https://doi.org/10.3311/PPci.16386

Periodica Polytechnica Civil Engineering, 65(2), pp. 450–462, 2021

Analytical Estimation of the Residual Drift of Reinforced Concrete Columns under the Ultimate Displacement Capacity

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Received: 05 May 2020, Accepted: 09 December 2020, Published online: 18 December 2020

Abstract

Reinforced concrete columns are the most important structural elements that determine the ductility of the structures. The main parameters affecting the behavior of reinforced concrete columns are axial load level, shear span, percent of longitudinal reinforcement and percent of transverse reinforcement. The aim of this study is to examine residual damage behavior of RC columns under cyclic loading similar to the earthquake loads combined depend on variable axial load level, spanning to depth ratio, longitudinal reinforcement ratio and transverse reinforcement ratio. When the results of experiments are examined, it can be seen that the residual drift ratio of reinforced concrete columns can be used to characterize the damage occurred in the structure after earthquake or loading. In addition, the performance level of the reinforced concrete columns according to the residual drift ratio is defined in FEMA356. As a result of this study, the analytical equation that calculates the residual drift ratio of the reinforced concrete columns at the ultimate displacement limit is proposed.

Keywords

RC column, residual drift ratio, damage, seismic analysis

1 Introduction

In recent years, the design of reinforced concrete structural systems has been made on the basis of force or displacement-based approaches. Reinforced concrete elements are designed to be stronger than earthquake loads in force-based approaches. Irreparable damages were occurred in the buildings exposed to the earthquake after the earthquakes in the 1990s (e.g.: Kobe 1995, Northridge 1995, Loma Prieta 1989). As a result, the performance-based design principle has been started to be used in seismic codes due to the economic losses. Performance-based design is the approach in which the target damage expected to occur after the earthquake is defined. The use of performance-based design to reach post-earthquakes functionality of critical structures is most commonly thought of as applied to structures (e.g.: hospitals, fire stations).

Residual damages occur depending on the magnitude of the earthquake in reinforced concrete structures exposed to earthquake loads. Experimental and analytical studies have been carried out by many researchers to identify these damages [1–3]. Lehmann et al. [4] suggest that key damage states of residual cracking, cover spalling, and core crushing can best be related to engineering parameters, such as longitudinal reinforcement tensile strain and concrete compressive strain, using cumulative probability curves. Erduran and Yakut [5] determined the damage functions of reinforced concrete columns depend on drift. According to Priestley and Kowalsky [6], it is shown that current code-based design approaches, which imply a constant ductility factor, will generally result in damage levels that are highly variable. Goodnight et al. [7] the importance of displacement history and its effects on performance limit states, the relationship between strain and displacement, and the spread of plasticity in RC structures are investigated. Cheng et al. [8] have researched on the influencing factors for residual displacements of RC bridge columns subjected to earthquake loading. In addition, the residual drift ratio becomes larger due to the increase of the maximum lateral drift ratio, the displacement ductility factor, and the aspect ratio. Then, a larger longitudinal reinforcement ratio can induce a larger residual drift ratio due to the contribution of the bar pulling out deformation. A new post-earthquake seismic performance evaluation method

Cite this article as: Cansız, S. " Analytical Estimation of the Residual Drift of Reinforced Concrete Columns under the Ultimate Displacement Capacity", Periodica Polytechnica Civil Engineering, 65(2), pp. 450–462, 2021. https://doi.org/10.3311/PPci.16386

for structures which takes into account residual deformation is suggested by Yazgan and Dazio [9]. The post-earthquake residual deformations and the traceable damage to the structure are considered to obtain developed predicts of the maximum deformations that took place during the earthquake. A new plastic hinge model was proposed in the study by Bae and Bayrak [10]. The proposed plastic hinge model has been compared with existing models, taking into account the effect of the axial load.

In the study conducted by Vui et al. [11], the damage indices commonly used were investigated and a new damage model was proposed According to this model, residual displacement is considered as the most important parameter of the damage and the energy-related correlation is suggested. It has been stated that the results are usable by comparing the results obtained with the other damage models.

Residual drift can be shown as the most important indicator left by seismic loads on structures. Many seismic codes in the world use different methods in the performance of reinforced concrete structures. In these seismic codes, it is necessary to know the loading history in order to determine the performance of the building. It is difficult to determine the current performance in columns with limited knowledge. Within the scope of this study, the prediction of damage due to the residual drift ratio of reinforced concrete columns was investigated. According to this method, the performance level of the columns with limited knowledge can be found. The main words in the title start with capital letter, articles, and conjunctions with lowercase letters.

2 Material and method

The performance level of reinforced concrete columns is calculated by different methods in many seismic codes. The performance of reinforced concrete elements using the material strain values in Turkey earthquake building code are determined [12]. Panagiotakos and Fardis [13] provided formulations for chord rotation capacity at yielding and "ultimate" (at 20 % strength drop), the latter through an empirical and a semi-empirical (i.e., based on the plastic hinge length) approach based on a large database of flexure-controlled experimental tests for RC elements. According to researchers, loading profile is needed to determine the current performance of the reinforced concrete column. However, in practice, the most important parameter that can be determined in existing building inspections for performance determination of buildings is the residual drift ratio. Therefore, defining the damage in terms of residual drift ratio could guide engineers during the implementation phase.

2.1 Properties of the columns

Within this study, columns investigated in previous experimental studies were used [14]. The properties of the columns examined in this paper are presented in Table 1.

Table 1 Properties of the columns

Specimen Name	L/h	$N/A_g f_c$	ρ_t	ρ_{sh}	f_c
Ang No. 3 [15]	4.00	0.38	0.015	0.006	23.6
Ang No. 4 [15]	4.00	0.21	0.015	0.004	25.0
Azizinamini et al. NC-2 [16]	3.00	0.21	0.019	0.005	39.3
Azizinamini et al. NC-4 [16]	3.00	0.31	0.019	0.003	39.8
Mo and Wang C1-1 [17]	3.50	0.11	0.021	0.003	24.9
Mo and Wang C1-2 [17]	3.50	0.16	0.021	0.003	26.7
Mo and Wang C1-3 [17]	3.50	0.22	0.021	0.003	26.1
Nosho et al. No. 1 [18]	7.64	0.34	0.010	0.001	40.6
Saatcioglu and Grira BG-1 [19]	4.70	0.43	0.020	0.003	34.0
Saatcioglu and Grira BG-2 [19]	4.70	0.43	0.020	0.005	34.0
Saatcioglu and Grira BG-3 [19]	4.70	0.20	0.020	0.005	34.0
Saatcioglu and Grira BG-4 [19]	4.70	0.46	0.029	0.003	34.0
Saatcioglu and Ozcebe U3 [20]	2.86	0.14	0.032	0.006	34.8
Saatcioglu and Ozcebe U4 [20]	2.86	0.15	0.032	0.009	32.0
Soesianawati No. 1 [21]	4.00	0.10	0.015	0.002	46.5
Soesianawati No. 2 [21]	4.00	0.30	0.015	0.003	44.0
Soesianawati No. 3 [21]	4.00	0.30	0.015	0.002	44.0
Soesianawati No. 4 [21]	4.00	0.30	0.015	0.002	40.0
Tanaka No. 2 [22]	4.00	0.20	0.016	0.007	25.6
Watson No. 5 [23]	4.00	0.50	0.015	0.003	41.0
Watson No. 6 [23]	4.00	0.50	0.015	0.001	40.0
Zahn No. 7 [24]	4.00	0.22	0.015	0.003	28.3
Kanda et al. 85STC-1 [25]	3.00	0.11	0.016	0.004	27.9
Galeota et al. CB3 [26]	4.56	0.30	0.060	0.008	80.0
Galeota et al. CB2 [26]	4.56	0.20	0.060	0.008	80.0
Wehbe et al. A1 [27]	3.83	0.10	0.022	0.001	27.2
Xiao and Martirossyan, 8L19-T10-0.1P [28]	2.00	0.10	0.035	0.010	76.0
Xiao and Martirossyan, 8L19-T10-0.2P [28]	2.00	0.20	0.035	0.010	76.0
Xiao and Martirossyan, 8L16-T10-0.1P [28]	2.00	0.10	0.025	0.010	76.0
Sugano UC15L [29]	2.00	0.36	0.019	0.006	118.0
Sugano UC15H [29]	2.00	0.60	0.019	0.006	118.0
Bayrak and Sheikh AS-2HT [30]	6.04	0.36	0.026	0.007	71.7
Bayrak and Sheikh AS-4HT [30]	6.04	0.50	0.026	0.014	71.9
Legeron and Paultre, No. 1006015 [31]	6.56	0.14	0.022	0.011	92.4
Legeron and Paultre, No. 1006025 [31]	6.56	0.28	0.022	0.011	93.3
Legeron and Paultre, No. 1006040 [31]	6.56	0.40	0.022	0.011	98.2

Where L/h is the shear span to depth ratio, $N/A_c f_c$ is axial load ratio, ρ_l is longitudinal reinforcement ratio, ρ_{sh} is transverse reinforcement volumetric ratio (TBEC-2018), N is axial load, Ac is gross area and f_c is concrete strength. Calculation of reinforcement ratios is shown in the Eqs. (1)–(2).

$$\rho_l = \frac{A_s}{bd} \quad (1)$$

$$\rho_{sh} = \frac{A_{sh}}{b_k s} \quad (2)$$

Where A_s is longitudinal reinforcement total area, b is column width, d is effective depth, A_{sh} is transverse reinforcement area, b_k is core concrete width and s is hoop spacing. The parameters taken into consideration in the selection of column properties are shear span to depth ratio, axial load ratio, longitudinal reinforcement ratio and transverse reinforcement ratio, respectively. In the columns selected within the scope of the study, these properties are determined in the value range allowed in the seismic codes. In addition, columns with high concrete strength are not included in the study. In order to ensure that the study is independent of the effect of concrete compressive strength, columns with frequently used concrete strength have been selected. In this context, the ranges of the columns properties value used in the study are shown in Table 2.

2.2 Seismic analysis results of the columns

The displacement capacity of RC elements has been investigated by many researchers in recent years. Some of the studies in this area are considered as limit values in the codes. In the nonlinear static procedure of TBEC-2018, in order to predict the performance level, the strain limits of concrete and reinforcement are used as the main parameters. EUROCODE-8 includes a part for the assessment of RC columns that proposes the calculation of chord rotations with the given equations in the code [32]. These equations are functions of many variables such as axial load ratio, longitudinal reinforcement ratio, transverse reinforcement ratio and yield strength of the transverse reinforcement.

Table 2 Ranges of the columns properties value

Parameter	Range of value	
	Minimum	Maximum
Span to depth ratio (L/h)	2.86	7.64
Axial load ratio ($N/A_c f_c$)	0.10	0.60
Longitudinal reinforcement ratio (ρ_l)	0.010	0.060
Transverse reinforcement ratio (ρ_{sh})	0.001	0.009
Concrete strength (f_c)	23.6	118.0

FEMA 356 is the American pre-standard and commentary for the seismic rehabilitation of buildings [33]. The document expresses deformation limits, which are in the form of plastic rotations. In FEMA 356, deformation limits are specified in terms of plastic rotation for RC columns. Some seismic codes define the displacement capacity for reinforced concrete columns as an approximately 20 % decrease in lateral load bearing capacity. Figs. 1–36 illustrate load-displacement curves with ultimate displacement capacity and residual displacement.

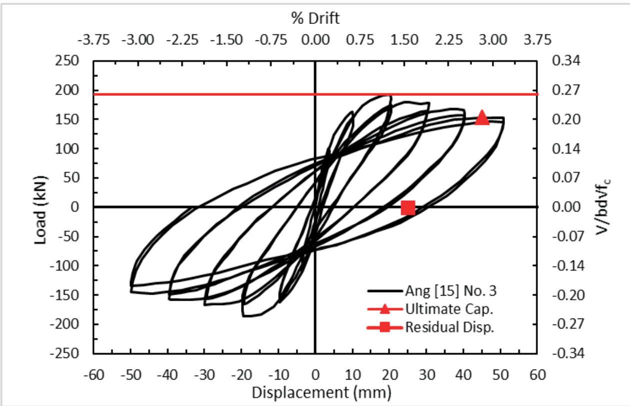

Fig. 1 Load-displacement curve of the Ang [15] No.3

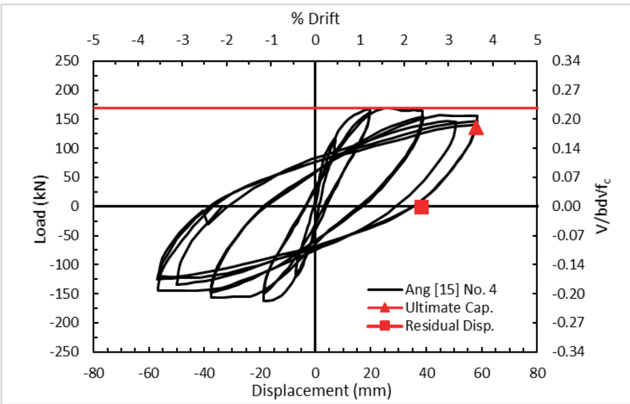

Fig. 2 Load-displacement curve of the Ang [15] No.4

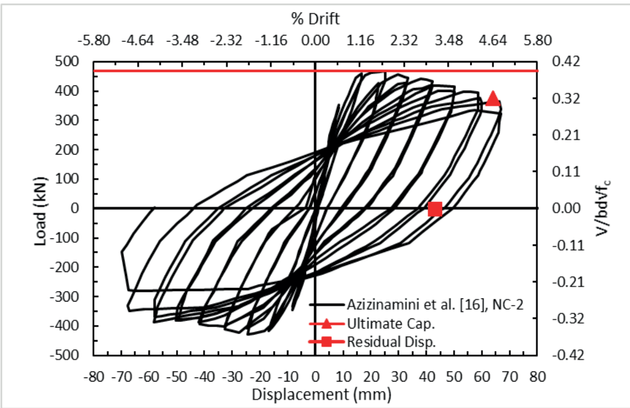

Fig. 3 Load-displacement curve of the Azizinamini et al. [16], NC-2

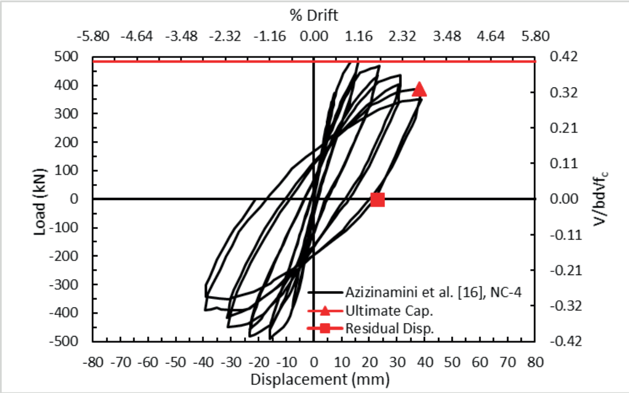

Fig. 4 Load-displacement curve of the Azizinamini et al. [16], NC-4

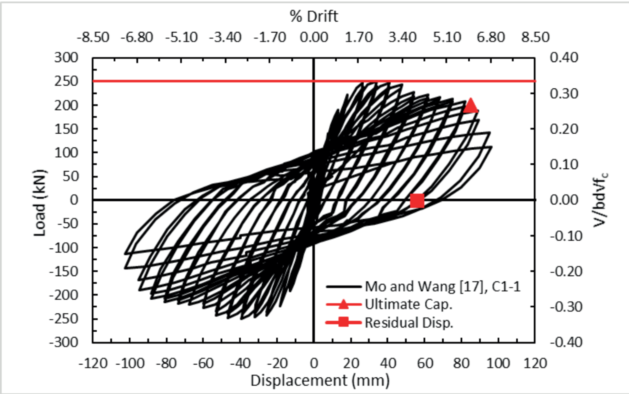

Fig. 5 Load-displacement curve of the Mo and Wang [17], C1-1

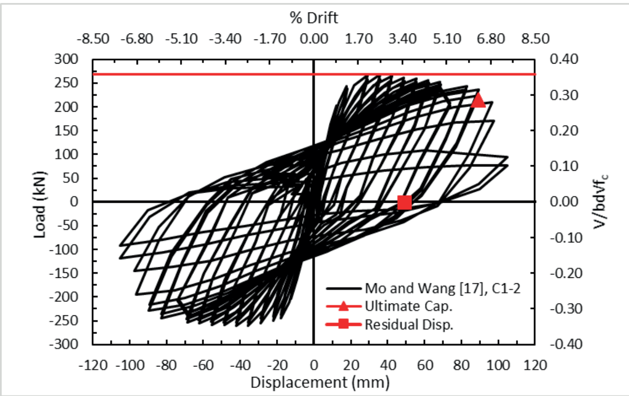

Fig. 6 Load-displacement curve of the Mo and Wang [17], C1-2

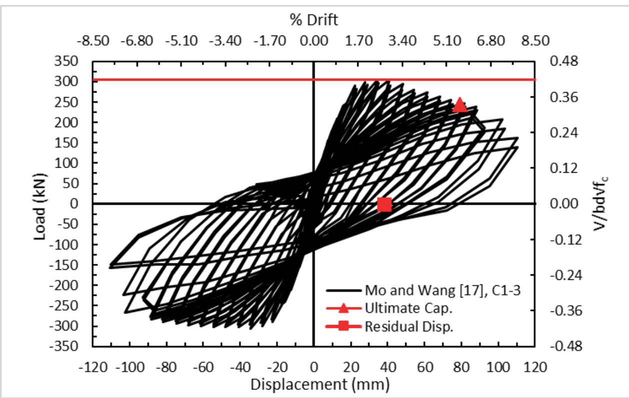

Fig. 7 Load-displacement curve of the Mo and Wang [17], C1-3

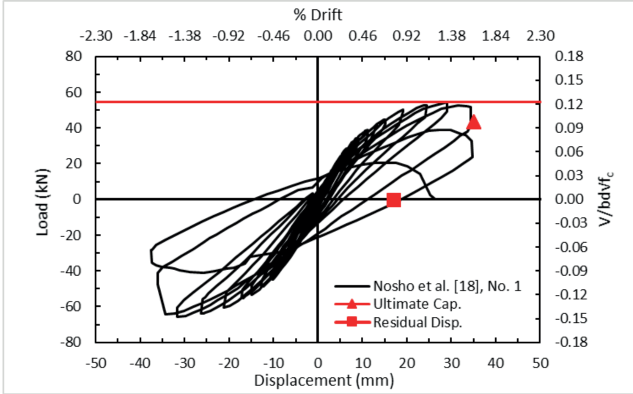

Fig. 8 Load-displacement curve of the Nosho et al. [18], No. 1

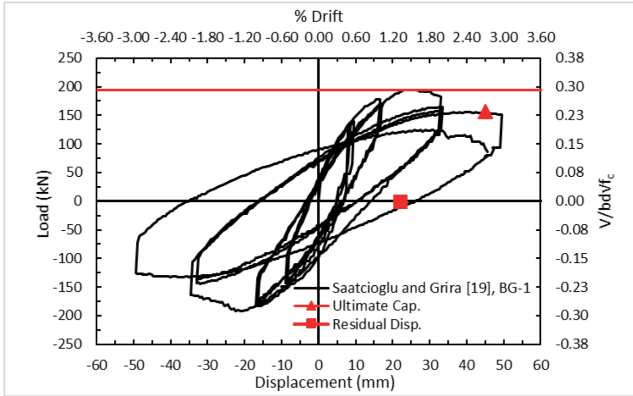

Fig. 9 Load-displacement curve of the Saatcioglu and Grira [19], BG-1

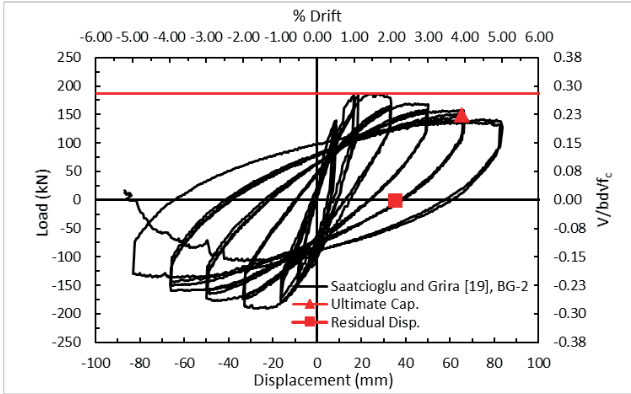

Fig. 10 Load-displacement curve of the Saatcioglu and Grira [19], BG-2

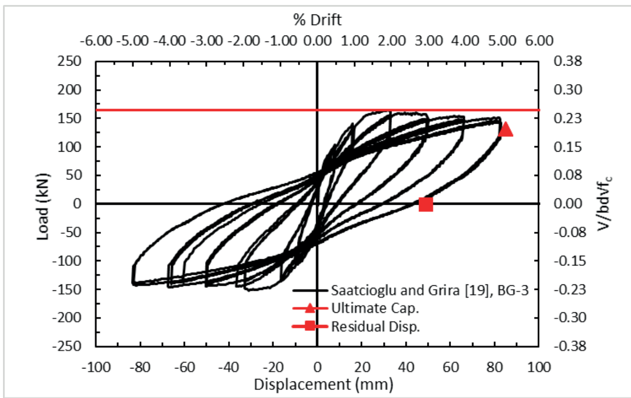

Fig. 11 Load-displacement curve of the Saatcioglu and Grira [19], BG-3

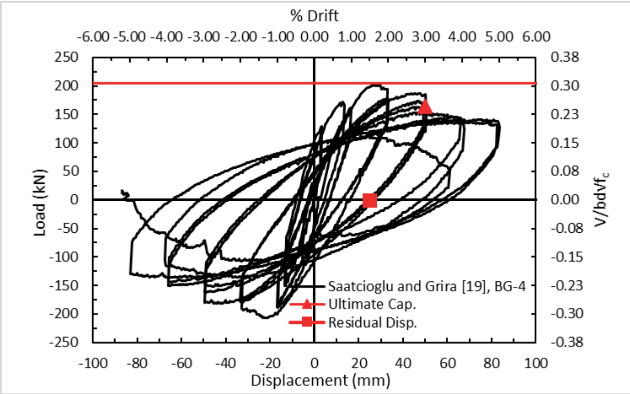

Fig. 12 Load-displacement curve of the Saatcioglu and Grira [19], BG-4

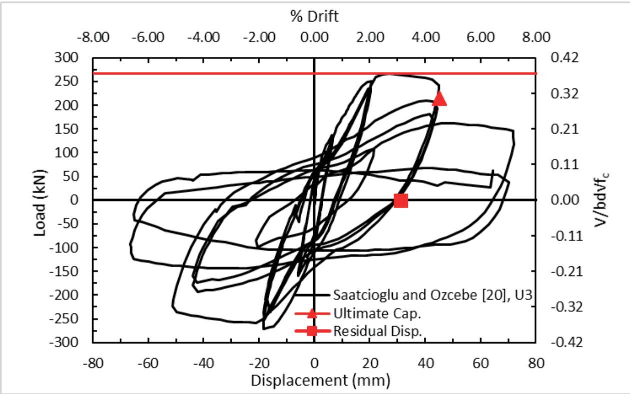

Fig. 13 Load-displacement curve of the Saatcioglu and Ozcebe [20], U3

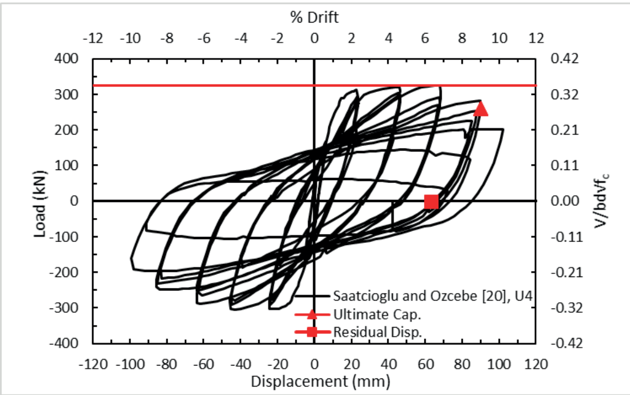

Fig. 14 Load-displacement curve of the Saatcioglu and Ozcebe [20], U4

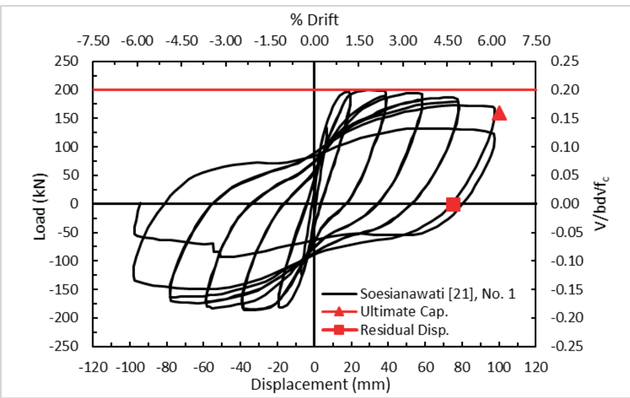

Fig. 15 Load-displacement curve of the Soesianawati [21], No. 1

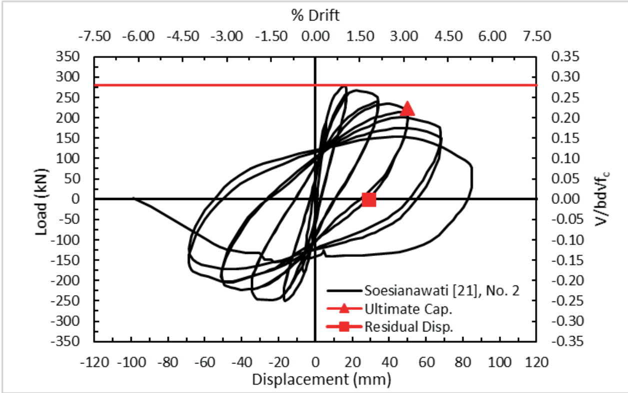

Fig. 16 Load-displacement curve of the Soesianawati [21], No. 2

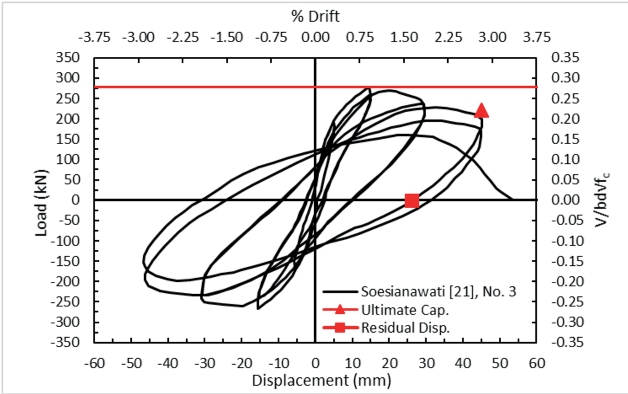

Fig. 17 Load-displacement curve of the Soesianawati [21], No. 3

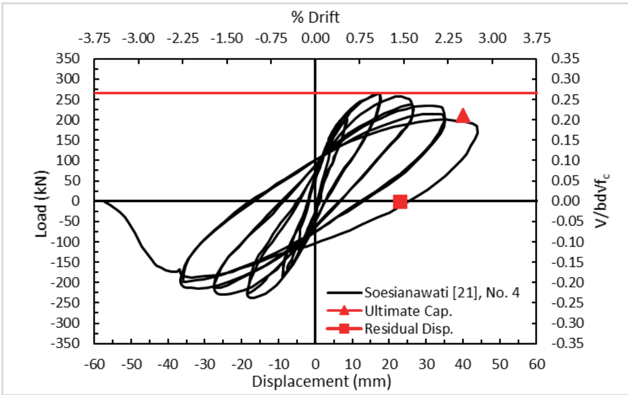

Fig. 18 Load-displacement curve of the Soesianawati [21], No. 4

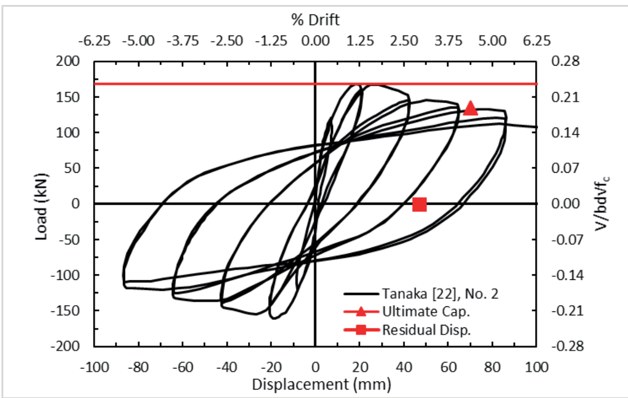

Fig. 19 Load-displacement curve of the Tanaka [22], No. 2

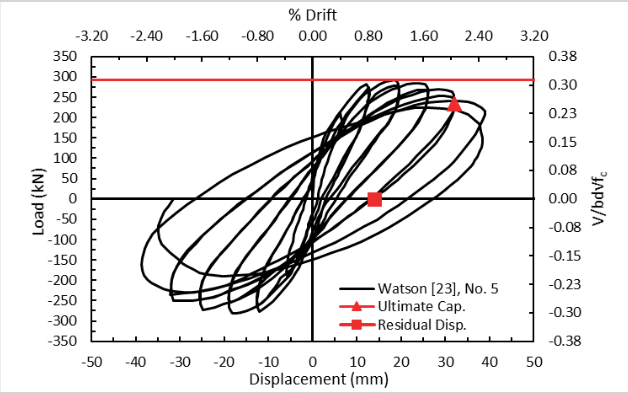

Fig. 20 Load-displacement curve of the Watson [23], No. 5

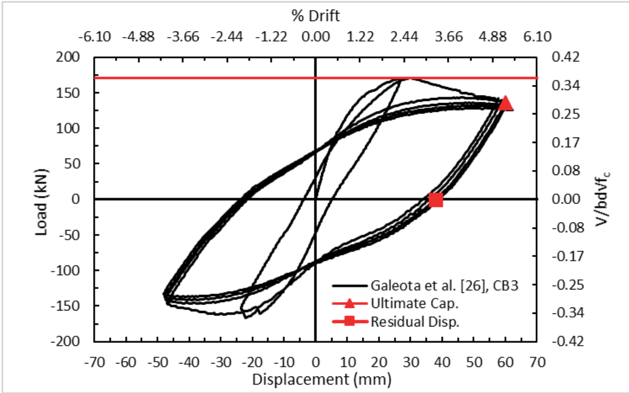

Fig. 24 Load-displacement curve of the Galeota et al. [26] CB3

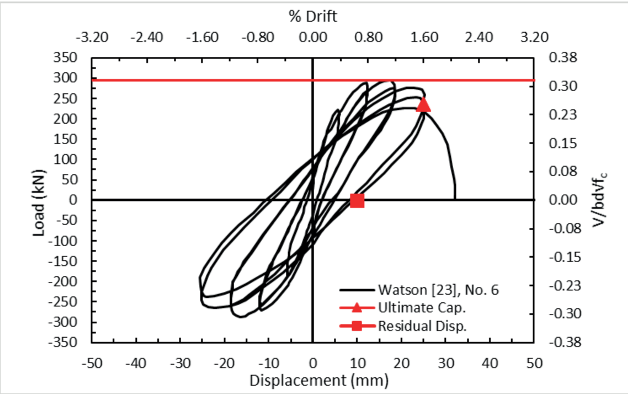

Fig. 21 Load-displacement curve of the Watson [23], No. 6

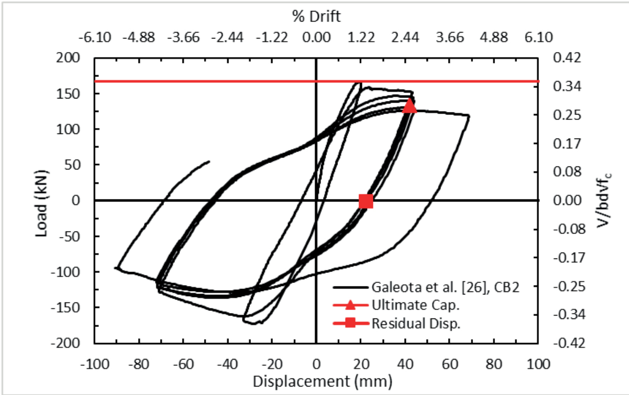

Fig. 25 Load-displacement curve of the Galeota et al. [26] CB2

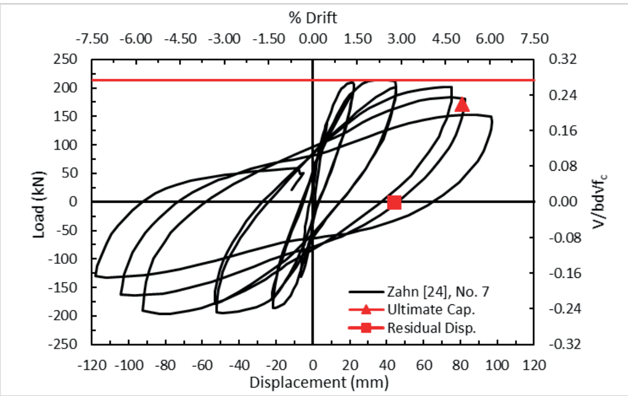

Fig. 22 Load-displacement curve of the Zahn [24], No. 7

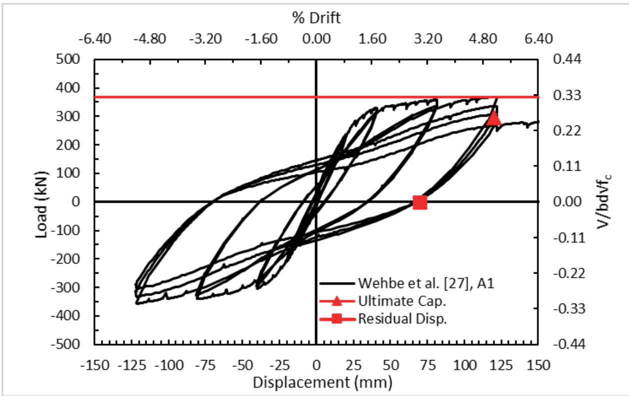

Fig. 26 Load-displacement curve of the Wehbe et al. [27] A1

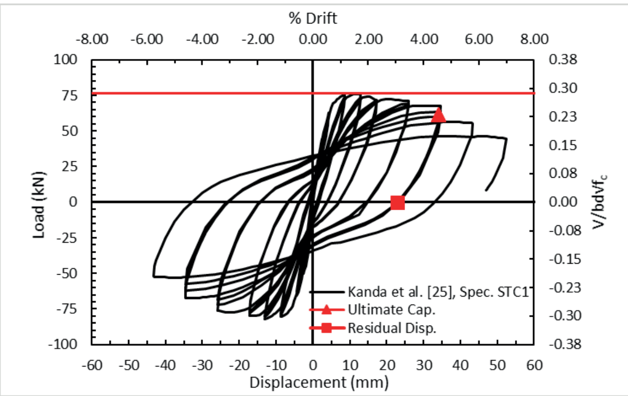

Fig. 23 Load-displacement curve of the Kanda et al. [25] Spec. STC1

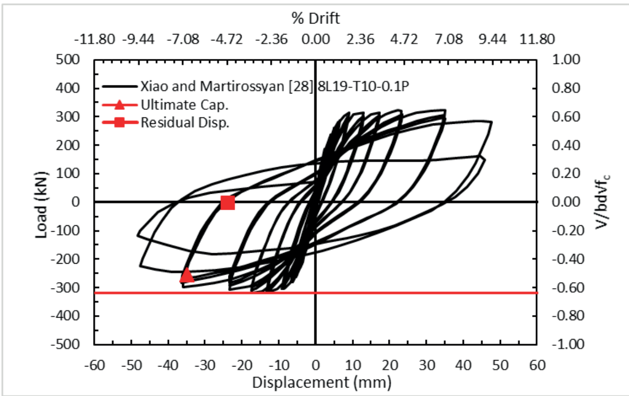

Fig. 27 Load-displacement curve of the Xiao and Martirossyan [28] 8L19-T10-0.1P

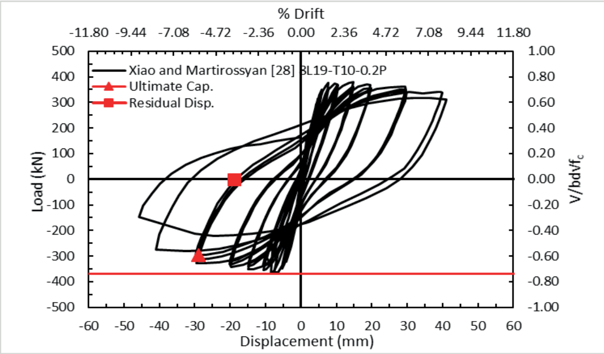

Fig. 28 Load-displacement curve of the Xiao and Martirossyan [28] 8L19-T10-0.2P

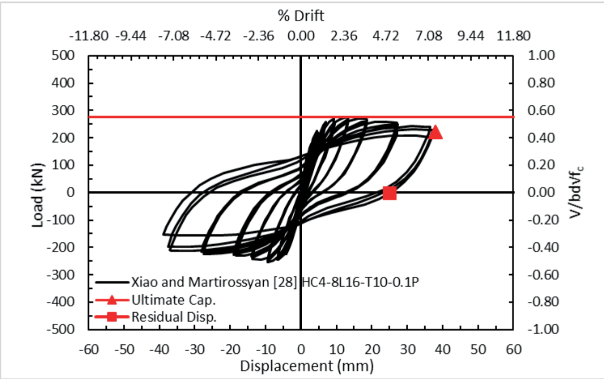

Fig. 29 Load-displacement curve of the Xiao and Martirossyan [28] HC4-8L16-T10-0.1P

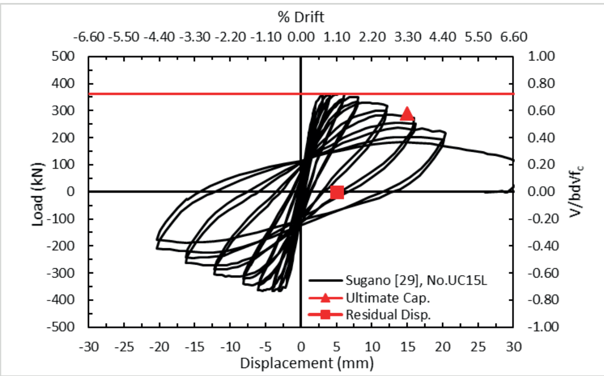

Fig. 30 Load-displacement curve of the Sugano [29] No. UC15L

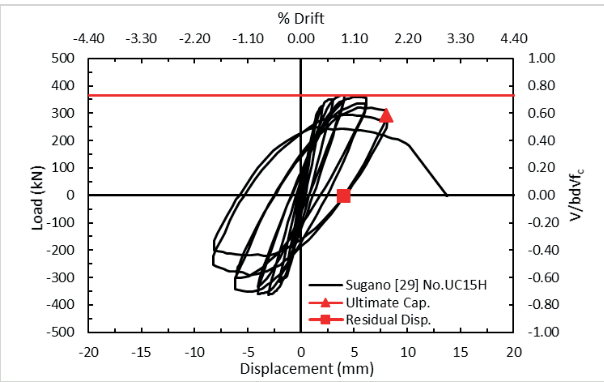

Fig. 31 Load-displacement curve of the Sugano [29] No. UC15H

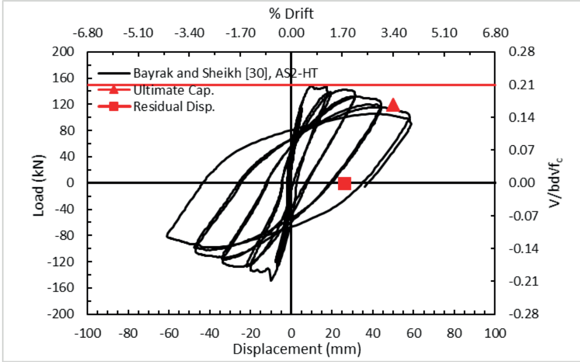

Fig. 32 Load-displacement curve of the Bayrak and Sheikh [30] AS2-HT

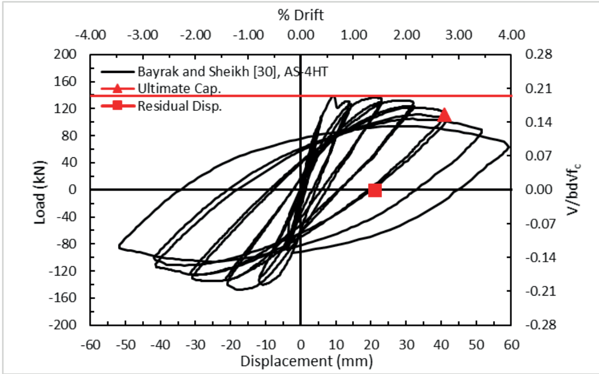

Fig. 33 Load-displacement curve of the Bayrak and Sheikh [30] AS-4HT

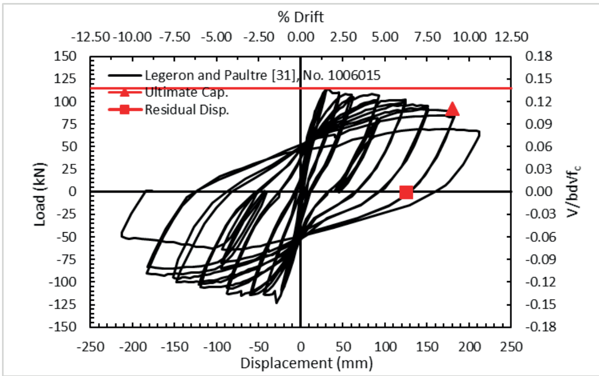

Fig. 34 Load-displacement curve of the Legeron and Paultre [31], No. 1006015

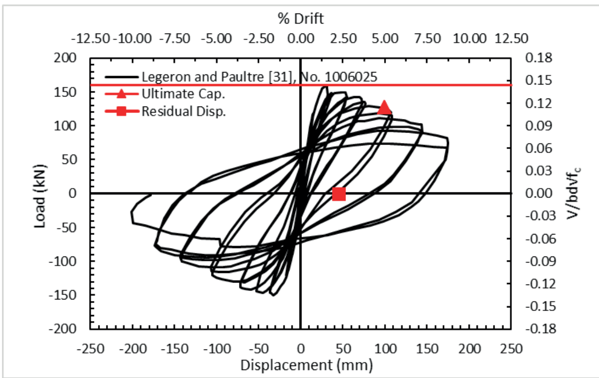

Fig. 35 Load-displacement curve of the Legeron and Paultre [31], No. 1006025

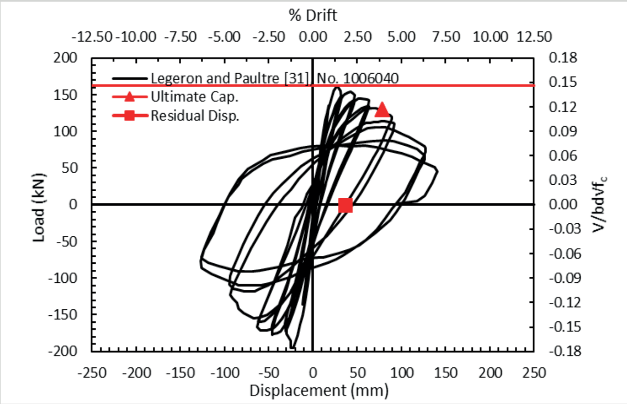

Fig. 36 Load-displacement curve of the Legeron and Paultre [31], No. 1006040

3 Estimation of the residual drift

Residual displacement take place over the yield displacement value due to the nonlinear behavior of the reinforced concrete column. When the figures are examined, permanent displacement values determined at the capacity point for each column have been marked. Residual displacement values of calculated for all columns are shown in the Table 3.

Where Δu is the ultimate displacement capacity, Δr is the residual displacement at ultimate capacity, θ_u is the ultimate drift ratio and θ_r is the residual drift ratio at ultimate capacity. When residual drift ratio were examined, it was seen that it was affected by various parameters. These interaction graphics are shown in Figs. 37–40.

When the Figures are examined, it is seen that the residual drift ratio of reinforced concrete columns is mostly related to the axial load level. In order to better understand this situation, the correlation matrix showing the relationship between the Statistica program and the parameters was determined. This correlation matrix is presented in the Table 4 [34].

The axial load level and the shear spanning to depth have positive correlation, while the transverse reinforcement ratio and the longitudinal reinforcement ratio have negative correlations. When the results of the columns are examined, residual displacement consist of the range of 40–80 % of the capacity displacement value. The graphic representing this situation is shown in Fig. 41.

Approximately 50 % residual displacement of the total displacement occurs in a column that has been damaged due to inelastic behavior. As it is known, reinforced concrete columns are definitely damaged during an earthquake. The most important indicator of this damage can be considered as residual displacement ratio. For this purpose, Statistica program has been used to estimate the residual drift ratio. According to statistical analysis the most accurate estimation of the residual drift ratio is given in Eq. (3).

Table 3 Residual drift ratio of the columns

Specimen Name	Δu (mm)	Δr (mm)	θ_u	θ_r
Ang [15], No. 3	45	25	0.028	0.016
Ang [15], No. 4	61	40	0.038	0.025
Azizinamini et al. [16], NC-2	64	43	0.047	0.031
Azizinamini et al. [16], NC-4	38	23	0.028	0.017
Mo and Wang [17], C1-1	85	56	0.061	0.040
Mo and Wang [17], C1-2	89	49	0.064	0.035
Mo and Wang [17], C1-3	79	38	0.056	0.027
Nosho et al. [18], No. 1	35	17	0.016	0.008
Saatcioglu and Grira [19], BG-1	45	22	0.027	0.013
Saatcioglu and Grira [19], BG-2	65	35	0.040	0.021
Saatcioglu and Grira [19], BG-3	85	51	0.052	0.031
Saatcioglu and Grira [19], BG-4	50	25	0.030	0.015
Saatcioglu and Ozcebe [20], U3	60	38	0.060	0.038
Saatcioglu and Ozcebe [20], U4	90	61	0.090	0.061
Soesianawati [21], No. 1	100	72	0.063	0.045
Soesianawati [21], No. 2	50	29	0.031	0.018
Soesianawati [21], No. 3	45	26	0.028	0.016
Soesianawati [21], No. 4	40	23	0.025	0.014
Tanaka [22], No. 2	70	47	0.044	0.029
Watson [23], No. 5	32	14	0.020	0.009
Watson [23], No. 6	25	11	0.016	0.007
Zahn [24], No. 7	81	44	0.051	0.028
Kanda et al. [25]85STC-1	34	23	0.045	0.030
Galeota et al. [26] CB3	60	38	0.052	0.033
Galeota et al. [26] CB2	42	20	0.036	0.017
Wehbe et al. [27] A1	38	25	0.017	0.011
Xiao and Martirossyan [28], 8L19-T10-0.1P	35	24	0.069	0.047
Xiao and Martirossyan [28], 8L19-T10-0.2P	29	20	0.057	0.039
Xiao and Martirossyan [28], 8L16-T10-0.1P	38	28	0.075	0.055
Sugano [29] UC15L	15	5	0.033	0.011
Sugano [29] UC15H	8	4	0.017	0.008
Bayrak and Sheikh [30] AS-2HT	50	26	0.033	0.017
Bayrak and Sheikh [30] AS-4HT	41	21	0.027	0.014
Legeron and Paultre [31], No. 1006015	180	125	0.090	0.062
Legeron and Paultre [31], No. 1006040	99	48	0.049	0.024
Legeron and Paultre [31], No. 1006025	75	36	0.037	0.018

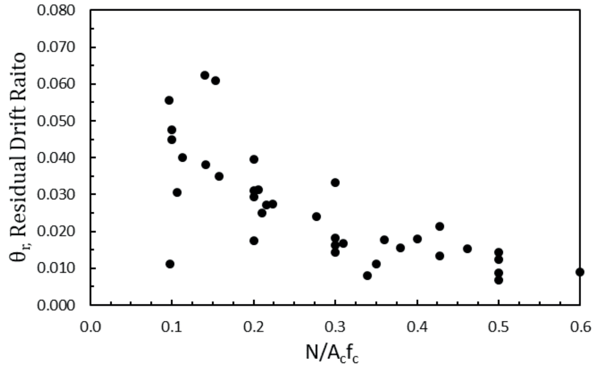

Fig. 37 Interaction between residual drift ratio and axial load ratio

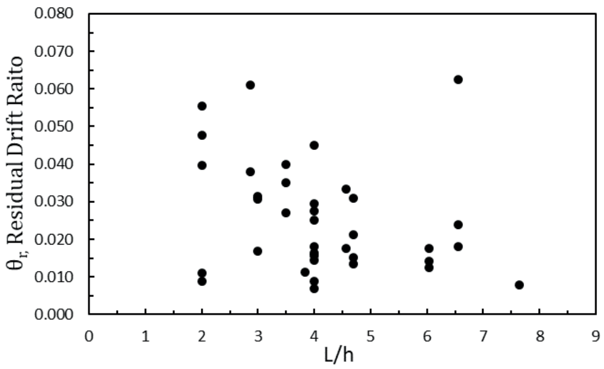

Fig. 38 Interaction between residual drift ratio and spanning to depth ratio

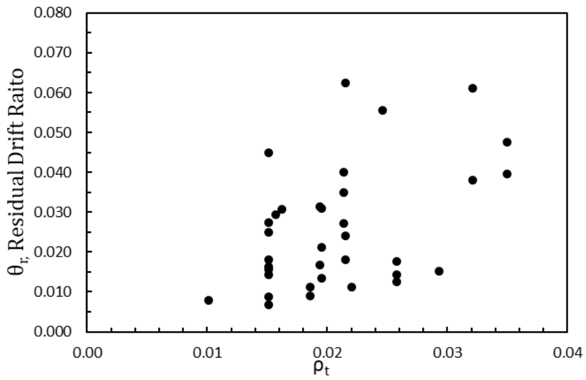

Fig. 39 Interaction between residual drift ratio and longitudinal reinforcement ratio

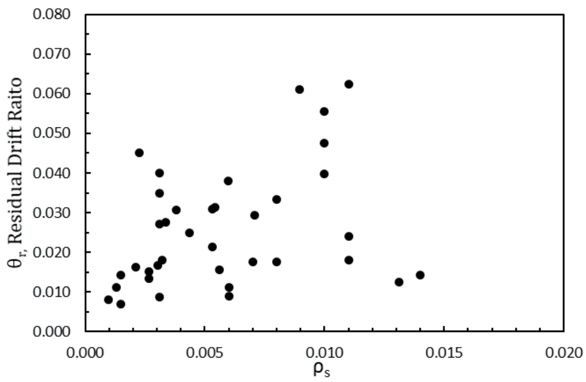

Fig. 40 Interaction between residual drift ratio and transverse reinforcement ratio

$$\theta_{r,est.} = -1.67\left(\frac{N}{A_c f_{ck}}\right)^{-1.93}\left(\frac{L}{h}\right)^{-0.005}\left(\rho_t\right)^{1.88} + \rho_t\left(\rho_h^{0.209}\right)\left(\frac{N}{A_c f_{ck}}\right)^{-1.36} \quad (3)$$

The estimates of the proposed equation are compared with the experimental results in Fig. 42. The proposed equation accurately predicts residual drift ratio with a 89 % correlation.

When the Fig. 42 is examined, it is seen that the proposed equation estimates the residual drift ratio very closely. This equation gives proper results in columns complying with seismic codes. In addition, this equation

Table 4 Correlation matrix of parameters of the columns

Parameter	L/h	$N/A_c f_c$	ρ_t	ρ_s	θ_r
L/h	1.00	0.47	-0.34	0.00	-0.54
$N/A_c f_c$	0.47	1.00	-0.14	0.01	-0.83
ρ_t	-0.34	-0.14	1.00	0.53	0.49
ρ_s	0.00	0.01	0.53	1.00	0.30
θ_r	-0.54	-0.83	0.49	0.30	1.00

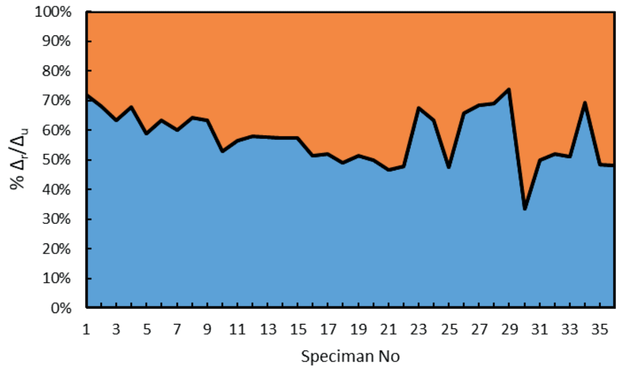

Fig. 41 Interaction between residual drift ratio and ultimate drift ratio

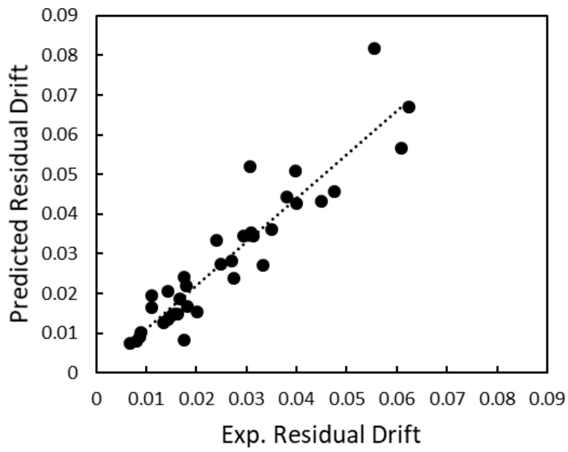

Fig. 42 Comparison with experimental residual drift and predicted residual drift

does not give suitable results in very high strength concrete (e.g.: C60 and over C60) and very high axial load levels (e.g.: between 0.6N/$A_c f_c$ and 0.9 N/$A_c f_c$).

4 Estimation ultimate displacement capacity

Within the scope of this study, the residual drift ratio of reinforced concrete columns under the ultimate displacement was estimated. According to Fig. 41, it is seen that reinforced concrete columns have an average of 60 % residual displacement under ultimate displacement capacity. In addition, axial load level and span to depth ratio seem to be the most important parameters that changes the percentage of residual displacement. The curve showing the relationship between these parameters are presented in Figs. 43–44.

In order to simplify the relation, it has expressed depending on the axial load level that affects the most. The effect of other parameters is applied in Eq. (3). Since Eq. (3) is used in Eq. (4), it affects the result in other parameters. The relationship between these two parameters is given in Eq. (4).

$$(\%)\Delta_r/\Delta_u = 41.49\left(\frac{N}{A_c f_c}\right)^{-0.23} \quad (4)$$

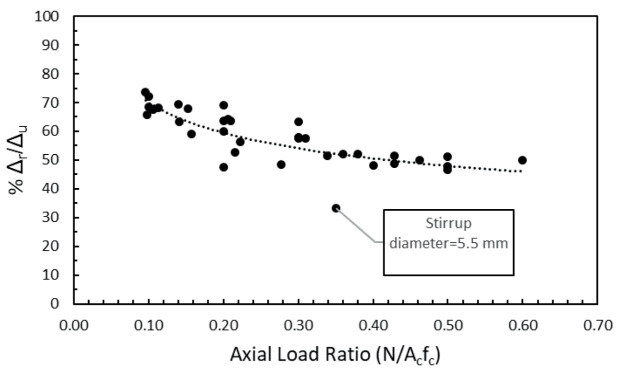

Fig. 43 The relationship between axial load ratio and residual displacement to ultimate displacement

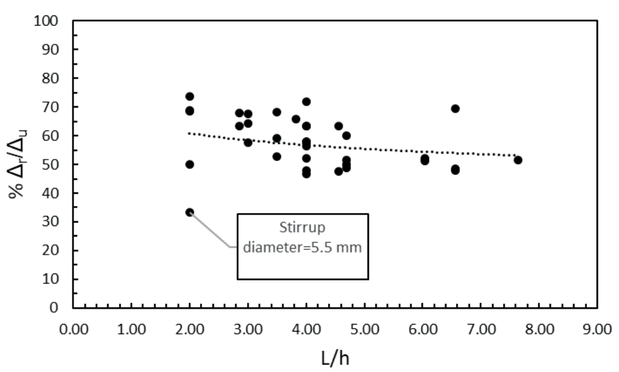

Fig. 44 The relationship between span to depth ratio (L/h) and residual displacement to ultimate displacement

After necessary simplification in the Eq. (4), the ultimate displacement capacity can be expressed with the Eq. (5) for the collapse prevented performance level.

$$\Delta_r = \theta_r L$$

$$\Delta_u = \frac{\Delta_r}{0.4149\left(\frac{N}{A_c f_c}\right)^{-0.23}} \quad (5)$$

Comparison of the ultimate displacement capacity and experimental ultimate displacement capacity calculated according to Eq. (5) is shown in Fig. 45.

According to the study for a limited number of columns, the proposal equation has made predicts close to the real value.

5 Analytical results

In order to verify this study, reinforced concrete columns has modeled in the SeismoStruct program [35]. Properties of columns created in SeismoStruct program are presented in the Table 5.

The schematic cross-section and loading arrangement of the columns are shown in Fig. 46.

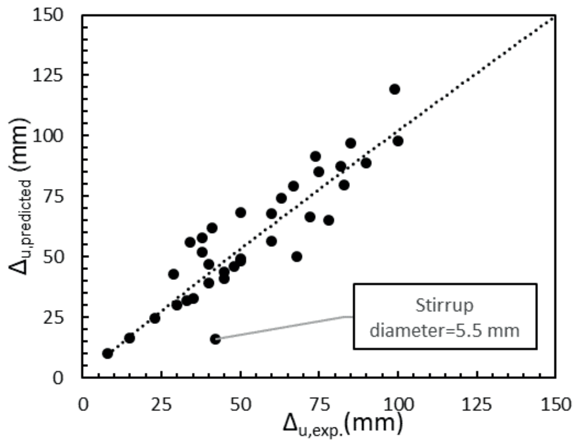

Fig. 45 Comparison with experimental displacement capacity and predicted ultimate displacement capacity

Table 5 Properties of the analytical columns

Specimen Name	$N/A_c f_c$	L/h	ρ_t	ϕ_s/s
S-10-3-01-50	0.1	3	0.01	ϕ8/50
S-40-3-01-50	0.4	3	0.01	ϕ8/50
S-10-3-01-100	0.1	3	0.01	ϕ8/100
S-40-3-01-100	0.4	3	0.01	ϕ8/100
S-10-5-01-50	0.1	5	0.01	ϕ8/50
S-40-5-01-50	0.4	5	0.01	ϕ8/50

Where $N/A_c f_c$ the axial load level, L/h is the span to depth ratio, ρ_t is a longitudinal reinforcement ratio, ϕ_s is transverse reinforcement diameter and s is hoop spacing.

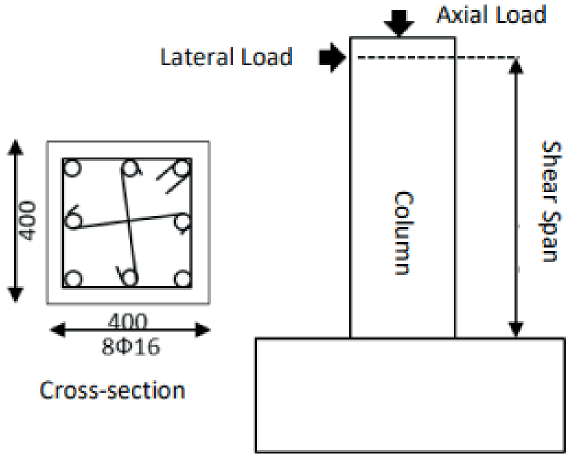

Fig. 46 Schematic cross section and loading assembly

Same test procedure has been applied to all column. Same lateral displacement profile has been used in all columns. For each column, one full cycle of loading has been performed in the pre-yield stage. The pre-yield stage consisted of $0.5\Delta_y$ and $0.25\Delta_y$. Then, the columns have been subjected to cyclic loading with increasing amplitudes after every three cycles up to failure. Comparison of analytical results is shown in the Figs. 47–52.

When the results are examined, it is seen that the equation proposed in this study is compatible with the analytical results. It is determined in the graphs that the correlation obtained from the experimental studies predict ultimate displacement and residual displacement well in analytical models.

6 Conclusions

In this study, the analytical calculation of the residual drift ratio of the reinforced concrete columns under the ultimate displacement capacity was investigated. The determined results in the study are listed as follows:

- The residual drift ratio can be shown as the most important indicator of the damage state under the earthquake load or operating loads of reinforced concrete columns. According to experimental results, approximately $0.6\Delta_u$ value residual displacement occurs under the displacement capacity of reinforced concrete columns.
- The residual drift ratio required for the collapse prevented performance level of the columns whose axial load level, shear span and reinforcements ratios are known can be calculated. In this way, the performance level of the existing columns depending on the residual drift ratio can be determined quickly and without cost.
- Using residual drift ratio the displacement capacity of reinforced concrete columns can be estimated. Although there are wide range of values in the study for a limited number of columns, ultimate displacement capacity estimation close to experimental ultimate displacement capacity has been made.

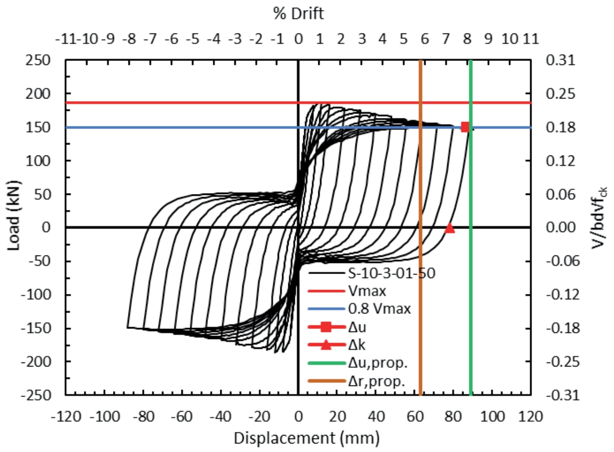

Fig. 47 Load-displacement curve of S10-3-01-50 column

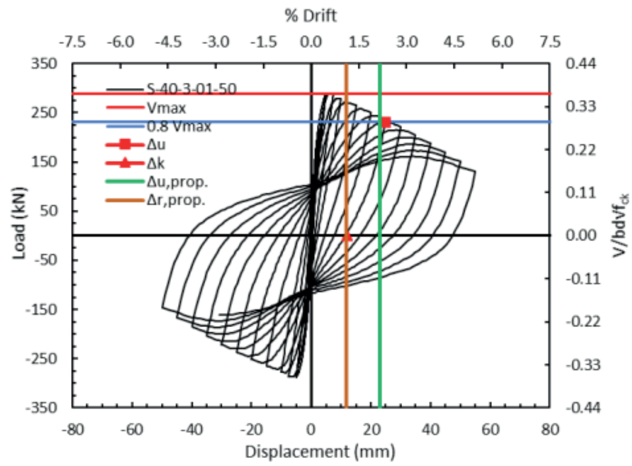

Fig. 48 Load-displacement curve of S40-3-01-50 column

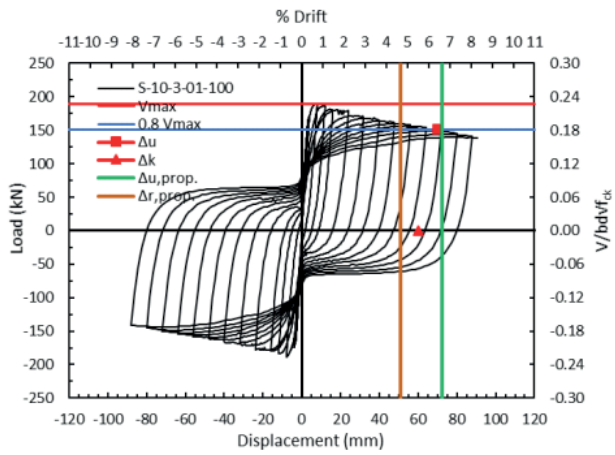

Fig. 49 Load-displacement curve of S10-3-01-100 column

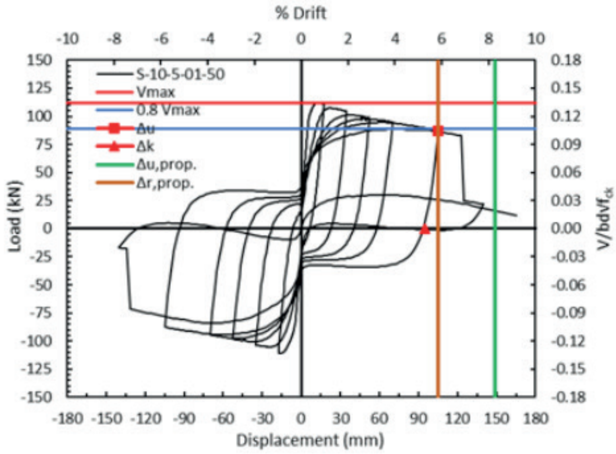

Fig. 51 Load-displacement curve of S10-5-01-50 column

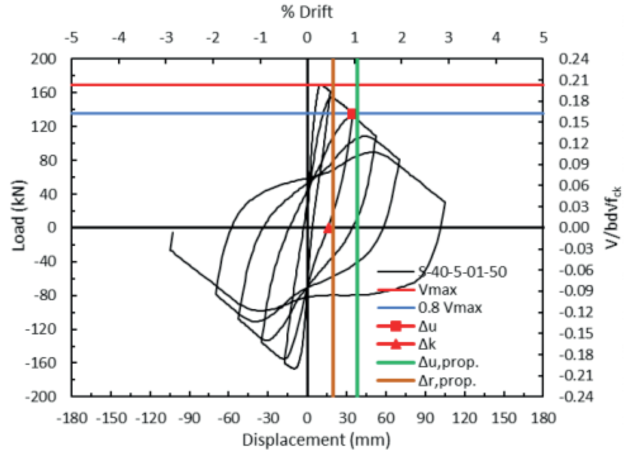

Fig. 52 Load-displacement curve of S40-5-01-50 column

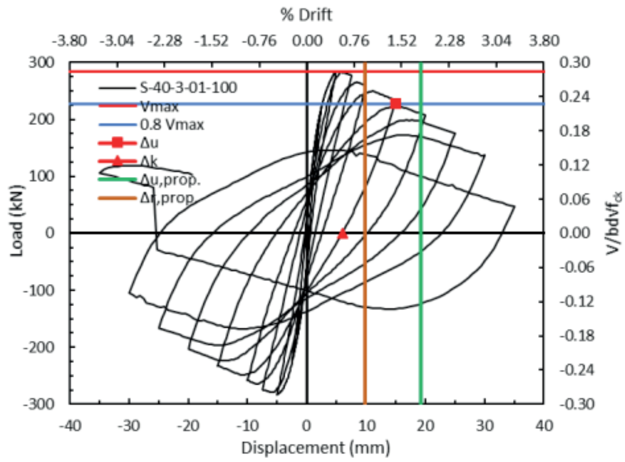

Fig. 50 Load-displacement curve of S40-3-01-100 column

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