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Pushover Analysis of a Reinforced Cement Concrete (RCC) Structure Incorporating Fibre-Reinforced Polymers to Address Vertical Irregularities

Vinod Vawadra, Roshni John

Abstract: India has had four of the world's most destructive earthquakes in the past ten years, and our country is often rocked by earthquakes of low to moderate intensity. Since many buildings were severely damaged or collapsed, it has sparked debate about whether framed constructions are sufficiently sturdy to withstand significant vibrations. As a result, the strength or ability of existing reinforced concrete structures to withstand seismic loads can be evaluated. The performance level of earthquake-prone buildings is evaluated using a performance-based design. One seismic technique for assessing a building's performance level is push-over analysis. It is possible to determine whether damage occurs at the member or structure level using pushover analysis. The study employs pushover analysis, as outlined in the Applied Technology Council (ATC) – 4, a seismic assessment technique, to evaluate the ability of 20-story buildings in Seismic Zone III (with complex soil characteristics) to resist earthquake-induced forces. The primary objective was to assess the performance of structures reinforced with different fibre-reinforced polymer (FRP) materials, including aramid, glass, and carbon fibres, which are known for their high flexibility and strength in seismically active regions. To determine the optimal fibre-reinforced polymer configuration, the study considers the following parameters: pushover curve, target displacement, story shear, period, maximum story displacement, and story drift, all of which are evaluated independently through pushover analysis. Through the pushover analysis method, the research discovers that FRP wrapping can significantly improve the seismic performance of reinforced concrete buildings. The findings aim to enhance building design practices by recommending fibre-reinforced polymer configurations that improve earthquake resistance, ensuring future constructions are better equipped to handle seismic activity.

Keywords: Target Displacement, Lateral Displacement, Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP), and Aramid Fiber Reinforced Polymer (AFRP)

I. INTRODUCTION

The shaking of the earth's surface that occurs after a sudden release of energy in the crust is known as an earthquake. The earthquake puts RCC constructions at risk of collapsing.

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*Correspondence Author(s)

Vinod Vawadra*, Department of Civil Engineering, Saraswati College of Engineering, Navi Mumbai (Maharashtra), India. Email ID: vawadravinod@gmail.com, ORCID ID: 0009-0001-0972-4238

Prof Roshni John, Department of Civil Engineering, Saraswati College of Engineering, Navi Mumbai (Maharashtra), India. Email ID: roshni.john@civil.sce.edu.in, ORCID ID: 0009-0002-3977-5439

As a result, there are numerous fatalities, injuries, and financial losses. Buildings and high-rise structures are typically impacted by lateral motions brought on by earthquakes, which eventually compromise the structure's stability and trigger sideways collapse. Many conventional construction techniques are not very resistant to lateral stresses because structures are often built to withstand gravity loads. It has been demonstrated that strengthening these structures is a more practical and affordable short-term shelter option than replacing them. Therefore, a pushover analysis has been carried out to examine how well RCC-framed buildings will fare in future, unforeseen earthquakes.

Developing straightforward yet precise techniques to estimate seismic demand on structures while accounting for their inelastic behaviour is the primary challenge in performance-based engineering. Pushover analyses are unavoidably used in place of intricate, nonlinear time-history methods that are too complicated for general professional use. The process involves applying loads until the structure's weak point is identified, after which the model is updated to account for the structural changes resulting from the weak point. The structure is "pushed" once more in the second iteration until the second weak link is found. Until the entire structure reaches its yield point, this process continues.

II. LITERATURE

A brief review of previous studies on the Pushover analysis of the RCC Structure is presented. This literature review aims to investigate the behaviour of symmetrical and asymmetrical RCC structures with infill of single and double layers under earthquake conditions. Literature helps understand previous studies carried out on a particular topic.

Yurizka and Rosyidah (2020): This research was conducted to determine the performance of a setback building with a soft first story in the event of an earthquake, based on the results of the pushover analysis curve. A 10-floor irregular structure with a soft story on the 1st floor, consisting of two structural models with setback ratios of 0.3 and 0.6, representing Type 1 and Type 2 buildings, respectively. The results of the analysis in this study indicate that the maximum shear force for type 1 buildings is 50260.55 kN, and for type 2 buildings, it is 53560.49 kN. Buildings with smaller setback area ratios, i.e., Type 2 buildings, have a displacement of 515.68 mm in the X direction and 558.105 mm in the Y direction. Story drift 0.0186 m in the X and 0.0043 m in the Y direction. Performance of type 1 and type 2 building structures that refer to ATC-40 and FEMA 356 are at the Damage Control level [1].

Shinde et al. (2016): - The present study represents the seismic response of the vertical irregular building frame as compared to the regular building frame. There are various types of vertical irregularities. The building frame considered for this study that are irregular in elevation. Performed static nonlinear analysis on G+7 RCC building frame with and without vertical irregularity design and analysis software ETABSv9.5.0 as per the Indian Standard 456:2000 and 1893:2002. The structure has a height of 3m, a bay width of 4.5m along the x-direction and 3m along the Y-direction. The results of the analysis in this study indicate that the maximum shear force based on capacity curves in Model 1 is 2000.698 kN, and in Model 2, it is 827.97 kN. Models 1 and 2 have displacements of 0.187 m and 0.115 m, respectively. Story drift 0.001878 m and 0.003011 in the Model 1 and Model 2, respectively. The building frame with vertical irregularity has a lower performance point value as compared to the building frame without vertical irregularity [2].

Selim et al. (2015): The present study involves a layer made of Engineered Cementitious Composite (ECC) that has recently been used to modify the behaviour of many structural components. Eleven frame models were examined in this study: the bare frame (BF0), the infilled frame (IF-0), the infilled frame with a single layer of ECC (IF-1), and the infilled frame with double layers of ECC (IF-2). The first four frames were chosen as single-degree-of-freedom (SDOF) models. The other seven frames, however, were MDOF (multi-degree-of-freedom) models. The following building has been modelled in SeismoStruct. The pushover analysis results showed that the Peak load is increased by around 1.7 times when an infilled frame is used instead of a bare frame. Infilled frames with the ECC layer are stiffer than other infilled frame constructions. Peak load is increased by 1.178 times over (IF) when only one ECC layer is used, and by 1.20 times over (IF when two ECC layers are used [3].

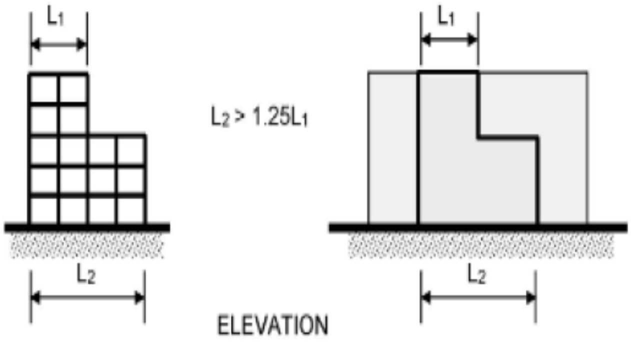
III. DESCRIPTION

A. Vertical Geometric Irregularity

Vertical geometric irregularity shall be considered to exist when the vertical dimension of the lateral force-resisting system in any story is more than 125 percent of the story below.

- For Model 1, Model 2, Model 3 and Model 4 in the X-direction,
  1.25 x L1 = 1.25 x 25.51= 31.88
  L2 = 43.51
  L2 > 1.25L1
- For Model 1, Model 2, Model 3 and Model 4 in the Y-direction,
  1.25 x L1 = 1.25 x 12.8 = 16
  L2 = 19.54
  L2 > 1.25L1

In the present study, we have considered Vertical Geometric Irregularity in Model 1, Model 2, Model 3, and Model 4 as per IS 1893:2016 Table 6.



[Fig.1: Vertical Geometric Irregularity as per IS 1893:2016 (Table 6)]

B. Pushover Analysis

Seismic analysis, a branch of structural analysis, aims to understand how structures respond to earthquakes. It's a crucial process, especially in seismically active regions. By ensuring that buildings are earthquake-resistant, seismic activity can be mitigated, reducing financial damage and saving lives.

Nonlinear static seismic analysis can be performed using the pushover method.

Pushover analysis is a series of incremental analyses conducted to develop a capacity curve for the building. Fig. 2 illustrates a pushover analysis. This procedure involves performing a nonlinear static analysis of the structure, enabling the monitoring of the progressive yielding of the structural component. The building is subjected to a lateral load. The load magnitude increases until the building reaches the target displacement. This target displacement represents the top displacement when the building is subjected to design-level seismic criteria.

Pushover analysis produces a pushover curve, also known as a capacity curve, that presents the relationship between base shear (V) and roof displacement. The Pushover curve depends on the deformation and strength capacities of the structure and describes how the structure acts beyond the elastic limit.

The structural response to ground motion during an earthquake cannot be accurately predicted due to the complexity of both structural properties and ground motion parameters. In pushover analysis, a series of lateral displacements is used as a design condition. The displacement is an estimate of the maximum expected response of the structure during seismic activity. Once pushover analysis is defined, the performance level can be determined using demand displacement. The performance verifies that the structure meets the acceptable limits of the performance level.

Recently, there have been some codes, such as Applied Technology Council (ATC)-40, Federal Emergency Management Agency (FEMA) 356 and Federal Emergency Management Agency (FEMA) 440, adopted standards and guidance provisions regarding the assessment of existing structures. Some programs are also developed for pushover analysis, such as ETABS and Staad.Pro.

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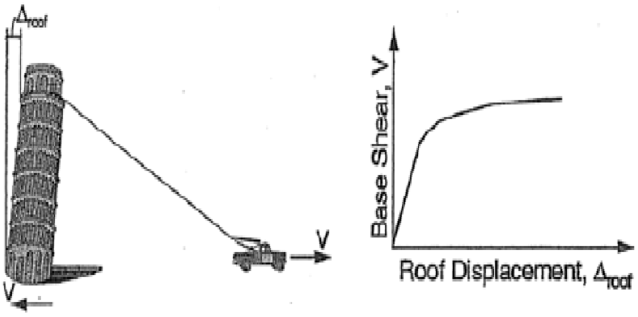
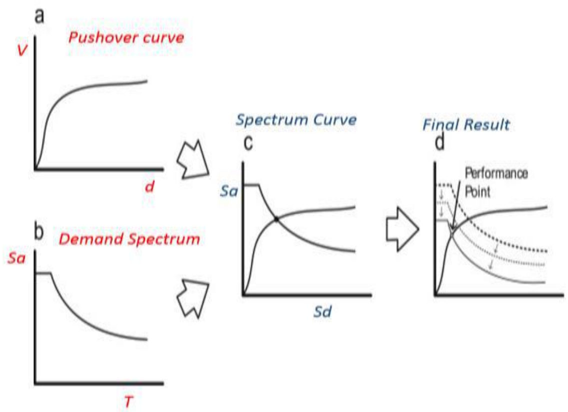


[Fig.2: Illustration of Pushover Analysis (ATC 40)]

C. Capacity Spectrum Method

Building performance level can be determined by target displacement using the capacity spectrum method (ATC 40). Utilising the capacity spectrum method, we get a graphical comparison between the seismic demand and structure capacity. The response spectrum curve represents the seismic demand, and the pushover curve represents the vertical resisting capacity of the structure. The capacity spectrum method, as shown in Figure 3, begins by generating a force-displacement curve that accounts for inelastic conditions. The obtained result is then plotted together in Acceleration Displacement Response Spectrum (ADRS) format. Demand is also converted into ADRS format so that the capacity curve and demand curve are in the same format.



[Fig.3: Capacity Spectrum Method]

In the Capacity Spectrum method, we obtain performance points by superimposing the demand spectrum on the capacity curve in spectral coordinates or Acceleration Displacement Response Spectrum (ADRS) format. The capacity spectrum method has been built into the ETABS program.

Table 1: Performance Levels of Buildings as per Applied Technology Council (ATC) - 40

Operational	Very light damage, no permanent drift, structure retains original strength and stiffness, and all systems are standard.
Immediate Occupancy	Light damage; no permanent drift. The structure retains its original strength and stiffness. The elevator can be restarted. Fire protection is operable.
Life Safety	Moderate damage, with some permanent drift, remains in all stories, leaving some residual strength and stiffness. There is damage to the partition, and the building may be beyond economical repair.
Collapse Prevention	With severe damage, large displacement, and slight residual stiffness and strength, the building is still able to bear loading on the column and wall, but is on the verge of collapse.

D. Fiber Reinforced Polymer

A composite material composed of a polymer matrix reinforced with fibres is known as a Fibre-Reinforced Polymer (FRP). Carbon, glass, and aramid are the most commonly utilised fibres. The ultimate strength and elastic modulus of these FRPs are higher than those of any other material, which ultimately improves the structure's ductility without significantly increasing the dead weight of the current structure.

E. Application of Fibre Reinforced Polymer

Fibre-reinforced polymer (FRP)'s exceptional properties make it an ideal choice for structural strengthening. Here are some of the key advantages and applications of FRP in the construction industry.

- Fibre-reinforced polymer (FRP) sheets can be used to wrap columns in buildings and bridges to improve their confinement and axial load-carrying capability.
- To improve strength, FRP is very successful at enhancing the flexural capacity of structural elements like beams and slabs on both the bottom and sides.
- To increase the load-bearing capacity of concrete, steel, or timber structures, FRP can be externally attached to them. Buildings, bridges, and other infrastructure that may have deteriorated over time are typically reinforced using this technique.
- In concrete constructions, FRP can be used to fix cracks and stop them from spreading. It aids in preserving the structural integrity and longevity of damaged components.
- FRP is an excellent material for constructions exposed to adverse environmental conditions, like those seen in industrial or maritime settings, because it is naturally resistant to corrosion.

IV. DESCRIPTION OF BUILDING

The following parameters are used for modelling and analysing irregular RCC structures.

Table 2: Configuration of Models

Model Number	Type of Configuration
Model 1	RCC without FRP
Model 2	RCC with AFRP
Model 3	RCC with GFRP
Model 4	RCC with CFRP

Table 3: Input Data for Modelling

Height of Building	61.5 M
Slab thickness	150 mm
Beam size	230 X 600 mm
	230 X 325 mm
	230 X 450 mm
Shear Wall	300 mm
Floor-to-floor height	2.9 m

Table 4: Material Properties of Structure

Grade of Concrete	M30
Grade of Steel	Fe500
Density of Reinforced Concrete	25 kN/m^3
Density of lightweight blockwork	10 kN/m^3
Density of water	10 kN/m^3

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Table 5: Seismic Data for Structure

Seismic Parameter (As Per IS 1893 Part -1 2016)	
Seismic Zone (Z) (From Table 3)	III
Zone Factor	0.16
Importance Factor (From Table 8)	1.2
Soil category	I
Response reduction factor (R) (From Table 9)	4

Table 6: Loading on Structure

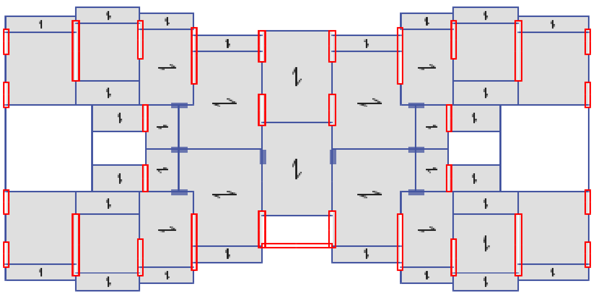
Loading (As Per IS: 875: Part 2: 2018)	
Live load	Floor = 2 kN/m^2. Terrace Floor = 3 kN/m^2.
Floor finish load	Floor = 1.5 kN/m^2. Terrace floor = 3 kN/m^2.
Wall load	0.23*3*10 = 6.9 kN.

Table 7: Wind Data for Structure

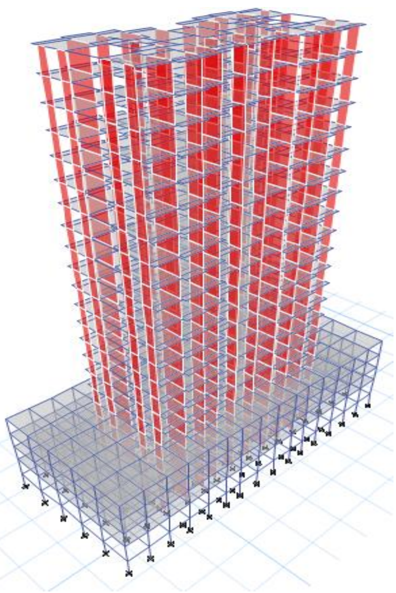
Loading (As Per IS: 875: Part 3: 2018)	
Wind speed	44 m/s
Terrain category	3

Table 8: Physical and Mechanical Properties of Different FRPs from Gudonis et al. (2013) [4]

Properties	CFRP	GFRP	AFRP
Elastic Modulus (GPa)	250	72.4	62
Fabric Weight (kg/m3)	1700	2500	1440
Ultimate Strength (MPa)	3700	3450	2760
Poisson ratio	0.2	0.22	0.35
Coefficient of thermal expansion 10–6/°C	1.2	5	2



[Fig.4: Plan of Vertical Irregularity Models]



[Fig.5: 3D Frame Structure of Vertical Irregularity Models]

V. VALIDATION

The pushover analysis is validated with examples taken from the National Program on Technology Enhanced Learning (NPTEL) and Dhiraj D. Ahiwale, Rushikesh R. Khartode, and Kaustubh V. (2020).

In this validation, we used a story RCC frame with a height of 3.5 m and a bay width of 4 m, situated in seismic zone IV, with hard rock strata, and a mass of 1500 kg on each floor.

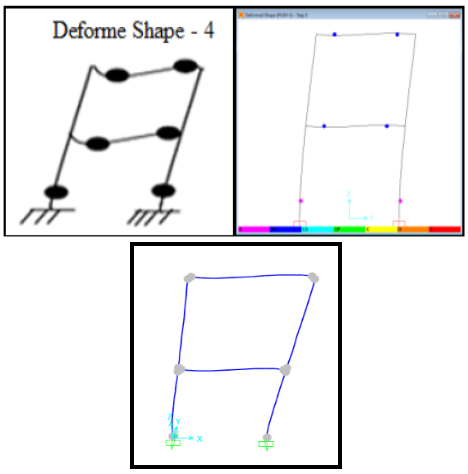
The details of the solved example are given below.

A pushover analysis for a two-story RCC frame having the given properties is done as follows:

- RCC frame with single bay and two-storey
- Floor-to-floor height is 3.5 m, and bay width is 4 m
- Reinforcement – Fe 415 and Concrete – M20
- Column Size – 400 mm x 230 mm
- Beam Size – 300 mm x 230 mm
- Response Spectra- IS: 1893 (Part 1)-2002
- Soil strata- Hard Rock
- Zone – IV
- Importance Factor- 1
- Lumped Mass – 1500 kg on each floor
- Modal Combination – Square root of the sum of squares (SRSS)
- Directional Combination - Square root of the sum of squares (SRSS)
- Load Combination- 1.5 (DL+EL) as per IS: 1893-2002

Table 9: Shows the Comparison of Performance Parameters as per NPTEL, Ahiwale et al. (2020) and Present

Parameters	Standard Problem	Ahiwale et al. (2020)	Present Study
Performance point- V (kN), D (m)	41.063, 0.019	46.249, 0.013	40.85, 0.017
Performance point (Sa, Sd)	0.700, 0.015	0.811, 0.011	1.278, 0.013
Performance point (Teff, Beff)	0.297, 0.137	0.231, 0.089	0.202, 0.126



[Fig.6: Shows the Deformed Shape of the Frame as per Model Analysis per NPTEL, Dhiraj D. Ahiwale, Rushikesh R. Khartode and Kaustubh V. Raut Ahiwale (2020) and Present Study]

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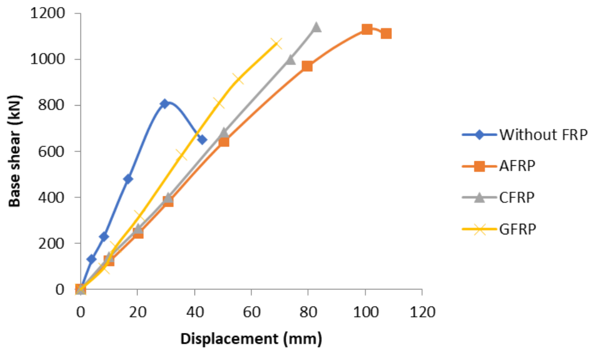
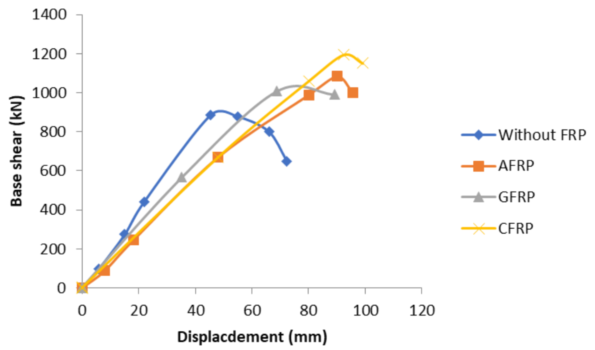
VI. RESULTS AND DISCUSSION



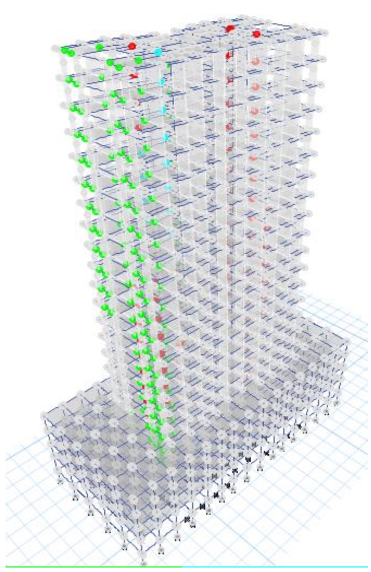
[Fig.7: Comparison of Pushover Curve of Models with Vertical Irregularity in X Direction]



[Fig.8: Comparison of Pushover Curve of Models with Vertical Irregularity in Y Direction]

Table 10: Comparison of Total Hinges of Models with Vertical Irregularity

Model No	Description	A-IO	IO-LS	LS-CP	>CP	Total
Model 1	Without FRP	6734	218	38	186	7176
Model 2	With AFRP	7005	171	0	0	7176
Model 3	With GFRP	7007	169	0	0	7176
Model 4	With CFRP	7072	104	0	0	7176

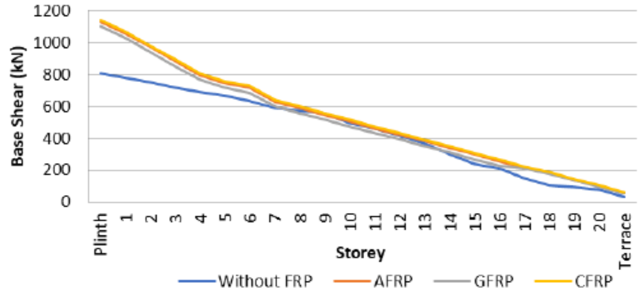


[Fig.9: Hinges Observed in Model 1 (without FRP)]

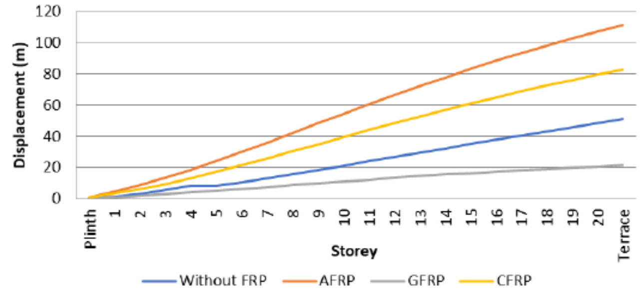
Table 11. Comparison of Target Displacement of Models with Vertical Irregularity

Model No	Description	Target Displacement (mm)
Model 1	Without FRP	45.49
Model 2	With AFRP	90.00
Model 3	With GFRP	68.68
Model 4	With CFRP	92.38

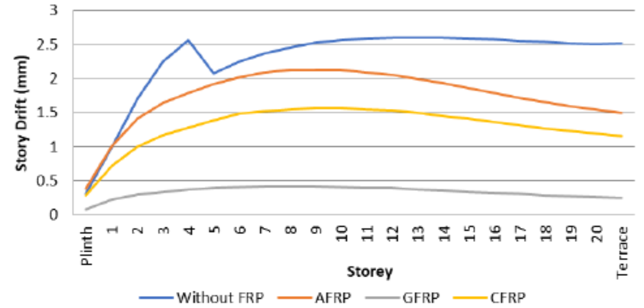
- Model 1, which is with vertical irregularity without FRP, shows the nonlinear inelastic transition from 29.694 mm in the X direction and 45.49 mm in the Y direction, lower than all other models.
- Model 4, which has vertical irregularity with CFRP, shows more target displacement and fewer hinges than all other models.



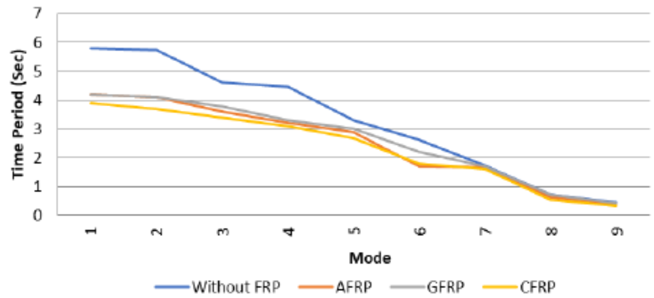
[Fig.10: Comparison of Base Shear]



[Fig.11: Comparison of Displacement]



[Fig.12: Comparison of Story Drift]



[Fig.13: Comparison of Period]

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VII. CONCLUSION

- Model 4, which is an RCC structure with CFRP, shows more target displacement and fewer hinges among all the models with vertical irregularity.
- Model 4, which is an RCC structure with CFRP, shows more storey shear among all the models with vertical irregularity.
- Model 4, which is an RCC structure with carbon fibre-reinforced polymer (CFRP), shows 236.53% less story displacement and 195.77% less story drift compared to Model 1, which is without FRP and exhibits vertical irregularity.
- Model 4, which is made with CFRP, has a minimum period of 3.9 seconds among all other models, which exhibit vertical irregularity.
- Models with CFRP are showing better results in vertical irregularity.
- The performance level of models without FRP is at the collapse prevention level, and all models with FRP are at the immediate occupancy level.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it was conducted without any external influence.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

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AUTHORS PROFILE

Vinod Vawadra, I obtained my B.E. degree in Civil Engineering from Saraswati College of Engineering (formerly affiliated with Mumbai University), Mumbai, Maharashtra, India, in 2019. I am pursuing my M.E. in the Department of Civil Engineering at the University of Mumbai. My current research interests include pushover analysis of vertical irregular structures with aramid fibre-reinforced polymers, glass fibre-reinforced polymers, and carbon fibre-reinforced polymers. I have good experience in Commercial and high-rise building structural audit and structural design. I am well-versed in Indian codes, such as IS 456, IS 800, IS 1893, and IS 13920, among others.

Prof. Roshni John, B. Tech (Civil Engg.) M.E(Structural Engg.) is working as an Associate Professor in the Department of Civil Engineering at Saraswati College of Engineering, Navi Mumbai—dedicated and passionate faculty with a proven record of fostering academic excellence and personal development in students. I strive to create an inspiring and supportive learning environment. My teaching philosophy centres on encouraging curiosity, creativity, and critical thinking. My expertise lies in structural engineering, with research publications in the fields of dynamic analysis of multistory buildings, structural dynamics, earthquake engineering, concrete technology, and the design of concrete structures.

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