PROGRESSIVE COLLAPSE OF RC BUILDING FRAMES: ONE DIRECTION FAILURE

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Abstract - *Progressive collapse in reinforced concrete (RC) building frames occurs when the failure of a single structural element triggers a chain reaction, potentially leading to partial or total structural failure. This research explores the mechanisms of progressive collapse, emphasizing the influence of structural design, load redistribution, and failure progression. RC frames with insufficient redundancy, weak load paths, or irregular geometries Are especially vulnerable, especially when subjected to extreme forces such as earthquakes or unexpected impacts. Analytical and numerical simulation techniques are employed to assess the behavior of RC structures during progressive collapse and identify key failure points. Effective mitigation strategies, including improved structural robustness, enhanced redundancy, and optimized load path continuity, are essential to reducing the risk of collapse.*

Key Words: One- direction collapse, load redivision, structural failure, seismic vulnerability, collapse propagation, structural robustness, redundancy, failure medium, erecting canons.

1.INTRODUCTION

Progressive collapse in reinforced concrete (RC) building frames occurs when the failure of a single joint or structural element initiates a chain reaction, ultimately leading to partial or total structural failure. The strength and stability of structural joints play a vital role in preventing progressive collapse, as they function as crucial load-bearing connections within the structure. Gaining insight into the response of RC building frames during progressive collapse is fundamental to improving structural resilience. Analytical and numerical modelling approaches are commonly used to examine failure mechanisms and evaluate the performance of joints under extreme conditions. This research examines the impact of joint failure on the progressive collapse of RC frames and emphasizes effective prevention techniques to improve overall structural integrity.

When a joint fails due to excessive loading, material degradation, seismic activity, or design deficiencies, the redistribution of forces can overstress adjacent members, triggering a domino-like collapse. The study of progressive collapse in RC frames is essential for improving structural resilience and preventing catastrophic failures. Scientists and engineers employ analytical and computational modelling methods to replicate joint failures and assess their effects on overall structural integrity.

Fig.1: Collapsed Building Due to Earthquake

1.1 THEORETICAL BACKGROUND

Progressive collapse is a structural failure process where the localized failure of a component initiates a chain reaction, resulting in either partial or total collapse of the structure. In reinforced concrete (RC) building frames, progressive collapse can be initiated by joint failure, which disrupts the load transfer mechanism and weakens the overall structural integrity.

Beam-column joints are critical components in RC frames, responsible for transferring loads between beams and columns. Inadequate detailing or poor construction quality further increases the vulnerability of joints to failure under extreme loading conditions. When a joint fails, its supported load is redistributed to the surrounding structural elements. To analyze and anticipate progressive collapse resulting from joint failure, researchers employ both analytical and numerical modeling methods. Finite element analysis (FEA) and nonlinear dynamic simulations are employed to assess failure propagation, load redistribution, and the overall structural response under extreme conditions.

Several design approaches can improve the resistance of RC building frames to progressive collapse initiated by joint failure. These include: Enhancing joint reinforcement to increase strength and ductility. Incorporating these strategies into design and construction practices can substantially minimize the risk of progressive collapse in RC building frames, enhancing structural safety and resilience.

1.2 Progressive Collapse in One Direction

Progressive collapse in a single direction describes a failure mechanism in which structural damage spreads primarily along one axis of the building frame. In reinforced concrete (RC) structures, this type of collapse often occurs when a critical joint or load-bearing element fails, causing adjacent structural components to sequentially lose their load-carrying capacity. The failure spreads through the structure in a linear or domino-like manner, leading to partial or total collapse.

Structural Layout: Structures with extended-span frames or insufficient lateral stability in a particular direction are more susceptible to this type of failure.

Failure Mechanism

The collapse process typically starts with the failure of an individual joint due to overloading, insufficient reinforcement, or unexpected external forces. It then progresses in one direction, following the weakest load path of the structure. However, in structures with inadequate lateral stability, the collapse can rapidly propagate until a significant portion of the building is compromised.

- Creating Alternative Load Paths: Incorporating additional load-bearing elements to ensure force redistribution in the event of primary joint failure.
- Enhancing Joint Reinforcement: Utilizing proper reinforcement techniques and detailed design to improve the strength and flexibility of beam-column joints.
- Impact of Beam-Column Joints: Insufficient detailing or substandard construction quality significantly heightens the susceptibility of joints to failure under extreme loads.

Load redistribution and structural response when a joint fails, the load originally carried by that joint is redistributed to surrounding structural elements. If these elements are not designed to withstand additional stress, they may also fail, triggering a chain reaction of collapses. Structural systems with robust alternative load paths, such as moment-resisting frames or catenary action in beams, have a higher chance of preventing total collapse.

To comprehend and predict progressive collapse resulting from joint failure, researchers utilize both analytical and numerical modeling methods. Finite element analysis (FEA) and nonlinear dynamic simulations aid in evaluating the failure sequence, load redistribution, and structural performance under extreme conditions.

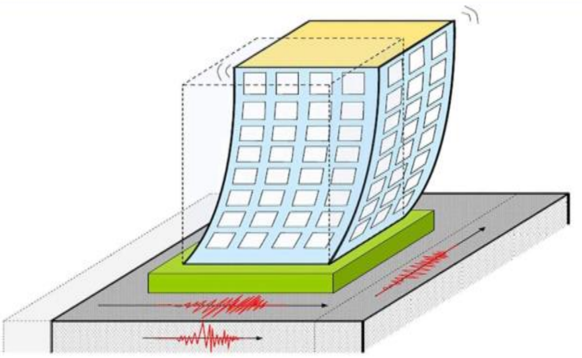

Fig. 2. Progressive Collapse effect

2. LITERATURE REVIEW

Anjali G. Dhole et al.(2021) estimated the progressive collapse threat of a 15- story concrete- framed structure under different column junking scripts using the alternate load path system. Linear static and dynamic analyses in ETABS 2019 revealed demand- to- capacity rates exceeding permissible limits in all cases, indicating high collapse threat. Mitigation strategies, similar as bottom- position bracing and adding ray sizes, were assessed for effectiveness.

Bhavik R. Patel et al. (2017) investigated the effects of soil-structure interaction (SSI) on progressive collapse in RC frames. Utilizing the Winkler model and SAP2000 software, they analyzed a 15-story building under various column failure scenarios. The findings emphasized that SSI impacts load redistribution and foundation behavior, highlighting nonlinear static analysis as an effective method for evaluating collapse resistance.

Zahrai et al.(2014) compared four logical approaches for assessing progressive collapse in intermediate RC frame structures direct static, nonlinear static, direct dynamic, and nonlinear dynamic styles. Dynamic methods were found to provide the most precise results for assessing collapse vulnerability in various column removal scenarios, as specified in the GSA guidelines.

A. R. **Rahai et al.(2012)** examined progressive collapse in RC structures due to both immediate and gradational column junking. Gradational junking, modelled as strength declination from fire, revealed different redivision patterns of forces and plastic distortion compared to immediate junking scripts.

3. OBJECTIVES

1. **Identify Critical Structural Elements:** Determine key RC components whose failure triggers one-direction progressive collapse and its propagation.

2. **Analyze Load Transfer:** Evaluate how loads are redistributed after critical failures, emphasizing structural instability and possible secondary risks.
3. **Develop computational models**: Simulate one-directional progressive collapse under severe conditions to assess failure propagation.
4. **Propose Structural Enhancements:** Suggest design and retrofitting strategies to prevent or limit collapse.
5. **Evaluate Connection Performance:** Assess structural connections in resisting failure and preventing progressive collapse.

4. METHODOLOGY

Progressive collapse takes place when the failure of one or more essential structural elements triggers a cascading effect, resulting in either partial or complete structural failure. In this research, a hybrid computational approach is utilized, incorporating ABAQUS 2024 and STAAD Pro to achieve the objectives.

4.1 Modelling process

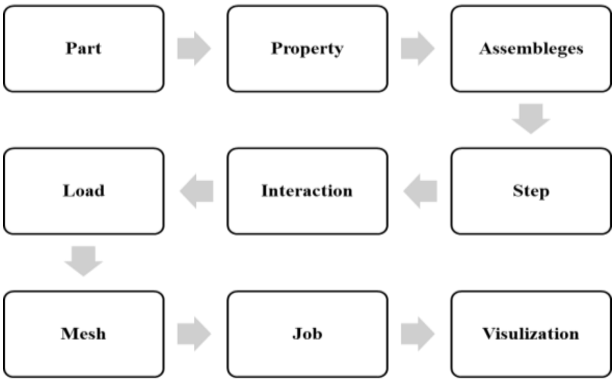

Fig 3 Abaqus Flowchart

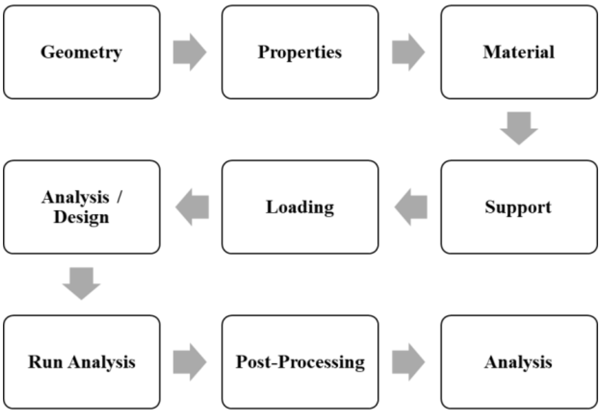

Fig 4 Staad Pro Flowchart

4.2 Model Summary

Staad Pro V22

i. Plan Size: G+10 – 15 x 15m
G+20 – 25 x 25m
G+30 – 40 x 40m
ii. Spacing between column – 5m c/c
iii. Height of Building – 30m, 60m, 90m
iv. Slab Thickness – 150mm
v. Floor to floor height – 3m
vi. Column Size: G+10 – 500 x 500mm
G+20 – 550 x 550mm
G+30 – 762 x 762mm
vii. Beam Size: G+10 – 300 x 500mm
G+20 – 400 x 600mm
G+30 – 500 x 700mm
viii. Grade of Concrete – M30
ix. Grade of Steel – Fe415

Loading on Structure:

Dead Load: 3.75 kN/m^2
Live Load: 2 kN/m^2
Live Load: 1.5 kN/m^2

Seismic Parameters (As Per IS 1893 part-1 2016):

Seismic Zone (Z): V [0.36] (As Per Clause 6.4.2)
Soil Category: II [Medium Soil] (As Per Clause 6.4.2)
Response Reduction Factor (R): 5 [SMRF] (As Per Clause 7.2.6)
Importance Factor (I): 1.0 (As Per Clause 7.2.3)
Damping: 5% (As Per Clause 7.2.4)

Abaqus 2024

i. Joint Connection - Corner, Exterior, Interior
ii. Column Cover 40 mm
iii. Beam Cover 25 mm
iv. Column size 500 mm x 500mm
v. Beam size 300 mm x 500 mm
vi. Beam span 5000 mm
vii. Reinforcement: Main Ø16mm
Stirrups Ø 8mm @ 150 mm c/c

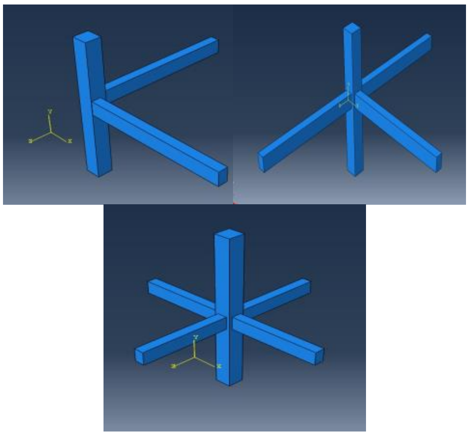

Fig. 5 represent Corner, Exterior, Interior Joint connection model on Abaqus 2024

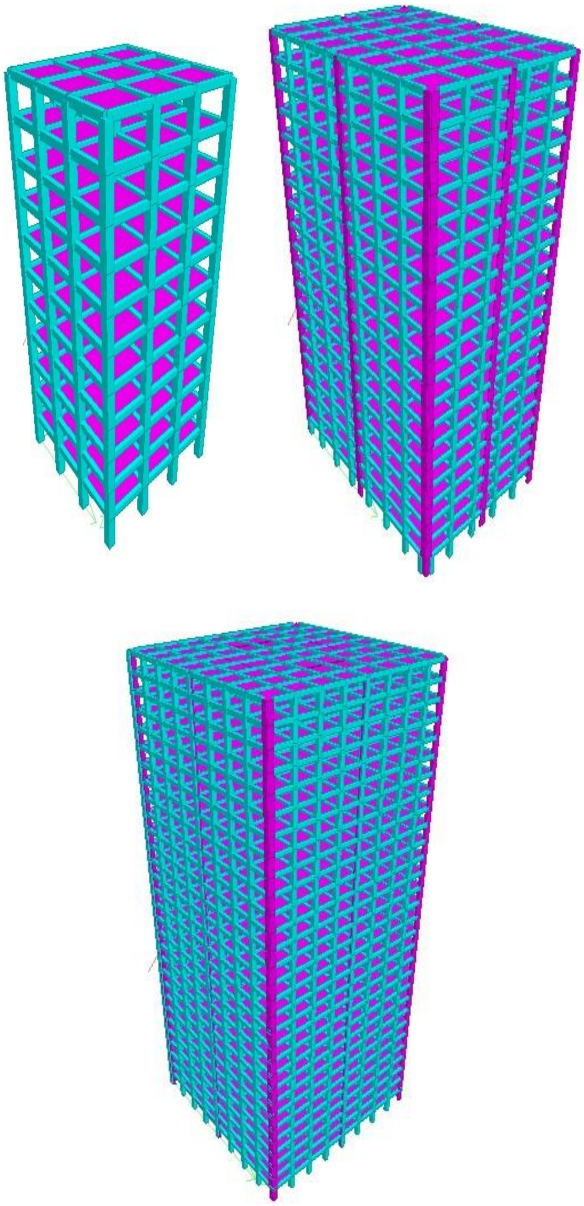

Fig. 6 represent G+10, G+20, G+30 model on Staad pro v22

5. RESULTS AND DISCUSSIONS

Result Report on Element Joint Connection Under One-Direction Progressive Collapse Using ABAQUS and STAAD Pro. This report presents the results of a detailed analysis of element joint connections subjected to one-direction progressive collapse, using ABAQUS and STAAD Pro. Joint performance was assessed under redistributed loads and cascading effects.

- Abaqus 2024 analysis of connection
- Stress - Strain Dissipation
- Time Displacement response
- Plastic & Damage Dissipation
- Demand Capacity Ratio (DCR)

5.1 Abaqus 2024 analysis of connection

The analysis represents the concentrated area in the connection element in corner, exterior and interior joint.

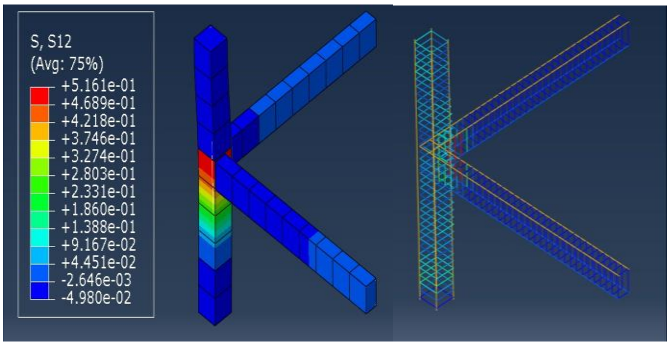

Fig 7 Corner connection analysis

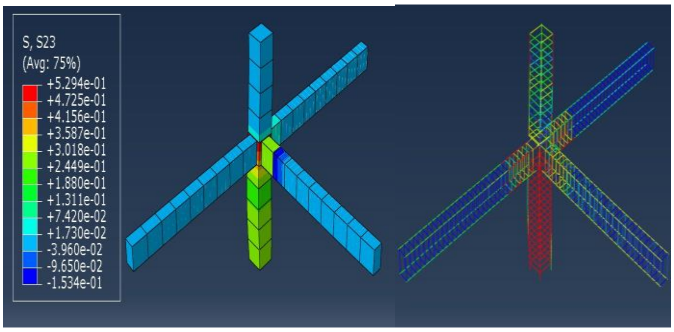

Fig 8 Exterior connection analysis

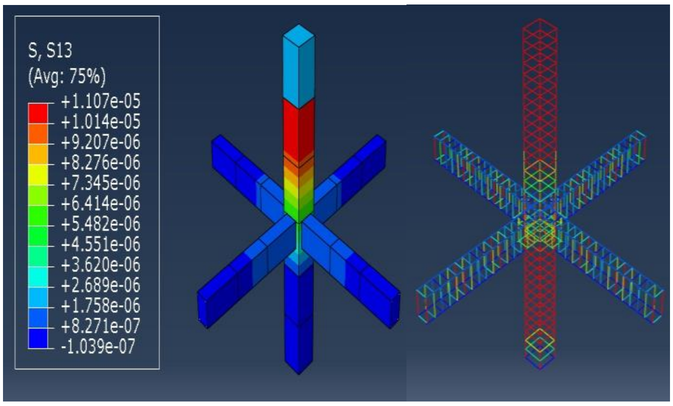

Fig. 9 Interior connection analysis

5.2 Stress & Strain Dissipation

Visuals or contour plots showing stress and strain across critical elements during failure.

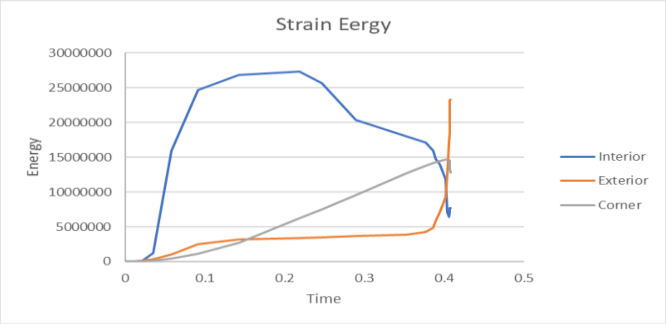

Chart 1 – Strain Energy in connection

5.3 Time – Displacement Response

Plot showing how key points displace over time during the progressive collapse. Tracks the immediate behavior of critical joints after the elimination of structural components. Shows peak displacements, residual deformations, and oscillatory behavior

- Maximum joint displacement: Interior - 550 mm, Exterior – 650mm, Corner – 100mm

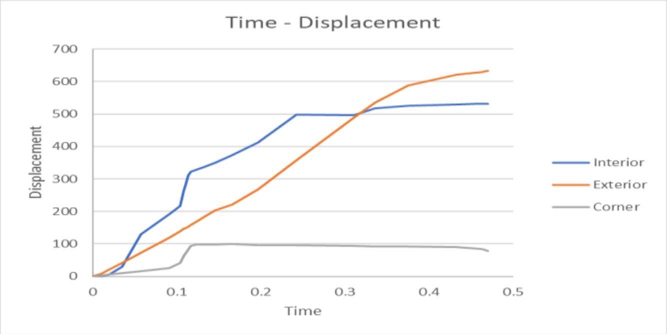

Chart 2 – Time – Displacement Graph of joint

5.4 Plastic & Damage Dissipation

Locations and progression of plastic dissipation & damage dissipation initiated at the beam-column interface

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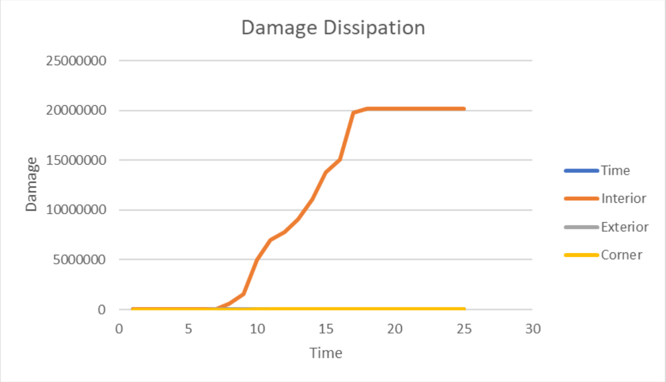


Chart 3 – Damage Dissipation Graph of joint

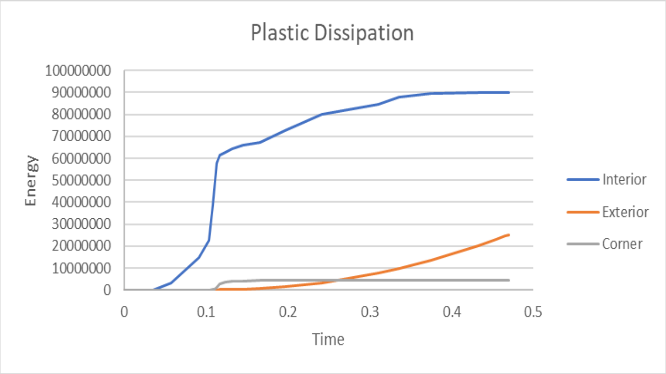


Chart 4 – Plastic Dissipation Graph of joint

Deflection and dispalcement in Staad Pro V22

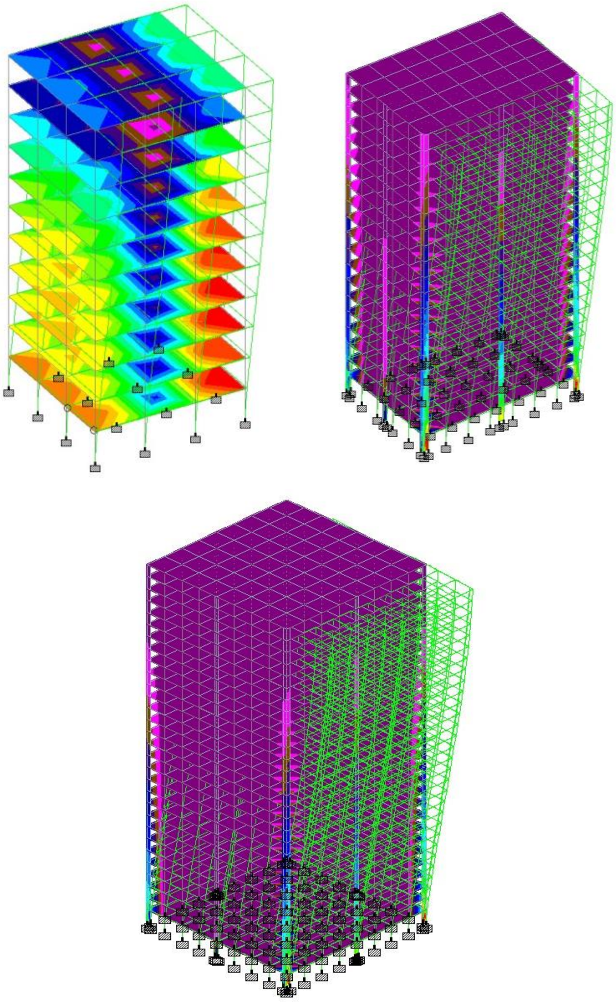


Fig. 10 Represent defelction of G+10, G+20, G+30

Bar representation of damage dissipation, displacement, plastic dissipation, strain energy, and froce act on connection joint

Corner Connection

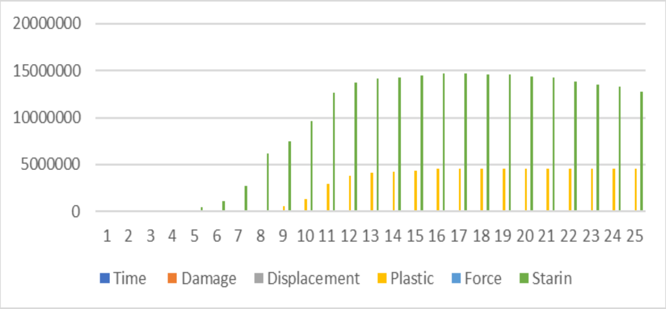
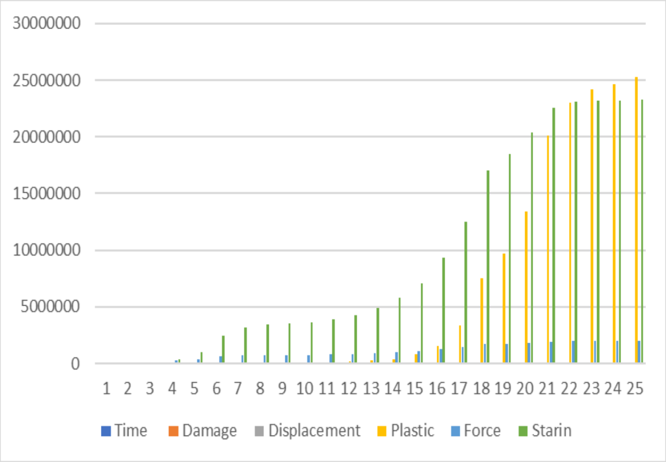


Chart 5- Bar repersentation of corner joint

Exterior Connection



Char 6 – Bar reperesentation of exterior joint

Interior Connection

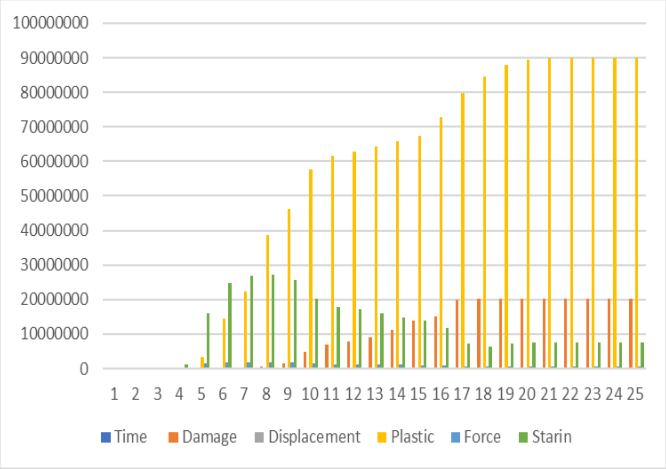


Chart 7 - Bar repersentation of interior joint

5.5 Demand Capacity Ratio (DCR)

Assess whether the structure complies with design criteria for progressive collapse resistance (e.g., in accordance with UFC 4-023-03 or GSA guidelines). The Demand-to-Capacity Ratio (DCR) is a key metric in progressive collapse evaluation, used to determine the structural sufficiency of components under extreme load conditions.

DCR	Corner	Interior	Exterior
Axial Force	0.243	1.46	0.292
Shear Force	2.19	2.07	2.24
Moment0.256	0.27	0.32	

- **Acceptable Range**: DCR ≤ 1.0 (elements remain within capacity).
- **Critical Range**: DCR > 1.0 (indicating potential failure or collapse).

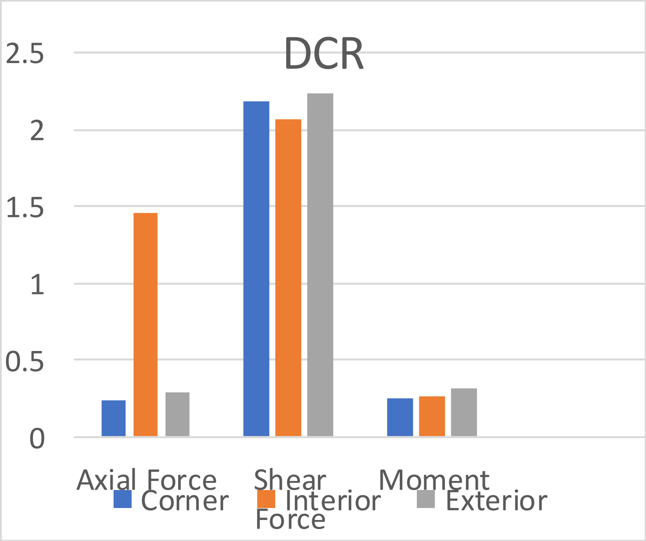


Chart 8 – Bar representation of DCR ratio

6. CONCLUSION

Progressive collapse in reinforced concrete (RC) building frames, particularly due to joint failure, is a critical structural issue that can lead to disproportionate damage or total collapse. The failure of a single joint or load-bearing component can initiate a chain reaction, causing sequential failures in the structure.

This phenomenon is influenced by factors such as structural configuration, load redistribution, joint detailing, material properties, and external forces like seismic activity or blast loads.

1. Collapse Mechanism:

The failure of critical connections caused a significant redistribution of loads, resulting in a progressive collapse mechanism predominantly in the direction of the failure.

2. Critical Connections:

Connection like corner connection, exterior connection, interior connection is more useful for the collapse of building structure in chain reaction at a particular direction.

3. Load Redistribution:

Key structural weaknesses were identified at joints and critical load-transfer paths, emphasizing their importance in collapse resistance.

4. Material Behavior:

The behavior of materials during progressive collapse is crucial in determining how a structure responds to localized failures. The mechanical properties of concrete, reinforcement steel, and other structural materials influence load redistribution, failure propagation, and the overall structural response.

5. Software Comparison:

Abaqus 2024: Best for detailed nonlinear dynamic analysis and material-specific failure mechanisms. Staad .Pro is well-suited for preliminary analysis and assessing the overall structural response.

7. FUTURE SCOPE

1. Developing innovative beam-column joint systems with enhanced flexibility, reinforcement, and impact resistance can improve structural robustness.
2. Zone V and Medium soil has been considering in this studies, other zone and soil type can be use.
3. Conducting full-scale and reduced-scale experimental evaluations on RC frames can provide valuable understanding of failure mechanisms and contribute to the enhancement of design guidelines.
4. Regular updates and advancements in building regulations that address progressive collapse will contribute to safer construction practices globally.

REFERENCES

[1] Pavel Korenkov & Sergey Meliksetyan (2024) “Influence of Compliance of the Connection of Reinforced Concrete Structures in the Analysis of Progressive Collapse Hazard” – E3S Web of Conferences 533, 02004 (2024)

[2] Vitaly I. Kolchunov & Natalia V. Fedorova & Sergei Y. Savin & Pavel A. Kaydas (2024) “Progressive Collapse Behaviour of a Precast Reinforced Concrete Frame System with Layered Beams” – Buildings 2024, 14, 1776

[3] Qiao-Ling Fu & Liang Tan & Bin Long & Shao-Bo Kang (2023) “Numerical Investigations of Progressive Collapse Behaviour of Multi-Storey Reinforced Concrete Frames” – Buildings 2023, 13, 533

[4] Dong Chang & Bin Zeng & Lin-Jie Huang & Zhen Zhou (2023) “Investigation on progressive collapse resistance of prestressed concrete frames with infilled walls” – Engineering Failure Analysis, Volume 143, Part A, January 2023, 106866

[5] Gaurav Verma & Gajendra Singh (2023) “Study on Structural Collapse Behaviour of Reinforced Concrete Building Collapse Study” – International Research Journal of Engineering and Technology (IRJET) Volume: 10 Issue: 04 | Apr 2023

[6] Said Elkholy & Ahmad Shehada & Bilal El-Ariss ((2022) ‘Effects of Floor System on Progressive Collapse Behaviour of RC Frame Sub-Assemblages” – “Buildings 2022, 12, 122.”

[7] Saif Uddin & Shaik Mohammed Javid (2022) “Assessing the Progressive Collapse of Reinforced Concrete Frame by Non-Linear Dynamic Approach” – International Journal of Creative Research Thoughts (IJCRT), Volume 10, Issue 2, February 2022

[8] Pawan Kumar & Samrat Lavendra & T Raghavendra (2021) “A Review on the Progressive Collapse Analysis of Reinforced Concrete Frame Structures” – IOP Conf. Series: Earth and Environmental Science 822 (2021) 012003

[9] Anjali G. Dhole & Prof. D.H. Tupe & Dr. G.R. Gandhe (2021) “Progressive Collapse Analysis of R.C.C. Framed Structure using Etab’s” – International Research Journal of Engineering and Technology (IRJET) Volume: 08, Issue: 04, Apr 2021

[10] Bhavik R. Patel & Dr. Bharat J. Shah (2017) “Progressive Collapse Assessment of Reinforced Concrete Frame Structure with And Without Considering Actual Soil Condition” – Kalpa Publications in Civil Engineering Volume1,2017

[11] Zahrai, S.M. & Ezoddin, A.R. (2014) “Numerical Study of Progressive Collapse in Intermediate Moment Resisting Reinforced Concrete Frame Due to Column Removal”– Civil Engineering Infrastructures Journal, 47(1): 71 – 88, June 2014

[12] A.R. Rahai & M. Banazadeh & M.R. Seify Asghshahr & H. Kazem (2012) “Progressive Collapse Assessment

of RC Structures under Instantaneous and Gradual Removal of Columns" - Department of Civil Engineering, Amirkabir University of Technology (Tehran Polytechnic), Iran

[13] IS 456 (2000) Reaffirmed 2021, "Plain and Reinforced Concrete - Code of Practice", Fourth Revision, BIS, New Delhi, India.

[14] IS 1893: Part 1 (2016) Reaffirmed 2021, "Criteria for Earthquake Resistant Design of Structures," Bureau of Indian Standards, Sixth Revision, BIS, New Delhi, India.

[15] IS 875: Part 1 (1987) Reaffirmed 2018, "Code of Practice for Dead Loads (Other Than Earthquake) For Building and Structure", Second Revision, BIS, New Delhi, India.

[16] IS 875: Part 2 (1987) Reaffirmed 2018, "Code of Practice for Design Load (Other Than Earthquake) For Building and Structure", Second Revision, BIS, New Delhi, India.

[17] IS 875: Part 3 (2020) "Code of Practice for Design Load (Other Than Earthquake for Building and Structure Part 3 Wind Load)", Third Revision, BIS, New Delhi, India.

[18] IS 13920 (2016) "Ductile Design and Detailing of Reinforce Concrete Structure Subjected to Seismic Forces - Code of Practice ", First Revision BIS, New Delhi, India.

[19] ABAQUS Documentation - Dassault System.

[20] STAAD Pro User Manual - Bentley Systems.