SHEAR BEHAVIOR OF REINFORCED CONCRETE COUPLING BEAMS PREDICTED USING NONLINEAR FINITE ELEMENT ANALYSIS

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Abstract - ACI 318-14 stipulates the use of reinforced concrete (RC) coupling beams with diagonal reinforcing bars to improve seismic performance of buildings. Because of the large energy dissipation of coupling beam, it plays an important role in resisting lateral load. In this study, the shear behavior of RC coupling beams is predicted using RCAHEST(Reinforced Concrete Analysis in Higher Evaluation System Technology), a nonlinear finite element analysis program, and compared with the results of previous experiments. RC coupling beams with various aspect ratios and reinforcement details are used for analysis. The results of analysis of the RC coupling beams obtained by RCAHEST showed a good agreement with the experimental results obtained from the previous studies.

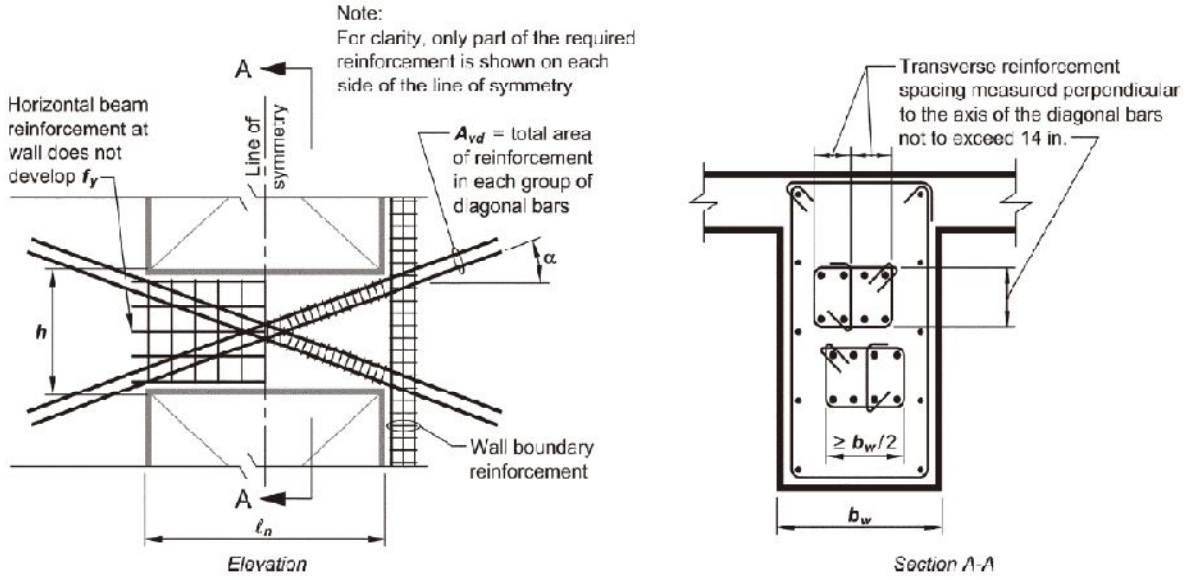
Index Terms - Reinforced Concrete, Coupling Beams, Special Shear Wall, Diagonal Reinforcing Bars

I. INTRODUCTION

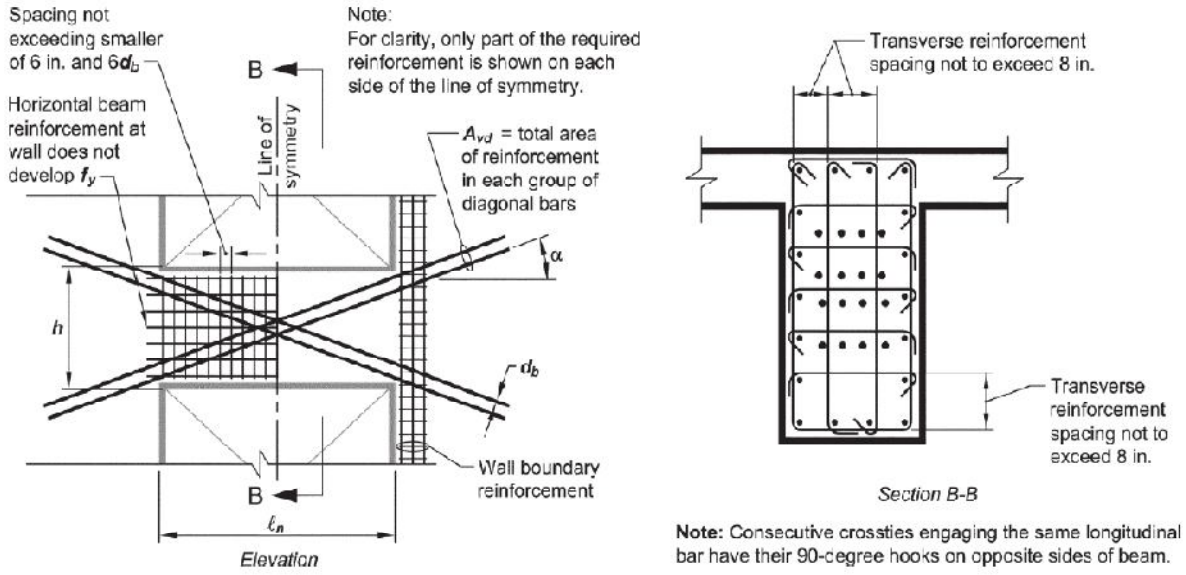
With the increased trend of high-rise dwellings, reinforced concrete (RC) shear walls are also widely used to resist lateral loads such as wind and earthquake. The shear walls have excellent lateral loading capacity. However, the strength of the shear wall may be reduced or the structural performance may be deteriorated owing to the formation of openings; i.e. windows, doors, etc. The walls with the reduced cross-sections due to openings; structurally behave like a beam connecting the separate walls. The structural behavior of these walls matches the behavior of coupling beams connecting two shear walls. Such separated walls due the openings act as coupled shear wall systems. Coupled shear wall systems are widely used as structural systems that can effectively resist lateral loads. When lateral loads are applied to the coupled shear wall systems, the strength and stiffness of the coupling beam become very important because the coupling beam requires large deformation.

Prior to the 1964 Alaska Earthquake,the coupling beams were designed with conventionally reinforcement arrangement. However, during this earthquake, the coupling beam designed with conventionally reinforced arrangement failed with brittle shear failure mode. Consequently, large number of studies to improve the structural performance of coupling beams were initiated. Among them, the design method using diagonal reinforcing bars proposed by Paulay and Binney, showed higher structural performance than that of a conventionally reinforced coupling beam [1 and 2]. Based on the results of this study, ACI 318-14 building code stipulated two confinement options of diagonal reinforcing bars for coupling beams as shown in the Fig. 1. In the first confinement option (Fig. 1(a)), each diagonal element consists of a cage of longitudinal and transverse reinforcement and each cage contains at least four diagonal bars. However, this has the disadvantage that it is very difficult to apply in the field because the reinforcing bars are complicated. Fig. 1(b) describes a second option for confinement of diagonals. This second option is to confine entire beam cross section instead of confining each diagonal reinforcement. This method was designed to increase field applicability. In order to obtain adequate structural performance, the coupling beam with such details must maintain a certain angle of inclination. However, studies on behavior of coupling beams showed that the angle of inclination of diagonal reinforcements highly depends on the aspect ratio. Santhakuman [4] proved that there was almost no difference in the structural performance between the conventionally reinforcement arrangement and diagonally reinforcement arrangement in case of coupling beam with aspect ratio of 2.5 to 5. Therefore, ACI 318-14 placed a limit to the use of diagonal bars for the coupling beams with aspect ratios less than 4. For a coupling beam with an aspect ratio of less than 2 and a factored shear force of more than $0.33\sqrt{f_c'(MPa)}bh$, a diagonal reinforcing bar must be used. Although, several experimental studies to investigate the shear behavior of coupling beams with diagonal reinforcement arrangements subjected to reversed cyclic loading have previously been carried out, yet the mechanism of shear transfer and corresponding ductility is not fully understood. Therefore, in this study a Nonlinear Finite Element analysis was carried out to investigate the shear behavior of RC coupling beams with different arrangements of reinforcements and effect of aspect ratio on the shear strength and corresponding ductility using RCAHEST(Reinforced Concrete Analysis in Higher Evaluation System Technology). The analytical results obtained using RCAHEST showed similar behavior as reported in test results.

II. NONLINIEAR FINITE ELEMENT PROGRAM



(a) Confinement of individual diagonals



(b) Full confinement of diagonally reinforced concrete beam section

Fig. 1 Coupling beams with diagonally reinforced concrete beam section

A. RCAHEST

In this study, the RC coupling beams were analyzed using RCAHEST, a nonlinear finite element analysis program. RCAHEST is based on FEAP (A Finite Element Analysis Program) developed by Taylor of the University of Berkeley. FEAP can define one-dimensional, two-dimensional and three-dimensional mesh. It has various linear and nonlinear analysis algorithms, and it enables various graphics processing of analysis results. In addition, elements directly developed by the user can be added, and it is also possible to use them in combination [5]. In order to accurately predict the nonlinear finite element analysis results of the RC structure, it is important that the model used in the analysis accurately describes the behavior of the structure. For this reason, RC plane stress elements, interface elements, beam-column elements and shell elements developed by Shin et al. were applied to RCAHSET [6].

B. NONLINEAR MATERIAL MODEL OF RC

Already exiting RC nonlinear material model developed by Kim, T. H. et al. [7] was used in this research. The concrete model before cracking was based on the elasto-plastic fracture model [8] in the two-dimensional stress state. This model presented the relationship of equivalent stress-equivalent strain in terms of initial elastic modulus, fracture parameter, and equivalent plastic strain, as shown in equations (1) to (3).

$$\sigma = E_0 K_0 (\epsilon - \epsilon_p) = E_0 K_0 \epsilon_e \quad (1)$$

$$\epsilon_p = \epsilon_{max} - \frac{20}{7}[1 - Exp(-0.35\epsilon_{max})] \quad (2)$$

$$K_0 = Exp\{-0.73\epsilon_{max}[1 - Exp(-1.25\epsilon_{max})]\} \quad (3)$$

Where σ is the equivalent stress, ϵ is the equivalent strain ($\epsilon = \epsilon_e + \epsilon_p$), E_0 is the initial elastic modulus of the concrete and K_0 is the fracture parameter.

Concrete has lower rigidity after cracking than concrete without cracks [9]. The fracture parameter K of the cracked concrete and the fracture parameter K_0 of the non-cracked concrete have a relationship as shown in equation (4). The elasto-plastic fracture model of the cracked concrete is shown in equation (5).

$$K = \omega K_0 \quad (4)$$

$$\sigma_y = E_0 K(\epsilon_y - \epsilon_p) \quad (5)$$

Where E_0 is the initial modulus of elasticity of the concrete, ϵ_y is the strain in the crack parallel direction, and ϵ_p is the plastic strain in the crack parallel direction.

When cracks occur, the stress of the reinforcing bars in the concrete is not constant and becomes maximum on the crack face. The rebar behaves elastically before yielding. The average stress-strain relationship of the rebar deviates from the elastic region when the rebar is first yielded on the crack plane. Since the reinforcement located outside the crack plane has not yet yielded, the stress increases as the strain increases. Since the reinforcing bar located on the crack surface yielded, the stress does not increase. However, the average stress is increased due to the increase of the stress of reinforcing bar located inside concrete. This is expressed as Equation (6).

$$\sigma_s = \sigma_{sy} + E_{sh}(\epsilon_s - \epsilon_{sy}) \quad (6)$$

Where σ_s is the average stress of the steel bars, σ_{sy} is the average stress at the starting point of strain hardening, E_{sh} is the strain hardening rate of the steel, ϵ_s is the average strain of the steel bars, ϵ_{sy} is the average strain of the steel bars corresponding to the starting point of strain hardening.

III. ANALYSIS USING RCAHEST

A. Specimens

In order to predict the shear behavior of RC coupling beams with RCAHEST, ten specimens were collected from previous studies [10]-[11]. Coupling beams were classified in to four groups depending on the aspect ratio. Groups CB10 and CB20 had aspect ratio 1.0 and 2.0, while CB30 and CB40 groups were with aspect ratio of 3.0 and 4.0, respectively. Group CB10 and CB20 were designed with two different rebar details, conventional reinforced arrangement and diagonal reinforcement arrangement. However, CB30 and CB40 had coupling beams using a hybrid layout, introduced in 2005 [12]. The list of all specimens and the material properties are shown in Table I and Table II.

No.	Specimen	b (mm)	h (mm)	ln (mm)	Ln/h	α (°)	Longitudinal reinforcement	Transverse reinforcement	Diagonal reinforcement
1	CB10-1	250	500	500	1.0	26.0	10-D10	D13@100mm	8-D25
2	CB10-2	250	500	500	1.0	-	4-D13 4-D25+2-D29	D13@100mm	-
3	CB20-1	300	500	1000	2.0	16.0	10-D13	D13@100mm	8-D29
4	CB20-2	300	500	1000	2.0	-	4-D13 4-D32+2-D36	D13@70mm	-
5	CB30-C	300	500	1500	3.0	-	4-D10 4-D32+2-D36	D13@100mm	-
6	CB40-C	400	500	2000	4.0	-	4-D13 8-D32	D13@100mm	-
7	CB30-DA	300	500	1500	3.0	8.8	4-D13	D13@200mm	8-D32
8	CB30-DB	300	500	1500	3.0	8.8	10-D10	D10@100mm	8-D32
9	CB30-H	300	500	1500	3.0	9.0	4-D13 2-D22+4-D25	D13@100mm	4-D32
10	CB40-H	400	500	2000	4.0	7.2	4-D13 8-D29	D13@100mm	4-D22

Table I. Selected specimens for analysis

No.	Specimen	f_c', MPa	Yieldong strength of bars, MPa						
			D10	D13	D22	D25	D29	D32	D36
1	CB10-1	34.5	-	468.4	-	485.7	439.6	-	-
2	CB10-2	36.1	-	468.4	-	485.7	439.6	-	-
3	CB20-1	52.1	-	502.0	-	-	466.3	450.3	447.8
4	CB20-2	52.2	-	502.0	-	-	466.3	450.3	447.8
5	CB30-C	47.9	475	441	-	-	-	465	470
6	CB40-C	58.0	-	486	-	-	-	455	-
7	CB30-DA	39.7	475	441	-	-	-	465	-
8	CB30-DB	38.4	475	-	-	-	-	465	-
9	CB30-H	58.0	-	486	458	449	-	455	-
10	CB40-H	59.0	-	486	458	-	509	-	-

Table I. Material property

B. RCAHEST modeling

To carry out the analysis of shear behavior of the RC coupling beams using RCAHEST, the specimens were divided into elements as shown in Fig 2. The longitudinal, transverse and diagonal reinforcement used in the RC coupling beam were analyzed using a suitable material model. A total of 43 RC Plane Stress Elements and Interface Elements were used in the coupling beam with conventional reinforcement arrangement, and Reinforcing Bar Elements were added in case of coupling beam with diagonal reinforcement.

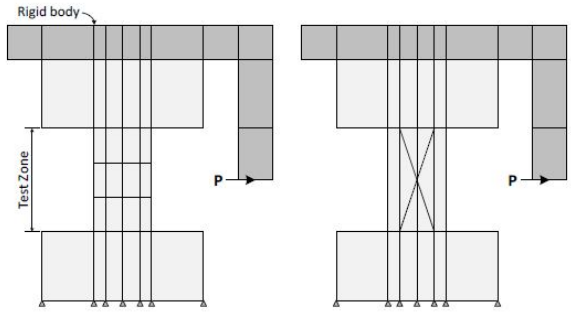


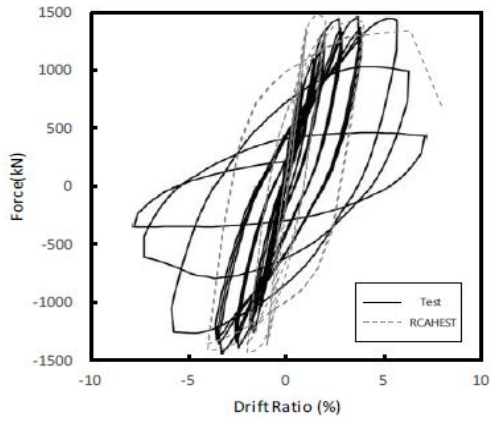
Fig. 2Element division for finite element analysis.

C. Analysis result

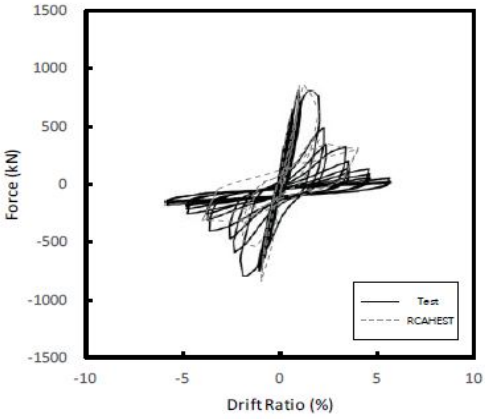
Finite element analysis results of RC coupling beams were compared with results from experimental tests. Fig. 3 shows the load-deflection relationship obtained through finite element analysis using RCAHEST, compared with experimental data. In all groups, coupling beam with diagonal reinforcement arrangement showed improved shear strength, corresponding ductility and energy dissipation capacity and the reduced the pinching effect. Investigation of analysis results showed that the aspect ratio adversely affected the shear strength of coupling beams. As the aspect ratio of the member increased, the angle of inclination of the diagonal reinforcing bar became smaller, consequently reduced the shear strength of the member. For instance, even though beams CB30-DA and CB30-DB were with large amount of diagonal reinforcement than that of CB10-1 and CB20-1, but the maximum shear strength was less than CB10-1 and CB20-1, because of higher aspect ratio of CB30-DA and CB30-DB. Comparison of analytical and experimental results showed that the Nonlinear Finite Element Analysis using RCAHEST predicted that maximum shear strength in a rational margin of error with minimum 3% to maximum of 13%. The analytical results and the experimental results are shown in Table III.

Specimen	Maximum shear strength (kN)		
	V_{test}	$V_{RCAHEST}$	$V_{RCAHEST}/V_{test}$
CB10-1	1443.8	1488.2	1.03
CB10-2	873.6	861.4	0.99
CB20-1	1073.0	1123.7	1.05
CB20-2	1098.0	1105.1	1.01
CB30-C	682.2	755.7	1.11
CB40-C	668.7	735.3	1.10
CB30-DA	671.0	709.6	1.06
CB30-DB	728.2	793.6	1.09
CB30-H	752.4	848.4	1.13
CB40-H	754.5	775.6	1.03

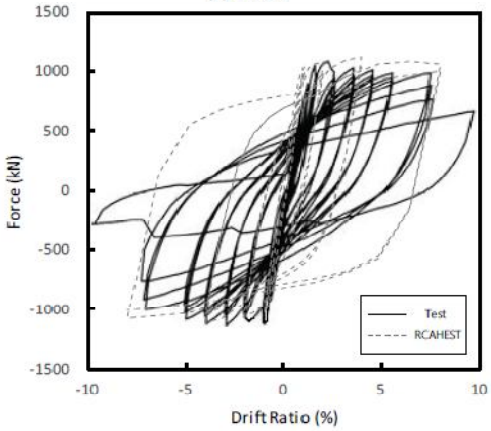
Table I. Strength prediction of specimens



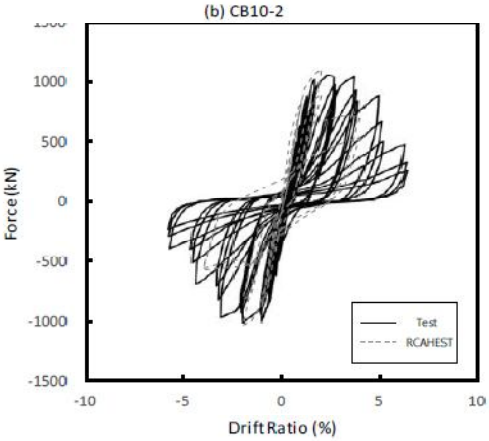
(a) CB10-1



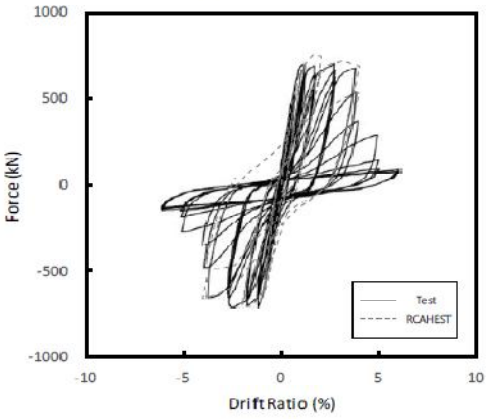
(b) CB10-2



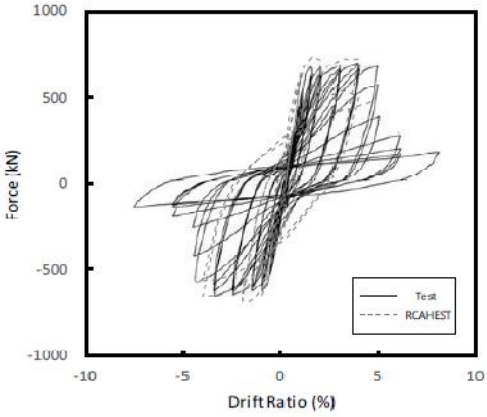
(c) CB20-1



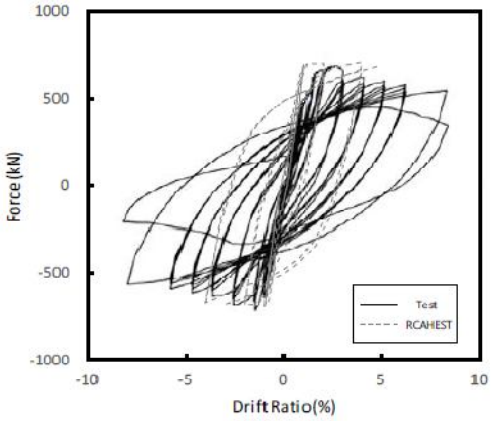
(d) CB20-2



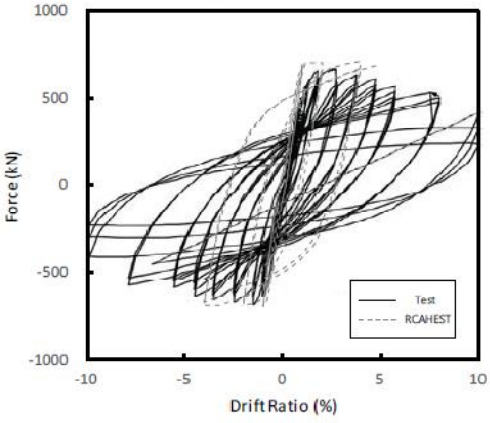
(e) CB30-C



(f) CB40 C



(g) CB30-DA



(h) CB30-DB

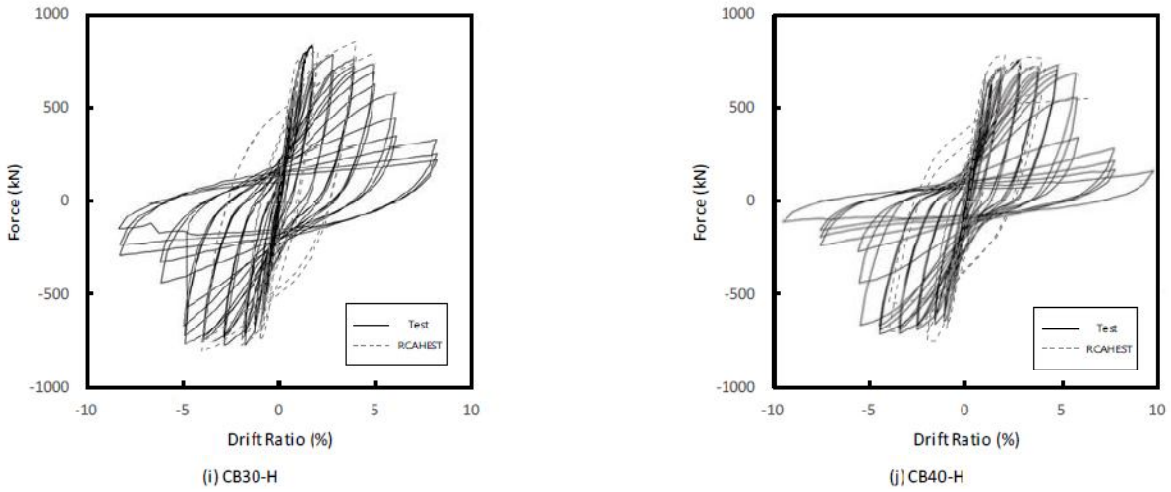


Fig. 3 Load-deflection curves

CONCLUSION

In this study, a nonlinear finite element analysis was carried out to investigate the shear behavior of RC coupling beams using RCAHEST. Ten specimens reported in the previous study was used to analyze the effect of aspect ratio on the shear strength and ductility. The specimens depicting the behavior of the coupling beam under cyclic loading were analyzed by applying the existing material models. The validity of the analysis results was verified by comparing with the experiment results reported in the literature. Based on this study following conclusions can be made.

1. Analytical results showed that the structural performance of RC coupling beams using diagonal reinforcing bars was improved. Analysis of coupling beams with diagonal reinforcing bars, showed improved shear strength and the reduced the pinching effect.
2. As the aspect ratio of the member increased, the diagonal reinforcement became less effective on the behavior of the members. It is considered that as the aspect ratio of the member increases, the inclination angle of the diagonal reinforcing bar becomes smaller, which results reduced shear strength of the member.
3. Comparison of analysis and experimental results showed that nonlinear finite element analysis program RCAHEST can effectively be used to carry out the analysis of shear behavior of RC coupling beams with a very reasonable accuracy if members are analyzed by applying appropriate discretization of elements.

ACKNOWLEDGMENTS

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