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A New Approach to Determine the Flexural Stiffness Coefficient for Reinforced Concrete Shear Walls According to Non-Linear Behaviour

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Abstract

The precision in calculating the stiffness of reinforced concrete sections is critical for establishing accurate values for structural stiffness and the associated seismic loads. This study investigated effective stiffnesses recommended for use in designing and analysing structures. A total of 135 section models with transverse and longitudinal reinforcement ratios, compressive strength of concrete and axial load levels affecting the analytical analysis of the nonlinear behavior of reinforced concrete shear walls with high ductility levels were considered. The key parameters influencing effective stiffness an aspect that encompasses the impact of cracking and theoretical yielding within structural sections were identified through thorough moment-curvature analyses conducted on a range of shear wall sections. According to the numerical analysis results of the shear wall models, it was found that these design parameters were effective on the stiffness coefficient of the sections. Considering the effective stiffness of section models, a secure and simpler equation is proposed to include these parameters. The equation provides a high degree of accuracy in design and analysis by considering the nonlinear behavior of shear walls in buildings concerning important design parameters. Based on the results of the nonlinear analysis, the proposed predictions for the effective stiffness coefficient, relations proposed by many researchers, standards, and codes, are verified by comparisons with moment-curvature relations. The proposed equation for the effective stiffness of shear wall sections with high ductility levels offers fairly accurate and consistent estimates since it considers all design parameters that affect the non-linear behavior of the sections. This equation has been compared with nonlinear analyses of section models and existing relationships in the literature and has been proven to be reasonably accurate for practical engineering design applications. In the proposed equation, the stiffness coefficients of shear walls can be calculated according to these effective design parameters, and it can verify and design high ductility shear walls with sufficient accuracy in practical engineering design and analysis applications.

1. Introduction

Nonlinear response and cracking in bearing elements under severe seismic effects are generally accepted, and seismic design and analysis of reinforced concrete (RC) structures are based on linear response [1]. Being able to define the flexural stiffness of RC sections as realistically as possible has become more important because the performance-based solution has emerged as an important method in determining the earthquake behavior [2]. The shear and flexural stiffness of structural bearing elements are reduced by concrete cracks. Therefore, the analyses performed without considering the cracking effect on the bearing elements may not represent the actual behavior of the bearing elements and structures [3]. The purpose of sizing and detailing structural load-bearing elements under the influence of vertical and horizontal loads is to provide sufficient rigidity, strength, and ductility under the anticipated effects for the structure and to fulfil the structural performance and displacement limit conditions defined by the regulation [4]. The seismic analysis and assessment of structures under maximum accepted seismic effects require the use of reduced stiffness calculations for cracks in load-bearing elements and degraded materials. Appropriate definitions of effective stiffness for different load-bearing elements in structures are important for seismic design, analysis, and assessment [5]. The results obtained from the analysis of the load-bearing elements under horizontal and vertical loads may vary depending on the section stiffness. The flexural stiffness in RC structural systems is effective both in the determination of displacements and in the distribution of internal forces compared to other structural systems [6]. The effective flexural stiffness values obtained after cracking for RC bearing elements are the most important feature that affects the force contribution of the bearing elements of RC structures [7].

In the design and assessment of RC shear walls, the strength, rigidity, and ductility of the cross-sections should be taken into attention, and it is clearly known that it is an important parameter in terms of structural seismic safety [8], [9]. The amount of shear and flexural cracking, as well as the distribution and intensity of stress on a load-bearing member, determine the amount of effective stiffness in RC shear walls. The flexural stiffness of the shear wall section decreases as a result of a decrease in moment of inertia, net cross-sectional area, and bending cracking in concrete [10]. The flexural stiffness varies depending on the section dimensions, material elasticity modules, and reinforcement ratio. While examining the section behavior with the relationship of moment and curvature, the flexural stiffness has a maximum value depending on the material elasticity modulus and the section moment of inertia in cases where the moment is small and no cracks occur in the section. With the moment reaching large values and the formation of cracks, the bending stiffness decreases and the effective section stiffness becomes effective. The moment-curvature-based approach is used to develop expressions for estimating the flexural stiffness of RC elements subjected to short-term loads [11].

In numerous established codes and guidelines, the effective stiffness of structural members is characterized as a function of the stiffness derived from their overall section properties. Uncracked section characteristics are typically taken into account in determining structural stiffness, as some seismic design standards and regulations require the exact effective stiffness to be employed in the seismic analysis of structural elements. In commonly used standards, the stiffness of load-bearing elements is defined by the coefficient of their stiffness obtained based on their cross-sectional characteristics. The analysis of existing codes and previous studies has demonstrated that effective stiffness is typically articulated in relation to the axial load level in RC sections. In certain studies, it is posited that the effective stiffness remains relatively consistent across different section properties. Furthermore, a definitive definition of effective stiffness is not provided. In various methodologies, the focus is directed towards the cracked state of the structural elements, whereas other approaches consider stiffness based on the slope of the bilinear moment-curvature diagram.

It has been determined that load-bearing elements' stiffness coefficients differ from the values expected in the event of an earthquake. It is known that the stiffness of RC structures exposed to earthquake effects will decrease greatly; therefore, it is recommended to use cracked section stiffness in the relevant sections of the standards and codes to provide more realistic results. To design bearing systems most accurately, the behavior of elements must be understood correctly. The behavior of the elements in the structural system is determined by the section's behavior. One of the best methods to determine the behavior of the bearing element section depending on the material and geometry is to know the moment-curvature relation of the cross-section. The accuracy level in calculating the stiffness values of structural elements is important for determining realistic structural stiffness values and therefore effective earthquake effects.

In research focused on the effective stiffness of RC structural elements, various factors and equations have been proposed to enhance design practices. A comprehensive study was conducted to examine the critical design parameters influencing the effective stiffness of RC shear walls characterized by high ductility, specifically those with confined boundary zones. Additionally, the study aimed to assess the adequacy of the values outlined in the current code. This study conducts a parametric analysis of the response characteristics of shear wall sections incorporating various parameters. The objective of this study is to propose new equations that account for the key parameters influencing the effective stiffness of the designed shear wall models and to conduct a comparative analysis with existing equations. This analysis will consider various structural codes [12]–[18] and pertinent design parameters. Different parameters such as reinforcing steel ratio, axial load, concrete strength, bearing element dimension, and geometry are taken into account in studies conducted with effective stiffnesses of structural elements. In research and studies on stiffness coefficients that take into account the design parameters affecting the stiffness of structural elements, the proposed relations for design and assessment have been examined. The proposed equation for the stiffness coefficient encompasses all parameters influencing the nonlinear behavior of the shear wall models. As a result, the nonlinear behavior of the elements can be reflected in the stiffness coefficient of shear walls by calculation.

The stiffness coefficient of the RC shear wall models in different parameters was investigated analytically by obtaining from the Turkish Building Earthquake Code (TBEC) [19], Seismic Evaluation and Retrofit of Existing Buildings (ASCE/SEI41) [20], American Concrete Institute (ACI318) [21], Assessment and Retrofitting of Buildings (Eurocode 8-Part 3) [22], Design of Structures for Earthquake Resistance (Eurocode 8) [23], Biskinis [24], Biskinis and Fardis [25], Fenwick and Bull [26], moment-curvature, and the proposed equation. A simple equation based on the design parameters affecting the stiffness coefficient of shear walls is proposed and compared with the values found in the literature. Different parameters such as reinforcing steel ratio, axial load, concrete strength, bearing element dimension, and geometry are taken into account in studies conducted with effective stiffnesses of structural elements. The equation provides a high degree of accuracy in design and analysis by considering the nonlinear behavior of RC shear walls in buildings concerning important design parameters. This equation has been compared with nonlinear analyses of section models and existing relationships in the literature and has been proven to be reasonably accurate for practical engineering design applications. This equation has been compared with nonlinear analyses of section models and existing relationships in the literature and has been proven to be reasonably accurate for practical engineering design applications. In the proposed equation, the stiffness coefficients of RC shear walls can be calculated according to these effective design parameters, and it can verify and design high ductility shear walls with sufficient accuracy in practical engineering design and analysis applications. For shear wall models, the results obtained from the analyses according to different parameters are presented in graphics and examined.

2. Effective Flexural Stiffness of RC Shear Walls

In order to design RC load-bearing systems in the most accurate way, the behavior of elements must also be understood correctly. The behavior of the elements in the load-bearing system is determined by the section behavior. A highly effective method for assessing the behavior of a section, which is influenced by both the material properties and the geometry of the section, is to understand the moment-curvature relationship associated with it. By considering the moment-curvature relationship, information can be obtained about the strength, rigidity, ductility of the RC section, and the effect of the deformation of the concrete and reinforcement on the element behavior.

In accordance with established regulations, it is essential to employ the effective section stiffnesses of the cracked section in RC structural system elements during the design phase. This approach is necessary to accurately assess the earthquake performance of structures. Seismic analysis and design of structures are typically conducted with a focus on linear response. However, it is widely recognized that in the event of severe earthquakes, structures may undergo inelastic responses and experience cracking. The effective bending stiffnesses of cracked RC sections are determined by considering the yield moment and the ratio associated with the yield curvature, in accordance with the moment-curvature relationship [3].

High-rise buildings use RC shear walls as important structural elements to increase resistance against horizontal loads (wind, earthquakes, etc.) and ensure the stability of the building. The effective bending stiffness of these walls is a critical parameter in terms of their bearing capacity and performance. Effective bending stiffness determines the deformation characteristics of the shear wall under bending moment and the displacements in the structure. Accurately determining the effective bending stiffness of RC shear walls is very important to increase structural safety and improve performance. Therefore, structural engineers should consider this parameter in the design and analysis processes. Cracked section analyses provide more accurate results in determining the effective stiffness and deformation behavior of shear walls after cracking. These analyses are critical to reflecting the actual behavior of the walls. Geometric features such as thickness, height, and width of the shear wall and reinforcement arrangement significantly affect the effective bending stiffness. Correct evaluation of these factors is of great importance in terms of building safety and performance. Cracking behaviors of RC elements under load reduces the effective bending stiffness and requires nonlinear behaviors to be taken into account. Therefore, post-cracking stiffnesses need to be taken into account in structure design. Post-cracking behaviors of RC shear walls should be taken into account in structural design and analysis.

It is known that the stiffness of RC structures exposed to earthquake effects will decrease greatly; therefore, it is recommended to use cracked section stiffness in the relevant sections of the standards and codes to obtain more realistic results [27]. For linear or nonlinear analysis of structures subjected to earthquake loads, current design codes provide constant coefficients and different relations for the stiffness of the structural elements, often providing rough indications on how to evaluate the stiffness of the elements [28]. A number of proposed equations for stiffness do not adequately consider the primary design parameters that significantly influence the nonlinear behavior of elements [29]. Table 1 compares the different effective stiffness equations from the literature and the design codes.

Table 1 *Comparison of different effective stiffness equations*

Author and Codes	Effective section stiffness
Moment-Curvature Relations	$k_e = EI_e / EI;\ EI_e = M_y / \varphi_y,\ E_c = 3250\sqrt{f_{ck}} + 14000MPa$
TBEC [19] according to the lumped plastic behavior	$(EI)_e = \frac{M_y}{\theta_y}\frac{L_s}{3},\ \theta_y = \frac{M_y L_s}{3EI}$ [linear method] $\theta_y = \frac{\varphi_y L_s}{3} + 0.0015\eta\left(1+1.5\frac{h}{L_s}\right) + \frac{\varphi_y d_b f_{ye}}{8\sqrt{f_{ce}}},\ \eta = 1$: in shear wall [nonlinear methot]
Eurocode 8-Part 3 [22]	$EI_e = \frac{M_y L_v}{3\theta_y},\ \theta_y = \varphi_y\frac{L_v + a_v z}{3} + 0.0013 + \varphi_y\frac{d_{bL} f_y}{6\sqrt{f_c}}$
Biskinis [24]	$\frac{EI_{eff}}{E_c I_c} = a\left(0.8 + \ln\left[\max\left(\frac{L_s}{h};0.6\right)\right]\right)\left(1 + 0.048\min\left(50MPa;\frac{N}{A_c}\right)\right),\ a = 0.115$ for walls
Biskinis and Fardis [25]	$EI_{eff} = \frac{M_y L_s}{3\theta_y},\ \theta_y = \varphi_y\frac{L_v + a_v z}{3} + 0.0013 + a_{sl}\frac{\varphi_y d_{bL} f_y}{8\sqrt{f_c}},\ L_s = \frac{M}{V},\ a_{sl} = 1$ for walls. $V_{RC} = \left\{\max\left[180(100\rho_1)^{1/3},\ 35\sqrt{1+\sqrt{\frac{0.2}{d}}}f_c^{1/6}\right]\left(1+\sqrt{\frac{0.2}{d}}\right)f_c^{1/3} + 0.15\frac{N}{A_c}\right\}b_w d$
Fenwick and Bull [26]	$\frac{I_e}{I_g} = 0.267\left(1 + 4.4\frac{N}{f_c' A_g}\right)\left(0.62 + \frac{190}{f_y}\right)\left(0.76 + 0.005 f_c'\right)$

In TBEC [19], the effective stiffness is taken to be constant, and the stiffness coefficient for RC shear walls is accepted as 0.50. The shear span of the element, yield moment, and yield rotation values of the section may all be utilized for calculating the stiffness of the shear wall that was developed using the stacked plastic behavior model outlined in TBEC [19]. It is specified as $0.3E_cI_c$ of the cracked shear walls in ASCE/SEI-41 [20]. ACI318 [21] gives a ratio of $0.35E_cI_c$ of the cracked shear walls and $0.70E_cI_c$ of the uncracked shear walls. A more accurate stiffness can be obtained using an equation based on yield rotation and moment-shear ratio, as discussed in Part 3 of Eurocode 8 [22]. Considering that the effective stiffness is not constant, a formulation based on parameters such as section dimension, reinforcing steel ratio and concrete strength is recommended. It is specified as $0.5E_cI_g$ of shear walls in Eurocode 8 [23]. In Eurocode 8 [23], design parameters such as bearing element geometry and dimension, reinforcing steel ratio, concrete strength and axial load level affecting the section are not taken into account. The most important design parameters and section properties affecting the effective stiffness, reflecting the cracking effect as well as the theoretical yielding of the RC sections, are calculated by extensive moment-curvature analysis of the sections. In the stiffness coefficient equations proposed by some researchers for shear walls, important design parameters in load-bearing elements are not taken into consideration, as in the codes. It means ignoring the effects of important design parameters that affect the nonlinear and seismic behavior of load-bearing elements such as concrete strength, reinforcement ratio, confining effect in confined boundary regions and axial load levels. Neglecting to consider the design characteristics that impact the nonlinear behaviors of sections may result in inflated results when evaluating load-bearing elements. For this reason, it is of great importance to obtain moment-curvature relations and stiffness values in the design and assessment of elements to provide more realistic results. In this article, the internationally accepted regulations and codes currently in use and the relationships found in the literature were considered to investigate the effective section stiffness of RC shear walls. The reason for these relationships selected from the literature is that the design parameters for the carrier element are taken into account in the calculation of the effective section stiffness. Thus, meeting and verifying the new equation proposed for the effective section stiffness will be more realistic with the relationships taken from the regulations, codes and literature.

In the Table 1, EI: uncracked section stiffness, EI_e: Effective section stiffness of the cracked section, E_c: modulus of elasticity of the concrete. M_y, $\emptyset_y$: yield moment and curvature, f_c, f_{ck}, f_c' is the concrete strengths, θ_y rotation of the chord at the yielding and L_s shear span of the bearing element. f_y: steel reinforcement's yield strength, f_{ye} and f_{ce}: expected yield strength of transverse reinforcement and concrete strength (f_{ye}=1.2 f_{yk}, f_{ce}=1.3 f_{ck}). d_b and d_{bL}: is the longitudinal reinforcement diameter and h section height. V_{RC}: shear resistance of member without web reinforcement, $a_V z$: is the tension shift of the flexural moment diagram, $z = 0.8\ h$ in shear walls, d effective section depth. A_g, A_c, A_{sl} is the area of concrete section and reinforcement. ρ_1 is the reinforcement ratio, b_w is the web thickness of wall and N is the axial load.

3. MATERIAL and METHOD

For stiffness, not the dimension of the structure, but the location of the vertical RC bearing elements and the dimensions of these elements in both directions are important. The properties of the material used in the elements and the cross-section dimensions of the element are effective in the calculation of the stiffness of the vertical bearing elements. Shear wall sections with different the longitudinal reinforcement's diameter (d_l), the transverse reinforcement's diameter (d_{tr}), transverse spacing of reinforcements (s), concrete strength (f_{ck}) and axial load (N/N_{max}) were designed to investigate stiffness coefficients. The most important design parameters, which reflect the effect of cracks affecting the stiffness of structural elements and the theoretical efficiency of the elements, are determined by comprehensive moment-curvature analysis of the bearing elements. In the analytical study for RC shear wall sections, moment-curvature relations were obtained and presented graphically by considering the non-linear behavior of the materials. Unconfined and confined concrete model proposed by Mander et al. [30], mandated in TBEC [19] and universally accepted, was used to determine the non-linear moment-curvature relations of the designed shear wall sections.

The details and properties of the shear wall models considered in the numerical analysis are summarized in Table 2. The RC shear wall models, details and properties of which are given in Table 2, are taken from the article titled 'Effective flexural stiffness for RC shear walls having confined boundary elements' by Foroughi and Yuksel [9]. In addition to the study of Foroughi and Yuksel [9], a simple equation is proposed in this study to calculate the stiffness coefficient of cracked sections of shear walls having confined boundary regions according to different design parameters. The effective stiffnesses of the shear wall models according to different N/N_{max}, d_l, d_{tr}, s and f_{ck} parameters were calculated from the non-linear moment-curvature relations of the sections, and the correlations presented in the literature by different researchers and suggested in different codes.

Examining the nonlinear behavior of RC shear walls with high ductility is of great importance, especially in terms of earthquake engineering and durability. Such walls are characterized by their high ductility capacity due to their ability to absorb energy and can perform without serious loss of structural integrity even when subjected to large deformations. The high ductility shear wall models which were taken into account in the analytical studies were designed with a rectangular cross-section. In TBEC [19], the ratio of the length of the long edge ($l_w = 3000\ mm$) to the thickness in plan ($b_w = 300\ mm$) of shear walls with high ductility level was determined as greater than six ($l_w > 6\ b_w$). According to TBEC [19], shear walls with $H_w/l_w > 2$ should be designed taking into account the confined boundary regions. Since the total height of the designed shear wall is $H_w = 10000\ mm$ and the length in the plan is $l_w = 3000\ mm$, the confined boundary region dimensions of 300 mm × 600 mm are taken into account at both confined boundary of the shear wall models. The reinforcement ratios taken into account in the design of shear walls were selected by considering the reinforcement arrangement and requirements of the web and confined boundary regions of the shear walls defined in TBEC [19]. The gross section area of the shear wall, when combined with the combined effects of gravity and seismic loads (N_{dm}), must satisfy condition $A_c \geq N_{dmax}/0.35\ f_{ck}$ [19]. The nonlinear behaviors of the shear wall models were investigated for the N/N_{max} ratios of 0.15, 0.25 and 0.35 ($N_1 = 0.15\ A_c f_{ck}$, $N_2 = 0.25\ A_c f_{ck}$ and $N_3 = 0.35\ A_c f_{ck}$). The maximum axial load level for RC shear walls in TBEC [19] is defined as $N_3 = 0.35\ A_c f_{ck}$. In order to examine the effect of the axial load level on the effective stiffness in shear walls, three different ratios were taken into account by taking this limitation into account. The design and modelling of the shear wall were carried out by taking into account the important design parameters affecting the nonlinear behavior of the RC elements. To prefer high ductility level shear walls in earthquake zones, the high ductility level shear wall model was also taken into account in this study. Different longitudinal and transverse reinforcement ratios were taken into account in the shear wall models with confined boundary and web regions. The longitudinal and transverse reinforcement ratios within the confined boundary regions of the RC shear wall were established in accordance with the guidelines provided in TBEC [19]. Concrete with a compressive strength lower than C25 is not permitted for use in all RC buildings constructed in accordance with the provisions of TBEC [19]. In the models of RC shear walls, five distinct concrete classes C30, C35, C40, C45, and C50 were considered.

To perform structural design under the influence of earthquakes and to examine the seismic behavior of the structure, first of all, the behavior of the materials and elements that make up the structure should be known. The behavior of the bearing element under the effect of simple flexural and normal force or only simple flexural can be examined by obtaining the moment-curvature relation, and the changes in ductility level and stiffness can be observed by looking at its behavior. The moment-curvature relations were calculated by considering the Mander unconfined and confined concrete models [30] and the material properties given for the reinforcing steel in Table 3. Using the SAP2000 [31] program, the moment-curvature relations corresponding to the non-linear behavior of the materials in the shear wall sections have been obtained and graphically presented. Material models used in nonlinear analyses should be chosen to reflect the actual behavior of concrete and steel. Correct application of these models allows realistic prediction of moment-curvature relationships. Nonlinear analyses on moment-curvature relationships of highly ductile RC shear walls provide critical information regarding the safety and durability of structures. These studies form the basis for the design of safer structures and the strengthening of existing structures. Therefore, it is of great importance to perform such analyses and take their results into account in structural engineering practice.

Table 2 *Details and properties of reinforced concrete shear wall models* [9]

Concrete Grade (MPa)	Shear Wall Confined Boundary Region		Shear Wall Web Region		Axial Load (N/N_{max})
	Longitudinal Reinforcement (LR)	Transverse Reinforcement (TR)	Longitudinal Reinforcement (LR)	Transverse Reinforcement (TR)	
C30 C35 C40 C45 C50	10 Φ 18 mm	Φ 8/50 mm	18 Φ 14 mm	Φ 8/50 mm	0.15 0.25 0.35
		Φ 10/50 mm		Φ 10/50 mm	
		Φ 12/50 mm		Φ 12/50 mm	
		Φ 14/50 mm		Φ 14/50 mm	
		Φ 10/75 mm		Φ 10/75 mm	
		Φ 10/100 mm		Φ 10/100 mm	
		Φ 10/125 mm		Φ 10/125 mm	
		Φ 10/150 mm		Φ 10/150 mm	
	10 Φ 14 mm	Φ 10/50 mm		Φ 10/50 mm	
	10 Φ 16 mm				
	10 Φ 18 mm				
	10 Φ 20 mm				

Cross-Sectional Dimensions

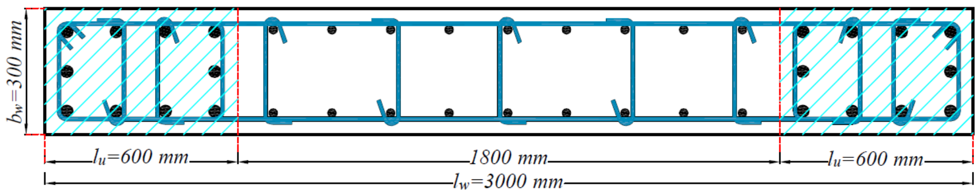


Table 3 *Parameters for materials used to reinforce concrete and steel [20]*

Material	Parameters	Values
Reinforcing steel: B420C	Steel reinforcement's yield strength (f_{yk})	420 MPa
	The steel reinforcement's ultimate strength (f_{su})	550 MPa
	Steel reinforcement's yield strain (ε_{sy})	0.0021
	reinforcing steel's hardening strain (ε_{sp})	0.008
	Steel reinforcement's ultimate strain (ε_{su})	0.08
Concrete: C30-C50	Unconfined concrete compressive strength (f_{ck})	30-50 MPa
	Strain of unconfined concrete at maximum stress (ε_{co})	0.002
	Ultimate compression strain of unconfined concrete (ε_{cu})	0.0035

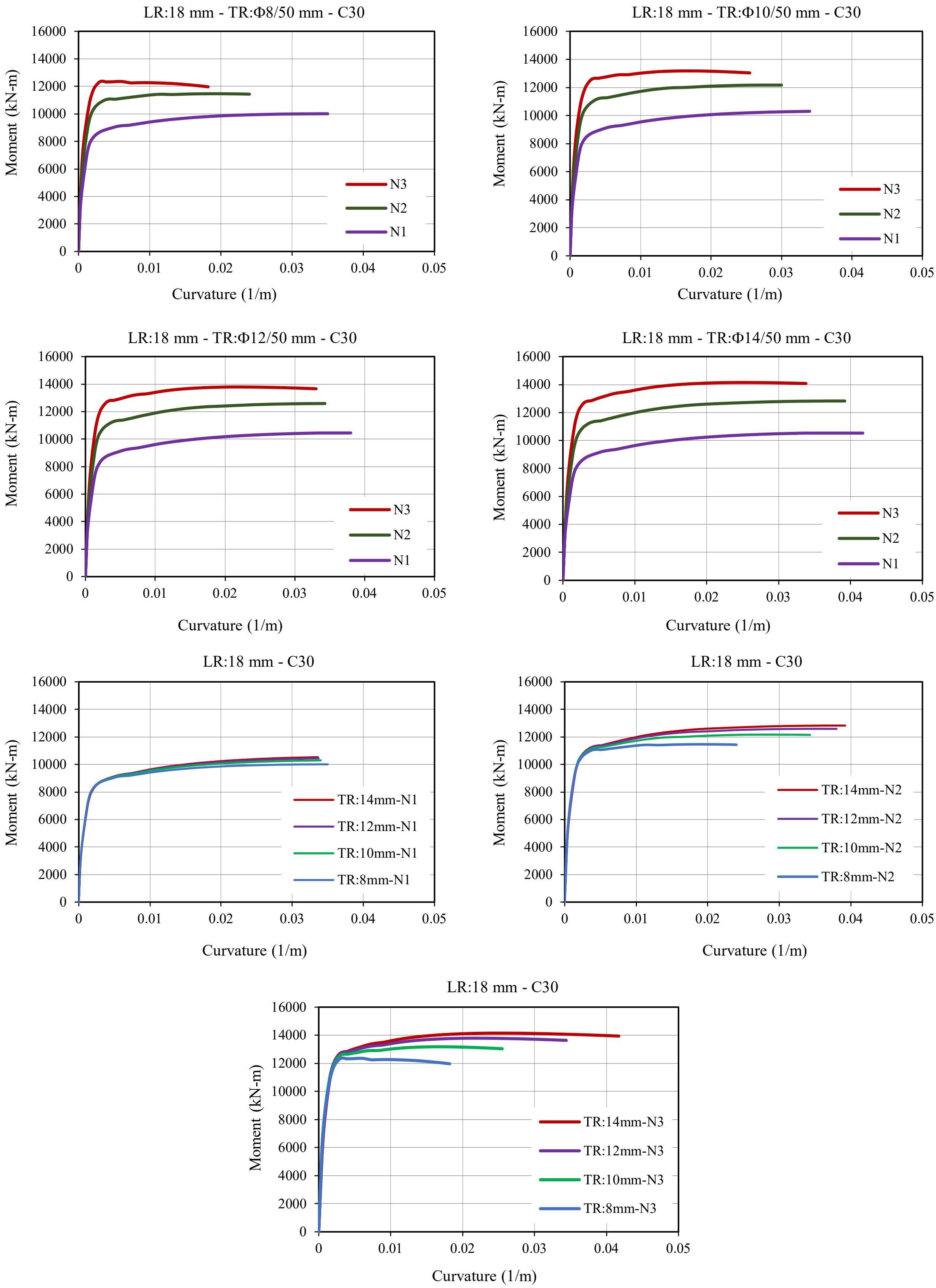
Different design codes and standards provide different parameters and codes for modifying the stiffness of RC bearing elements. In the analyses and calculations made according to the standards and codes, the actual behavior value is not taken into account for the stiffness of the sections. Accurate and realistic stiffness factors should be determined by calculating non-linear behavior values according to design parameters instead of defined approximate values. Calculating the values to be used in the analysis according to the non-linear behavior in the designed RC shear wall models, taking into account the design parameters, material properties, and cross-section information, requires very detailed processes and a long time. This situation makes it almost impossible to determine the stiffness of the cracked section according to the non-linear behavior of the RC-bearing members. This process is avoided because it is very laborious to create a model by calculating the stress-strain and moment-curvature relations of a real RC-bearing element in the scientific and practical environment and by calculating the effective section stiffnesses. In the analysis software, calculations and analyses are made by using the constant coefficients given in the standard and codes or by determining the effective stiffness values according to simple relations (ignoring important design parameters). In this case, more realistic results cannot be obtained without considering the cross-sectional and material properties and reinforcement ratios of the RC-bearing members. In designing and evaluating RC-bearing elements, determining their non-linear behavior and obtaining effective stiffness values are very important to obtain more realistic results. In this study, a simple equation covering all design parameters has been developed to overcome very long and detailed calculations that require non-linear behavior modelling to determine the stiffness of the cracked section. Based on the numeric analysis of the cross-sectional behavior and stiffness of shear walls with different design parameters and properties. The investigated effects on the non-linear behavior of shear wall members according to different design parameters such as material properties, longitudinal reinforcement ratio, transverse reinforcement ration, and configuration were evaluated by calculating the section in terms of effective stiffness. The proposed predictions for the stiffness coefficient are verified by comparisons with other prediction formulas. The adequacy of the proposed equation for the stiffness coefficient is evaluated as an element-level parametric study by comparing it with the existing relations and coefficients. For shear wall models, the stiffness coefficient was calculated according to the proposed new equation and the relationships explained in this study, and the results are presented comparatively in the following sections.

3.1 Research Findings

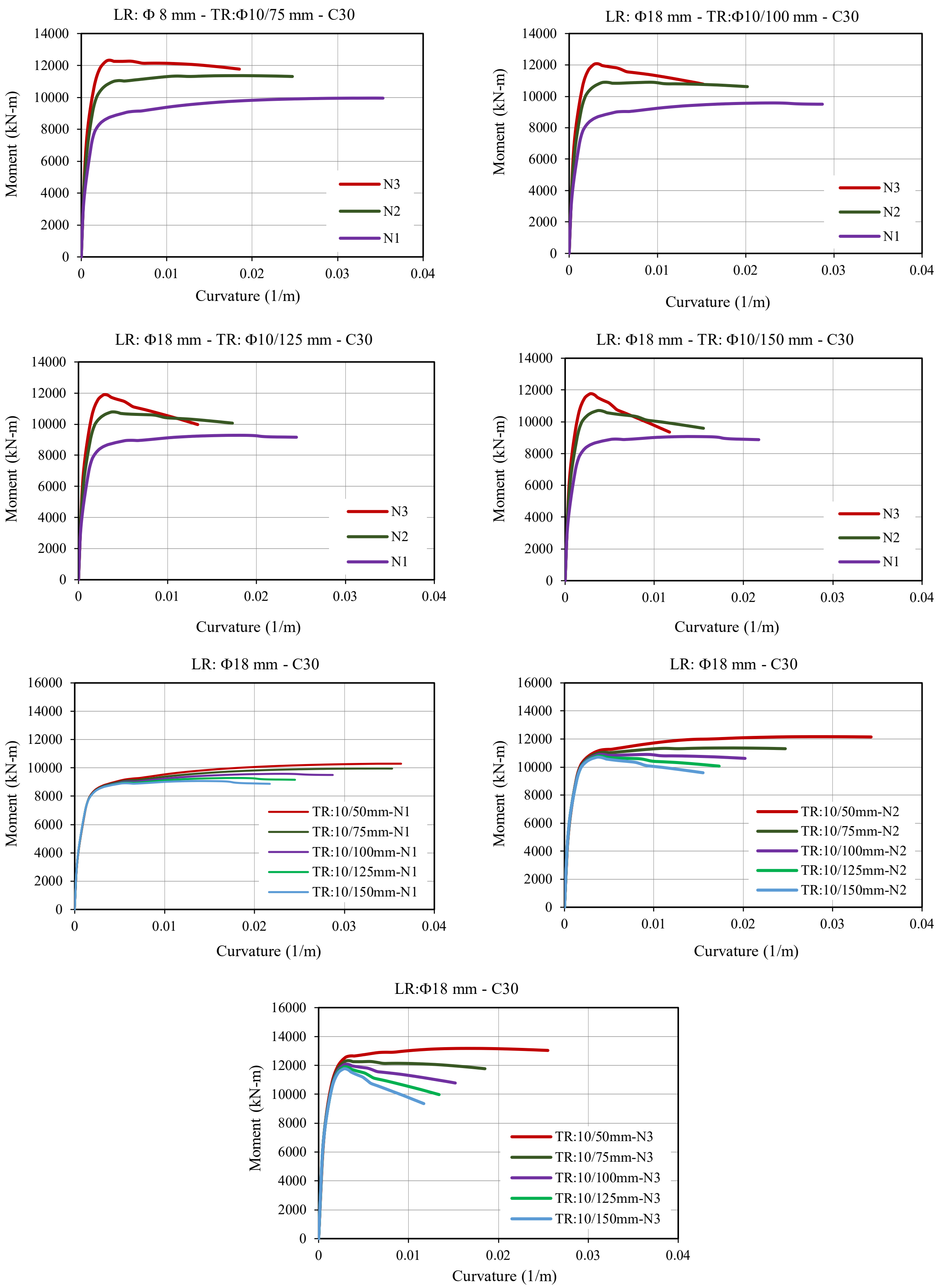
The findings of the nonlinear analysis of the RC shear wall models indicate that new relations-based important design parameters affecting the stiffness coefficient of the shear wall models were proposed and compared with the relations proposed in the codes and by researchers. In order to investigate the nonlinear behavior and stiffness coefficients of shear walls with high ductility levels, a total of 135 shear wall analyses were carried out with different design parameters. The effective flexural stiffness due to concrete cracking was obtained depending on key design parameters include material properties, axial load levels, and transverse and longitudinal reinforcement ratios. The moment-curvature relations obtained for the wall sections are presented in Fig. 1 comparatively according to different design parameters. In Fig. 1; N_1, N_2 and N_3 are the axial load level, C30, C35, C40, C45 and C50 are the concrete compressive strength, TR is the transverse reinforcement's diameter and LR is the longitudinal reinforcement's diameter.

Examining the nonlinear moment-curvature relationships of RC shear walls is an important issue in structural engineering because this relationship is necessary to understand the elastic and plastic behavior of the structure and take it into account in design. It is necessary to understand how shear walls behave under earthquakes and other dynamic loads and to increase safety and performance in design. Examining these relationships is usually done using advanced numerical methods and material models. This relationship is used to understand the load-bearing capacity, deformation behavior, and overall structural performance of shear walls. Especially in earthquake zones, the use of such walls ensures the safety of life and property by increasing the general performance of buildings.

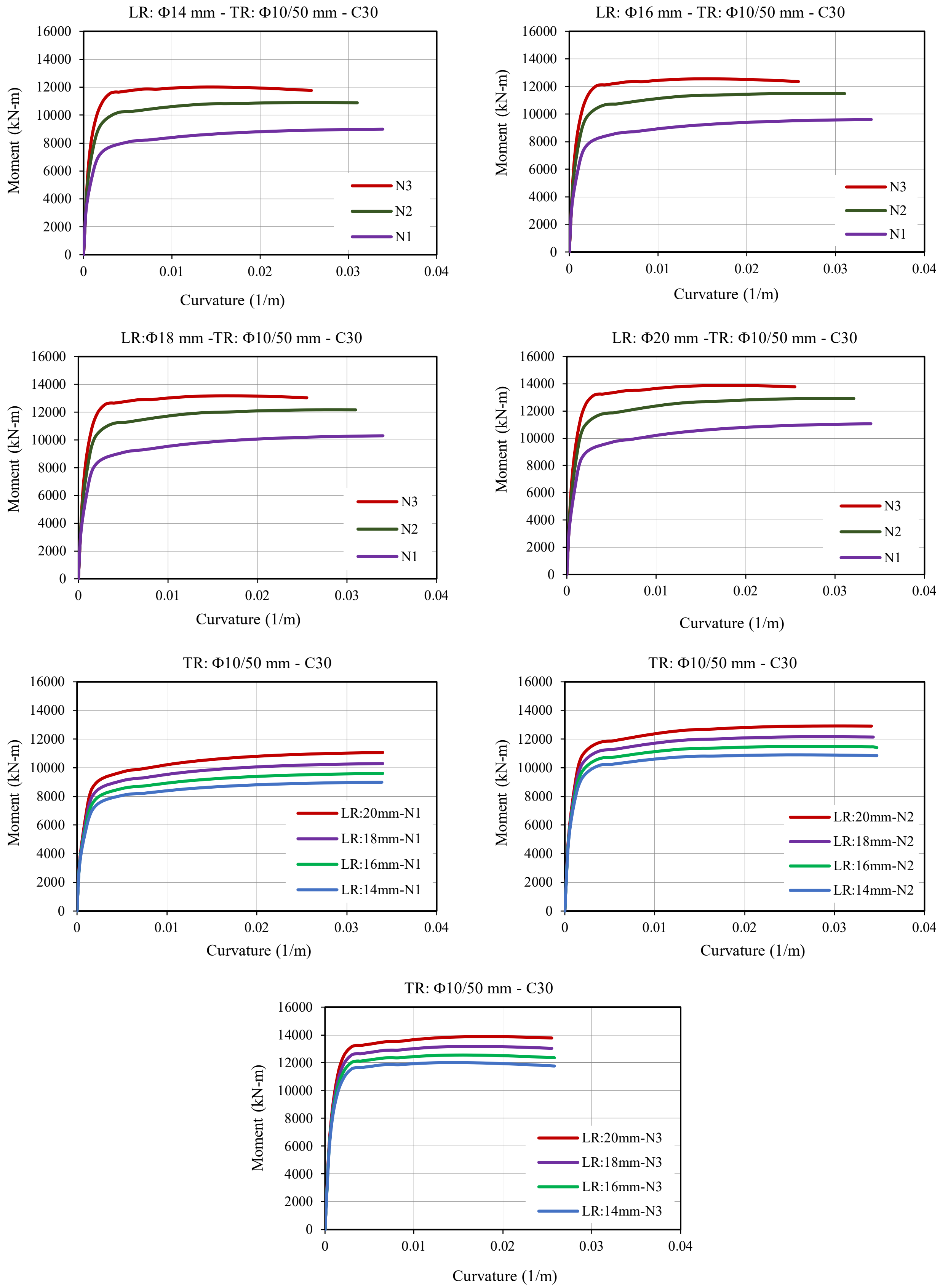
Based on the shear wall models' non-linear relationships, the yield moment, yield curvature, and maximum moment of the section all increase with increasing axial load level, whereas maximum curvature and ductility decrease. At constant axial load levels acting on the shear walls, the moment-carrying capacity and ductility of the sections the response improves with an increase in the transverse reinforcement ratio (a reduction in the transverse spacing of reinforcement). The section's bearing capacity increases and its ductility decreases as the longitudinal reinforcement ratio in the shear wall's constrained boundary increases. One factor that increases the section bearing capacity is the compressive strength of the concrete. Section ductility decreases when concrete strength increases along with a decrease in the section's curvature values. When the moment-curvature curves were examined, it was seen that such walls could be subjected to plastic deformations beyond the elastic limit and significantly preserved their load-carrying capacity. RC shear walls with high ductility have the capacity to absorb energy under large deformations. This allows the structure to withstand sudden loads such as earthquakes without collapsing.



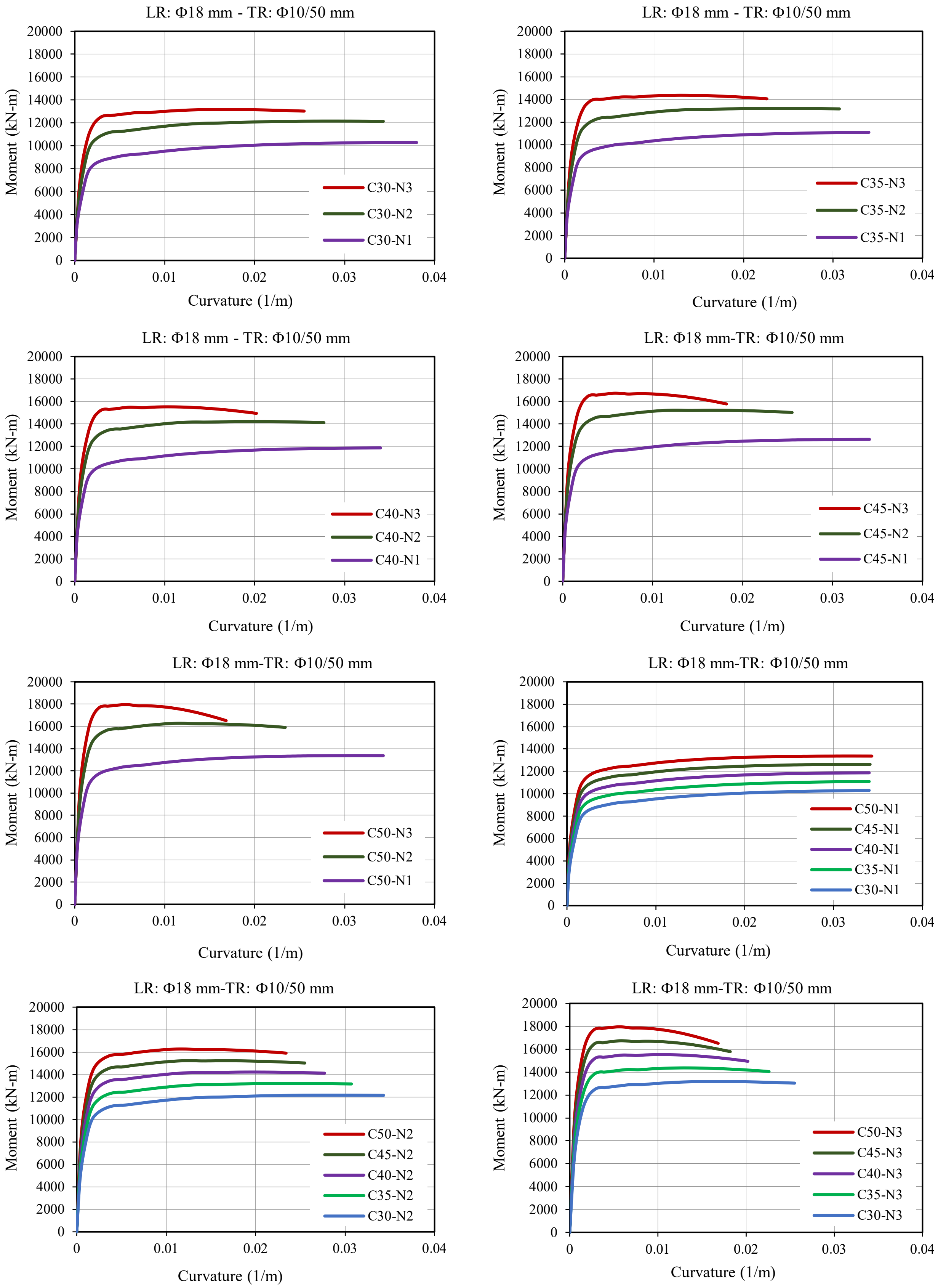
(a) Different transverse reinforcement's diameter



(b) Different transverse spacing of reinforcements



(c) Different the longitudinal reinforcement's diameter



(d) Different concrete strength and axial load levels

Fig. 1 *Moment-curvature relationships of the shear walls for the different design parameters*

3.2 Proposed $k_{e,prop}$ for Reinforced Concrete Shear Wall

Multilinear regression analysis was used to develop the stiffness coefficient equation by considering N/N_{max}, d_l, d_{tr}, s and f_{ck} parameters determined for shear walls having web and confined boundary regions. The basic formation of the $k_{e,prop}$ for shear wall sections can be expressed as following. The N/N_{max}, d_l, d_{tr}, s and f_{ck} have an increasing effect on k_e depending on the behavior of the wall section. The basic formation of the $k_{e,prop}$ equation for shear wall sections can be expressed as $f\{(N/A_c f_{ck}), (d_l), (d_{tr}), (s), (f_{ck})\}$. Considering the numerical results, the relations of $k_{e,prop}$ and f_{ck} parameters can be obtained by regression analysis as Equation (1).

$$k_{e,cal-1} = 0.0012(f_{ck}) + 0.28 \tag{1}$$

The relations between the ratio of k_e to k_{e,cal_1} and the d_l can be obtained from the Equation (2).

$$k_{e,cal-2} = 0.029(d_l) + 0.48 \tag{2}$$

The relationship between the ratio of k_e to $[k_{e,cal\_1} \times k_{e,cal\_2}]$ and the d_{tr} can be obtained from the Equation (3).

$$k_{e,cal-3} = -0.006(d_{tr}) + 1.06 \tag{3}$$

The relationship between the ratio of k_e to $[k_{e,cal\_1} \times k_{e,cal\_2} \times k_{e,cal\_3}]$ and the s can be obtained from the Equation (4).

$$k_{e,cal-4} = -0.0005(s) + 1.2 \tag{4}$$

The relationship between the ratio of k_e to $[k_{e,cal\_1} \times k_{e,cal\_2} \times k_{e,cal\_3} \times k_{e,cal\_4}]$ and the $N/A_c f_{ck}$ can be obtained from the Equation (5).

$$k_{e,cal-5} = 1.04\left(\frac{N}{A_c f_{ck}}\right) + 0.7 \tag{5}$$

Proposed $k_{e,prop}$ for the rectangular shear walls can be expressed as Equation (6).

$$k_{e,prop} = (0.0012 f_{ck} + 0.28) \times (0.029 d_l + 0.48) \times (-0.006 d_{tr} + 1.06) \times (-0.0005 s + 1.2) \times \left(1.04\frac{N}{A_c f_{ck}} + 0.7\right) \tag{6}$$

3.3 Verification of The Proposed Prediction Equation for Effective Stiffness Factor

In this part of the study, it was calculated analytically the effective stiffness coefficient of shear walls designed with various design parameters according to the proposed $k_{e,prop}$. The stiffness coefficient calculated from the shear wall analyses were interpreted and compared from the moment-curvature relations, different codes, researchers and proposed equation ($k_{e,prop}$). The effect of each factor on the stiffness coefficient of shear wall sections is presented in the following. Comparison of predicting $k_{e,prop}$ and numerical results ($k_{e,num}$) for shear walls are given in Fig. 2. Comparison of the stiffness coefficient values calculated for different design parameters according to the proposed equation for shear wall models with other estimation formulas and relations are presented in Fig. 3 comparatively. The comparison of the values obtained for various design parameters according to the proposed equation with the results obtained from the moment-curvature relationships according to the nonlinear behavior is given in Fig. 4.

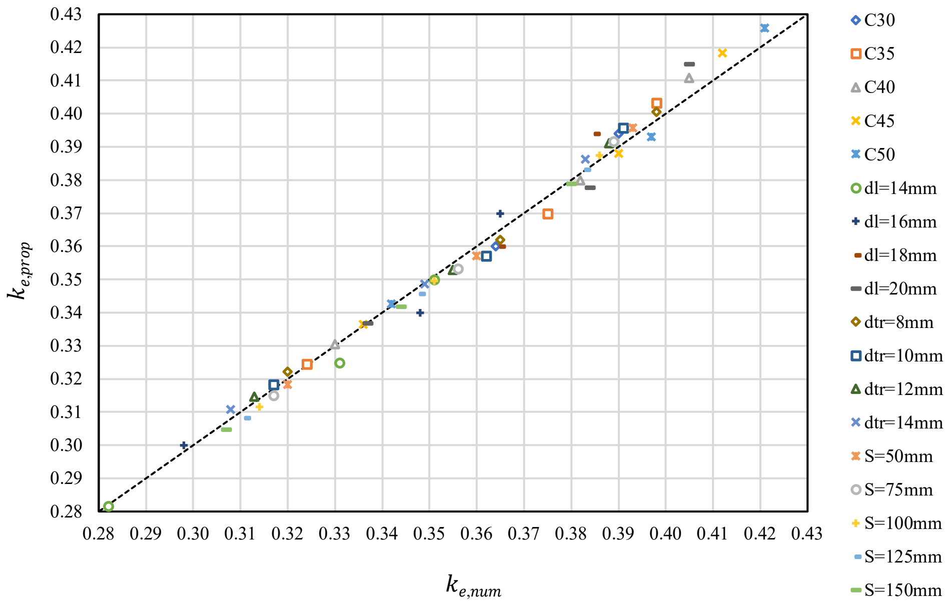
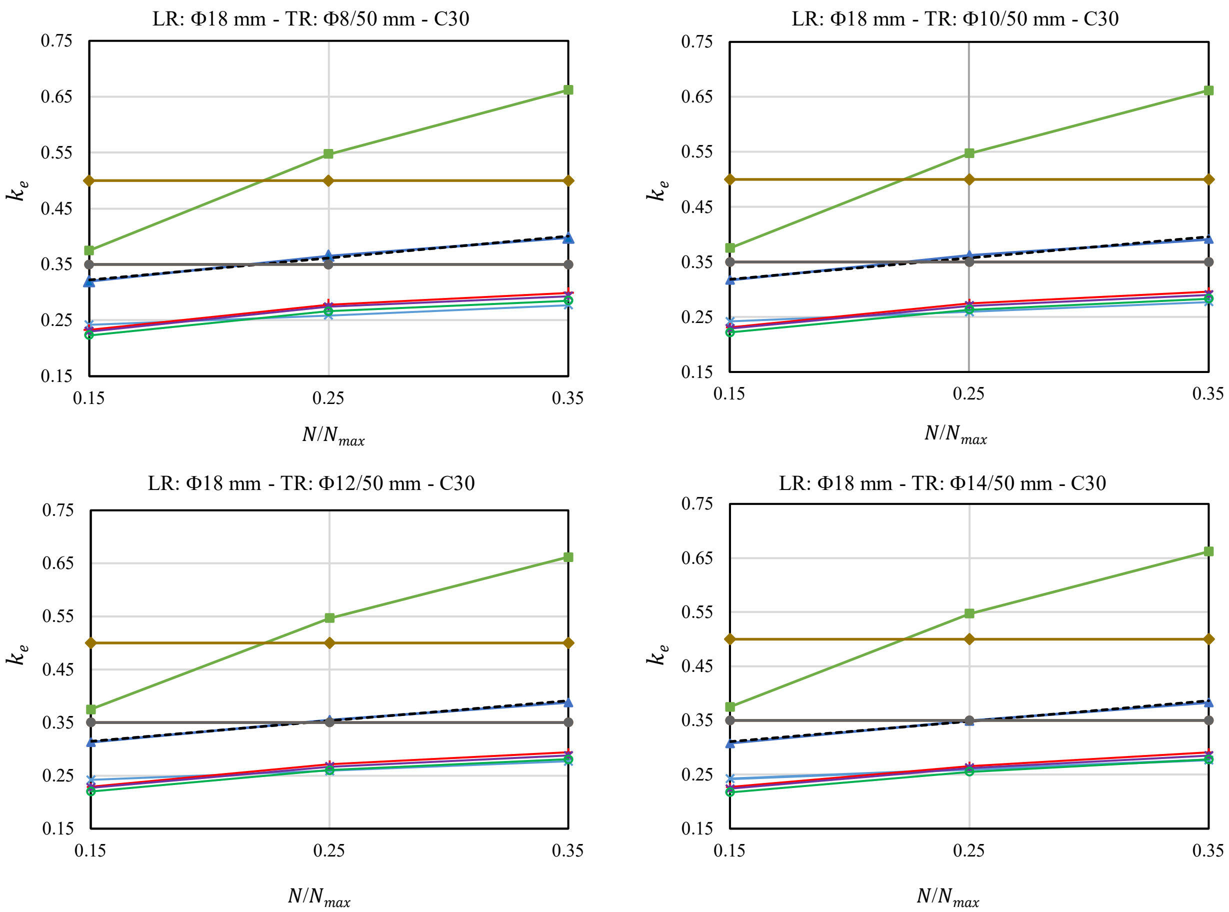
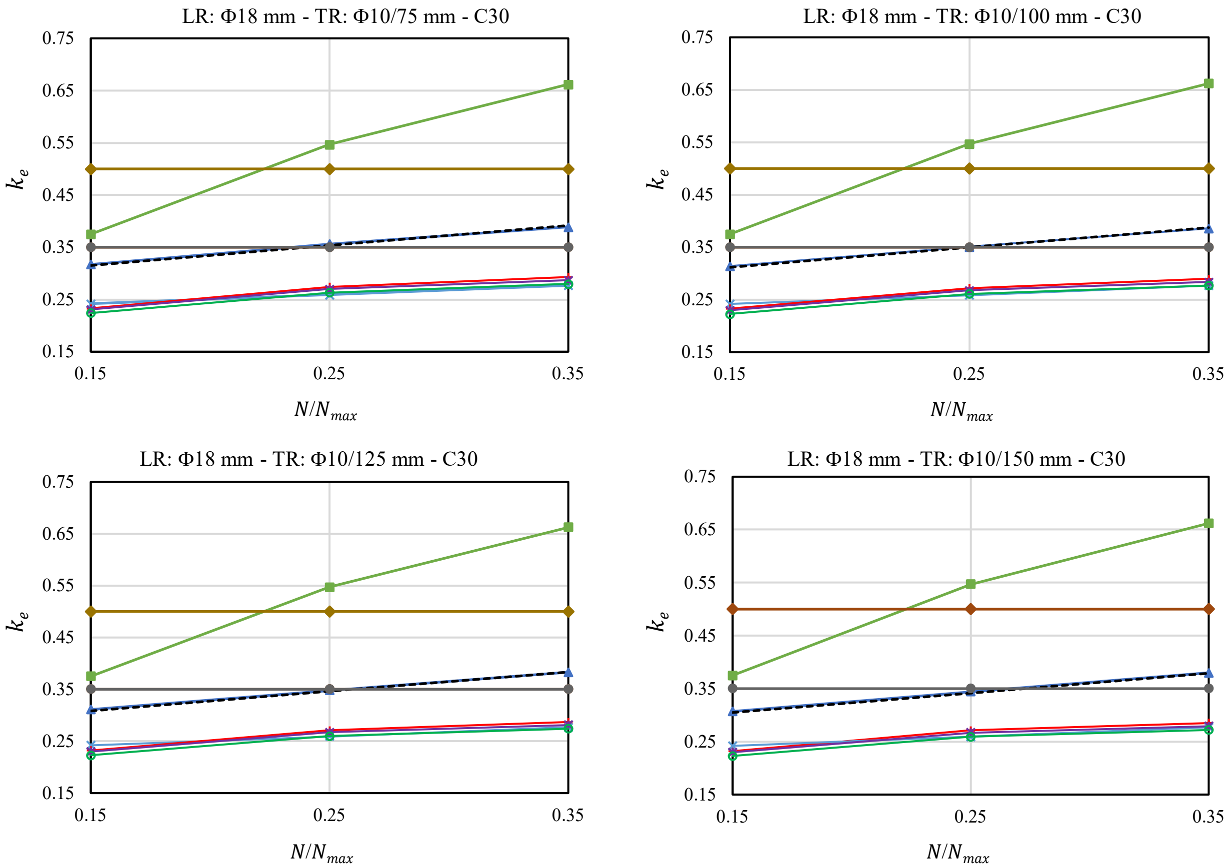


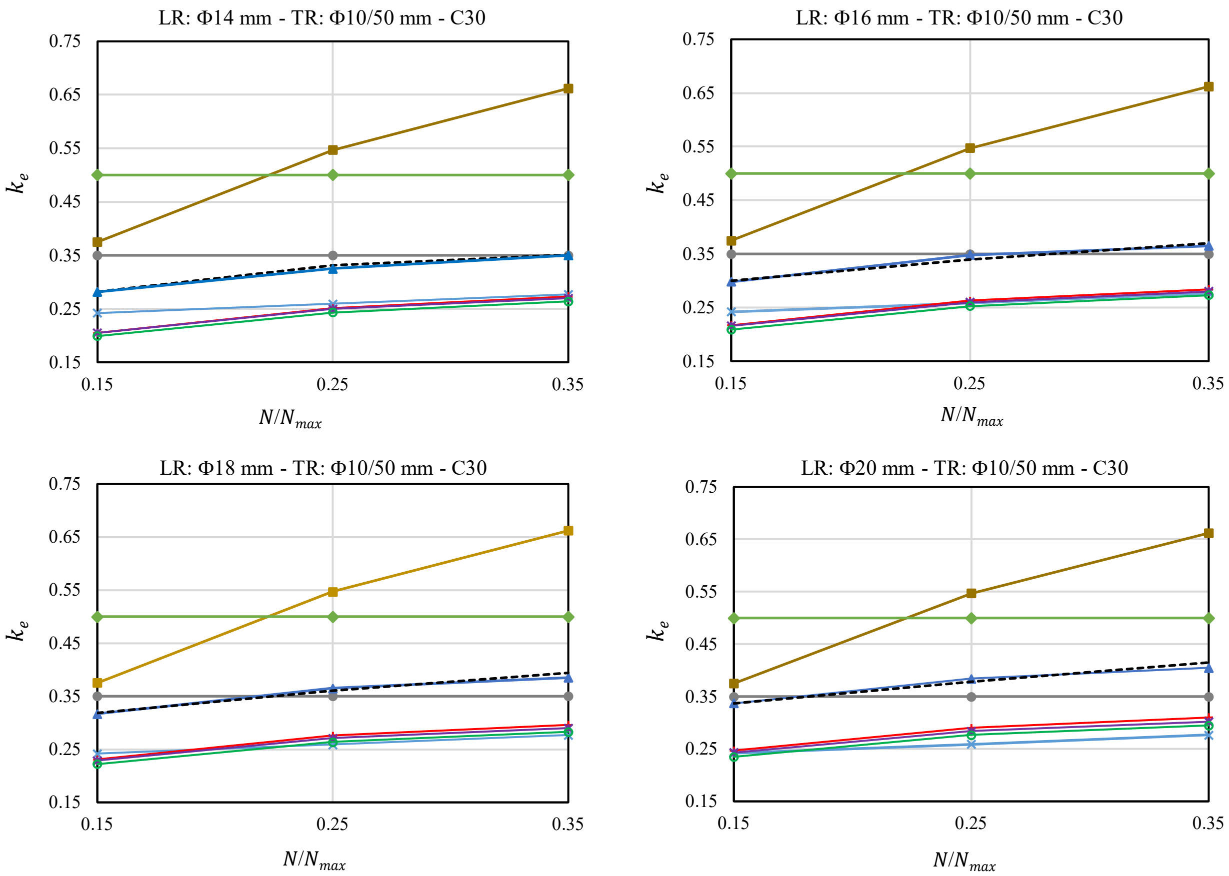
Fig. 2 *Comparison of predicting $k_{e,prop}$ and numerical results ($k_{e,num}$) for shear walls*



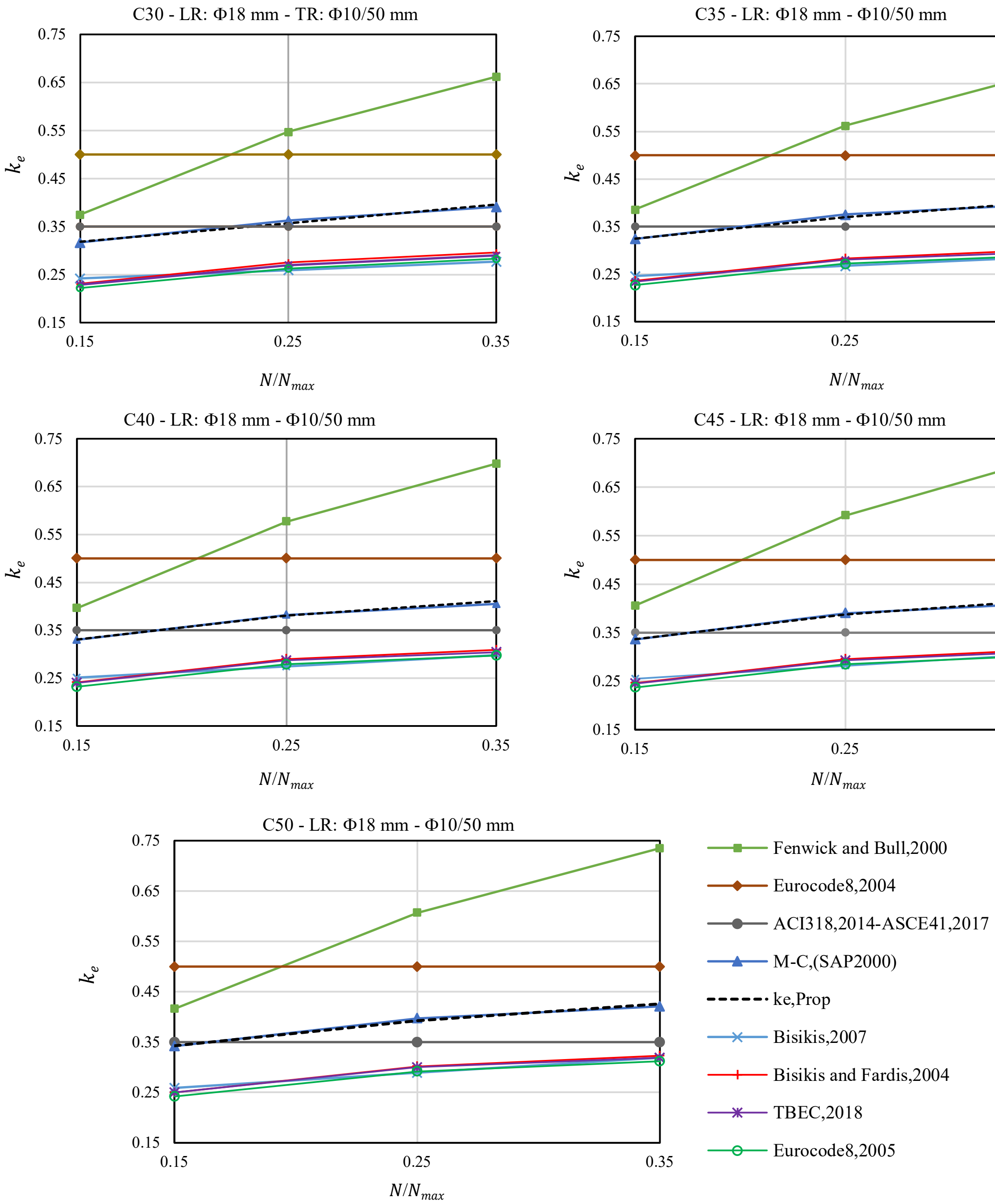
(a) Different transverse reinforcement's diameter



(b) Different transverse spacing of reinforcements



(c) Different the longitudinal reinforcement's diameter



(d) Different concrete strength and axial load levels

Fig. 3 *A comparison of the values that were estimated for various design parameters according to the proposed equation with other estimation formulas and relations*

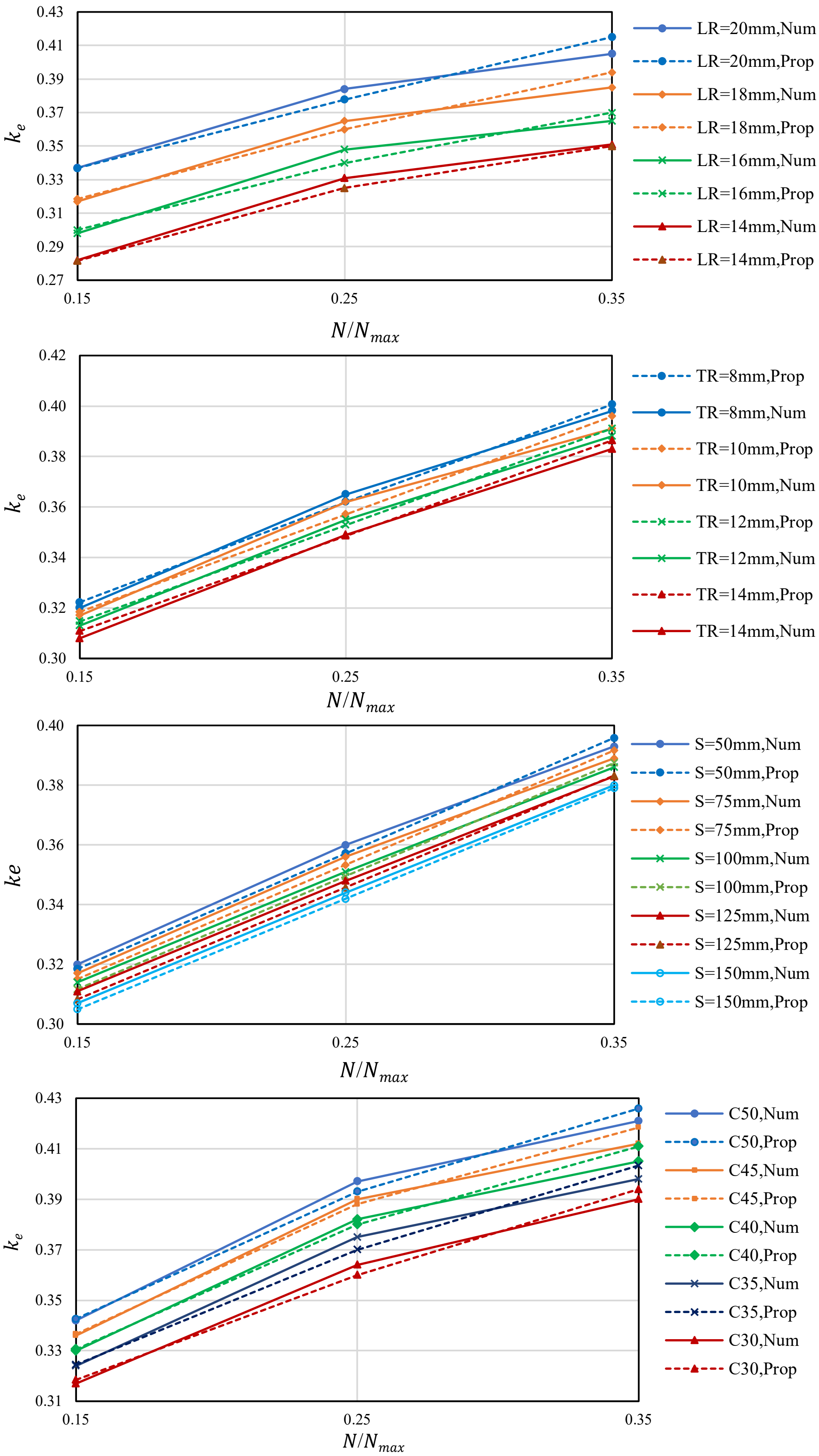


Fig. 4 *Comparison of the results obtained from the proposed equation and nonlinear moment-curvature relationships for various design parameters*

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According to the proposed equation and other estimation relations, the numerical analysis results for the calculation of the effective section stiffness of RC and the shear wall models were obtained differently from each other. The variation in results stems from the differing parameters considered in the effective section stiffness relations proposed by various researchers, as opposed to the constant coefficients established in the relevant standards and codes. In most relations, parameters such as axial load level and section dimension are taken into account. In some relations, axial load and longitudinal reinforcement ratio are taken into account. For RC shear walls, parameters affecting the behavior of sections such as transverse reinforcement are not taken into account. To obtain more realistic findings in the effective section stiffness calculation, the study considered the most significant design parameters influencing the behavior of shear wall models. Thus, missing parameters found in previous studies have been completed, and a suitable bit equation has been proposed for effective stiffness. It is evident that, across all parameter ranges, the suggested equation corresponds to the numerical findings. From numerical analysis and examination of the results obtained from the proposed equation, with the increase of axial load levels, longitudinal reinforcement diameters, and concrete compressive strength, the stiffness coefficient increases. The stiffness coefficient decreases with increasing transverse reinforcement ratio. The coefficients of correlation R^2 are significantly over 0.99, indicating excellent agreement between the provided predictions for shear walls. Additionally, the ratio of the suggested effective stiffness factor, which was determined by Equation (6), to the numerical result has a maximum mean value of 1.025 and a standard deviation of 3.31%, respectively.

4. Conclusions

Effective section stiffness of shear wall with high ductility level according to different design parameters; a comprehensive parametric study was carried out according to the relations given in the literature, non-linear relations, and the equation obtained from the numerical analysis results. The analysis results are different because different limit values are taken into account for parameters such as material properties, design parameters, and longitudinal and transverse reinforcement in studies and regulations in the literature. The structural stiffness will be overstated if the effective stiffness of the cracked section is assumed to be different or greater than the actual value in the analytical programs. This will result in significant inaccuracies in the design and assessment of the structures. In the analyses made by adhering to the regulations, the effective stiffness of the section is not a realistic behavior value. To determine the effective stiffness factor of RC structural elements, the stiffness values should be calculated by considering the non-linear behavior of the carrier elements instead of the factor values defined in the standard and codes.

The results are different because researchers or standards and codes consider parameters such as different materials and reinforcements and ignore some important design parameters. The adequacy of the proposed $k_{e,prop}$ equations has been verified by comparing the $k_{e,num}$ results obtained from the moment-curvature relations of the sections according to the nonlinear behavior of the materials with the parametric studies given in the literature. The ratio between the numerical results affected by changes in N/N_{max}, d_l, d_{tr}, s and f_{ck} and the results obtained from Equation (6). It can be seen that there is good agreement between the stiffness values calculated from the numerical analysis results and the proposed equation according to different design parameters for shear wall models. $k_{e,prop}$ values, which are calculated with the increase of N/N_{max}, d_l, d_{tr}, s and f_{ck}, also increase. Correlation coefficients R^2 are significantly above 0.99, which indicates that the proposed equation exhibits high agreement. Furthermore, the research findings and discussion provide an explanation of the highest mean value and standard deviation for each shear wall section regarding the ratio of the suggested effective stiffness factor, as determined by Equation (6), to the numerical result (1.025% and 3.31%).

The precision with which the stiffness of RC sections is estimated is essential for establishing realistic values of structural stiffness, which consequently influences the evaluation of applied seismic forces. The key parameters influencing the effective stiffness, which illustrate the impacts of cracking and theoretical yielding in RC sections, have been established through thorough moment-curvature analyses of various sections. The magnitude of axial load, concrete strength, and the quantities of transverse and longitudinal reinforcement have been recognized as critical factors influencing the effective stiffness. Comprehensive equations that adequately represent the effective stiffness of RC shear walls have been thoroughly developed. The findings of the numerical study indicate that the parameters under investigation have a significant influence on the effective stiffness coefficient of shear walls. According to the proposed equation, considering the nonlinear behavior of the shear walls, all parameters affecting this behavior are considered. Since the equation proposed for the stiffness factor considers the most important design parameters that affect the non-linear behavior of confined boundary wall sections, and as can be seen from the examination of the numerical results, it offers fairly accurate and consistent effective stiffness factor estimation. By using Equation (6), the stiffness factors of the cracked section of rectangular cross-section confined boundary wall sections according to different design parameters can be conveniently and simply calculated and compared.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

***Saeid Foroughi**: The study encompasses a comprehensive analysis plan, the design of reinforced concrete shear wall models, the systematic collection and evaluation of data, a thorough assessment of the findings, and the meticulous composition of the article. **Suleyman Bahadır Yüksel**: The study's analytical plan, the models developed for reinforced concrete shear walls, and an assessment of the numerical results articulated in terms of absolute error.*

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