Proceedings of the Tenth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Pacific
6-8 November 2015, Sydney, Australia

Analytical Prediction of Cyclic Performance of RC Frame Structures

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ABSTRACT: The prediction of nonlinear behaviour of reinforced concrete (RC) structures under seismic loading is generally complex because of the strength and stiffness degradation associated with pinching at the higher drift levels. The performance of a RC flexural member is largely controlled by the crushing of compression concrete, tensile cracking, bond failure, and tension stiffening characteristics. The energy dissipation and drift distribution over the height of a RC frame under seismic excitations not only depend on the characteristics of individual components (i.e., beams and column), but also on the load transferring mechanism of the beam-column joints. Very often, several approximations are made in the seismic analysis of RC frames. It is, hence, important to model the nonlinear behaviour of all the components of a RC frame in order to predict its cyclic performance accurately. In this study, two geometrically-identical single-bay single-story RC frame, representing 0.4-scale model of a prototype frame, were tested under a gradually-increasing cyclic displacements and a constant gravity loading. The frames were casted using plain concrete and steel fiber reinforced concrete. The test frames are modelled in *OpenSees* simulation platform to predict their cyclic response and to compare with the experimental results. All members are modelled as *nonlinear BeamColumn* elements using fiber sections in the *OpenSees* platform. The compression crushing and pinching behaviour of concrete is considered by using *Concrete02* and *Pinching4* properties in addition to the tension-stiffening characteristics of the RC members. Cyclic pushover analysis is conducted to evaluate the energy dissipation, lateral strength, stiffness and failure mechanism of the RC frame. The analytical predictions matched very well with the experiment results.

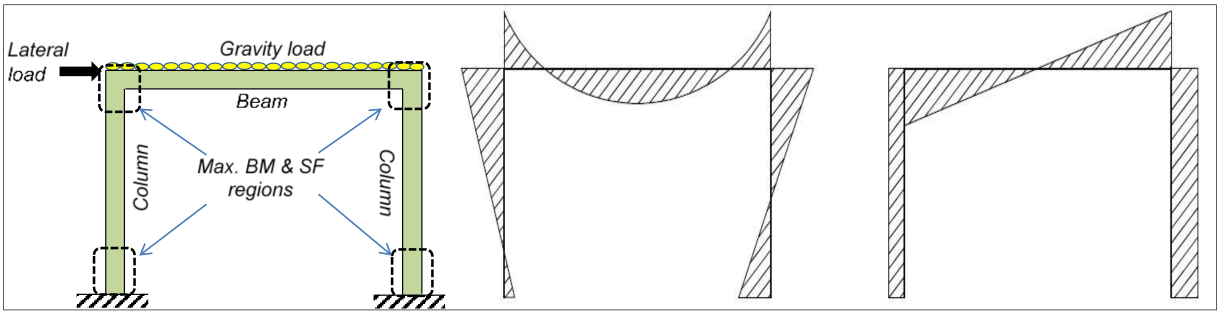
1 INTRODUCTION

Past earthquakes and experimental studies have indicated that the reinforced concrete (RC) buildings are vulnerable to complete collapse or severe damages in the absence of (i) adequate confinement of concrete in the potential plastic hinge regions; (ii) sufficient amount of transverse reinforcement in the joint regions; (iii) sufficient amount of longitudinal and transverse steels in main members, (iv) adequate anchorage detailing of reinforcement bars; and (v) proper lap splicing of longitudinal reinforcement bars (Oinam et al., 2014). These deficiencies are commonly noticed in the existing RC structures. Modern seismic codes emphasize on the requirement of transverse reinforcement with adequate toughness and ductility of structural members during strong ground shakings. Hence, the existing RC buildings require retrofitting to enhance their seismic performance (ASCE-41, 2007; FEMA-547, 2006).

The selection of a cost-effective retrofitting technique requires the precise evaluation of the lateral strength, stiffness and ductility of the existing RC frame. This study is focussed on the analytical prediction of the cyclic performance of the RC frames. Two geometrically-identical single-story single-bay RC frames are experimentally investigated under constant gravity loading and gradually-increased cyclic lateral displacements. Out of two test frames, one represents the conventional (control) RC frame, whereas the other specimen is prepared with steel fiber reinforced concrete (SFRC) at the expected plastic hinge regions and beam-column joints. The objectives of this study are to investigate the hysteretic response and failure mechanism of the non-ductile RC frames. Analytical models are developed in the *OpenSees* platform to predict their hysteretic response, stiffness degradation with cyclic excursions, ultimate resistance and failure mechanism. The analytical results are compared with the experimental results.

2 SIGNIFICANCE OF THE RESEARCH

The collapse of a RC buildings during the strong ground motions can be caused due to the failure of components under shear, flexure, axial or a combination of these. Generally, the existing buildings are mainly designed for gravity loading which do not satisfy the strong column-weak beam criteria to control the damage/collapse of the structures. This leads to severe damages or complete collapse of columns rather than beams of a RC structure. In order to improve the shear capacity of columns and beam-column joints, fiber reinforced concrete has been suggested by various researchers. One of the test specimens chosen in this study consisted of SFRC at the critical locations as shown in Figure 1. In this SFRC specimen, steel fiber concrete mix was used only in the joint regions, while plain concrete and for the remaining portion plain mix was used. For both the frames, cyclic pushover analysis was carried out experimentally and analytically under constant gravity load. The experimental results were used to validate the modelling technique adopted in the analytical study.



(a) (b) (c)

Figure 1. (a) Study frame under constant gravity loading and lateral loads showing plastic hinges zone, (b) BM diagram for given loading, (c) SF diagram for given loading.

3 PROTOTYPE STUDY FRAME

3.1 Description of Frame

A single-storey single-bay reinforced concrete (RC) frame representing an interior bay of a prototype framed structure was considered as the test frame in this study. All the dimensions and percentage of reinforcement of test frame was simulated using 0.4 scale factor. The overall width and height of test frame was taken as 3200 mm and 2100 mm respectively. The cross sectional dimension of beam was taken as 160x130 mm, whereas both the columns dimension was 160x160 mm. To include the slab effect on the overall cyclic performance of test frames, a monolithic slab of 50 mm thick and 500 mm wide was cast over the beam (Oinam et al., 2014). Figure 2(a) shows the details of the geometric properties of the test frame. In representing the existing non-earthquake resistant building, ductile detailing was not considered. Detailing was carried out as per Indian standard IS-456 (IS-456 2000) provisions. SFRC matrix was casted on joints extended up to maximum plastic hinge locations as shown by the hatched region in Figure 2(b). The length of plastic hinge (*lp*) was calculated using the following expression (Paulay and Priestley 1992):

$$l_p = 0.008l + 0.002 d_b f_y \quad \text{(Mpa)} \tag{1}$$

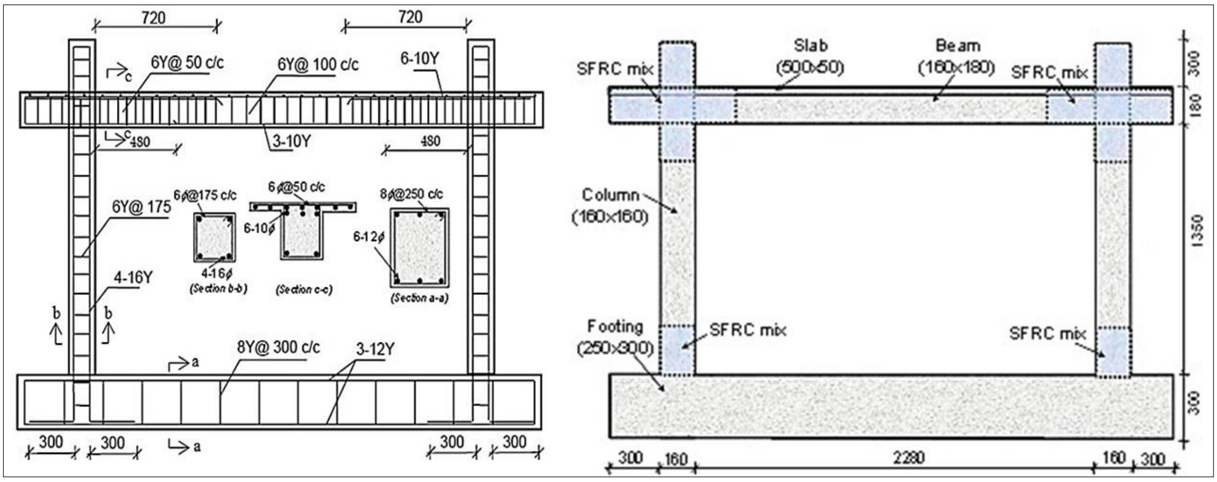
Where, *lp* = plastic hinge length, l = length of beam, d_b = diameter of main bar, f_y = yield strength of main bar. Here, the plastic hinge length l_p was found to be 1.6 times of column depth. Hence, the steel fiber matrix was provided for a distance of 1.5 times column depth from the joints. The RC frame was tested under cyclic load up to 3.5% lateral drift, while the SFRC frame was tested up to 4.5% lateral drift.

3.2 Material Properties

Table 1 summarizes the cube and cylinder compressive strengths of plain and fiber reinforced concrete used in the test frames. The details of mix design and quantity of materials used in the respective concrete mixes can be found elsewhere (Oinam et al. 2014). The characteristic cube compressive strength of concrete used in the mix design was 25 MPa (referred as M25 grade of concrete), which resulted in a target mean cube compressive strength of 31.6 MPa as per IS: 10262 (2009) provisions. The compressive cube strength is used in analytical modelling as input parameter.

Table 1. Summary of cube and cylinder compressive strengths of concrete at 28-days of curing

Specimen type	*Cube comp. strength (MPa)*	*Mean cube comp. strength (MPa)*	*Cylinder comp. strength (MPa)*	*Mean cylinder comp. strength (MPa)*
Plain concrete	37.0	34.6	26.2	24.6
	33.6		22.5	
SFRC concrete	33.1	39.1	25.0	28.0
	37.5		28.7	
	40.1		27.5	
	39.7		27.5	



(a) (b)

Figure 2. (a) Details of prototype study frame, (b) SFRC matrix location on plastic zones (blue colours portion)

3.3 Analytical Modelling in *Opensees*

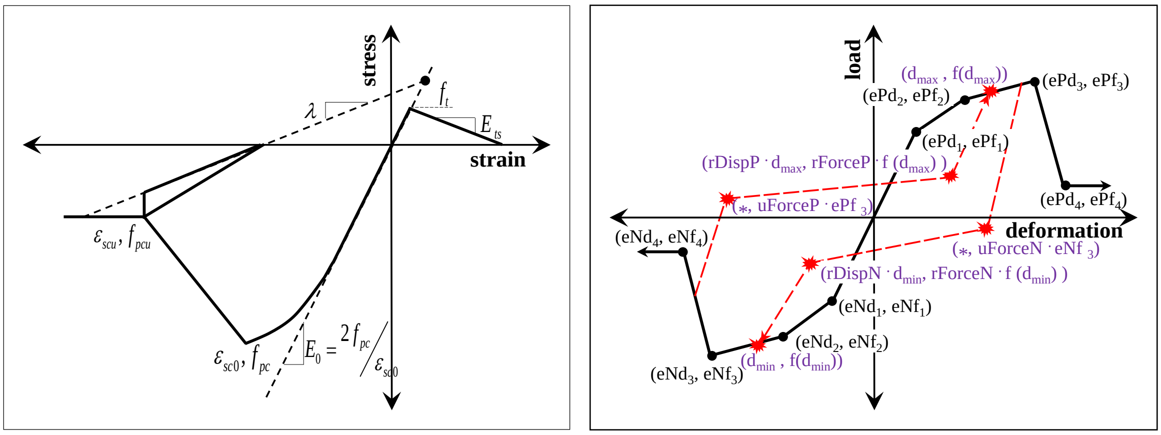
Both test frames were modelled analytically in an analysis software *Opensees* (Mckenna et al., 2000) platform. The details of modelling technique used in this study are discussed in the following sections. Both columns and beams are modelled as nonlinear frame elements with fiber sections. The respective materil properties are assigned to these elements.

3.3.1 *Concrete model*

Uniaxial material model "*Concrete02"* has been used to account for the compression as well as tensile behaviour of concrete. The tensile strength of the concrete is generally not taken into account in the design of concrete members due to very week in tension. But, for validating the experimental result tensile strength can't be ignored. Direct tensile strength of M25 grade concrete is 8-11 percent of compressive strength (Shetty, 2005). The values of concrete compressive strength for the plain concrete and SFRC used in the analytical model are 34.6 MPa and 39.1 MPa, respectively (See Table 1). The tensile strength of the plain and fiber reinforced concrete are taken 10% and 12% of their mean compressive strengths (Shetty 2005). The nonlinear monotonic behaviour of concrete was characterised by a multi-linear curve, defined by seven parameters as shown in Figure 3a. These parameters (a) maximum compressive strength ($\boldsymbol{f}_{pc}$); (b) strain at maximum compressive strength ($\boldsymbol{\varepsilon}_{sc0}$); (c) crushing strength ($\boldsymbol{f}_{pcu}$); (d) strain at crushing strength ($\boldsymbol{\varepsilon}_{scu}$); (e) ratio of unloading slope and initial slope (λ); (f) tensile strength of concrete ($\boldsymbol{f}_t$); (g) tension softening stiffness (E_{ts}).

3.3.2 *Pinching effect model*

Pinching effect in the hysteretic response of the RC members at the higher cyclic excursions is a very common phenomenon. The hysteresis loops converging towards the origin point is termed as pinching. This is an inherent property of concrete, and it happens due to the combined effect of stiffness and strength degradation in the non-linear range while loading and unloading occurs. Due to this effect concrete members dissipate less energy compared to steel structures. To consider pinching effect in the modelling of the concrete members a uniaxial material called *pinching4* is used from *Openseess* library which is one of the most suitable material in the library. Figure 3(b) shows the load deformation curve of *pinching4* material. The speciality of *pinching4* material is that it considers material degradation (strength-stiffness). The strength-stiffness cycle degradation occurs in three ways; namely (a) unloading stiffness degradation; (b) reloading stiffness degradation; and (c) strength degradation.



(a) (b)

Figure 3. Stress Strain Curve of (a) *Concrete02* and (b) *Pinching4*

Table 2. Damage Parameters of *Pinching4*

Pinching4 Damage Parameters												
F_y (Mpa)	*E_S (Mpa)*	*rDisp*		*rForce*		*uForce*		*γK*	*γD*	*γF*	*γE*	*dam*
		Pos	*Neg*	*Pos*	*Neg*	*Pos*	*Neg*					
								0.25	0.5	0		
								0.35	0.5	0		
415	2.1×10^5	0.4	0.4	0.1	0.1	0.12	0.12	0.4	2	0	10	En-ergy
								0.2	2	0		
								0.5	0.5	0		

Beam column section was modelled using fibre sections and to predict accurately the inelastic behaviour of concrete, “Force-Based Beam-Column Elements (*nonlinearBeamColumn*)” was used as an element. Table 2 shows the damage parameters of *pinching4* materials. The damage parameter includes the following factors (i) ratio of deformation *rDisp*, (ii) ratio of force *rForce*, (iii) ratio of strength developed *uForce*, (iv) cyclic stiffness degradation *γK* and *γD*, (v) cyclic strength degradation *γF*, (vi) maximum energy dissipation under cyclic loading *γE* and (vii) type of damage. Figure 4 shows the distribution of elements on the model frames.

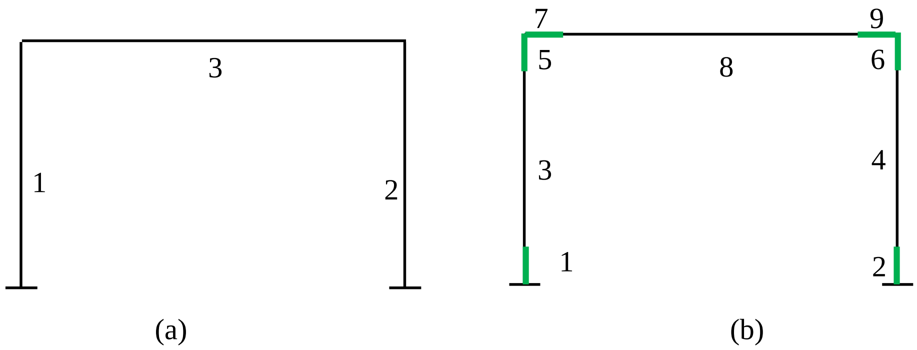


Figure 4. Distribution of elements in RC and SFRC model frame (a) RC, (b) SFRC

3.4 Nonlinear Cyclic Pushover Analysis

Prototype frames were investigated both experimentally and analytically. In both conditions, frame were subjected to gradually increased reversed cyclic displacement with constant gravity load. ACI Committee 374.1-05 (ACI 2006) recommended predefined cyclic displacement cycles was used to conduct the cyclic pushover analysis of the RC structure. This displacement history consists of drift cycles of 0.20%, 0.35%, 0.50%, 0.75%, 1.10%, 1.40%, 1.75%, 2.20%, 2.75%, 3.50% and 4.50%. Story drift (or drift ratio) may be defined as the ratio of the roof displacement to height of the story measured from the bottom level of column to the centre line of top beam. Each displacement cycle was repeated for three times at any drift ratio and then, followed by a single drift cycle of the smaller magnitude.

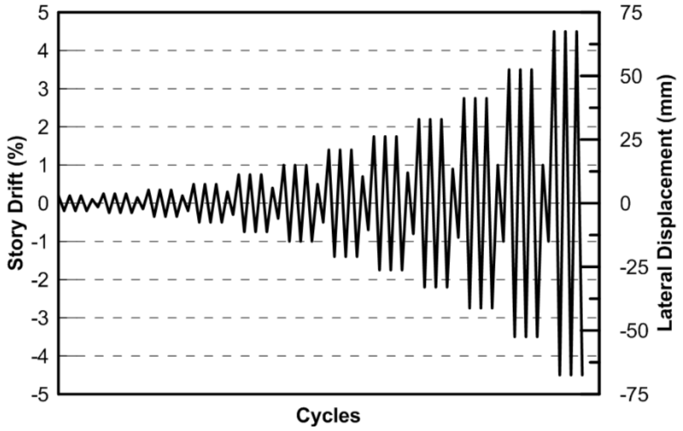


Figure 5. Cyclic Displacement profile applied on study frame

A constant gravity load of 7.25 kN was applied at the slab level of the prototype frame. Since the axial load ratio in columns is found to be nearly 10% in practice, the applied axial load does not truly represent the site condition. During the experiment, RC frame was tested up to 3.5% lateral drift, while SFRC frame tested up to 4.5% lateral drift, so same displacement profile was used in the analytical model as well.

3.5 Result and Discussion

Validation of the experimental result is the main objective of this study. The following parameter are validated analytically. These are (a) time period of structures, (b) lateral load carrying capacity of prototype frame, and (c) plastic hinge formation on columns. The explanation of above mentioned points are in following sections.

3.5.1 *Time period of structures*

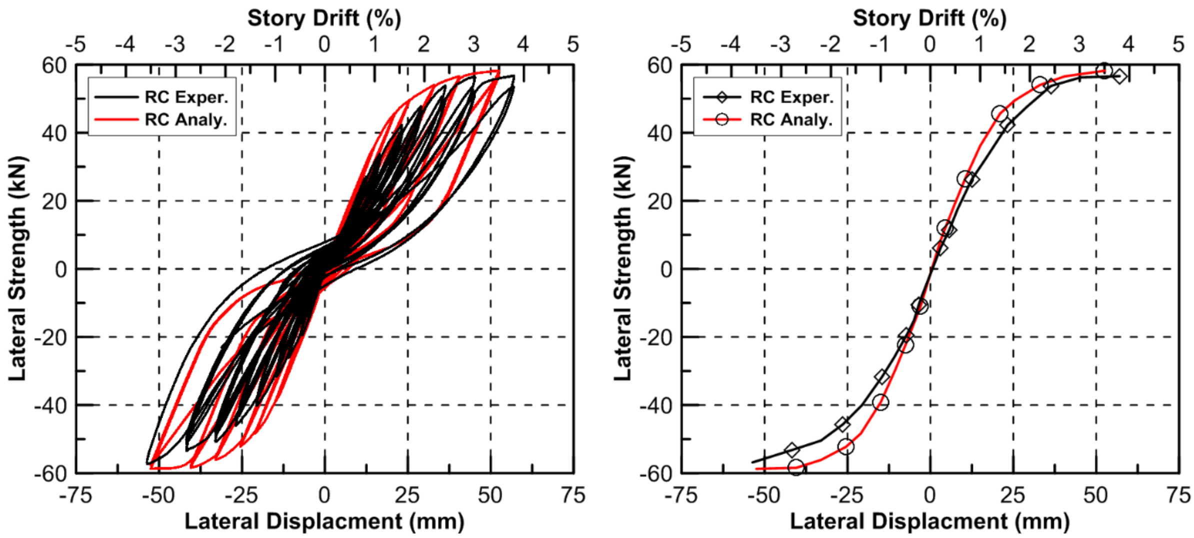
Experimentally the frames were checked for their natural frequency with the help of APS 400 Electro-Seis long-stroke shaker, and it was observed as 10Hz and 11Hz for RC and SFRC frame correspondingly i.e. 62.83 rad/sec and 69.1 rad/sec. From this observed value, time period of the prototype frames were calculated using the equation 2.

$$T = \frac{2\pi}{\omega_n} \tag{2}$$

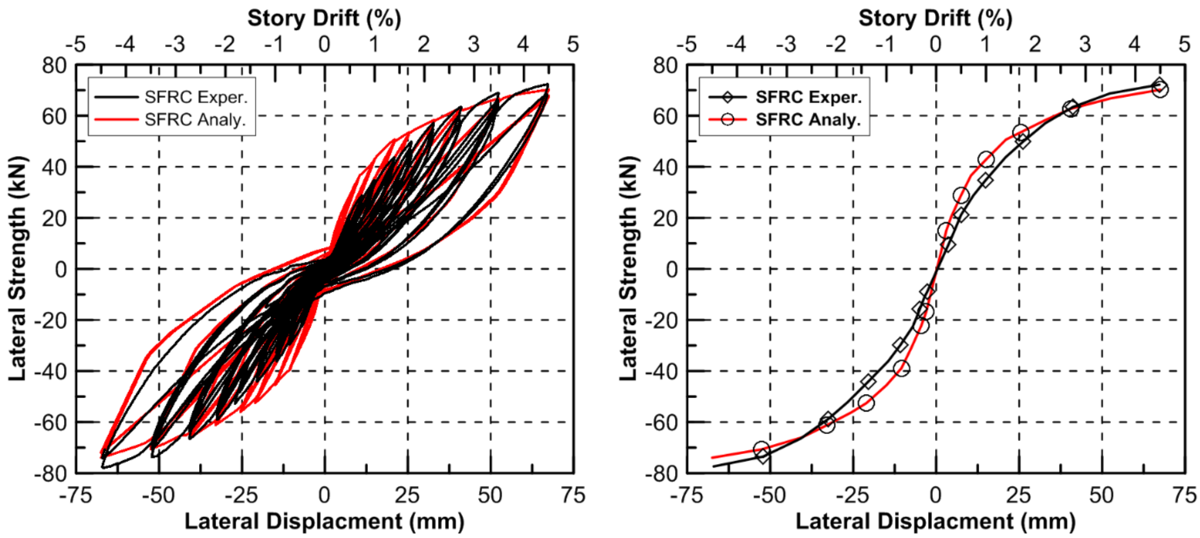
Where, T is time period of the frame in second, and ω_n is the natural circular frequency in radian/second. From Eigen value analysis of the analytical model the time period of both the frame was found to be 0.08 second. This value is close to the experimentally calculated value.

3.5.2 *Lateral load carrying capacity (Hysteresis Response)*

Experimentally RC frame resist lateral force up to 56.6 kN and 56.8 kN in compression and tension particularly at 3.5% drift. Analytically the frame resist 58.2 kN and 58.7 kN in tension and compression, these values are close to the experimental values. The difference of lateral load carrying capacity of frame experimentally and analytical is 2.8% and 3.3% in compression and tension. Over all hysteresis behaviour are also found to be more or less same. At 4.5% lateral drift, SFRC frame resisted lateral force up to 72.2 kN and 77.4 kN in compression and tension. Analytically this frame resist 70.2 kN and 73.9 kN in tension and compression respectively. It shows that analytical and experimental values are not much different i.e. 2.8% and 4.5% in tension and compression. Figure 6 shows the comparison between experimental and analytical frame in terms of hysteresis and backbone for both frames. From this figure overall comparison of hysteresis can be observed in terms of lateral load carrying capacity, pinching formation etc. Unlike steel structure concrete structure has a tendency to show pinching effect. Here the analytical model validated the pinching behaviour of prototype frame, which is seen to be almost same as the experimental hysteresis.



(a) (b)

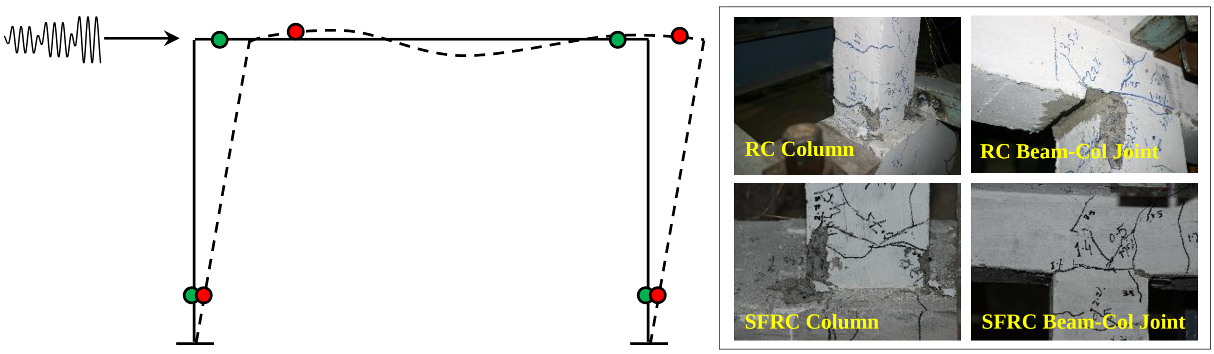


(c) (d)

Figure 6. (a, c) Hysteresis comparison of RC and SFRC frames, (b, d) Backbone comparison of RC and SFRC frames

3.5.3 *Plastic hinge formation on frame members*

Experimentally RC frame yielded at 0.5% drift, while SFRC frame yielded at 0.75% drift. Analytically both frames yielded at 0.75% drift level. During the experiment, it was observed that maximum damage was observed at the bottom of the column in both the frames. Similarly in analysis, frame sections yielded at lower drift level in the column bottom. Figure *7* shows the hinge mechanism on study frames and damage at column bottom and beam-column joint due to lateral cyclic displacement. Table 3 shows the comparison of experimental and analytical yield rotation. Experimental yielding rotations values are found to be nearly same as the analytical results. It means the results of the analytical model matches the experimental frame over all parameters like lateral loading capacity, hysteresis behaviour, plastic hinge mechanism and level of plastic hinge.



(a) (b)

Figure 7. (a) Plastic hinge mechanism on study frame, (b) damage on column and beam

Table 3. Comparison of experiments and analytical yielding values

Types of Hinge	*RC Column*		*SFRC Column*	
	Experimental	*Analytical*	*Experimental*	*Analytical*
$\theta_y\,(rad)$	0.011	0.00694	0.012	0.01

CONCLUSIONS

Parameter like lateral load capacity, strength and stiffness degradation during loading and unloading, time period and hinge mechanisms of the analytical model matched with the experimental results. Pinching effect modelling is not so easy in other software, but *Opensees* has the capability of modelling various effect including pinching and tensile strength of concrete using their vast material library. In RC frame the difference between experimental and analytical results is 2.8% and 3.3% in compression and tension in terms of lateral load carrying capacity, while SFRC frame showed a difference of 2.8% and 4.5% in tension and compression respectively. Over all hysteresis behaviour and initial stiffness of RC frames matched perfectly. In SFRC frame initial stiffness was a bit different but the difference was found to be very small, and the overall behaviour is exactly same as the experimental results.

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