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Investigation of Displacement Behavior of Reinforced Concrete Shear Walls with Different Plastic Hinge Relationships

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Abstract

The aim of this study is to investigate the plastic hinge length and peak displacement relationship for rectangular cross-sectional high ductile concrete shear walls in seismic zones. For plastic hinge lengths related to seismic design; the conditions given in the current regulations are used in the literature. An analytical study was conducted to evaluate the peak displacement relationship of reinforced concrete shear walls in seismic loads under plastic hinge regions. The length of the plastic deformation zone called the plastic hinge length has been investigated in this study by considering the regulations proposed by different regulations and researchers. Plastic hinge lengths of the designed reinforced concrete shear walls were calculated by plastic hinge models proposed by different researchers and regulations. Then, according to the plastic hinge lengths obtained from different relations, the yield displacement and plastic displacement values of the reinforced concrete shear walls were calculated and the total peak displacement values of the shear walls were obtained. The results of this study indicated that increase in plastic hinge length has a significant effect on the displacement and displacement ductility values of reinforced concrete shear walls. The most important parameter affecting the plastic hinge length is the dimensions of the reinforced concrete shear walls.

Anahtar Kelimeler: Plastic hinge, Seismic load, Shear wall, Peak displacement, Critical zone.

Betonarme Perde Duvarların Farklı Plastik Mafsal İlişkilerine göre Deplasman Davranışlarının Araştırılması

Özet

Bu çalışmanın amacı, sismik bölgelerde bulunan dikdörtgen en-kesitli süneklik düzey yüksek betonarme perde duvarlar için plastik mafsal uzunluğunu ve yük-tepe deplasman ilişkisini araştırmaktır. Sismik tasarım ile ilgili plastik mafsal uzunlukları için; literatürde önerilen bağıntılar ile mevcut yönetmeliklerde verilen koşullar kullanılmaktadır. Betonarme perde duvarların tepe yük-deplasman ilişkisinin yatay yükler altındaki plastik mafsal bölgelerinde değerlendirilmesi için analitik çalışma yapılmıştır. Plastik mafsal boyu olarak adlandırılan plastik şekil değiştirme bölgesinin uzunluğu bu çalışmada farklı yönetmelikler ve araştırmacılar tarafından önerilen bağıntılar dikkate alınarak araştırılmıştır. Tasarlanan betonarme perde duvarlarda plastik mafsal modelleri için farklı araştırmacılar tarafından ve yönetmeliklerde önerilen bağıntılar araştırılarak kesit geometrisi ve detaylarına göre plastik mafsal uzunlukları elde edilmiştir. Daha sonra farklı bağıntılardan elde edilen plastik mafsal uzunluklarına göre betonarme perde duvarların akma yer değiştirme ve plastik yer değiştirme değerleri hesaplanarak perde duvarların toplam tepe deplasman değerleri elde edilerek karşılaştırılmıştır. Bu çalışmanın sonucu, plastik mafsal uzunluğunun betonarme perde duvarların yer değiştirme ve deplasman süneklik değerlerinde önemli bir etkiye sahip olduğu göstermiştir. Plastik mafsal yüksekliğini etkileyen en önemli parametre betonarme perde duvarların boyutlarıdır.

Keywords: *Plastik mafsal, Sismik yük, Perde duvar, Tepe deplasman, Kritik bölge*.

1. Introduction

Plastic hinge region length of frame element over which flexural yielding is intended to occur due to earthquake design displacements, extending not less than a distance section height from the critical section where flexural yielding initiates (ACI318, 2014). Slender reinforced concrete walls, which are designed to have a larger shear resistance than flexural resistance, and whose behavior is therefore controlled by flexure rather than shear, behave in a ductile flexural mode when loaded beyond the elastic limit (Beyer et al., 2012). In order to idealize the inelastic non-linear behavior in respect to the materials, the models that are proved to be valid in the literature can be utilized. However, due to its practicability and extensiveness in engineering practices, lumped plastic behavior model is taken as a basis point for the inelastic non-linear analysis applied in the following sections. In this model that corresponds to the plastic support hypothesis in case of simple bending, it is assumed that the plastic deformations are formed in an evenly-distributed manner all along the finite length zones in which the inner forces in the beam, column and frame-type load-bearing components idealized as stick components reach to their plastic capacities. The length of the plastic deformation zone referred to as plastic support length (L_p) shall be taken as the half of the section length (h) in the active direction ($l_p = 0.5h$). For the frames where $H_w/L_w \leq 2$, the plastic deformations under the bending effect will not be taken into consideration. In reinforced concrete frames, plastic sections may be allowed to be placed on the bottom end zone of the frame zone for each floor (TSC, 2018).

The aim of this study is to investigate the plastic hinge length and peak displacement relationship for rectangular cross-sectional high ductile concrete shear walls in seismic zones. For plastic hinge lengths related to seismic design; the conditions given in the current regulations are used in the literature. The length of the plastic deformation zone called the plastic hinge length has been investigated in this study by considering the regulations proposed by different regulations and researchers. Reinforced concrete shear walls have been designed for the purpose of investigating plastic hinge length and peak displacement behavior. For the design of reinforced concrete shear walls, the rules for reinforced concrete shear walls with high ductility level were considered in Turkish Seismic Code (TSC, 2018). Then, according to the plastic hinge lengths obtained from different relations, the yield displacement and plastic displacement values of the reinforced concrete shear walls were calculated and the total peak displacement values of the shear walls were obtained. Nonlinear displacement, plastic rotation, plastic hinge length, yield displacement, plastic displacement and total peak displacement of reinforced concrete shear walls are given in the following sections.

2. Nonlinear Displacement in Reinforced Concrete Shear Walls

An important part of the seismic design of concrete wall buildings is ensuring that the flexural displacement capacity of the walls is greater than the flexural displacement demand. The inelastic (plastic) portion of flexural displacement results from a concentration of inelastic curvatures near the base of a wall (Bohl and Adebar, 2011). The flexural displacement profile of a cantilever wall is typically the summation of two components: the yield displacement profile and the plastic displacement profile. Reinforced concrete walls with an aspect ratio greater than 2 are typically governed by flexural action, rather than shear mechanisms, with plastic behavior at the base of the wall (Hoult et al. 2018). Although advanced analysis tools and procedures are currently available to determine the seismic response of reinforced concrete structural walls, the plastic hinge method and analysis derived from it are still used extensively in displacement-based seismic design and performance assessment procedures to estimate the inelastic displacement demand and capacity (Kazaz, 2013). The lumped plastic rotation (θ_p), along the plastic hinge length (L_p) is then computed as Eq. (1). Where $\emptyset_u$; is the maximum curvature and $\emptyset_y$; is the yield curvature, as shown in Fig. 1. In the plastic hinge analysis, the total peak displacement (Δ_u) of a cantilever is obtained as the sum of its yield displacement (Δ_y) and plastic displacement (Δ_p) component [Eq. (2, 3 and 4)].

H_w; is the height of the shear walls, Δ_y; yield displacement, Δ_p; plastic displacement, Δ_u; total peak displacement.

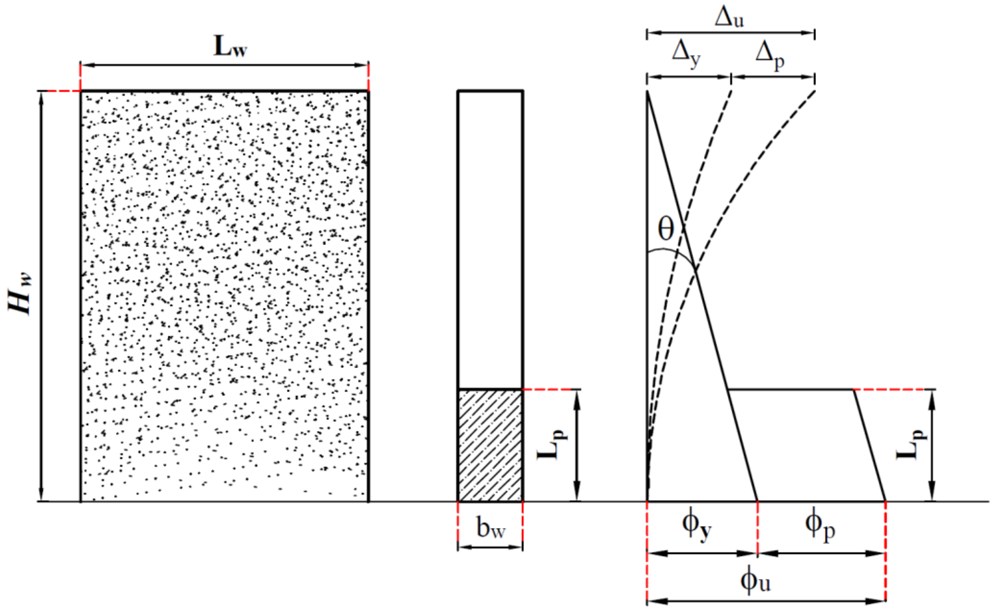

Figure 1. Theoretical model of cantilever shear walls.

$$\theta_p = \emptyset_p L_p = (\emptyset_u - \emptyset_y)L_p \tag{1}$$

$$\Delta_y = \frac{\emptyset_y\, H_w^2}{3}\ , \qquad \emptyset \leq \emptyset_y \tag{2}$$

$$\Delta_p = \theta_p(H_w - 0.5L_p) = (\emptyset_u - \emptyset_y)L_p(H_w - 0.5L_p)\ , \qquad \emptyset_y < \emptyset \tag{3}$$

$$\Delta_u = \Delta_y + \Delta_p = \frac{\emptyset_y\, H_w^2}{3} + (\emptyset_u - \emptyset_y)L_p(H_w - 0.5L_p)\ , \quad \emptyset > \emptyset_y \tag{4}$$

The need to establish a proper plastic hinge length stems from the idea that the assumption of elasto-plastic model under the Bernoulli-hypothesis of plane section remain plane with a simple plastic hinge length (L_p) as the half of the wall length (L_w) does not hold for the parameters which effect the spread of plasticity. Those phenomenas expilicitly explained by Priestley and Park (1987), which are moment gradient effect, tension shift and strain penetration effect (Aydin, 2018). The plastic hinge length (L_p) that formed at the ends of the shear wall significantly influences the flexural deformation capacity of a shear wall that can be evaluated by double integrating curvature distribution over the length of the shear wall (Zhi et al. 2019).

3. Plastic Hinge Models for Walls (Overview of plastic hinge lengths)

In this section, the models developed by various researchers to determine the plastic hinge length will be presented. According to Turkish Seismic Code (TSC, 2018) the length of the plastic deformation zone referred to as plastic support length (L_p) shall be taken as the half of the section length in the active direction.

$$L_p = 0.5L_w \tag{5}$$

Seismic Evaluation and Retrofit of Existing Buildings Code (ASCE41, 2017) and Building Code Requirements for Structural Concrete Code (ACI318, 2014), modified Eq. (16) for application to concrete walls by assuming that $\alpha = 0.5$ and $\beta = 0.1$.

$$L_p = \alpha\, 0.8L_w + \beta H_w = 0.4L_w + 0.1H_w \tag{6}$$

A recent study by Altheeb et al. (2015) used scaled-down experiments on lightly reinforced concrete elements to derive a plastic hinge length [Eq. (7)] based on the strain penetration length from the formation of a single crack:

$$L_p = \frac{\left(f_u - f_y\right) d_{bl}^2}{4\sqrt{f_c'}} \tag{7}$$

From the numerical results Bohl and Adebar (2011) concluded that the shear stress was sufficiently accounted for by including both the wall length L_w and shear span L_s in the Eq. (8) but that the axial load ratio should explicitly be considered. Where P is the axial load and A_w the gross cross-sectional area.

$$L_p = (0.2L_w + 0.05H_w)\left(1 - 1.5\frac{P}{A_w f_c'}\right) \leq 0.8L_w \tag{8}$$

Biskinis and Fardis (2010) proposed plastic hinge lengths which foremost depend on the type of loading that is applied. Based on a large experimental database, which comprised also test units with a rectangular wall-type cross section, they proposed plastic hinge lengths width, which the ultimate rotation was captured best on average. This empirical investigation led, for structural members with good seismic detailing, to the following proposed plastic hinge length equation, which is merely dependent on the member geometry.

$$L_{p,cyc} = 0.2L_w(1 + \frac{1}{3}\min\left(9\,;\,\frac{L_s}{L_w}\right) \tag{9}$$

The same components are included in the proposal by Priestley et al (2007) but with partially different factors. The first component was assumed to account for the spread of plasticity along the member and was hence chosen dependent on the ratio of ultimate to yield strength of the reinforcement steel.

$$L_p = \min\left(0.2\left(\frac{f_u}{f_y} - 1\right); 0.08\right)L_s + 0.2L_w + 0.022f_y d_l \tag{10}$$

The expression proposed for the plastic hinge length in Eurocode 8, Design of Structures for Earthquake Resistance (Part 3: Assessment and Retrofitting of Buildings) reads as (CEN, 2005):

$$L_p = \frac{L_s}{30} + 0.2L_w + 0.11\frac{d_l f_y}{\sqrt{f_c}} \tag{11}$$

The plastic hinge length recommended by Thomsen and Wallace (2004) calculated from Eq. (12).

$$L_p = 0.33L_w \tag{12}$$

Uniform Building Code (UBC, 1997) provides the equation for the plastic hinge length recommended Eq. 13.

$$L_p = 0.5L_w \tag{13}$$

Priestley et al. (1996) and Mattock (1967) proposed similar expressions to estimate the plastic-hinge length. According to Priestley et al. (1996); $\alpha = 0.08$, $\beta = 0$, and $\xi = 0.022$. Where l; member length, D; member depth and d_b; bar diameter of the longitudinal reinforcement.

$$L_p = \alpha l + \beta D + \xi f_y d_b = 0.08L_w + 0.022 f_y d_b \tag{14}$$

According to Paulay and Priestley (1992) based on a research specifically applicable to walls Eq. (15) is proposed.

$$L_p = 0.2L_w + 0.07\left(\frac{M}{V}\right) \tag{15}$$

Paulay and Uzumeri (1975), modified Eq. (18) for application to concrete walls by assuming that $d = 0.8L_w$ and $\zeta = H_w$, resulting in the following modified Sawyer (1964) equation. Paulay and Priestley (1993) recommended $\alpha = 0.5$ and $\beta = 0.044$ in Eq. (16) for a lower-bound estimate of L_p of shear walls. Where L_w; is the wall length and H_w; is the wall height.

$$L_p = \alpha d + \beta \zeta = \alpha\, 0.8L_w + \beta H_w \tag{16}$$

According to Park and Paulay (1975) the plastic hinge length is calculated from Eq. (17).

$$L_p = 0.5L_w \tag{17}$$

Sawyer (1964) developed a seminal equation for plastic hinge length. Sawyer (1964) assumed that plasticity would spread over a length of $d/4$, resulting in a total plastic hinge length of Eq. (18). Where $\alpha = 0.25$ ve $\beta = 0.075$ it is assumed. d; effective flexural depth and ζ; shear span ($\zeta = M/V$).

$$L_p = \alpha d + \beta \zeta = 0.25d + 0.075\zeta \tag{18}$$

4. Materials and Methods

In this study, different regulations for reinforced concrete elements and plastic hinge length relations proposed by the researchers were investigated. Plastic hinge length analytical investigation on the shear walls was performed according to the proposed plastic hinge length relations. For this analytical study, a rectangular cross-sectional concrete shear wall was designed. The design of reinforced concrete shear wall section geometry and reinforcement are seen in Fig. 2. In Turkish Seismic Code (TSC, 2018) the ratio of the length of the long edge ($L_w = 3.5m$) of the reinforced concrete shear walls to the thickness ($b_w = 0.3m$) in the plan has been determined to be greater than six. As the ratio of the total height ($H_w = 12m$) in the reinforced concrete shear walls to the plan length ($L_w = 3.5m$) is chosen to be greater than two, the shear walls confined boundary elements are formed at both ends of the walls. Confined boundary region dimensions of reinforced concrete shear walls are chosen as 300mm×700mm. The reinforcement diameters and reinforcement ratio used in the cross-sections were determined by considering the limitations given TSC (2018). According to TSC (2018), total cross section area of each of the vertical and horizontal web reinforcement on both faces of structural wall shall not be less than 0.0025 of the gross section area of the wall web remaining in between the wall boundary regions. The spacing of longitudinal and transverse reinforcement in wall web shall not be more than 250mm. Excluding the wall boundary regions, at least 10 special seismic crossties per unit square meter of the wall surface shall be used along the critical wall height. Crosstie diameter shall be at least equal to that of the horizontal reinforcement. The ratio of the total area of vertical reinforcement at each wall boundary regions to the gross wall cross section area shall not be less than 0.002 along the critical wall height. Diameter of transverse reinforcement to be used at wall boundary regions shall not be less than 8mm. Horizontal distance between the legs of hoops and crossties shall not be more than 25 times the diameter of hoops or crossties. Vertical spacing of hoops and crossties shall not be more than half the wall thickness and 150 mm, the spacing shall be greater than 50mm. The vertical and horizontal web reinforcement areas and vertical reinforcement area at wall boundary regions of the shear wall were designed according to TSC (2018).

$$\frac{A_s}{(L_w - 2l_u) \times b_w} \geq 0.0025 \leftrightarrow \frac{A_s}{(3500 - 2 \times 700) \times 300} \geq 0.0025 \leftrightarrow A_s \geq 1575mm^2$$

$$\frac{A_s}{L_w \times b_w} \geq 0.002 \leftrightarrow \frac{A_s}{3500 \times 300} \geq 0.002 \leftrightarrow A_s \geq 2100mm^2$$

For the designed shear wall, considering the limitations given in the regulations for web reinforcement, the longitudinal web reinforcements were selected as 22Φ12mm and the horizontal web reinforcement as Φ12/100mm. The longitudinal reinforcements in boundary regions of the designed shear wall were selected as 12Φ20mm, considering the limitations given in the TSC (2018). Longitudinal web reinforcement and longitudinal reinforcements in boundary regions limitations were checked for the designed shear wall according to the TSC (2018).

$$\frac{(A_s)_{22\emptyset 12}}{(L_w - 2l_u) \times b_w} = \frac{2488.14mm^2}{(3500 - 2 \times 700) \times 300} = 0.00394 > 0.0025 \surd$$

$$\frac{(A_s)_{12\emptyset 20}}{L_w \times b_w} = \frac{3769.91mm^2}{3500mm \times 300mm} = 0.00359 > 0.002 \surd$$

The details of the Longitudinal and horizontal reinforcement placement and ratios of the designed shear wall were given in Fig. 2 and Table 1.

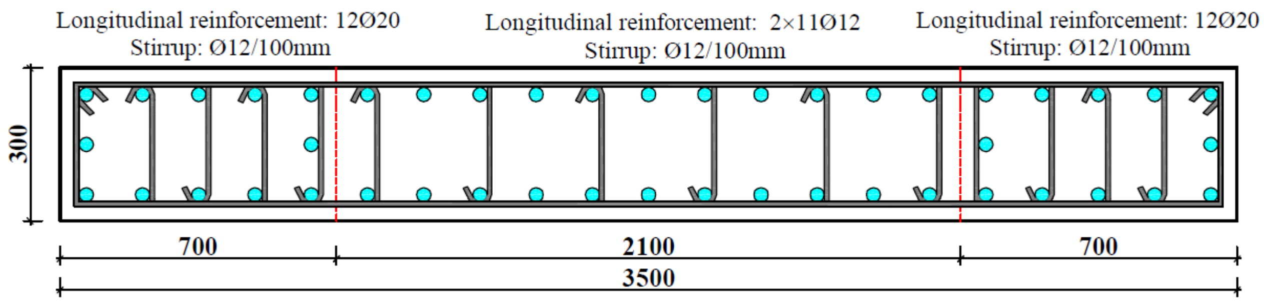

Figure 2. The sectional geometry and reinforcement appearance of reinforced concrete shear walls

Table 1. Details for the designed shear wall cross-sections

No	confined boundary region dimensions (mm)	Transverse Reinforcement Type	longitudinal reinforcement on confined boundary region	transverse reinforcement on confined boundary region	longitudinal reinforcement on shear wall web region	transverse reinforcement on shear walls
P1	700×300	Stirrup-crossties	12Φ20	Φ12/100	22Φ12	Φ12/100mm

In the first part of the study, moment-curvature relations of the elements were obtained by considering the nonlinear behavior of the reinforced concrete shear walls. Moment-curvature relationships were obtained by SAP2000 Software which takes the nonlinear behavior of materials into consideration. The moment-curvature relationships for different axial load levels of the reinforced concrete shear walls cross-sections were obtained considering Mander confined model (Mander et al., 1988). Yield curvatures ($\emptyset_y$) and ultimate curvatures ($\emptyset_u$) values are calculated from the moment-curvature relationships (Table 4, 5 and 6). The combined effect of vertical loads and seismic loads (N_{dm}), gross section area of shear wall shall satisfy the condition $A_c \geq N_{dm}/0.35f_{ck}$ (TSC, 2018). The moment-curvature, displacement and displacement ductility values were obtained for 0.15, 0.25 and 0.35 of N/N_{dm} ratio for the reinforced concrete shear wall sections. To investigate the effect of axial force on the cross-section behavior, the shear wall models were investigated for three different axial forces ($N_1 = 4725kN$, $N_2 = 7875kN$ and $N_3 = 11025kN$)

In the plastic hinge analysis, the tip displacement of a cantilever is obtained as the sum of its yield displacement (Δ_y) and plastic displacement component (Δ_p). Yield displacement (Δ_y), plastic displacement (Δ_p) and total displacement (Δ_u) values of the elements were calculated for different axial load levels according to the calculated by plastic hinge length in reinforced concrete shear wall sections. Whereas the Δ_y is calculated by double integrating the curvature distribution along the shear wall, the Δ_p component is calculated by multiplying the height (H_w) of the shear wall by the θ_p, up, at the base as expressed in Eq. (2, 3 and 4). Elastic and plastic displacements are taken into consideration in the total displacement relations of reinforced concrete shear walls. In calculating the total displacement of the reinforced concrete shear walls, the yield and maximum curvature values were obtained from the moment-curvature relationships which take into account the section height, plastic hinge length and nonlinear behavior are taken into consideration.

In the literature, plastic hinge lengths of reinforced concrete shear walls were calculated according to the different equations proposed for plastic hinge lengths (L_p). According to the obtained plastic hinge lengths and axial load levels, the proposed total displacement values of Eq. (4) are calculated and presented comparatively. The results obtained are reviewed and interpreted.

In the analytical study for reinforced concrete walls, the parameters and values given in Table 2 are used. For all models, C30 was chosen as concrete grade and S420 was selected as reinforcement for the reinforcement behavior model, the stress-strain curves given in TS500 (2000) and TSC (2018) were used (Table 2). The computed results for the models are summarized in the following Tables.

Table 2. Material parameters in property values (TS500, 2000; TSC, 2018)

Standard Strength	Parameters	Value
Concrete: C30	Strain at maximum stress of unconfined concrete (ε_{co})	0.002
	Ultimate compression strain of concrete (ε_{cu})	0.0035
	Characteristic standard value of concrete compressive strength (f_{ck})	30MPa
Reinforcement: S420	Yield strain of reinforcement (ε_{sy})	0.0021
	Spalling strain in reinforcing steel (ε_{sp})	0.008
	Strain in reinforcing steel at maximum strength (ε_{su})	0.08
	Characteristic yield strength of reinforcement (f_{yk})	420MPa
	Ultimate strength of reinforcement (f_{su})	550MPa

5. Research Findings and Discussion

The plastic hinge length and the total displacement behavior of the reinforced concrete shear walls having high ductility level were compared by comparing the results of the different plastic hinge relations and axial load levels. The recommended relationships for plastic hinge lengths with the conditions given in the current regulations are used. Plastic hinge relations are used to calculate the load-deformation relations of reinforced concrete shear walls. The plastic hinge relationships offered by different regulations and researchers are listed in Table (3) according to the dates of the study and the equation numbers given in the study. Plastic hinge lengths are calculated according to the proposed different plastic hinge relations of reinforced concrete shear walls and are given in Table (3).

Table 3. Plastic hinge length values calculated according to different plastic hinge relationships

Regulations / Researcher	No	Recommended Equation No	Plastic hinge length (L_p) mm
TSC (2018)	L_{p1}	5	1750
ASCE41 (2017) and ACI318 (2014)	L_{p2}	6	2600
Altheeb et al. (2015)	L_{p3}	7	1557,23
Bohl and Adebar (2011)	L_{p4}	8	1007,50
Biskinis and Fardis (2010)	L_{p5}	9	700,23
Priestley et al. (2007)	L_{p6}	10	849,90
CEN (2005)	L_{p7}	11	836,76
Thomsen and Wallace (2004)	L_{p8}	12	1155
UBC (1997)	L_{p9}	13	1750
Priestley et al. (1996)	L_{p10}	14	429,69
Paulay and Priestley (1992)	L_{p11}	15	700,24
Paulay and Uzumeri (1975)	L_{p12}	16	1228
Park and Paulay (1975)	L_{p13}	17	1750
Sawyer (1964)	L_{p14}	18	1320

Yield curvature ($\emptyset_y$) and maximum curvature ($\emptyset_u$) values of the moment-curvature relations of the sections were obtained for the calculation of the Δ_u values of the reinforced concrete shear walls. The calculated plastic hinge lengths according to the obtained $\emptyset_y$ and $\emptyset_u$ values are given in Table (3). According to different axial load levels, the displacement ductility of the shear walls was calculated by obtaining Δ_y, Δ_p and Δ_u values of reinforced concrete shear walls. The results of the calculations are summarized in Tables (4, 5 and 6) respectively according to different axial loads levels. Plastic hinge length-total peak displacement curve for different axial loads it is given Fig. 3 and plastic hinge length-displacement ductility curve for different axial loads is given Fig. 4.

Table 4. Result values for different plastic hinge relationships in reinforced concrete shear wall

N/N_{max}=0.15		Curvature (Rad/m)		Displacement			Displacement ductility
Plastic hinge length (m)		$\emptyset_y$	$\emptyset_u$	Δ_y	Δ_p	Δ_u	μ_Δ
L_{p1}	1,75	0,001	0,0049	0,048	0,076	0,124	2,58
L_{p2}	2,60				0,108	0,156	3,26
L_{p3}	1,56				0,068	0,116	2,42
L_{p4}	1,01				0,045	0,093	1,94
L_{p5}	0,70				0,032	0,080	1,66
L_{p6}	0,85				0,038	0,086	1,80
L_{p7}	0,84				0,038	0,086	1,79
L_{p8}	1,16				0,052	0,100	2,08
L_{p9}	1,75				0,076	0,124	2,58
L_{p10}	0,43				0,020	0,068	1,41
L_{p11}	0,70				0,032	0,080	1,66
L_{p12}	1,23				0,055	0,103	2,14
L_{p13}	1,75				0,076	0,124	2,58
L_{p14}	1,32				0,058	0,106	2,22

Table 5. Result values for different plastic hinge relationships in reinforced concrete shear wall

N/N_{max}=0.25		Curvature (Rad/m)		Displacement			Displacement ductility
Plastic hinge length (m)		$\emptyset_y$	$\emptyset_u$	Δ_y	Δ_p	Δ_u	μ_Δ
L_{p1}	1,75	0,0011	0,0033	0,0528	0,043	0,096	1,81
L_{p2}	2,60				0,061	0,114	2,16
L_{p3}	1,56				0,039	0,091	1,73
L_{p4}	1,01				0,026	0,078	1,48
L_{p5}	0,70				0,018	0,071	1,34
L_{p6}	0,85				0,022	0,074	1,41
L_{p7}	0,84				0,021	0,074	1,41
L_{p8}	1,16				0,029	0,082	1,55
L_{p9}	1,75				0,043	0,096	1,81
L_{p10}	0,43				0,011	0,064	1,21
L_{p11}	0,70				0,018	0,071	1,34
L_{p12}	1,23				0,031	0,084	1,58
L_{p13}	1,75				0,043	0,096	1,81
L_{p14}	1,32				0,033	0,086	1,62

Table 6. Result values for different plastic hinge relationships in reinforced concrete shear wall

N/N_{max}=0.35		Curvature (Rad/m)		Displacement			Displacement ductility
Plastic hinge length (m)		$\emptyset_y$	$\emptyset_u$	Δ_y	Δ_p	Δ_u	μ_Δ
L_{p1}	1,75	0,0013	0,0024	0,060	0,021	0,084	1,34
L_{p2}	2,60				0,031	0,093	1,49
L_{p3}	1,56				0,019	0,082	1,31
L_{p4}	1,01				0,013	0,075	1,20
L_{p5}	0,70				0,009	0,071	1,14
L_{p6}	0,85				0,011	0,073	1,17
L_{p7}	0,84				0,011	0,073	1,17
L_{p8}	1,16				0,015	0,077	1,23
L_{p9}	1,75				0,021	0,084	1,34
L_{p10}	0,43				0,006	0,068	1,09
L_{p11}	0,70				0,009	0,071	1,14
L_{p12}	1,23				0,015	0,078	1,25
L_{p13}	1,75				0,021	0,084	1,34
L_{p14}	1,32				0,016	0,079	1,26

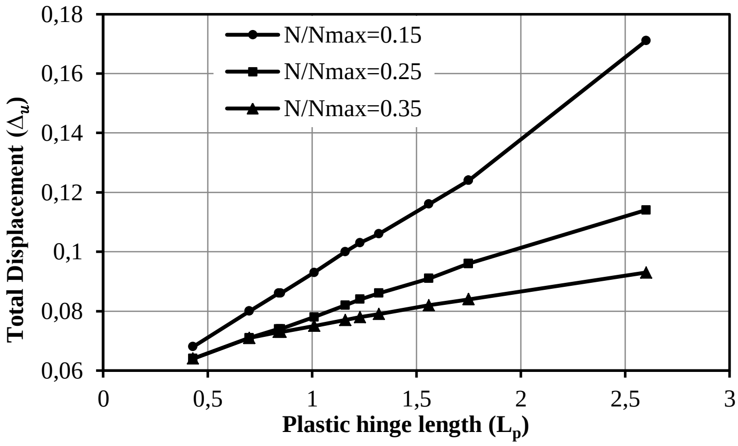

Figure 3. Plastic hinge length-total displacement curve for different axial load

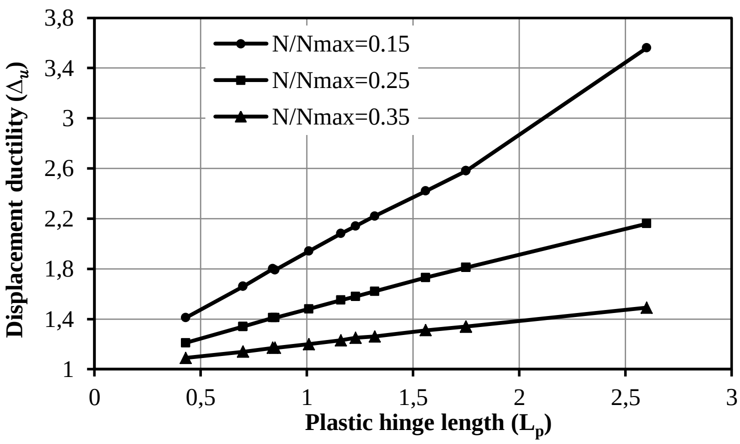

Figure 4. Plastic hinge length-displacement ductility curve for different axial load

6. Result

The following results were obtained from the analysis of reinforced concrete shear walls with high ductility level.

- Plastic hinge models are widely used to predict the load-deformation relationships of reinforced concrete members. The cross-sectional geometry of the elements is based on experimental and analytical studies and depending on the types of loading applied, different regulations are presented by the existing regulations and different researchers.
- Researchers in the study of plastic hinge length, H_w/L_w ratio, M/V ratio, axial load levels, the length of the strain penetration due to the formation of damage in the sections, the effect of the elements in experimental studies, the type of load applied in experimental studies, element geometry, material strength (concrete strength, reinforcement diameter and strengths), stress limits, different coefficient values and different analytical studies etc. have considered such parameters.
- The equations proposed to estimate the plastic lengths are for the ultimate damage state. It has been found that the widely used assumption that the plastic hinge length is half the wall length ($L_p = 0.5L_w$), underestimates the plastic hinge length as the wall length increase and shear effects become more pronounced.
- According to the proposed relations, the most important parameter affecting the plastic hinge length is the dimensions of the reinforced concrete shear wall (H_w and L_w).
- Different relations were obtained according to different parameters. As can be seen from the comparison of the results obtained from these different relations, different plastic hinge length values are obtained.
- Since some studies have common parameters, the difference in the plastic hinge length values is reduced.
- In order to calculate the total displacement values of the reinforced concrete shear walls, yield curvature ($\emptyset_y$) and maximum curvature ($\emptyset_u$) values were obtained from moment-curvature relationships according to the different axial load levels of the sections.
- Axial load value was found to be effective in moment-curvature relationships of reinforced concrete shear wall.
- As can be seen from the comparison of the values of $\emptyset_y$ and $\emptyset_u$ obtained according to the different axial load levels, with the increase of axial load level, the value of $\emptyset_y$ increases in small orders and $\emptyset_u$ value decreases.

- There are differences in the values of $\emptyset_y$ and $\emptyset_u$ values, different plastic hinge lengths and yield displacement (Δ_y), plastic displacement (Δ_p), total tip displacement (Δ_u) and displacement ductility (μ_Δ) values calculated according to different axial load levels. As can be seen from the comparison, the Δ_y value increases, Δ_p, Δ_u and μ_Δ value decreases with increasing axial load level.
- The value of μ_Δ decreases with increasing Δ_y values and decreasing of Δ_u values.
- There are differences in the calculated Δ_y, Δ_p, Δ_u and μ_Δ values according to $\emptyset_y$ and $\emptyset_u$ values, different plastic hinge lengths and different axial load levels.
- According to different axial load levels and plastic hinge lengths, different total displacement and ductility values are natural result.
- The term, $(\emptyset_u - \emptyset_y)L_p$, refers to the plastic rotation up and is based on the assumption that the plastic curvature is lumped in the center of the equivalent plastic hinge length (L_p). The actual physical length over which the plasticity spreads is larger and referred to as the plastic zone. It is assumed that inelastic curvatures vary linearly in walls over the plastic zone. Because the plastic hinge analysis is based on the condition that up $\theta_p = \emptyset_p . L_p$ as illustrated in Fig. 1.
- As can be seen from the comparison of the displacement values of reinforced concrete shear walls in terms of plastic hinge length values; the yield displacement value remains constant with the increase in plastic hinge length (independent of the length of the plastic hinge), plastic displacement value, total displacement and displacement ductility values are increasing.
- It is seen from the comparison results that the increase in plastic hinge length has a significant effect on the displacement and displacement ductility values of reinforced concrete shear walls.
- Smaller values of plastic-hinge length should be used to employ the plastic hinge analysis method safely in the displacement calculation of concrete shear wall.

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