Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 371

EVALUATION OF SHEAR WALL INDEXES FOR RC BUILDINGS

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ABSTRACT

Observations made after devastating earthquakes revealed that presence of shear walls improves seismic performance of reinforced concrete buildings. However, the correlation between seismic performance and shear wall area in RC buildings has not been studied in detail. For this reason, an analytical study was carried out to evaluate shear wall indexes for low to mid-rise reinforced concrete buildings. Forty five 3D building models with two, five and eight storeys having different wall ratios were generated. These building models had the same floor plan with different orientation and area of shear walls. The ratio of shear wall area to the floor area varied between 0.53 to 3.60 percent. Linearly elastic and nonlinear static pushover analyses of the models were performed by SAP2000. The response of buildings was investigated under the response spectrum given in the Turkish seismic code considering that all buildings were located in the highest seismic zone. The variation of roof drift with shear wall ratio was obtained and the results were compared with the results of approximate procedures given in the literature. The results indicated that despite a strong trend between the wall ratio and the drift up to a wall ratio of 2 percent, the increase in the shear wall ratio does not result in a significant change beyond the shear wall ratio of 2.5 percent. This implies that an increase in the wall ratio beyond 2 to 2.5 percent does not lead to significant improvement in the response.

Introduction

Satisfactory performance of buildings with shear walls in recent severe earthquakes has led to research on behavior of such buildings. These earthquakes showed that the large in-plane stiffness provided by shear walls reduces lateral drifts which in turn limit damage of both structural and non-structural components. This fact reveals motivation on investigation of relationship between the shear wall ratio and lateral drift ratio of buildings. The relationship between shear wall ratio and lateral drift ratio can be used to suggest sufficient shear wall ratio at the preliminary design stage of buildings.

Shear wall index is an indicator of the proportioning of walls that are used for seismic resistance of buildings. Wall index for a structure is generally obtained by the ratio of total area of shear walls at a typical storey in the direction of seismic analysis (ΣA_w) to floor plan area at

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that storey (A_p) or total floor plan area of the building (ΣA_p). There are several studies about wall indexes in the literature that propose approximate index values for adequate strength and rigidity at the preliminary design stage. These studies are generally based on approximate force-based relations or empirical index values obtained from structures that are exposed to severe earthquakes in the past but experienced slight or no damage.

Hassan and Sozen (1997) present a simplified method of ranking reinforced concrete, low-rise (1 to 5 storey), monolithic buildings according to their vulnerability to seismic damage by using wall and column indexes. A study of Wallace and Moehle (1992) demonstrates that the ratio of 1 percent is used widely in typical US construction for concrete buildings five to twenty stories tall.

Earthquake ground motions induce lateral forces that cause lateral deformations on both structural and nonstructural components of a building. Lateral drift is a well-known type of lateral deformation used frequently in determination of expected damage of a building. However, there is limited study on the change of lateral drift with shear wall ratio in the literature. Existing studies generally investigate the effect of different wall ratios with different aspect ratios on roof drift (ratio of maximum lateral displacement of the roof to the height of structural wall). Wallace (1994) uses an analytical procedure to estimate the variation of roof drift ratio as a function of wall ratio. The procedure is approximate and based on many assumptions. Gülkan and Sözen (1997) gives similar procedure with Wallace (1994) in determination of roof drift vs. wall ratio. The studies differ from each other in determination of elastic displacement response spectrum which results in different roof drift ratios for the same wall ratio.

In order to evaluate shear wall indexes for reinforced concrete structures, five 3D models, low to mid-rise (2, 5 and 8 stories) buildings with different wall ratios are generated. Linearly elastic and inelastic analyses (nonlinear static pushover analysis) of these model buildings are performed by SAP2000 v 11.0.8 according to the procedures defined by TEC 2007 (2007). Target displacements for inelastic analyses are determined by displacement coefficient method of FEMA 440 (2005). Change of elastic and inelastic roof drifts with shear wall ratio is obtained and results are compared with approximate methods.

Description of Building Models

Five different models for each number of story having same floor dimensions but different shear wall ratio are created for use in the analyses. A typical first storey plan of these models is given in Fig. 1. Shear wall ratio is determined by dividing total shear wall area in one direction to the floor plan area of one storey. The structural models used in the analysis are based on a previous investigation about the building inventory in Zeytinburnu / İstanbul. The geometric properties of the building models like storey height, floor area and etc. are determined according to the average values obtained from this inventory. Shear walls are located in axes similar to the practice in the inventory. Then, shear wall ratios of the model buildings are changed to obtain different shear wall ratios. Although the average values of the geometric properties are used in formation of building models, they are re-designed according to TEC 2007. As shown in Fig. 2, wall ratios change from 0.53 to 3.60 percent in the models.

Shear wall thickness is the same for all walls in a given model but is changed as 20, 25 and 30cm to obtain different wall ratios. Considering the building stock of Turkey, 2, 5 and 8 story buildings that have 2.9m story height totaling to 5.8, 14.5 and 23.2m heights are analyzed. All columns have square cross-section with 0.4x0.4m dimension and all beams have rectangular cross-section with 0.25x0.4m dimension in all models.

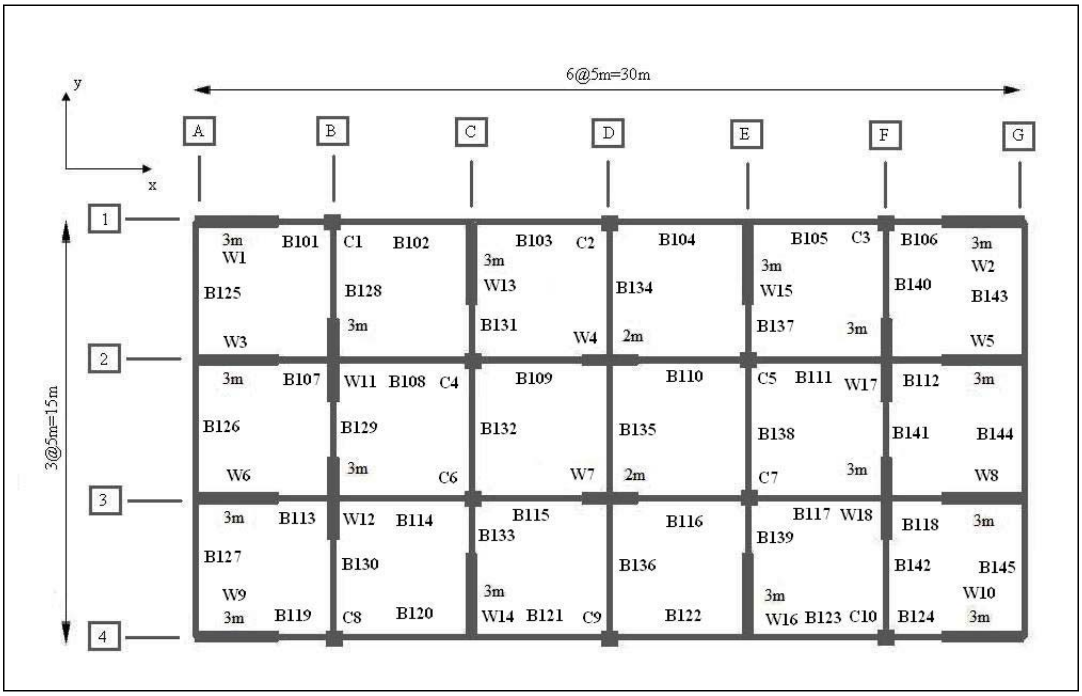

Figure 1. A typical floor plan for building models employed.

The structural members (beams and columns) are modeled with frame elements. Equivalent beam model is used for modeling of structural walls. Rigid beams are used as link elements between structural walls and beams. Concrete class and longitudinal reinforcing steel are chosen to be C20 (characteristic compressive strength of concrete is 20 MPa) and S420 (characteristic yield strength of steel is 420 MPa), respectively. Cracked section stiffness is calculated according to TEC 2007. It is assumed that the buildings are located in the first seismic zone with Z1 soil type defined in TEC 2007.

Analyses of Buildings

All building models were analyzed using elastic and inelastic procedures described in the Turkish earthquake code (TEC 2007). Equivalent lateral load procedure and nonlinear static analysis based on triangular load pattern were used. Modal analyses of the model buildings are performed with SAP2000, and building periods, modal participation factors for the fundamental vibration modes, and effective modal mass coefficients for the fundamental vibration modes of the model buildings were determined for each principle directions. Modal participation factor varied from 1.2 to 1.4 and effective modal mass coefficients were determined to be between 0.7-0.85. Variation of building periods with shear wall ratio and storey number (n) is given in Fig. 3. Examination of the results reveals that the behavior of these building models is dominated by the first mode response. In all buildings, variation of building period with the wall ratio shows significant change at lower wall ratios with total change being approximately 50 percent for a constant building height.

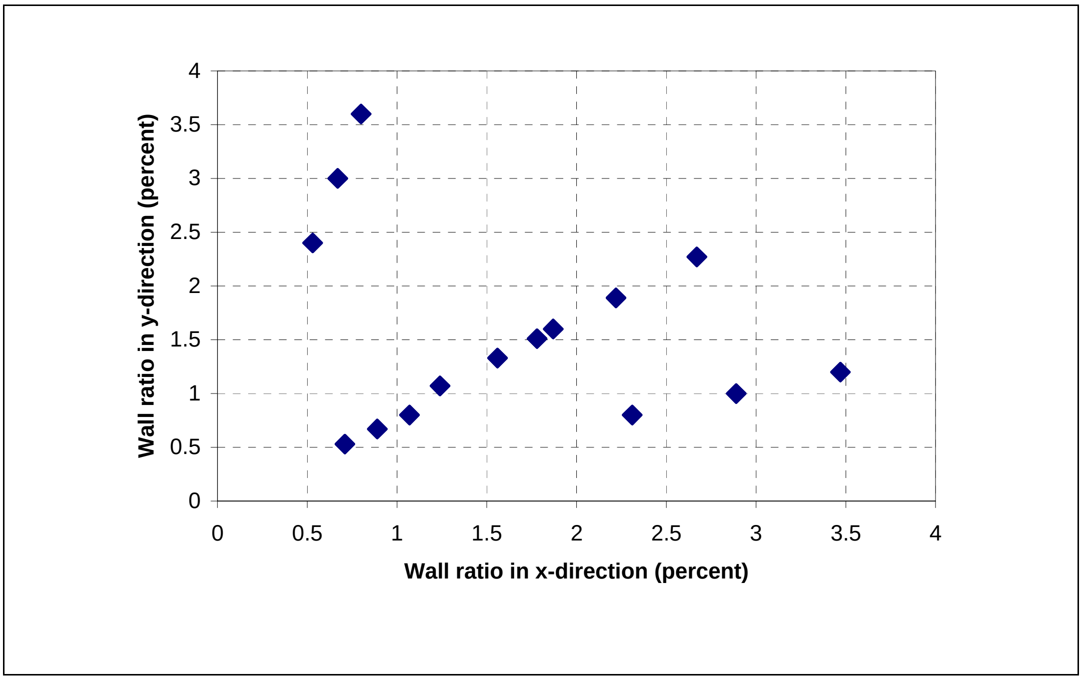

Figure 2. Wall ratios for the building models employed.

Pushover curves obtained from nonlinear static analyses were idealized using the approach given in FEMA 356 (2000). The variation of yield strength reduction factor (R_y) and displacement ductility (μ_t) with wall ratio is plotted in Fig. 4. Distribution of points is approximated by second order polynomials for each storey number as shown. These curves show that variation up to a certain wall ratio (approximately 2 percent) is more significant especially for low rise buildings.

Influence of Wall Index on Elastic Drift

Lateral drift that is caused by earthquake ground motions is one of the fundamental parameters that affect the damage level of both structural and nonstructural elements in buildings. Therefore, reasonable estimation of lateral drift is important at preliminary design stage of new buildings or for a rapid and easy seismic evaluation of existing buildings. In order to investigate the influence of wall index on elastic drift ratio, results obtained from elastic analyses as well as from approximate procedures given in literature were compared. Approximate methods of Wallace (1994) and Miranda and Reyes (2002) are used in the analysis.

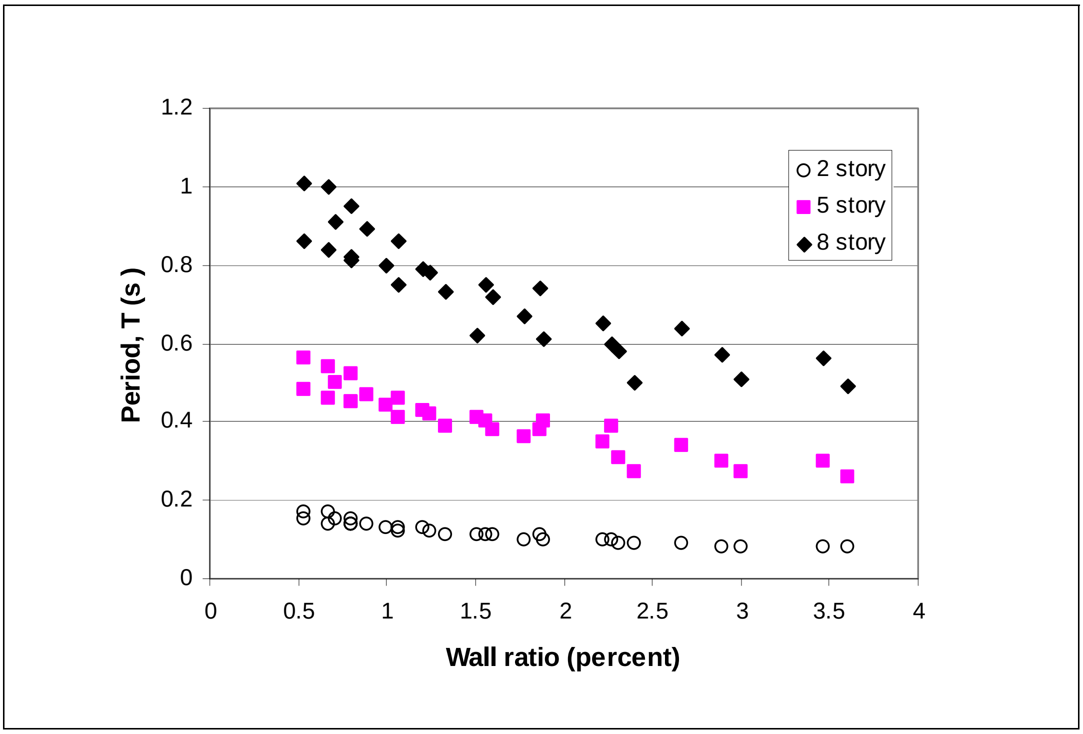

Figure 3. Variation of Period with Shear Wall Ratio.

Wallace (1994) proposes a relation for determination of elastic spectral displacement ($S_d(T)$) and modifies it with a coefficient to find the elastic lateral drift. Assuming that the roof displacement can be approximated by 1.5 times the spectral displacement to account for the difference between the displacement of a single degree of freedom oscillator and the building system the oscillator represents, Wallace approximates roof drift ratio (roof displacement divided by building height, δ_u / h_w) as;

$$\frac{\delta_u}{h_w} = \frac{1.5 S_d(T)}{h_w} \tag{1}$$

Miranda and Reyes (2002) propose a simple method considering only the fundamental mode of vibration to estimate elastic lateral drift. According to this method, roof displacement, is estimated by multiplying elastic spectral displacement by a coefficient which is indeed participation factor as follows;

$$u_{roof} = \beta_1 S_d \tag{2}$$

Where S_d : Spectral displacement evaluated at the fundamental period of the structure

β_1 : Dimensionless amplification factor for the continuum model and can be computed assuming a uniform mass distribution as follows;

$$\beta_1 = \frac{\sum_{j=1}^{N} \psi_j}{\sum_{j=1}^{N} \psi_j^{\,2}} \tag{3}$$

Where ψ_j is the normalized lateral displacement shape given by:

$$\psi_j = \psi_j(z_j) = u(z_j)/u(H) \tag{4}$$

z_j : Height of the jth floor measured from the ground level
N: Number of stories in the building
$u(z_j)$, $u(H)$: Lateral displacements computed in the continuum model at heights z_j and H, respectively.

Elastic lateral drift estimations are made by approximate methods proposed by Wallace, and Miranda and Reyes for different shear wall ratios. In order to evaluate the results of the analyses obtained from approximate methods, linear elastic analysis is carried out with SAP2000 v 11.0.8 for the model buildings. The variation of roof drift ratio with shear wall ratio for 2, 5 and 8 stories is plotted in Figure 5.

As it is evidenced in these graphs, the increase in the shear wall ratio does not result in a significant change in the drift ratio beyond the shear wall ratio of 2.5 percent. This indicates that increasing wall ratio furthermore does not affect the roof drift ratio too much for high shear wall ratios. For shear wall ratios smaller than 1 percent, Wallace underestimates roof drift for 2 storey buildings and overestimates roof drift for 5 and 8 storey buildings. For 5 and 8 storey buildings and wall ratios smaller than 1 percent, the overestimates by Wallace are unreasonably high and do not result in realistic values. However, for 5 storey buildings, the method is better than other methods in roof drift estimations for wall ratios between 1-2 percent. Miranda and Reyes generally underestimate roof drift for 2, 5 and 8 storey buildings. However, the deviation from elastic analysis is not too much especially for wall ratios greater than 2 percent. Although a larger discrepancy can be observed for lower wall ratios, they generally provide a reasonable estimate for elastic drifts. According to the elastic analysis, change of roof drift ratio with the wall ratio is higher in 2 storey buildings. However, for 8 storey buildings, change of drift ratio with the wall ratio is less significant.

Influence of Wall Index on Inelastic Drift

In this section, various approximate procedures proposed for the calculation of inelastic displacement demand are evaluated for the model buildings employed based on the comparisons with the results obtained through pushover analyses using SAP2000. The displacement coefficient method of FEMA 440 (2005) is used in this study for inelastic demand estimation.

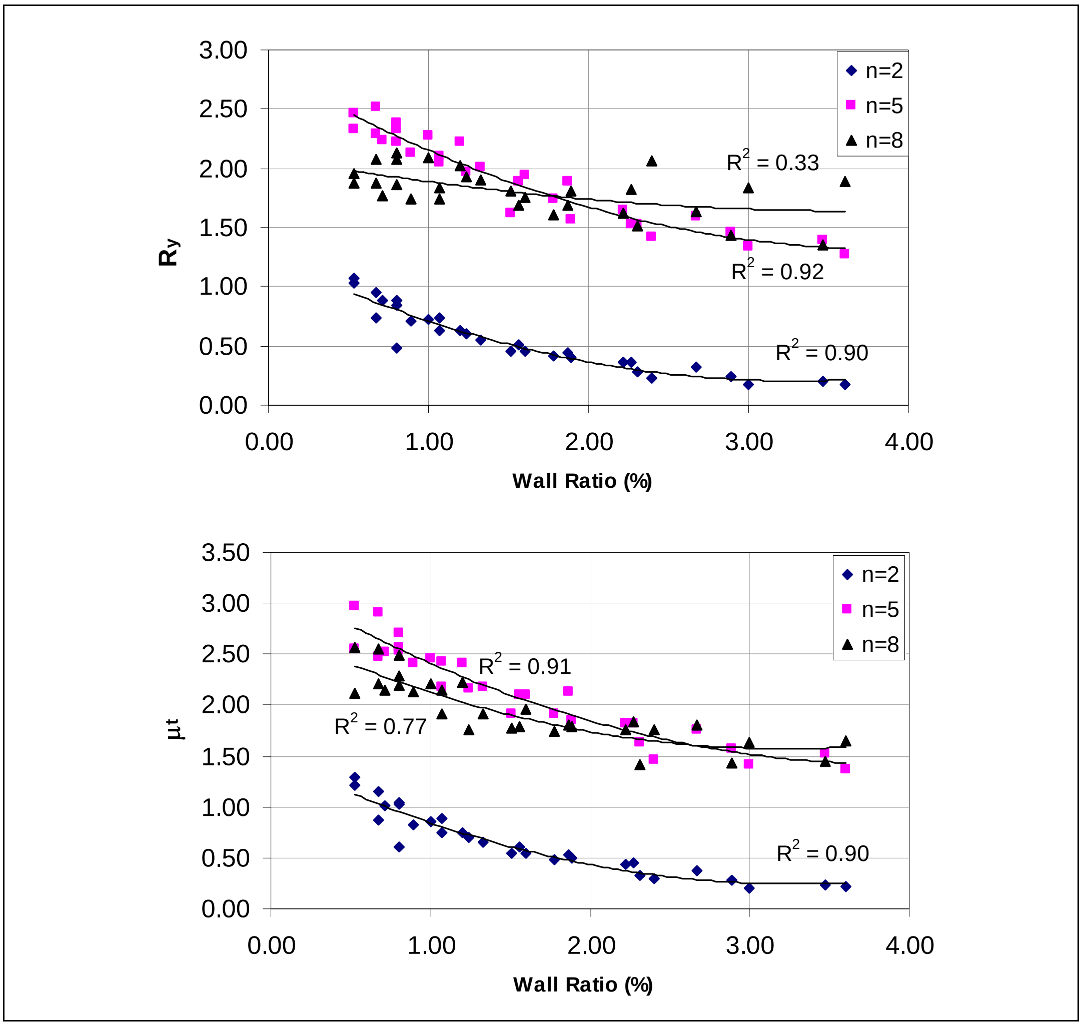

Figure 4. Variation of Yield strength reduction and displacement ductility with Wall Ratio

Miranda (1999) proposes Eq. 5 to compute the inelastic roof displacement. it is considered that the ratio of maximum inelastic to maximum elastic displacement is dependent on the period of vibration of the system, on the level of inelastic deformation (ductility, μ) and on the local soil conditions.

$$u_{roof} = \beta_1 \beta_3 S_d \tag{5}$$

where S_d : Spectral displacement evaluated at the fundamental period of the structure

β_1 : Dimensionless amplification factor calculated as given in Eq. 3

β_3 : Inelastic displacement ratio defined as the ratio of the maximum inelastic displacement, u_i to maximum elastic displacement, u_e which can be estimated as:

$$\beta_3 : \frac{u_i}{u_e} = \left[1 + \left(\frac{1}{\mu} - 1\right)\exp\left(-12T\mu^{-0.8}\right)\right]^{-1} \qquad (6)$$

The procedure given in the previous section by Wallace (1994) for elastic drift estimation can also be used for inelastic drift estimation. According to this study, linear spectrum can be used to provide an estimate of the maximum elastic and inelastic displacement for all periods considering equal displacement for long periods. Therefore, the procedure may yield conservative results for periods less than 0.3s.

The variation of roof drift ratio with shear wall ratio for 2, 5 and 8 stories is plotted in Fig. 6. According to these results, none of the approximate methods estimate roof drift well for 2, 5 and 8 storey model buildings. However, Wallace's estimates are generally better than Miranda for all storeys. As it is evidenced in the graphs, the increase in the shear wall ratio does not result in a significant change in the drift ratio beyond the shear wall ratio of 2.5 percent.

For 2 storey buildings, Wallace underestimates the roof drift for all wall ratio range. However, the discrepancy decreases as the wall ratio exceeds 2 percent. For 5 storey buildings, Wallace overestimates roof drift up to 1 percent wall ratio. Beyond this ratio, the method estimates roof drift better. For 8 storey buildings, the method is very conservative up to wall ratios of 2.5 percent. Although the method overestimates roof drifts beyond this ratio, the difference is reduced.

Miranda (1999) is very conservative in estimation of roof drift for 2 storey buildings. Roof drift ratios obtained for this storey number is far beyond in reasonable estimation. For 5 storey buildings, method underestimates the roof drift for all wall ratio range. However, compared to 2 storey buildings, roof drift of 5 storey buildings are estimated better. For 8 storey buildings, the method again underestimates the roof drift. But, for wall ratios smaller than 1.5 percent, Miranda is better than Wallace in roof drift estimation. According to the inelastic analysis, change of roof drift ratio is affected less for 8 storey buildings.

Conclusions

In all buildings, variation of building period with the wall ratio showed significant change at lower wall ratios with total change being approximately 50 percent for a constant building height. As the ratio of walls increased, the interstorey drift ratio decreased. The change in decrease was too small for wall ratios greater than 2 percent. According to the results of the both elastic and inelastic analysis, roof drift decreased by increasing wall ratio and did not exceed 1 percent for all stories. The change in roof drift was not significant beyond the shear wall ratio of 2.5 percent. This indicated that increasing wall ratio furthermore does not affect the roof drift ratio too much for high shear wall ratios. As a result of both elastic and inelastic analysis, the change of roof drift ratio with the wall ratio was higher in 2 storey buildings. However, for 8 storey buildings, change of drift ratio with the wall ratio is less significant. Among the approximate methods of elastic analysis, Wallace had superiority for 5 storey buildings with wall ratios between 1-2 percent. Miranda and Reyes generally underestimated roof drift for 2, 5 and 8 storey buildings although the deviation from elastic analysis was not too much especially for wall ratios greater than 2 percent. Among the approximate methods of inelastic analysis, none of them estimated roof drift in an acceptable accuracy. However, Wallace generally estimated roof drift better than Miranda for all storeys.

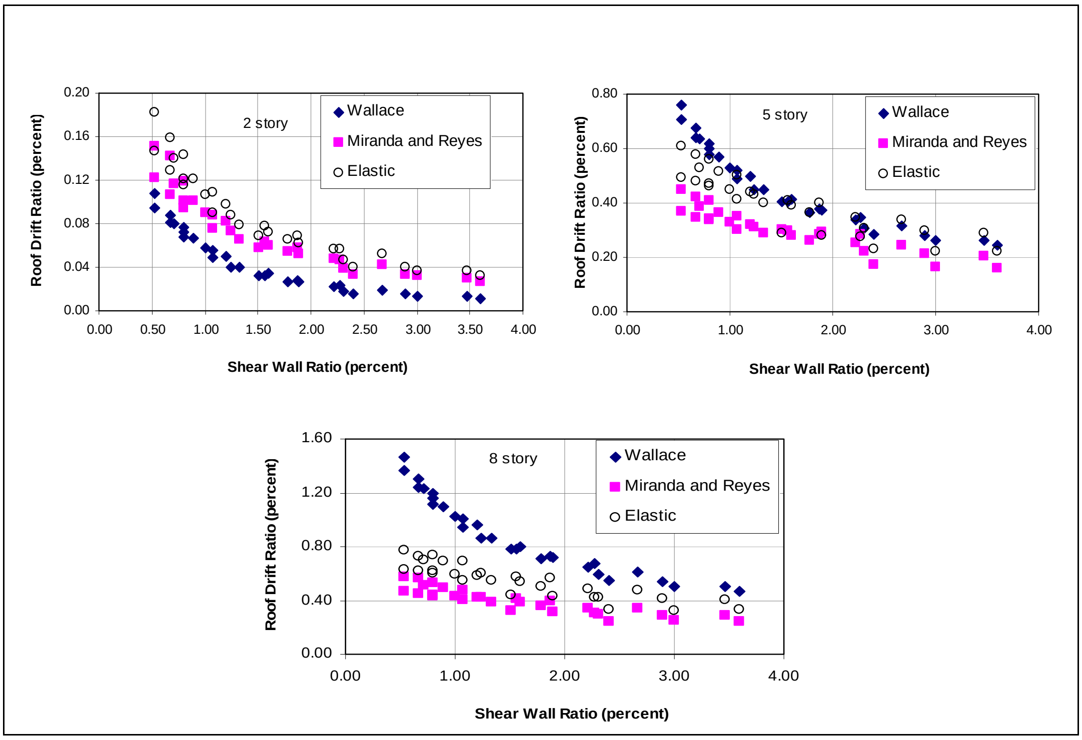

Figure 5. Comparison of Elastic Drift Ratios

Acknowledgments

A substantial support has been received through the collaborative EU FP7 project SYNER-G (244061). This grant is gratefully acknowledged

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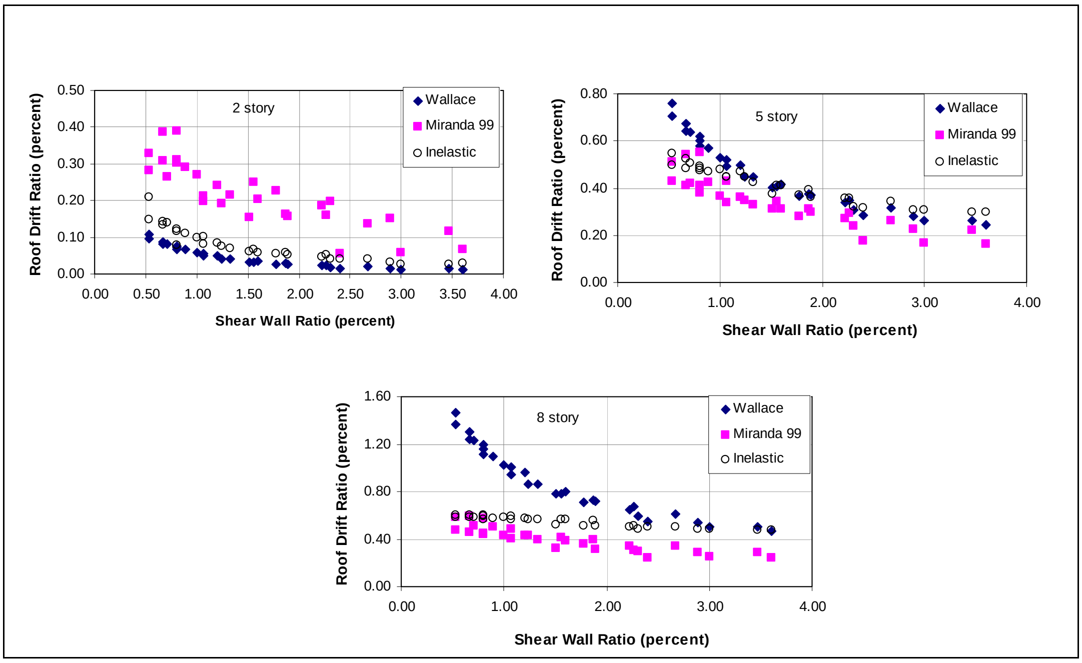

Figure 6. Comparison of Inelastic Drift Ratio