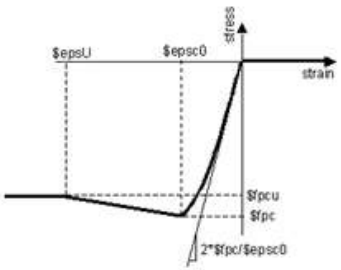
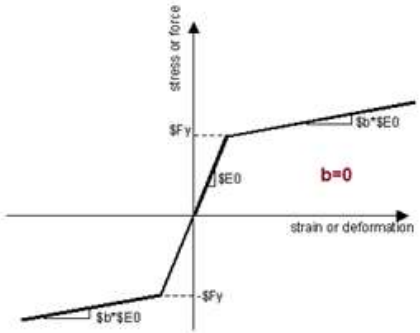
IN THE NAME OF ALLAH, THE MOST GRACIOUS, THE MOST MERCIFUL

COMPARATIVE ANALYSIS OF AXIAL FORCE-MOMENT (P-M) INTERACTION BEHAVIOR IN CONFINED REINFORCED CONCRETE CROSS-SECTIONS: EVALUATING STRAIN HARDENING EFFECTS AND ULTIMATE STRAIN CRITERIA

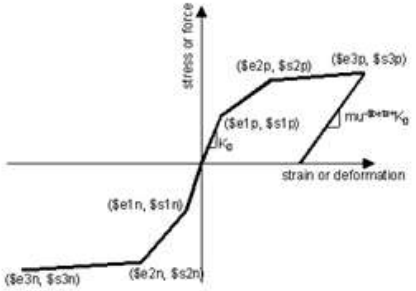
WRITTEN BY SALAR DELAVAR GHASHGHAEI (QASHQAI)



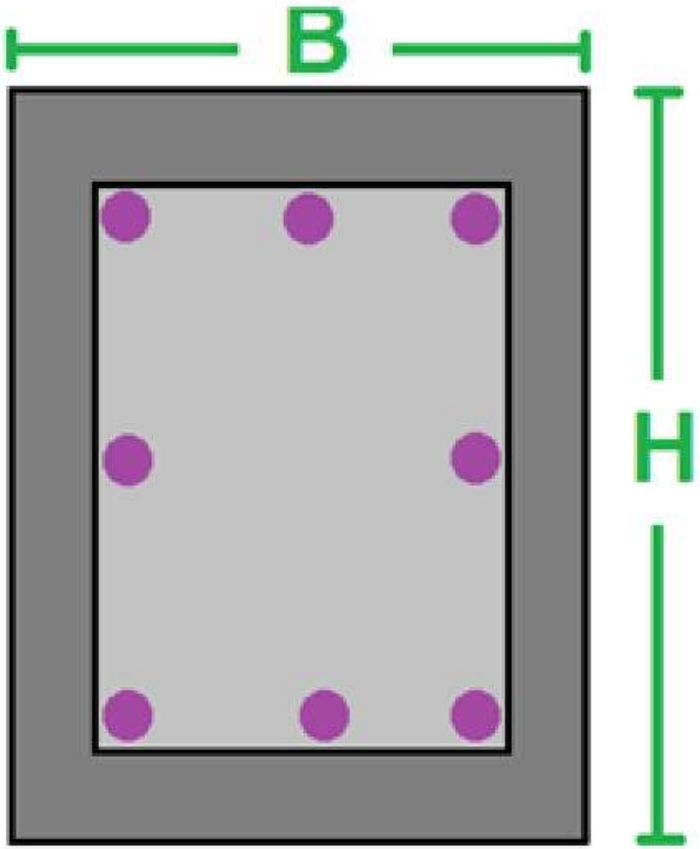
CORE AND COVER CONCRETE RELATION



WITHOUT HARDENING AND ULTIMATE STRAIN



WITH HARDENING AND ULTIMATE STRAIN



Spyder (Python 3.12)

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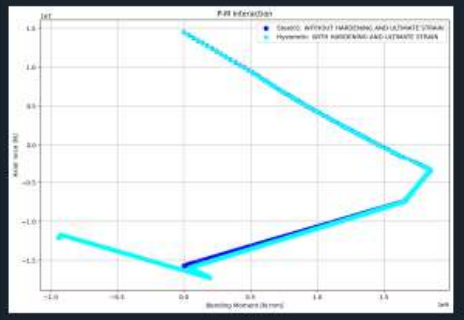
C:\Users\Dell\Desktop\OPENSEES_FILES\P-M_INTERACTION\CONCRETE

C:\Users\Dell\Desktop\OPENSEES_FILES\P-M_INTERACTION\CONCRETE\P-M_INTERACTION_CONCRETE.py

P-M_INTERACTION_CONCRETE.py

```
##########################################################################################################
#                >> IN THE NAME OF ALLAH, THE MOST GRACIOUS, THE MOST MERCIFUL <<                        #
#             COMPARATIVE ANALYSIS OF AXIAL FORCE-MOMENT (P-M) INTERACTION BEHAVIOR IN CONFINED           #
#  REINFORCED CONCRETE CROSS-SECTIONS: EVALUATING STRAIN HARDENING EFFECTS AND ULTIMATE STRAIN CRITERIA   #
#--------------------------------------------------------------------------------------------------------#
#                          THIS PROGRAM WRITTEN BY SALAR DELAVAR GHASHGHAEI (QASHQAI)                    #
#                                   EMAIL: salar.d.ghashghaei@gmail.com                                  #
##########################################################################################################
"""
Performs a comparative analysis of reinforced concrete columns' axial force-moment (P-M)
 interaction behavior using OpenSeesPy.

1. Objective:
    Evaluates how steel reinforcement strain hardening and ultimate strain criteria affect P-M
    interaction capacity, crucial for seismic design where ductility matters.

2. Materials:
   - Concrete: Confined (core) and unconfined (cover) modeled with `Concrete01` material laws.
   - *Steel: Two models - `Steel01` (elastic-perfectly plastic) vs. `Hysteretic` (includes hardening & fracture).

3. Section Modeling: Creates a rectangular RC cross-section with fiber discretization. Core concrete is confined,
 cover concrete unconfined, with rebars placed at edges and mid-depth.

4. Analysis Method: Uses a displacement-controlled approach to simulate increasing curvature/strain. For each stre
   - Applies strain compatibility (plane sections remain plane)
   - Computes axial force (P) and moment (M) using nonlinear static analysis.

5. Key Outputs:
   - P-M interaction diagrams
   - Moment-curvature relationships
   - Neutral axis depth trends
   - Flexural rigidity (EI) variations

6. Comparison: Contrasts two steel models:
```

20 %



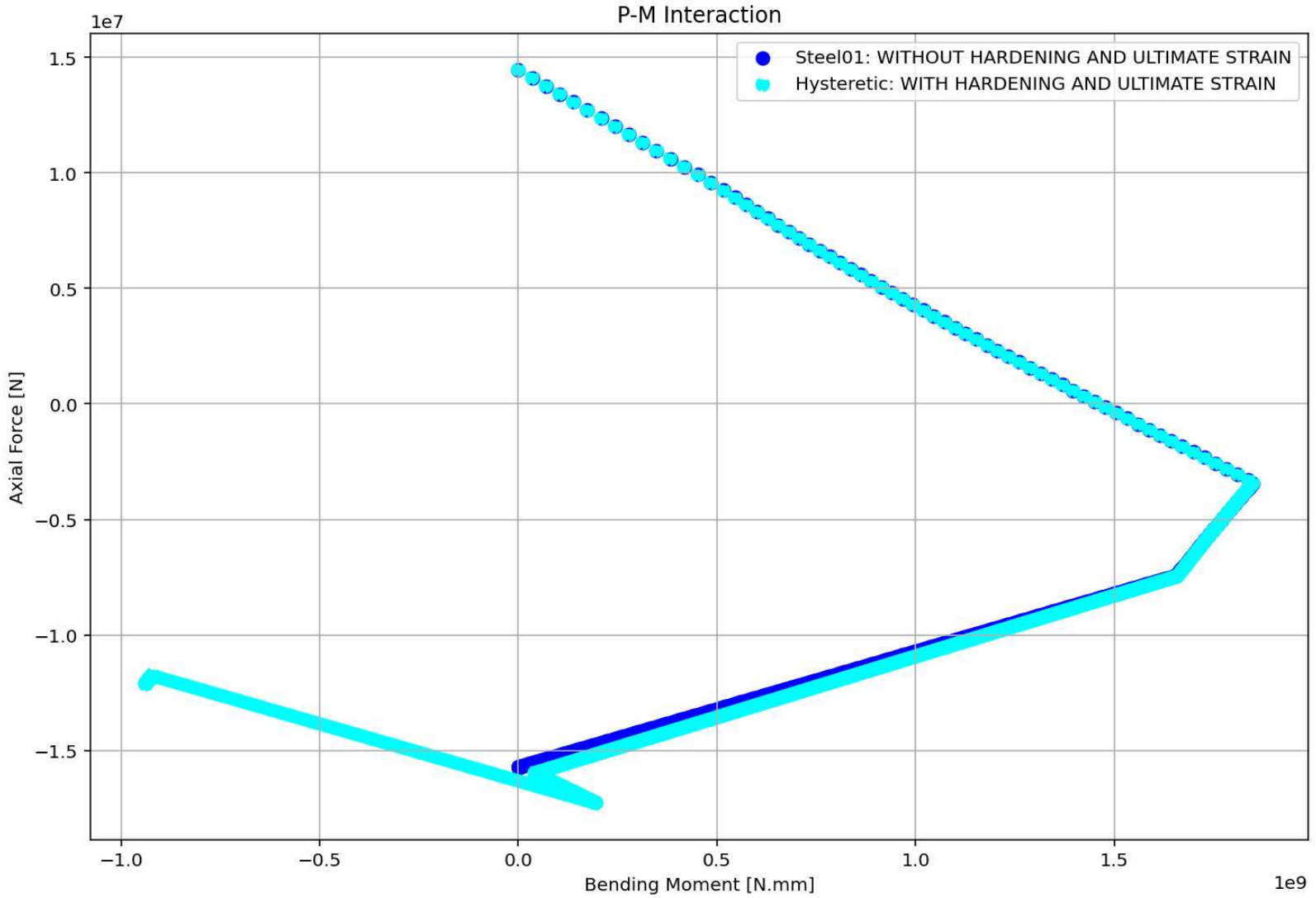
Help Variable Explorer Debugger Plots Files

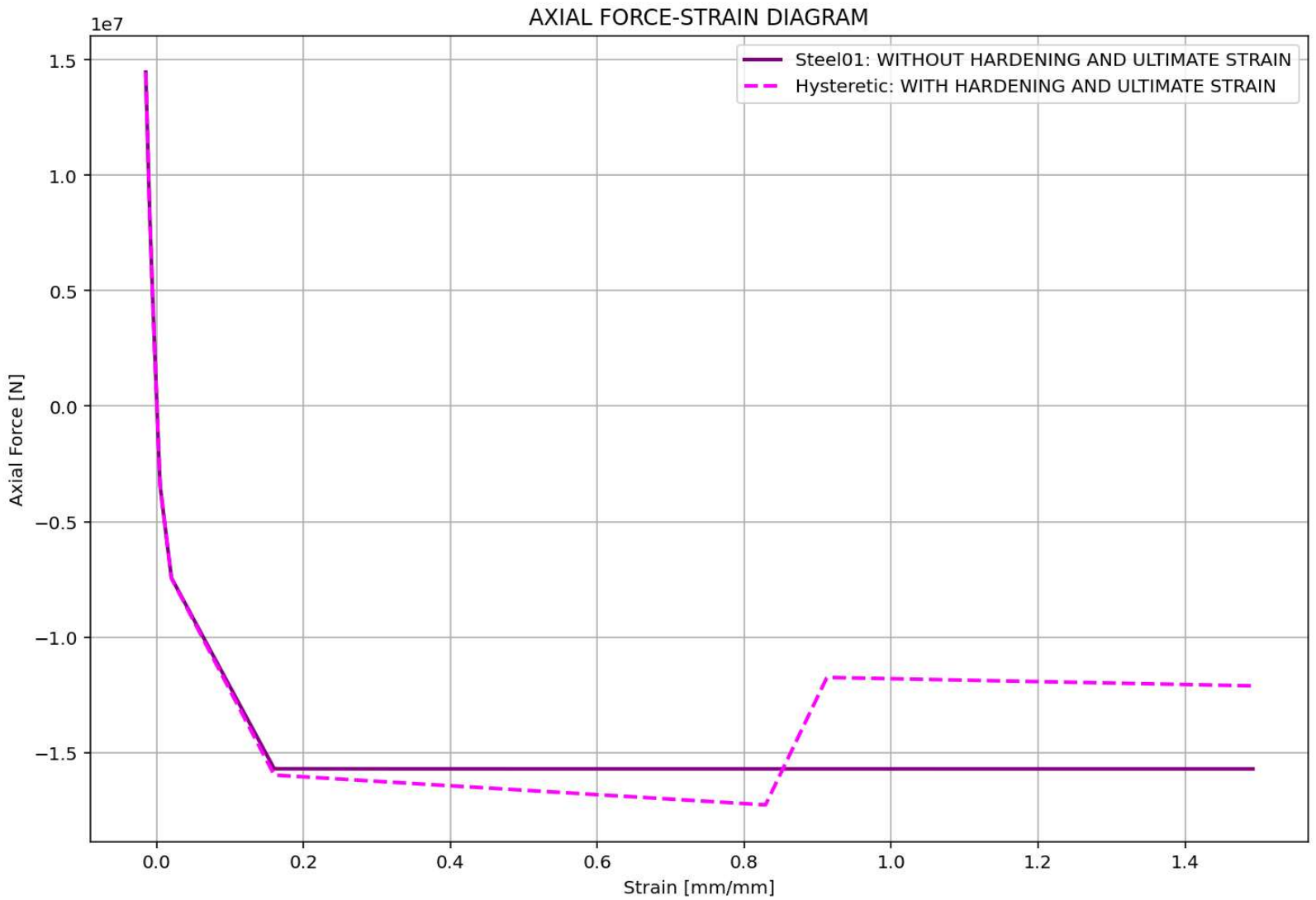
Console 1/A

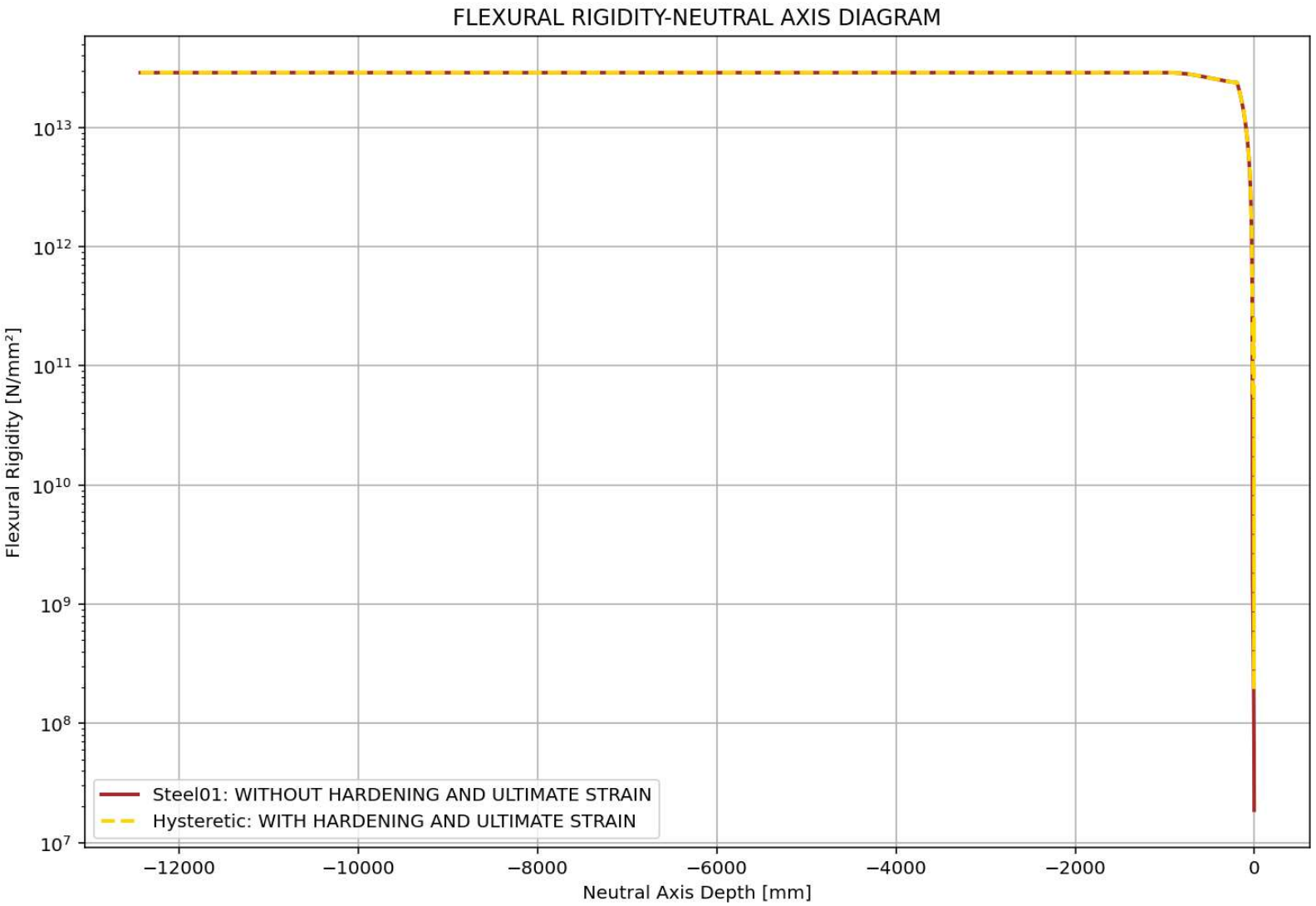
```
c:\users\dell\desktop\opensees_files\p-
m_interaction\concrete\p-m_interaction_concrete.py:166:
RuntimeWarning: divide by zero encountered in scalar
divide
  x = ECU / Z  # Neutral Axis Depth
c:\users\dell\desktop\opensees_files\p-
m_interaction\concrete\p-m_interaction_concrete.py:185:
RuntimeWarning: invalid value encountered in scalar divide
  EI.append(np.abs(m)/np.abs(cur))

In [2]:
```

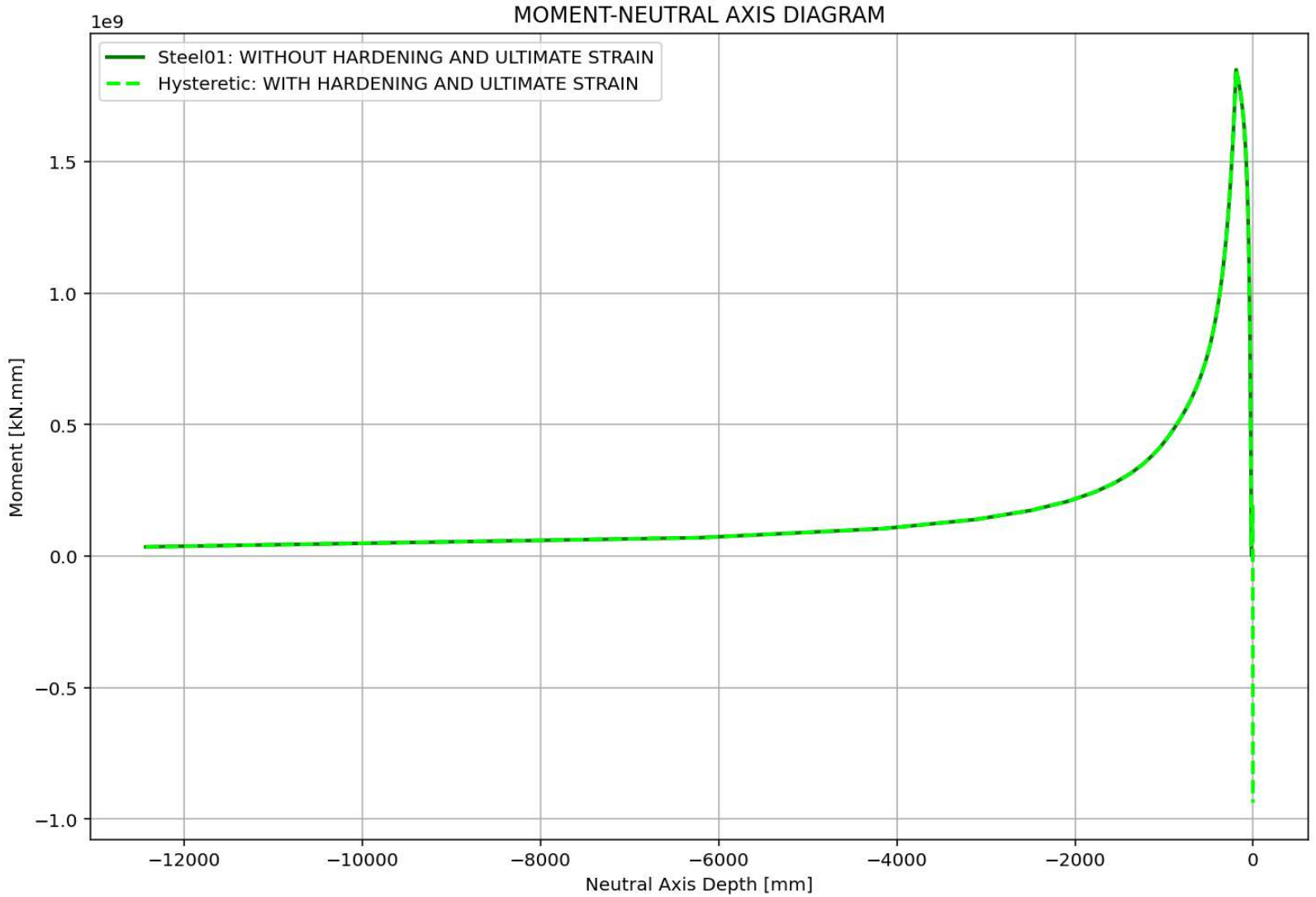
IPython Console History

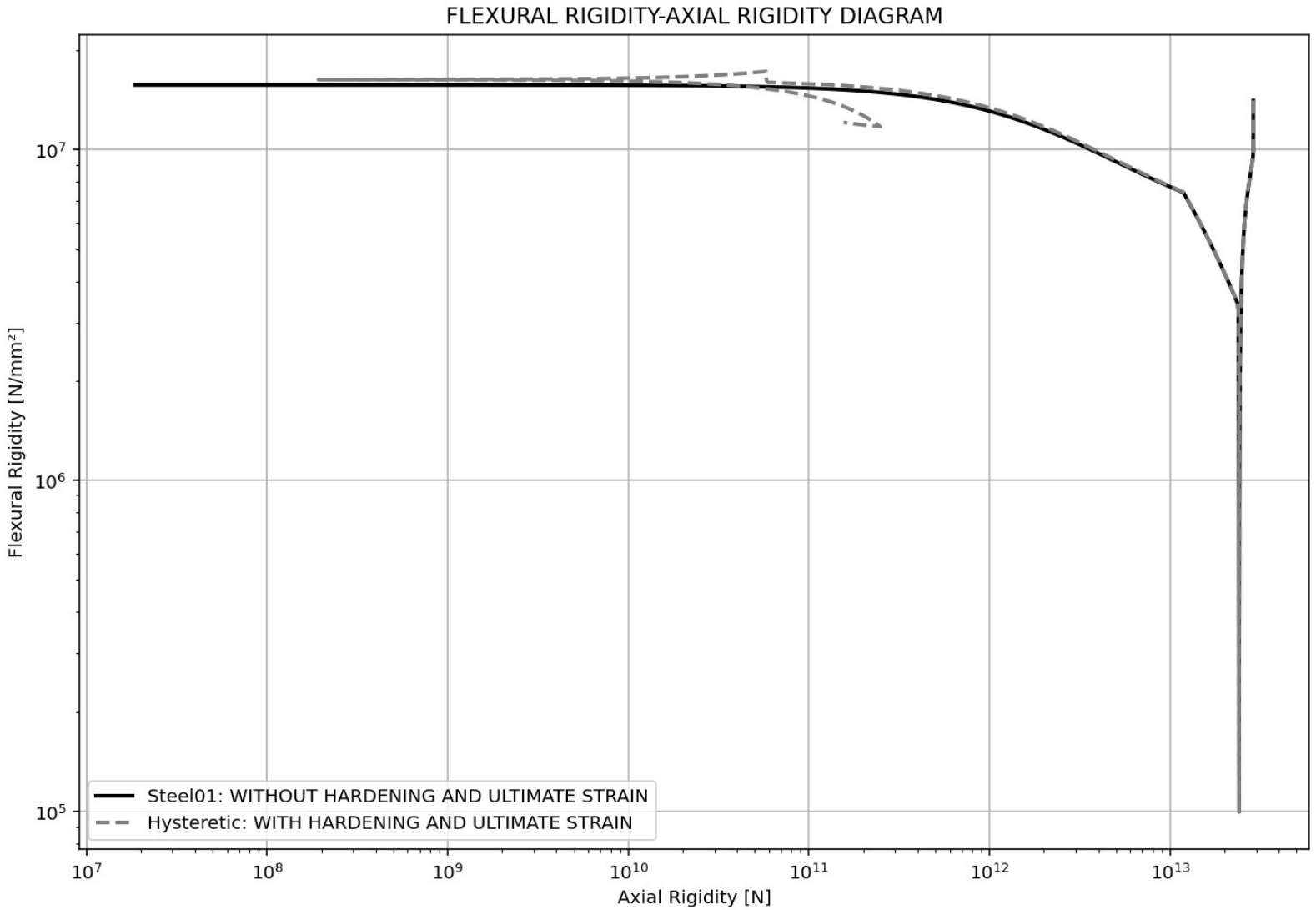
Inline Conda: anaconda3 (Python 3.12.7) LSP: Python Line 2, Col 19 UTF-8 CRLF RW Mem 35%


P-M Interaction
1e7
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
Axial Force [N]
Steel01: WITHOUT HARDENING AND ULTIMATE STRAIN
Hysteretic: WITH HARDENING AND ULTIMATE STRAIN
−1.0
−0.5
0.0
0.5
1.0
1.5
Bending Moment [N.mm]
1e9


AXIAL FORCE-STRAIN DIAGRAM
1e7
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
Axial Force [N]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Strain [mm/mm]
Steel01: WITHOUT HARDENING AND ULTIMATE STRAIN
Hysteretic: WITH HARDENING AND ULTIMATE STRAIN


FLEXURAL RIGIDITY-NEUTRAL AXIS DIAGRAM
Flexural Rigidity [N/mm²]
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
−12000
−10000
−8000
−6000
−4000
−2000
0
Neutral Axis Depth [mm]
Steel01: WITHOUT HARDENING AND ULTIMATE STRAIN
Hysteretic: WITH HARDENING AND ULTIMATE STRAIN


MOMENT-NEUTRAL AXIS DIAGRAM
1e9
Steel01: WITHOUT HARDENING AND ULTIMATE STRAIN
Hysteretic: WITH HARDENING AND ULTIMATE STRAIN
Moment [kN.mm]
1.5
1.0
0.5
0.0
−0.5
−1.0
−12000
−10000
−8000
−6000
−4000
−2000
0
Neutral Axis Depth [mm]


FLEXURAL RIGIDITY-AXIAL RIGIDITY DIAGRAM
Flexural Rigidity [N/mm²]
Axial Rigidity [N]
10^7
10^6
10^5
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
Steel01: WITHOUT HARDENING AND ULTIMATE STRAIN
Hysteretic: WITH HARDENING AND ULTIMATE STRAIN