ESTIMATION OF DISPLACEMENT CAPACITY OF RECTANGULAR RC SHEAR WALLS USING EXPERIMENTAL AND ANALYTICAL DATABASE

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ABSTRACT

This study is focused on the evaluation of the displacement capacity of RC shear walls using both experimental and analytical results. The first observation of the study is that few experimental results for slender RC shear walls having thicknesses larger than 150 mm are available in the literature. From the experimental database, it was observed that the mean and the median ultimate drift of squat RC shear walls is about half of that obtained for slender RC shear walls. Considering the limitation of the experimental database, the simple empirical model for the ultimate drift ratio of slender RC shear walls proposed in this study is also based on available analytical results from the literature. The model provides a good fit with the observed results and besides, due to the fact that it does not require sectional analysis of the element, it allows a rapid assessment of the displacement capacity of slender RC shear walls as a function of the seismic design code parameters. The proposed formula can be inserted in future revisions of the seismic assessment guidelines for RC structures for rapid seismic evaluation purposes.

KEYWORDS

Regression analysis; Correlation coefficient; Experimental database; Numerical modelling; RC shear wall; Displacement capacity

INTRODUCTION

The assessment of the strength and displacement capacity of structural elements is a key step in the seismic performance assessment of structures. Among the structural elements used for earthquake resistant structures, the shear walls are commonly used in regions of medium and high seismicity for medium and high-rise structures. The ultimate displacement capacity of structural elements is a key part in the assessment of the seismic performance which is, at its turn, a key part of the seismic risk assessment.

Eurocode 8-3 proposes two different models for the evaluation of the ultimate rotation capacity of beams, columns, and shear walls. However, the two relations proposed in Eurocode 8-3 require data obtained from sectional analysis which requires a significant amount of computation time [1]. The strength, deformation, and failure modes of RC shear walls under cyclic loading are also analysed in the paper of Grammatikou et al. in which updated models similar to the ones in Eurocode 8-3 are also proposed [2]. The cyclic shear and displacement capacity of squat or slender RC shear walls are analysed in a number of papers in the literature [3-14]. In the paper of Wallace, the observed seismic behaviour of shear walls structures during the Chile and New Zealand earthquakes is discussed. Based on the seismic performance of code-compliant thin RC shear walls, several changes were recommended by [15]. The seismic behaviour of a RC shear-wall building that

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collapsed during the 2003 Bingöl earthquake was investigated by nonlinear static analysis and nonlinear dynamic analysis in the study of Çavdar et al. [16]. The study of Ugalde and Lopez-Garcia notes that only 2% of the residential building inventory consisting mainly of RC shear walls structures suffered significant damage as a result of the Maule 2010 earthquake [17]. The study of Pavel and Vacareanu discusses the seismic performance of RC shear walls structures during the Vrancea earthquake of March 1977 and analyses the seismic performance of a building similar with one that collapsed in 1977 [18]. Segura and Wallace [19] and Abdullah and Wallace [20] have also proposed relations for the computation of the drift capacity of reinforced concrete structural walls based on experimental data. Shegay et al. have developed a relation for the computation of the curvature ductility of structural walls [21]. Cando et al. have analysed the effect of the stiffness on the seismic performance of residential shear wall buildings designed according to current Chilean regulation [22]. The study of Arteta et al. [23] has shown that ductile behaviour of thin boundary elements of special structural walls under pure compression is not achievable by only complying with the detailing provisions given in ACI 318-08 [24]. The study of Marzok et al. analysed the results in terms of displacements and bending moment capacities for RC shear walls given by various commonly-used codes [25]. The displacement capacity of unreinforced masonry or confined masonry shear walls has been analysed by [26-29].

A critical aspect related to the cyclic seismic behaviour of rectangular RC shear walls is the occurrence of significant out-of-plane displacement and which can induce a significant reduction of the deformation capacity. This aspect is discussed in the studies of [30-33]. These studies show that the onset of buckling instability occurs earlier in the case of boundary elements of higher longitudinal reinforcement ratios. Moreover, it was observed that the maximum tensile strain corresponding to initiation of out-of-plane deformation and out-of-plane instability was lower in squat wall models when compared to the slender ones.

Thus, in this paper, we analyse the ultimate drift ratio of slender RC shear walls using an experimental database, and besides, using analytical results from the study of Pavel [34]. As previously mentioned, the use of analytical results is due to the scarcity of experimental results of RC shear walls having thicknesses larger than 150 mm. The limited numbers of such tests are also confirmed by the test data collected by Abdullah [35]. In addition, a simple empirical model for evaluating the ultimate drift ratio of slender RC shear walls is also proposed in this study using both experimental and analytical results. The model is recommended to be used for rapid seismic assessments.

EXPERIMENTAL DATABASE

The first database used in this study is the experimental one developed by Zhou et al. which consists of 226 tests on rectangular RC shear walls [36]. The database contains test results for both squat (ratio between the wall height and its length $H_w/l_w < 2$) and slender ($H_w/l_w \geq 2$) RC shear walls. It is true that the database compiled by Abdullah contains a much larger number of experimental results, however, the database is not public and the authors did not have access to the test results [35].

The experimental results have the following characteristics:
- concrete strength (f_c): 12.3 – 63.4 MPa;
- section length (l_w): 0.15 – 5.50 m;
- height of the wall (H_w): 0.42 – 3.96 m;
- thickness of the wall (t_w): 20 – 160 mm;
- axial load ratio (ALR): 0 – 0.25;
- H_w/l_w: 0.35 – 5.86;
- l_w/t_w: 5.31 – 57;
- web horizontal reinforcement ratio ρ_{wh}: 0 – 0.037;
- web vertical reinforcement ratio ρ_{wv}: 0 – 0.037;
- boundary element horizontal reinforcement ratio: ρ_{bh}: 0 – 0.021;

- boundary element vertical reinforcement ratio: ρ_{bv}: 0.005 – 0.099.

The ultimate drift ratios obtained experimentally for squat and slender RC shear walls are compared in Figure 1. The statistical indicators of the ultimate drift ratios for the two types of RC shear walls are reported in Table 1. It can be easily observed that the mean and median ultimate drift of squat RC shear walls is about half of that obtained for slender elements. The limited number of experimental results for RC slender shear walls can also be observed from Figure 1.
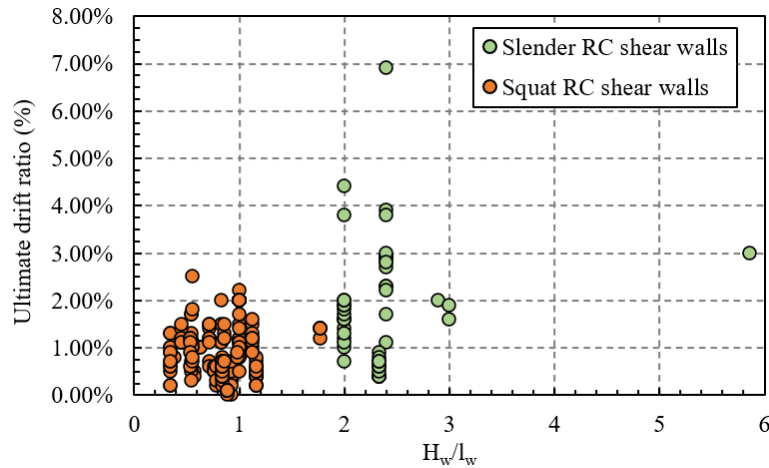

Fig. 1 – Comparison of the ultimate drift ratios obtained experimentally for slender and squat RC shear walls

Tab. 1: Statistical indicators of the experimental ultimate drift ratio for squat and slender RC shear walls

Statistical indicator of the experimental ultimate drift ratio	Squat RC shear walls	Slender RC shear walls
Mean value	0.009	0.019
Median value	0.007	0.017
Standard deviation	0.005	0.013
Skewness	0.673	1.430
Kurtosis	-0.046	3.568
5th percentile	0.001	0.004

Subsequently, a correlation analysis between the experimental ultimate drift ratios for squat and slender RC shear walls and some of the characteristics of the database shown previously is performed. The results of the correlation analysis are shown in Table 2. The largest correlation coefficient is observed between the ultimate drift of slender RC shear walls and the thickness of the web. It can be observed from Figure 2 that, as the thickness of the web increases so does the ultimate drift. The limited number of experimental results for RC shear walls with thicknesses in excess of 100 mm is noteworthy.

Tab. 2: Correlation coefficient between the experimental ultimate drift ratio for squat and slender RC shear walls and the characteristics of the test characteristics

| Statistical indicator of the experimental ultimate drift ratio	Squat RC shear walls	Slender RC shear walls
concrete strength (f_c)	-0.21	0.28
section length (l_w);	0.43	0.62
height of the wall (H_w)	0.56	0.62
thickness of the wall (t_w)	0.60	0.71
axial load ratio (ALR)	0.31	-0.11
h_w/l_w	0.04	0.15
h_w/t_w	-0.19	-0.13
web horizontal reinforcement ratio (ρ_{wh})	0.09	0.30
web vertical reinforcement ratio (ρ_{wv})	0.10	-0.19
boundary element horizontal reinforcement ratio (ρ_{bh})	0.46	0.66
boundary element vertical reinforcement ratio (ρ_{bv})	-0.11	0.15
yield strength of the web horizontal reinforcement ($f_{y,wh}$)	0.56	0.14
yield strength of the web vertical reinforcement ($f_{y,wv}$)	0.53	0.19
yield strength of the boundary element horizontal reinforcement ($f_{y,bh}$)	0.39	0.40
yield strength of the boundary element vertical reinforcement ($f_{y,bv}$)	0.28	0.44
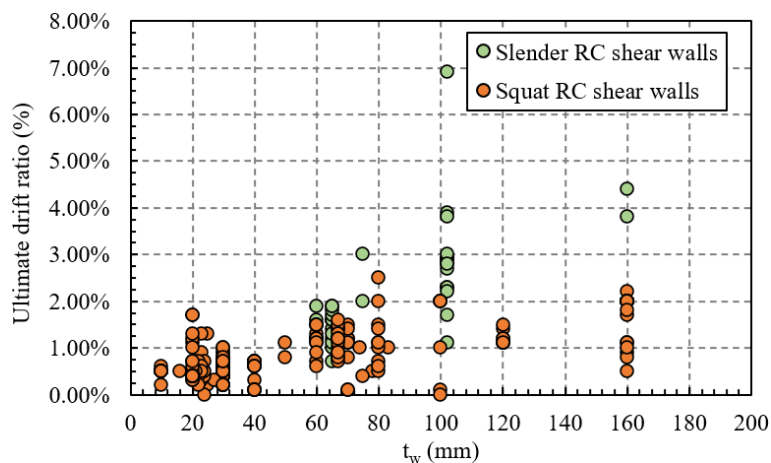
Fig. 2 – Variation of the ultimate drift ratio as a function of the thickness of the RC shear walls

Figure 3 shows a comparison between the empirical and the normal CDF (cumulative distribution function) for the experimental ultimate drift ratio of slender RC shear walls. One can notice that the normal CDF provides a good fit of the experimental results. The adequacy of the fit is confirmed by statistical testing (Kolmogorov-Smirnov, Anderson-Darling and Chi-squared) performed on the sample. The null hypothesis is not rejected for any significance level α ranging between 0.01 and 0.20. The lognormality assumption is accepted for all significance when using the Kolmogorov-Smirnov and Anderson-Darling statistical tests and is rejected for three significance levels (out of five) when employing the Chi-squared statistical test.
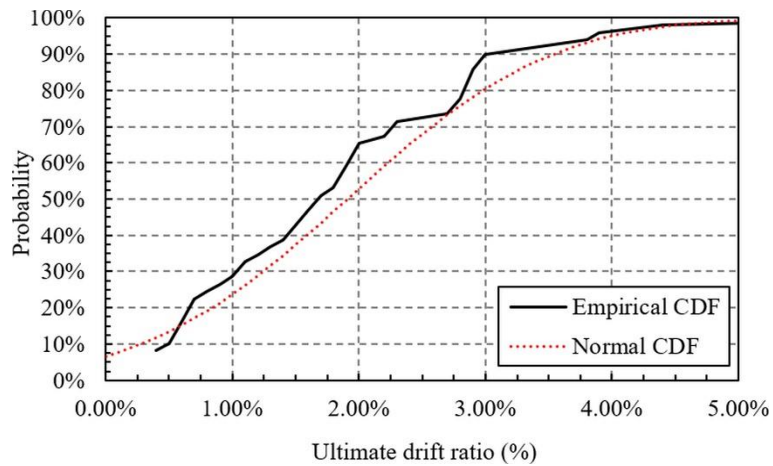

Fig. 3 – Comparison of the empirical and normal CDF for the experimental ultimate drift ratio of slender RC shear walls
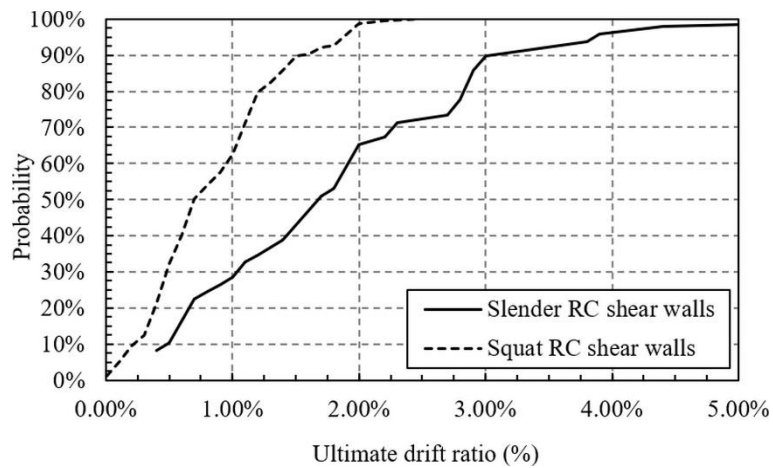

Fig. 4 – Comparison between the CDFs for the experimental ultimate drift ratio of slender and squat RC shear walls
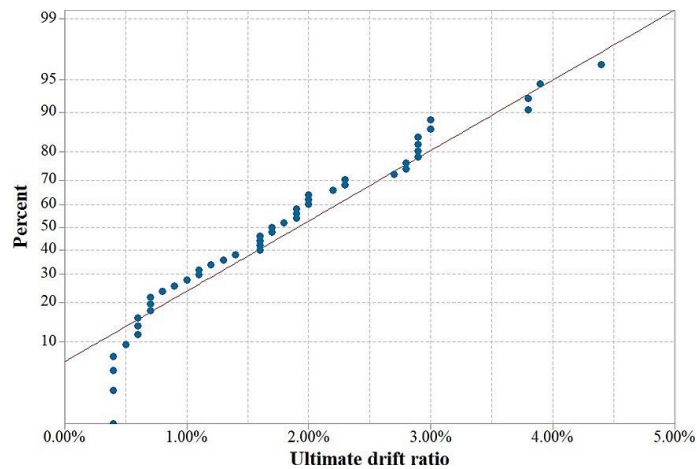

Fig. 5 – Normality test check for the experimental ultimate drift ratio of slender RC shear walls

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The CDFs in terms of the experimental ultimate drift ratio for the squat and slender RC shear walls are compared in Figure 4. One can notice the much larger ultimate drift ratios of slender RC shear walls. The normality assumption is further checked in Figure 5 using a normal probability plot. The distribution can be regarded as normal starting from an ultimate drift ratio of about 0.7%.

ANALYTICAL DATABASE

Due to the scarcity of available date for slender RC shear walls having thicknesses larger than 150 mm, as observed from the experimental database compiled by Abdullah, we decided to employ in this study a second database [35]. The second database used in this study is the analytical one developed by Pavel [34] which comprises 81 cyclic analyses of rectangular RC shear walls performed using the code VecTor4 [37]. The shear walls were designed according to the current seismic design regulations from Romania. All the shear walls analysed in this study are slender with the ratio $H_w/l_w \geq 2$. The analytical database of Pavel [34] has the following characteristics:

- concrete strength (f_c): 30 MPa, 40 MPa, 50 MPa;
- section length (l_w): 3.60 m, 4.50 m, 5.40 m;
- height of the wall (h_w): 12.5 m, 13.8 m, 18.8 m;
- thickness of the wall (t_w): 0.25 m, 0.30 m, 0.35 m;
- axial load ratio (ALR): 0.02 – 0.08;
- H_w/l_w: 3.07, 3.47, 3.48;
- l_w/t_w: 14.4, 15.0, 15.42;
- web horizontal reinforcement ratio ρ_{wh}: 0.006 – 0.010;
- web vertical reinforcement ratio ρ_{wv}: 0.004 – 0.007
- boundary element horizontal reinforcement ratio: ρ_{bh}: 0 – 0.0201;
- boundary element vertical reinforcement ratio: ρ_{bv}: 0.007 – 0.008.

The ultimate drift ratios obtained analytically in the study of Pavel [34] are illustrated in Figure 6. It is noticeable from Figure 5 that the analytical results have a much smaller spread as compared to the experimental ones. The statistical indicators of the ultimate drift ratios for the analytical RC slender shear walls are reported in Table 3. It can also be observed that only the mean and median analytical ultimate drifts are close to the statistical indicators obtained from experimental results.
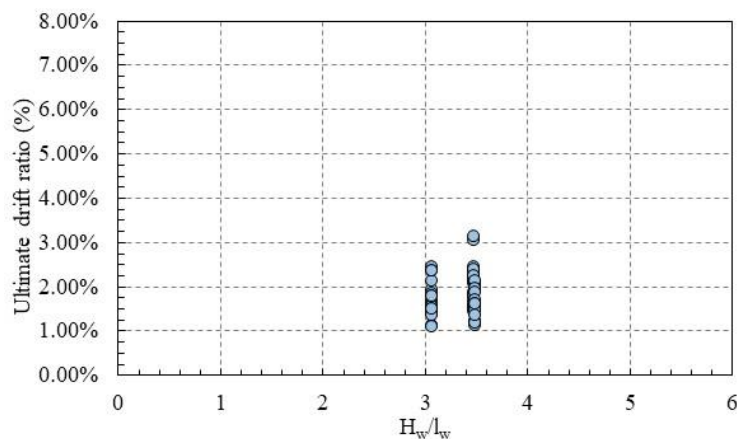

Fig. 6 – Ultimate drift ratios obtained analytically for slender RC shear walls [34]

Tab. 3: Statistical indicators of the analytical ultimate drift ratio for slender RC shear walls [34]

Statistical indicator of the experimental ultimate drift ratio	Slender RC shear walls
Mean value	0.018
Median value	0.017
Standard deviation	0.004
Skewness	0.754
Kurtosis	0.741
5th percentile	0.012

The correlation analysis between the analytical ultimate drift ratios for slender RC shear walls and some of the characteristics of the database shown previously is performed. The results of the correlation analysis are shown in Table 4. The yield strength for both horizontal and vertical reinforcement in the web and in the boundary elements for all the shear walls analysed in the study of Pavel [34] is 550 MPa. Thus, these parameters are disregarded from the correlation analysis shown in table 4. It can be observed that the correlation coefficient between the analytic ultimate drift ratio and the first four parameters in Table 4 are negative, which is exactly the opposite to what can be observed from Table 2.

Tab. 4: Correlation coefficient between the analytic ultimate drift ratio for squat and slender RC shear walls and the characteristics of the analytical models [34]

Statistical indicator of the experimental ultimate drift ratio	Slender RC shear walls
concrete strength (f_c)	-0.09
section length (l_w);	-0.33
height of the wall (H_w)	-0.22
thickness of the wall (t_w)	-0.33
axial load ratio (ALR)	-0.45
h_w/l_w	0.27
h_w/t_w	-0.36
web horizontal reinforcement ratio	0.25
web vertical reinforcement ratio	-0.12
boundary element horizontal reinforcement ratio	-0.31
boundary element vertical reinforcement ratio	0.04

Figure 7 shows a comparison between the empirical and the normal CDF for the empirical ultimate drift ratio of slender RC shear walls. In this case, too, it can be observed that the normal CDF provides a good fit of the experimental results. The normality assumption of the analytic ultimate drift ratio is further checked in Figure 8 using a normal probability plot. The distribution can be regarded as normal starting from an ultimate drift ratio of about 1.2%. The adequacy of the fit is evaluated by statistical testing (Kolmogorov-Smirnov, Anderson-Darling, and Chi-squared) performed on the sample. The Kolmogorov-Smirnov and Anderson-Darling statistical tests confirm the hypotheses for all significance levels, while in the case of the Chi-squared statistical test, the hypothesis is rejected. As in the case of the normality assumption test, the lognormality assumption is accepted for all significance when using the Kolmogorov-Smirnov and Anderson-Darling statistical tests and is rejected for all significance levels when employing the Chi-squared statistical test.
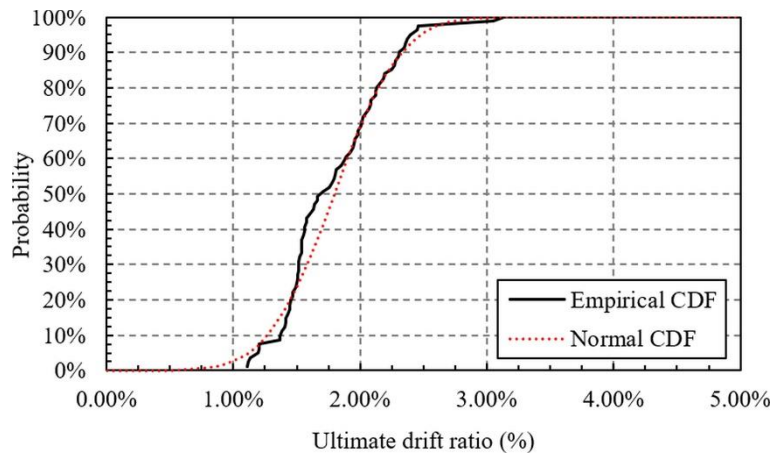

Fig. 7 – Comparison of the empirical and normal CDF for the analytical ultimate drift ratio of slender RC shear walls
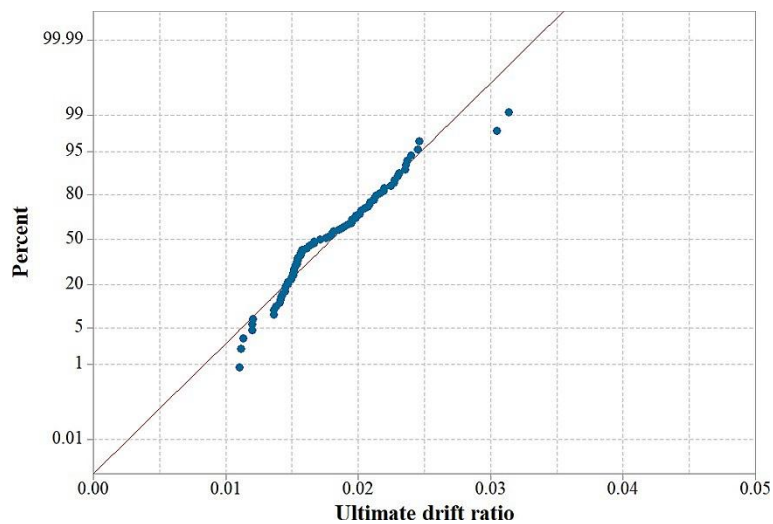

Fig. 8 – Normality test check for the analytic ultimate drift ratio

AN EMPIRICAL MODEL FOR THE ULTIMATE DRIFT RATIO

Subsequently, an empirical model for the displacement capacity of RC slender shear walls is obtained by combining the experimental and analytical results. Unlike models given in Eurocode 8-3 [1] or by Segura and Wallace [19] or Abdullah and Wallace [20], the model proposed in this study uses a much smaller number of input parameters and is readily available to any designer. In addition, the parameters of the proposed empirical model do not require any sectional analysis of the reinforced concrete structural wall, as necessary in the above-mentioned empirical models. Moreover, this model, unlike other models available in the literature also provides uncertainty in evaluating the median drift capacity. The empirical model obtained from the least-squares regression for the ultimate drift ratio (Y) has the following functional form:

$$\log Y = -1.537 - 1.719 \cdot ALR - 0.026 \frac{H_w}{l_w} - 0.023 \frac{l_w}{t_w} + 5.08 \cdot \rho_{wh} + 35.14 \cdot \rho_{bh} \qquad (1)$$

The standard error of the estimate obtained from regression analysis is 0.136. The comparison between the observed and predicted values is illustrated in Figure 9. The mean ratio between the observed and the predicted values is 1.05, while the median value is 0.98, the standard

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deviation is 0.38 and the correlation coefficient is 0.63. The empirical model proposed in this study employs directly the ALR as a parameter, while the model proposed by Abdullah and Wallace [20] uses the ALR indirectly through the neutral axis depth parameter. Netrattana et al. [11] state that the ALR is the most influential parameter for the displacement capacity of RC shear walls.
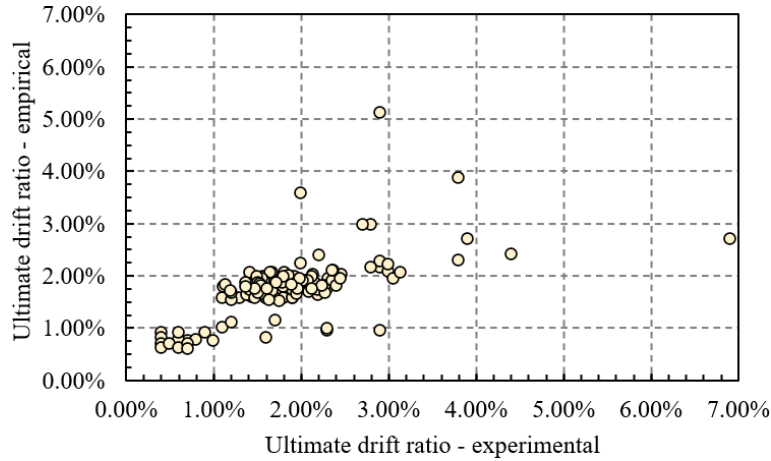

Fig. 9 – Comparison between experimental and empirical ultimate drift ratios of slender RC shear walls

The histogram of residuals (the difference between the observed and the predicted values) is illustrated in Figure 10. In addition, the normal distribution computed for the mean and standard deviation of the residuals is superimposed on the histogram shown in Figure 9. It is visible the fact that the distribution of the residuals follows a normal distribution.
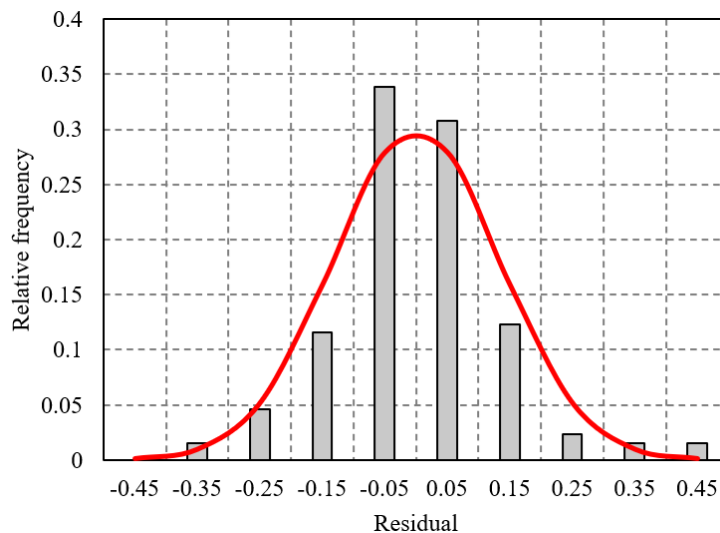

Fig. 10 – Histogram of residuals for the proposed empirical model and fitted normal distribution (red line)

SENSITIVITY ANALYSIS

Finally, in order to validate the empirical model obtained in this study, a sensitivity analysis is performed by varying the parameters of the proposed empirical model (ALR, H_w/l_w, l_w/t_w, ρ_{bh} and ρ_{wh}). The results of the sensitivity analysis are illustrated in Figure 11.

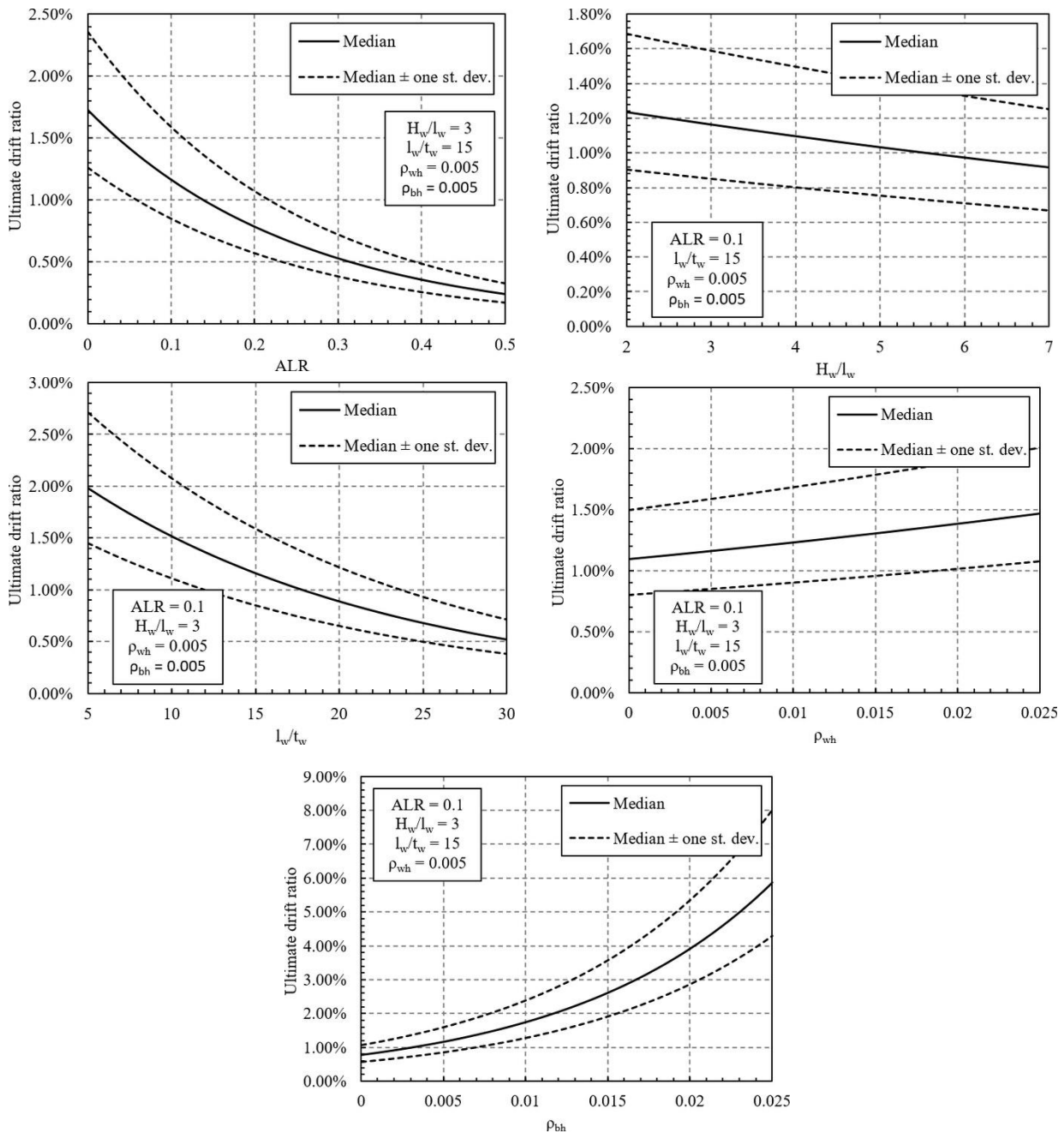

Fig. 11 – Sensitivity analysis for the proposed empirical model

It can be observed that among the parameters of the empirical model, the horizontal reinforcement in the boundary elements is the most important. It can also be observed that the ultimate drift ratios have a similar order of magnitude to the limits proposed by Ghobarah [38]. The current Romanian seismic design code P100-1/2013 [39] which follows the format of the Eurocode 8 [1] proposes a drift limit of 0.025 associated with the Ultimate Limit State (ULS) for all types of structures and limits in the range 0.005 – 0.01 for the Serviceability Limit State (SLS). Based on the results obtained using the proposed empirical model, it might appear as necessary that the drift limits for both SLS and ULS in the case of slender RC shear walls should be adjusted.

The first application of the proposed empirical model is performed for a case-study RC shear wall shown in Figure 12. The thickness of the web is in all cases 20 cm, while its height is 30.25 m. The case-study RC shear wall was designed according to four generations of seismic design

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regulations in Romania and its main characteristics, as well as the median ultimate drift ratios, are summarized in Table 5.
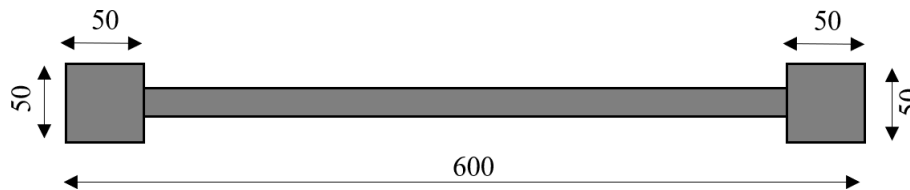

Fig. 12 – Case-study RC shear wall

Tab. 5: Characteristics of the first case-study RC shear wall shown in Figure 12

Seismic code level	ALR	H_w/l_w	l_w/t_w	ρ_{wh}	ρ_{bh}	Median ultimate drift
1	0.156	5.04	24	0.0015	0.0010	0.0035
2	0.117	5.04	24	0.0025	0.0025	0.0047
3	0.117	5.04	24	0.0030	0.0025	0.0047
4	0.078	5.04	24	0.0050	0.0050	0.0069

The probability that the median ultimate drift of the RC shear wall is in excess of 0.005 ranges from 0.54% for the first specimen to 99.2% for the last one which is designed according to the current seismic design regulations in Romania. Thus, based on this analysis, we can expect at least a double displacement capacity of modern RC shear walls in Romania as opposed to the ones designed during the '60s and '70s. The ultimate drifts were also evaluated using SeismoStruct [40] code and according to the relation proposed by Abdullah and Wallace [20] are reported in Table 6. The results in Table 6 show that the results obtained using the relation of Abdullah and Wallace [20] and using SeismoStruct [40] code are superior to the ones computed with the relation from this study. SeismoStruct [40] code provides the largest drift capacities, with the exception of the last RC shear wall. The ultimate drifts computed in SeismoStruct were obtained considering a tension strain limit of 0.05 as recommended in the study of Segura and Wallace [19]. It can be observed that the proposed empirical model provides values which are lower than the ones provided by the relation of Abdullah and Wallace [20] or by using SeismoStruct [40], which is an advantage considering the fact that the model is to be used for rapid seismic assessments.

Tab. 6: Comparison of drift capacities for the analysed RC shear walls

Seismic code level	Median ultimate drift – (this study)	Median ultimate drift – Abdullah and Wallace [20]	Median ultimate drift – SeismoStruct [40]
1	0.0035	-	0.0049
2	0.0047	0.0061	0.0073
3	0.0047	0.0070	0.0076
4	0.0069	0.0129	0.0093

The second application is related to the probability of exceedance of the ultimate drift for a case-study RC shear wall structure consisting of four slender RC shear walls with the characteristics given in Table 7 [41]. The incremental dynamic analysis curve (IDA) is illustrated in Figure 13. The exceedance probability is computed considering a lognormally distributed ALR having the mean value = 0.13 and a coefficient of variation of 0.31. The results obtained using FORM (first-order reliability method) by Melchers [42] in terms of probabilities of exceedance of the ultimate drift capacity as a function of the spectral acceleration level ($SA(T_1)$) are summarized in Figure 14. It can be observed that the median fragility corresponds to $SA(T_1) = 1.15$ g, a value about 50% larger than the elastic design spectral acceleration (equal to 0.75 g) used for this structure. Thus, it can be

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observed that the slender RC shear walls designed according to modern seismic regulations offer an adequate level of protection.

Tab. 7: Characteristics of the second case-study RC shear wall

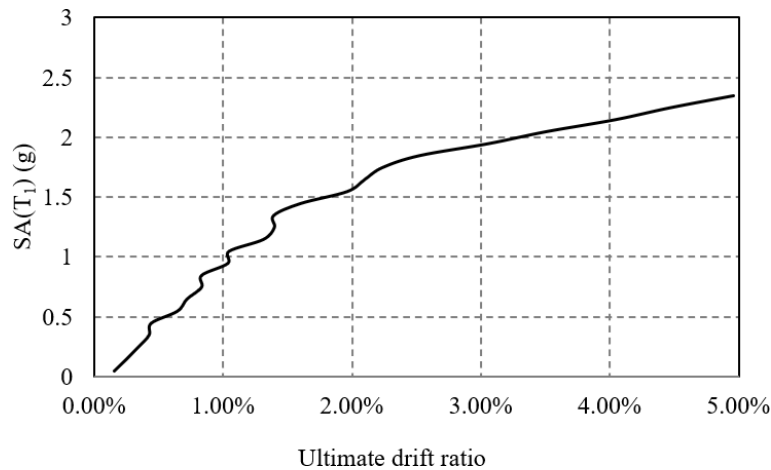| H_w (cm)	l_w (cm)	t_w (cm)	ρ_{wh}	ρ_{bh}
3500	300	35	0.005	0.006

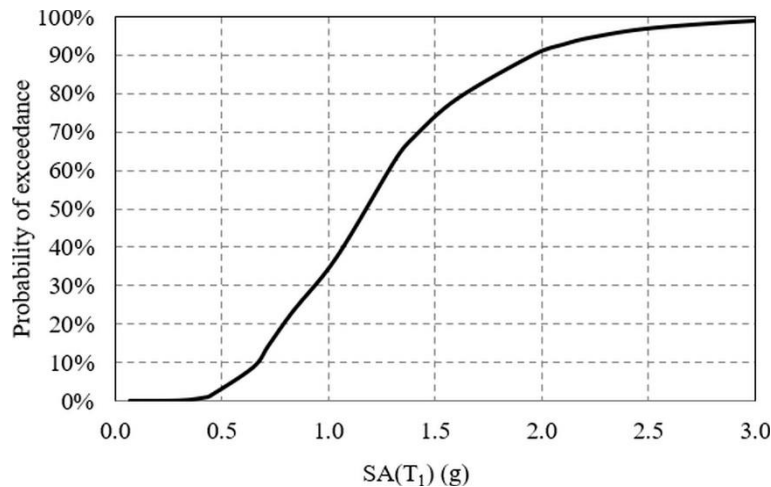*Fig. 13 – IDA curve for the second case-study RC shear wall structure [41]*

Fig. 14 – Probability of exceedance of the ultimate drift capacity for the second case-study RC shear wall structure [41]

CONCLUSIONS

In this study, we have evaluated the displacement capacity of RC shear walls using both experimental and analytical results. The main reason for using both analytical results is due to the scarcity of test data for slender RC shear walls having thicknesses larger than 150 mm. This situation is also confirmed by the recent test database compiled by Abdullah [35]. An empirical model for the assessment of the ultimate drift ratio is proposed in this study using input parameters readily available for each designer and which does not require the results of sectional analyses, unlike other models proposed in the literature. The proposed model allows a rapid assessment of the displacement capacity of slender RC shear walls as a function of the seismic design code and can

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be used for rapid seismic assessments. The most important observation of the study can be summarized as follows:

- few experimental results for slender RC shear walls having thicknesses larger than 150 mm are available in the literature. Thus, the use of empirical models based purely on experimental data, especially for slender RC shear walls is subjected to a significant degree of uncertainty;
- the mean and median ultimate drift of squat RC shear walls is about half of that obtained for slender RC shear walls;
- the mean and median ultimate drift obtained experimentally and analytically for slender RC shear walls are almost identical;
- both the normal and the lognormal CDF provide a good fit of both the experimental and analytic ultimate drift ratios;
- opposite correlation coefficients have been observed between the same RC shear walls characteristics and the ultimate drift ratios obtained experimentally and analytically;
- the mean ratio between the observed and the predicted values using the proposed empirical model is 1.05, while the median value is 0.98, the standard deviation is 0.38 and the correlation coefficient is 0.63;
- the proposed empirical model provides lower-bound seismic capacities when compared with the results of the model proposed by Abdullah and Wallace [20] and with the results from SeismoStruct [40];
- modern RC shear walls in Romania have at least a double displacement capacity as opposed to the ones designed during the '60s and '70s. This is an important observation, especially since there are more than 3000 high-rise RC shear wall structures designed and built-in that period;
- based on the results obtained using the proposed empirical model, it might appear as necessary to adjust the drift limits for both SLS and ULS given in the current Romanian seismic design code P100-1/2013 in the case of slender RC shear walls;
- the median fragility in terms of spectral accelerations obtained for a case-study structure by applying the empirical model proposed in this study is about 50% larger than the elastic design spectral acceleration.

The proposed model, after further testing, can be incorporated in future versions of the seismic assessment guidelines for RC structures for rapid evaluation purposes. By no means the proposed model aims at replacing detailed nonlinear analyses for predicting the force and displacement capacities of RC shear walls.

ACKNOWLEDGEMENTS

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