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Nonlinear Behaviour of the Concrete Core of the Diagonally Reinforced Coupling Beams

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Highlights

- Contained concrete in diagonal bundles has different stress-strain characteristics than plain concrete.
- Strength and the maximum strain of the concrete increase with the confinement reinforcement ratio.
- Ductility and strength have significant effect on the seismic behaviour of the coupling beams.

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Abstract

Coupled shear walls with coupling beams are constructed because of openings such as doors, windows, or other installations that are left behind due to functional reasons in shear walls. In coupling beams having a ratio of span-to-depth less than two, shear fracture occurs rather than flexural fracture. In order to meet the shear force and the bending moment formed by the coupling beams, diagonal bundles are used in the coupling beams. Diagonal reinforced coupling beams are generally preferred because diagonal reinforced coupling beams exhibit better behaviour than conventional reinforced coupling beams. The diagonal reinforcement bundles have to be confined by transverse reinforcements prescribed in the codes. Confined concrete in the diagonal reinforcement bundles has stress-strain characteristics that are distinctly different from those of plain concrete. The effects of longitudinal and transverse reinforcement ratios on the stress-strain behaviour of confined concrete inside the diagonal reinforcement bundles were investigated. Fifty-four reinforced concrete coupling beams with different confining parameters of the diagonal reinforcement bundles and different variables were analysed using the program. It was demonstrated that the strength and the maximum strain of the concrete inside the diagonal reinforcement bundles increase with the reinforcement ratio of the confinement reinforcement. The increase in the diameter of the transverse reinforcement and the decrease in the spacing of the transverse reinforcement diagonal bundles, increase the confining effect, strength, and ductility in the concrete sections. The increase in the ratio of transverse and diagonal reinforcement significantly affects the seismic behaviour of the coupling beams.

1. INTRODUCTION

In high-rise reinforced concrete structures, coupled shear walls with coupling beams are taken into account in order to resist lateral earthquake effects. Shear walls with coupling beams with sufficient strength and deformation capacity should be designed to dissipate the energy generated by earthquakes, have a large displacement capacity, and provide the transfer of earthquake effects between the shear walls. [1]. If openings such as windows and doors are placed regularly in shear walls, a load-bearing system with large lateral stiffness and durability can be obtained. The coupling beams between the shear walls connect the walls to each other, providing energy distribution and rigidity [2,3]. Extensive study and research on coupling beams have led to design guidelines for seismic load-resistant shear walls with coupling beams [4,5].

In coupling beams, the span-to-depth ratio is normally quite smaller than that of conventional frame beams, together with the different layouts of reinforcing. The shear force between wall piers may cause diagonal cracking in coupling beams, which results in simultaneous tension in both top and bottom reinforcing steel, with poor ductility. It has been seen from the previous test results [6,7] that the diagonal reinforcements

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confined by the transverse reinforcements in the deep coupling beams provide sufficient resistance. Existing seismic design provisions offer the use of cross-reinforced deep coupling beams to meet strength, stiffness, and energy distribution demands. Diagonal reinforcements defined in the standard and codes should be constructed as passing through each other at the middle point of coupling beams and as anchorage into the shear walls confined boundary regions for the embedment length. Diagonal reinforcement in coupling beams are subjected to axial tensile and compressive forces under the effect of seismic loads. Under the influence of the seismic force, the entire tensile force generated in the element is covered by the diagonal reinforcement, while the compressive force is carried by the diagonal reinforcement and the confined concrete inside the diagonal bundles of reinforced concrete coupling beams. The conditions of confinement by transverse reinforcements are very effective in increasing the compressive strength and ductility of the coupling beams. based on different regulations; Diagonal bars in coupling beams should be confined by transverse reinforcement [8].

Considering the importance of coupled shear walls and the importance of seismic behaviour, in this article, in the first part, the rules and regulations related to the design of coupling beams have been investigated based on various regulations. Since diagonal reinforcement in coupling beams have good structural and seismic performance, in this article the coupling beam with diagonal reinforcement has been designed and investigated. The real performance of reinforced concrete members requires knowledge of the nonlinear relation of reinforced concrete members. In the second part of this article, the non-linear behaviour and stress-strain relations of coupling beams are investigated. The strength and deformation capacity of reinforced concrete structural members can be improved by confining the members. This improvement ensures the overall stability and strength of the structure during a strong earthquake. Since under the effect of seismic load, the bundles of diagonal reinforcement are subjected to tensile and compressive axial force, the bearing capacity (compressive strength) of diagonal reinforcement confinement by transverse reinforcement plays an important role in the strength, stiffness and ductility of coupling beams. Due to the importance of the compressive bearing capacity of diagonal reinforcement confinement with transverse reinforcement, the non-linear behaviour and stress-strain curves of coupling beams were investigated based on the presented models for stress-strain relations. This study aimed to investigate the stress-strain relation of the core region of the diagonal reinforcement bundles in short and deep coupling beams. By changing the ratio of the diagonal and transverse reinforcement, it was investigated how the stress and strain of the confined concrete inside the diagonal reinforcement bundles of reinforced concrete coupling beams change.

1.2. Diagonal Reinforcement of Code Specified Reinforcement

The numbers and dimensions of the coupling beams in the coupled shear walls affect the structural behaviour and the internal force distribution of coupling beams and shear walls. The seismic design provisions for the diagonal reinforcements of coupling beams existing in different seismic codes (American Concrete Institute (ACI318) [9], Design of Structures for Earthquake Resistance (Eurocede8) [10], Turkish Building Earthquake Code (TBEC) [11,12] and Iranian Code of Practice for Seismic Resistant Design of Buildings (IRSC) [13]), were compared in the following sections. The minimum number of diagonal rebars in crosswise bundles, minimum diameter of the confinement reinforcement, maximum spacing of the confinement reinforcement and anchorage length of diagonal reinforcements inside the shear walls according to different seismic codes have been compared in Table 1.

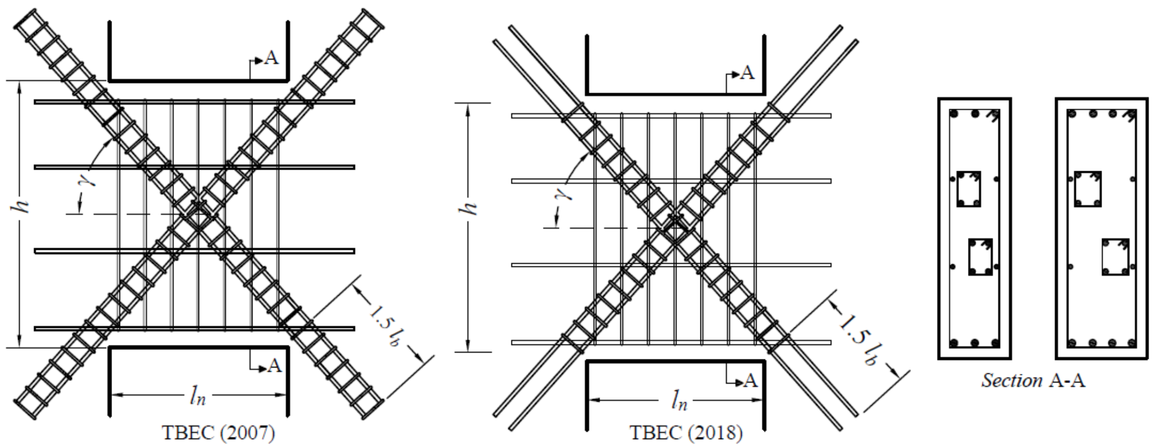
Table 1. *Rules and conditions of coupling beams of the coupled shear walls according to different seismic codes*

Specified code	Minimum bundle of cross rebars	Hoops diameter	Hoops spacing (s)	Anchorage length cross rebars extended into the wall
ACI318, 2019 [9]	4	Φ8mm	≤203.2mm	$1.25l_b$
Eurocode8, 2004 [10]	4	Φ8mm	≤25Φ ≤250mm	$1.5l_b$
TBEC, 2007 [11]	4	Φ8mm	≤ 8Φ cross rebars ≤100mm	$1.5l_b$

TBEC, 2018 [12]	4	Φ8mm	≤ 8Φ cross rebars ≤100mm	$1.5l_b$
IRSC, 2007 [13]	4	Φ8mm	≤ 8Φcross rebars ≤ 24Φhoops ≤125mm	$1.5l_b$
Cross-sectional conditions and shear force limits				
ACI318 [9]	$l < 2h$		$V_n = 2A_s f_y sin\alpha \leq 10A_{cw}\sqrt{f_c'}$	
Eurocode8, 2004 [10]	$l_n < 3h_k$		$V_{ED} \geq f_{ctd} b_w d \leftrightarrow V_{ED} = 2A_{si} f_{yd} sin\alpha$	
TBEC, 2007 [11]	$l_n < 3h_k$		$V_d \geq 1.5 b_w d f_{ctd}$	
TBEC, 2018 [12]	$l_n < 2h_k$		$V_d \geq 1.5 b_w d f_{ctd}$	
IRSC, 2007 [13]	$l < 3h$		$V_u > 0.24 b_w l_n \sqrt{f_c'}$	

1.3. Comparisons of the Hoop Spacing for Diagonal Reinforcement for Different Seismic Codes

The minimum number of diagonal reinforcements in crosswise bundles, the minimum diameter and maximum spacing of the transverse reinforcement, and the anchorage length of diagonal reinforcements inside the shear walls according to different seismic codes have been compared in Table 1. The minimum number of diagonal reinforcements in crosswise bundles and minimum diameter of the transverse reinforcement are the same in five different seismic codes as can be seen in Table 1. The spacing of transverse reinforcement for the diagonal reinforcement is the same in both TBEC [11-12]. According to TBEC [11,12] codes, the transverse reinforcement spacing in crosswise bundles shall not be 8 times greater than the diameter of the diagonal reinforcement and not more than 100 mm. According to AC1318 [9] the spacing of transverse reinforcement in the diagonal reinforcement shall not be more than 6 in.(152.4mm) and 6db of the smallest diagonal reinforcement. According to IRSC [13] transverse reinforcement spacing in diagonal bundles shall not be 8 times greater than the diameter of the diagonal reinforcement, 24 times greater than the diameter of the transverse reinforcement, and not more than 125mm. According to ACI318 [9], the diagonal reinforcement anchorage length shall be extended into the shear wall section by at least 1.25 times the development length. Apart from ACI318 [9], in all other seismic codes given in Table 1, the diagonal reinforcement anchorage length shall be extended into the wall sections by at least 1.5 times the development length. The reinforcement configuration of diagonally confined special reinforcements in coupling beams according to different standards and codes is presented in Figure 1.



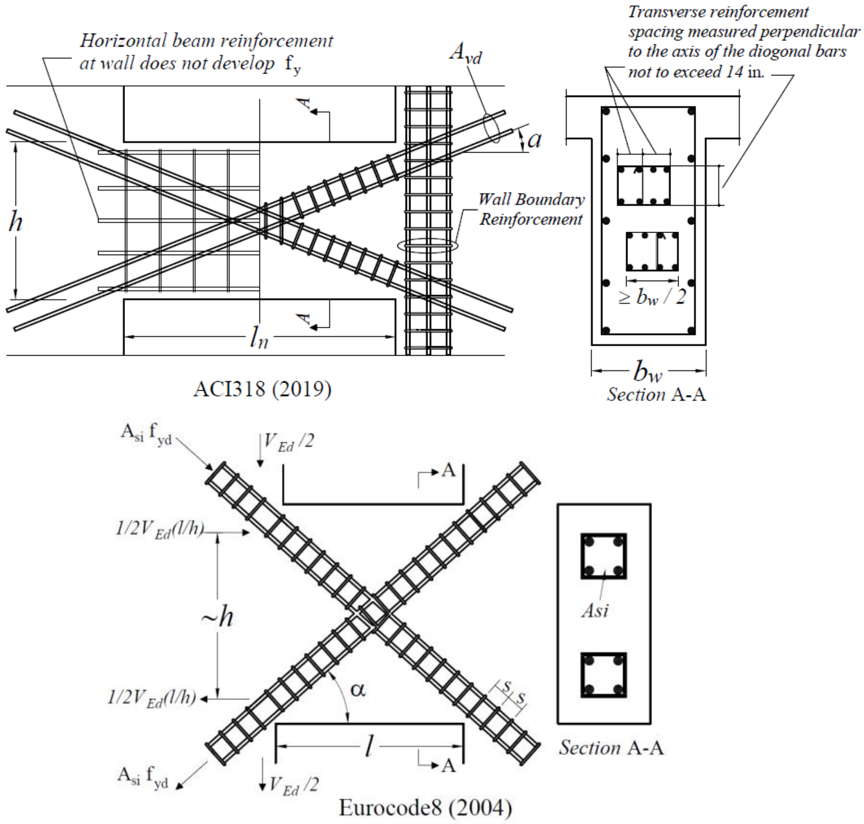


Figure 1. *Reinforcement configuration of diagonally confined special reinforcement in coupling beams*

2. THEORETICAL STRESS-STRAIN MODELS FOR CONFINED CONCRETE

The effect of confinement on the strength and deformation capacity of concrete members has been extensively studied [14]. The concrete core within the diagonal reinforcement is treated as confined or unconfined depending on the transverse reinforcement surrounding the diagonal reinforcement. The confinement model suggested by Mander et al. [15] is adopted herein, as it is a generalized model that is applicable to all section shapes. In this model, as shown in Figure 2, the arching action is again assumed to act in the form of second-degree parabolas with an initial tangent slope of 45°. Arching occurs vertically between layers of transverse reinforcement and horizontally between longitudinal reinforcement. The effectively confined area of concrete at the transverse reinforcement (confining reinforcement) level is found by subtracting the area of the parabolas containing the ineffectively confined concrete. For one parabola, the ineffectual area is $(w_i')^2/6$, where w_i' is the ith clear distance between adjacent longitudinal reinforcement (see Figure 2).

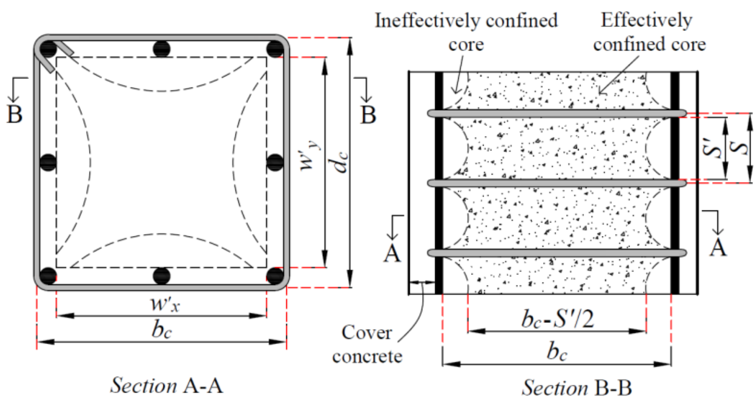


Figure 2. *Effectively confined core for transverse reinforcement*

Thus, when there are n longitudinal reinforcements, the total plan area of the ineffectively core concrete at the transverse reinforcement level can be calculated from Equation (1). Incorporating the influence of the ineffective areas in the elevation (Figure 2), the area of the effectively confined concrete core midway between the transverse reinforcement levels is calculated from Equation (2). Therefore, the confinement effectiveness coefficient (k_e), which represents the ratio of the smallest effectively confined concrete area (A_e) to the confined core concrete area (A_{cc}), could be given by the following Equations. The confinement effectiveness coefficient can be calculated from Equation (3) for rectangular confining reinforcement (hoop). s' clear vertical spacing between transverse reinforcement, ρ_{cc} is the ratio of the longitudinal reinforcement area to core concrete area, b_c and d_c is the core concrete dimension to center-line of perimeter transverse reinforcement in x and y direction

$$A_i = \frac{\sum_i^n (w_i')^2}{6} \tag{1}$$

$$A_e = \left(b_c d_c - \sum_i^n \frac{(w_i')^2}{6}\right)\left(1 - \frac{S'}{2b_c}\right)\left(1 - \frac{S'}{2d_c}\right) \tag{2}$$

$$k_e = \frac{A_e}{A_{cc}} = \frac{\left(1 - \sum_i^n \frac{(w_i')^2}{6b_c d_c}\right)\left(1 - \frac{S'}{2b_c}\right)\left(1 - \frac{S'}{2d_c}\right)}{(1-\rho_{cc})}, \quad A_{cc} = b_c d_c (1 - \rho_{cc}). \tag{3}$$

It is calculated from Equation (4) when the rectangular cross-section members have different quantities of transverse reinforcement in the x and y directions

$$\rho_x = \frac{A_{sx}}{s.d_c}, \quad \rho_y = \frac{A_{sy}}{s.b_c}, \quad \rho_s = \rho_x + \rho_y. \tag{4}$$

The lateral confining stress (f_l) on the concrete in the x and y directions are obtained from Equation (5). Effective lateral confining stresses in the x and y directions and effective lateral confining pressure (f_l') are obtained from Equation (6). f_{yh} yield stress of the transverse reinforcement, A_{sx} and A_{sy} total area of transverse reinforcement in the x and y directions

$$f_{lx} = \frac{A_{sx}}{s.d_c} f_{yh} = \rho_x f_{yh}, \qquad f_{ly} = \frac{A_{sy}}{s.b_c} f_{yh} = \rho_y f_{yh} \tag{5}$$

$$f_{lx}' = k_e \frac{A_{sx}}{s.d_c} f_{yh} = k_e f_{lx}, \quad f_{ly}' = k_e \frac{A_{sy}}{s.b_c} f_{yh} = k_e f_{ly}, \quad f_l' = \frac{f_{lx}' + f_{ly}'}{2}. \tag{6}$$

To calculate the strength of confined concrete (f_{cc}') from Equation (7), a constitutive model involving a specified maximum strength surface for multiaxial compressive stresses is used in this model

$$f_{cc}' = f_{co}' \left(-1{,}254 + 2{,}254\sqrt{\frac{1 + 7{,}94 f_l'}{f_{co}'}} - 2\frac{f_l'}{f_{co}'}\right) MPa. \tag{7}$$

The concrete stress (f_c) is given by the following relation as the function of the concrete strain (ε_c). Where f_{cc}'; compressive strength of confined concrete

$$f_c = \frac{f_{cc}' \, x \, r}{r - 1 + x^r}, \quad x = \frac{\varepsilon_c}{\varepsilon_{cc}}, \quad r = \frac{E_c}{E_c - E_{sec}}, \quad E_c = 5000\sqrt{f'_{co}} \, MPa, \quad E_{sec} = \frac{f'_{cc}}{\varepsilon_{cc}}. \tag{8}$$

The calculation of f_{cc}' is not sufficient to obtain the stress-strain relation of confined concrete. Therefore, the strain corresponding to the maximum concrete compressive strength (ε_{cc}) has to be calculated from Equation (9). In addition, the maximum strain value (ε_{cu}) must be calculated from Equation (10) at the first fracture occurring in confining reinforcement. f'_{co} and ε_{co}; strain corresponding to the unconfined concrete strength (ε_{co}= 0.002). To define the stress-strain behaviour of the cover concrete (outside the confined core concrete) the part of the falling branch in the region where ε_c>2ε_{co} is assumed to be a straight line which reaches zero stress at the spalling strain (ε_{sp})

$$\varepsilon_{cc} = \varepsilon_{co}\left[1 + 5\left(\frac{f'_{cc}}{f'_{co}} - 1\right)\right] \tag{9}$$

$$\varepsilon_{cu} = 0.004 + \frac{1.4.\rho_s.f_{yw}.\varepsilon_{su}}{f'_{cc}}. \tag{10}$$

3. MATERIAL AND METHOD

The effects of transverse and diagonal reinforcement ratios in crosswise bundles of the coupling beams on the stress-strain behaviour of the cross-sections were investigated. The details of transverse and diagonal reinforcement for the diagonal bundles of different coupling beams are presented in Table 2. Typical view and geometric parameters of the coupled shear wall, coupling beam, and the configuration of diagonal reinforcement used in parametric studies are shown in Figure 3. Fifty-four diagonal bundles with different properties were designed to investigate the effect of the transverse and diagonal reinforcement ratios on the behaviour of the coupling beams. As seen in Figure 3, the diagonal bundles having 150mm×150mm dimensions were selected for the parametric study. The diameters of the reinforcement ratios used in the diagonal bundles have been determined by considering the limitations given in seismic codes [12]. Different diagonal reinforcement diameters; Φ14mm-Φ30mm, transverse reinforcement; Φ8-Φ10 and transverse reinforcement spacing 50mm, 75mm and 100mm were selected in order to investigate the effect of the reinforcement on the coupling beams behaviour. For all coupling beam models, C30 was chosen as concrete compressive strength and B420C was selected as reinforcement for the reinforcing steel behaviour model. The ratio of reinforcement used in coupling beams is one of the most important factors affecting the non-linear behaviour of coupled shear walls and has allowed the nonlinear behaviour and ductility of such structures to be investigated. For the recommended confined concrete model [15], the k_e, f_l, f'_l, f'_{cc}, ε_{cc} and ε_{cu} values were calculated. Stress-strain relations were obtained by calculating the values of confined concrete strength and confined concrete strain for the designed coupling beam models.

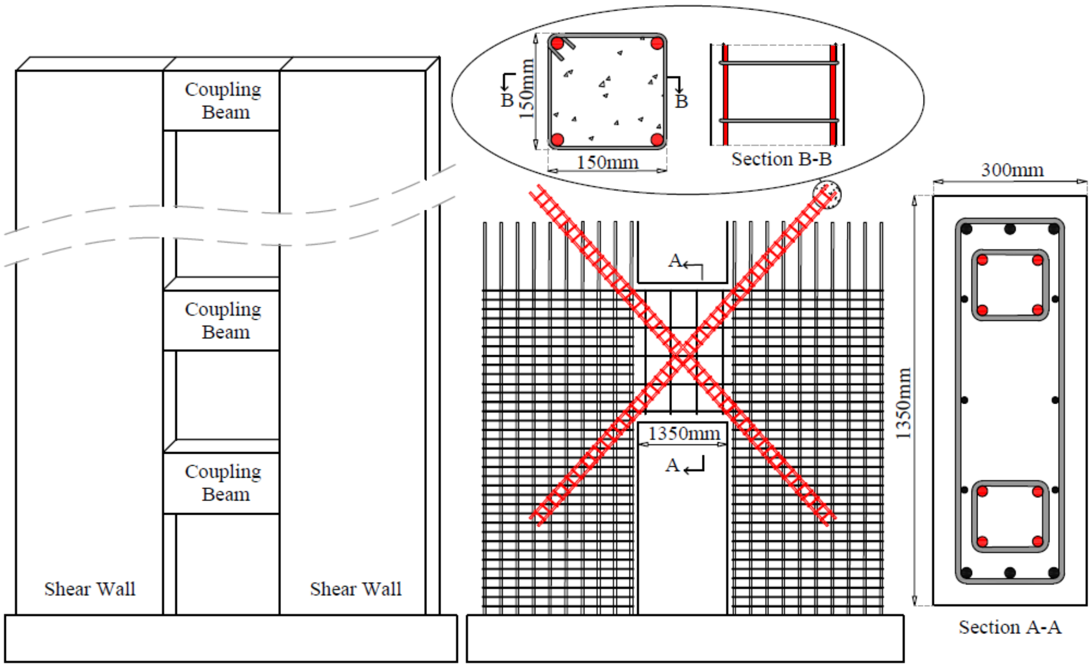


Figure 3. *Typical view and geometric parameters of the coupled shear wall, coupling beam and the configuration of diagonal reinforcement used in parametric studies*

Table 2. *Cross-section properties of designed coupling beam models*

No	Diagonal reinforcement	ρ_t	Transverse reinforcement	ρ_{cc}	$\rho_x \cdot \rho_y$	ρ_s	No	Transverse reinforcement	ρ_{cc}	$\rho_x \cdot \rho_y$	ρ_s
C1			Φ8/50mm		0.0142	0.0283	C4	Φ10/50mm		0.0224	0.0449
C2	Φ14mm	0.027	Φ8/75mm	0.0305	0.0094	0.0189	C5	Φ10/75mm	0.0314	0.0150	0.0299
C3			Φ8/100mm		0.0071	0.0142	C6	Φ10/100mm		0.0112	0.0224
C7			Φ8/50mm		0.0142	0.0283	C10	Φ10/50mm		0.0224	0.0449
C8	Φ16mm	0.036	Φ8/75mm	0.0399	0.0094	0.0189	C11	Φ10/75mm	0.0410	0.0150	0.0299
C9			Φ8/100mm		0.0071	0.0142	C12	Φ10/100mm		0.0112	0.0224
C13			Φ8/50mm		0.0142	0.0283	C16	Φ10/50mm		0.0224	0.0449
C14	Φ18mm	0.045	Φ8/75mm	0.0505	0.0094	0.0189	C17	Φ10/75mm	0.0519	0.0150	0.0299
C15			Φ8/100mm		0.0071	0.0142	C18	Φ10/100mm		0.0112	0.0224
C19			Φ8/50mm		0.0142	0.0283	C22	Φ10/50mm		0.0224	0.0449
C20	Φ20mm	0.056	Φ8/75mm	0.0623	0.0094	0.0189	C23	Φ10/75mm	0.0641	0.0150	0.0299
C21			Φ8/100mm		0.0071	0.0142	C24	Φ10/100mm		0.0112	0.0224
C25			Φ8/50mm		0.0142	0.0283	C28	Φ10/50mm		0.0224	0.0449
C26	Φ22mm	0.067	Φ8/75mm	0.0754	0.0094	0.0189	C29	Φ10/75mm	0.0776	0.0150	0.0299
C27			Φ8/100mm		0.0071	0.0142	C30	Φ10/100mm		0.0112	0.0224
C31			Φ8/50mm		0.0142	0.0283	C34	Φ10/50mm		0.0224	0.0449
C32	Φ24mm	0.080	Φ8/75mm	0.0897	0.0094	0.0189	C35	Φ10/75mm	0.0923	0.0150	0.0299
C33			Φ8/100mm		0.0071	0.0142	C36	Φ10/100mm		0.0112	0.0224
C37			Φ8/50mm		0.0142	0.0283	C40	Φ10/50mm		0.0224	0.0449
C38	Φ26mm	0.094	Φ8/75mm	0.1053	0.0094	0.0189	C41	Φ10/75mm	0.1084	0.0150	0.0299
C39			Φ8/100mm		0.0071	0.0142	C42	Φ10/100mm		0.0112	0.0224
C43			Φ8/50mm		0.0142	0.0283	C46	Φ10/50mm		0.0224	0.0449
C44	Φ28mm	0.109	Φ8/75mm	0.1221	0.0094	0.0189	C47	Φ10/75mm	0.1257	0.0150	0.0299
C45			Φ8/100mm		0.0071	0.0142	C48	Φ10/100mm		0.0112	0.0224
C49			Φ8/50mm		0.0142	0.0283	C52	Φ10/50mm		0.0224	0.0449
C50	Φ30mm	0.126	Φ8/75mm	0.1402	0.0094	0.0189	C53	Φ10/75mm	0.1443	0.0150	0.0299
C51			Φ8/100mm		0.0071	0.0142	C54	Φ10/100mm		0.0112	0.0224

4. PARAMETRIC STUDY

The seismic behaviour of coupled shear walls with coupling beams depends on the structural performance of the coupling beams. The effects of diagonal and transverse reinforcement ratios of the diagonal bundles in short and deep coupling beams of the coupled shear walls were investigated. The diagonal reinforcement bundles have to be confined by transverse reinforcements prescribed in the codes. Confined concrete in the diagonal reinforcement bundles has stress-strain characteristics that are distinctly different from those of plain concrete. By changing the ratio of the diagonal and transverse reinforcement, it was investigated how the stress-strain behaviour of the confined concrete inside the diagonal bundles of reinforced concrete coupling beams changes. The ρ_t, ρ_{cc}, ρ_x , ρ_y and ρ_s values of the confined concrete regions inside the diagonal bundles are calculated and presented for different design parameters in Table 2 respectively. k_e, f_l' and f_{cc}' values of the confined concrete regions inside the diagonal bundles are calculated. The k_e, f_l' and f_{cc}' values of the confined concrete regions inside the diagonal bundles are presented for Φ8mm and Φ10mm confining reinforcement at Table 3. As can be seen in Table 3, as transverse reinforcement spacing decreases and diagonal reinforcement diameter increases the lateral confining pressure and confined strength values of the confined core concrete increase. It is natural that the strength of the confined concrete increases as a result of the increase in the lateral pressure applied to the core concrete. As seen in the comparison from the results given in Table 3 decreasing the spacing of the confinement reinforcement (increasing the transverse reinforcement diameter) not only has had an effect on confined concrete strength but also increased its corresponding strain significantly.

Table 3. *The calculated* k_e, f_l' *and* f_{cc}' *values of the confined concrete regions inside the diagonal bundles of the coupling beams for the different design parameters*

No	Diagonal reinforcement	Transverse reinforcement	k_e	Confined stress (MPa)			No	Transverse reinforcement	k_e	Confined stress (MPa)		
				f_l	f_l'	f_{cc}'				f_l	f_l'	f_{cc}'
C1	Φ14mm	Φ8/50mm	0.471	5.95	2.80	41.1	C4	Φ10/50mm	0.490	9.42	4.62	48.5
C2		Φ8/75mm	0.378	3.96	1.50	34.6	C5	Φ10/75mm	0.393	6.28	2.47	39.5
C3		Φ8/100mm	0.296	2.97	0.88	31.1	C6	Φ10/100mm	0.307	4.71	1.45	34.4
C7	Φ16mm	Φ8/50mm	0.496	5.95	2.95	41.7	C10	Φ10/50mm	0.516	9.42	4.86	49.4
C8		Φ8/75mm	0.399	3.96	1.58	35.1	C11	Φ10/75mm	0.414	6.28	2.60	40.2
C9		Φ8/100mm	0.312	2.97	0.93	31.4	C12	Φ10/100mm	0.323	4.71	1.52	34.8
C13	Φ18mm	Φ8/50mm	0.522	5.95	3.10	42.4	C16	Φ10/50mm	0.542	9.42	5.11	50.3
C14		Φ8/75mm	0.420	3.96	1.66	35.5	C17	Φ10/75mm	0.435	6.28	2.73	40.8
C15		Φ8/100mm	0.329	2.97	0.98	31.7	C18	Φ10/100mm	0.340	4.71	1.60	35.2
C19	Φ20mm	Φ8/50mm	0.548	5.95	3.26	43.1	C22	Φ10/50mm	0.569	9.42	5.36	51.2
C20		Φ8/75mm	0.441	3.96	1.75	36.0	C23	Φ10/75mm	0.456	6.28	2.87	41.4
C21		Φ8/100mm	0.345	2.97	1.03	32.0	C24	Φ10/100mm	0.356	4.71	1.68	35.6
C25	Φ22mm	Φ8/50mm	0.575	5.95	3.42	43.8	C28	Φ10/50mm	0.596	9.42	5.62	52.1
C26		Φ8/75mm	0.462	3.96	1.83	36.4	C29	Φ10/75mm	0.478	6.28	3.01	42.0
C27		Φ8/100mm	0.362	2.97	1.08	32.3	C30	Φ10/100mm	0.374	4.71	1.76	36.0
C31	Φ24mm	Φ8/50mm	0.602	5.95	3.58	44.5	C34	Φ10/50mm	0.624	9.42	5.88	53.0
C32		Φ8/75mm	0.484	3.96	1.92	36.8	C35	Φ10/75mm	0.501	6.28	3.15	42.6
C33		Φ8/100mm	0.379	2.97	1.13	32.6	C36	Φ10/100mm	0.391	4.71	1.84	36.5
C37	Φ26mm	Φ8/50mm	0.631	5.95	3.75	45.2	C40	Φ10/50mm	0.653	9.42	6.16	53.9
C38		Φ8/75mm	0.507	3.96	2.01	37.3	C41	Φ10/75mm	0.524	6.28	3.29	43.2
C39		Φ8/100mm	0.397	2.97	1.18	32.9	C42	Φ10/100mm	0.410	4.71	1.93	36.9
C43	Φ28mm	Φ8/50mm	0.661	5.95	3.93	45.9	C46	Φ10/50mm	0.684	9.42	6.44	54.8
C44		Φ8/75mm	0.531	3.96	2.11	37.8	C47	Φ10/75mm	0.549	6.28	3.45	43.9
C45		Φ8/100mm	0.416	2.97	1.24	33.2	C48	Φ10/100mm	0.429	4.71	2.02	37.3
C49	Φ30mm	Φ8/50mm	0.692	5.95	4.11	46.6	C52	Φ10/50mm	0.715	9.42	6.74	55.7
C50		Φ8/75mm	0.556	3.96	2.20	38.3	C53	Φ10/75mm	0.574	6.28	3.61	44.6
C51		Φ8/100mm	0.435	2.97	1.29	33.5	C54	Φ10/100mm	0.448	4.71	2.11	37.8

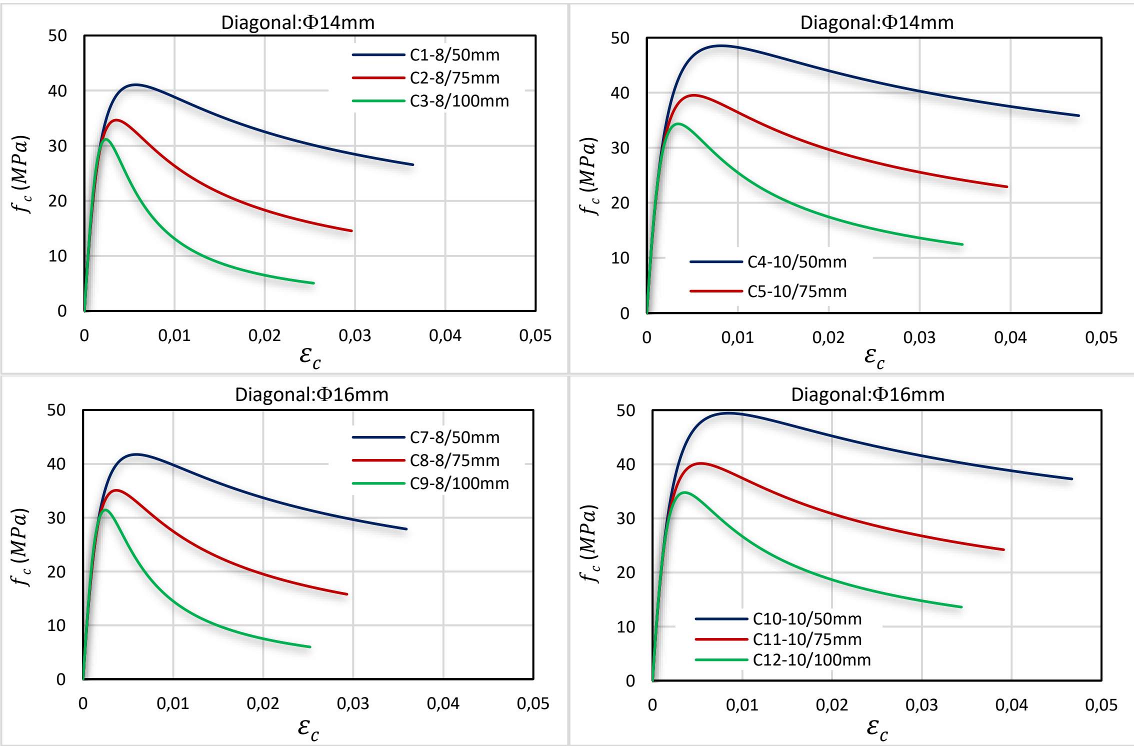
The calculation of f_{cc}' is not sufficient to obtain the confined concrete stress-strain relations. Therefore, the ε_{cc} and ε_{cu} has to be calculated too. The confined strain values calculated for the confined concrete regions within the diagonal bundles of the coupling beams with different diagonal and transverse reinforcements are summarized in Table 4. ε_{cc} is seen to have increased due to the increase of the diagonal and transverse reinforcement ratios as seen for different diagonal bundles. With increasing transverse reinforcement spacing, f_{cc}', ε_{cc}, and ε_{cu} values for confined concrete decreases. It was also seen that the increase of the diagonal and transverse reinforcement ratios also affected the ε_{cu} value.

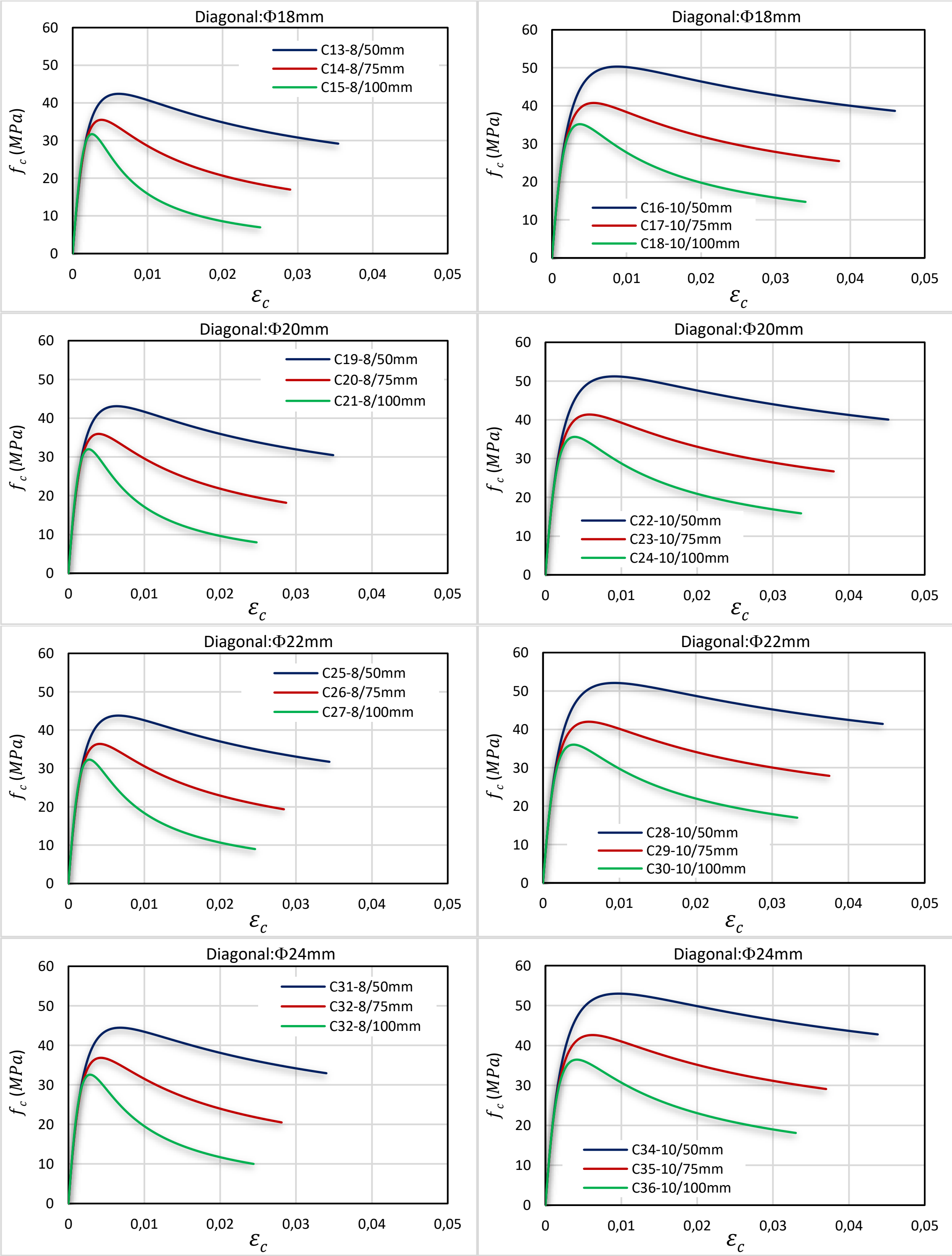
Table 4. *The calculated* r, ε_{cc}, *and* ε_{cu}*values of the confined concrete regions inside the diagonal bundles of the coupling beams for the different design parameters*

No	Diagonal reinforcement	Transverse reinforcement	r	Confined strain		No	Transverse reinforcement	r	Confined strain	
				ε_{cc}	ε_{cu}				ε_{cc}	ε_{cu}
C1	Φ14mm	Φ8/50mm	1,401	0,0057	0,0364	C4	Φ10/50mm	1,307	0,0082	0,0475
C2		Φ8/75mm	1,631	0,0035	0,0296	C5	Φ10/75mm	1,433	0,0052	0,0396
C3		Φ8/100mm	2,074	0,0024	0,0254	C6	Φ10/100mm	1,651	0,0035	0,0347
C7	Φ16mm	Φ8/50mm	1,388	0,0059	0,0359	C10	Φ10/50mm	1,300	0,0085	0,0467
C8		Φ8/75mm	1,603	0,0037	0,0293	C11	Φ10/75mm	1,419	0,0054	0,0391
C9		Φ8/100mm	2,012	0,0025	0,0252	C12	Φ10/100mm	1,622	0,0036	0,0344
C13	Φ18mm	Φ8/50mm	1,377	0,0061	0,0354	C16	Φ10/50mm	1,294	0,0088	0,0460
C14		Φ8/75mm	1,579	0,0038	0,0290	C17	Φ10/75mm	1,406	0,0056	0,0385

C15		Φ8/100mm	1,956	0,0026	0,0250	C18	Φ10/100mm	1,597	0,0037	0,0340
C19		Φ8/50mm	1,366	0,0064	0,0349	C22	Φ10/50mm	1,288	0,0091	0,0452
C20	Φ20mm	Φ8/75mm	1,556	0,0040	0,0287	C23	Φ10/75mm	1,395	0,0058	0,0380
C21		Φ8/100mm	1,907	0,0027	0,0248	C24	Φ10/100mm	1,574	0,0039	0,0337
C25		Φ8/50mm	1,357	0,0066	0,0344	C28	Φ10/50mm	1,283	0,0094	0,0445
C26	Φ22mm	Φ8/75mm	1,536	0,0041	0,0284	C29	Φ10/75mm	1,384	0,0060	0,0375
C27		Φ8/100mm	1,862	0,0028	0,0246	C30	Φ10/100mm	1,553	0,0040	0,0333
C31		Φ8/50mm	1,348	0,0068	0,0340	C34	Φ10/50mm	1,277	0,0097	0,0438
C32	Φ24mm	Φ8/75mm	1,517	0,0043	0,0281	C35	Φ10/75mm	1,374	0,0062	0,0370
C33		Φ8/100mm	1,822	0,0029	0,0244	C36	Φ10/100mm	1,534	0,0041	0,0330
C37		Φ8/50mm	1,340	0,0071	0,0335	C40	Φ10/50mm	1,273	0,0100	0,0432
C38	Φ26mm	Φ8/75mm	1,500	0,0044	0,0278	C41	Φ10/75mm	1,364	0,0064	0,0365
C39		Φ8/100mm	1,785	0,0030	0,0243	C42	Φ10/100mm	1,515	0,0043	0,0326
C43		Φ8/50mm	1,332	0,0073	0,0330	C46	Φ10/50mm	1,268	0,0103	0,0425
C44	Φ28mm	Φ8/75mm	1,483	0,0046	0,0275	C47	Φ10/75mm	1,355	0,0066	0,0361
C45		Φ8/100mm	1,751	0,0031	0,0241	C48	Φ10/100mm	1,498	0,0044	0,0323
C49		Φ8/50mm	1,325	0,0075	0,0326	C52	Φ10/50mm	1,264	0,0106	0,0419
C50	Φ30mm	Φ8/75mm	1,468	0,0048	0,0272	C53	Φ10/75mm	1,347	0,0069	0,0356
C51		Φ8/100mm	1,720	0,0032	0,0239	C54	Φ10/100mm	1,482	0,0046	0,0319

The stress-strain relations of the confined core regions in the diagonal bundles of the coupling beams according to different design parameters were obtained from the analytical analysis results. The obtained stress-strain relations of the f_c as a function of the ε_c is summarized in Figure 4 according to the Mander model.





Diagonal:Φ18mm
C13-8/50mm
C14-8/75mm
C15-8/100mm
Diagonal:Φ18mm
C16-10/50mm
C17-10/75mm
C18-10/100mm
Diagonal:Φ20mm
C19-8/50mm
C20-8/75mm
C21-8/100mm
Diagonal:Φ20mm
C22-10/50mm
C23-10/75mm
C24-10/100mm
Diagonal:Φ22mm
C25-8/50mm
C26-8/75mm
C27-8/100mm
Diagonal:Φ22mm
C28-10/50mm
C29-10/75mm
C30-10/100mm
Diagonal:Φ24mm
C31-8/50mm
C32-8/75mm
C32-8/100mm
Diagonal:Φ24mm
C34-10/50mm
C35-10/75mm
C36-10/100mm
$f_c\,(MPa)$
ε_c
0
10
20
30
40
50
60
0,01
0,02
0,03
0,04
0,05

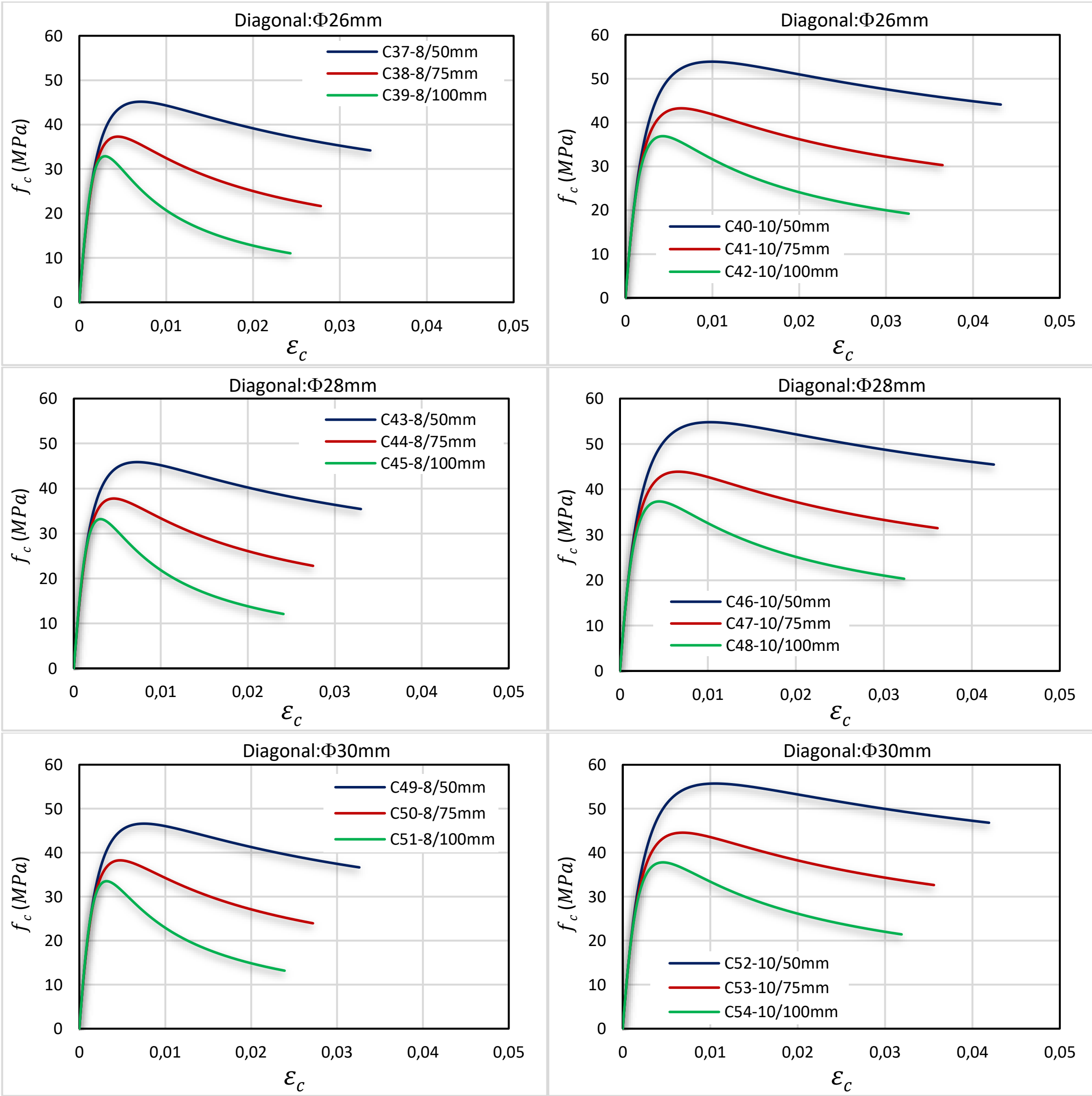


Figure 4. *Stress-strain relationships of the confined core regions inside the diagonal bundles of the coupling beams*

Results obtained for reinforced concrete coupling beam models according to confined concrete model for the different parameters are presented comparatively. A comparison of f_l' and f_{cc}' obtained for different diagonal and transverse reinforcement ratios are given in Figure 5. A comparison of ε_{cc} and ε_{cu} obtained for different diagonal and transverse reinforcement ratios are given in Figure 6. f_l' and f_{cc}' increase by increasing the diagonal and transverse reinforcement ratios. When the transverse reinforcement ratio is steady the increasing diagonal reinforcement ratio increases f_l' and f_{cc}'.

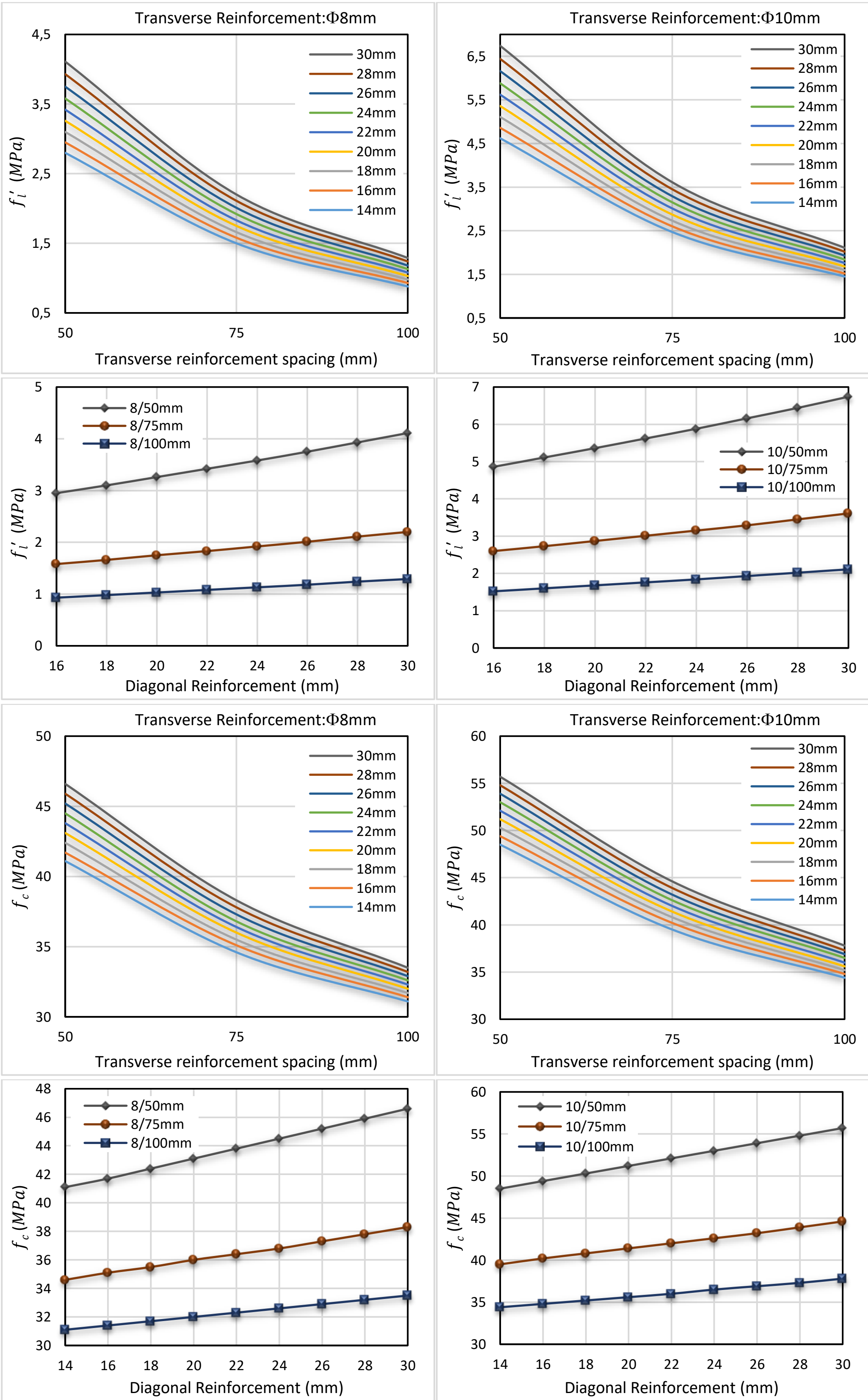


Figure 5. *Comparison of* f_l' *and* f_{cc}' *obtained for confined core regions inside the diagonal bundles of the coupling beams*

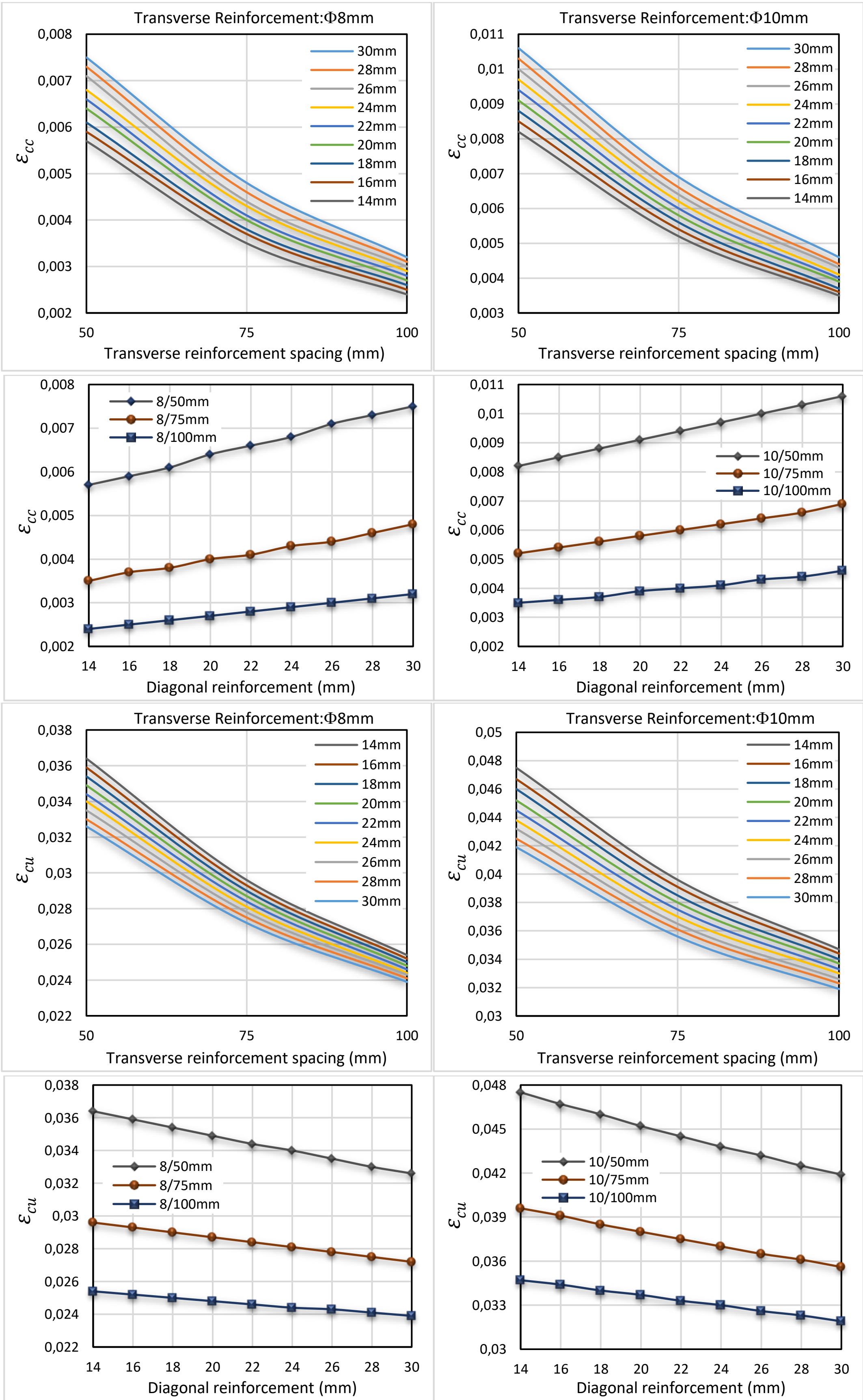


Figure 6. *Comparison of ε_{cc} and ε_{cu} obtained for confined core regions inside the diagonal bundles of the coupling beams*

The ratio of the confined concrete compressive strength calculated from the analysis results for the confined core regions inside the diagonal bundles of the coupling beams to the strength value taken into account for the unconfined concrete ($0.85f_{co}$) and its relations are given in Figure 7. The ratio of the strain at maximum concrete stress and maximum concrete compressive strain of the confined concrete calculated from the analysis results for the confined core regions inside the diagonal bundles of the coupling beams to the strain value taken into account for the unconfined concrete (ε_{co}) and its relations are given in Figures 8 and 9 respectively.

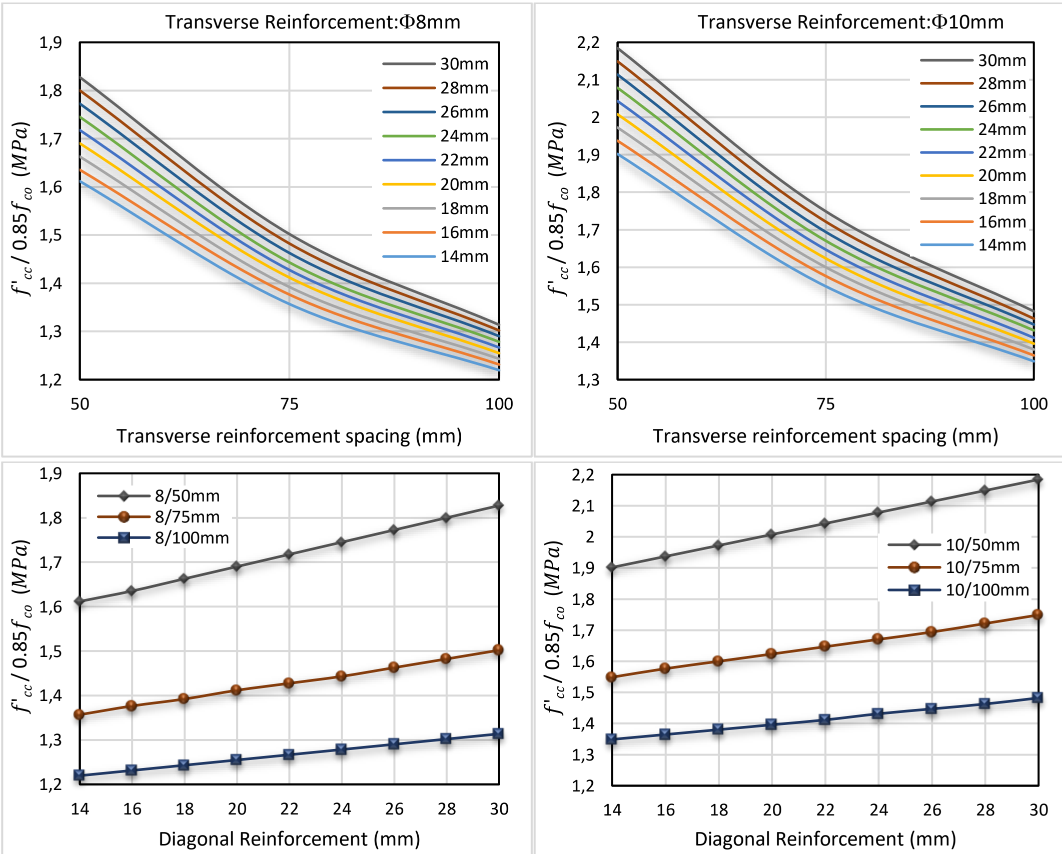
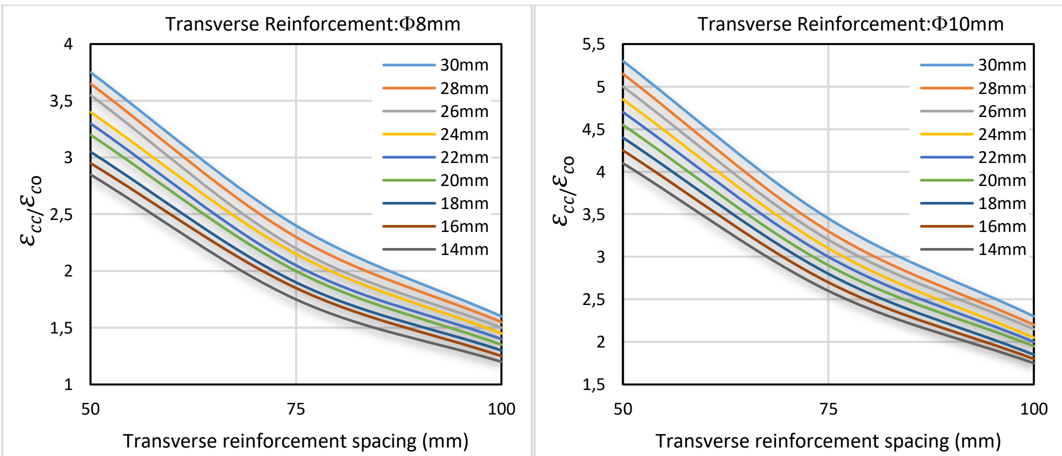


Figure 7. *Comparison of* $f'_{cc}/0.85f_{co}$ *relations obtained for confined core regions inside the diagonal bundles of the coupling beams*



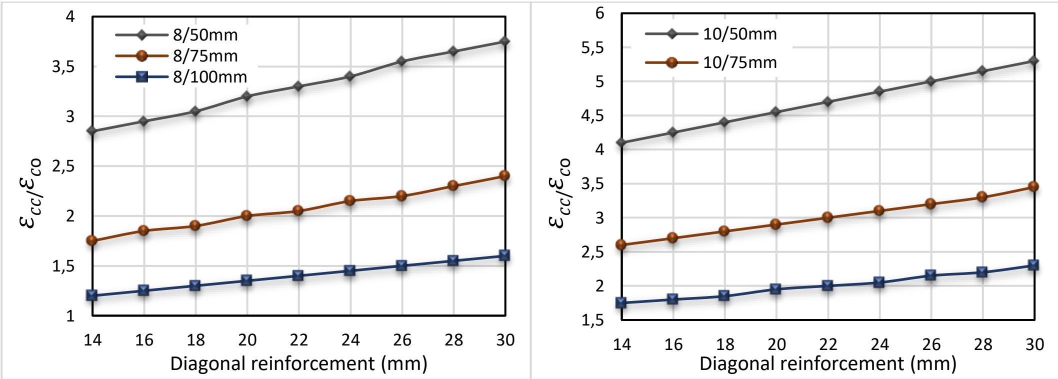


Figure 8. *Comparison of $\varepsilon_{cc}/\varepsilon_{co}$ relations obtained for confined core regions inside the diagonal bundles of the coupling beams*

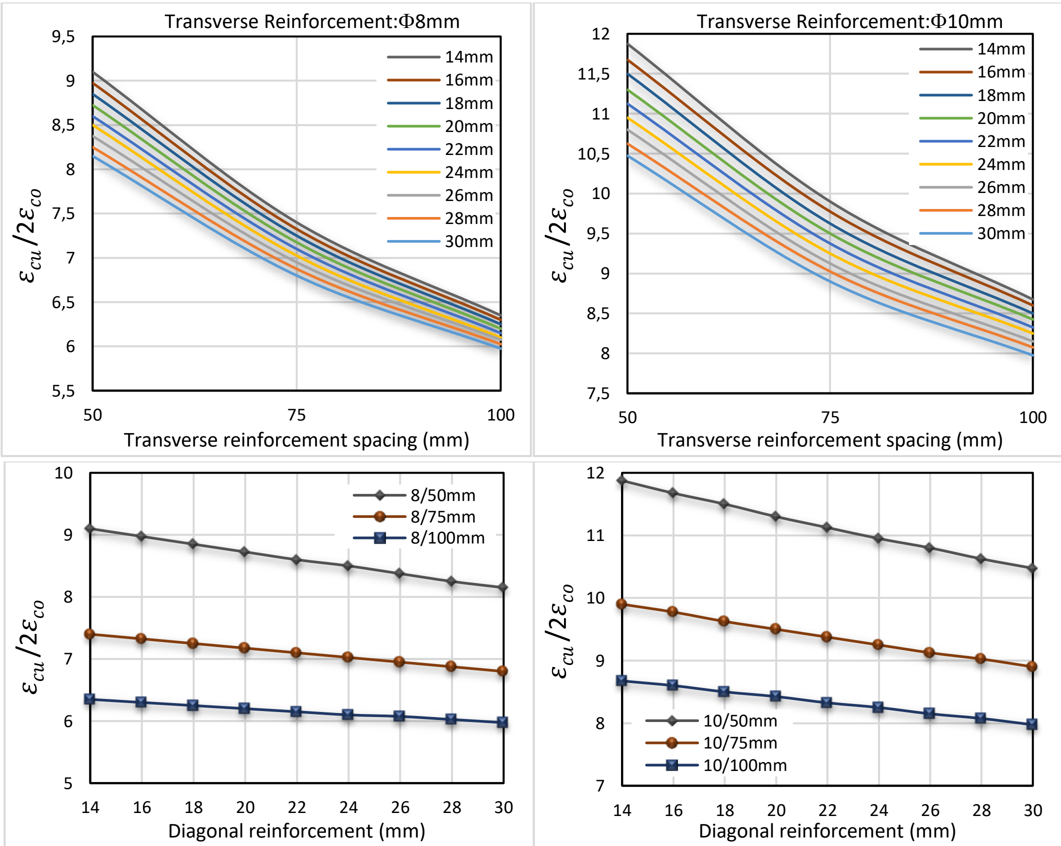


Figure 9. *Comparison of $\varepsilon_{cu}/2\varepsilon_{co}$ relations obtained for confined core regions inside the diagonal bundles of the coupling beams*

Based on the analytical calculations; diagonal and transverse reinforcement ratios were found to be factors that increase the compressive strength and strain of confined concrete. In diagonal bundles, the $f'_{cc}/0.85f_{co}$ ratio increases with the increase of the transverse reinforcement diameter, but the $f'_{cc}/0.85f_{co}$ ratio values decrease by decreasing the confining effect with the increase in the transverse reinforcement spacing. ε_{cc} and $\varepsilon_{cc}/\varepsilon_{co}$ ratio values increase with the increase in the diameter of the diagonal reinforcement and the diameter of the transverse reinforcement, but the ε_{cc} and $\varepsilon_{cc}/\varepsilon_{co}$ ratio decrease by decreasing the confining effect with the increase in the transverse reinforcement spacing. From the obtained curves, it can be seen that the compressive strength of confined concrete decreases with the increase in $\varepsilon_{cu}/2\varepsilon_{co}$ ratio. Based on the calculated values it was observed that as the diagonal reinforcement ratio and transverse reinforcement spacing increased maximum concrete compressive strain (ε_{cu}) and $\varepsilon_{cu}/2\varepsilon_{co}$ decreased. ε_{cu} and $\varepsilon_{cu}/2\varepsilon_{co}$ values increase with increasing transverse reinforcement diameter.

5. CONCLUSIONS

In order to control the bearing capacity, ductility and failure mode in reinforced concrete structures, it is necessary to investigate the non-linear behaviour of structural members. Since ductility and bearing capacity are important in reinforced concrete structures under the influence of lateral loads, methods that increase the ductility and bearing capacity of structural elements should be considered. The main factors in the design of earthquake resistant buildings are to provide sufficient strength and rigidity against lateral forces. As coupling beams are very effective in the seismic performance of coupled shear walls, diagonal reinforcements also a very effective parameter in the performance and bearing capacity of coupling beams. In this paper, the stress-strain characteristics of the confined concrete inside the code-specified diagonal reinforcement bundles of reinforced concrete short and deep coupling beams were investigated by considering the confinement effect. An extensive parametric study was conducted and the parameters affecting the confinement characteristics inside the diagonal reinforcement bundles of reinforced concrete coupling beams were evaluated considering the Mander model. The compressive concrete strength, strain at maximum compressive stress, and maximum concrete compressive strain values for the confined core regions inside the diagonal bundles of the coupling beams were calculated by considering different diagonal reinforcement and transverse reinforcement ratios.

The stress-strain relations of confined concrete and the stress-strain relations of unconfined concrete are distinctly different from each other. Transverse reinforcement ratios have been observed to increase confined concrete strength. As the spacing of the transverse reinforcement decreases, the confinement effect increases considerably. Based on the analytical calculations; it is demonstrated that the stress and strain characteristics of the core region inside the diagonal bundles can be greatly influenced by confining the diagonal bundles. Thus, the transverse reinforcement ratios and longitudinal reinforcement ratios are important parameters affecting the stress-strain relation of the core regions of the reinforcement bundles. When the diagonal reinforcement ratio keeps constant ratio, the increasing transverse reinforcement diagonal reinforcement ratio increases the compressive strength of confined concrete. The compressive strength of confined core concrete inside diagonal bundles increases with an increasing diagonal reinforcement ratio. The increase in the diameter of the transverse reinforcement and the decrease in the transverse reinforcement spacing in the diagonal bundles, increase the confining effect in the concrete sections, increasing the ductility and strength, and has a significant effect on the seismic behaviour of the coupling beams.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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