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Article

Investigation On Concrete Filled Steel Tubes Columns with Collapse Performance with Varying End Conditions

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Abstract: This research examines the collapse behavior of Concrete-Filled Steel Tube (CFST) columns with different end conditions using a nonlinear finite element method. Circular CFST samples with a diameter of 100 mm, a wall thickness of 4 mm and a length of 1250 mm, made with Mild Steel (fy = 250 MPa) and M30 grade concrete, were used. Four boundary conditions (Fixed–Free, pinned–Pinned, fixed Pinned and Fixed–Fixed) were analyzed under axial compression to study deformation behavior, strain distribution, stress concentration, and failure mechanism. ANSYS Workbench 2023 R2 was used to develop a model with the capability to simulate the nonlinearity of the material, the effect of confinement, geometry, localized buckling, and the behavior of CFST columns. The Fixed–Free condition showed the largest total deformation (3.554 mm) and the greatest von Mises stress (1145 MPa), which indicates a unstable condition at the restrained end, beyond the yield strength of steel. Increasing end condition restraint reduced total deformation, strain, and directed stress, resulting in the Fixed–Fixed boundary condition having the greatest collapse resisting capacity. From the results, it can be concluded that the boundary conditions of CFST columns have a strong influence on the structural stability and collapse. Also, current Indian Standard codes don't have any provision for the design of CFST columns and thus stress the need for modeling end conditions in designing performance-based composite columns.
Keywords: Concrete-Filled Steel Tube, End Conditions, Collapse Performance, Finite Element Analysis, ANSYS, Axial Compression, Composite Columns.

1. Introduction

Concrete-Filled Steel Tube (CFST) columns are composite systems that integrate concrete and steel. Concrete-Filled Steel tubes are hollow tubes of steel that are filled with concrete. The combination of concrete and steel is better than either component separate[1]. Steel and Concrete interact to provide ductility and the ability to absorb energy. Because of these properties, CFST columns are becoming a standard column type for modern engineering design. Because of these special properties, CFST columns also accommodate large deformations without sudden failure of the member[2]. This ensures that the CFST column will remain safe and functional even under extreme loading. In the last 20 years, the design and construction of CFST columns is becoming more popular because of the advantages and benefits of using CFST columns over using regular concrete or steel columns[3]. The boundary restraints of the concrete and steel will also affect the buckling and mechanical properties of the CFST columns. The end conditions specify how members engage with the column, how loads are transmitted, and the nature of support resistance. They influence stiffness, buckling modes, buckling strength, and failure modes[4]. They can be pinned-pinned, fixed-fixed, fixed-free (cantilever), pinned-fixed, or semi-rigid. These provide varying end restraints and allow different modes of

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rotation and translation, producing dissimilar load deformation and failure strength characteristics. For instance, a fixed-fixed column of the same size can be subjected to a considerably higher axial load than a pinned-pinned column due to having more flexural restraint. Therefore, it is important to understand the effects of end conditions in order to improve analytical models and design codes[5].

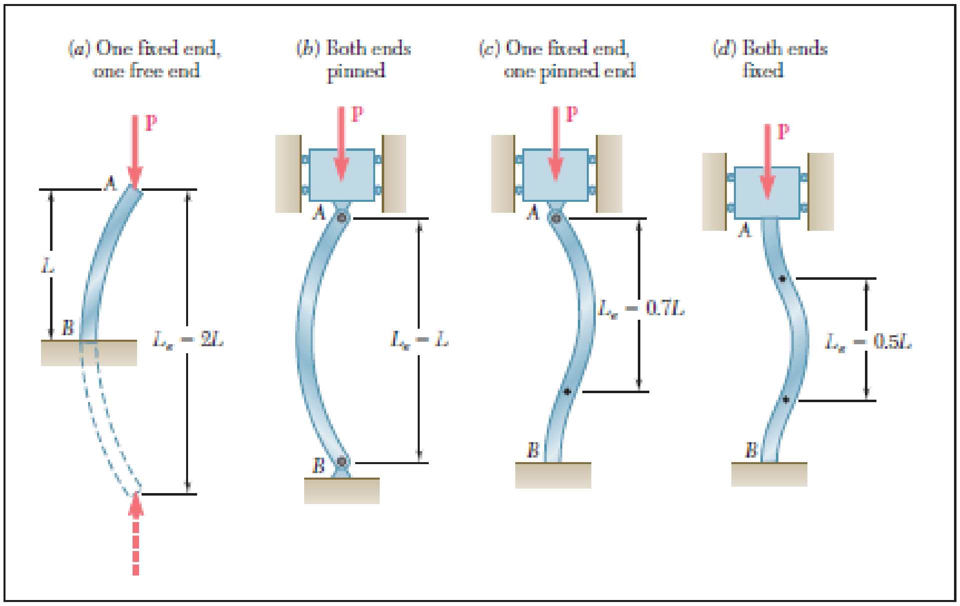

Fig 1. Types of End Conditions

Source: Ali Yousuf Khenyab (2018)

The boundary conditions shown in Fig. 1, include: pinned-pinned, cantilever, fixed-fixed and pinned-fixed ends. Boundary conditions set the effective length and critical buckling load (Pcr) and the deformation and failure modes, which relate to the stability and strength of CFST. Therefore, boundary conditions play a critical role in the analysis of the stability of CFST columns. There is a need for the accurate comprehensive assessment of the behavior of CFST columns, which can only be accomplished via numerical methods. Addressing phenomena such as local buckling, material nonlinearity, stress concentrations and concrete confinement, numerical methods allow for the assessment of the response of the columns under axial compression. The numerical phase of this study utilized a detailed finite element approach with the use of the ANSYS code for the successful approximation of material nonlinearity, contact, initial imperfections, and local buckling. This phase analyzed multiple configurations of CFST at both ends with varying fixed conditions to identify axial deflection, strain, stress and failure modes. The various edge restraints illustrated the critical role they play regarding the failure mode, strength and failure load of CFST columns. Fixed end columns demonstrated more stiffness with less local bucking compared to the pinned-pinned condition, while the cantilevered columns were more flexible and showed a greater degree of local bucking at the free end. Most of the existing literature discusses partial aspects of failure such as failure load and buckling, with the full failure response of columns (ductility, post-peak response and residual strength) remaining unexplored. Therefore, this study adopts a fully integrated numerical approach to address this aspect and provide detailed guidance to structural designers.

The use of concrete filled steel tubular (CFST) columns is increasing in seismic regions as they can withstand large levels of inelastic deformation without collapsing. In a seismic event, the CFST columns can undergo stable energy dissipation while maintaining life safety. The circular or rectangular steel jackets act as a permanent formwork which removes the requirement for an additional steel framework[6]. CFST columns, in a composite frame system, are usually connected to steel beams and reinforced concrete (RC) slabs using shear connectors. The composite joints modify the frame's stiffness and strength and can also increase the lateral-torsional buckling strength of the beam. The interaction of axial force, end restraint, and the joint needs more attention[7]. Depending on the beam-column-RC slab end restraints and load placement, the "strength" of the column can be "increased" or "decreased." of the failure mechanism of CFST columns with respect to practical end boundary restraints and collapse prevention of a composite frame system with high axial loading is of primary importance. Aside from the seismic applications, modern sustainable engineering can benefit from CFST technology. Using high strength concrete, thin-walled steel tubes use less material and provide composite effects without an increase in cross-section. This creates lower embodied energy. Thanks to these innovations, CFSTs can provide a sustainable and resilient future[8].

This study focuses on the numerical analysis of the collapse behavior of Concrete-Filled Steel Tube columns with various boundary conditions. It emphasizes the importance of advanced finite-element analysis to understand the role of end supports on the axial capacity, stiffness, and ductility. This study involves the design and construction of CFSTs with pinned, fixed, semi-rigid, and mixed end-conditions, as well as simulating the CFSTs in ANSYS to study the effect of critical parameters. The correlation of the computational results offers the opportunity to validate the models and formulate some design parameters. The purpose of this study is to analyze the effect of end supports on the ultimate strength and failure modes of CFST columns to refine the design predictive models[9]. This would improve the representation of realistic end conditions which are typically over-simplified in code-based design methods. These design methods provide either conservative or unsafe end results. Design methods in the future will use the outcomes of this study to build predictive models for design cases that are more challenging, including dynamic loading, cyclic loading, and design cases that incorporate concrete slabs with beams or joists. The future design methods will incorporate the effects of temperature, corrosion, and long-term creep-shrinkage of the concrete to improve service life. The design of CFST columns with various end conditions and loading scenarios will be facilitated by accurate machine learning based predictive design models. The primary aim of this study is to contribute to the design and construction of more efficient and sustainable CFST structures that will enhance safety in construction[10].

1.1 Significance of CFST Structural Systems

The use of concrete-filled steel tubes (CFST) is gaining popularity due to their high axial loading, flexibility, and stability in the structural field.The Advantages of the CFST columns rely on the combination of the steel tube and the concrete core. The steel tube has high strength and ductility while the concrete core has high compression strength. The steel tube contains the concrete core which delays and increases the strength of the concrete and aids the concrete with a three-axis tri-axial pressure effect. Furthermore, the core of the concrete aids in the stability of the tube which helps reduce the risk of local buckling. The combination of all the advantages fo CFST provides high energy dissipation and makes them most suitable for taller buildings and larger buildings and structures. Their design is further enhanced and flexible by the tubular design of the structure, helping integrate cables and other utilities. another huge advantage of the CFST designs is the compact design with smaller cross sections compared to other RC designs, benefiting aesthetics and space as well without sacrificing strength.

CFST members exhibit superior performance under combined bending and axial loads, fatigue, and impact, which are critical for mid- and high-rise buildings. Their collapse response is enhanced due to ductility and confinement effects, which are also advantageous for structures subjected to extreme loading, such as earthquakes, explosions, and fire. Numerical studies have shown that CFST columns can sustain large deformations while retaining their load-carrying capacity, leading to ductile failure mechanisms. Additionally, due to different end conditions (fixed, pinned, semi-rigid supported, etc.), stress patterns and load distributions change, affecting the load-carrying capacity. Therefore, modeling boundary conditions is essential for accurate simulations. The safety and sustainability of CFSTs are further demonstrated by their presence in contemporary design codes, such as the Eurocode 4 and the American Institute of Steel Construction (AISC). They are also a highly innovative option to safely and sustainably design the infrastructure of the 21st century, due to their construction speed, and optimal strength and ductility.

2. Related Work

Recent studies have furthered the understanding of the collapse and deformation modeling of CFSTs based on integrated experimental and FE modeling. Gao et al. (2024) and others have used FE modeling in conjunction with drop-weight tests to assess the stiffness degradation and residual deformation of square CFSTs under repeated lateral impacts. This work has offered a better understanding of post-impact stability and damage and the mechanisms of collapse[11]. Mansour et al. (2024) developed 3D nonlinear models in ABAQUS, calibrated to experimental data, to evaluate the response of FRP-strengthened CFSTs to monotonic and seismic-type cyclic loadings. This study indicated that ductility and energy dissipation are critical to resist collapse under large seismic loadings[12]. Addressing the scale effect that may induce premature local buckling, Almasabha et al. (2024) adjusted the modeling of wide-diameter CFST stub columns to enhance the prediction of their axial load capacity (i.e. to avoid over- or under-predicting peak force and the behavior following peak force)[13]. Yang et al. (2024) developed FE models of cross-shaped CFSTs subjected to axial/eccentric loading that included the concept of confinement and instability in the deformation and strain capacity, as well as the failure of the CFSTs[14]. Finally, in axial/cyclic loading of CFSTs, Hou et al. (2024)

combined field testing with FE modeling of high-strength steel CFSTs to examine local buckling and collapse under transverse loading[15].

New studies are expanding to examine the effects of boundary fixity and restraints on capacity, ductility, and collapse. Shi et al. (2025) studied round-ended, stainless-steel CFST (Concrete Filled Steel Tube) columns. They built models of columns to prove that end detailing and structural non-linearity affect pinching, stiffness reduction, and damage accumulation, which are primary contributors to collapse under low-cycle loading[16]. In a review of evidence and code provisions, Hamoda et al. (2025) examined the influence of size on circular CFSTs (Concrete Filled Steel Tubes) subjected to concentric compression and found that existing design provisions, in some cases, may be conservative for short, large diameter CFSTs due to an increased sensitivity to base/top restraints[17]. Zhu et al. (2024) studied the effects of compression configuration on confining pressures and hoop stress, revealing a link between contact/constraint and dilation control and ultimate load, thus creating a boundary-condition approach for delaying local buckling[18]. For CFRP-wrapped CFST columns, Sabih et al. (2024) defined boundary conditions (matched in ABAQUS) and demonstrated that fixity must be accounted for to capture failure modes and residual capacity of columns[19]. For T-shaped CFSTs, Zhang et al. (2023) added data to the open-access FE (PMC) and showed that confinement improved stability, but, critically, that peak and post-peak capacity were sensitive to loading eccentricity and restraints, which suggested design and collapse checks for restraints and end conditions[20].

2.1 Research Gap

Although studies have investigated the axial behavior buckling, and confinement of CFST columns, there is limited research on the role of end supports on the collapse behavior of CFST columns. It is clear that the contemporary design standards (for example the IS codes) do not explicitly specify how to model the end supports of CFST columns - supports that are pinned/hinged, fixed/semi-rigid, or a combination of pinned-fixed. Because of this, idealized supports are most often used in the majority of analytical and numerical studies which do not accurately model the stiffness, stress concentration, ductility, and failure mechanism. The study provides sufficient evidence that end supports will fix the deformation, localized strain, and the von Mises Stress distribution, but the IS codes do not have any direction of end supports in design. Because of this, the lack of standardization of modeling end conditions will be the primary focus of the study.

2.2 Limitations of IS Code Provisions for CFST Columns

Concrete-Filled Steel Tube (CFST) columns are not included in the existing Indian Standards (IS) design codes, making modelling, analysis, and collapse assessment problematic. Guidelines for reinforced concrete members and steel structures are provided in IS 456:2000 and IS 800:2007, respectively. However, neither provides guidance regarding the composite action and the confinement or local buckling of CFST members. IS 11384:1985 includes composite structures, but does not provide a framework, criteria, or parameters for the boundary conditions, stiffness, and collapse of CFST columns. Furthermore, the IS codes do not define end-condition modelling (pinned, fixed, semi-rigid), which affects buckling length, stiffness, ductility, and collapse. Due to these deficiencies, designers frequently rely on Eurocode 4 and AISC composite columns, which address confinement and boundary conditions. An absence of IS provisions, along with reliance on other standards, results in conservative or unsafe seismic estimates. Ultimately, performance-based end conditions of CFST columns need to be included for the future of the Indian design codes.

3. Materials And Methods

This research will implement a joint numerical-optimization model to analyze the failure of Concrete-Filled Steel Tube (CFST) columns due to varying end conditions. The design of the methodology is structured to yield the appropriate model of actual structural behavior in the case of uniaxial compression. The general framework will consist of a finite element simulation, validation of numerical results, and optimization of results in MATLAB.

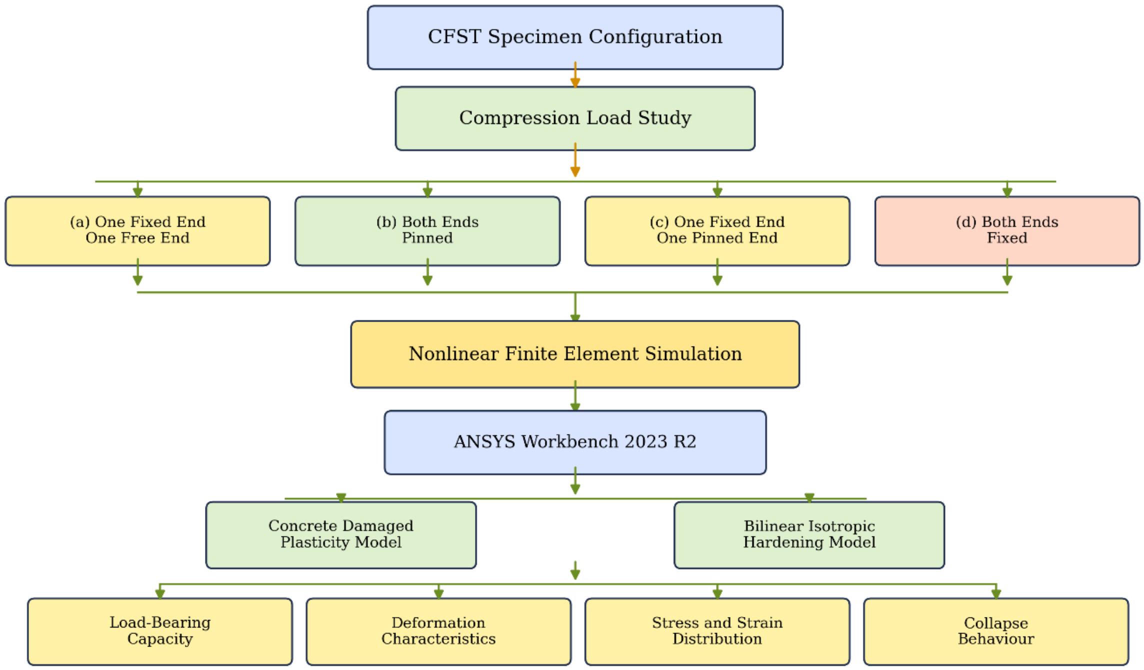

Fig. 2. Research Methodology

This study included four sets of boundary conditions: (a) cantilever, (b) two-pin, (c) one-fixed one-pin, and (d) fully-fixed. Each boundary condition is designed to evaluate the effects of end restraints on stiffness, buckling behaviour and deformation, stress concentration and collapse mechanisms of CFST columns. This study combines the observed structural behaviour and advanced finite element analysis to develop a holistic performance-based assessment on CFST columns under various end restraint scenarios.

3.1 Materials Used

1. Steel Tube

1. Steel Tube

The steel tubes were made of mild structural steel that met the specifications of IS 1161:2014. The cross-sectional shape of the tubes was circular, diameter of the tube was 100 mm, thickness was 4 mm and length was 1250 mm. The steel had a yield strength of 250 Mpa, ultimate tensile strength was between 410 and 460 Mpa. The tube was wiped with an anti-rust coating and then cast to make sure that the tube bonded with the concrete. The steel tube is both a permanent formwork and confining reinforcement, which increases the ductility and imparts retarding of local buckling of the composite member.

2. Concrete

Infill concrete of grade M30 was made with a mix proportion of 1:1.5:3 (cement: sand: coarse aggregate) with a water cement ratio of 0.45. The cement used was Ordinary Portland Cement (43-grade) as per IS 8112:2013. The sand used as fine aggregate was clean river sand sieved to 4.75 mm and the coarse aggregates were of 10 mm and 20 mm crushed granite. All mixing and curing were done with potable water to maintain the workability. To achieve the target compressive strength of 30 Mpa at 28 d, cube tests were conducted and the CFST specimens were cast.

2. Concrete

The bulk fill concrete was M30 grade concrete with a mix of 1:1.5:3 (cement: sand: coarse aggregate) and a water cement ratio of 0.45. It was Ordinary Portland Cement (43 grade) and met the specification of IS 8112:2013. The fine aggregate was clean river sand and coarse aggregate was 10 mm and 20 mm crushed granite. Both sand and granite were used after grading. Mixing and curing were done using potable water. Cube testing was done to reach the target of 30 Mpa compressive strength at 28 d. CFST specimens were cast thereafter.

3. Reinforcement and End Fixtures

Although CFST columns typically do not require internal reinforcements, steel end plates were welded in this study for the desired boundary conditions. For the fixed-end conditions, 10 mm thick steel plates were welded at the ends to allow zero rotation and translation. For the hinged-end conditions, cleavages were drilled through and steel pins were placed in the holes to allow rotation but no axial movement. This method was adopted to achieve the equivalent conditions of pinned-pinned and fixed-fixed configurations subjected to axial loading.

3.2 CFST Column Geometry

The geometry of the column was designed to reflect the geometry of a Concrete-Filled Steel Tube (CFST) column, which was to be employed in the axial compression tests. The test specimens were fabricated from circular steel-tubes with a concrete core. Each specimen had a diameter of 100 mm, a wall thickness of 4 mm, and a length of 1250 mm.

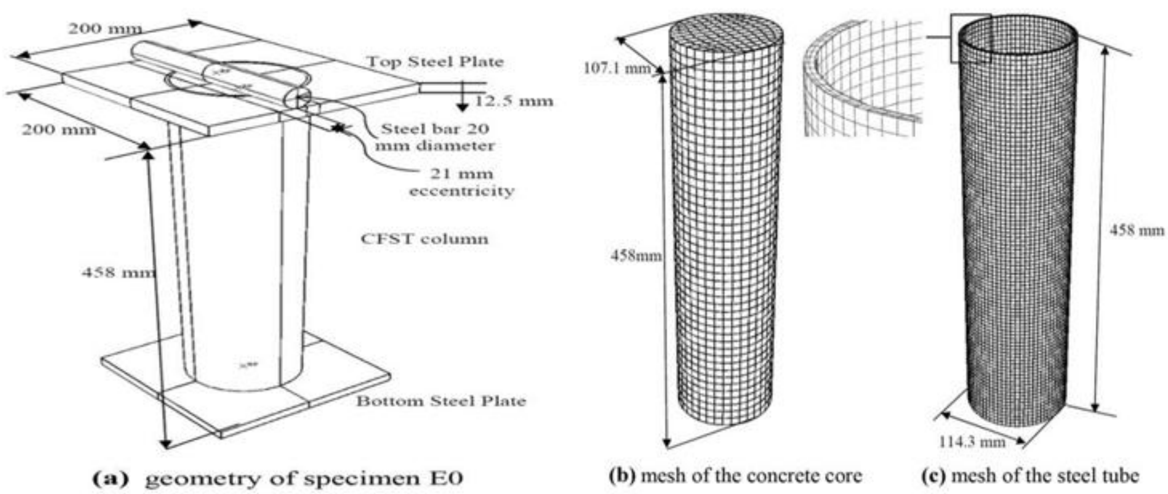

Fig 3. Schematic Diagram of CFST Column Geometry

Source: Zhongwei Guan (2022)

The end plates were joined with steel end plates to simulate different conditions at the boundaries (e.g., fixed-fixed, pinned-pinned). The top and bottom steel plates introduced uniformity in the load transfer and minimized end distortions during the test. A 20 mm diameter steel bar was used to convey the load and provide a support/post to control the eccentricity, in order to render the effects of real-world imperfections negligible. Localized buckling and deformation of the fine mesh, which discretized the geometry, was easily achieved. The structure simulates the interaction that occurs between the steel tube and the confined concrete, and provides a good foundation to the numerical analysis of the column behavior of CFST.

3.3 Numerical Modeling

1. Software and Model Setup

ANSYS Workbench 2023 R2 has been adopted to numerically investigate the nonlinear structural behavior. The software accommodates nonlinear behavior's structural interactions with a high level of accuracy. For this study, a 3D model of a Concrete-Filled Steel Tube (CFST) column was incorporated in the setup. To effectively model the core with concrete and the steel tube in order to capture local buckling and confining behavior was constructed using SOLID185 and SHELL181 respectively. The model geometry was representative of the 100 mm diameter, 1250 mm length with 4 mm thickness steel test specimens with both fixed-fixed and pinned-pinned end conditions. The mesh was adjusted to be fine at the mid-span and at the ends to ensure that global deformations and local buckling were recorded and that analysis converged.

2. Material Models

Axial loading: To capture realistic behavior with axial loading, nonlinear material models were developed. Stiffness reduction, cracking, and crushing for concrete were captured using the Concrete Damaged Plasticity Model

(CDPM). For the steel tube, an elastic-plastic model with strain hardening was developed using the Bilinear Isotropic Hardening Model. The contact interaction of the steel and concrete was defined as a surface-to-surface contact with some slip to model imperfect bonding. A friction coefficient of 0.6 was assigned. To achieve the responses both before and after yield, a displacement-controlled loading approach was used. With these models, axial load–deformation characteristics were accurately captured, as well as the collapse behavior of CFST columns for varying end conditions.

3. Boundary Condition

The numerical model took into account the four boundary conditions:

- One Fixed End–One Free End (Cantilever)
- Both Ends Pinned
- One Fixed End–One Pinned End
- Both Ends Fixed

All translational and rotational degrees of freedom were fixed to support, whereas limits on translation relaxed rotational degrees of freedom. Controlled displacement for axial load on top was implemented, which captured pre/yield and post/yield behaviour. This method allowed for the modelling of global deformation, initiation of buckling, and collapse progression on the global scale.

3.4 MATLAB-Based Optimisation Method

MATLAB-based optimisation methods were employed in this project. These methods relied on critical response parameters and numerical analysis to improve the performance of CFST columns. The method involved post processing finite element analysis (FEA) results, followed by an iterative optimisation process to control the stress and displacement of the columns. The optimisation process integrated into MATLAB compared the original and modified responses and included graphical output. The method enabled performance-based design and rapid evaluation of the structural response of columns subjected to varied load conditions, and assessed the safety, stability, and reliability of CFST columns having various end conditions.

3.5 Governing Equations for CFST Validation

To verify the findings of this study, the numerical results were compared to that of recently published studies. Almasabha (2024) worked on circular concrete-filled steel tubular (CFST) columns, stating that a refined finite element model would predict the axial load strain response of CFST sections under compression, and provided results that were in close agreement and reproduced the ultimate load. The finite element method used in that study was verified by the results and showed good of the load-displacement and stress distribution and offered good prediction. Similarly, the response of the ANSYS numerical models of this study remained close to the observed response, including the load deformation and von Mises stress distribution. As for the cross-validation, this agreement indicates that the extent of the structural responses and the general findings of this study were in agreement with the finite element predictions, as described in the literature. The agreement of the present results and those of Almasabha (2024) shows that the modeling and the procedures used in this study were sufficiently accurate, and the effects of the end conditions on the CFST column collapse can be accepted with confidence. To validate the failure performance of CFST columns, the composite axial strength, confined concrete strength, Euler's buckling theory, effective flexural rigidity, and von Mises stress criterion were considered. The combination of these governing equations describes the load resistance, stiffness, stress distribution, and stability under various end conditions, ensuring adequate analytical and numerical performance evaluations.

1. Composite Axial Load Carrying Capacity of CFST Column

The steel tube and encasement-concrete core contribute to the total axial strength of a Concrete-Filled Steel Tube (CFST) column. When the column is subjected to axial compression, the load-carrying capacity and structural efficiency of the composite are further enhanced. The ultimate axial capacity with composite action is given as:

$$P_u = A_s f_y + A_c f'_{cc} \tag{1}$$

2. Confinement Effect on Concrete Strength

The steel tube improves the effective compressive strength and ductility of the concrete core by providing lateral confinement. This also delays crushing and improves the post-peak behavior when axial loads are applied. The strength of confined concrete as a result of this can be defined as:

$$f'_{cc} = f'_c\left(1 + \frac{A_s f_y}{A_c f'_c}\right) \quad (2)$$

3. Critical Buckling Load under End Conditions

Boundary restraints greatly affect the collapse behavior of CFST columns. The critical buckling load is evaluated with consideration of effective stiffness and end-condition factor using Euler's stability theory:

$$P_{cr} = \frac{\pi^2 EI_{eff}}{(KL)^2} \quad (3)$$

4. Equivalent Flexural Rigidity of Composite Section

Combining the elastic contributions of steel and concrete yields the effective flexural stiffness of a CFST column. This parameter controls deformation and the stability of the assembly structure:

$$EI_{eff} = E_s I_s + \eta E_c I_c \quad (4)$$

5. Von Mises Stress Criterion for Collapse Validation

The equivalent von Mises stress criterion is used to evaluate the yielding and collapse initiation in finite element simulations. When used in such a context, the criterion accounts for the multiaxial stress case on yielding of steel:

$$\sigma_{vm} = \sqrt{\frac{1}{2}\left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2\right] + 3\tau_{xy}^2} \quad (5)$$

4. Ansys Modelling

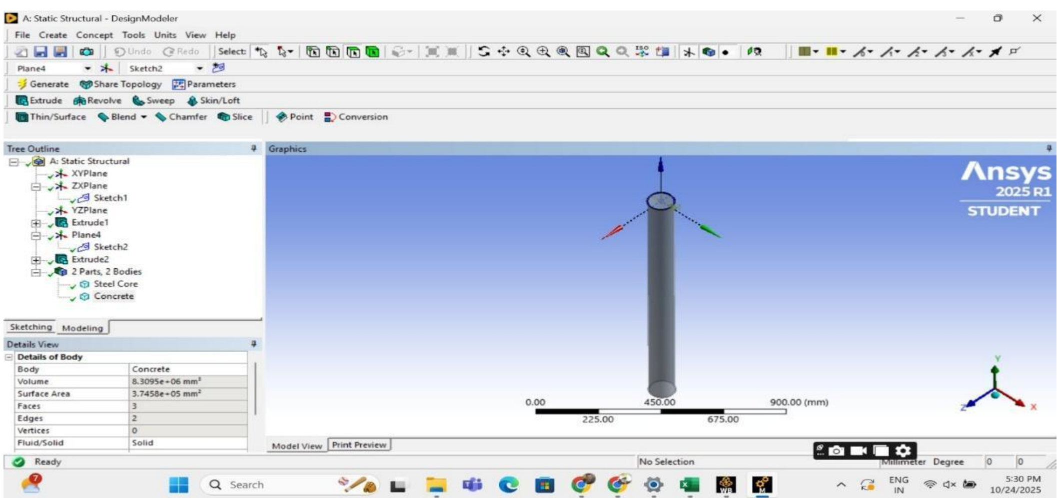

Fig 4. CFST Column Numerical Model

Figure 4 shows a 3D finite element model of a Concrete-Filled Steel Tube (CFST) column developed within ANSYS Design Modeler for a static structural analysis. Boundaries define the concrete core of the model and the enclosing steel tube, along with the definition of dimensions and material domains. This model will help define the boundary conditions and applied axial load in order to assess the distribution of stress, deformation, and buckling and collapse under various end conditions.

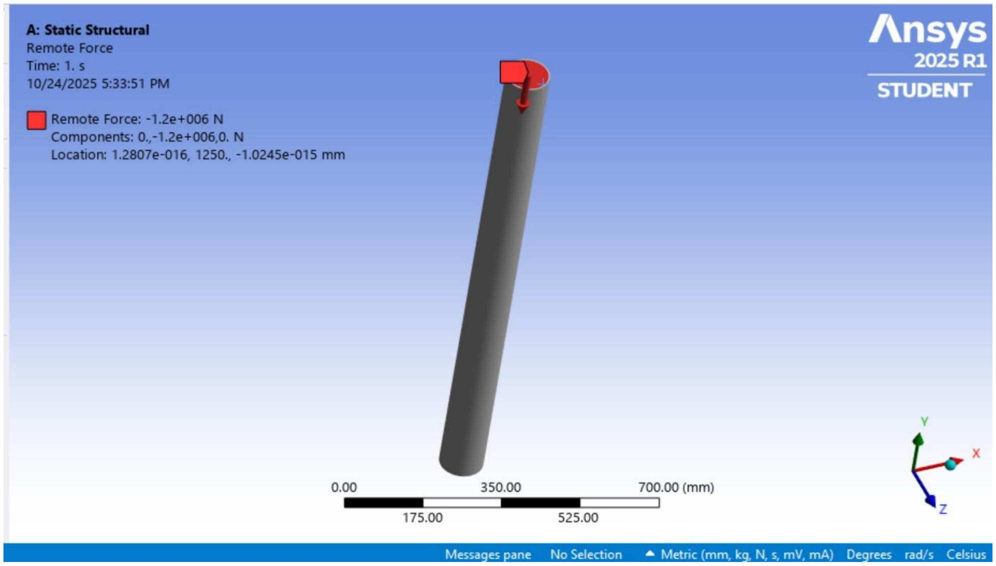

Fig 5. Axial Load Application in CFST

Figure 5 illustrates the application of a remote axial compressive force on a CFST column using ANSYS Static Structural analysis. To simulate axial compression with realistic boundary conditions, the load is applied at the upper end. This method of loading ensures that stress is distributed uniformly throughout the cross-section. It also allows for the assessment of global deformation, as well as the buckling and collapse behavior of the CFST column under critical loading conditions.

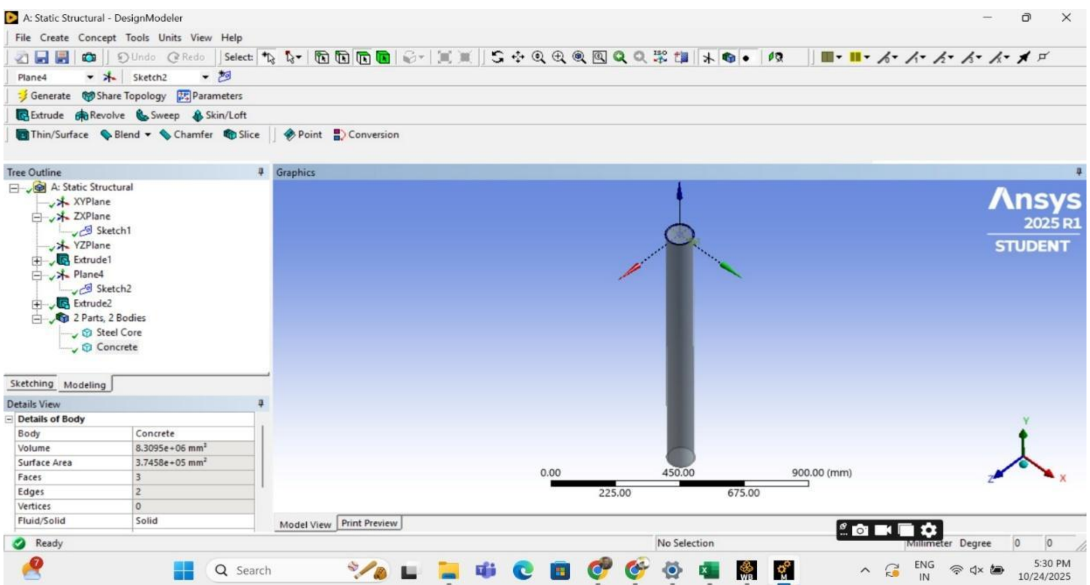

Fig 6. CFST Column Geometry Model

Figure 6 presents the geometric modeling of a Concrete-Filled Steel Tube (CFST) column in ANSYS Design Modeler. It also separates the concrete core and the surrounding steel tube, allowing the correct material assignment for both and the definition of interaction between the two. An accurate geometric model like this is essential for finite element analysis, and it is used to simulate the realistic aspects of the loading, the confinement, and the effects of deformation and collapse under axial compression and the changes in end conditions.

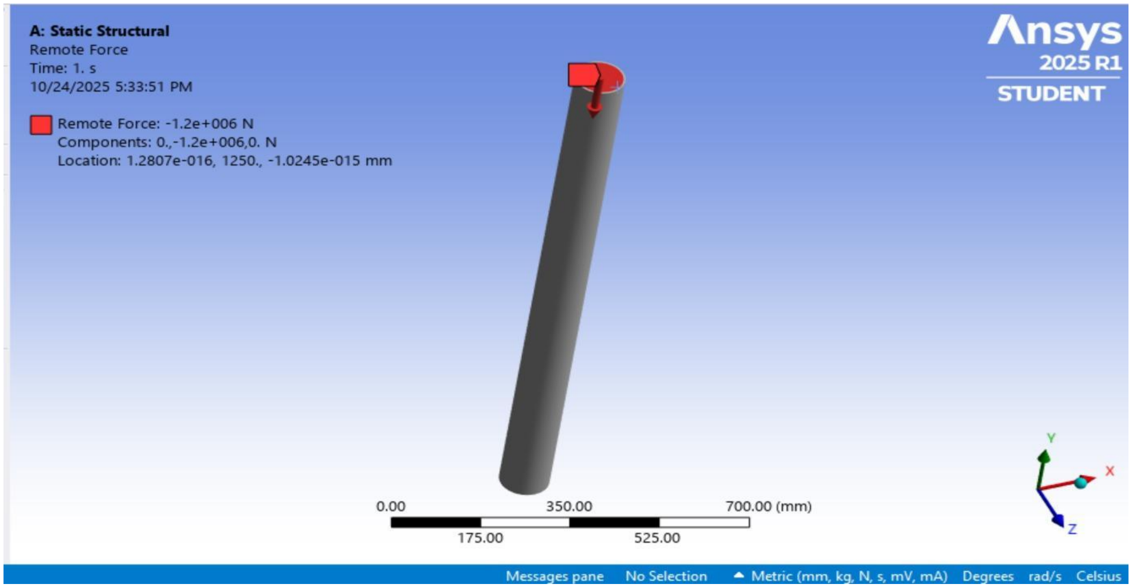

Fig 7. CFST Column under Axial Load

Figure 7 shows a CFST column subjected to a remote force in an ANSYS Static Structural analysis. Here, the load at the top of the column is modeled to create compressive stress and cause global deformation to the column. First, small lateral deflections begin to grow due to the axial load increasing and exhibiting initial buckling behavior. With the above-defined configurations, it is possible to analyze critical load capacity, stability response and collapse characteristics of CFST columns under real load and boundary conditions.

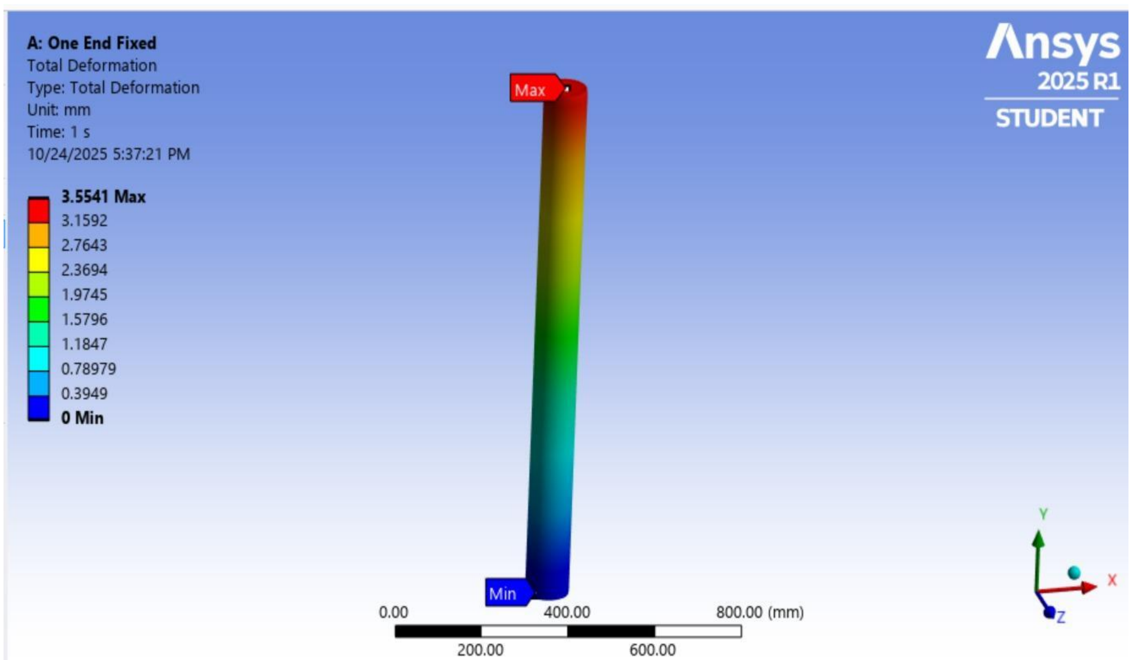

Fig 8. Total Deformation of CFST Column

Fig. 8 displays the complete deformation profile of a CFST column with a single end laterally supported. The observed maximum and minimum deformations of 3.5541 mm and 0 mm, respectively, occurred at the fixed support and free end (shown on the color scale). This gradient confirms the behavior of cantilever columns, which state that the largest lateral displacement occurs at the end of the column subjected to lateral loading. This illustrates that the behavior of deformation and buckling were largely influenced by the support conditions at the ends of the column.

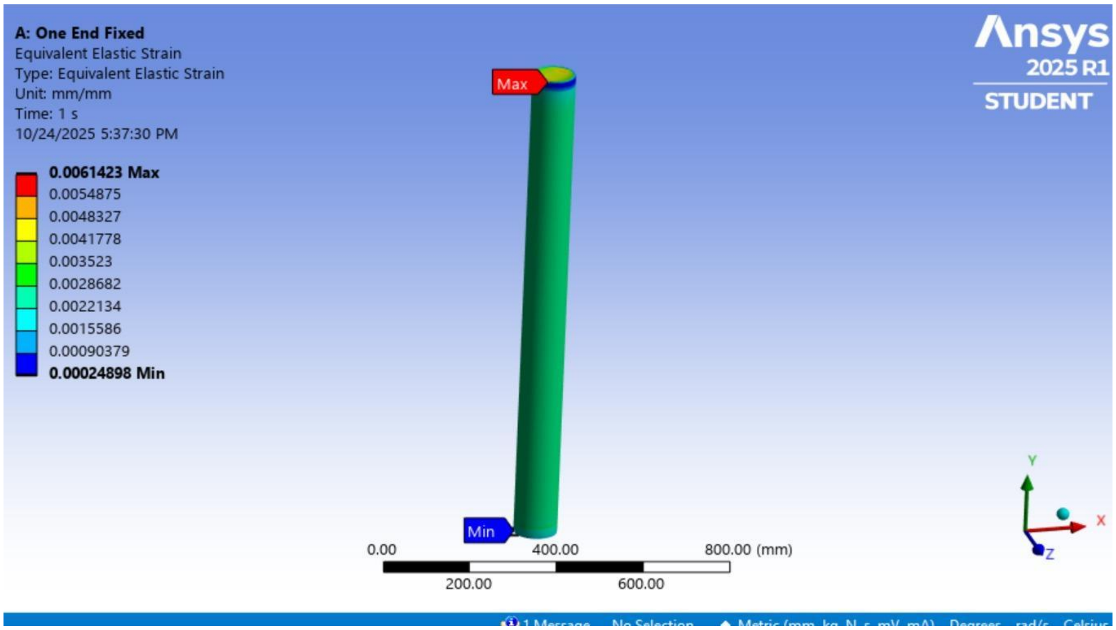

Fig 9. Equivalent Elastic Strain Distribution

Figure 9 displays the elastic strain distribution in a CFST column with one end fixed under axial compression. The strain was a minimum of 0.00024898 mm/mm near the fixed end and a maximum of 0.0061423 mm/mm at the free end. Because upper segment strain is greater, that segment is requested to a greater degree, indicating the beginning of upper segment instability. Fixed end conditions are of primary importance in controlling strain localization and the collapse mechanism.

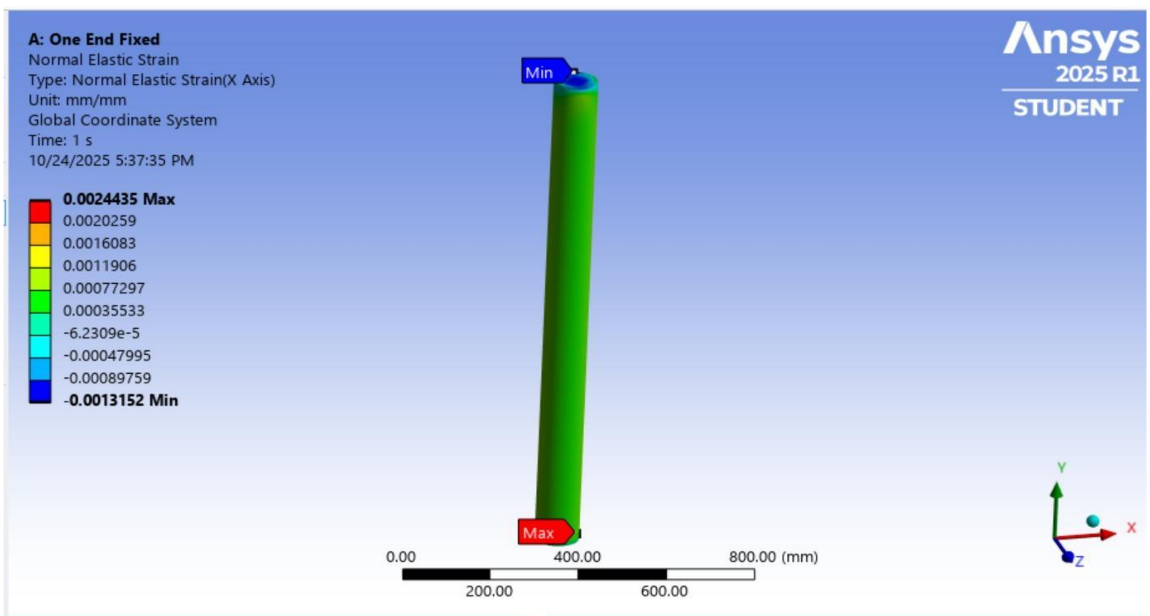

Fig 10. Normal Elastic Strain Distribution

The figure 10 depicts the typical elastic strain distribution along the X-axis of a CFST column with a freely rotating end subjected to axial compression. The strain varies from a maximum tensile strain value of 0.0024435 mm/mm near the fixed end to a maximum compressive strain value of -0.0013152 mm/mm near the free end. This variation depicts the combined effect of axial compression and bending, which is the strain reversal and reflects the end fixation effect on strain, stress, and buckling response.

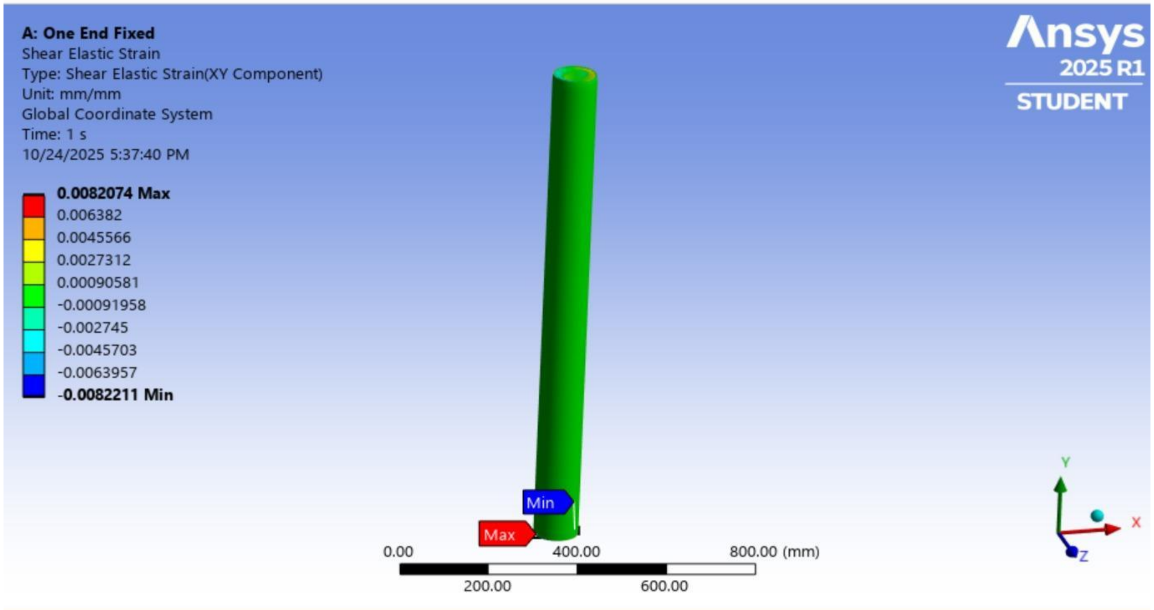

Fig 11. Shear Elastic Strain Distribution

Figure 11 shows the distribution of shear elastic strain (XY component) of a CFST column with one end fixed in axial compression. Shear strain has a value of 0.0082074 mm/mm at the fixed end and a value of -0.0082211 mm/mm at the free end of the column. The significant concentration of shear strain at the fixed end indicates a pronounced bending-shear coupling due to end fixity, which affects local deformation and discontinuity in localized deformation and instability of the column.

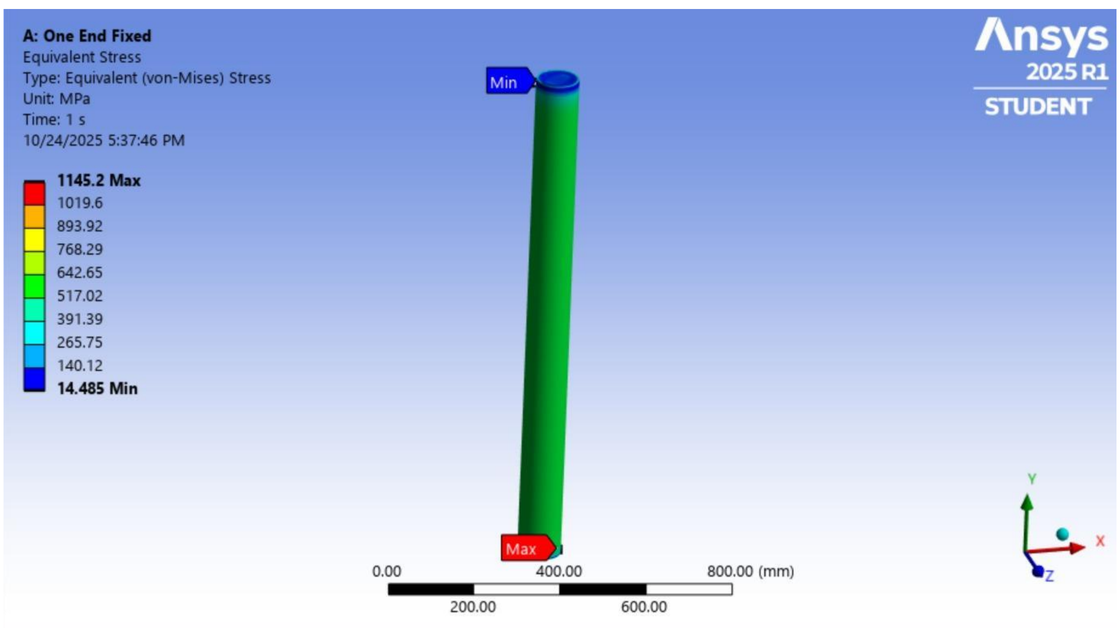

Fig 12. Equivalent Stress Distribution

Fig. 12 shows stress distribution in a CFST column with a lower fixed end during an axial compressive test. Per the contours, the free end shows stress of 14.485 MPa, and 1145.2 MPa at the fixed end. The stress focus at the fixed end shows that critical yielding is near, and collapse is possible. Thus, the fixed end significantly impacts the stress and collapse development.

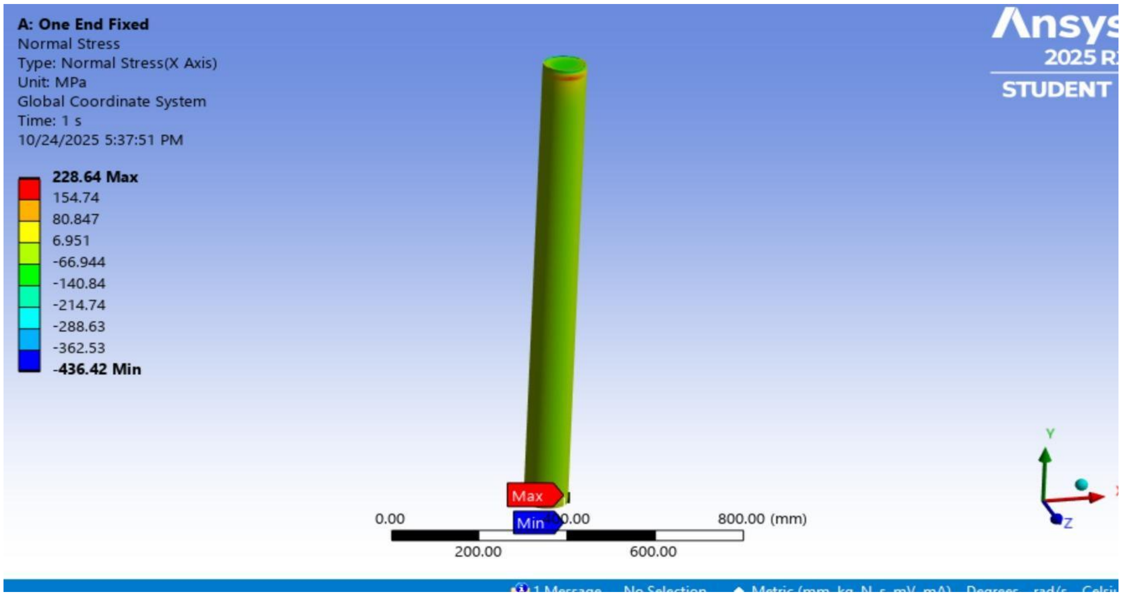

Fig 13. Normal Stress Distribution

Figure 13 depicts the distribution of normal stresses along the X-axis in a CFST column of fixed total length subjected to uniaxial compression. The extremes are the highest tension stress of 228.64 MPa near the top and the lowest compressive stress of -436.42 MPa at the fixed bottom. This stress distribution exhibits dual compressive and bending stresses, with the compressive stresses concentrated at the restrained end, indicating a critical point of yielding and ultimate failure.

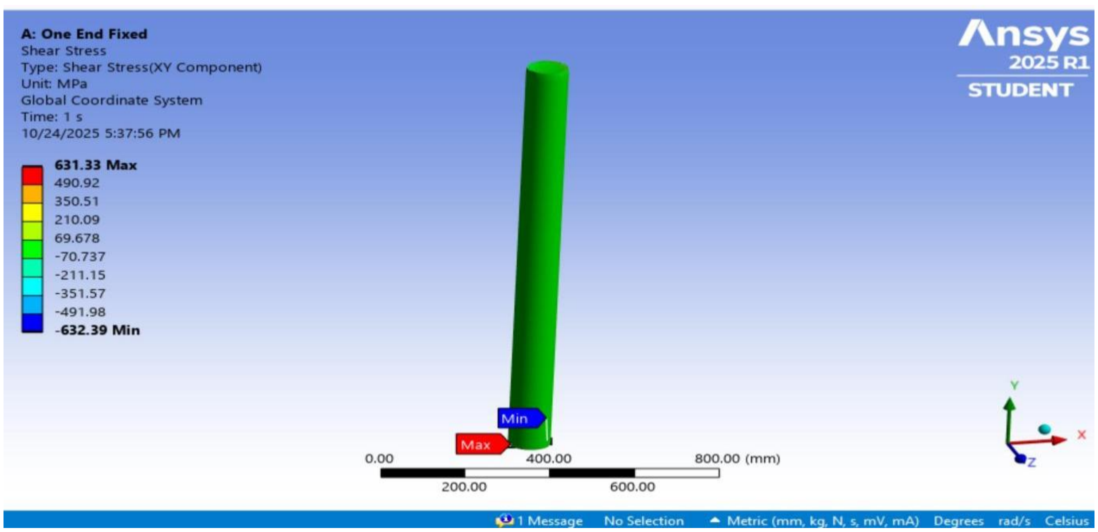

Fig 14. Shear Stress Distribution

The fig 14. Shows the distribution of shear stress (XY component) in CFST columns with fixed ends under axial loads. Shear stress is maximum (631.33MPa) at the restrained end and minimum (-632.39MPa) in the middle of the column. Higher shear stress at the fixed end denotes higher bending shear interaction and yields a critical zone of local yield and instability under combined bending and axial loads.

4. Results and Discussion

This section examines the structural behavior of Concrete-Filled Steel Tube (CFST) columns with four different end fixity conditions: Fixed-Free, Pinned-Pinned, Fixed-Pinned, and Fixed-Fixed. Analysis of behavior combines results from finite element simulations and fundamental stability theory to identify deformation and strain concentrations, stress, and collapse behavior. Some of the parameters considered in the analysis include the total deformation, and the types of strain and stresses. This portion of the analysis also examines the influence of end fixity on the stability of the structure. The results of the analysis show that the boundary conditions influence the stiffness, effective length, and load redistribution of the columns. It was also observed that with increased end fixity, the deformation and stress concentration was reduced. This was explained by the increased confinement and the delay of the yield point. The role of combined performance analysis on the instability of the CFST columns is explained as well as the influence of rotational restraints on CFST columns in increasing collapse resistance of the columns under the action of axial loads.

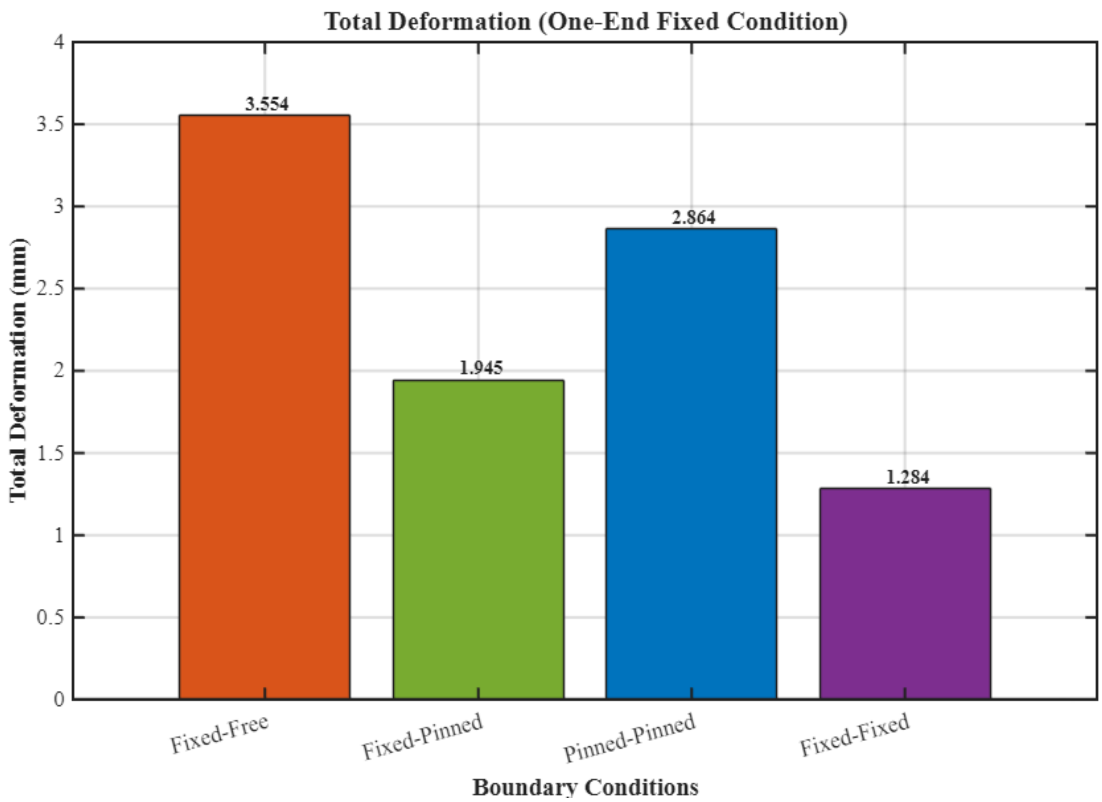

Fig 15. Total Deformation (one-End Fixed Condition)

Boundary restraint highly influences the deformation behavior of the CFST column. Fixed Free displayed the greatest total deformation at 3.554 mm, exhibiting cantilever-like instability. On the other hand, deformation decreased to 2.864 mm in the Pinned-Pinned and to 1.945 mm in the Fixed-Pinned, showing greater stiffness in both cases. The Fixed Fixed case had a deformation of 1.284 mm, which correlates with greater stiffness. End fixity in Fig. 15, advances and amplifies the effective length and transverse displacements, thus decreasing overall stability of the system. The improvements in stiffness with the integration of rotational restraints is clearly illustrated by the approximately 64 percent reduction in deformation from Fixed Free to Fixed Fixed.

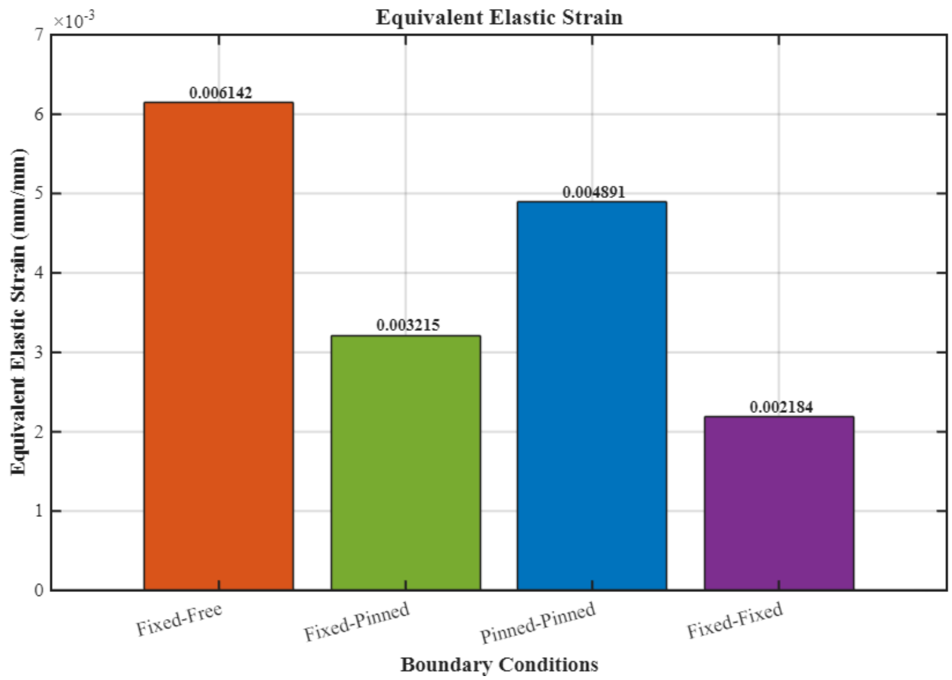

Fig 16. Equivalent Elastic Strain

The elastic strain trends similarly to boundary restraint, showing a decreasing correlation. The Fixed Free condition showed the highest strain, calculated as 0.006142 mm/mm, which indicates an increased level of stress concentration around the fixed base. Strain was minimized to 0.004891 mm/mm in the Pinned-Pinned condition and to 0.003215 mm/mm in the Fixed-Pinned condition. The lowest level of strain was recorded in the Fixed-Fixed case, with a value of 0.002184 mm/mm. The results in Fig. 16 show a decreasing trend of strain with Fixed-Fixed case showing the best stress redistribution/confinement. The cantilevered vs. fully restrained condition showed a 64% reduction in strain and illustrates the increasing boundary stiffness and its usefulness in the strain yielding and border restraint relationship.

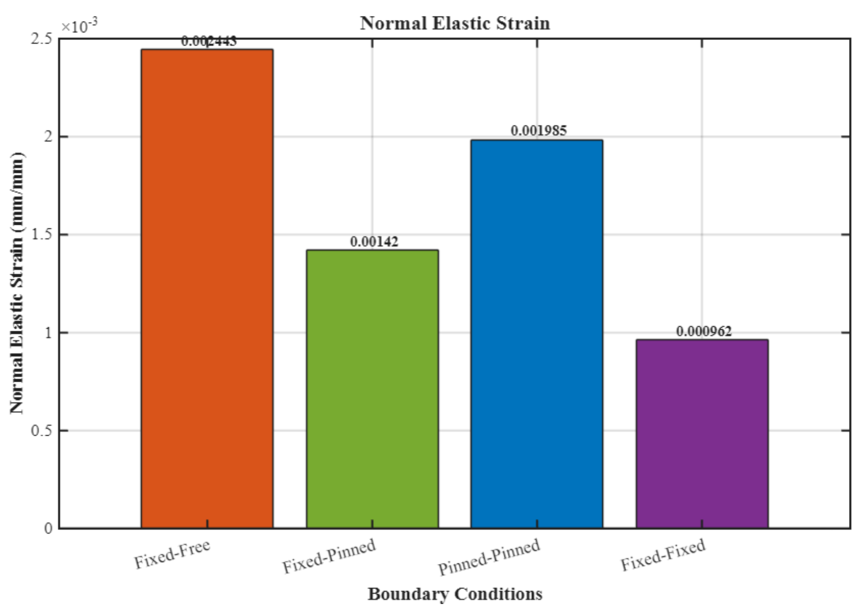

Fig 17. Normal Elastic Strain

Normal elastic strain results from a combination of axial and bending effects. The Fixed – Free setup recorded the largest strain of -0.002443 mm/mm, indicating significant bending at the fixed support. The Pinned-Pinned setup was measured at -0.001985 mm/mm, and the Fixed-Pinned setup recorded -0.001420 mm/mm. The overall lowest recorded strain of ±0.000962 mm/mm was measured in the Fixed – Fixed setup, indicating the set condition was consistently transferring axial stresses. Weak rotational restraints, shown in Fig. 17, are ineffective in reducing strain amplification. The results indicate normal strain was reduced by roughly 60 percent between the Fixed – Free and Fixed systems, indicating improved stability and reduced bending deformation.

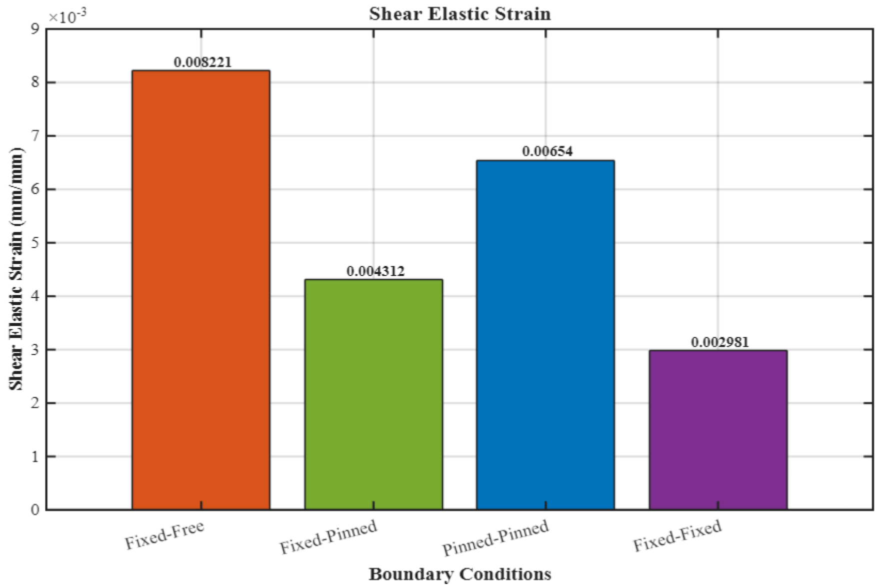

Fig 18. Shear Elastic Strain

Shear strain distribution suggests the presence of a bending- shear interaction. The Fixed-Free condition demonstrated a significant deformation with the highest shear strain value of ±0.008221 mm/mm, occurring at the location of the fixed base. The Pinned-Pinned system showed shear strain of -0.006540/mm/mm, while Fixed-Pinned showed -0.004312/mm/mm. The lowest shear strain of the Fixed- Fixed condition was ±0.002981 mm/mm, showing the effect of fixed boundary condition. The decline highlighted in Fig. 18 suggests that enhanced end conditions contribute to a rise in shear strain. The observed decrease in shear strain was around 63%, particularly in comparison with the completely cantilever and fixed systems.

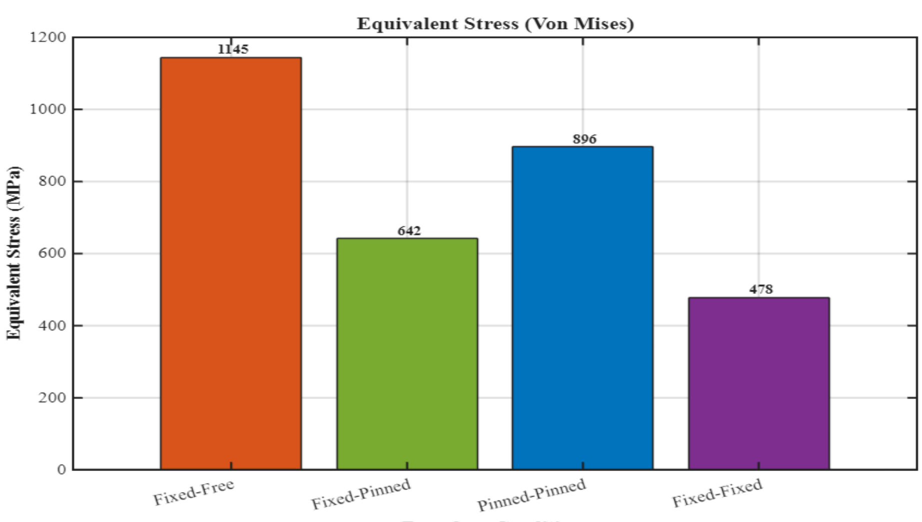

Fig 19. Equivalent Stress

Parallel stress analysis gives insight about the yielding behavior. In cases when von Mises stress was a maximum (Fixed-Free) 1145 Mpa, which is significantly higher than the steel yield strength (250 Mpa), the collapse was identified to have initiated at the early plastic stage. The stress dropped to 896 MPa in the Pinned Pinned case and 642 Mpa in the Fixed Pinned case. The minimum stress was observed to be 478 Mpa in the Fixed-Fixed case. Notice from Fig. 19, the stress concentration decreased with increasing end restraint. The stress reduction of approximately 58% between the cantilever and the fully fixed case provides evidence of load distribution, and also delaying the yielding.

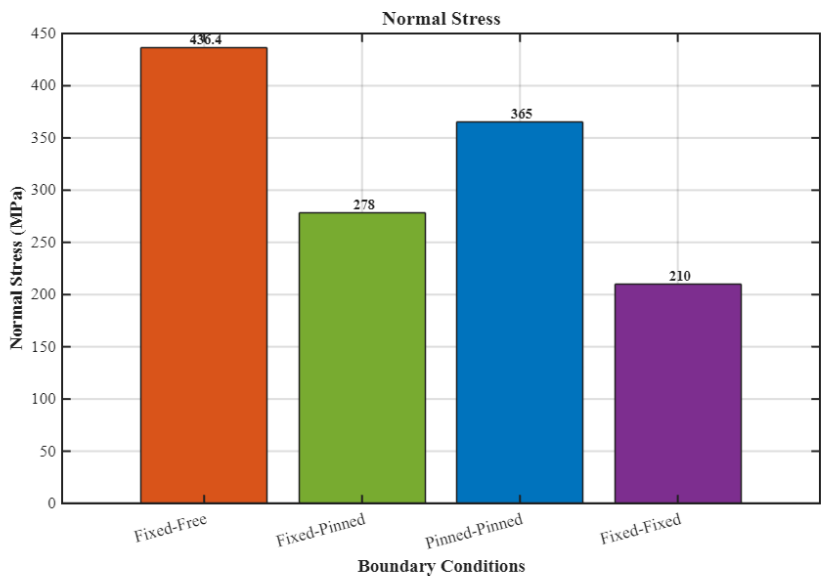

Fig 20. Normal Stress

Normal Stress results include the effects of both the Axial Compression and Bending effects. The highest Compressive Stress of -436 Mpa and +228 Mpa of Tensile Stress was observed in the Fixed – Free scenario. Compressive Stress of -365Mpa was observed in the Pinned Pinned scenario and -278Mpa in the Fixed Pinned. The Fixed-Fixed case showed the least magnitude of Compressive Stress of -210 Mpa. The Increased Boundary Restraint, as shown in Fig. 20, enhances the homogenization of the stress transfer and minimizes the localized concentrations. The results show that Compressive Stress was reduced by almost 52 percent between Fixed-Free and Fixed-Fixed cases.

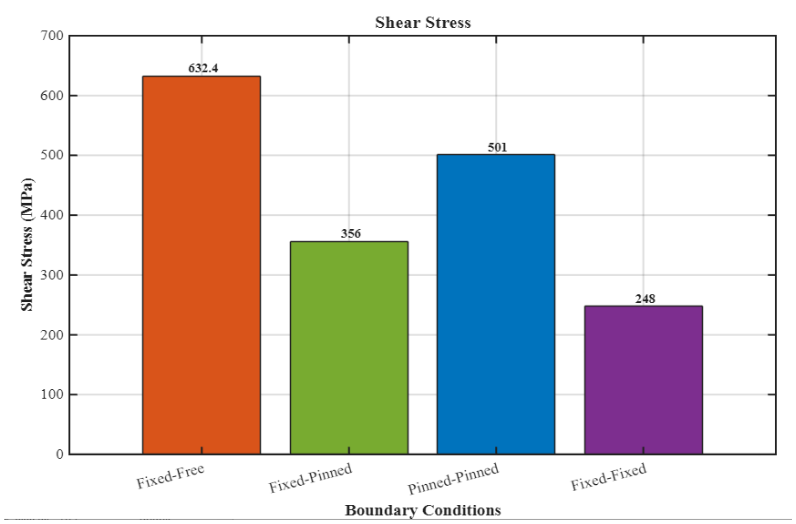

Fig 21. Shear Stress

The effect of boundary restraint on stability is also verified by shear stress. Of the four restraints considered, the Fixed-Free had the most shear stress of ±632 Mpa followed by Pinned-Pinned of ±501 Mpa. The Fixed-Pinned form had the least applied shear stress of ±356 Mpa, and Fixed-Fixed had the least shear pressure of ±248 Mpa. According to Fig. 21, of all boundary restraints, the Fixed condition had the most adverse effect on shear stress concentration and instability. The results also show a 61% decrease in shear stress of cantilever versus fully restrained systems, which shows the improved resistance to collapse.

5. Conclusion

The present study systematically examined the collapse behavior of Concrete-Filled Steel Tube columns subjected to four different boundary conditions using a combined finite element and optimization approach. The results show that end restraints significantly affect axial stiffness, the nature of deformation, strain localization, stress concentration, and the overall failure mode. In the Fixed Free (cantilever) configuration, the largest deformation and localization of von Mises stress (3.554 mm and 1145 MPa, respectively) was observed. The magnitude of von Mises stress was significantly higher than the yield stress of steel (250 MPa), indicating that plastic deformation occurred early, and considerable instability was observed in the Fixed Free configuration. On the other hand, the Fixed-Fixed configuration was the most stable, as an increase in the degree of end fixity resulted in a reduction of deformation, strain, and an increase of stress. The models were also able to reproduce confinement effects, local buckling, and the nonlinear stress-strain behavior, thus validating the modeling approach. The ability to control the stresses in the framework of a performance-based design using MATLAB and a scaling coefficient ($k \approx 0.218$) demonstrated the effectiveness of the design, as stresses were kept within a safe range and deformation was minimized to 0.77 mm. One important finding of this research is that the current Indian Standards (IS 456:2000, IS 800:2007 & IS 11384:1985) have a major shortcoming because they do not specify CFST composite action or boundary conditions modelling. This creates a need for codal provisions with realistic end constraints and confinement effects. Future research in this area may also include the effects of cyclic loading and design of seismic-resistant CFST structures, as well as the design of provisions based on the IS that frames CFST structures.

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