# Impact of Coupled Axial-flexure-shear Modeling on Seismic Demand of High rise Walls

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**SUMMARY:**
High rise reinforced concrete wall structures are effective system for resisting lateral load, imposed due to wind and earthquake. During such severe loading, structural wall undergoes the stages of cracking, yielding and buckling of longitudinal reinforcement in critical regions. One of the problems in modeling of shear walls is the selection of appropriate modeling technique. Most common approach is fiber modeling for high rise walls. It is believed that due to high aspect ratio, high rise walls are dominated by flexure response therefore shear behaviour is mostly considered as linear. Some researchers suggested the use of an uncoupled flexure shear model for walls, in which a non-linear shear spring is assigned to flexure element. Calculation of shear strength for such non-linear shear spring is another problem since available code based empirical equation for shear strengths lack in theoretical background. Also such models do not account for coupled axial-flexure-shear interaction behaviour. In this study a more refined axial-flexure-shear interaction FEM model based on Modified Compression Field Theory (MCFT) has been used. Model is first compared with reverse cyclic experimental results available in the literature and then later on this model is used for Time History Analysis to study the higher modes effects. Results are compared and discussed with the model considering flexure behaviour non-linear only in this paper. Findings of this research study indicate that use of model considering flexure behaviour non-linear only; can lead to erroneous estimation of seismic dynamic demand for high rise wall.

*Keywords: Axial-flexure-shear interaction, Seismic demand, Higher modes.*

## 1. INTRODUCTION

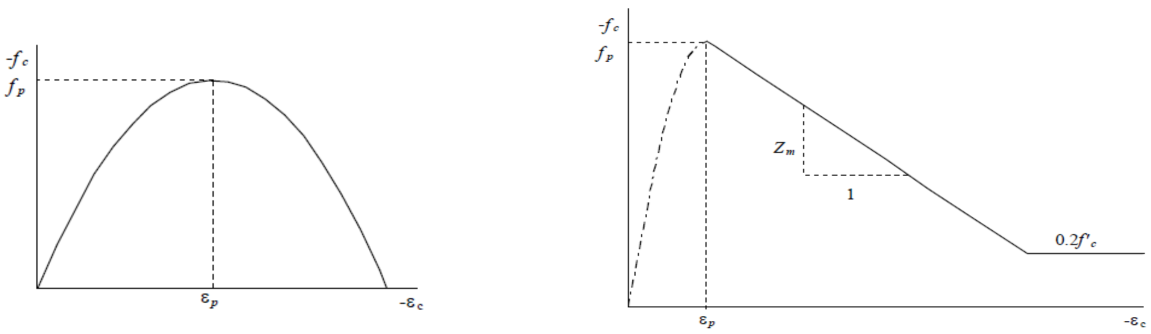
It is believed that due to high aspect ratio high rise walls are dominated by flexure response therefore shear behaviour mostly considered as linear. Orakcal K, Wallace JW and Massone LM (2004, 2006) conducted the series of tests on slender shear walls their findings show the presence of non-linear behaviour in shear even for walls with higher aspect ratio. The effect of non-linear shear response is very important on seismic demand of high rise walls. Different researchers carried out research to quantify the effects of non-linearity in shear response on seismic demand. Previous studies ( i.e BR Rad and Adebar 2008) conclude that when the shear rigidity of a cracked concrete wall is equal to 10% of the uncracked section shear rigidity, which is a typical value, the maximum shear force at the base reduced to about 27%. This shows the significance of considering better modelling approach. Although BR Rad and Adebar (2008) considers the non-linear shear behaviour but they have used an un-coupled flexure-shear model which inconsistent with experimental findings as shown by Orakcal K, Wallace JW and Massone LM (2004, 2006). Their results indicate that as the flexure yielding occurs non-linear behaviour in shear versus deformation can be observed even though the nominal shear capacity is the twice of flexure yielding lateral load.

Shear behaviour in commonly available equivalent beam-column and fiber models is uncoupled from flexural behavior. In an uncoupled model, flexural yielding occurs in combination with elastic shear behavior, or shear yielding occurs with elastic flexural response, depending on geometry, materials, or loading conditions. Available software programs generally do not account for coupled shear-flexure interaction behavior. There is need to do more research in this area for better understanding of non-linear modeling of high rise walls. Vecchio and Collins (1986) proposed Modified compression field theory (MCFT) to predict the response of reinforced concrete beams loaded in combined shear, moment and axial force. The MCFT determines the average and local strains and stresses of the concrete and reinforcement, and the widths and orientation of cracks throughout the load-deformation response of the element. Based on this information, the failure mode of the element can also be determined. Model is first compared with reverse cyclic experimental results available in the literature and then later on this model is used for Time History Analysis to study the higher modes effects. Results are compared and discussed with the model considering flexure behavior non-linear only.

## 2. VERIFICATION OF COUPLED AXIAL-FLEXURE-SHEAR MODEL

Vector2 (Wong and Vecchio 2002) is finite element software based on Modified Compression Field Theory. It can perform the reversed cyclic analysis. Recently (2003) Vector2 is extended to perform the dynamic analysis (Palermo and Collins 2003). In this study first the model is compared with the available reversed cyclic experiments.

The pre-peak response of concrete is modeled by using Hognestad (Parabola) whereas the post peak response is modeled by Modified Park-kent model. Hysteretic model of Plastic offsets with linear loading/unloading for concrete is selected.  This model can include the plastic offset strains as proposed by Vecchio (1999).




(a) (b)

**Figure 2.1.**Constitutive Models for concrete (a) Hognestad (Parabola)  (b) Modified Park-kent model

For reinforcement a tri-linear model is used which can take into account the strain-hardening. It consists of an initial linear-elastic response, a yield plateau, and a linear strain-hardening phase until rupture

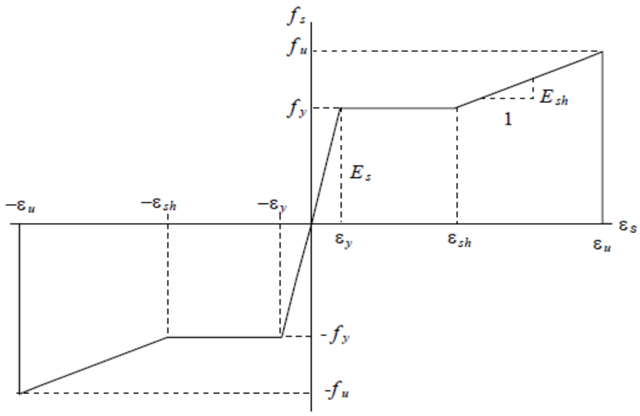



**Figure 2.2.** Constitutive Models for Reinforcement

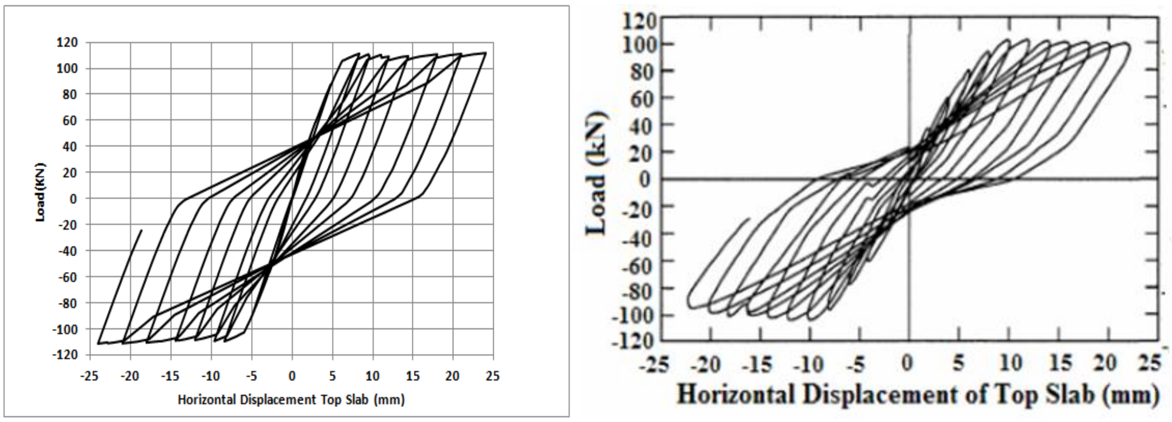
Seckin model is used for the hysteretic response of the reinforcement which can take into account the

Bausichinger effect. Buckling of reinforcement is also considered by using Dhakal-Maekawa model for the buckling of longitudinal reinforcement. Furthermore the tension stiffening effect is modeled through Bentz et  al (2006) model.

Tale 2.1 shows the material properties of verified experimental specimens.

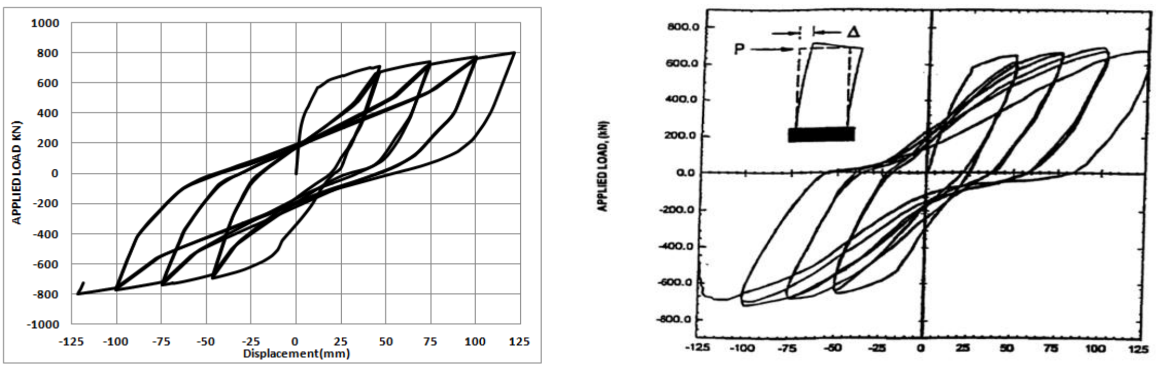
**Table 2.1.**Material Properties of Specimens

| Concrete | | | Reinforcement | | | | Aspect ratio |
|---|---|---|---|---|---|---|---|
| Wall | Zone | Concrete *fc(Mpa)* | Horizontal | | Vertical | | *a/d* |
| | | | *ρ( %)* | *fy(Mpa)* | *ρ( %)* | *fy(Mpa)* | |
| SW4 | Web | 37.0 | 0.39 | 532 | 3.89 | 445 | 2.0 |
| | Boundary | 37.0 | 1.18 | 545 | 0.50 | 545 | |
| B2 | Web | 53.7 | 0.63 | 750 | 0.29 | 650 | 2.3 |
| | Boundary | 53.7 | 0.63 | 750 | 3.67 | 750 | |
| M3 | Web | 20.1 | 0.3 | 745 | 0.3 | 504 | 1 |



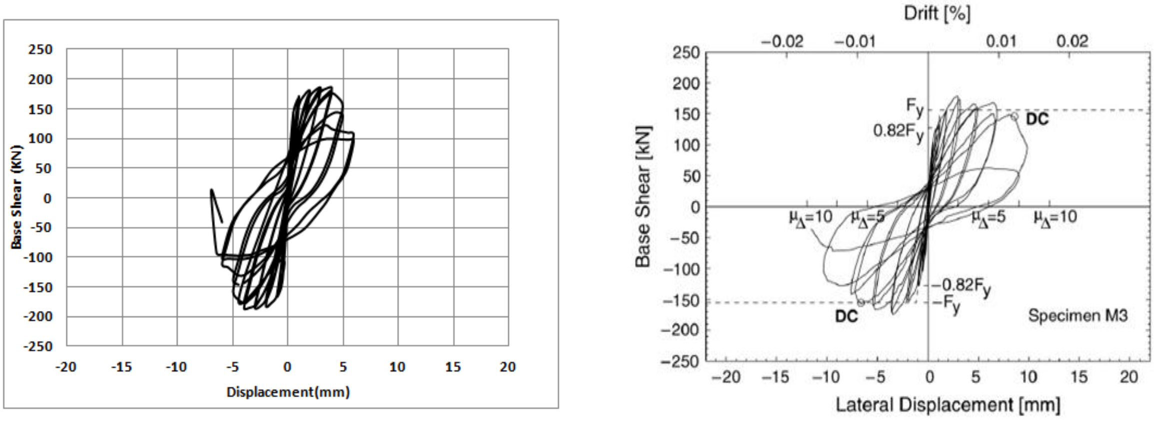

(a) (b)

**Figure 2.3.**Comparison of analysis and experimental results SW4 Wall. (a)Analysis (b) Experiment




(a) (b)

**Figure 2.4.**Comparison of analysis and experimental results B1 Wall. (a)Analysis (b) Experiment




(a) (b)

**Figure 2.5.**Comparison of analysis and experimental results M3 Wall. (a)Analysis (b) Experiment

Figure 2.3 to Figure 2.5 show the comparison of analysis and experimental results. As we can see the Vector2 is capable reproducing the experimental observed reverse cyclic force deformation relationship. Initial stiffness, which is an important parameter for seismic demand of high rise wall, is in good agreement with experimental results.

## 3. SEISMIC DEMAND OF HIGH RISE WALLS

Most common approach is fiber modeling for high rise walls. It is believed that due to high aspect ratio, high rise walls are dominated by flexure response therefore shear behaviour is mostly considered as linear. Previous research (BR Rad and Adebar 2008) shows that if the non-linear shear behaviour is taken into account the seismic demand of high rise is significantly lowered. In previous research an uncoupled non-linear shear spring is adopted along with the non-linear flexure spring, to consider diagonal cracking effects. Calculation of shear strength and shear deformation for such uncoupled model is not a straight forward task. Empirical code based shear strength equations need strong calibration and verification with the experimental data. Moreover in an uncoupled model axial-shear and flexure-shear interaction cannot be taken into account. In this research a more refined axial-flexure-shear coupled model (Vector2) is used. As explained in previous section this model presents an excellent agreement with experimental results. To get a clear picture Results of axial-flexure-shear coupled model are compared with a fiber model. In a fiber model shear behaviour is ignored. Software platform OpenSees is used for the fiber modelling.

### 3.1. Design of High Rise Wall

20 storey shear wall is selected. Figure 3.1 shows the section of wall. Storey height is 2.7 m. It is assumed that selected shear wall is located in seismic zone 4 according to UBC-97. Soil type is $S_D$, whereas the value of $C_a$ and $C_v$ are 0.44 and 0.64 respectively. Figure 3.2 show the 5% damped UBC-97 Response spectrum.

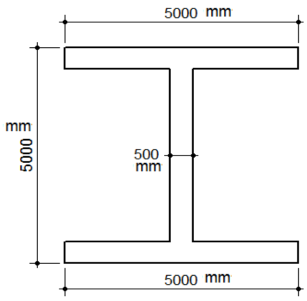



**Figure 3.1.**Section of Shear Wall

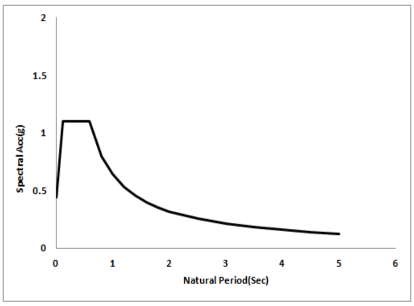
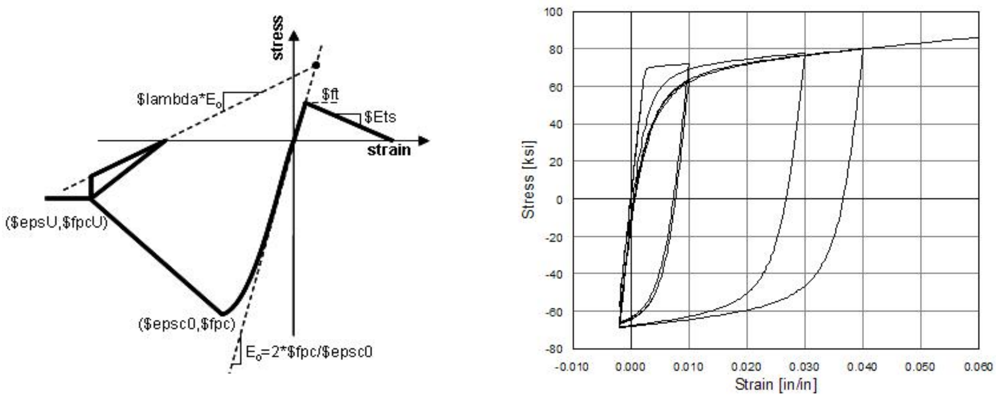



**Figure 3.2.**5% Damped UBC-97 Spectra

Ductility force reduction of R= 5.5 i.e. Building frame system with concrete shear walls is used for design of 20 storey shear wall. It is also required that the Design Base shear must not be more that 90% of the static base shear demand. R factor is replaced by effective response modification factor of 4.16 to satisfy said requirement. Flexure reinforcement is provided such that the nominal flexure strength times the strength reduction factor (Φ =0.90) is equal to the design base moment. Steel of 60 Grade is used as flexure reinforcement having expected yield strength of 484 Mpa which is 1.17 of nominal yield strength. Shear reinforcement for coupled model is provided such that nominal shear strength times the strength reduction factor (Φ =0.75) is equal to the design base shear. Flexure strength and shear strength reduce in three steps along the height of wall linearly. Shear Wall is subjected to $10\%A_g\, f_{c'}$ ($f_{c'}$ is 27.56 Mpa).

### 3.2. Modeling of High Rise Wall

Modeling of shear wall in vector2 is done in the same way as explained in section 2. To compare the results of seismic demand, shear wall is also modeled by using a fiber model in OpenSees. Non-linear beam-column element is used for the fiber modeling of shear wall. Uni-axial concrete 02 material is used for the concrete and steel 02 (Giuffre-Menegotto-Pinto) is used for the Modeling of reinforcement. It should be noted that Non-linear beam column element cannot take into account the no-linear shear deformation.




(a) (b)

**Figure 3.3.**Consititutive models for fiber modelling (a) Concrete (b) Reinforcement

### 3.3. Analysis of Shear Wall

For the verification of seismic demands by the Non-linear time history analysis procedure, it is required to have a set of ground motion records that can represent Maximum Considered Earthquake (i.e. MCE). Here, the MCE response spectrum is assumed to be 1.5 times the DBE response spectrum as shown in Figure 3.4. Seven free-field horizontal ground motion records whose spectra resemble the target MCE spectrum are selected from the PEER NGA and COSMOS databases (PEER, 2005, COSMOS 1999-2007) (Munir 2010). A spectral matching software RSPMATCH 2005, originally developed by Abrahamson (1992) as RSPMATCH and modified by Hancock et al. (2006) is used in this study. Table 3.1 shows the ground motion used in the study.

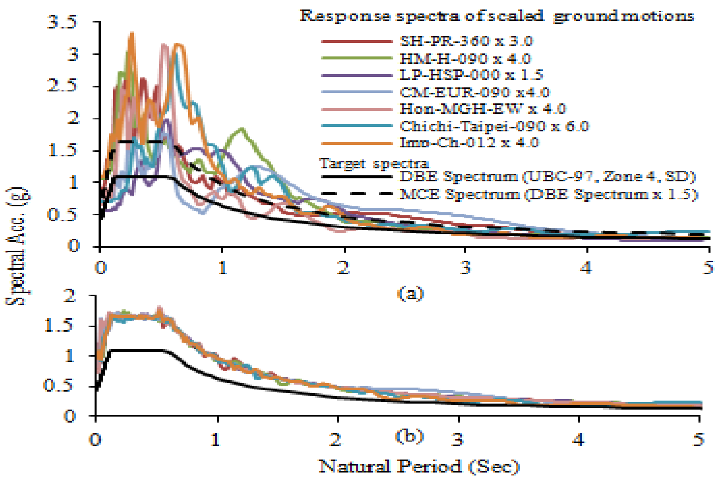



**Figure 3.4.**Comparison of (a) Scaled and (b) Spectrum matched ground Motion records

**Table 2.1.**Ground Motion Records

| No | Earthquake Event | Year | Abbreviation | Mw | R (km) | Site Geology | PGA (g) | Duration (sec) |
|---|---|---|---|---|---|---|---|---|
| 1 | Superstition Hills | 1987 | SH-PR-360 | 6.5 | 11 | Stiff Soil | 0.30 | 15.5 |
| 2 | Hector Mine | 1999 | HM-H-000 | 7.1 | 26 | Very dense soil & soft Rock | 0.27 | 11.7 |
| 3 | Loma prieta | 1989 | LP-HSP-000 | 6.9 | 48 | Very dense soil & soft Rock | 0.37 | 16.4 |
| 4 | Cape Mendocino | 1992 | CM-EUR-090 | 7.0 | 53 | Stiff Soil | 0.18 | 19.8 |
| 5 | Honshu Earthquake | 1968 | Hon-MHG-EW | 7.9 | 280 | Diluvium, sand Gravel | 0.16 | 30.4 |
| 6 | Chi Chi Taiwan | 1999 | Chichi-Taipei-090 | 7.6 | 157 | Stiff Soil | 0.12 | 24.0 |
| 7 | Imperial Valley | 1979 | Imp -Ch-012 | 6.5 | 19 | Stiff Soil | 0.27 | 20.0 |

Note: Mw = moment magnitude, R = distance from recording site to epicenter, PGA = peak ground acceleration, Duration = Duration of strong ground motion, Abbreviation = short name comprising of event, station and component of earthquake.

Rayleigh damping is used in the analysis. Recommendations of (CTBUH, 2008) are followed in this study for selection of damping. A damping ratio of between 1% and 2% for fundamental translational modes appears reasonable for buildings more than 160 ft and less than 820 ft in height (CTBUH, 2008). Vector2 is capable of modeling majority of source of energy dissipation in a reinforced concrete structure such material hysteresis, concrete cracking and bond slippage. Therefore the damping values for 1$^{st}$ and 2$^{nd}$ modes are selected as 1% which resulted in the 1%, 1%, 2.16%, 3.6%, 5.2%, and 6.8% damping values for first 6 modes respectively.

### 3.4. Results and Discussion

Results of Fiber Model and Coupled Axial-Flexure-Shear model are compared for shear and moment demand in Figure 3.5 and 3.6 respectively. Fiber model results show same amplification of 2.75 of shear force whereas Coupled Model shows an amplification of 2.05.The difference of dynamic shear amplification of two models is 32%. Results of moment demand show difference of about 8 to 10% for both models. Figure 3.7 shows the typical cracking pattern observed during the time history analysis. At the base and mid height of wall diagonal cracking can be seen clearly. Due to diagonal cracking shear demand reduces as can been seen from Figure 3.5. This reduction is shear demand is attributed to the reduction in shear stiffness of wall.

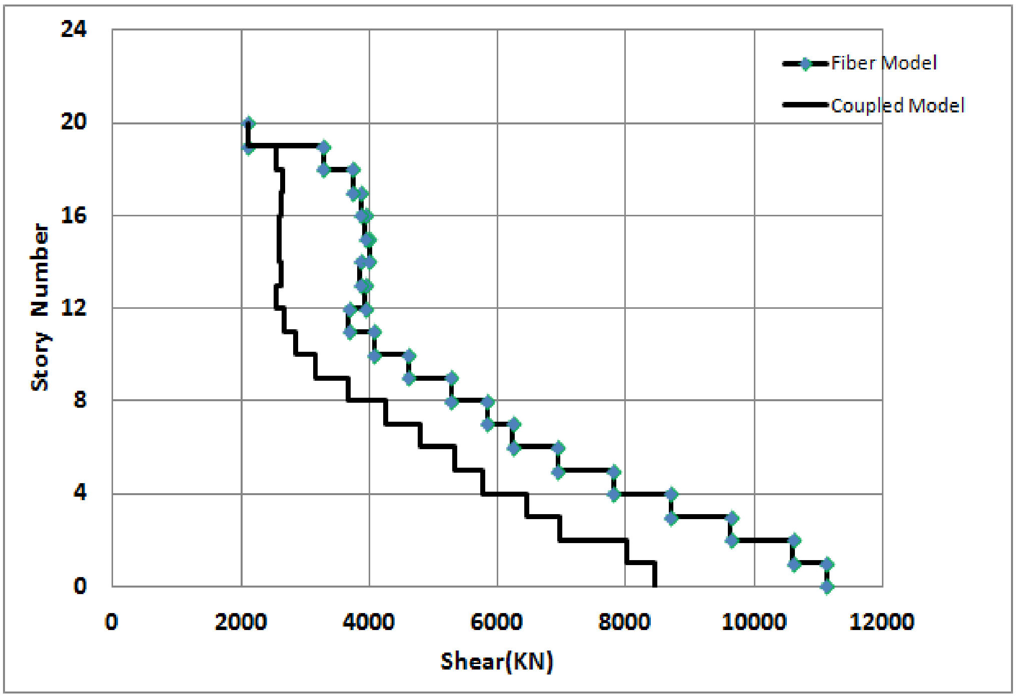



**Figure 3.5.**Comparison of Fiber and Axial-Flexure-Shear Coupled Mode for Shear demand

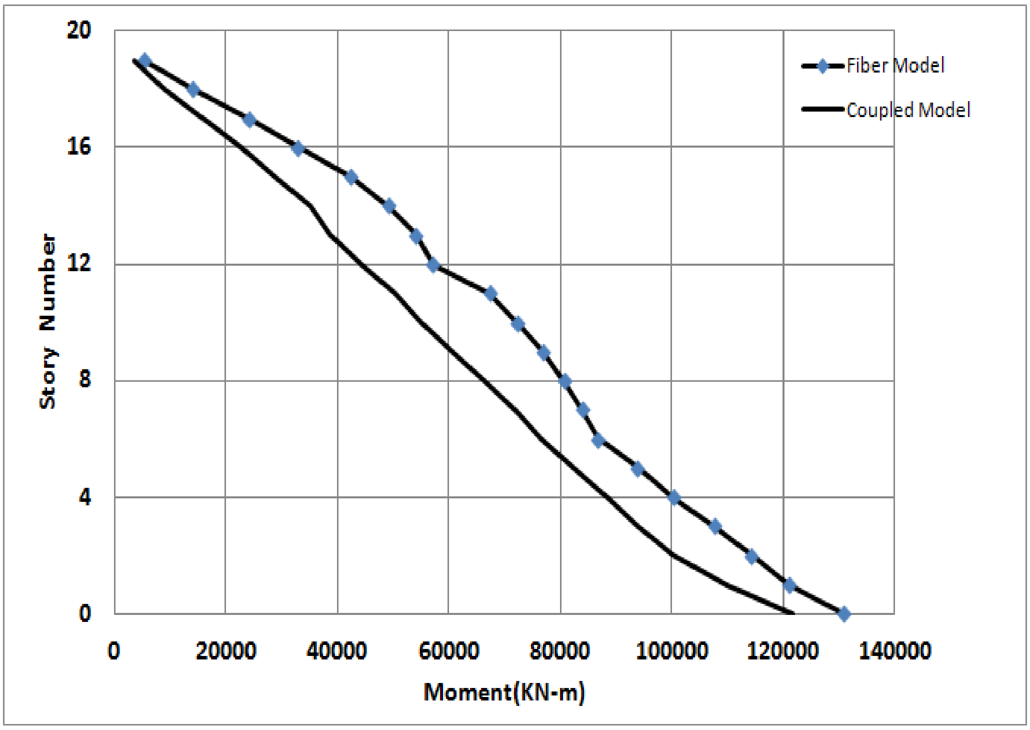



**Figure 3.6.**Comparison of Fiber and Axial-Flexure-Shear Coupled Mode for Moment demand

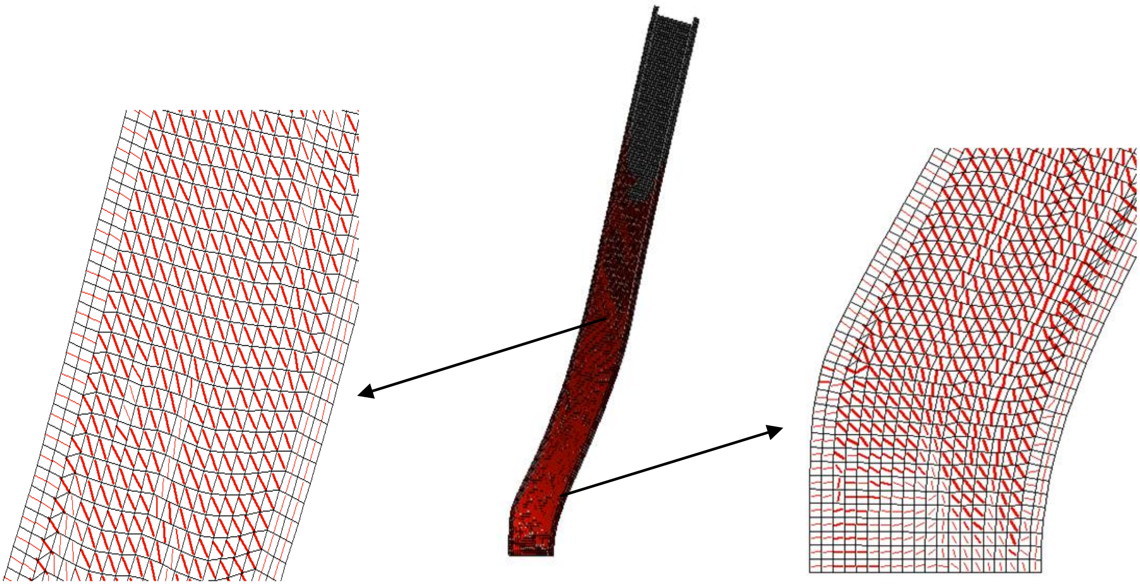


**Figure 3.7.**Typical cracking formation during Time History Analysis

### 3.5. Conclusions

A state of the art Axial-Flexure-Shear Coupled model is used in this study for static and dynamic modeling of shear walls. Comparison of reversed cyclic loading test results with model suggests that the Modified Compression Field Theory (MCFT) is capable enough to model the complicated shear wall cracking behaviour. Later this Coupled Axial-Flexure-Shear model is used for dynamic analysis.

Results of dynamic analysis show that due to shear cracking shear demand reduces to about 32% as compared to the results obtained using a conventional Fiber modelling technique.

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