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Dynamic Performance Evaluation of Precast T-beam Structures under Seismic Loading

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Abstract

Reinforced Concrete Moment Resisting Frames (RCMRFs) are structural systems designed to effectively dissipate energy under seismic loading. In line with modern seismic design philosophy, the widely adopted capacity design approach emphasizes a "strong-column, weak-beam" configuration to promote ductility and a favorable collapse mechanism. When the flexural strength of the longitudinal beams governs the structural response, beam-column joints typically exhibit ductile behavior, with the joint panel zone remaining predominantly elastic. This beam-hinging failure mode is considered optimal, as it ensures significant global energy dissipation with minimal strength degradation at the joints. While many international design codes recommend maintaining a beam-to-column moment capacity ratio greater than one, discrepancies persist among these codes, and the Indian Standard currently lacks specific guidance on this critical aspect.

Major Findings: *The dynamic performance of precast T-beam structures under seismic loading reveals that precast models exhibit significantly lower total deformation compared to traditional Reinforced Concrete (RCC) structures, suggesting better structural stability. The stress levels, including equivalent stress, normal stress, and shear stress, are higher in precast models, with precast model 3 showing the highest resistance, indicating enhanced structural integrity. Additionally, the use of advanced dynamic analysis tools like ANSYS provides critical insights into the structural response, highlighting vulnerabilities and optimizing design for enhanced earthquake resilience.*

Keyword: *Ground Motion, Linear and Nonlinear Analysis, Precast Beam-column Connections, RCC*

1.0 Introduction

The increasing demand for faster and more efficient construction methods has led to the widespread adoption of precast concrete elements in modern structural systems. Among these, precast T-beams are commonly used in buildings, bridges, and other infrastructure due to their structural efficiency and ease of assembly[1]. However, the behavior of precast T-beam systems under dynamic and seismic loading conditions remains a critical area of study, especially in regions prone to earthquakes. Unlike monolithic cast-in-place systems, precast elements rely heavily on joint integrity and connection detailing, which can significantly influence the seismic response of the entire structure[2].

This study focuses on evaluating the dynamic performance of precast T-beam structures subjected to seismic loading, using both linear and nonlinear analysis approaches[3]. By examining parameters such as natural frequency, mode shapes, displacement, and stress distribution during ground motion, the research aims to understand how these systems behave under earthquake conditions[4]. The findings will help identify vulnerabilities in connection design and provide recommendations to

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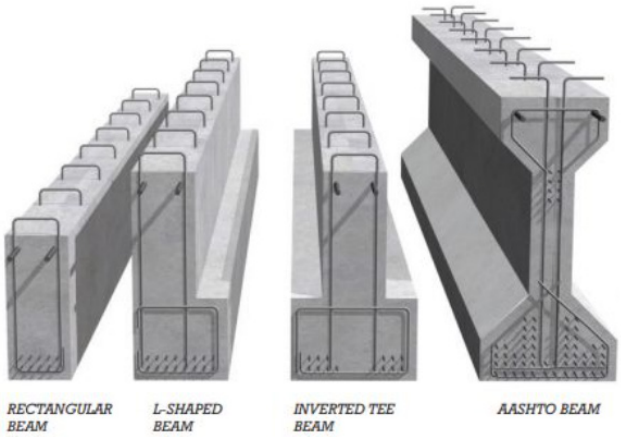


Figure 1. Precast beam[5].

enhance the seismic resilience of precast T-beam systems, contributing to safer and more sustainable construction practices in earthquake-prone regions.

1.1 History of Precast Technology

Ancient Roman builders used concrete and soon poured the material into molds to build their complex network of aqueducts, sewers, and tunnels[6]. Modern applications of precast technology cover a large number of architectural and static applications, from individual parts to complete building systems. In the modern world, prefab panel buildings were introduced in 1905 in Liverpool, England[7]. The process was invented by municipal engineer John Alexander Brodie, a creative genius who also came up with the idea for the soccer goal. In 1906 they followed the Walton tram stops in Liverpool. The idea was not widely accepted in the UK[8]. However, it has become popular all over the world, especially in Eastern Europe and Scandinavia. In the US, precast concrete has developed as two sub industries, each represented by a large association[9]. The precast concrete industry focuses on utility, underground, and other non pre-stressed products and is represented primarily by the National Precast Concrete Association (NPCA)[10]. The precast concrete industry focuses on pre-stressed concrete elements and other precast concrete elements used in above-ground structures such as buildings, parking lots and bridges[11]. This industry is represented primarily by the Precast or Pre-stressed Concrete Institute (PCI).

1.2 Objective

1. To evaluate the seismic response of precast T-beam structures using dynamic analysis.
2. To assess the performance of beam-to-column connections under earthquake loading.
3. To compare the dynamic behavior of precast T-beams with standard design provisions.

2.0 Literature Review

2.1 Review of Literature

Table 1. Finite element analysis studies[12]

Researcher(s)	Study Focus	Methodology	Conclusions
[13]	Nonlinear finite element analysis of precast hybrid beam-column connection under cyclic loads.	Developed detailed 3D nonlinear FE model considering pre-tension in post-tensioning strand and nonlinear concrete behavior; validated with experimental tests at NIST.	FE modeling is practical and economical for investigating such connections.
[14]	3D nonlinear FE model of exterior precast beam-column connection under reverse cyclic loading.	Tested 1/3 scale exterior beam-column connections with monolithic and two types of precast connections (J-bolt and Cleat Angle); used ANSYS for nonlinear analysis.	Suitable constitutive and failure models enable accurate FE prediction of seismic behavior.
[15]	Nonlinear response analysis of composite concrete beams.	2D plane stress FE model with biaxial concrete model; modeled reinforcement, bond-slip, shear-slip, dowel action using linkage and interface elements.	FE analysis is reliable for composite concrete beam behavior.
[16]	FE analysis of four types of precast connections including a new proposed connection.	Evaluated stiffness from load-deflection slope; applied seismic loading from modified El Centro earthquake with different accelerations.	New connection is suitable with good seismic performance.
[17]	Cost and feasibility analysis of precast *vs* traditional cast-in-situ building design.	Case study of one building designed both ways; cost and duration compared.	Provided feasibility insights for precast building adoption.

2.2 Research Gap

While considerable research has been conducted on the seismic behavior of cast-*in-situ* reinforced concrete components, limited attention has been given to the dynamic performance of precast T-beam structures under seismic loading conditions. Most existing studies focus on static load testing or generalized seismic performance of entire precast systems without isolating the unique structural characteristics and connection behaviors specific to T-beams. Moreover, the interaction between precast joints, beam-column connections, and the effects of cyclic loading on these joints remains insufficiently explored. There is also a noticeable lack of real-time dynamic simulations and experimental validations for assessing the nonlinear behavior and energy dissipation capacity of precast T-beams during seismic events. This gap is particularly critical as the widespread adoption of precast systems in urban construction demands a deeper understanding of their safety and resilience. Therefore, a comprehensive investigation combining numerical analysis, experimental testing, and parametric studies is needed to evaluate the seismic adequacy and optimize the design of precast T-beam structures.

3.0 Methodology

The methodology adopted in this study involves both numerical simulation and analytical evaluation to assess the dynamic performance of precast T-beam structures under seismic loading. The following subsections describe the research design, modeling approach, seismic loading input, and analysis techniques in detail.

3.1 Research Design

The study follows an analytical and simulation-based approach to evaluate the behavior of precast T-beams under dynamic seismic loads. The main objective is to understand how such structures respond to ground motions and to identify critical parameters influencing their seismic performance. The research is divided into 3 phases:

1. Geometric and material modeling of precast T-beam structures.
2. Application of seismic loading using real earthquake data.
3. Analysis and interpretation of dynamic responses.

3.2 Structural Modeling

A typical precast T-beam section was selected based on standard dimensions commonly used in residential and commercial buildings. The beam was modeled using Finite Element Analysis (FEA) software (such as ANSYS// ETABS/) with the following specifications:

1. Concrete modeled as a nonlinear material using appropriate constitutive laws (*e.g.*, Concrete Damaged Plasticity).
2. Reinforcement modeled as bilinear elastic-perfectly plastic steel.
3. Beam-to-column connections were modeled explicitly to reflect realistic boundary and joint behavior.

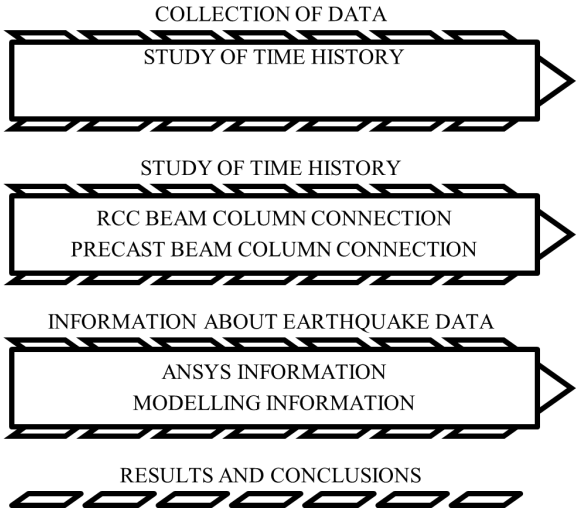


Figure 2. Flowchart[18].

4. Appropriate meshing techniques and convergence criteria were applied to ensure accuracy and computational stability.

3.3 Seismic Loading

The dynamic analysis employed ground motion records from actual earthquakes, such as:

1. El Centro earthquake (1940)
2. Kobe earthquake (1995)
3. Bhuj earthquake (2001)

These records were scaled according to the Indian seismic code (IS 1893:2016) and applied as base excitation in the form of time-history input. Spectral matching was used where necessary to align with local soil conditions and structural natural frequencies.

3.4 Dynamic Analysis Techniques

To assess the seismic performance, the following analysis types were conducted:

1. Modal analysis: To identify natural frequencies, mode shapes, and participation factors of the structure.
2. Linear and nonlinear time-history analysis: To evaluate the displacement, acceleration, base shear, and internal forces under earthquake loads.
3. Response spectrum analysis: For comparative assessment with code-defined limits and design provisions.

3.5 Performance Metrics

Key response parameters analyzed include:

1. Maximum displacement and inter-story drift.
2. Acceleration response at various nodes.
3. Stress and strain in concrete and steel
4. Hysteresis behavior and energy dissipation.
5. Ductility and residual deformation.

3.6 Validation

To ensure the reliability of simulation results, validation was performed by comparing the obtained data with published experimental results and standards (*e.g.*, ACI 318, IS 456, IS 1893). Where the possible, existing test data for precast beam elements under dynamic or cyclic loading were used for cross-checking the simulation output.

3.7 ANSYS Model

3.7.1 Details for ANSYS Models for Precast and RCC

Column Size - 300 x 750 mm
Reinforcement for Column - 12T-16No
Beam Size - 230 x 450 mm
Reinforcement for Beam - Top - 12T -2, Bottom- 12T -2, Shear - 10T@120 C/C
Total Maximum Load - 1824 KN

3.8 RCC Model

3.8.1 Geometry

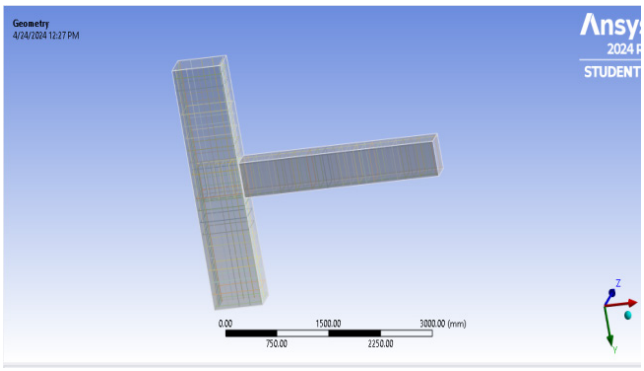


Figure 3. Geometry.

The above figure shows the geometry of structure.

3.8.2 Meshing

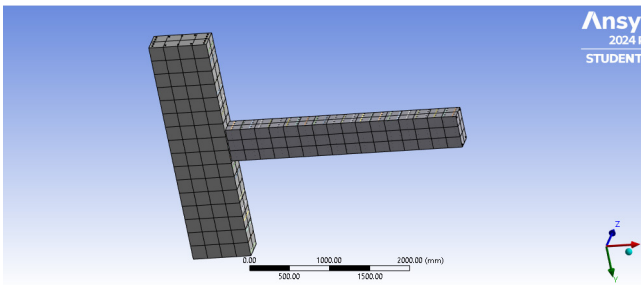


Figure 4. Meshing.

The above figure shows the meshing of structure.

3.8.3 Boundary Condition

The above figure shows the boundary condition of structure the reaction is at away from joint at end point of beam and at top of the beam.

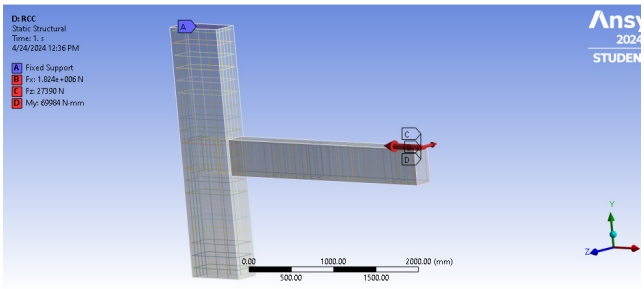


Figure 5. Boundary condition.

3.8.4 Total Deformation

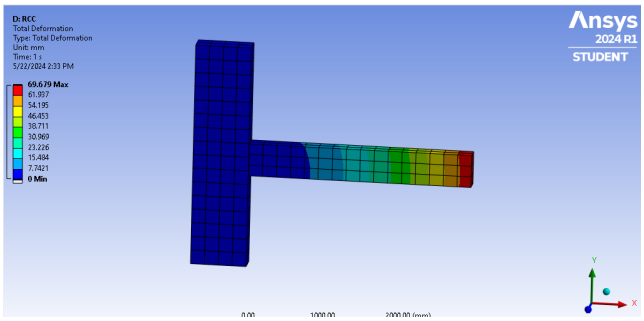


Figure 6. Total deformation.

The above figure shows the total deformation of structure in that maximum value is 69.679 mm.

3.8.5 Equivalent Stress

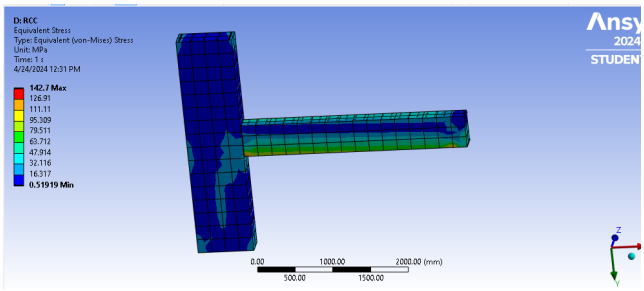


Figure 7. Equivalent stress.

The above figure shows the equivalent stress of structure in that maximum value is 142.7.

3.8.6 Normal Stress

The above figure shows the normal stress of structure in that maximum value is 63.577.

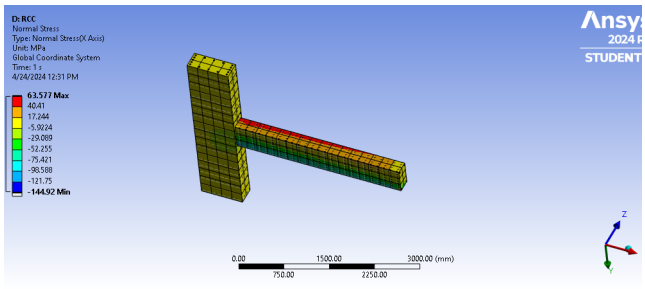


Figure 8. Normal stress.

3.8.7 Shear Stress

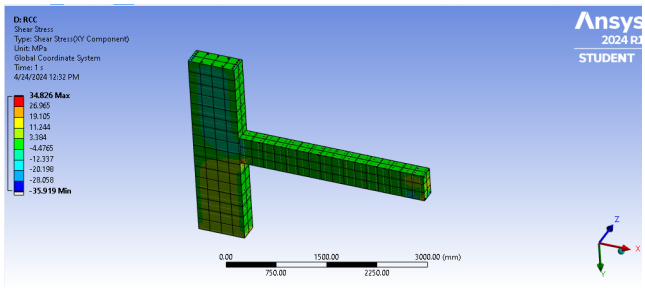


Figure 9. Shear stress.

The above figure shows the shear stress of structure in that maximum value is 34.826.

3.8.8 Maximum Principle Stress

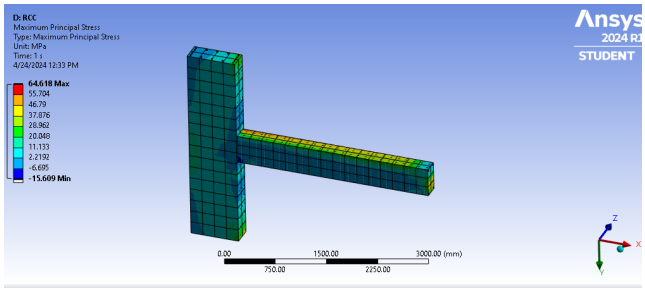


Figure 10. Maximum principle stress.

The above figure shows the maximum principle stress of structure in that maximum value is 64.618.

3.8.9 Equivalent Elastic Strain

The above figure shows the equivalent elastic strain of structure in that maximum value is 0.0068434.

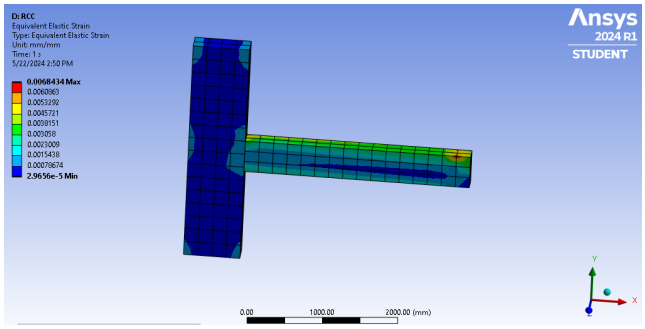


Figure 11. Equivalent elastic strain.

Table 2. The maximum BM beam column junction is further modeled in ansys details of precast models

S. No.	Model No.	Description
1	RCC	Monolithic beam column joint.
2	Precast model 1	Precast beam column with trapezoidal haunch size 0.3 x 0.45 with 2 bolts of 20 mm diameter, Gusset plate of 30 mm thickness.
3	Precast model 2	Precast beam column with rectangular haunch size 0.2 x 0.45 2 bolts of 20 mm diameter, Gusset plate of 30 mm thickness.
4	Precast model 3	Precast beam column with haunch size 0.2 x 0.252 bolts of 20 mm diameter, Gusset plate of 30mm thickness.

4.0 Precast Model 1

4.1 Geometry

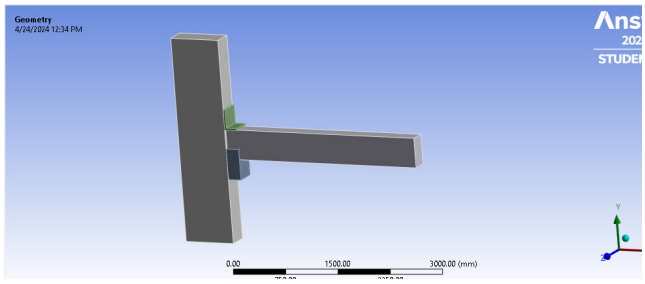


Figure 11. Geometry.

The above figure shows the geometry of structure.

4.2 Meshing

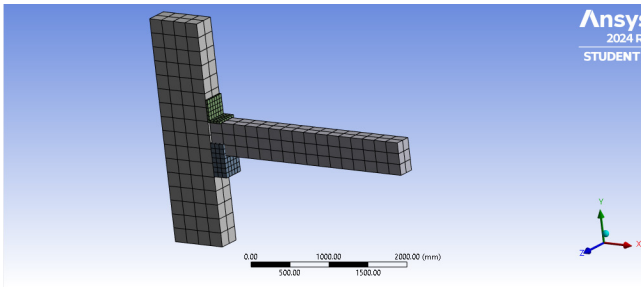


Figure 13. Meshing.

The above figure shows the meshing of structure.

4.3 Boundary Condition

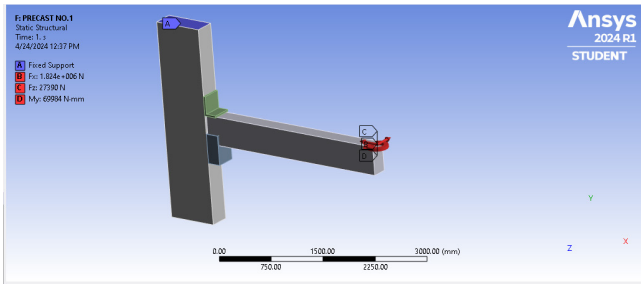


Figure 14. Boundary condition.

The above figure shows the boundary condition of structure the reaction is at away from joint at end point of beam and at top of the beam.

4.4 Total Deformation

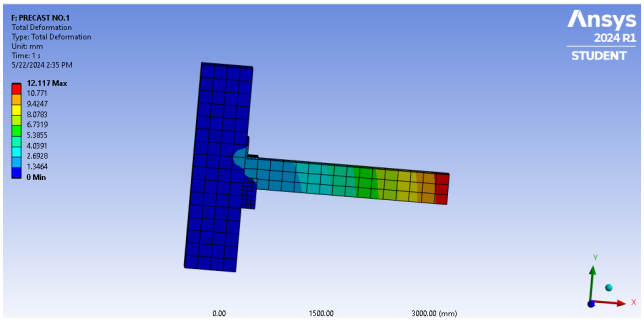


Figure 15. Total deformation.

The above figure shows the total deformation of structure in that maximum value is 12.117 mm.

4.5 Equivalent Stress

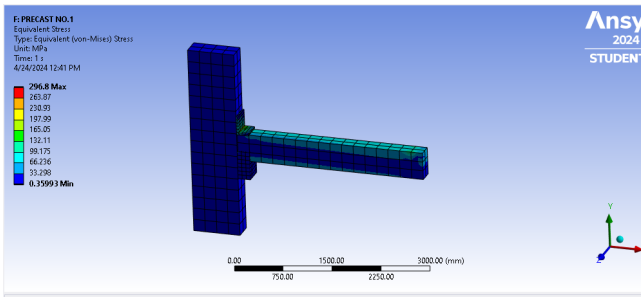


Figure 16. Equivalent stress.

The above figure shows the equivalent stress of structure in that maximum value is 296.8 Mpa.

5.0 Precast Model 2

5.1 Geometry

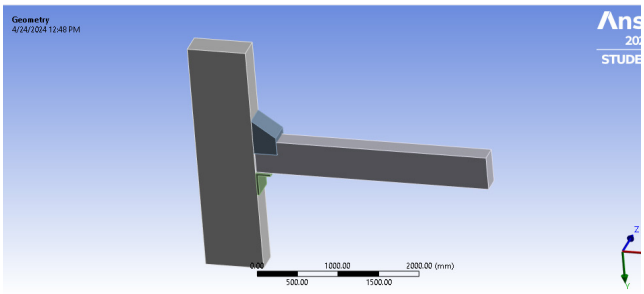


Figure 17. Geometry.

The above figure shows the geometry of structure.

5.2 Meshing

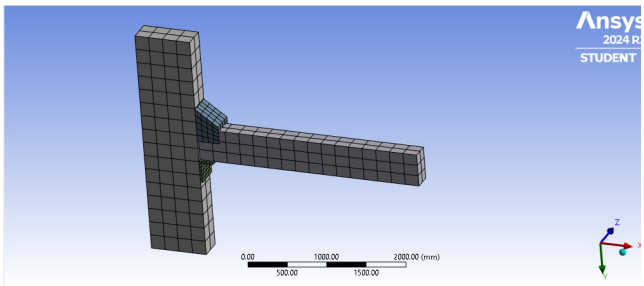


Figure 18. Meshing.

The above figure shows the meshing of structure.

5.3 Boundary Condition

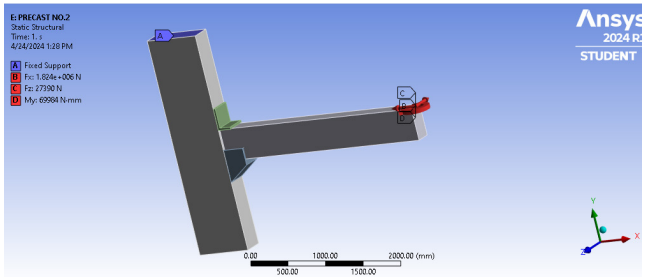


Figure 19. Boundary condition.

The above figure shows the boundary condition of structure the reaction is at away from joint at end point of beam and at top of the beam.

5.4 Total Deformation

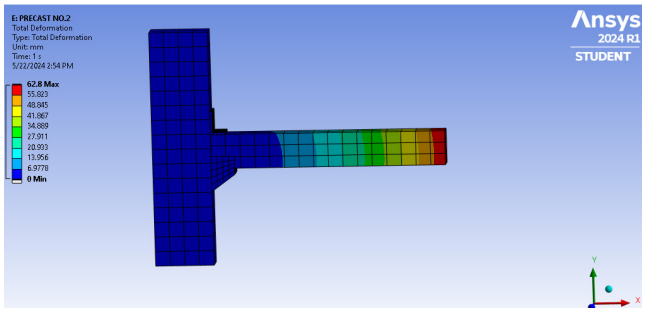


Figure 20. Total deformation.

The above figure shows the total deformation of structure in that maximum value is 62.8mm.

5.5 Equivalent Stress

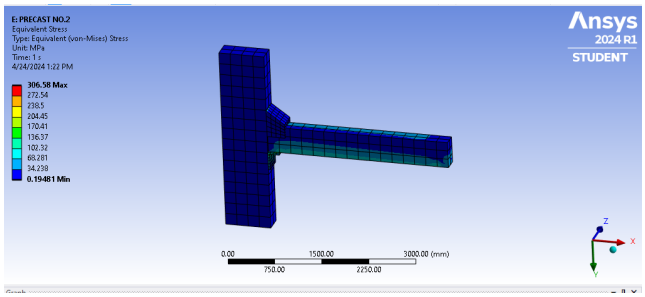


Figure 21. Equivalent stress.

The above figure shows the equivalent stress of structure in that maximum value is 306.58.

6.0 Precast Model 3

6.1 Geometry

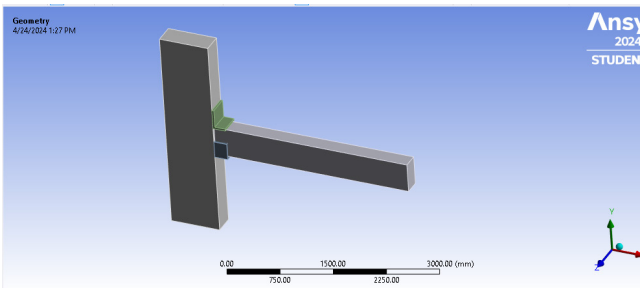


Figure 22. Geometry.

The above figure shows the geometry of structure.

6.1 Meshing

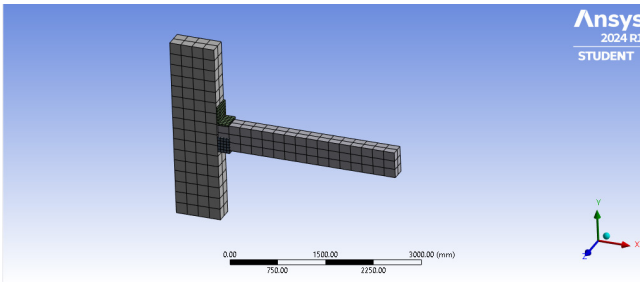


Figure 23. Meshing.

The above figure shows the meshing of structure.

6.2 Boundary Condition

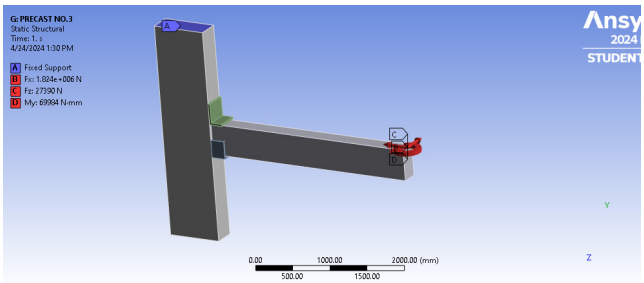


Figure 24. Boundary condition.

The above figure shows the boundary condition of structure the reaction is at away from joint at end point of beam and at top of the beam.

6.3 Total deformation

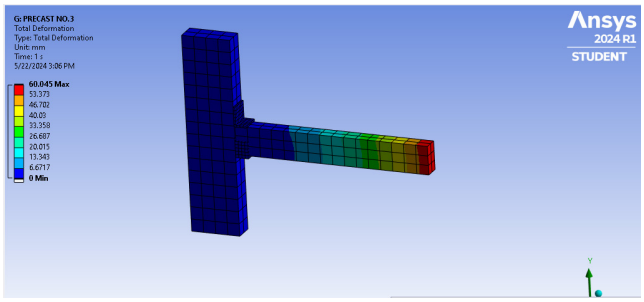


Figure 25. Total deformation.

The above figure shows the total deformation of structure in that maximum value is 60.045 mm.

6.4 Equivalent Stress

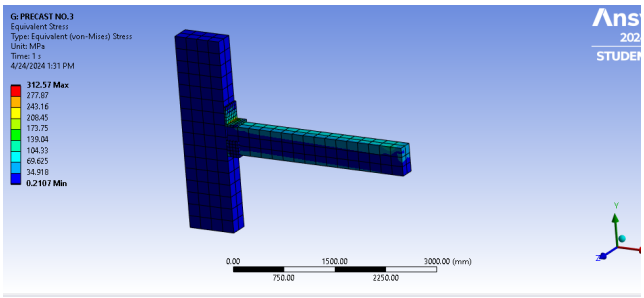


Figure 26. Equivalent stress.

The above figure shows the equivalent Stress of structure in that maximum value is 312.57 Mpa.

7.0 Case Study

The time history is the series of values of any time-varying variable (such as a measurement of ground motion) taken at a set of fixed times. This may be thought of as a record of the past, alternately referred to as time series. The accelerogram was captured by an instrument that was connected to the concrete floor of the El Centro Terminal substation building. This means that it was not recorded in a free-field environment. It's possible that the record didn't do a good job of capturing the high-frequency vibrations of the earth because of the soil-structure interaction that occurred between the enormous foundation and the soft soil in the surrounding area. When compared to other nonlinear analysis methods, time history analysis is often regarded as the approach with the highest degree of accuracy.

7.1 About Bhuj Earthquake

Bhuj earthquake of 2001 is a massive earthquake that occurred on January 26, 2001, in the Indian state of Gujarat, on the Pakistani border. The earthquake struck near the town of Bhuj on the morning of India's annual Republic Day (celebrating the creation of the Republic of India in 1950), and it was felt throughout much of Northwestern India and parts of Pakistan. The moment magnitude of the quake was 7.7 (6.9 on the Richter scale). In addition to killing more than 20,000 people and injuring more than 150,000 others, the quake left hundreds of thousands homeless and destroyed or damaged more than a million buildings. A large majority of the local crops were ruined as well. Many people were still living in makeshift shelters a year later.

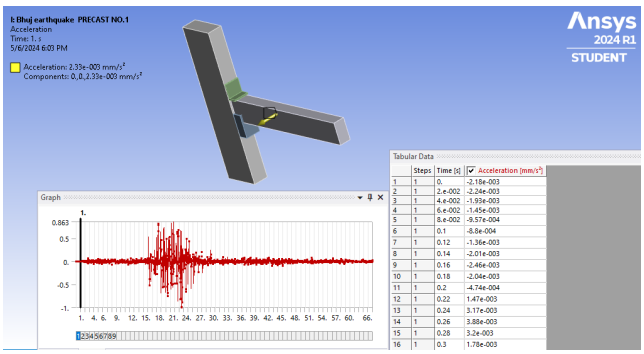


Figure 27. Time history analysis.

The above figure shows the time history analysis. The analysis showed that the acceleration of the block was 2.33e-003 mm/s². The table also shows that the acceleration was negative at earlier time steps, reaching a minimum value of -2.46e-003 mm/s² at 0.16 seconds.

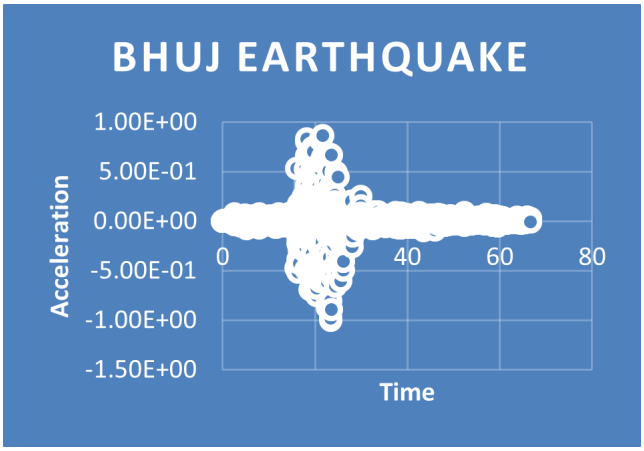


Figure 28. Bhuj earthquake data.

7.1.1 Total Deformation

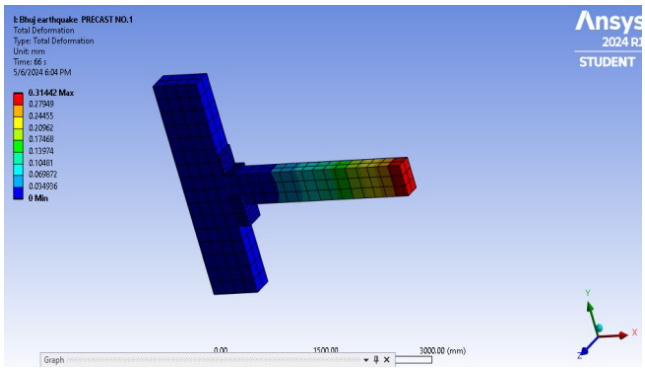


Figure 29. Total deformation.

The above figure shows the Total deformation of structure.

7.1.2 Equivalent Stress

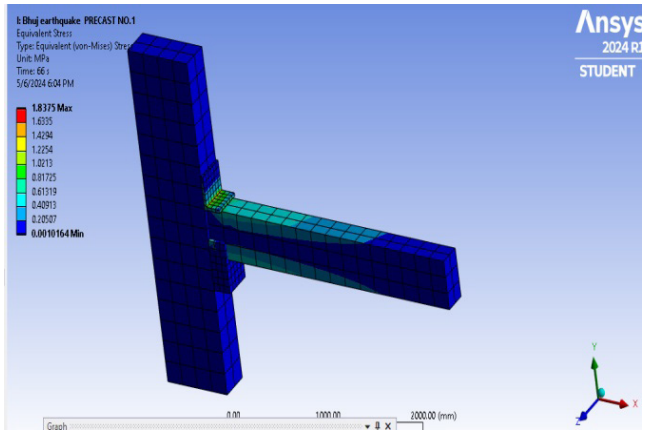


Figure 30. Equivalent stress.

The above figure shows the equivalent stress of structure.

7.1.3 Normal Stress

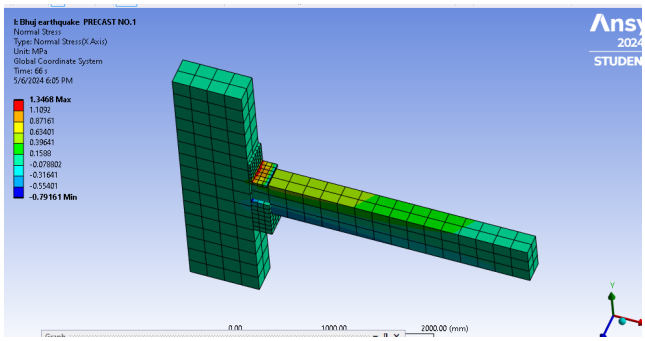


Figure 31. Normal stress.

The above figure shows the normal stress of structure.

7.1.4 Shear Stress

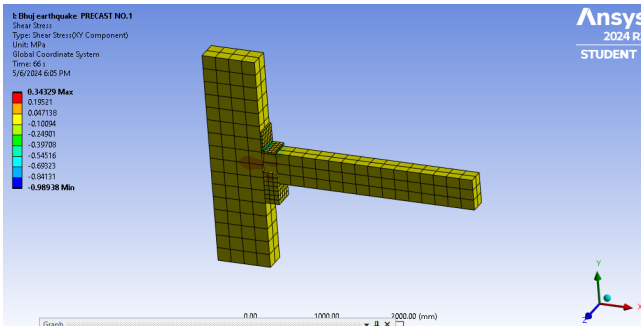


Figure 32. Shear stress.

The above figure shows the shear stress of structure.

7.1.5 Maximum Principle Stress

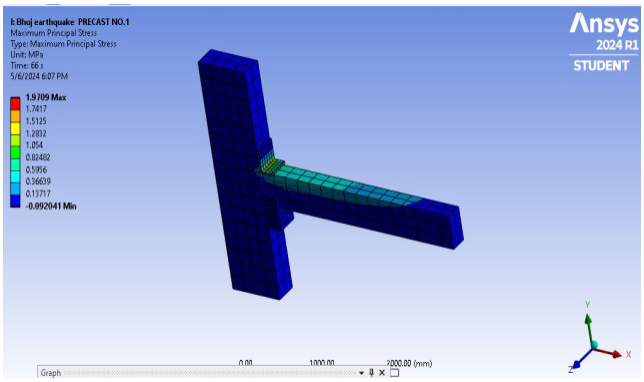


Figure 33. Maximum principle Stress.

The above figure shows the maximum principle stress of structure.

8.0 Result and Discussion

8.1 Introduction

In this chapter, I delve into a comprehensive comparative analysis between Reinforced Concrete (RCC) and three distinct precast concrete models using ANSYS simulation software. Concrete structures are the backbone of modern infrastructure, and understanding their behavior under various loading conditions is paramount for ensuring structural integrity and safety. ANSYS, with its powerful finite element analysis capabilities, offers a robust platform for simulating and analyzing the performance of concrete structures. The primary focus of this study is to evaluate and compare the structural responses of RCC and Precast Concrete models under different loading scenarios. By examining these models, we aim to gain insights into their respective strengths, weaknesses, and overall performance characteristics. Through meticulous analysis and interpretation of results, we seek to provide valuable insights that can inform engineering decisions and enhance the design and construction processes. This chapter begins by outlining the methodology employed for creating and simulating the RCC and Precast Concrete models in ANSYS. Subsequently, I have presented a detailed description of the loading conditions and boundary constraints applied to the models. Following this, we meticulously analyze and interpret the results obtained from the simulations, focusing on key parameters such as stress distribution, deformation behavior, and structural response under varying loading conditions. The comparative analysis presented in this chapter serves as a valuable resource for engineers, researchers, and practitioners involved in the design, analysis, and optimization of concrete structures. By elucidating the performance disparities between RCC and precast concrete models, we aim to contribute to the ongoing advancement of structural engineering practices and foster innovation in construction methodologies.

Table 3. Deformation comparison table

Precast Model	Total Deformation (mm)
RCC	69.68
Precast Model 1	12.12
Precast Model 2	62.80
Precast Model 3	60.05

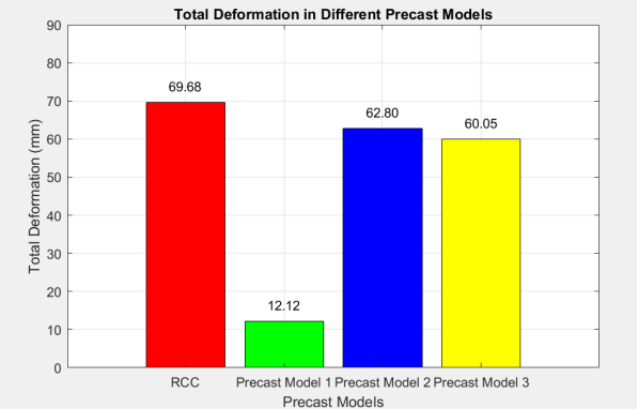


Figure 34. Precast model.

Table 4. Stress comparison table

Precast Model	Equivalent Stress (MPa)
RCC	142.70
Precast Model 1	296.80
Precast Model 2	306.58
Precast Model 3	312.57

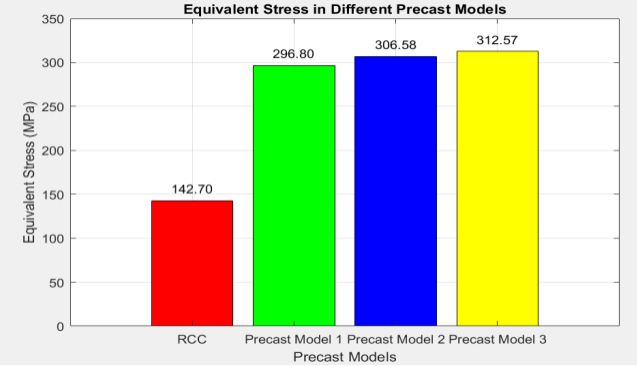


Figure 35. Equivalent stress in Mpa.

The graph presents the total deformation in millimetres for three different precast models compared to a standard Reinforced Concrete (RCC) structure. From the data provided, it's evident that all three precast models have significantly lower total deformation compared to the RCC structure. Precast Model 1 exhibits the least total deformation at 12.117 mm, followed by Precast Model 2 at 62.8mm, and Precast Model 3 at 60.045mm. This suggests that the use of precast elements in construction can potentially result in reduced deformation under load compared to traditional RCC structures.

The graph presents the equivalent stress values in Megapascals (MPa) for different models: RCC (Reinforced Concrete Construction), Precast Model 1, Precast Model 2, and Precast Model 3. It's evident that the equivalent stress values increase from RCC to Precast Model 3. RCC has the lowest equivalent stress at 142.7 MPa, while Precast Model 3 has the highest at 312.57 MPa. This progression suggests that as we move from traditional Reinforced Concrete Construction (RCC) to precast models, there's a general trend of higher stress levels. The precast models, there's a noticeable increase in equivalent stress from Model 1 to Model 3. Model 1 has an equivalent stress of 296.8 MPa, Model 2 has 306.58 MPa, and Model 3 has 312.57 MPa.

The graph displays the normal stress values, measured in Megapascals (MPa), for 3 different precast models

Table 5. Normal stress table

Precast Model	Normal Stress (MPa)
RCC	63.58
Precast Model 1	96.22
Precast Model 2	119.39
Precast Model 3	125.24

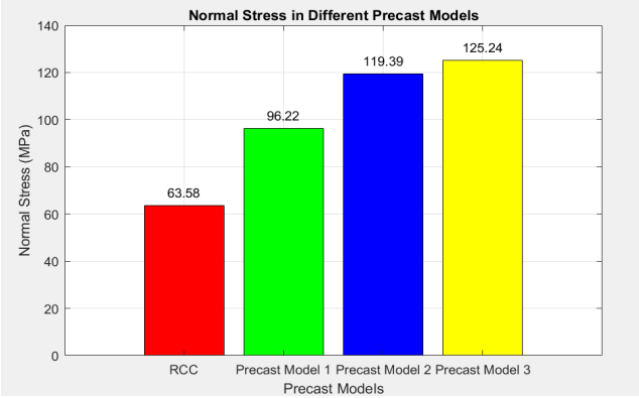


Figure 36. Normal stress Mpa.

(Model 1, Model 2, and Model 3), as well as for RCC (Reinforced Cement Concrete). RCC exhibits the lowest normal stress value at 63.577 MPa, while Precast Model 3 demonstrates the highest stress value at 125.24 MPa. Precast Model 1 and Model 2 fall in between, with stress values of 96.225 MPa and 119.39 MPa, respectively. This data suggests that there are variations in the normal stress levels among the different precast models and RCC. These differences could stem from various factors such as the materials used, design specifications, or manufacturing processes.

The provided graph outlines shear stress values in Megapascals (MPa) for 3 different models of precast concrete (RCC, Precast Model 1, Precast Model 2, and Precast Model 3). At first glance, it appears that Precast Model 3 consistently exhibits the highest shear stress values among the three models, followed by Precast Model 2 and Precast Model 1, with RCC having the lowest

Table 6. Shear stress table

Precast Model	Shear Stress (MPa)
RCC	34.83
Precast Model 1	156.29
Precast Model 2	161.60
Precast Model 3	164.14

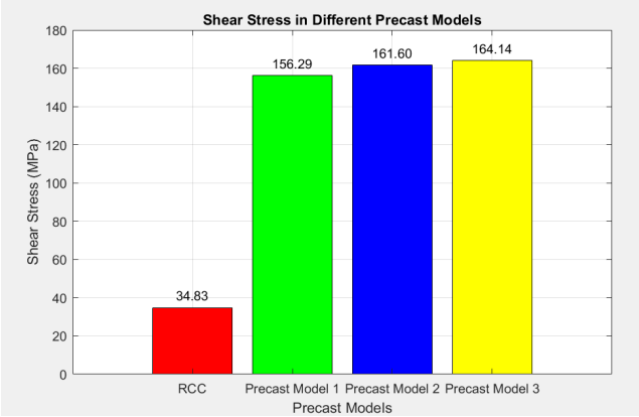


Figure 37. Shear stress Mpa.

Table 7. Principal stress table

Precast Model	Max Principal Stress (MPa)
RCC	64.62
Precast Model 1	96.31
Precast Model 2	161.60
Precast Model 3	125.31

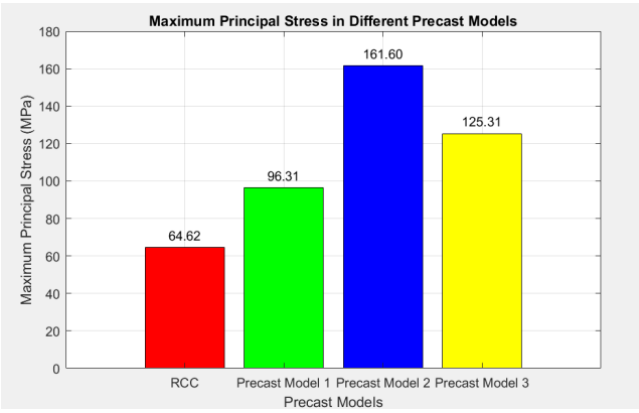


Figure 38. Maximum principle stress Mpa.

shear stress value. This suggests that as you move from RCC to Precast Model 3, there is an increase in shear stress resistance, indicating potentially better structural integrity or strength. The numerical values provide specific data points for each model's shear stress performance. For instance, RCC exhibits a shear stress of 34.826 MPa, while Precast Model 3 shows the highest shear stress of 164.14 MPa, indicating a significant improvement in shear stress resistance compared to RCC.

The graph provides the maximum principle stress values, measured in Megapascals (MPa), for different precast models of Reinforced Concrete (RCC). Each

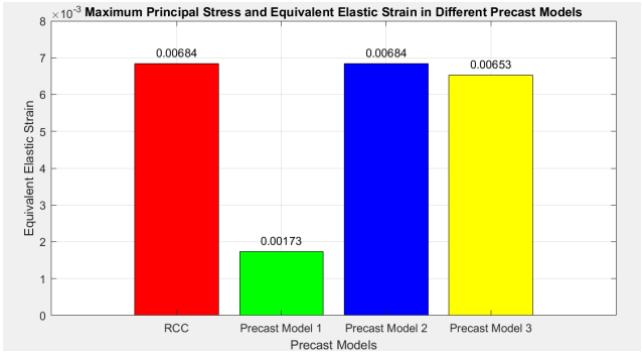


Figure 39. Equivalent elastic strain.

model, labelled as Precast Model 1, Precast Model 2, and Precast Model 3, underwent testing, and their respective maximum principle stress values were recorded. Precast Model 1 exhibited the lowest maximum principle stress value at 64.618 MPa, indicating that this particular model experienced relatively lower stress levels compared to the other models tested. On the other hand, Precast Model 3 demonstrated the highest maximum principle stress value at 161.6 MPa, suggesting that this model endured the highest stress levels among the three tested.

The graph provides the equivalent elastic strain across a traditional Reinforced Concrete (RCC) model and three precast concrete models. The RCC and Precast Model 2 share the same strain value of 0.00684, suggesting similar elastic behavior. Precast Model 1, with a significantly lower strain of 0.00173, indicates a higher stiffness or a better resistance to deformation. Precast Model 3, at 0.00653, shows slightly less strain than the RCC and Precast Model 2, suggesting a marginally better performance. Overall, Precast Model 1 exhibits the most favorable elastic properties, highlighting potential benefits in stiffness and durability compared to the other models.

The graph presents a comparative analysis between manual and software values across 5 parameters: Shear stress, normal stress, maximum principal stress, deformation, and maximum principal stress. The blue bars represent manual values, while the red bars represent software values. For shear stress, the manual value is 31.41 MPa, and the software value is 34.83 MPa. For normal stress, the manual value is 57.36 MPa, and the software value is 63.58 MPa. The maximum principal stress is 59.11 MPa (manual) versus 64.81 MPa (software). Deformation values are 0.01 (manual) and 0.01 (software). The final maximum principal stress is 50.11 MPa (manual) and 64.62 MPa (software). The differences indicate a slight

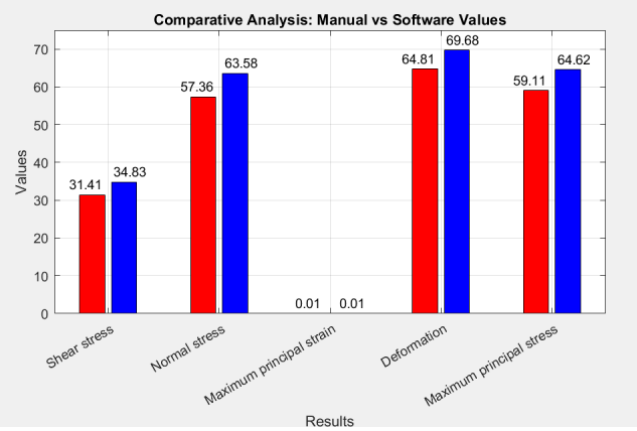


Figure 40. Comparative analysis manual value software value.

deviation between manual and software results, suggesting potential variations in modeling or computation methods.

9.0 Conclusion

The dynamic performance evaluation of precast T-beam structures under seismic loading is essential to ensure their safety, reliability, and resilience during earthquakes. This study highlights that precast T-beam systems, when properly designed and detailed, demonstrate significant potential to absorb and dissipate seismic energy effectively, exhibiting favourable ductility and strength characteristics. However, the seismic response is highly dependent on factors such as connection detailing, material properties, and structural configuration. Advanced dynamic analysis techniques provide critical insights into the behaviour of these structures, helping to identify vulnerabilities and optimize design parameters. Overall, the findings emphasize the importance of rigorous seismic performance assessment and adoption of innovative construction practices to enhance the seismic resilience of precast T-beam structures, thereby safeguarding lives and infrastructure in earthquake-prone regions.

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