NONLINEAR SEISMIC ANALYSIS OF REINFORCED CONCRETE SHEAR WALL, CONSIDERING BOND- SLIP EFFECT

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ABSTRACT

In this paper, the nonlinear behaviour of reinforced concrete shear wall with consideration of bond-slip effect between the bars and surrounding concrete is investigated. Bar and concrete stress-strain relations, the bond stress-slip relation and the shear stress-strain relation and, also, their cyclic behavior are adopted known specifications. In the modeling, shear wall is divided into two type of joint element and RC element. In RC element, the effect of shear deformation is considered and based on Timoshenko beam theory the effect of shear has been considered during the calculation. a numerical model based on the fiber method is used for nonlinear analysis of reinforced concrete shear wall. The effect of bond-slip has been considered in the formulation of a RC element by replacing the perfect bond assumption from the fiber analysis method. The effects of embedded length and pull-out force on the seismic behaviour of a reinforced concrete shear wall were investigated. The precision of the analytical results were compared with the experimental results achieved from two specimens under cyclic loading. The comparison showed that the proposed method can model the nonlinear behaviour of reinforced concrete shear walls with very good precision. A good agreement between experimental and analytical results is obtained for both cases of strength and stiffness during the analysis.

INTRODUCTION

Many analytical models have been devised for nonlinear analysis of reinforced concrete shear wall. The analytical model can be separated into two groups: macroscopic models and microscopic models based on finite element models. The macroscopic models is based on representing the overall behavior of the RC shear wall, such as the wall deformations, strength, and energy dissipation capacity. Various macroscopic models have been proposed to predict the nonlinear response of RC structural walls (Jalali and Dashti. 2010). In this way, several concentrated and distributed plasticity constitutive models and also modeling through the combination of sub-elements have been proposed. The most promising model for the nonlinear analysis of reinforced concrete elements is, presently, fiber section model. The fiber model, basically, adopts the perfect bond assumption. This assumption causes a considerable difference between experimental and analytical responses of the reinforced concrete shear wall in many cases. In this model, the member is divided longitudinally into several segment, and each segment is composed of parallel layers. Some layers would represent the concrete material and other layers would represent the steel material. Behavior of concrete and steel are separately defined, but the interaction between them, it is not considered. Monti and Spacone (2000) calculated the bond slip effect of the reinforcement bars in the fiber section model. This model was used by Kotronis et al (2005) to simulate the behaviour of RC shear walls under dynamic excitations. Assuming a linear shear deformation, the complexity of the simulation boundary conditions, and ignoring the bond slip effect that was the limitations of this model. In this paper, a numerical model based on the fiber method is used for nonlinear analysis of reinforced concrete shear wall. The theory of numerical calculation is similar to fiber method but the perfect bond assumption between the bars and surrounding concrete has been removed. Separate degrees of freedom are used for the steel and concrete parts in nonlinear modeling of the reinforced concrete elements (Hashemi and Vaghefi. 2012).

NONLINEAR MODELING OF RC SHEAR WALL

For the purpose of nonlinear analysing of RC shear wall and investigation the bond-slip effect, two type of RC and joint elements are modelled as Figure 1. The bond-slip effect has been considered in the formulation of reinforced concrete elements and joint element. The effect of bond-slip has been considered in the formulation of a reinforced concrete element by replacing the perfect bond assumption from the fiber analysis method. Joint elements are formulated upon major behaviour including the pull-out of embedded longitudinal bars (Hashemi and Vaghefi. 2012).

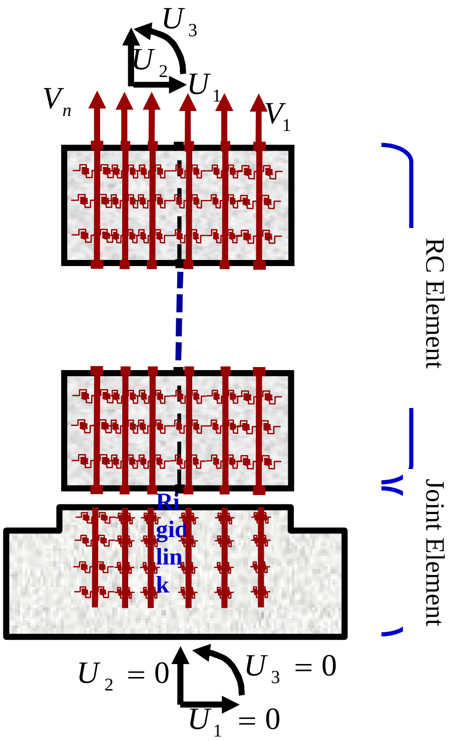


Figure 1. Numerical modeling of a RC Shear Wall

For modeling a RC Element based on research carried out by Limkatanyu and Spacone (2002), in the fiber model, the slip effect between concrete and bar is implemented without ignoring the compatibility of the strain between the concrete and bar. In this element the effect of shear deformation is considered and based on Timoshenko beam theory the effect of shear has been considered in calculation. Timoshenko beam theory, assumes that the cross section remains plane after deformation, but The Euler-Bernoulli beam theory neglects shear deformations by assuming that plane sections remain plane and perpendicular to the beam axis during bending. As a result, shear strains and stresses are removed from the theory. However, the Timoshenko beam theory is based on the shear deformation. It is assumed that being or not perpendicular to the neutral axis is because of shear deformation. In Figure 2 the comparison between Timoshenko beam theory and Euler Bernoulli beam theory is presented.

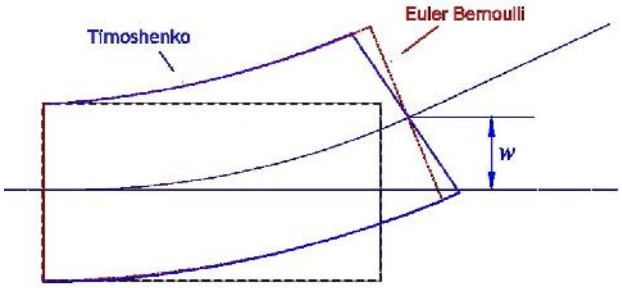


Figure 2. Comparison between Timoshenko beam theory and Euler Bernoulli beam theory

The free body diagram of an infinitesimal segment, *dx*, of RCE is shown in Figure 3. Each RCE is introduced as a combination of one 2-node concrete element and n number of 2-node bars with bond interfaces. Slippage is allowed to occur, because the nodal degrees of freedom of the concrete element and that of the bars are different. Based on small deformation assumptions, all equilibrium conditions are considered. Considering axial equilibrium in the concrete element and steel bars, as well as the vertical and moment equilibriums in segment dx, leads to a matrix form of equations given by Equation 1:

$$\partial_B^T \mathbf{D}_B(x) - \partial_b^T \mathbf{D}_b(x) - \mathbf{p}(x) = 0 \tag{1}$$

Where: $\mathbf{D}_B(x) = \left\{\overline{\mathbf{D}}(x) : \overline{\overline{\mathbf{D}}}(x)\right\}^T$ is the vector of RCE section forced. $\overline{\mathbf{D}}(x) = \{N(x) \quad V_y(x) \quad M_y(x)\}^T$ is the vector of concrete element section forces. $\overline{\overline{\mathbf{D}}}(x) = \{N_1(x) \quad \dots \quad N_n(x)\}^T$ is the vector of bar axial forces. This vector has n rows. $\mathbf{D}_b(x) = \{D_{b1}(x) \quad \dots \quad D_{bn}(x)\}^T$ is the vector of bond section forces. $\mathbf{P}(x) = \{0 \quad p_y \quad 0 \quad 0 \quad \dots \quad 0\}^T$ is the vector RCE force vector. n is the number of longitudinal bars in the cross section. and is the value of external load. ∂_B , ∂_b are differential operators and given in equation 2.

$$\partial_{RCE}^B = \begin{bmatrix} \bar{\partial}_{RCE}^B & 0 \\ 0 & \bar{\bar{\partial}}_{RCE}^B \end{bmatrix}, \bar{\partial}_{RCE}^B = \begin{bmatrix} \frac{d}{dx} & 0 & 0 \\ 0 & \frac{d}{dx} & -1 \\ 0 & 0 & \frac{d}{dx} \end{bmatrix}, \bar{\bar{\partial}}_{RCE}^B = \begin{bmatrix} \frac{d}{dx} & 0 & \dots & 0 \\ 0 & \frac{d}{dx} & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & \frac{d}{dx} \end{bmatrix} \partial_{RCE}^b = \begin{bmatrix} -1 & 0 & y_1 & 1 & 0 & \dots & 0 \\ -1 & 0 & y_2 & 0 & 1 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & 0 \\ -1 & 0 & y_n & 0 & 0 & \dots & 1 \end{bmatrix}_{n*(n+3)} \tag{2}$$

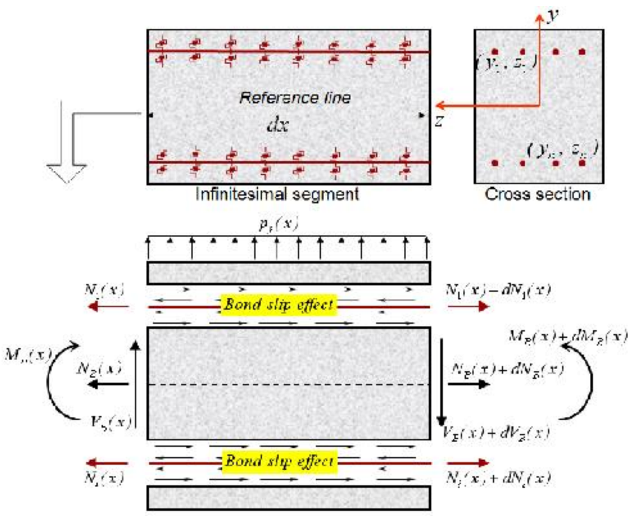


Figure 3. Free body diagram of infinitesimal segment of RC element and its components

A joint element is used as the footing connection of the RC shear wall. In this element the effect of pull-out is considered as the relative displacement between the steel bar and surrounding concrete and bond stress is referred to as the shear stress acting parallel to an embedded steel bar on the contact surface between reinforcing bar and concrete. Referring to Figure 4, the slippage of the bars can be defined in the form of equation 3, if the nodal displacement vector related to pull-out behaviour is defined as $\mathbf{U}_{PM} = [U_1 \quad U_2 \quad U_3 \quad V_1 \quad \dots \quad V_n]^T$.

$$\textbf{slip} = \begin{bmatrix} d_{b_1} \\ \cdots \\ d_{b_i} \\ \cdots \\ d_{b_n} \end{bmatrix} = \begin{bmatrix} -1 & 0 & y_1 & 0 & \ldots & 0 \\ -1 & 0 & y_2 & 0 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ -1 & 0 & y_n & 0 & 0 & 1 \end{bmatrix}_{n*(n+3)} \times \mathbf{U}_{PM} = \mathbf{A}_{PM} \times \mathbf{U}_{PM} \tag{3}$$

In this equation, y_n is the distance of the *n*th bar from the reference line.

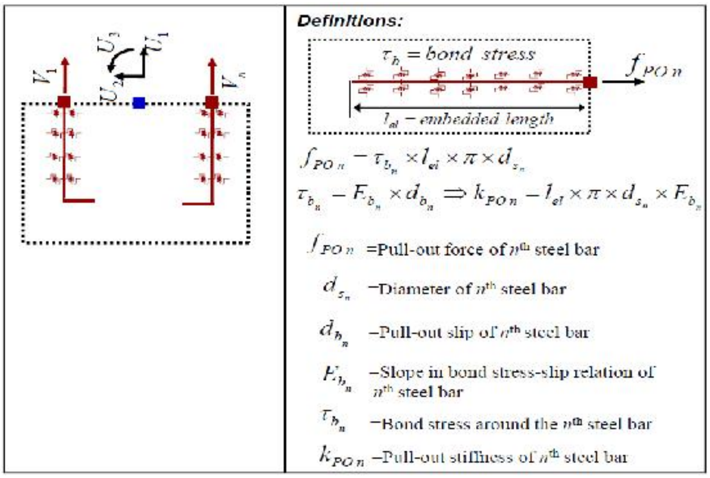


Figure 4. Numerical modelling of the bar's pull-out

MARERIAL BEHAVIORS

Bond stress is referred to as the shear stress acting parallel to an embedded steel bar on the contact surface between the reinforcing bar and the concrete. Bond slip is defined as the relative displacement between the steel bar and the concrete. The adopted model to represent the bond slip effect between bars and concrete is proposed by Eligehausen et al (1983), shown in Figure 5. In this model, the effect of many variables, such as the spacing and height of the lugs on the steel bar, the compressive strength of the concrete, the thickness of the concrete cover, the steel bar diameter, and the end bar hooks, are considered. Presented models in Table 1 are used for modeling the nonlinear behavior of concrete and steel materials.

Table1. Selected models for material behavior

Relationship	Description
Concrete stress-strain	Park et al (1972) and later extended by Scott et al (1982) for monotonic compressive envelope curve
Steel stress-strain	The initially proposed model by Giuffre and Pinto (1970) and later used by Menegoto and Pinto (1973)

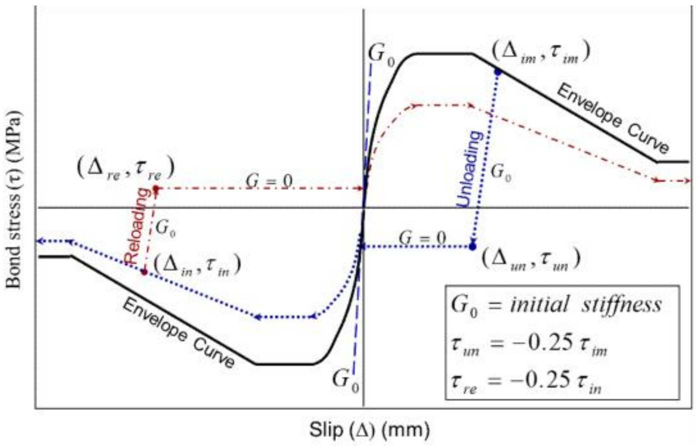


Figure 5. Cyclic bond stress- slip relation (Eligehausen et al, 1983)

NUMERICAL INVESTIGATION

For numerical investigation, first, for a reinforced concrete shear wall with geometric specifications according to Figure 6 and details provided under the name of specimens in the table 2, numerical validation has been done. This specimen is a shear wall under uni-axial bending and constant axial load with magnitude of 630 kN and 1420 kN Respectively, for specimens 1 and 2. Lateral cyclic displacement was imposed at the free end. It was tested by Dazio et al. (2009).

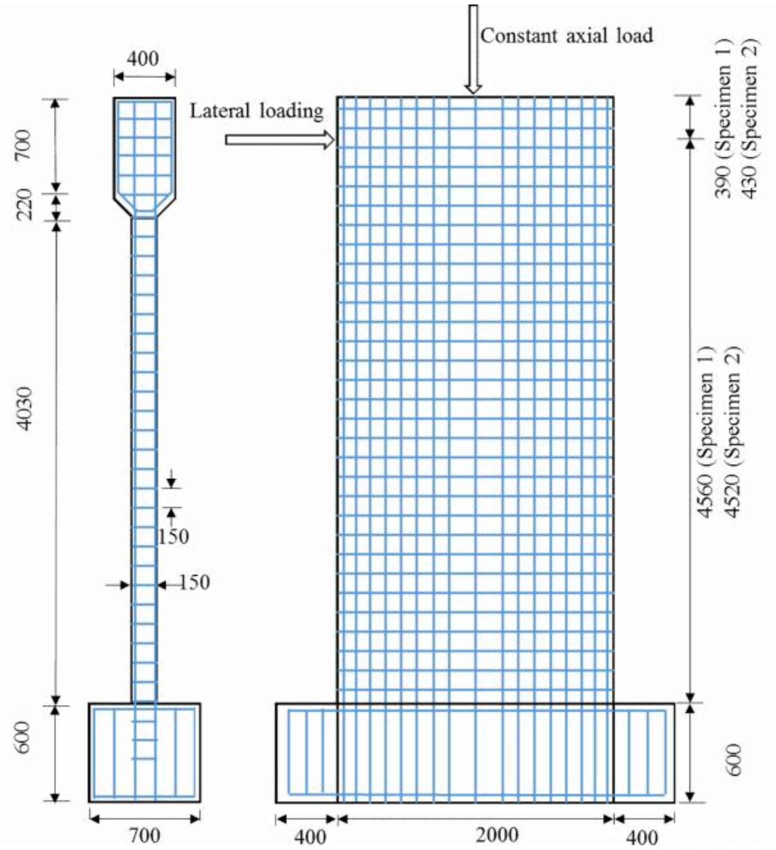
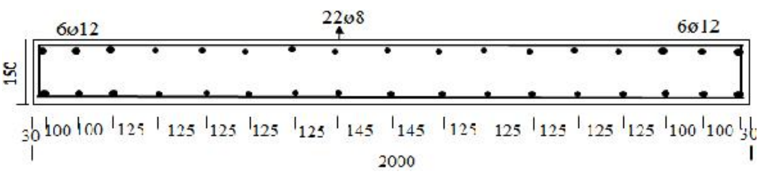
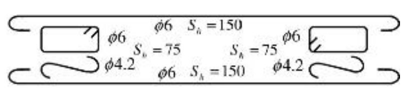
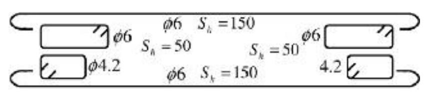
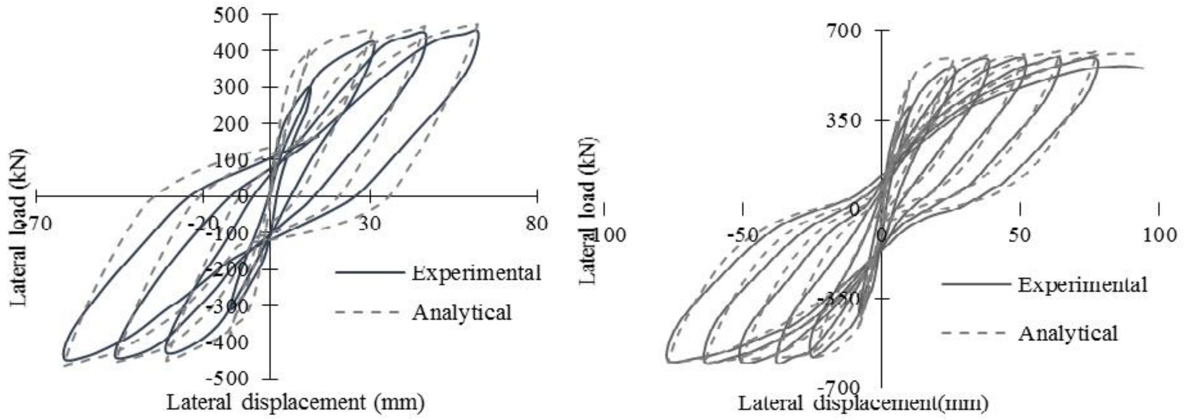


Figure 6. Geometry of the shear wall (All dimensions in mm)

Table 2. Details of investigated Specimens

	Specimen 1	Specimen 2
Section view		
		
Main bars	12Φ12mm & 22Φ8mm	12Φ12mm & 22Φ8mm
stirrups	Φ6@150mm&(Φ6& Φ4.2) @75mm	Φ6@150mm&(Φ6& Φ4.2) @50mm
f_y of main bars (MPa)	601 for Φ12 & 569.2 for Φ8	576 for Φ12 & 583.7 for Φ8
f_y of stirrups bars (MPa)	518.9	518.9
f_y of closed ties and S-shaped ties (MPa)	489 for Φ6 & 562.2 for Φ4.2	518.9 for Φ6 & 562.2 for Φ4.2
f_c (MPa)	39.2	45.6
Concrete cover (mm)	30	30

A computer program created in MATLAB software was used by the authors. In numerical modeling, the wall is subdivided into enough number of shorter elements. Because the formulation is displacement based and the response is depend on element size and it is needed the length of elements be enough short. For nonlinear solving of this model, a Newton-Raphson method which involved controlling displacement was used. Figure 7 shows the analytical and experimental load-displacement responses with good accordance for strength, stiffness, and their changes during cyclic loading.



(a) Specimen 1 (b) Specimen 2

Figure 7. Experimental and analytical cyclic load- displacement responses for tested specimen

In Figure 8 bar Number 1 is shown to evaluate cyclic behavior of bond slip stresses.

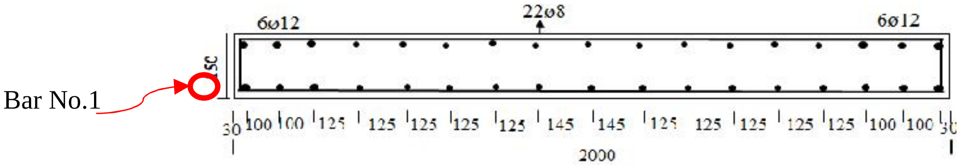
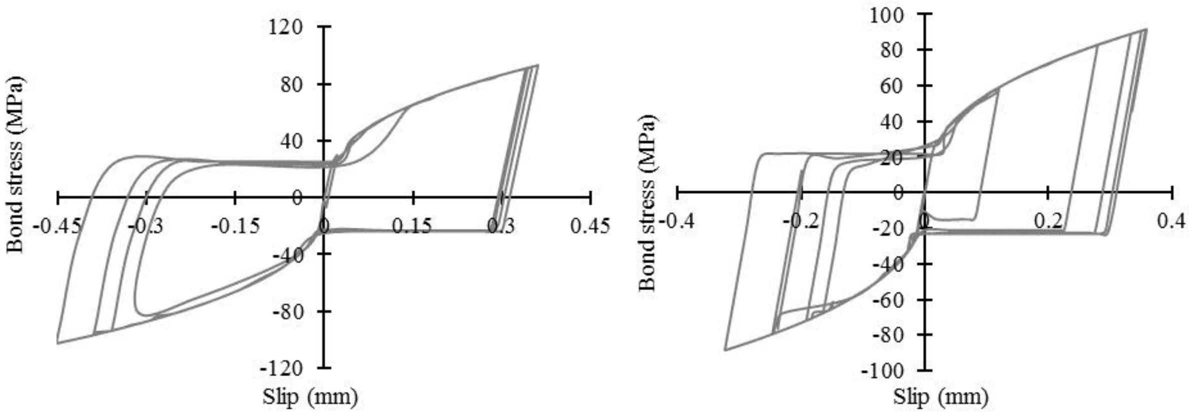


Figure 8. Bar number 1 in wall section to evaluate its behaviour

Cyclical behavior of bond slip of bar shown in Figure 8 recorded during the cyclical analysis in position of 370 mm and 580 mm from the wall respectively specimens 1 and 2 in Figure 9 is provided. As the results show that the maximum of slip at the specified position at the longitudinal hinge plastic is formed, is greater than the other longitudinal points of the wall. The position with zero distance from the wall the slip is low, due to sufficient of the embedded length of longitudinal reinforcing bars in the foundation.



(a) (b)

Figure 9. Experimental and analytical cyclic load- displacement responses, 370 mm above the top of the foundation for specimen1 and 580 mm above the top of the foundation for specimen 2

In Figure 10 analytical response of the specimen 2 using the theory of Euler Bernoulli and Timoshenko beam is shown. Response analysis using the Timoshenko theory in computation due consideration of effect of shear has better match with the experimental results and as shown applying the Euler Bernoulli theory in analyzing due to refraining from the shear deformation the initial slope is more, in other words, greater stiffness to estimate.

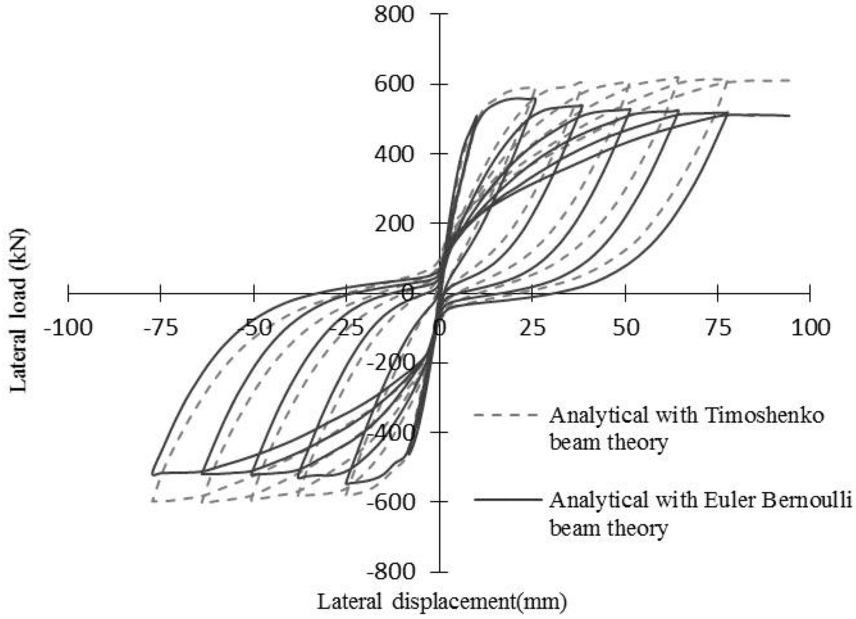


Figure 10. Analytical response of the specimen 2 using the theory of Euler Bernoulli and Timoshenko beam

CONCLUSIONS

In this article, a numerical model based on the fiber model is introduced for nonlinear seismic analysis of two dimensional RC shear wall. The advantage of the proposed analytical procedure is that it takes bond-slip, pull-out effects and shears deformation into account. Analytical method proposed in this study due to consider the effect of bond slip and the effect of shear deformation in the calculation of process modeling and analysis, the accuracy is very good. The results show that the presence or absence of slip effect and also shear in modeling and numerical analysis, different results in all responses like ultimate capacity and stiffness have been observed. The best numerical response is achieved when all mentioned factors are considered in the modelling and since proposed method used in this study takes into account all these factors, very good numerical response is result. The reliability of the method is assessed through for a variety of specimens tested under cyclic loading. Good agreement between experimental and analytical results is obtained for a variation of strength and stiffness during analysis.

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