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Failure Mode Identification of Reinforced Concrete Coupling Beams

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ABSTRACT

This paper presents a new approach to identify the ultimate failure state of reinforced concrete (RC) coupling beams subjected to lateral loadings. The proposed approach is based on simple geometric properties and reinforcement detailing of the coupling beam. A simple threshold expressed in terms of aspect ratio and main reinforcement to transverse reinforcement ratio is established to evaluate whether the ultimate failure state that would evolve during earthquake ground shaking in conventionally reinforced RC coupling beams is brittle or ductile. Another threshold stated in terms of main reinforcement to transverse reinforcement ratio and sloped reinforcement to transverse reinforcement ratio is recognized to evaluate whether the ultimate failure mode in the RC coupling beam with sloped reinforcement is brittle or due to sloped bar buckling during earthquake shaking. Brittle failure mode (shear failure) and sloped bar buckling should be avoided in design and mitigated in existing structures. Results from this proposed approach are compared with those obtained for twenty seven laboratory specimens tested by other researchers.

KEYWORDS: Reinforced concrete coupling beams, Seismic response, Shear failure, Buckling, Flexural failure.

INTRODUCTION

Reinforced concrete (RC) shear walls in buildings have often openings that serve as doors for stairwells and elevator shafts. This results in the formation of coupled shear walls composed of two vertical walls and connecting beams called coupling beams.

RC coupling beams interact with side walls and are required to withstand large shear deformation during earthquake excitations. Their response is essential to transfer force with side walls which structural designers should consider in the design process. One of the main difficulties of designing coupled shear walls is the vulnerability to brittle/shear failure of deep coupling beams or sloped bar buckling (Fig.1). If these types of failure are precluded and flexural failure is attained, increase in ductility and improvement of energy dissipation produced during a seismic event shall be achieved by coupling beams. Accordingly, building safety will be improved. In this paper, a simple method is proposed to identify whether the ultimate failure mode of a specific coupling beam is brittle/shear or ductile/flexural or due to sloped bar buckling. This categorization is found to be crucial to judge whether or not a specific RC coupling beam will improve the performance under seismic loads. The motivation is to develop a tool for engineering practice to identify the ultimate failure mode of RC coupling beams; i.e., whether or not the coupling beam is

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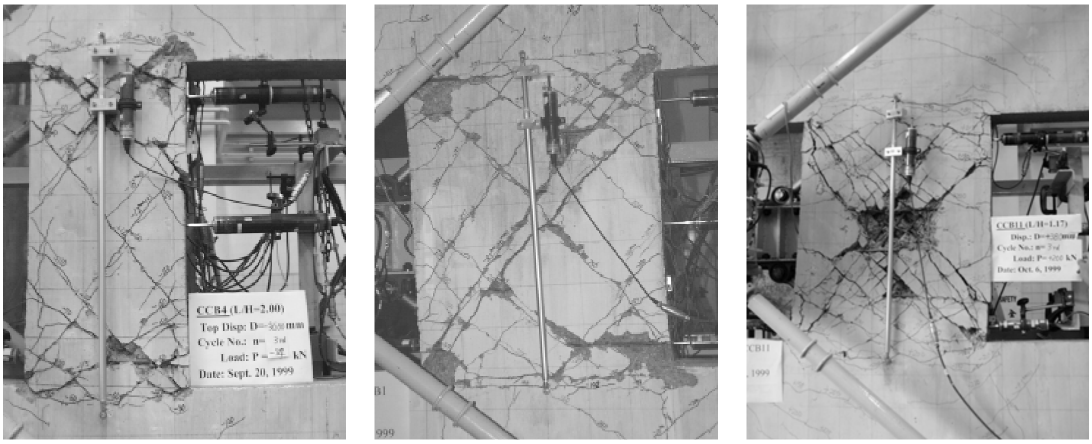
vulnerable to flexural failure only by using simple geometric properties and reinforcement details of the coupling beam.

Several researchers studied RC coupling beams experimentally to understand the performance of these structural members during ground motions (e.g. Tassios et al., 1996), Galano and Vignoli (2000) and Kwan and Zhao (2002)). In this paper, geometric and reinforcement data from twenty seven RC coupling beam specimens and their ultimate failure are presented and used to check the proposed method.



(a) (b) (c)

Figure (1): Failure pattern of RC coupling beam: (a) flexural failure, (b) shear failure and (c) diagonal bar buckling. Adopted from Kwan and Zhao (2002)

Reinforcement Configurations of Coupling Beams

Reinforcements of conventional coupling beams are arranged with longitudinal reinforcement and shear reinforcement (Fig. 2 (a)). Short dowels can be installed in conventionally reinforced coupling beams at beam-wall connections to control sliding cracks (Fig. 2 (b)). The brittle performance of conventionally reinforced coupling beams with short dowels encouraged the use of long dowels to limit sliding (Fig. 2 (c)), which results in a slightly better behavior.

A coupling beam reinforced with bars that are sloped at an angle about its center is a diagonally reinforced coupling beam. This arrangement of reinforcement assists in the conversion of shear force into an axial load by truss action. Fig. 2 (d) shows a typical diagonally reinforced coupling beam. Diagonal reinforcement can consist of a single bar or a group of bars. A coupling beam reinforced with bars that are sloped at an angle at the beam-wall connection is a rhombic reinforced coupling beam (Fig. 2 (e)). This layout of reinforcement contributes to the sliding capacity without significantly increasing the flexural resistance of the beam. Coupled beams with sloped reinforcement include diagonally reinforced and rhombic coupled beams.

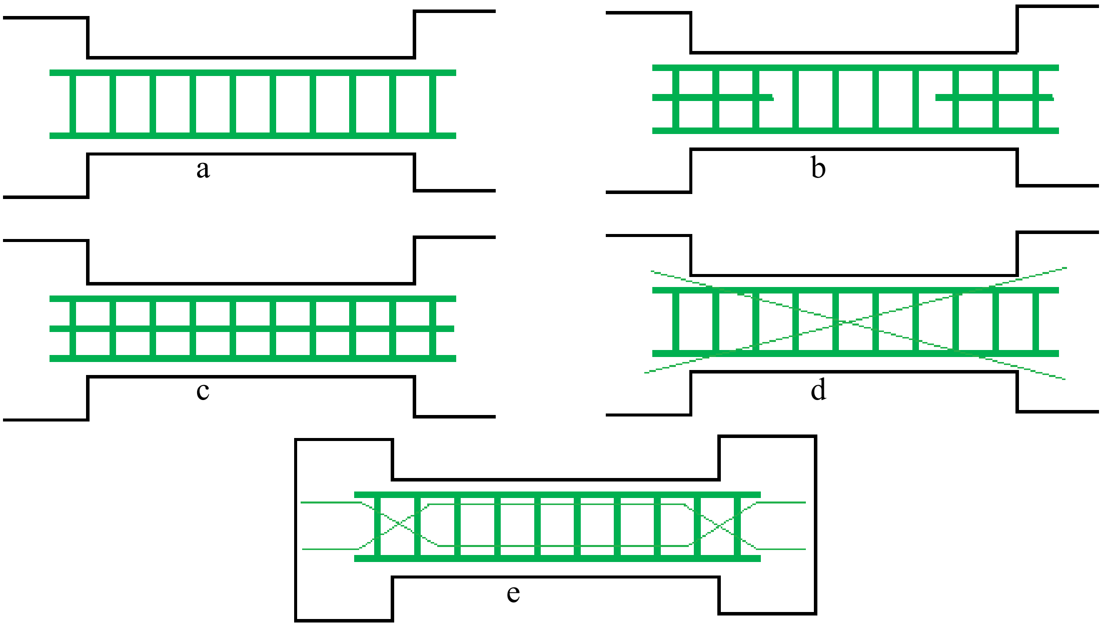


Figure (2): Reinforcement layout of coupled beams; (a) conventionally reinforced, (b) conventionally reinforced with short dowels, (c) conventionally reinforced with long dowels, (d) diagonally reinforced and (e) rhombic coupling beam

Failure Mode Identification

Various failure patterns of RC coupling beams, identified by Kwan and Zhao (2002) and Shastri (2010), are introduced in this section as follows:

- Shear-Compression (S-C): coupling beams fail by yielding of stirrups and crushing of concrete at beam-wall intersections or at zones between intersected inclined shear cracks (Fig. 3(a)).
- Shear-Tension (S-T): coupling beams fail by yielding of stirrups and widening the openings of the inclined shear cracks (Fig. 3(b)).
- Shear-Sliding (S-S): coupling beams fails at the intersections of coupling beams with side walls by yielding of stirrups and sliding movement of a through crack (Fig. 3(c)).
- Flexural Failure (FF): coupling beams fail by large local rotation at the intersections of coupling beams with side walls (Fig. 3(d)).
- Diagonal/rhombic Reinforcement Buckling (DRB): this type of failure might occur particularly in diagonally reinforced coupling beams or rhombic coupling beams. For diagonally reinforced coupling beams, the concrete near the center of the beam is extremely damaged due to repetitive opening and closing of cracks there. Accordingly, diagonal reinforcements are exposed. Eventually, when the compression load on the reinforcement exceeds the buckling load, the diagonal reinforcement bars buckle. For rhombic coupling beams, crushing occurs closer to beam-wall intersections (Fig. 3(e)).
- Local Sloped reinforcement failure (LS): this local failure might occur in diagonally reinforced or rhombic coupling beams with one of the failure modes described previously. At beam-wall intersections, sloped reinforcements might fail either in tension or in compression (Fig. 3(f)).

Coupling beam failure identification approaches based on failure mechanisms are found in literature. These are based on identifying all possible mechanisms and calculating the mechanism that gives the least lateral strength. This is a rather tedious process, during which various mechanisms should be overlooked.

In this paper, these types of failure are categorized in three major groups; shear failure, flexural failure and buckling of sloped reinforcement. The shear failure category includes shear-tension, shear-compression and shear-sliding types of failure. The local failure of sloped reinforcement is not a category, since it occurs with other main modes of failure. A simple method is proposed in this paper to identify whether a coupling beam will fail in shear or in flexure or due to buckling of sloped reinforcement. This classification is beneficial for engineers to avoid designing coupling beams that are vulnerable to shear failure or reinforcement buckling. The difficulty in obtaining such a method is to recognize what parameters could be used to qualify whether or not the coupling beam is vulnerable to fail in flexure.

EXPERIMENTAL DATA

Twenty seven specimens are considered in this paper to develop a method to classify the failure of RC coupling beams as shear failure, flexural failure or sloped reinforcement buckling. Ten specimens tested by Tassios et al. (1996) and subjected to cyclic loadings are considered here. Two aspect ratios with the five types of reinforcement configuration (Fig. 2 (a), (b), (c), (d) and (e)) are tested to compare the effect of reinforcement layout and aspect ratio on the ductility of coupling beams. This experimental study concluded that the layout shown in Fig. 2 (d) has the highest overall performance compared to all other layouts tested.

Eleven specimens were tested by Galano and Vignoli (2000) and subjected to monotonic and cyclic loadings. The main goal was to investigate the effect of loading history and reinforcement configuration on the response of coupling beams. For diagonally reinforced coupling beams, the effect of using ties along the set of diagonal bars was also studied. Instability was observed in diagonally reinforced specimens with ties along them due to sudden crushing of concrete strut. Such instability didn’t occur in diagonally reinforced specimens without ties.

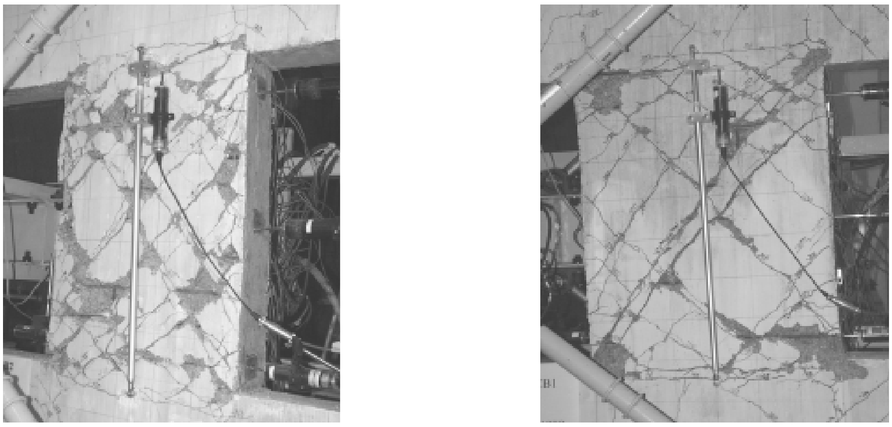
The arrangement of bent bars of rhombic specimens is different from the typical arrangement shown in Fig. 2(e). The bars were bent at an angle, but they didn’t intersect at the beam-wall connection. This layout of reinforcement contributes to the sliding capacity as well as to the flexural resistance. Since this is not a typical layout, these specimens are not considered in this study.

Kwan and Zhao (2002) tested six specimens under cyclic loads. Two types of reinforcement arrangement were tested; conventionally reinforced coupling beams with long dowels and diagonally reinforced coupling beams with long dowels. The reinforcement layout and aspect ratio were the parameters studied. Results of specimens of diagonally reinforced coupling beams with long dowels revealed higher stability, ductility and energy dissipation capacity compared to those of conventionally reinforced coupling beams with long dowels.

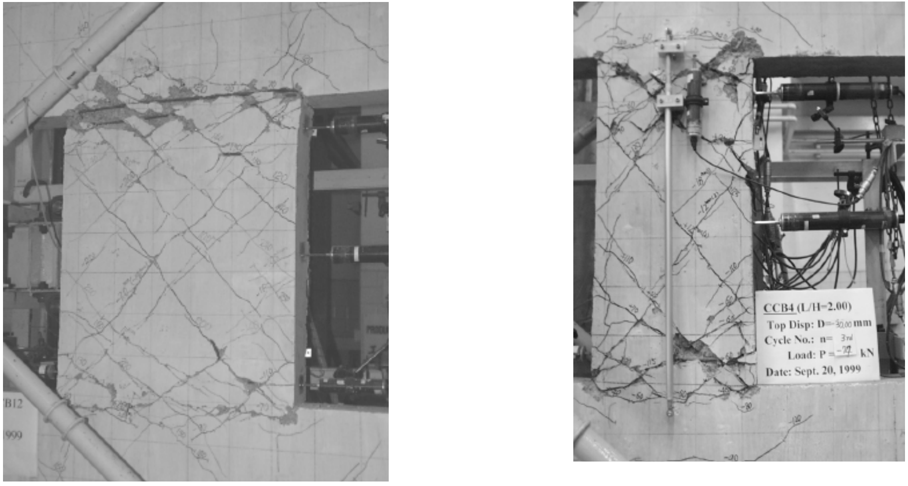
PARAMETER INVESTIGATION

The response of RC coupling beams to earthquake ground motion excitations depends on various parameters: material properties, reinforcement arrangement and detailing, aspect ratio of the structure and ground shaking characteristics. Since the ultimate failure mode is of interest, ground shaking characteristics are assumed to drive the structure to reach its failure mechanism. In this paper, these parameters are investigated and listed in Table 1, to present a simple method to identify the ultimate failure mode of RC coupling beams. The values of these parameters for the specimens considered in this paper and mentioned formerly are provided in Table 2.

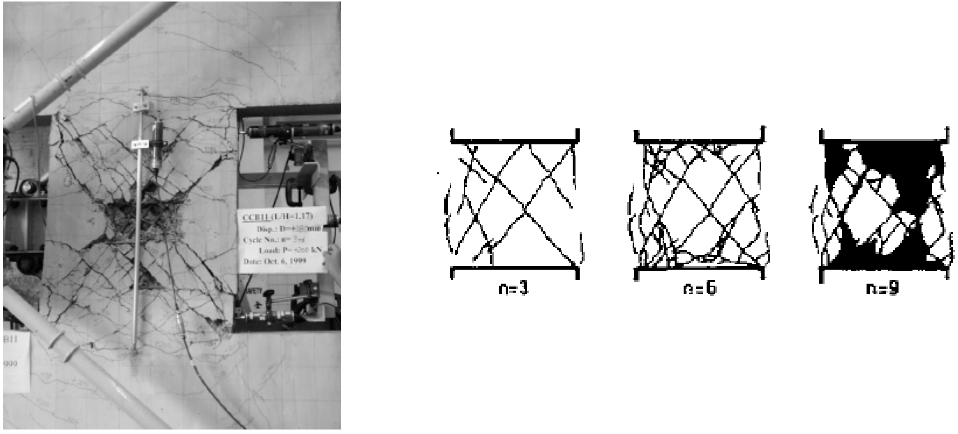
The failure mode could not be recognized by considering these parameters separately. Therefore, more condense statements of these parameters should be derived, such that they reflect the classical structural response and could distinct the specimens based on their ultimate failure mode. The ratio of main reinforcement area to transverse reinforcement area, the ratio of diagonal reinforcement area to transverse reinforcement area and aspect ratio (L/h) are proposed as the expressions required to identify the ultimate failure mode.



(a) Failure type S-C (b) Failure type S-T



(c) Failure type S-S (d) Failure type FF



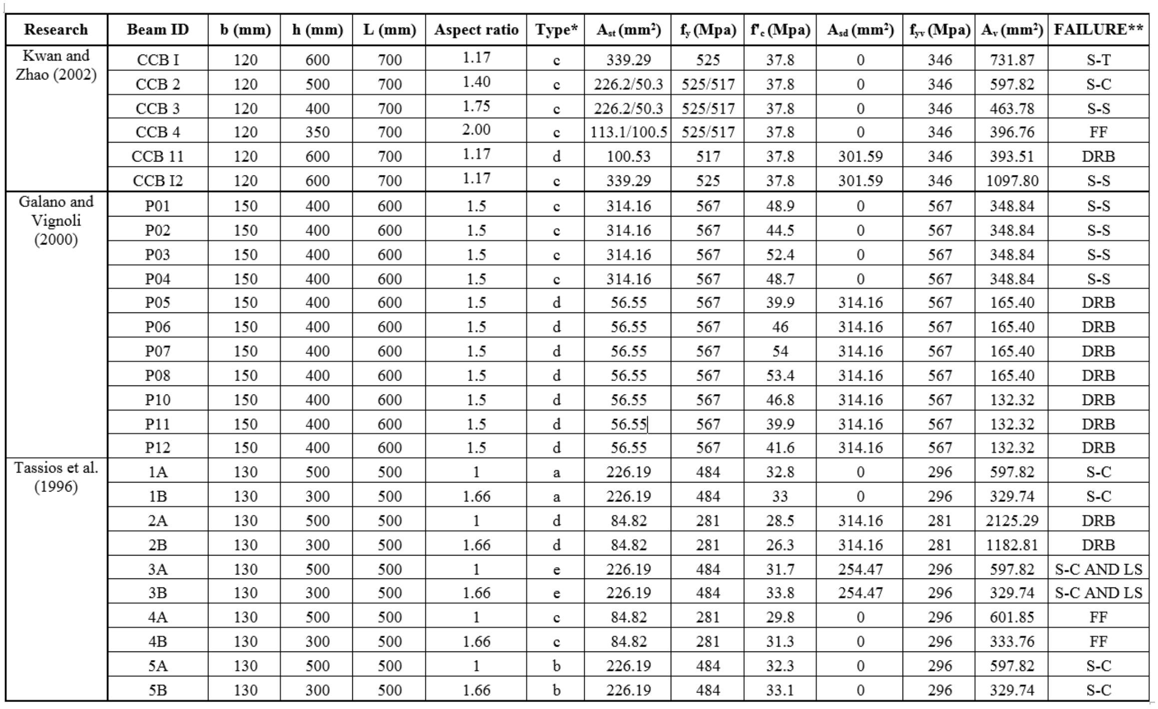
(e) Failure type DRB (f) Failure types S-C and LS

Figure (3): Various failure patterns of RC coupling beams; (a) to (e) adopted from Kwan and Zhao (2002) and (f) adopted from Tassios et al. (1996)

Table 1. Parameters for failure mode identification

Beam Parameters	Main Reinforcement Parameters	Shear Reinforcement Parameters	Sloped Reinforcement Parameters
Beam width, *b*	Beam longitudinal reinforcement area, A_{st}	Beam transverse reinforcement area, A_v	Beam diagonal/rhombic reinforcement area, A_{sd}
Beam length, *L*	Column longitudinal reinforcement yield strength, f_y	Beam transverse reinforcement yield strength, f_{yv}	Angle between diagonal/rhombic reinforcement and the horizontal level, θ
Beam depth, *d*	-	Beam transverse reinforcement spacing, *s*	-
Beam concrete compressive strength, f'_c	-	-	-

Table 2. Properties of coupled beam specimens considered



Research	Beam ID	b (mm)	h (mm)	L (mm)	Aspect ratio	Type*	A_{st} (mm^2)	f_y (Mpa)	f'_c (Mpa)	A_{sd} (mm^2)	f_{yv} (Mpa)	A_v (mm^2)	FAILURE**
Kwan and Zhao (2002)	CCB I	120	600	700	1.17	c	339.29	525	37.8	0	346	731.87	S-T
	CCB 2	120	500	700	1.40	c	226.2/50.3	525/517	37.8	0	346	597.82	S-C
	CCB 3	120	400	700	1.75	c	226.2/50.3	525/517	37.8	0	346	463.78	S-S
	CCB 4	120	350	700	2.00	c	113.1/100.5	525/517	37.8	0	346	396.76	FF
	CCB 11	120	600	700	1.17	d	100.53	517	37.8	301.59	346	393.51	DRB
	CCB I2	120	600	700	1.17	c	339.29	525	37.8	301.59	346	1097.80	S-S
Galano and Vignoli (2000)	P01	150	400	600	1.5	c	314.16	567	48.9	0	567	348.84	S-S
	P02	150	400	600	1.5	c	314.16	567	44.5	0	567	348.84	S-S
	P03	150	400	600	1.5	c	314.16	567	52.4	0	567	348.84	S-S
	P04	150	400	600	1.5	c	314.16	567	48.7	0	567	348.84	S-S
	P05	150	400	600	1.5	d	56.55	567	39.9	314.16	567	165.40	DRB
	P06	150	400	600	1.5	d	56.55	567	46	314.16	567	165.40	DRB
	P07	150	400	600	1.5	d	56.55	567	54	314.16	567	165.40	DRB
	P08	150	400	600	1.5	d	56.55	567	53.4	314.16	567	165.40	DRB
	P10	150	400	600	1.5	d	56.55	567	46.8	314.16	567	132.32	DRB
	P11	150	400	600	1.5	d	56.55	567	39.9	314.16	567	132.32	DRB
	P12	150	400	600	1.5	d	56.55	567	41.6	314.16	567	132.32	DRB
Tassios et al. (1996)	1A	130	500	500	1	a	226.19	484	32.8	0	296	597.82	S-C
	1B	130	300	500	1.66	a	226.19	484	33	0	296	329.74	S-C
	2A	130	500	500	1	d	84.82	281	28.5	314.16	281	2125.29	DRB
	2B	130	300	500	1.66	d	84.82	281	26.3	314.16	281	1182.81	DRB
	3A	130	500	500	1	e	226.19	484	31.7	254.47	296	597.82	S-C AND LS
	3B	130	300	500	1.66	e	226.19	484	33.8	254.47	296	329.74	S-C AND LS
	4A	130	500	500	1	c	84.82	281	29.8	0	296	601.85	FF
	4B	130	300	500	1.66	c	84.82	281	31.3	0	296	333.76	FF
	5A	130	500	500	1	b	226.19	484	32.3	0	296	597.82	S-C
	5B	130	300	500	1.66	b	226.19	484	33.1	0	296	329.74	S-C

* Based on Fig. (2).

**As identified by Shastri (2010).

Aspect Ratio

The effect of aspect ratio measured as span to height ratio of the coupled beam has been studied by many researchers; for example, it was observed by Kwan and Zhao (2002) that the ductility of their specimens was higher at a larger aspect ratio. It was also noticed that as the aspect ratio of such a conventionally reinforced coupling beam was decreased, the load capacity increased (Kwan and Zhao, 2002). The aspect ratio results of specimens considered in this paper are classified based on their ultimate failure mode, given in Table 3 and compared in Fig. (4).

Main Reinforcement to Transverse Reinforcement Ratio

The ratio of main/longitudinal reinforcement area (A_{st}) to transverse reinforcement area (A_v) is introduced for all considered specimens. Main/longitudinal reinforcement area is the area of bars at effective depth, d. Transverse reinforcement area is computed as:

$$A_v = \frac{A_{sv} d}{s} \tag{1}$$

where A_{sv} is the area of each tie leg. The other parameters are defined in Table 1.

This ratio is inspired from the mechanism analysis of coupled beams, where:

$$2M_p = V\,L \tag{2}$$

$$M_p = A_{st} f_y\, jd \tag{3}$$

Assuming shear strength to be also reached at this level:

$$V = \frac{A_{sv} f_{yv}\, d}{s} = A_v f_{yv} \tag{4}$$

There is no shear strength participation from concrete at this level. Therefore,

$$\frac{M_p}{V} = \frac{A_{st} f_y\, jd}{A_v f_{yv}} = \frac{L}{2} \tag{5}$$

Assuming 2j≈1.8, *d*=0.9*h* (calculated from specimens considered in this paper) and $f_y \approx f_{yv}$, the previous ratio becomes:

$$\frac{A_{st}}{A_v} \frac{1}{L/h} \approx 0.62 \tag{6}$$

Accordingly, A_{st} /A_v ratio and aspect ratio are counted upon in this paper to be key factors for identification of ultimate failure mode of coupled beams, ignoring the participation of sloped reinforcement in flexural and shear strength. The results of the ratio of main reinforcement area to transverse reinforcement area, categorized based on their ultimate failure mode, are presented in Table 3 and compared in Fig. (4).

Table 3. Key factors proposed to identify ultimate failure mode

Research	Beam ID	Aspect ratio	A_{st}/A_v	A_{sd}/A_v	FAILURE MODE
Kwan and Zhao (2002)	CCB I	1.17	0.46	0.00	S-T
	CCB 2	1.40	0.46	0.00	S-C
	CCB 3	1.75	0.60	0.00	S-S
	CCB 4	2.00	0.54	0.00	FF
	CCB 11	1.17	0.26	0.77	DRB
	CCB I2	1.17	0.31	0.27	S-S
Galano and Vignoli (2000)	P01	1.5	0.90	0.00	S-S
	P02	1.5	0.90	0.00	S-S
	P03	1.5	0.90	0.00	S-S
	P04	1.5	0.90	0.00	S-S
	P05	1.5	0.34	1.90	DRB
	P06	1.5	0.34	1.90	DRB
	P07	1.5	0.34	1.90	DRB
	P08	1.5	0.34	1.90	DRB
	P10	1.5	0.43	2.37	DRB
	P11	1.5	0.43	2.37	DRB
	P12	1.5	0.43	2.37	DRB
Tassios et al. (1996)	1A	1	0.38	0.00	S-C
	1B	1.67	0.69	0.00	S-C
	2A	1	0.04	0.15	DRB
	2B	1.66	0.07	0.27	DRB
	3A	1	0.38	0.43	S-C AND L-D
	3B	1.66	0.69	0.77	S-C AND L-D
	4A	1	0.14	0.00	FF
	4B	1.66	0.25	0.00	FF
	5A	1	0.38	0.00	S-C
	5B	1.66	0.69	0.00	S-C

Sloped Reinforcement to Transverse Reinforcement Ratio

The ratio of sloped reinforcement area (A_{sd}) to transverse reinforcement area (A_v) is introduced for all considered specimens. The sloped reinforcement area is the total area of the set of bars setting along an angle from the horizontal level of the coupled beam. Since the arrangement of the sloped reinforcement assists in the conversion of shear force into an axial load, this ratio is found to be vital by authors. The results of this ratio, grouped based on the ultimate failure mode, are presented in Table 3 and compared in Fig. (4).

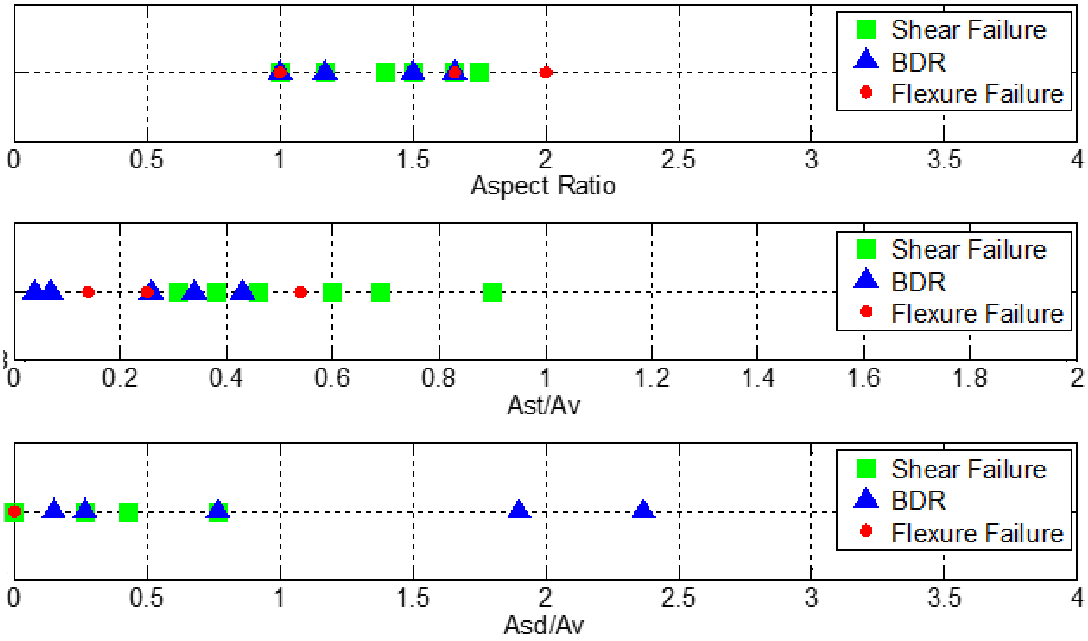


Figure (4): Key factors proposed in this paper for all considered coupled beam specimens

PROPOSED METHOD

It is shown from Fig. (4) that the previously presented key factors can't individually classify specimens considered based on their ultimate failure mode. For coupled beams of types (a), (b) and (c), the aspect ratio and A_{st}/A_v are found critical to identify whether the ultimate failure mode is shear failure or flexural failure (Fig. (5)). A clear threshold is defined such that all specimens above it are vulnerable to fail in shear. This threshold is proposed to be:

$$\frac{A_{st}}{A_v} = 0.3\,\frac{L}{h} \tag{7}$$

All specimens that have (L/h, A_{st}/A_v) above this threshold are assumed to be vulnerable to fail in shear and all specimens that have (L/h, A_{st}/A_v) below this threshold are assumed to be vulnerable to fail in flexure. This proposed method is for conventionally reinforced coupled beams with or without short or long dowels.

Coupled beams with sloped reinforcement can fail either by shear or due to sloped bar buckling. Flexural failure does not make sense in this case. For coupled beams of types (d) and (e), A_{st}/A_v and A_{sd}/A_v are found significant to recognize the ultimate failure mode as shear failure or sloped reinforcement buckling (Fig. (6)). An obvious threshold is specified such that all specimens below it are vulnerable to fail in shear. This threshold is proposed to be:

$$\frac{A_{sd}}{A_v} = 1.5\,\frac{A_{st}}{A_v} \tag{8}$$

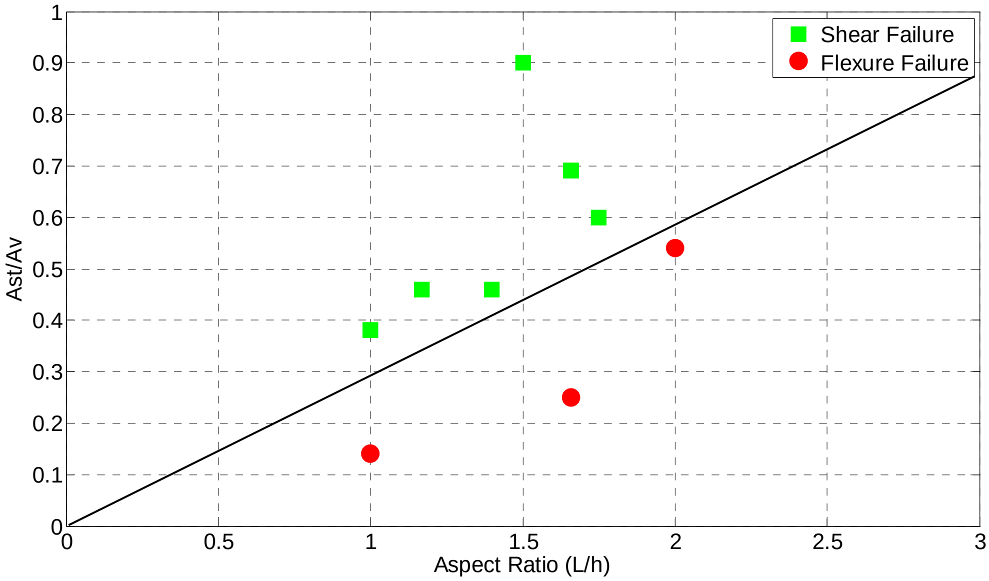


Figure (5): Aspect ratio *versus* main reinforcement to transverse reinforcement ratio for coupled beam specimens of types (a), (b) and (c)

All specimens that have (A_{st}/A_v, A_{sd}/A_v) above this threshold are assumed to be vulnerable to fail by buckling of sloped bars and all specimens that have (A_{st}/A_v, A_{sd}/A_v) below this threshold are assumed to be vulnerable to fail in shear. This proposed method is for coupled beams with sloped reinforcement, including diagonally reinforced or rhombic coupled beams.

This proposed method is a simple tool for engineers to identify the ultimate failure mode to avoid designing coupling beams that are vulnerable to shear failure or reinforcement buckling without running extensive calculations of different mechanisms.

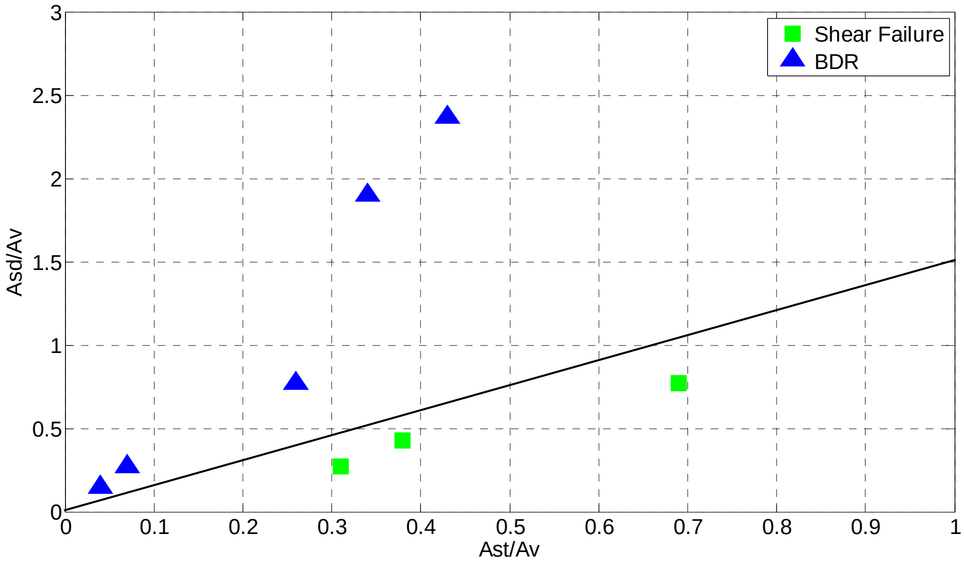


Figure (6): Main reinforcement to transverse reinforcement ratio *versus* sloped reinforcement to transverse reinforcement ratio for coupled beam specimens of types (d) and (e)

SUMMARY AND CONCLUSIONS

Experimental research on the response of RC coupled beams is rich with specimens that experience shear failure and sloped reinforcement buckling failure. Much less data are available for cases with flexural failure. Still, existing data help identify the key factors that affect the response and are used further in this paper to develop a practical engineering tool to recognize ductile ultimate failure mode being brittle failure in shear or buckling of sloped bars.

The aspect ratio, main to transverse reinforcement ratio A_{st}/A_v and sloped to transverse reinforcement ratio A_{sd}/A_v are found to be the key factors. These factors are meaningful to an engineer and incorporate the effects of simple geometric properties and reinforcement details of a coupling beam. They can be calculated easily as discussed in this paper. $\frac{A_{st}}{A_v} = 0.3\frac{L}{h}$ is proposed as a threshold to separate shear failure (brittle) and flexural failure (ductile) of conventional RC coupled beams. $\frac{A_{sd}}{A_v} = 1.5\frac{A_{st}}{A_v}$ is also proposed as a threshold to separate shear failure (brittle) and sloped reinforcement buckling of RC coupled beams with sloped reinforcements.

These threshold lines are proposed based on the study of results from 27 RC coupled beams tested in laboratory by other researchers. The aspect ratio (L/h) of the considered coupled beams ranges from 1 to 2. The concrete compressive strength ranges from 26.3 MPa to 54 MPa. The main and transverse yield strength of reinforcement varies from 281 MPa to 567 MPa.

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