CE491 PROJECT REPORT:

SEISMIC ANALYSIS AND DESIGN OF STEEL TRUSS MOMENT RESISTING FRAMES

DEPARTMENT OF CIVIL ENGINEERING

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Lastly, I am grateful to the entire Civil Engineering Department for creating an environment that supports exploratory learning and research-based project work.

INTRODUCTION

This project focuses on learning and applying structural modeling techniques using **OpenSees (Open System for Earthquake Engineering Simulation)**. As a part of this work, I began by studying the basics of OpenSees through the detailed video lectures provided by the course instructor. These sessions introduced me to the syntax, modeling strategies, and analysis procedures required for simulating the behavior of structural systems under various loading conditions.

After gaining initial familiarity with the software, I shifted my focus toward understanding **Steel Moment Resisting Frames (SMRFs)** by referring to a research paper that elaborates on their seismic behavior, structural detailing, and modeling considerations. This formed the conceptual basis for my modeling tasks.

To build up towards modeling a complex structureóa **5-bay, 9-storey steel moment frame**óI adopted a step-by-step approach. I started by modeling a **single-bay, single-storey** frame and performed a **linear elastic analysis** to verify geometry, boundary conditions, and element definitions. After validating this base model, I extended it to a **single-bay, 9-storey** frame for capturing vertical load distribution and ensuring correct floor-by-floor connectivity. Then, I developed a **nonlinear model for the single-bay, single-storey** frame to incorporate material inelasticity and fiber section behavior using displacement-based beam-column elements.

The modeling of the full **5-bay, 9-storey structure** is currently **a work in progress**, with the necessary groundwork laid in terms of section definitions, geometry generation strategies, and load application methods. This incremental process has not only helped in managing complexity but also ensured a clearer understanding of both the theoretical and practical aspects of structural simulation.

THEORY

OpenSees Basics

As the first step of this project, I spent a good amount of time learning the basic features of **OpenSees**, especially using **OpenSeesPy**, which is the Python version of the original OpenSees software. While the original version is based on Tcl (a programming language), OpenSeesPy u ses Python, which is easier to write and works well with other scientific tools in Python. This made the learning process smoother and more practical. With the help of the video lectures provided by the instructor, I slowly built a clear understanding of how OpenSees worksóstarti ng from simple commands and moving on to writing full scripts for different types of struct ures.

At its core, OpenSees is structured around several key components: **Domain** (the central work space that stores all components of the modelónodes, elements, loads, constraints, etc.), **Model Builder**, **Nodes & Elements**, **Constraints**, **Load Patterns**, **Analysis**, and **Recorders**.

Each OpenSeesPy script typically follows a modular structure, broken down into the followin g blocks:

- **Title**: Describes the model and objective of the script.
- **Inputs**: Parameters such as geometry dimensions, material and section properties.
- **Model**: Creation of nodes, elements, boundary conditions, and other definitions.
- **Loads**: Application of point loads, distributed loads, or load patterns.
- **Recorders**: Define what outputs (like displacements or forces) to track during analysis.
- **Analysis**: Specify analysis type (static/dynamic, linear/nonlinear), constraints, algorith ms, and solvers.
- **ScreenPrint**: Optional print statements for key outputs during runtime.
- **Plotting (using opsv)**: Visualization using the opsvis package to plot undeformed and d eformed shapes.

Through these lectures and hands-on scripting, I learned to model a variety of structural syst ems. These include:

- Basic truss elements
- Elastic beam-column elements
- Simple elastic frame models
- Combined beam and truss systems
- Elastic frames for multiple storeys
- Small variations in each model to understand effects of geometry, supports, and loadi ng

This structured learning approach helped me gradually build the necessary skill set to move f rom simple structural components to more complex frame systems, ultimately preparing for the modeling of large-scale multi-storey structures.

Review and Learnings from the Research Paper on Special Truss Moment Frames

Special Truss Moment Frames (STMFs) are a unique structural system designed specifically for use in high seismic regions. Unlike conventional moment frames, STMFs combine the be nefits of both moment-resisting behavior and truss action. The key innovation lies in **special ductile segments** placed near the midspan of the truss girders. These segments are deliberatel y designed to yield and dissipate energy during strong earthquakes, thereby protecting the res t of the structure. According to the authors, this targeted yielding strategy helps achieve bett er seismic performance and makes the system suitable for essential facilities like hospitals.

One of the main advantages of STMFs, as highlighted in the paper, is their **redundancy**. Each girder can form up to four plastic hinges, and if web members are included in the special seg ment, the system can offer even greater energy dissipation. The open-web configuration also allows for easy routing of utilities, making it architecturally appealing.

The paper uses a **nine-story, five-bay STMF** as an example to demonstrate the application of their performance-based plastic design (PBPD) approach. The structure, shown in **Figure 12**, r epresents an ordinary occupancy building (like an office or residential block). Its elevation an d plan were used as the basis for a detailed structural design using PBPD, which focuses on di rectly achieving a desired yield mechanism and target drift, without the need for iterative pus hover or time-history analyses after design.

For this example, detailed information about the **member sections at each floor** is provided. E ach level has carefully chosen **double-channel chord sections**, with increasing plate thicknesse s in the special segments as we go lower down the structure. For instance:

- At the top floor (9th), **C7x12.25** sections were used for chords, while the bottom floors use heavier **C10x30** sections with **1.5-inch plates**.
- Diagonal and vertical members are also varied, using standard MC and M shapes such as **MC6x12**, **MC9x25.4**, and **M10xC25**, reflecting the increased demand at lower stories .
- The **web plates** in the special segments span the full 5.5 ft length of each panel, ensuri ng continuous ductile behavior.

One practical learning from this example is the **gradation of member strengths and sizes** fro m top to bottom, helping to evenly distribute plastic rotations across all levelsóa key design g oal in PBPD. The analysis confirmed that plastic hinges formed where intended, and interstor y drifts remained within target limits.

This example serves as a valuable reference for modeling similar STMFs in OpenSees, partic ularly in understanding how to define section properties floor-wise, locate special segments, a nd interpret seismic performance goals.

OPENSEES MODELLING

Example 12 (Figure 12) Overview:

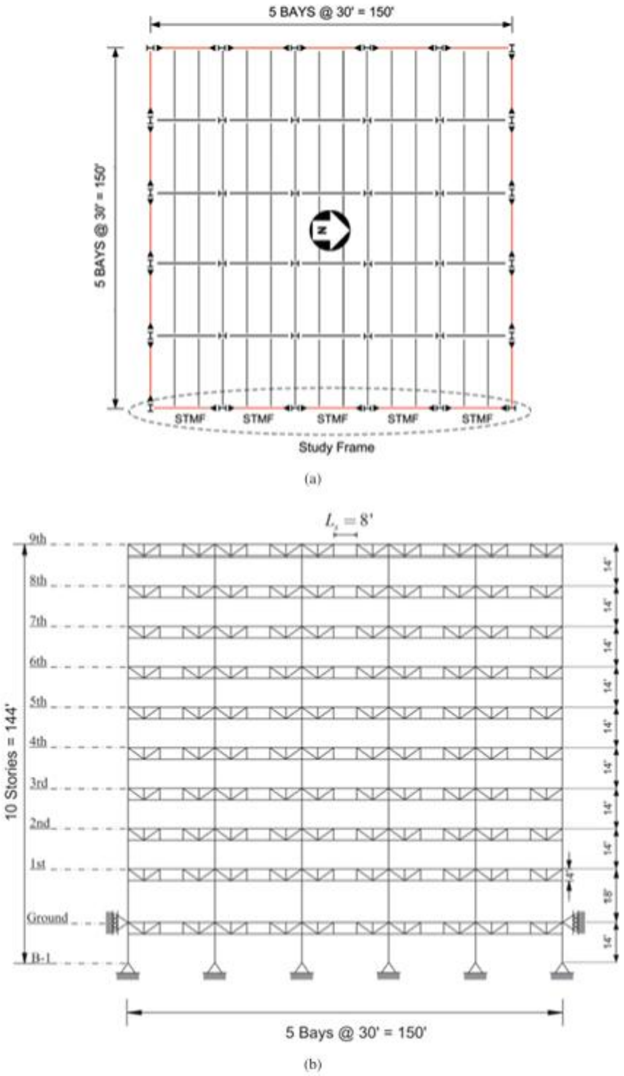
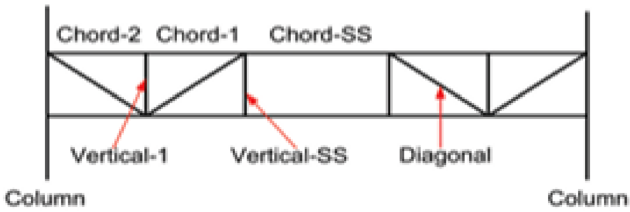


Fig. 12. Building plan and elevation of study STMFs.

Example 12 presents a **nine-story, five-bay Special Truss Moment Frame (STMF)** structure designed for **ordinary occupancy**, such as office or residential use. The building has a total height of **130 ft** and a fundamental period of approximately **1.93 seconds**. The **total seismic weight** is given as **19,839 kips**, and the **design base shear** calculated through the PBPD method is **1,956 kips**, which is significantly higher than what conventional elastic design would suggest. The **target story drifts** are 2% for moderate hazard (10% in 50 years) and 3% for maximum considered earthquake (2% in 50 years). As shown in **Figure 12**, each floor features truss girders spanning five bays, with **special ductile segments** placed at midspan to concentrate inelastic action during earthquakes. This configuration ensures that yielding occurs in controlled zones while the rest of the structure remains mostly elastic.

Chord and Vertical Member Details:



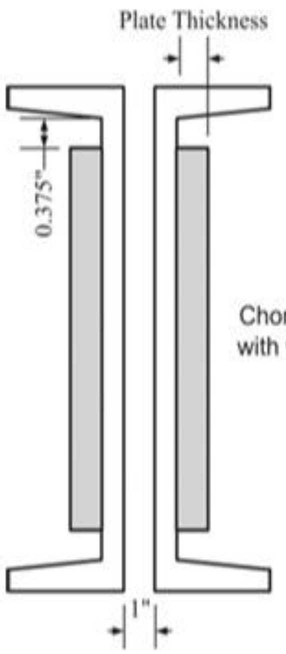


Fig. 14. Design special segment and truss member sections for the nine-story ordinary STMF.

The STMF in Example 12 uses **built-up double-channel sections** for all chord members, with sizes increasing from top to bottom to meet rising axial and flexural demands. For example, t he **9th floor chord** uses **C7x12.25**, while the **bottom three levels** use **C10x30** sections, each rei nforced with up to **1.5-inch cover plates** in the **special segments**. These plates span the entire **5.5 ft panel length**, ensuring continuity and ductility. The **vertical members** inside the special segments are typically **MC6x12**, while those outside vary with height, including sections like **MC6x16.3** and **MC8x22.8**. Similarly, **diagonal members** are selected to resist increasing shear demand at lower levelsóranging from **MC6x12** at the top to heavier sections like **MC9x25.4** a nd **M10xC25** at the base. All sections are designed to meet seismic compactness limits and to support the formation of the intended yield mechanism concentrated within the special segm ents. These member selections reflect a careful balance between strength, ductility, and fabri cation feasibility.

METHODOLOGY

Step 1: Modeling a Single-Bay, Single-Story STMF

To build a solid foundation for modeling more complex frames, the process began with a simplified structural model ó a **single-bay, single-story truss moment frame** ó to verify geometry, loading, and basic elastic behavior. The key steps and assumptions are outlined below:

- **Geometric and Structural Inputs:**
  - **Bay width:** 30 ft
  - **Story height (1st floor):** 18 ft
  - **Horizontal truss element length (l):** 5.5 ft
  - **Chord member length (Lc):** 8.0 ft
  - **Vertical member height (h):** 4.0 ft
- **Load and Mass Calculations:**
  - **Total building weight (W):** 19,839 kips
  - **Modeling 1/50th portion of the full 5-bay, 10-story frame " w = 19839 / 50 = 396.78 kips**
  - **Unit conversion:** 1 kip = 453.6 kg
- **Material Properties (Steel):**
  - **Elastic modulus, E:** 29,007.6 ksi (based on 200 GPa 145.038)
  - **Lumped mass at top node:** 396.78 kips
  - **Yield strength, Fy:** 50.0 ksi (assumed, typical for structural steel)
- **Cross-Sectional Properties (All as double-channel members):**
  - **Chord-SS / Vertical-SS / Chord-1:**
    - A = 17.62 in^2
    - I (minor axis for chords): 34.52 in^4
    - I (major axis for verticals): 206.0 in^4
  - **Chord-2 (C10x30 + 1.5 in cover plate):**
    - Properties calculated based on composite section geometry using Parallel axis method of calculating MOI assuming rectangles.
    - A = 31.495 in^2
    - I = 132.18 in^4

- Vertical-1 (MC6x16.3):
  - Area and MOI doubled due to double-channel usage
  - A = 9.58 in^2
  - I = 52 in^4
- Diagonals (MC1x25):
  - A = 14.68 in^2
  - I = 117.25 in^4
  - Calculated using concept of $I_d = I_x + I_y$

- Transformation and Analysis Settings:
  - Used **PDelta transformation** to capture second-order effects and better represe nt geometric nonlinearity under vertical loads.
  - Nodes and coordinates defined using Python loops for efficiency and clarity.
  - Assigned **'Elastic' uniaxial material** to all members for initial linear analysis.
- Elements, Load Definition and Boundary Conditions:
  - All members were modeled as **elasticBeamColumn elements** to represent linea r stiffness behavior.
  - The bases of the structure got support using a pin (rotation is allowed).
  - Load pattern applied using a **linear time series** and **Plain pattern**, with **vertical point load** applied at the **top-left node**.
  - The lean-on column and the beam with 10X properties are also added with lu mped mass on right top most (on the 3rd column) node.
- Recorders and Output:
  - Recorders were defined to track:
    - **Displacement of the top-right node**, and
    - **Support reactions** at base nodes.
- Analysis Setup:
  - Performed a **static linear analysis** to verify model behavior under gravity load, validate element connectivity, and ensure correct stiffness distribution.

This simplified model served as a critical check for geometry, transformation settings, load a pplication, and data recording. It also helped in understanding the basic behavior of truss and frame action before progressing toward multi-story and nonlinear models.

Step 2: Modeling a Single-Bay, Nine-Story STMF

To scale up the complexity and simulate vertical behavior over multiple levels, a **single-bay, nine-story STMF** was developed. This step focused on automating geometry and expanding model depth while retaining linear-elastic material assumptions.

- **Number of Stories:** 9
- **Storey Heights:**
  - Heights were generated in an array as: 18, 18+14, 18+14+14, ...(ft) corresponding to one **18 ft** base story and **14 ft** uniform stories above.
- **Structural and Material Properties:**
  - All internal members (chords, verticals, diagonals) assumed **identical across floors** for simplicity.
  - Only the **extreme (main) columns** were assigned different properties to reflect higher strength demands.
  - Section **areas (A)** and **moments of inertia (I)** were stored in arrays for clean looping and assignment.
  - Steel material: **Elastic**, with E = 29007.6 ksi and Fy = 50 ksi (same as Step 1).
- **Geometric Transformation:**
  - **PDelta transformation** was used again to include geometric nonlinearity due to vertical deformations.
- **Model Generation:**
  - **Nodes and Coordinates** were defined using a structured loop.
  - Logical node naming ensured easy tracking of joint locations across stories.
  - **Boundary conditions**: Pin supports applied at all **base nodes**.
  - All structural elements were defined using **elasticBeamColumn** and created through automated loops.
- **Lean-On Column and Beam:**
  - A simplified **lean-on column** (modeling gravity frame effect) and a **beam support** were included.
  - Both were assigned **10□ the stiffness and cross-sectional properties** of the main frame to act as rigid followers.
- **Loading:**
  - A **vertical point load** was applied at the **top-left node of the column**, consistent with the format used in Step 1.
  - Load was defined using a **linear time series** and a **plain load pattern**

- **Recorders and Analysis:**
  - Recorders set to monitor:
    - **Displacement at the top node**, and
    - **Reaction forces** at base.
  - Performed a **static linear analysis** using standard OpenSees solver flow.
- **Visualization:**
  - Used **opsvis (or opsv)** for structure plotting.
  - Plotted both undeformed geometry and the applied load to verify overall mode l setup.

This model validated the logic and scalability of multi-story STMFs. It tested the use of loops for parametric modeling and enabled a clear transition toward nonlinear behavior in the next phase.

Step 3: Single-Bay, Single-Story Non-Linear Elastic Model

This step focused on transitioning to a **nonlinear analysis framework**, still using elastic mater ial behavior, but incorporating **force-based elements** and **section integration** to better capture member behavior and prepare for inelastic modeling.

- **Basic Inputs and Geometry:**
  - All **geometric parameters**, **material properties**, and **PDelta transformation** wer e retained from Step 1.
  - The model represented a **single-story, single-bay frame** for simplicity.
- **Beam Integration Setup:**
  - Used **Lobatto beam integration** with **5 integration points** per element to impro ve accuracy of force-based formulation.
  - This setup allows the model to better capture internal force distribution along each element.
- **Section Definition:**
  - Defined **six different 'elastic' sections** based on required combinations of **A** (ar ea) and **I** (moment of inertia).
  - These represent variations across chord members, verticals, diagonals, and lea n-on elements.
- **Model Construction:**
  - Nodes and elements were defined as **forceBeamColumn elements** to allow sect ion-level integration and prepare for inelastic behavior in future steps.
  - Added **lean-on column and supporting beam** similar to previous steps, with **10 times stiffness** to act as rigid boundary references.

- **Recorders and Analysis:**
  - Defined **recorder files** to track nodal displacements and reaction forces.
  - Analysis performed using:
    - **Numberer**: RCM (Reverse Cuthill-McKee) for efficient DOF ordering
    - **System**: BandGeneral
    - **Test**: NormDispIncr with a tolerance of **1e-6**
    - **Analysis type**: Static
- **Screen Output and Plotting:**
  - Included print statements for displacement values of key nodes.
  - Used **opsv plotting** for visual verification of model geometry and load applicat ion.

This step successfully implemented **force-based element modeling** with **section integration**, w hile still remaining within linear elastic bounds. It formed the technical groundwork for futur e incorporation of fiber-based inelastic sections and pushover analysis.

Step 4: Single-Bay, Single-Story Nonlinear Inelastic Model Using Fiber Sections

To simulate inelastic behavior and material yielding, this final modeling step used **fiber-based sections** along with **nonlinear material models**. This approach allows accurate capture of me mber-level plasticity under lateral or vertical loading.

- **Basic Inputs and Setup:**
  - All **geometric and structural parameters**, as well as **PDelta transformation** and **Lobatto integration with 5 points**, were retained from the previous step.
  - Material nonlinearity was introduced using **Steel02** model in OpenSees.
- **Steel02 Material Definition:**
  - Steel02 uniaxial material was used with the following assumed parameters:
    - **b** (strain hardening ratio), **R0**, **cR1**, and **cR2** were set to standard genera l values used in nonlinear modeling.
    - Yield strength (Fy) and elastic modulus (E) carried forward from earlie r steps.
- **Fiber Section Definition:**
  - All structural members were assumed to have **I-shaped cross-sections**.
  - A custom function was defined to calculate the **number of fibers** in each regi on (flange and web) based on geometric inputs such as flange width, flange thi ckness, and web height.
  - Each section was built using ops.section('Fiber', ...) with the following patches:

    - **Top flange**, **web**, and **bottom flange** modeled using ops.patch('rect', ...).
  - All fiber sections were generated using loops for efficiency and scalability.
- **Model Construction:**
  - Nodes and **forceBeamColumn elements** were defined exactly as in previous steps.
  - Lean-on column and rigid beam were again included using 10□ stiffness sections for stability.
- **Loading and Recorders:**
  - Vertical point load applied to the top-left node, similar to earlier models.
  - Recorders set up to capture:
    - Top node displacements
    - Base reactions
    - (Optionally) section deformation or fiber stress/strain outputs
- **Analysis Setup:**
  - Analysis type: **Static nonlinear**
  - Algorithm: **Newton** method (to accommodate convergence under nonlinear material response)
  - System, numberer, and test settings remained consistent with Step 3.
- **Screen Output and Visualization:**
  - Included print statements for nodal displacement and key force outputs.
  - Used **opsv plotting** to visualize undeformed geometry, loading, and deformed shape.

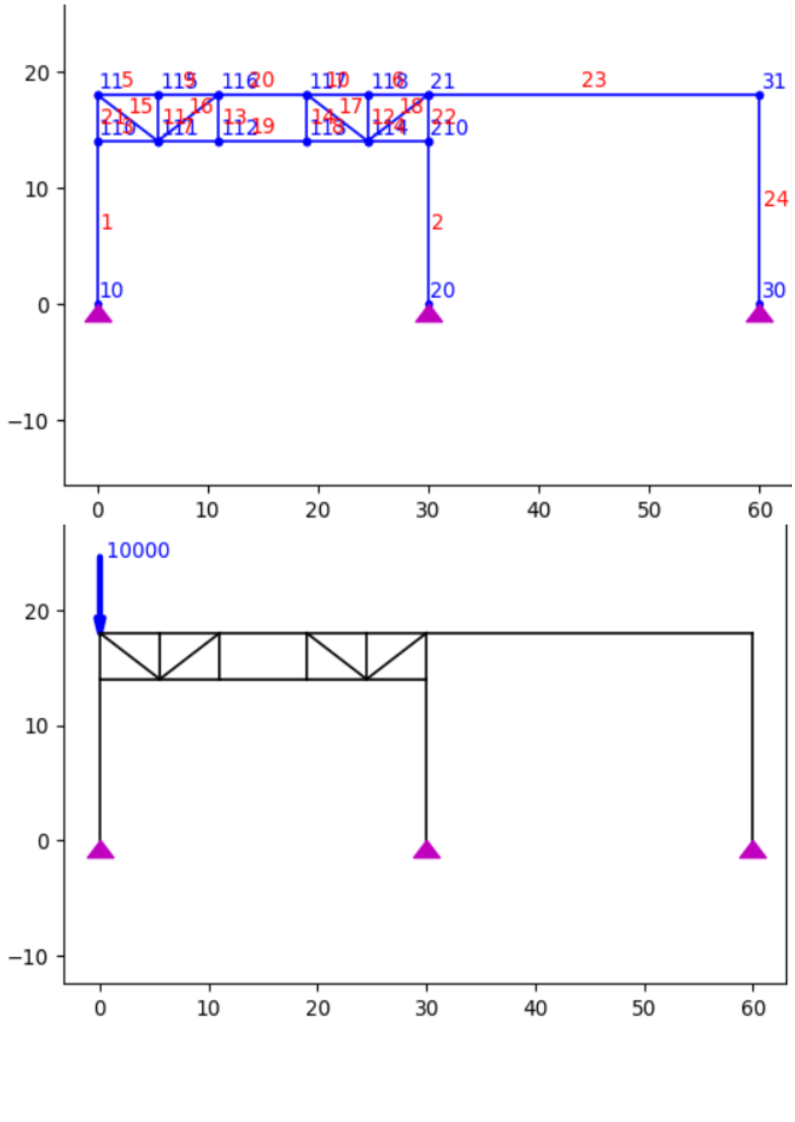
This step successfully implemented full **nonlinear inelastic fiber modeling** of a simplified frame. It established the workflow for defining custom fiber sections and capturing material yieldingósetting a foundation for scaling up to full 5-bay, multi-story STMF systems in future work.

Steps Remaining

With all the preliminary steps completed from modeling basic truss elements to building a single-bay, single-story nonlinear frame using fiber sectionsóI am now ready to extend the same modeling logic to the full **5-bay, 9-story STMF** structure as presented in **Example 12** of the reference paper. The overall plan is to follow the same modular and loop-based approach I used earlier. I will define all nodes and elements floor-wise and bay-wise using nested loops, carefully assigning coordinates based on story height and bay width. For each member (chord, vertical, and diagonal), I will assign fiber sections according to the cross-section data provided in the research paper, including cover plate adjustments in the special segments. The loads will be distributed proportionally across the structure to match the total building weight, and the boundary conditions will reflect fixed or pinned supports at the base columns. I will include lean-on columns as done before, and ensure that the PDelta transformation and nonlinear ma terial definitions are properly applied. Recorders will be placed at critical nodes and base supports to monitor displacement, drift, and reactions. While the coding structure is largely in place and tested through smaller models, the full integration of all components for the 5-bay, 9-story frame is currently **in progress**. With the core framework established, the final model will be ready soon for complete nonlinear static analysis, and possibly pushover simulations to assess its seismic performance in line with the design goals of Special Truss Moment Frames.

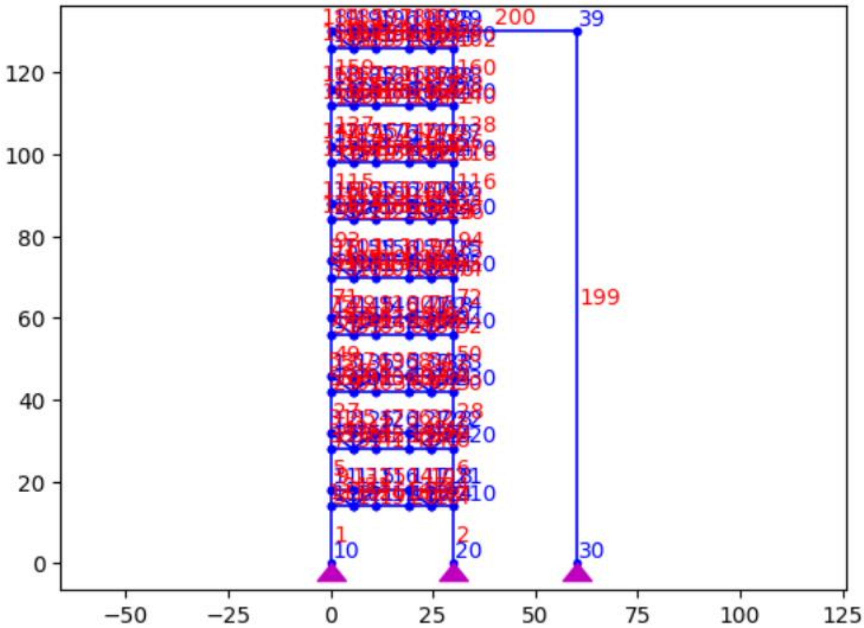
DISCUSSIONS

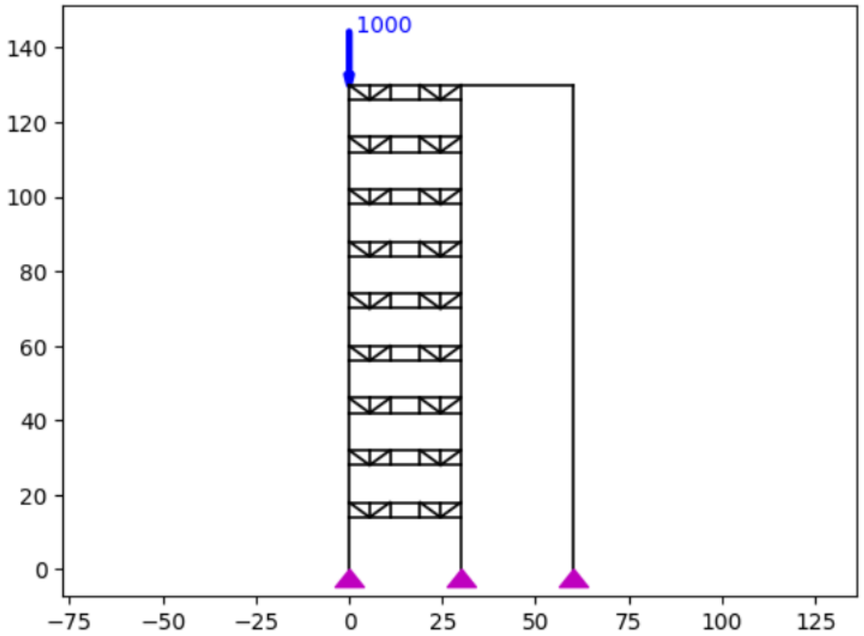
Single-Bay, Single-Story STMF



In the **first step**, where a single-bay, single-story model was created using linear elastic elements, the structure showed expected behavior under gravity load. Displacements were small, and the overall force distribution matched basic statics. This step was primarily used to verify that the model geometry, support conditions, and element connectivity were working correctly.

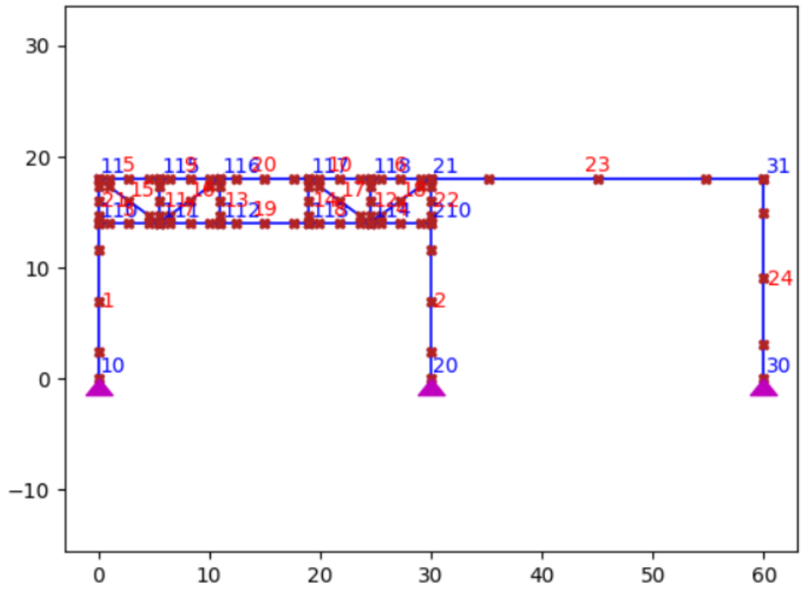
Single-Bay, Nine-Story STMF

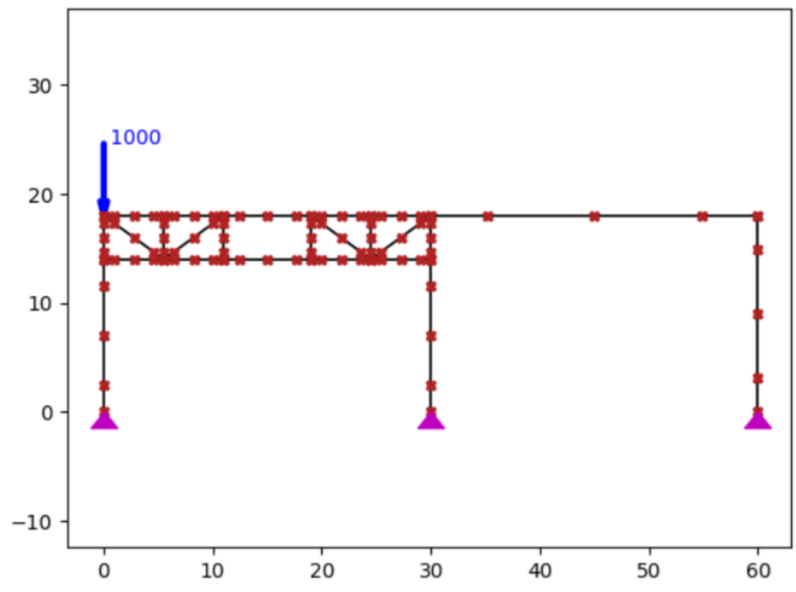




The **second step**, involving a nine-story frame, revealed the impact of adding vertical continuity and multiple load paths. Displacements increased with height, and the top node showed significant movement under the same load compared to the single-story frame. The inclusion of multiple levels helped visualize how stiffness accumulates across stories and how lateral stability is distributed in taller structures. It also confirmed that loop-based modeling was scalable and effective.

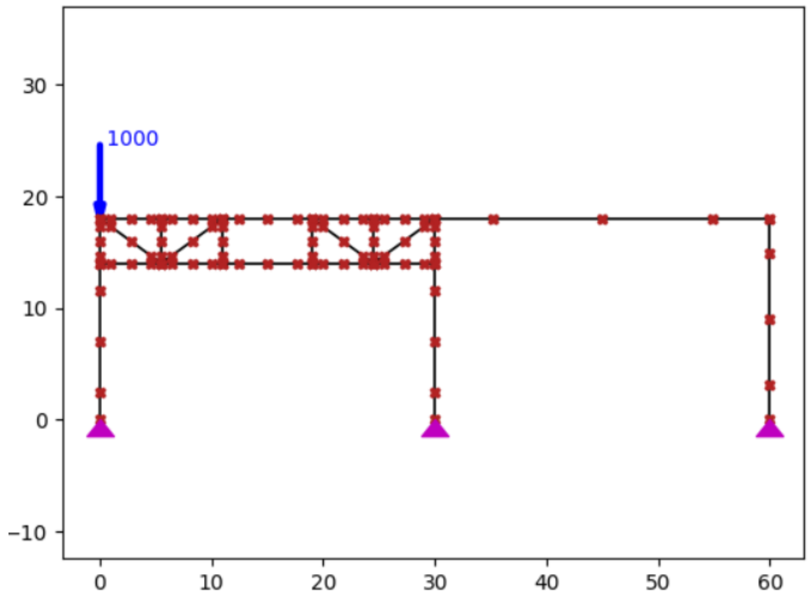
Single-Bay, Single-Story Non-Linear Elastic Model

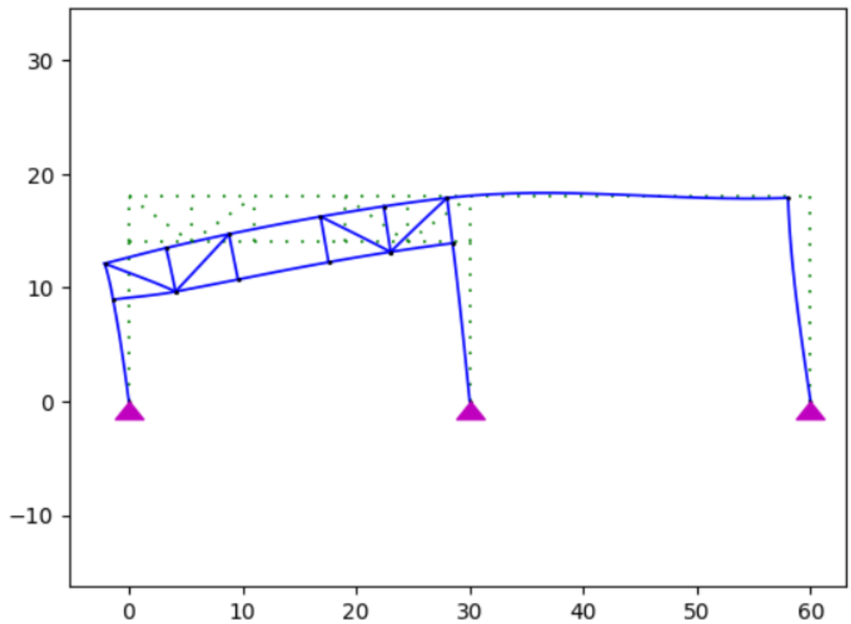




In the **third step**, switching to **force-based elements with section integration**, the internal behavior of members became more detailed. The model captured gradual changes in force along the length of each element, and the Lobatto integration allowed for better accuracy in simulating flexural effects. The overall displacement patterns remained similar to the elastic models, but the internal force diagrams were smoother and more realistic.

Single-Bay, Single-Story Nonlinear Inelastic Model Using Fiber Sections





Finally, in the **fourth step**, the inclusion of **nonlinear fiber sections** introduced material yieldi ng. Although the structure remained stable under the applied vertical load, local nonlinearity could be observed in the chord and web regions, especially within the special segment. This c onfirmed that the fiber-based approach can capture progressive inelastic behavior, setting the stage for more advanced analyses such as pushover or cyclic loading. The use of Steel02 mat erial also demonstrated how the model would respond post-yield, with stiffness reduction and redistribution of forces across the frame.

Overall, the results across steps showed a clear progressionófrom idealized linear behavior to more realistic nonlinear responseómirroring the increasing fidelity and complexity of the mo dels. This step-by-step approach helped build confidence in both the modeling process and th e structural performance outcomes.

CONCLUSION

This project focused on learning how to model and analyze Special Truss Moment Frames (STMFs) using **OpenSeesPy**, starting from basic structural elements and gradually moving toward more complex systems. I began with simple, single-story and single-bay frames to understand the software, define elements, and test loading and boundary conditions. With each step, I increased the complexityófirst by extending the model to multiple stories, then switching to more advanced element types like force-based elements and nonlinear fiber sections. These stages helped me understand not just the coding in OpenSeesPy, but also the structural behavior of frames under different conditions. The nonlinear fiber model, in particular, showed how yielding and inelastic behavior can be realistically captured in key members like chords and diagonals.

Now, with the basic framework ready and tested, I am in the final stages of applying all these learnings to build the complete **5-bay, 9-story STMF** model based on the example in the research paper. The coding strategy is clearóusing loops for geometry, defining fiber sections based on real member data, and applying proper transformations and analysis algorithms. The work is currently **in progress**, and the final model will allow for a complete nonlinear static analysis, making it possible to study the seismic performance of the structure in detail. This step-by-step process has not only helped in mastering OpenSees but also built a deeper understanding of how STMFs are designed to behave during earthquakes.

I am attaching all the code files along with the mail.

REFERENCES

Lecture videos for learning OpenSees:
https://1drv.ms/f/c/c199b86934d379e8/EqDTcJky6E1ErZYyfRdYrDQBejVwmhfAYoEOG7yITit0Zw?e=wrMHQY

Research Paper:
Performance-Based Plastic Design of Special Truss Moment Frames

PERFORMANCE-BASED PLASTIC DESIGN OF SEISMIC RESISTANT SPECIAL TRUSS MOMENT FRAMES by Shih-Ho Chao & Subhash C. Goel