

## Research Article

# Investigation of Ductility Reduction Factor in Seismic Rehabilitation of Existing Reinforced Concrete School Buildings

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**Abstract:** Converting existing Reinforced Concrete (RC) frames into RC infill walls is one of the most efficient seismic strengthening technique due to its simplicity in application providing high rigidity, stability and strength in structures. On the other hand, this method affects the seismic behavior of existing RC structure in terms of the energy dissipation capacity or in other words, ductility reduction factor,  $R_{\mu}$ . This research is an attempt to investigate the RC infill wall ratio effect on ductility reduction factor in terms of the seismic rehabilitation of the typical RC school buildings. For this purpose, nonlinear static pushover analyses are conducted for existing 3 and 5 story RC school buildings which were rehabilitated with different RC infill wall ratio. Numerical analyses are carried out by using the fiber element based modeling approach in the software, Perform-3D. Based on these analytical results, correlation between the ductility reduction factor and the RC infill wall ratio is obtained for the seismic rehabilitation of the RC school buildings. In addition, two mathematical expressions for the variation of the ductility reduction factor with RC infill wall ratios are proposed in terms of the preliminary seismic rehabilitation assessment of the existing RC school buildings.

**Keywords:** Fiber element based modeling, nonlinear static pushover analyses, perform-3D, shear walls, yield strength reduction factor

## INTRODUCTION

Among conventional Reinforced Concrete (RC) building structures, school buildings stand out by means of reducing the loss of life as well as serving as post-disaster shelters after an earthquake. Most of the existing RC school buildings in Turkey, which were designed; detailed and constructed according to past earthquake code regulations have inadequate strength and ductility capacity against the seismic demand. Therefore, these existing moment resisting frame RC buildings should be rehabilitated to improve their vulnerabilities. There are many methods to increase the seismic capacity of RC buildings such as jacketing of columns, steel bracing, CFRP wrapping or converting frames into RC infill walls. Among these retrofitting methods, RC infilled frames exhibited good structural performance during the recent earthquakes due to their high shear resistance and stability (Fintel, 1991). Therefore, converting an RC frame into an RC infill wall, which requires a simple construction technique with low economic cost, is increasing constantly for the seismic rehabilitation of existing RC frame systems. On the other hand, this method affects the energy dissipation capacity of the building by transforming the

existing moment-resisting frame structure to a dual system with ordinary RC moment frames and shear walls.

The main parameter of the dissipated energy during the earthquake is the ductility reduction factor,  $R_{\mu}$ , which is based on the inelastic deformation capability of the structure without collapse (Zafar, 2009). The first study for the evaluation of the ductility reduction factor was conducted by Newmark and Hall (1973, 1982). By several elastic and inelastic response spectral analyses, they proposed expressions to obtain ductility reduction factor, which depend on the displacement ductility ratio ( $\mu$ ) and the dominant vibration period ( $T$ ) of the structure. Lai and Biggs (1980) carried out inelastic analyses and suggested coefficients  $\alpha$  and  $\beta$  for the evaluation of the ductility reduction factor by employing 20 artificial ground motions. Nassar and Krawinkler (1991) examined the effect of strain hardening ratio, period and inelastic material behavior on the ductility reduction factor considering two different site conditions: rock and alluvium. Miranda (1993) conducted wide-range analyses for three different site conditions and proposed formulation that concerns soil condition, displacement ductility ratio and the period. Borzi and Elnashai (2000) performed

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regression analyses to obtain the ductility reduction factor and proposed a function depending on the period. Soydaş (2009) examined the ductility reduction factor variation with the shear wall index in RC structures, which have high strength material quality and adequate detailing according to the recent code regulations. Zafar (2009) obtained the ductility reduction factor by analyzing two prototype RC moment resisting frame structures.

As is seen, ductility reduction factor has been examined by many researchers for RC structures to be built according to the circumstances and recommendations of current codes but not for the rehabilitation of the existing RC buildings, which have been previously constructed with poor material quality, detailing and workmanship. The aim of this research is the investigation of the RC infill wall ratio effect on ductility reduction factor in terms of seismic rehabilitation of RC school buildings with typical structural layouts including the above mentioned structural deficiencies. For this purpose, nonlinear static analyses are conducted for the 3 and 5-story school buildings introducing different RC infill wall ratios, which can simply be described as the total RC infill wall area divided by the floor area.

### ANALYSES AND NUMERICAL SIMULATION DETAILS

In order to evaluate the effect of RC wall ratio on ductility reduction factor, structural models in numerical investigation are generated from an existing

RC school building, which is a commonly applied type in rather less populated towns of Turkey. The typical floor plan of the existing RC building is illustrated in Fig. 1. The other models, which have different RC infill wall ratios ranging between 0.35 to 2.40% are generated from this original model. All models have a rectangular floor plan having 36.45<sup>m</sup> in longitudinal direction and 18.45<sup>m</sup> in transversal direction. Dimensions of the structural elements in the generated models are similar to the original RC school building. The beams have flanged cross-sections with width to height ratio of 40<sup>cm</sup> by 60<sup>cm</sup> and columns have square geometry of side dimensions to be 60<sup>cm</sup>. The thicknesses of the floor and roof slabs are constant and equal to 20<sup>cm</sup>. Most of the existing school buildings in Turkey has low structural material qualities since they were constructed in 1960s and early 1970s. For this purpose, the concrete compressive strength is taken as 10 MPa, which is an approximate value (Tasdemir and Ozkul, 1999) and round bars denoted by S220 with 220 MPa of characteristic yield strength are used for transverse and longitudinal reinforcement in the entire structural systems. Typical reinforcement scheme for columns and beams are shown in Fig. 2.

**Loading phase:** The dead loads of the system is automatically calculated by the software, Perform-3D, while the superimposed load, 2.0 kN/m<sup>2</sup>, is applied as the external loads due to plaster, mortar and finishing. The live load is taken as 5.0 kN/m<sup>2</sup> for the normal floor and 1.5 kN/m<sup>2</sup> for the roof by considering the Turkish

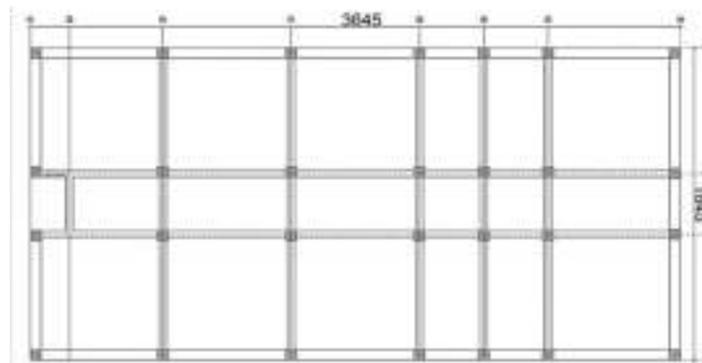


Fig. 1: Typical layout plan of the existing RC school building

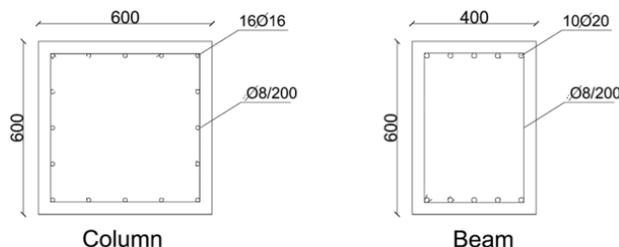


Fig. 2: Reinforcement details for columns and beams

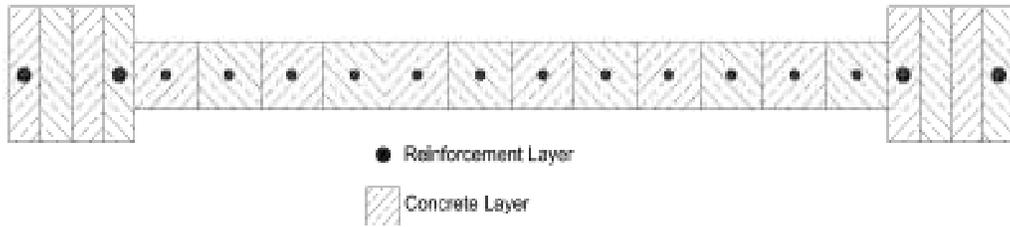


Fig. 3: Configuration of the concrete and reinforcement fiber layers in RC infill wall

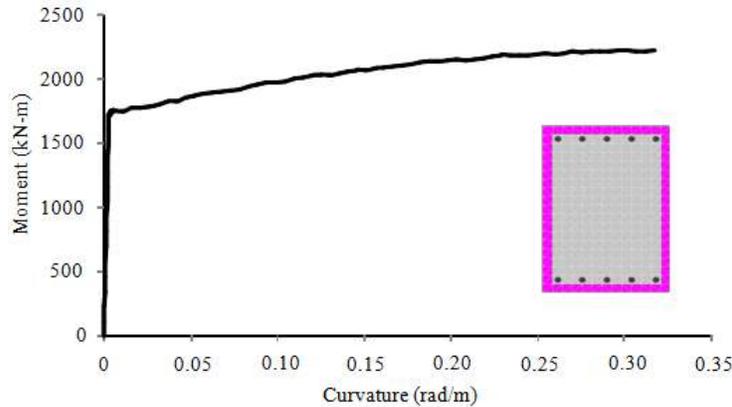


Fig. 4: Moment-curvature curve for the RC beam

Standard Design Loads for Buildings assignments (TS-498, 1987). Considering the building serving as a school, the live load participation factor is applied as 0.60 according to the Turkish Earthquake Resistant Design Code (TERDC, 2007) regulations. Load pattern for the pushover analyses is implemented into the mathematical model according to the equivalent earthquake load method which is compatible with the fundamental mode shape of the structure as specified in TERDC (2007). The control parameter of the displacement based pushover analyses is defined as the top drift of the structure. During the pushover analyses, loads are increased step by step until the plastic hinge occurrence in the section. Afterwards, the mathematical model is automatically modified and then increased loads are applied to the model till the next plastic hinge has occurred. Until the yield mechanism of the RC structure is exhibited or the target drift limit is achieved, this incremental process is continued.

**Modeling details:** Fiber element based model is the most preferred technique to simulate the non-linear behavior of RC elements in macroscopic approach (Guedes *et al.*, 1994). Therefore, the numerical simulation of the RC school building is evaluated by using fiber elements in the software Perform-3D. According to this model, the discretization of RC elements is made at the cross-section by dividing the section in an adequate number of fibers for concrete and steel reinforcement (Varum *et al.*, 2013). Precision of the mathematical model is getting better by increasing the fiber element number in section but this

method is not feasible solution by means of the simplicity and computer elapsed time especially for the non-linear analyses. In addition, each element in RC infill wall should be modeled at least two fiber concrete element to gain bending stiffness to the element. Therefore, optimum number of fibers is used to create the mathematical model. The configuration of the concrete and reinforcement fiber layers of the RC infill wall is illustrated in Fig. 3.

The general wall elements are preferred for RC infill walls and columns within the mathematical model. Due to the significant amount of computational time required during the analyses, beams are represented as frame model elements. Since all layers in fiber element model are interacted with each other and neutral axis shift can be simulated, calculation of the cracked moment of inertia ( $I_c$ ) for RC infill walls and columns is not required (CSI, 2006). For the RC beams, which are modeled with the frame elements, cracked moment of inertia ( $I_c$ ) is taken as the 40% of the gross moment of inertia ( $I_g$ ), as specified in TERDC (2007). Moment-curvature bilinear curve is defined for the beams according to lumped plasticity theory, as illustrated in Fig. 4. On the other hand, RC columns and RC infill walls are modeled with the fiber elements and the reinforcing bars are implemented in their exact locations. Therefore, material strains are directly occurred in the fiber sections. The non-buckling inelastic steel material is used for reinforcing steel and the inelastic 1D concrete material component is employed for the definition of the concrete. The trilinear curve is preferred for the representation

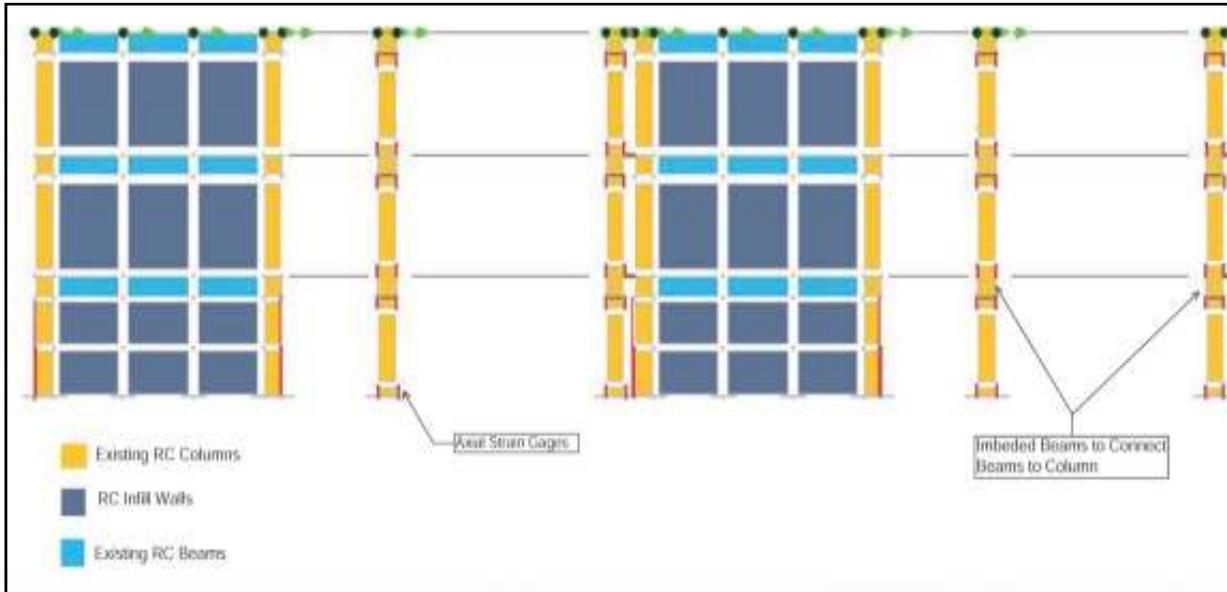


Fig. 5: The computer model of the 3 story RC school building for two consecutive frames

of the skeleton of the stress-strain curve for concrete and reinforcement constitutive models. The connecting surfaces between frame elements and the fiber elements are achieved by the imbedded beams. These fictive beams have high flexural stiffness while their axial stiffnesses are negligible. The 2D mathematical model of the 3 story RC school building is given in Fig. 5 for two consecutive frames.

### EVALUATION OF THE DUCTILITY REDUCTION FACTOR

Ductility reduction factor ( $R_\mu$ ), also known as the yield strength reduction factor in literature, is defined as the ratio between the maximum elastic ( $V_e$ ) and yield ( $V_y$ ) base shear force as given in Eq. (1) (Miranda and Bertero, 1994):

$$R_\mu = \frac{V_e}{V_y} \quad (1)$$

Elastic base shear ( $V_e$ ) is defined as the maximum demand force for the structure to remain elastic during an earthquake. In other words, if the structural design of the RC system is accomplished according to the elastic base shear forces, energy dissipation will not occur in RC structure. The elastic base shear can be simply calculated by the given Eq. (2):

$$V_e = W \times S_{ac}(T) \quad (2)$$

In this expression, elastic base shear ( $V_e$ ) depends on the elastic spectral acceleration  $S_{ac}(T)$  and the total weight ( $W$ ) of the building. Since the school building to

be considered herein settles on Z2 site class, spectrum characteristic periods are taken as  $T_A = 0.15$  and  $T_B = 0.40$ , respectively. The elastic base shear divided by total weight of the structure for the Z2 site condition in the highest seismic zone is obtained according to the TERDC (2007) requirements and illustrated in Fig. 6.

Yield base shear force ( $V_y$ ), which is the second parameter to calculate the ductility reduction factor ( $R_\mu$ ), is defined as the yield strength point of the structure. By using the bilinear approximation method, yield base shear force can be achieved from the pushover results. According to this method, the areas between the pushover curve and the bilinear approximation are balanced in terms of the equal energy method (Kessler, 2010). The main intend for this procedure is the area under the pushover curve, which corresponds to the dissipated energy during earthquake, should be equal the area under the bilinear curve. The end point of the bilinear curve is defined as the maximum displacement ( $\mu_{max}$ ) of the structure without being unstable. The typical pushover curve with the bilinear assessment is illustrated in Fig. 7.

During the analyses, the maximum displacement is assumed as the target displacement ( $u_0$ ) which is the performance point against the expected seismic demand. The performance point of each RC school building is obtained according to the procedure specified in TERDC (2007). In this method, pushover curves are transformed to the capacity spectrum by converting the lateral load ( $V$ ) and roof displacement ( $U$ ) values to modal acceleration ( $a$ ) and modal displacement ( $d$ ) by using the formula given in Eq. (3). According to the transition formula,  $\Phi$  is the modal displacement,  $\Gamma$  is the instantaneous participation factor and  $M$  is the effective modal mass:

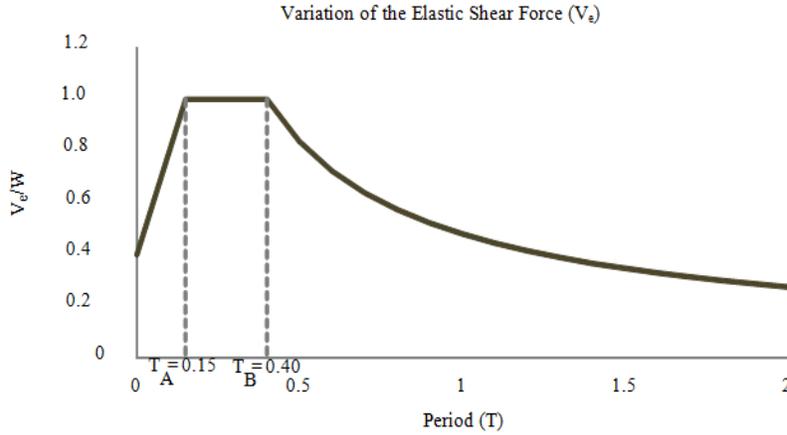


Fig. 6: Elastic base shear variation with the fundamental period of structure

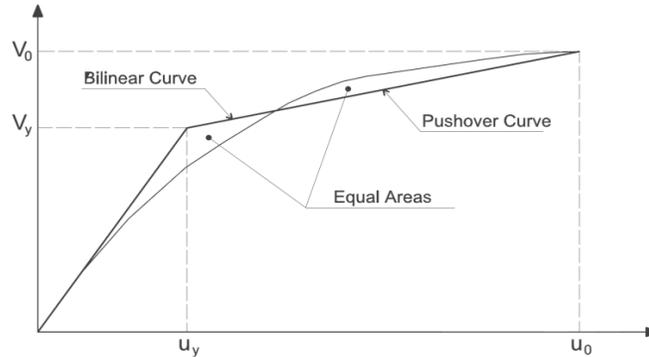


Fig. 7: Bilinear approximation method for pushover curve

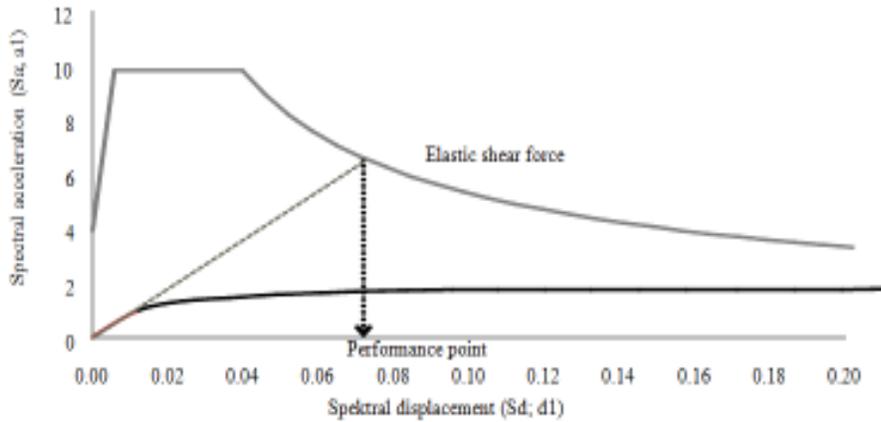


Fig. 8: Achievement of the elastic base shear force ( $V_e$ ) and the performance point ( $u_0$ )

$$d_i = \frac{u_{x1}}{\Phi_{x1}\Gamma_{x1}}; a_i = \frac{V_{x1}}{M_{x1}} \quad (3)$$

Following the axes transformation step of the procedure, target spectral displacement is established by intersecting capacity spectrum curve with the demand spectrum. For this purpose, straight line with slope, which is the initial stiffness of the capacity

spectrum, is extended through the demand spectrum to obtain the elastic spectral acceleration ( $S_{ac}$ ) and the target spectral displacement ( $d$ ). Afterwards, elastic displacement demand, also known as performance point ( $u_0$ ), can be calculated by converting the spectral displacement to elastic demand by using the Eq. (4):

$$U_1 = \Phi_{x1}\Gamma_{x1}d_1 \quad (4)$$

**ANALYSES RESULTS AND DISCUSSION**

Although analyses are performed for each direction, only results of the transversal direction are presented herein since no significant difference is occurred between the results of the two orthogonal directions. During the numerical analyses, vertical loads are applied first and then step by step incremental displacement based pushover analyses are performed until the 2% drift ratio of the top story is encountered for each building. Initially, obtained pushover curves are converted into the capacity curve and then performance point with elastic base shear of the each mathematic model is achieved. The procedure is graphically represented for the 5-story RC school building with 1% RC infill wall in Fig. 8.

According to the analyses results, variation of the elastic base shear force is obtained and illustrated in Fig. 9. Comparison of the elastic base shear forces shows that, providing excessive RC infill wall ratio decreases the elastic base shear in 3-story building while increasing in 5-story building. The reason for this phenomenon is the fundamental period of the RC structure. In other words, 3-story RC building is acted as very rigid structure and the natural period drops below the spectrum characteristic period  $T_A$  for high RC infill wall ratios. On the contrary, fundamental

period of the 5-story building is changing between the spectrum characteristic periods,  $T_A$  and  $T_B$ .

Once the target performance point is estimated from the intersection of the demand and capacity curve, yield base shear force ( $V_y$ ) is obtained from the pushover curve by using the bilinear approximation method. Finally, the ductility reduction factor ( $R_\mu$ ) is calculated from the ratio of the elastic base shear force ( $V_e$ ) and yield base shear force ( $V_y$ ). The variation of the ductility reduction factor according to the RC infill wall ratio is represented in Fig. 10 for 3- and 5-story buildings, respectively. As it is expected, using excessive RC infill wall ratio for seismic strengthening of the RC school building decreases the energy dissipation in the structure. Moreover, 3-story RC building, which is rehabilitated more than 1.5% RC infill wall ratio, responds with an elastic behavior without any energy dissipation during the earthquake. Variation of the ductility reduction factor for the 5-story RC buildings, which have 1.5% infill wall ratio or more, does not have a significant effect on  $R_\mu$ . As a result of these analyses, correlation between the ductility reduction factor and the RC infill wall ratio is obtained and given in Eq. (5) and (6):

$$R_\mu = -487446p^3 + 29000p^2 - 569p + 4.69..... \quad (5)$$

$p \geq 0.00.....3 \text{ Story Building}$

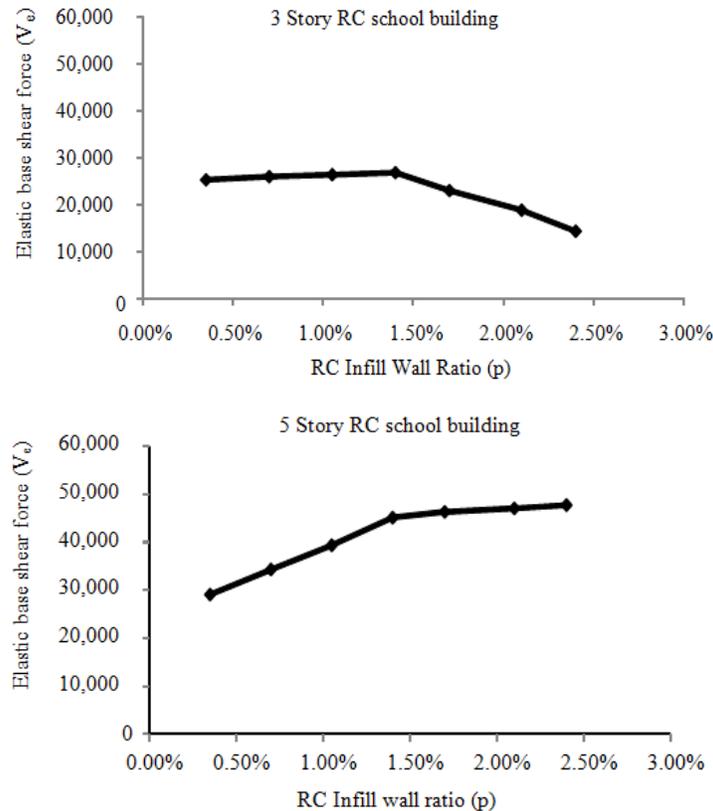


Fig. 9: Variation of the elastic base shear force ( $V_e$ )

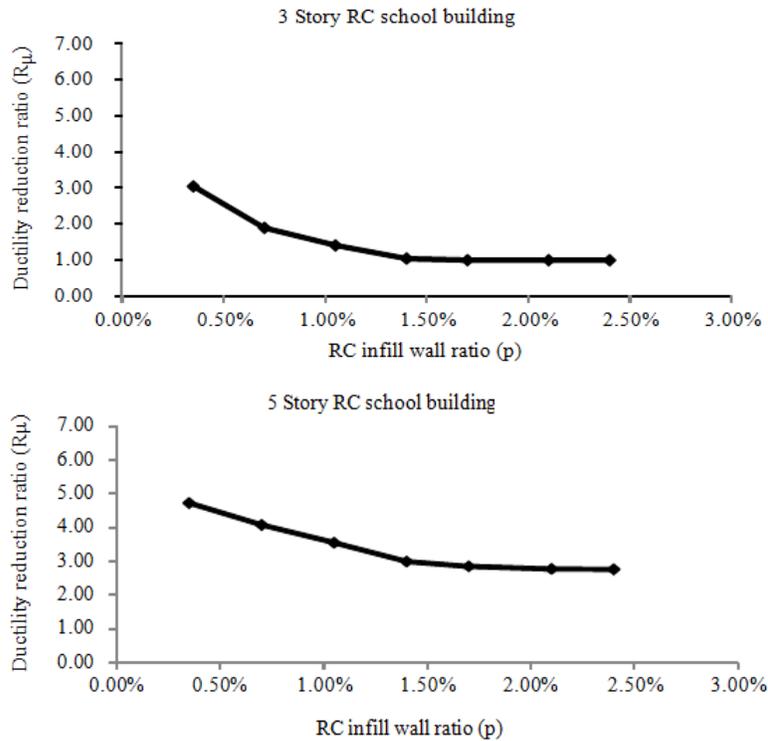


Fig. 10: Variation of ductility reduction factor

$$R_{\mu} = 72356 p^3 + 3289 p^2 - 234 p + 5.52 \dots \dots \quad (6)$$

$p \geq 0.00 \dots \dots 5 \text{ Story Building}$

**CONCLUSION**

The nonlinear static pushover analyses of the 3 and 5-story RC school buildings, which were rehabilitated with different ratios of RC infill walls, are performed by using the fiber element based modeling approach. Following the analysis procedure described in TERDC (2007), performance point, yield base shear force and elastic base shear force is obtained. Relationship between the ductility reduction factor and the RC infill wall is examined. According to the conducted numerical investigation, using 1.5% or more RC infill wall ratio for the seismic strengthening of the 3 story RC school buildings prevents the energy dissipation during earthquake. Indeed, RC structural system with high RC infill wall ratio behaves elastically without any ductile response. Therefore, rehabilitation of the existing low story RC school buildings with high RC infill wall ratio is neither feasible nor economical. On the other hand, preferring more than 1.4% RC infill wall ratio for the 5 story RC school buildings will not change the ductility reduction factor significantly. In addition, by using the given expressions for the variation of the ductility reduction factor with RC infill wall ratios, the preliminary seismic rehabilitation assessment can be achieved for the RC school buildings.

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**REFERENCES**

Borzi, B. and A.S. Elnashai, 2000. Refined force reduction factors for seismic design. *Eng. Struct.*, 22(10): 1244-1260.

CSI, 2006. *Perform Components and Elements For Perform-3D and Perform-Collapse*. Version 4, Computer and Structures Inc., Berkeley, CA.

Fintel, M., 1991. Shearwall: An answer for seismic resistance. *Concrete Int.*, 13(7): 48-53.

Guedes, J., P. Pegon and A.V. Pinto, 1994. *A Fibre/timoshenko Beam Element in CASTEM 2000*. JRC-Special Publication No. 1.94.31, STI, JRC, EC, Ispra, Italy.

Kessler, S., 2010. *A study of the seismic response modification factor for log shear walls*. M.Sc. Thesis, Kansas State University, Manhattan, Kansas.

Lai, S.P. and J.M. Biggs, 1980. Inelastic response spectra for a seismic building design. *J. Struct. Eng-ASCE*, 106(6): 1295-310.

Miranda, E., 1993. Site-dependent strength-reduction factors. *J. Struct. Eng-ASCE*, 119(12): 3503-3519.

- Miranda, E. and V.V. Bertero, 1994. Evaluation of strength reduction factors for earthquake resistant design. *Earthq. Spectra*, 10(2).
- Nassar, A.A. and H. Krawinkler, 1991. Seismic demands for SDOF and MDOF systems. Report No. 95, John A. Blume Earthquake Engineering Center, Stanford University, California.
- Newmark, N.M. and W.J. Hall, 1973. Seismic design criteria for nuclear reactor facilities. Report No. 46, Building Practices for Disaster Mitigation, U.S. Department of Commerce, National Bureau of Standards.
- Newmark, N.M. and W.J. Hall, 1982. Earthquake Spectra and Design. EERI Monograph Series, Earthquake Engineering Research Institute, Oakland, California, pp: 103.
- Soydaş, O., 2009. Evaluation of shear wall indexes for reinforced concrete buildings. M.Sc. Thesis, Middle East Technical University, Ankara, Turkey.
- Tasdemir, M.A. and M. Ozkul, 1999. Marmara depremi beton araştırması. *Hazır Beton Birliği*, 6(36): 32-35. (In Turkish)
- TERDC, 2007. Specification for Buildings to be Built in Seismic Zones. Turkish Standards Institution, Ministry of Public Works and Settlement, Ankara.
- TS-498, 1987. Design Loads for Buildings. Turkish Standards Institute, Ministry of Public Works and Settlement, Ankara.
- Varum, H., F.T. Dias, P. Marques, A.V. Pinto and A.Q. Bhatti, 2013. Performance evaluation of retrofitting strategies for non-seismically designed RC buildings using steel braces. *B. Earthq. Eng.*, 11(4): 1129-1156.
- Zafar, A., 2009. Response modification factor of reinforced concrete moment resisting frames in developing countries. M.Sc. Thesis, University of Illinois, Urbana, Illinois.