ones by using ellipse function, respectively. However, the calculations of the two specimens underestimate part of concrete contribution and overestimate part of shear reinforcement contribution. It, hence, results in smaller ductility than expected.

For the specimens in series II, the ultimate shear capacities of specimens B25_II and B45_II are respectively 1.06 and 0.82 of the calculations. It is noted that the crack propagation observation of specimen B25_II during the test, indicated that it failed in resembling the deep beam (while B45_II is slender beam). In other words, the ultimate capacities of specimen B25_II is closer to B0_II while the ultimate capacity of specimen B45_II is close to B90_II. Due to the apparent differences in slender and deep beam behavior, it can be said that the ellipse function should be divided into two equations based on the range of deep beam behavior and slender beam behavior. Research into the tilted angle determining the shifting point of the two different behaviors, is further needed.

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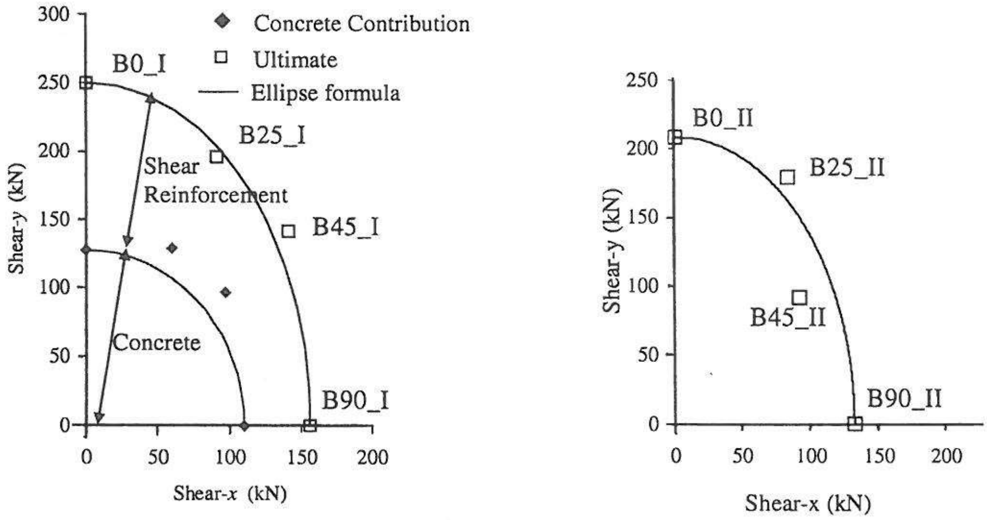
Table 2 Ultimate capacities of specimens

Series	Speci-men	Experiment (kN)			Calculation (Ellipse formula) (kN)			Exp./Cal.		
		V_u	V_c	^1V_s	V_u	V_c	V_s	V_u	V_c	V_s
I	B0_I	250.2	127.5	122.6	-	-	-	-	-	-
	B25_I	215.7	142.2	73.5	221.4	123.8	97.6	0.97	1.15	0.75
	B45_I	199.7	137.3	62.4	187.9	117.9	69.9	1.06	1.16	0.89
	B90_I	156.8	110.2	46.6	-	-	-	-	-	-
II	B0_II	208.5	-	-	-	-	-	-	-	-
	B25_II	197.3	-	-	185.5	-	-	1.06	-	-
	B45_II	129.85	-	-	158.2	-	-	0.82	-	-
	B90_II	132.55	-	-	-	-	-	-	-	-



(a) Specimens series I (b) Specimens series II

Fig.7 Bi-axial shear capacity of specimens associated with the calculation using ellipse formula

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