Tutorial 2:
Cross-section stability of a W36x150

Exploring higher modes, and the interaction of buckling modes

prepared by Ben Schafer, Johns Hopkins University, version 1.0

Acknowledgments

- Preparation of this tutorial was funded in part through the AISC faculty fellowship program.
- Views and opinions expressed herein are those of the author, not AISC.

Target audience

- This tutorial is targeted at the advanced undergraduate/beginning graduate level. Some familiarity with structural stability is assumed in the provided discussion.
- It is also assumed that Tutorial #1 has been completed and thus some familiarity with the use of CUFSM is assumed.

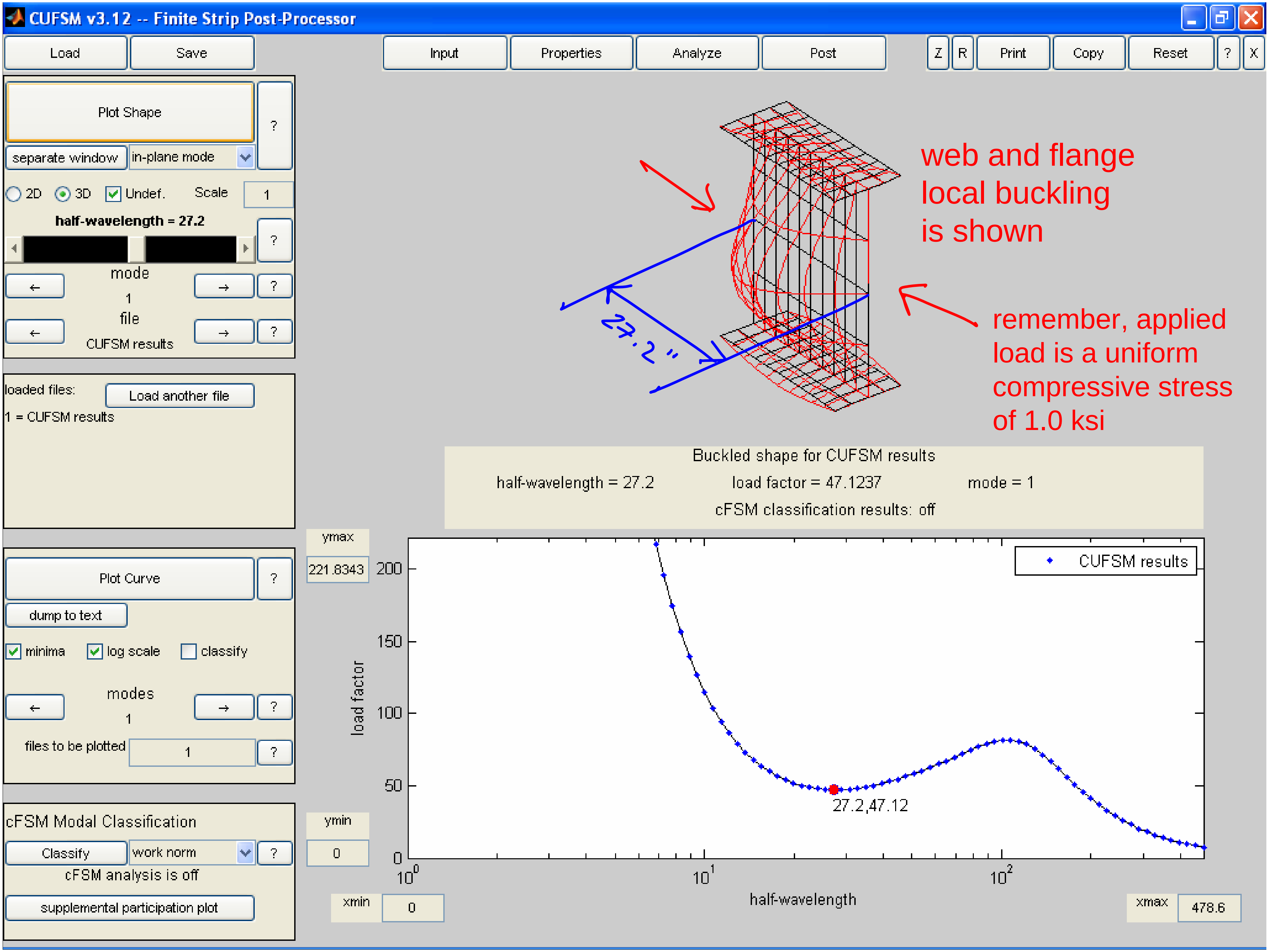
Learning objectives

- Understand the role of “higher” buckling modes in the analysis of a W-section, including
  - how higher buckling modes relate to strong-axis, weak-axis, and torsional buckling in columns
  - what higher buckling modes mean for local buckling
  - when knowledge of higher buckling modes may be useful in design
- Understand how interaction of modes may be identified and quantified using CUFSM for a W-section

Summary of Tutorial #1

- A W36x150 beam was analyzed using the finite strip method available in CUFSM for pure compression and major axis bending.
- For pure compression local buckling and flexural buckling were identified as the critical buckling modes.
- For major axis bending local buckling and lateral-torsional buckling were identifies as the critical bucklig modes.

W36x150 column – review of Tutorial 1


CUFSM v3.12 -- Finite Strip Post-Processor
Load
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Analyze
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Plot Shape
separate window
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2D
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Undef.
Scale
1
half-wavelength = 27.2
mode
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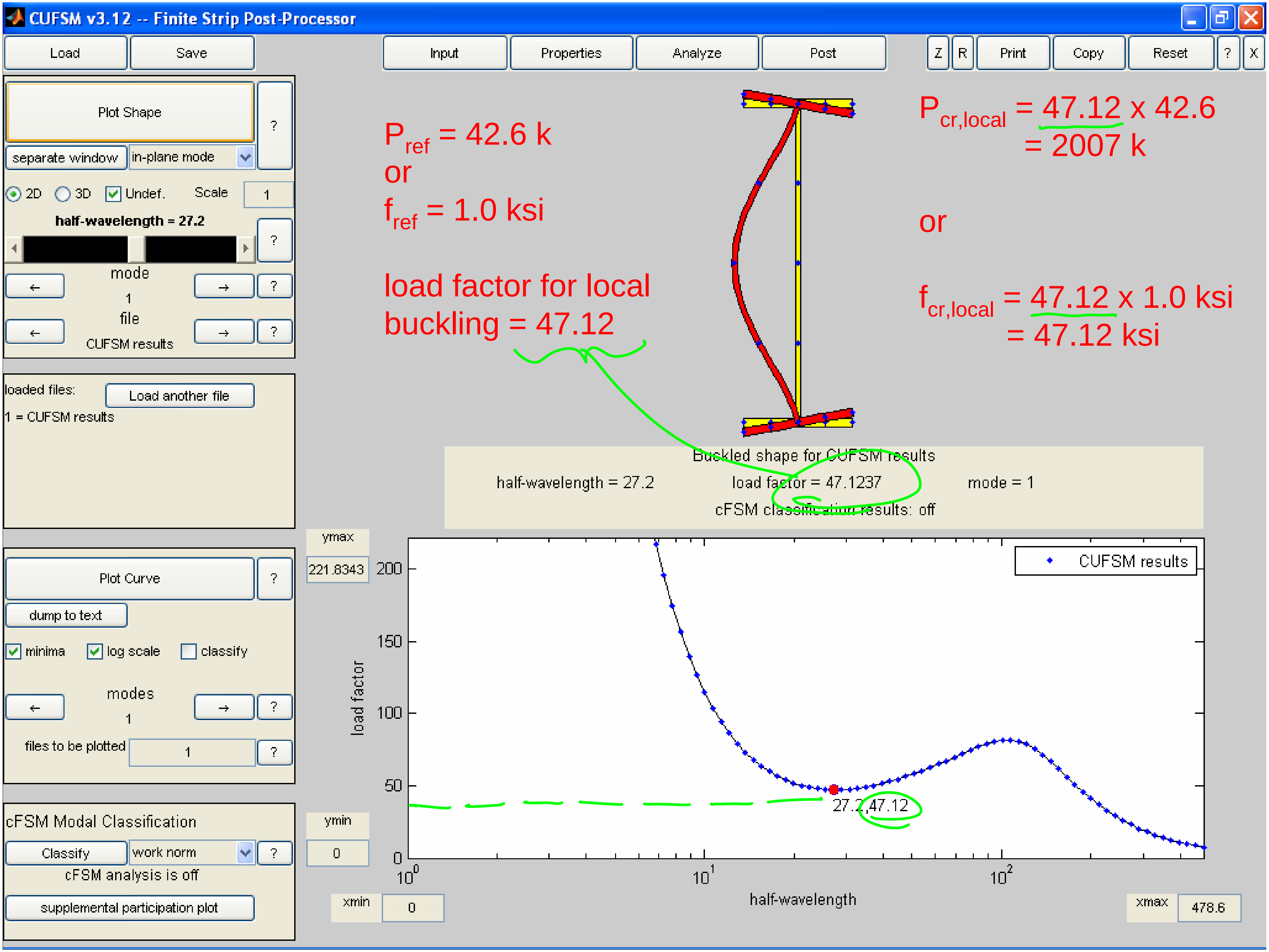
file
CUFSM results
loaded files:
Load another file
1 = CUFSM results
Plot Curve
dump to text
minima
log scale
classify
modes
1
files to be plotted
1
cFSM Modal Classification
Classify
work norm
cFSM analysis is off
supplemental participation plot
web and flange local buckling is shown
27.2"
remember, applied load is a uniform compressive stress of 1.0 ksi
Buckled shape for CUFSM results
half-wavelength = 27.2
load factor = 47.1237
mode = 1
cFSM classification results: off
ymax
221.8343
ymin
0
load factor
CUFSM results
27.2,47.12
half-wavelength
xmin
0
xmax
478.6


CUFSM v3.12 -- Finite Strip Post-Processor
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Plot Shape
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in-plane mode
2D
3D
Undef.
Scale
1
half-wavelength = 27.2
mode
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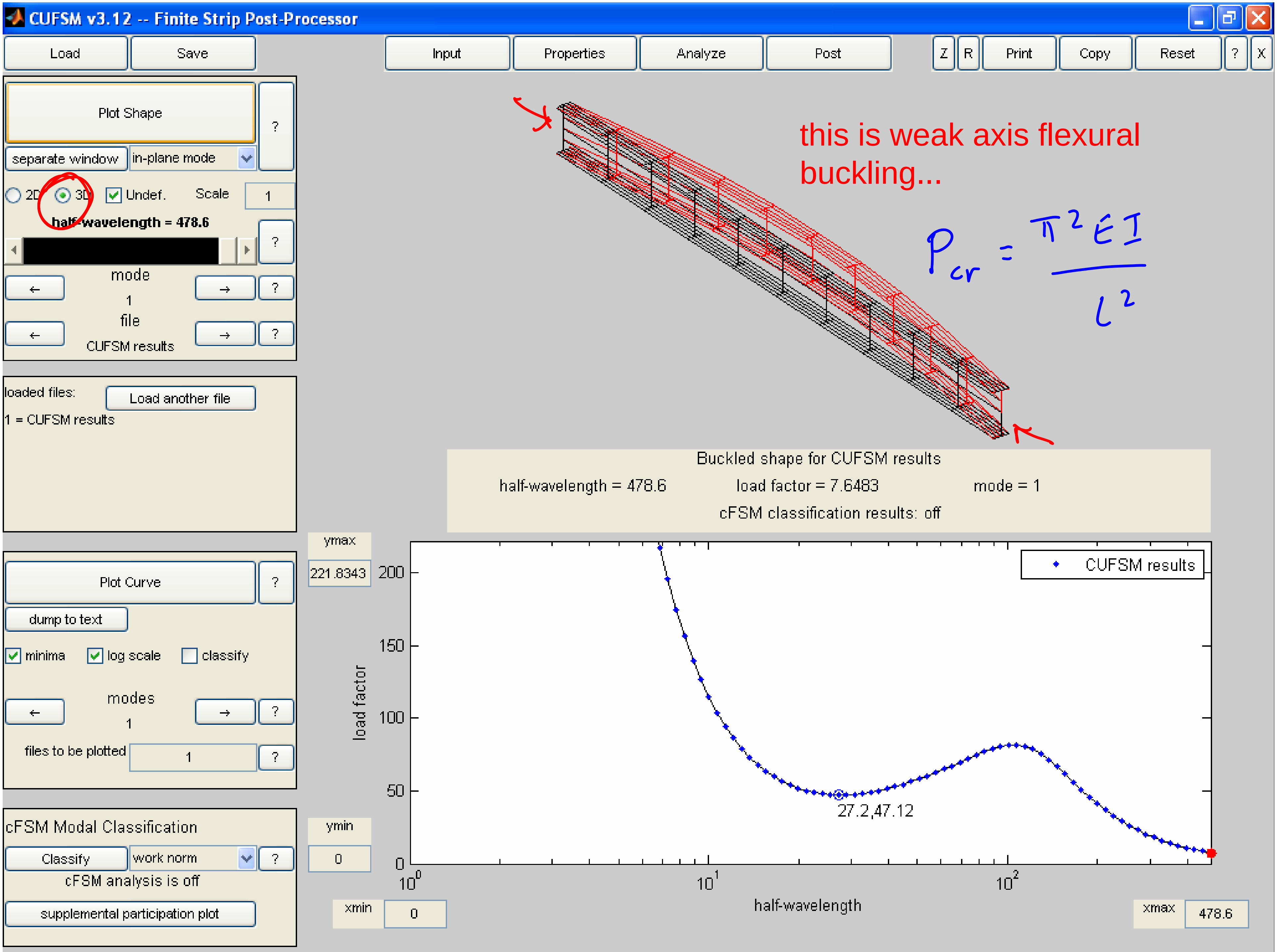
file
CUFSM results
loaded files:
Load another file
1 = CUFSM results
Plot Curve
dump to text
minima
log scale
classify
modes
1
files to be plotted
1
cFSM Modal Classification
Classify
work norm
cFSM analysis is off
supplemental participation plot
P_ref = 42.6 k
or
f_ref = 1.0 ksi
load factor for local buckling = 47.12
P_cr,local = 47.12 x 42.6
= 2007 k
or
f_cr,local = 47.12 x 1.0 ksi
= 47.12 ksi
Buckled shape for CUFSM results
half-wavelength = 27.2
load factor = 47.1237
mode = 1
cFSM classification results: off
ymax
221.8343
ymin
0
load factor
CUFSM results
27.2,47.12
half-wavelength
xmin
0
xmax
478.6


CUFSM v3.12 -- Finite Strip Post-Processor
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Plot Shape
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Scale
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half-wavelength = 478.6
mode
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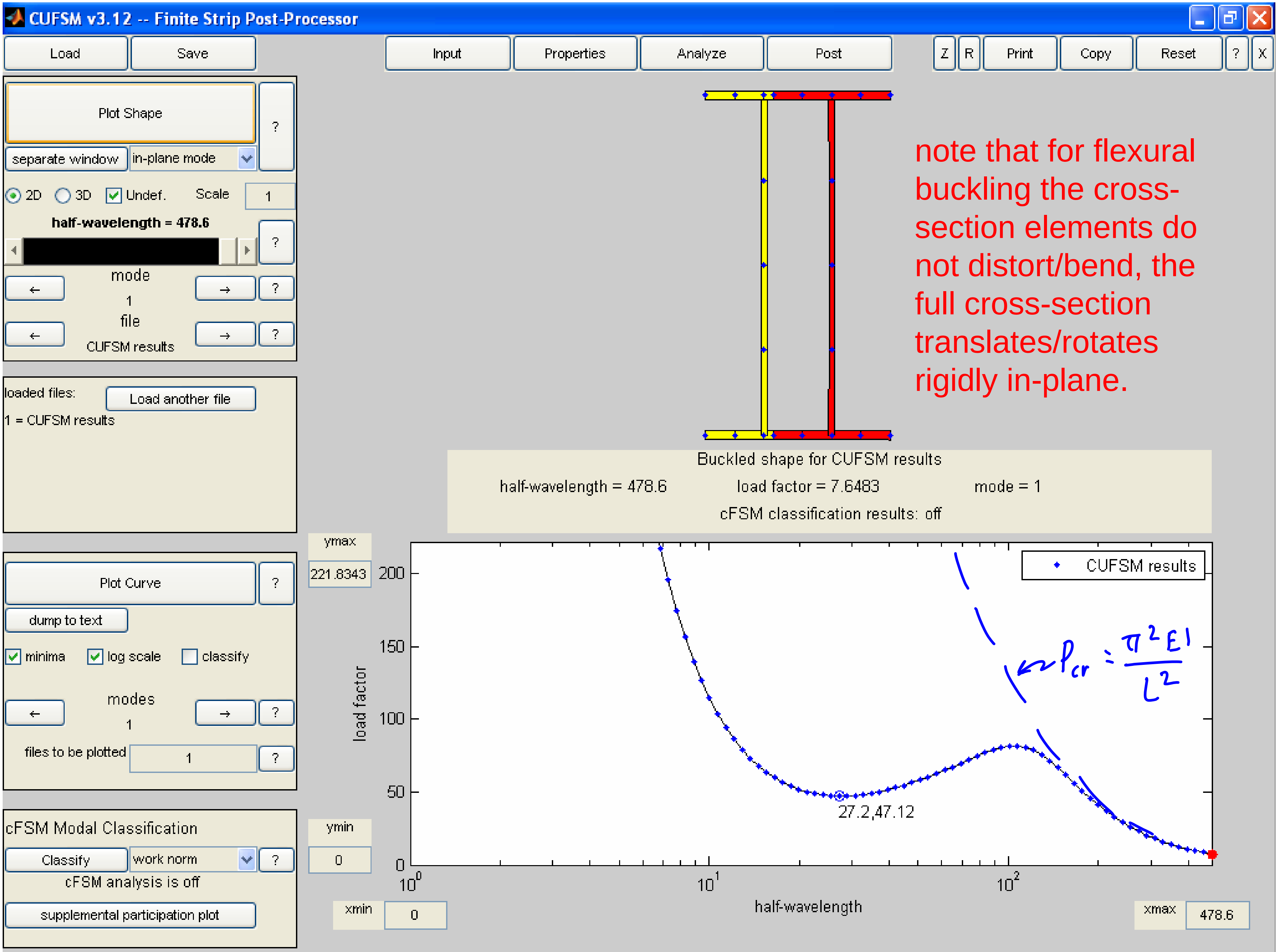
file
CUFSM results
loaded files:
Load another file
1 = CUFSM results
this is weak axis flexural buckling...
P_cr = π^2 EI / L^2
Buckled shape for CUFSM results
half-wavelength = 478.6
load factor = 7.6483
mode = 1
cFSM classification results: off
Plot Curve
dump to text
minima
log scale
classify
modes
1
files to be plotted
1
cFSM Modal Classification
Classify
work norm
cFSM analysis is off
supplemental participation plot
ymax
221.8343
ymin
0
xmin
0
xmax
478.6
CUFSM results
load factor
half-wavelength
27.2,47.12
200
150
100
50
0
10^0
10^1
10^2


CUFSM v3.12 -- Finite Strip Post-Processor
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Plot Shape
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half-wavelength = 478.6
mode
1
file
CUFSM results
loaded files:
Load another file
1 = CUFSM results
Plot Curve
dump to text
minima
log scale
classify
modes
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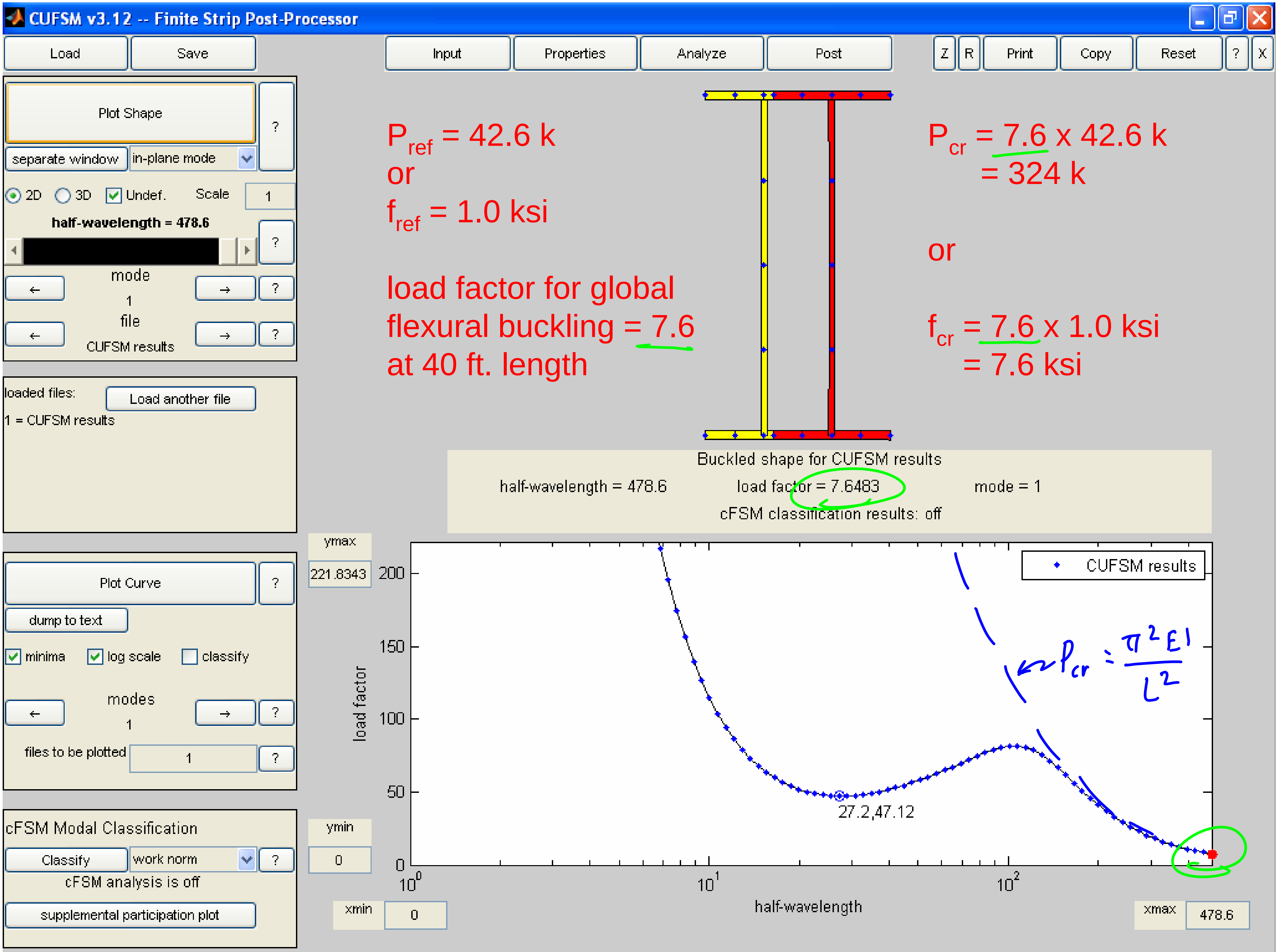
files to be plotted
1
cFSM Modal Classification
Classify
work norm
cFSM analysis is off
supplemental participation plot
note that for flexural buckling the cross-section elements do not distort/bend, the full cross-section translates/rotates rigidly in-plane.
Buckled shape for CUFSM results
half-wavelength = 478.6
load factor = 7.6483
mode = 1
cFSM classification results: off
ymax
221.8343
ymin
0
xmin
0
xmax
478.6
load factor
half-wavelength
CUFSM results
27.2,47.12
$P_{cr} = \frac{\pi^2 EI}{L^2}$



CUFSM v3.12 -- Finite Strip Post-Processor
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Plot Shape
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Scale
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half-wavelength = 478.6
mode
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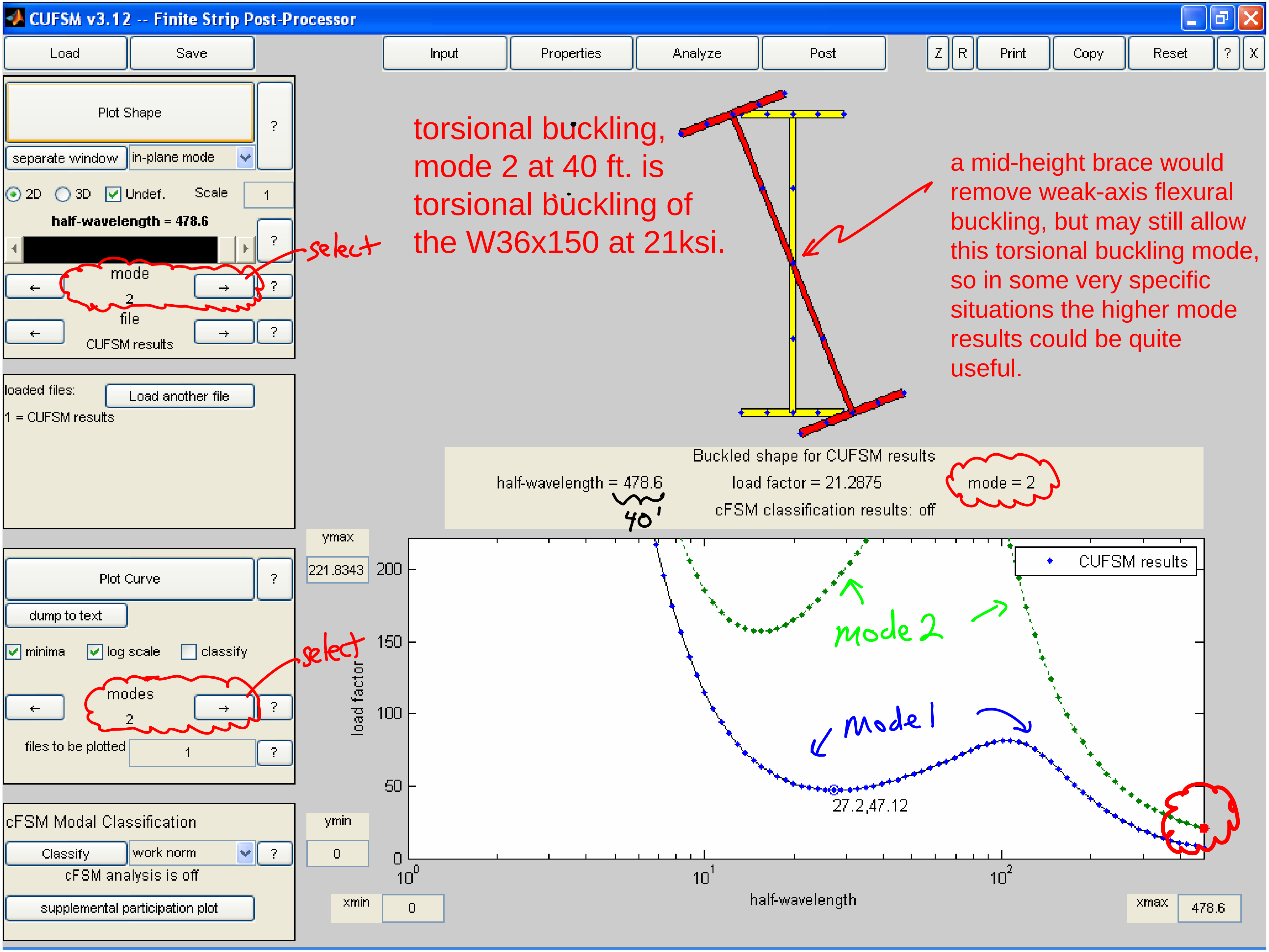
CUFSM results
loaded files:
Load another file
1 = CUFSM results
Plot Curve
dump to text
minima
log scale
classify
modes
1
files to be plotted
1
cFSM Modal Classification
Classify
work norm
cFSM analysis is off
supplemental participation plot
P_ref = 42.6 k
or
f_ref = 1.0 ksi
load factor for global flexural buckling = 7.6 at 40 ft. length
P_cr = 7.6 x 42.6 k
= 324 k
or
f_cr = 7.6 x 1.0 ksi
= 7.6 ksi
Buckled shape for CUFSM results
half-wavelength = 478.6
load factor = 7.6483
mode = 1
cFSM classification results: off
ymax
221.8343
ymin
0
xmin
0
xmax
478.6
load factor
half-wavelength
CUFSM results
27.2,47.12
P_cr = π²EI / L²

Tutorial #1: Column summary

- A W36x150 under pure compression (a column) has two important cross-section stability elastic buckling modes
- (1) Local buckling which occurs at a stress of 47 ksi and may repeat along the length of a member every 27 in. (it’s half-wavelength)
- (2) Global flexural buckling, which for a 40 ft. long member occurs at a stress of 7.6 ksi (other member lengths may be selected from the curve provided from the analysis results)

Higher modes

- We know global buckling of a column has more than one mode.. for instance the buckling can occur about the strong or weak axis: $P_{cr1} = \frac{\pi^2 E I_y}{L^2}$ $P_{cr2} = \frac{\pi^2 E I_x}{L^2}$ ....
- How is this reflected in CUFSM?
- Let’s investigate higher modes...



CUFSM v3.12 -- Finite Strip Post-Processor
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Plot Shape
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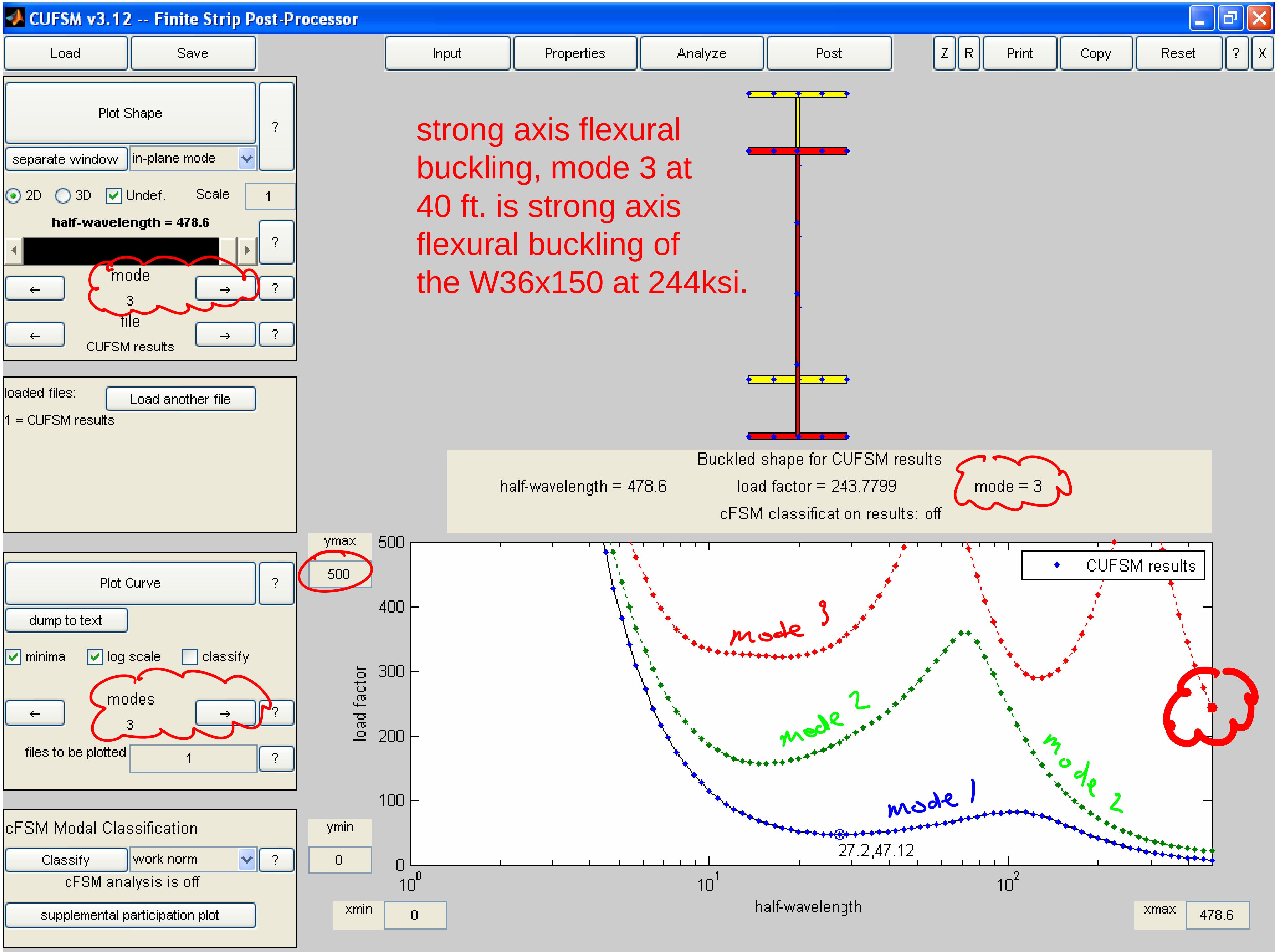
Scale
1
half-wavelength = 478.6
mode
2
file
CUFSM results
select
loaded files:
Load another file
1 = CUFSM results
Plot Curve
dump to text
minima
log scale
classify
modes
2
files to be plotted
1
select
cFSM Modal Classification
Classify
work norm
cFSM analysis is off
supplemental participation plot
torsional buckling, mode 2 at 40 ft. is torsional buckling of the W36x150 at 21ksi.
a mid-height brace would remove weak-axis flexural buckling, but may still allow this torsional buckling mode, so in some very specific situations the higher mode results could be quite useful.
Buckled shape for CUFSM results
half-wavelength = 478.6
load factor = 21.2875
mode = 2
cFSM classification results: off
40'
ymax
221.8343
ymin
0
CUFSM results
mode 2
mode 1
27.2,47.12
load factor
half-wavelength
xmin
0
xmax
478.6


CUFSM v3.12 -- Finite Strip Post-Processor
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Plot Shape
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in-plane mode
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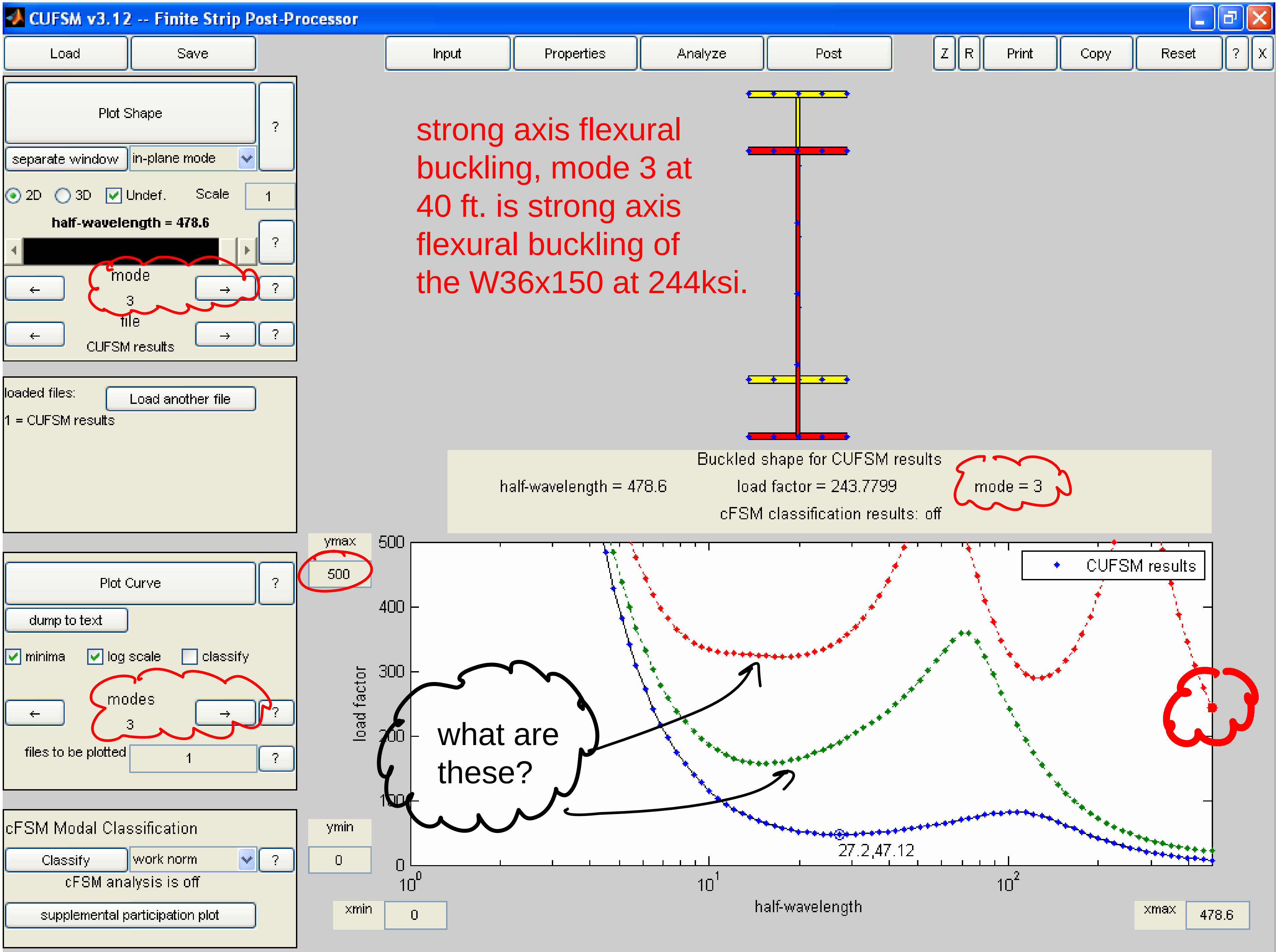
3D
Undef.
Scale
1
half-wavelength = 478.6
mode
3
file
CUFSM results
loaded files:
Load another file
1 = CUFSM results
strong axis flexural buckling, mode 3 at 40 ft. is strong axis flexural buckling of the W36x150 at 244ksi.
Buckled shape for CUFSM results
half-wavelength = 478.6
load factor = 243.7799
mode = 3
cFSM classification results: off
ymax
500
ymin
0
Plot Curve
dump to text
minima
log scale
classify
modes
3
files to be plotted
1
cFSM Modal Classification
Classify
work norm
cFSM analysis is off
supplemental participation plot
load factor
half-wavelength
CUFSM results
mode 3
mode 2
mode 2
mode 1
27.2,47.12
xmin
0
xmax
478.6



CUFSM v3.12 -- Finite Strip Post-Processor
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Plot Shape
separate window
in-plane mode
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3D
Undef.
Scale
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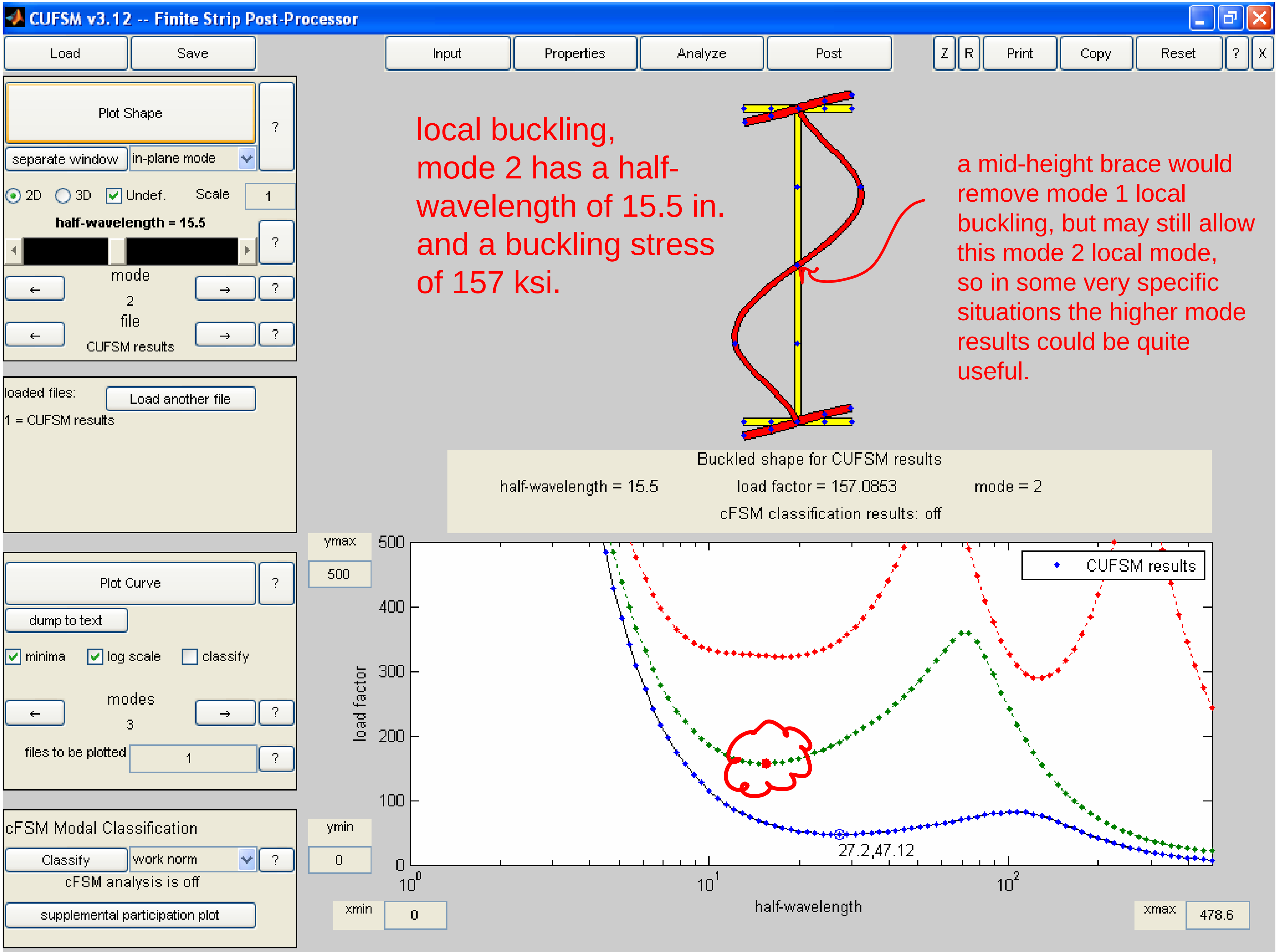
half-wavelength = 478.6
mode
3
file
CUFSM results
loaded files:
Load another file
1 = CUFSM results
Plot Curve
dump to text
minima
log scale
classify
modes
3
files to be plotted
1
cFSM Modal Classification
Classify
work norm
cFSM analysis is off
supplemental participation plot
strong axis flexural buckling, mode 3 at 40 ft. is strong axis flexural buckling of the W36x150 at 244ksi.
Buckled shape for CUFSM results
half-wavelength = 478.6
load factor = 243.7799
mode = 3
cFSM classification results: off
ymax
500
ymin
0
load factor
CUFSM results
what are these?
27.2,47.12
half-wavelength
xmin
0
xmax
478.6


CUFSM v3.12 -- Finite Strip Post-Processor
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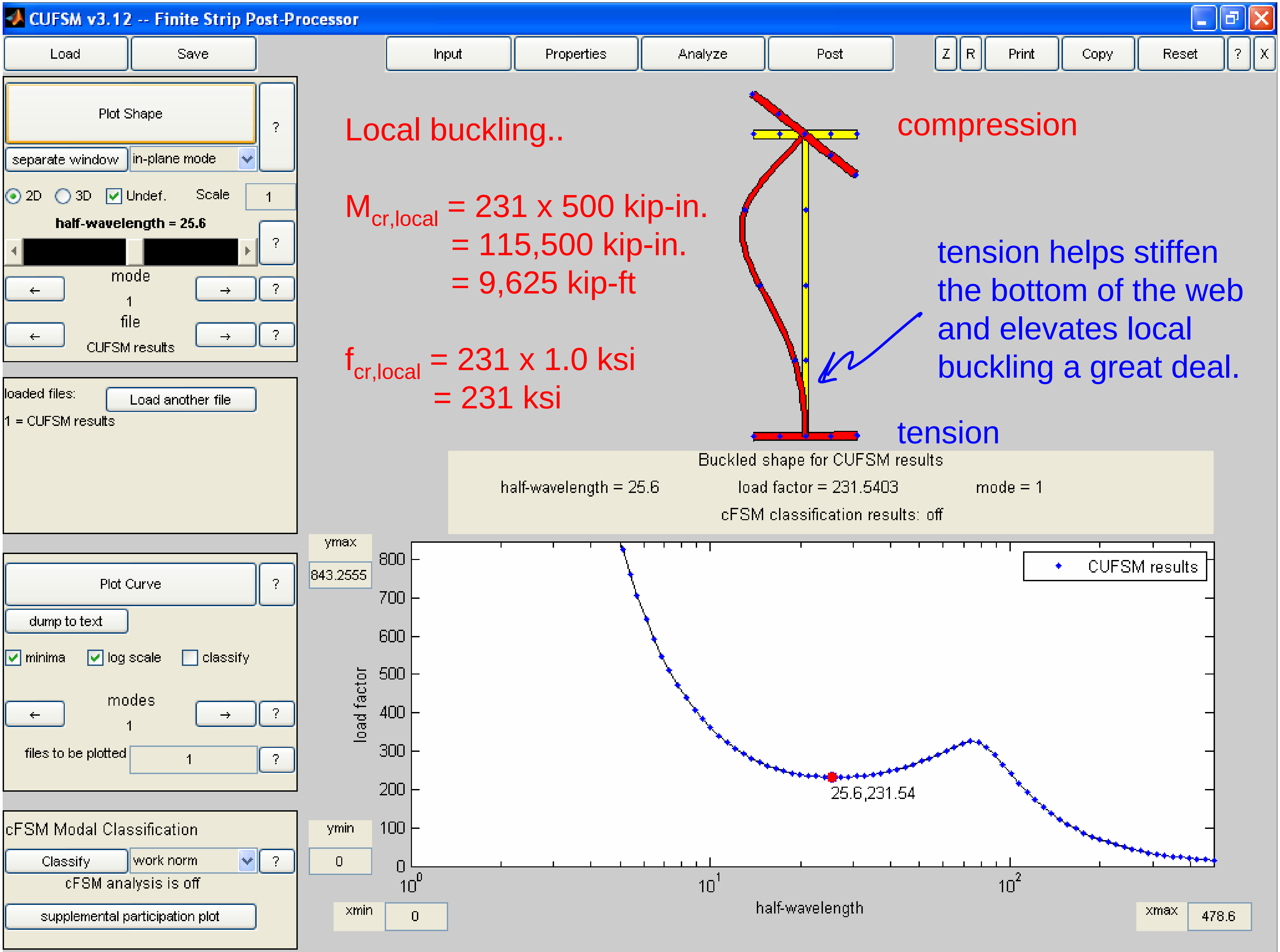
Print
Copy
Reset
Plot Shape
separate window
in-plane mode
2D
3D
Undef.
Scale
1
half-wavelength = 15.5
mode
2
file
CUFSM results
loaded files:
Load another file
1 = CUFSM results
Plot Curve
dump to text
minima
log scale
classify
modes
3
files to be plotted
1
cFSM Modal Classification
Classify
work norm
cFSM analysis is off
supplemental participation plot
local buckling, mode 2 has a half-wavelength of 15.5 in. and a buckling stress of 157 ksi.
a mid-height brace would remove mode 1 local buckling, but may still allow this mode 2 local mode, so in some very specific situations the higher mode results could be quite useful.
Buckled shape for CUFSM results
half-wavelength = 15.5
load factor = 157.0853
mode = 2
cFSM classification results: off
ymax
500
ymin
0
load factor
CUFSM results
27.2,47.12
half-wavelength
xmin
0
xmax
478.6

Higher modes summary

- At every half-wavelength investigated many buckling modes are revealed – the lowest of which is the 1st mode.
- Higher modes are those buckling modes at a given half-wavelength that have higher buckling stresses (load or moment) than the 1st mode.
- Higher buckling modes become more important as bracing and different boundary conditions are considered.
- In this W36x150 example it may be of surprise to some that torsional buckling may be the limiting global buckling mode when weak-axis flexural buckling is restricted

W36x150 beam – review of Tutorial 1


CUFSM v3.12 -- Finite Strip Post-Processor
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Analyze
Post
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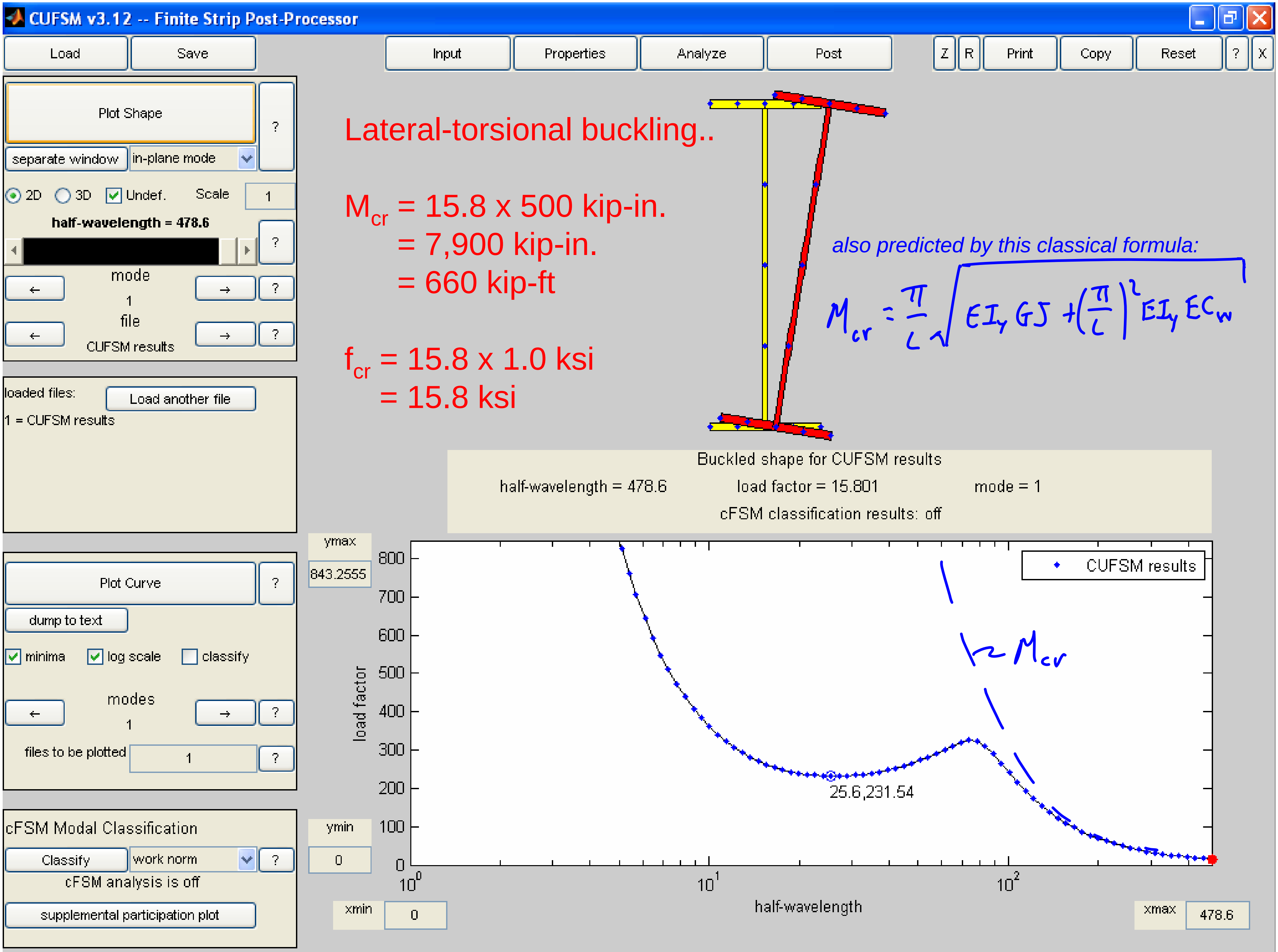
Copy
Reset
?
X
Plot Shape
separate window
in-plane mode
2D
3D
Undef.
Scale
1
half-wavelength = 25.6
mode
1
file
CUFSM results
loaded files:
Load another file
1 = CUFSM results
Plot Curve
dump to text
minima
log scale
classify
modes
1
files to be plotted
1
cFSM Modal Classification
Classify
work norm
cFSM analysis is off
supplemental participation plot
Local buckling..
M cr,local = 231 x 500 kip-in.
= 115,500 kip-in.
= 9,625 kip-ft
f cr,local = 231 x 1.0 ksi
= 231 ksi
compression
tension helps stiffen the bottom of the web and elevates local buckling a great deal.
tension
Buckled shape for CUFSM results
half-wavelength = 25.6
load factor = 231.5403
mode = 1
cFSM classification results: off
ymax
843.2555
ymin
0
CUFSM results
load factor
25.6,231.54
half-wavelength
xmin
0
xmax
478.6


CUFSM v3.12 -- Finite Strip Post-Processor
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Plot Shape
separate window
in-plane mode
2D
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Undef.
Scale
1
half-wavelength = 478.6
mode
1
file
CUFSM results
loaded files:
Load another file
1 = CUFSM results
Lateral-torsional buckling..
M_{cr} = 15.8 x 500 kip-in.
= 7,900 kip-in.
= 660 kip-ft
f_{cr} = 15.8 x 1.0 ksi
= 15.8 ksi
also predicted by this classical formula:
$M_{cr} = \frac{\pi}{L}\sqrt{EI_y GJ + \left(\frac{\pi}{L}\right)^2 EI_y EC_w}$
Buckled shape for CUFSM results
half-wavelength = 478.6
load factor = 15.801
mode = 1
cFSM classification results: off
Plot Curve
dump to text
minima
log scale
classify
modes
1
files to be plotted
1
cFSM Modal Classification
Classify
work norm
cFSM analysis is off
supplemental participation plot
ymax
843.2555
ymin
0
xmin
0
xmax
478.6
load factor
half-wavelength
CUFSM results
25.6,231.54
M_{cr}
800
700
600
500
400
300
200
100
0
10^0
10^1
10^2

Tutorial #1: Beam summary

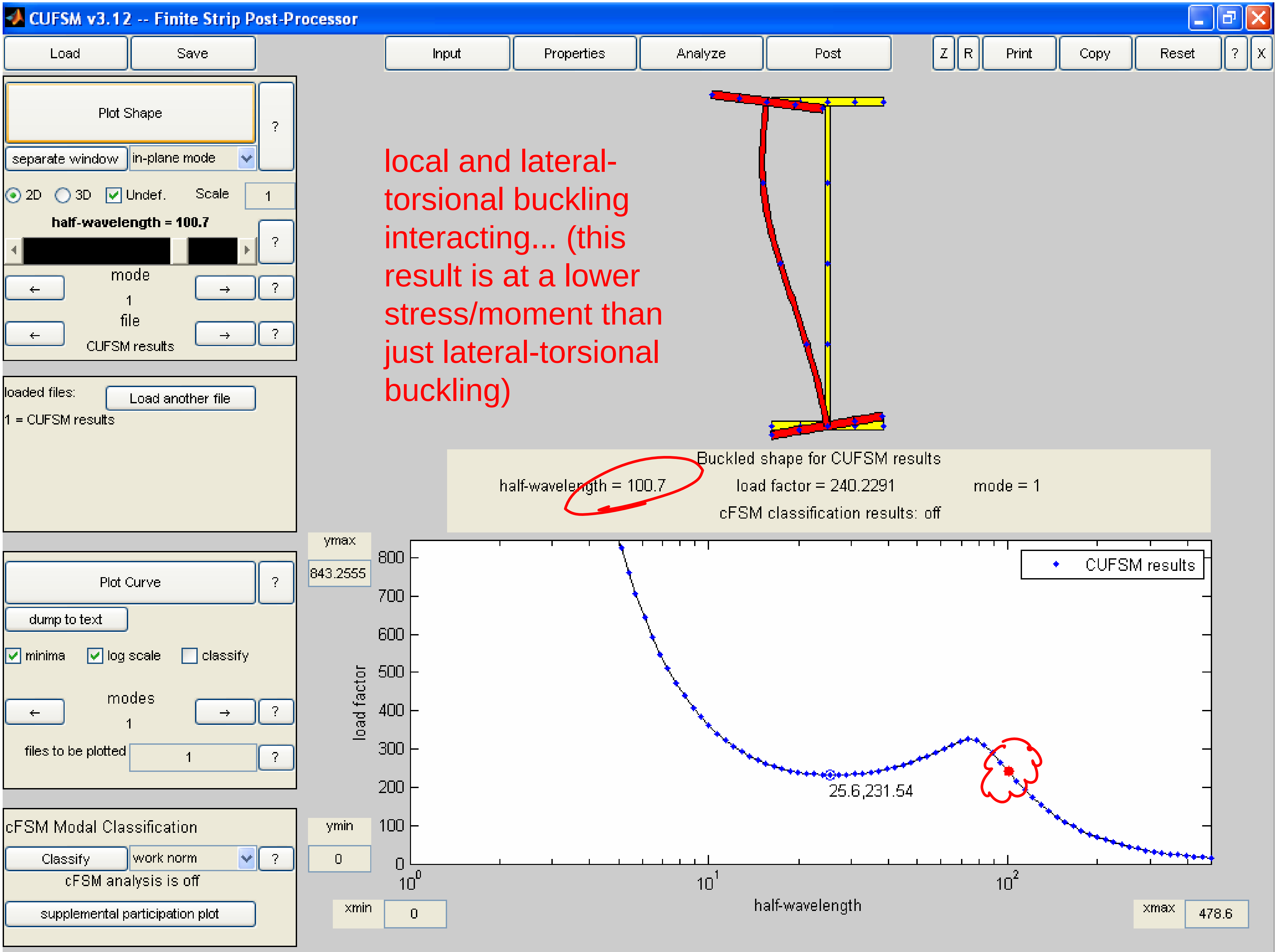
- A W36x150 under major-axis bending (a beam) has two important cross-section stability elastic buckling modes
- (1) Local buckling which occurs at a stress of 231 ksi and may repeat along the length of a member every 26 in. (it's half-wavelength)
- (2) Global lateral-torsional buckling, which for a 40 ft. long member occurs at a stress of 15.8 ksi (other member lengths may be selected from the curve provided from the analysis results)

Interaction of modes

- In the analysis so far we have looked at two half-wavelengths:
  - 26 in.: which is the first minimum in the curve and exhibits local buckling
  - 480in. or 40 ft.: which is the longest length investigated & exhibits lateral-torsional buckling

- What happens at other half-wavelengths?

  How about at 100in.?


CUFSM v3.12 -- Finite Strip Post-Processor
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Plot Shape
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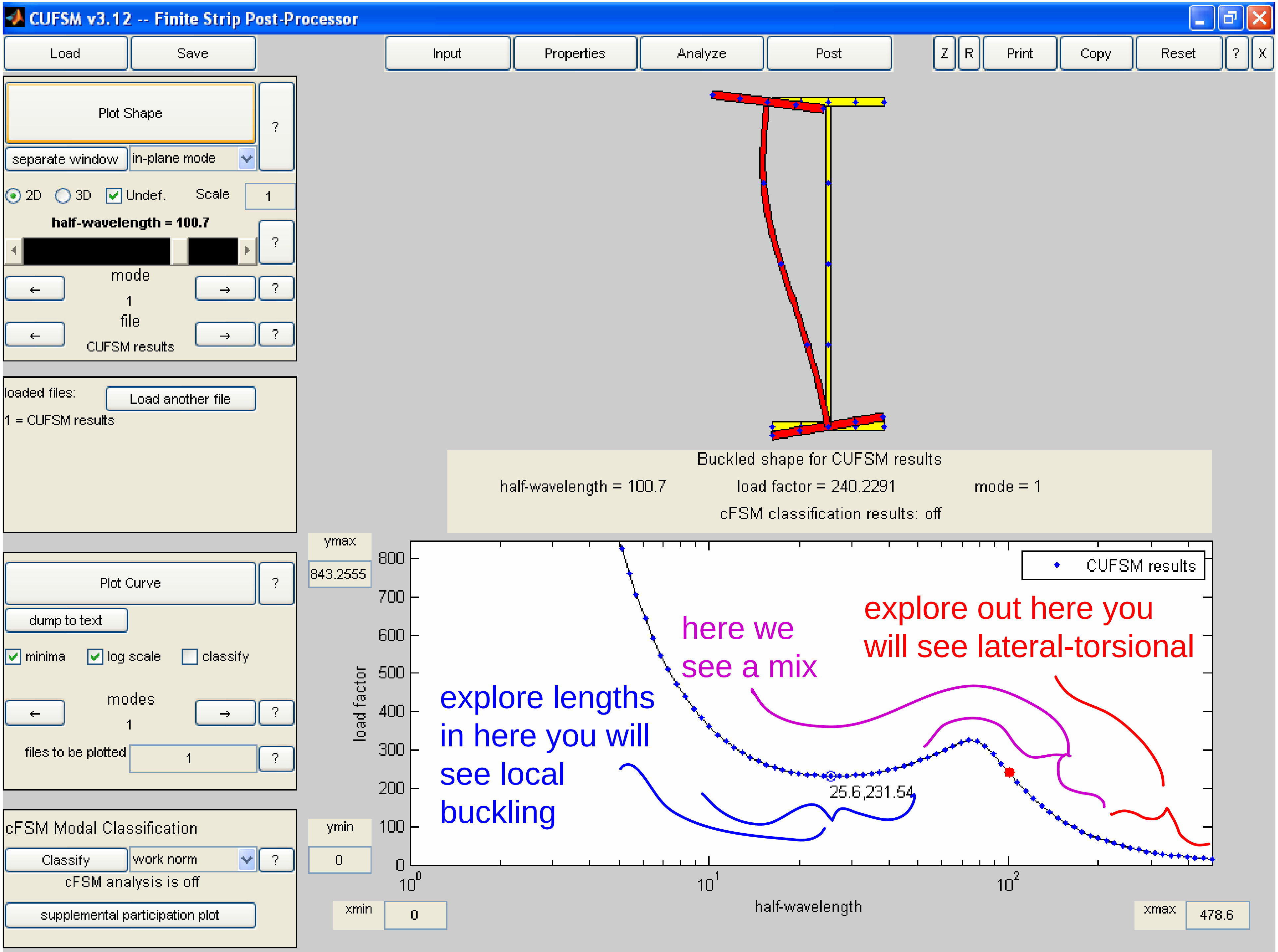
3D
Undef.
Scale
1
half-wavelength = 100.7
mode
1
file
CUFSM results
loaded files:
Load another file
1 = CUFSM results
Plot Curve
dump to text
minima
log scale
classify
modes
1
files to be plotted
1
cFSM Modal Classification
Classify
work norm
cFSM analysis is off
supplemental participation plot
local and lateral-torsional buckling interacting... (this result is at a lower stress/moment than just lateral-torsional buckling)
Buckled shape for CUFSM results
half-wavelength = 100.7
load factor = 240.2291
mode = 1
cFSM classification results: off
ymax
843.2555
ymin
0
xmin
0
xmax
478.6
load factor
half-wavelength
CUFSM results
25.6,231.54


CUFSM v3.12 -- Finite Strip Post-Processor
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Plot Shape
separate window
in-plane mode
2D
3D
Undef.
Scale
1
half-wavelength = 100.7
mode
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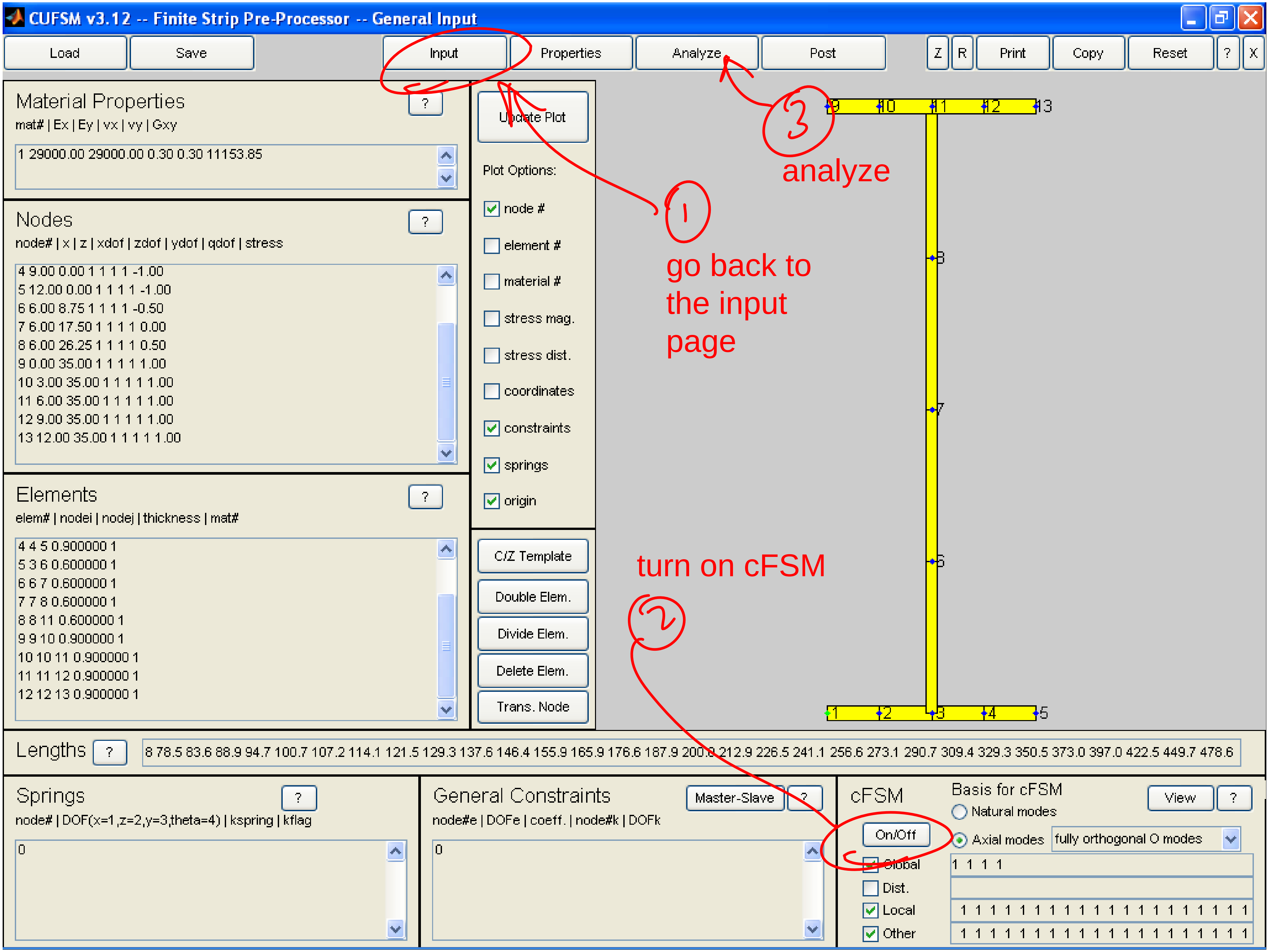
file
CUFSM results
loaded files:
Load another file
1 = CUFSM results
Plot Curve
dump to text
minima
log scale
classify
modes
1
files to be plotted
1
cFSM Modal Classification
Classify
work norm
cFSM analysis is off
supplemental participation plot
Buckled shape for CUFSM results
half-wavelength = 100.7
load factor = 240.2291
mode = 1
cFSM classification results: off
ymax
843.2555
ymin
0
load factor
half-wavelength
xmin
0
xmax
478.6
CUFSM results
25.6,231.54
explore lengths in here you will see local buckling
here we see a mix
explore out here you will see lateral-torsional

constrained Finite Strip Method

- Using the constrained Finite Strip Method (cFSM) we can formalize our predictions of modal interactions.
- The cFSM was developed and implemented by Schafer and Adany and can be explored in CUFSM
- Let's run an analysis with cFSM on and examine the modal interactions..


CUFSM v3.12 -- Finite Strip Pre-Processor -- General Input
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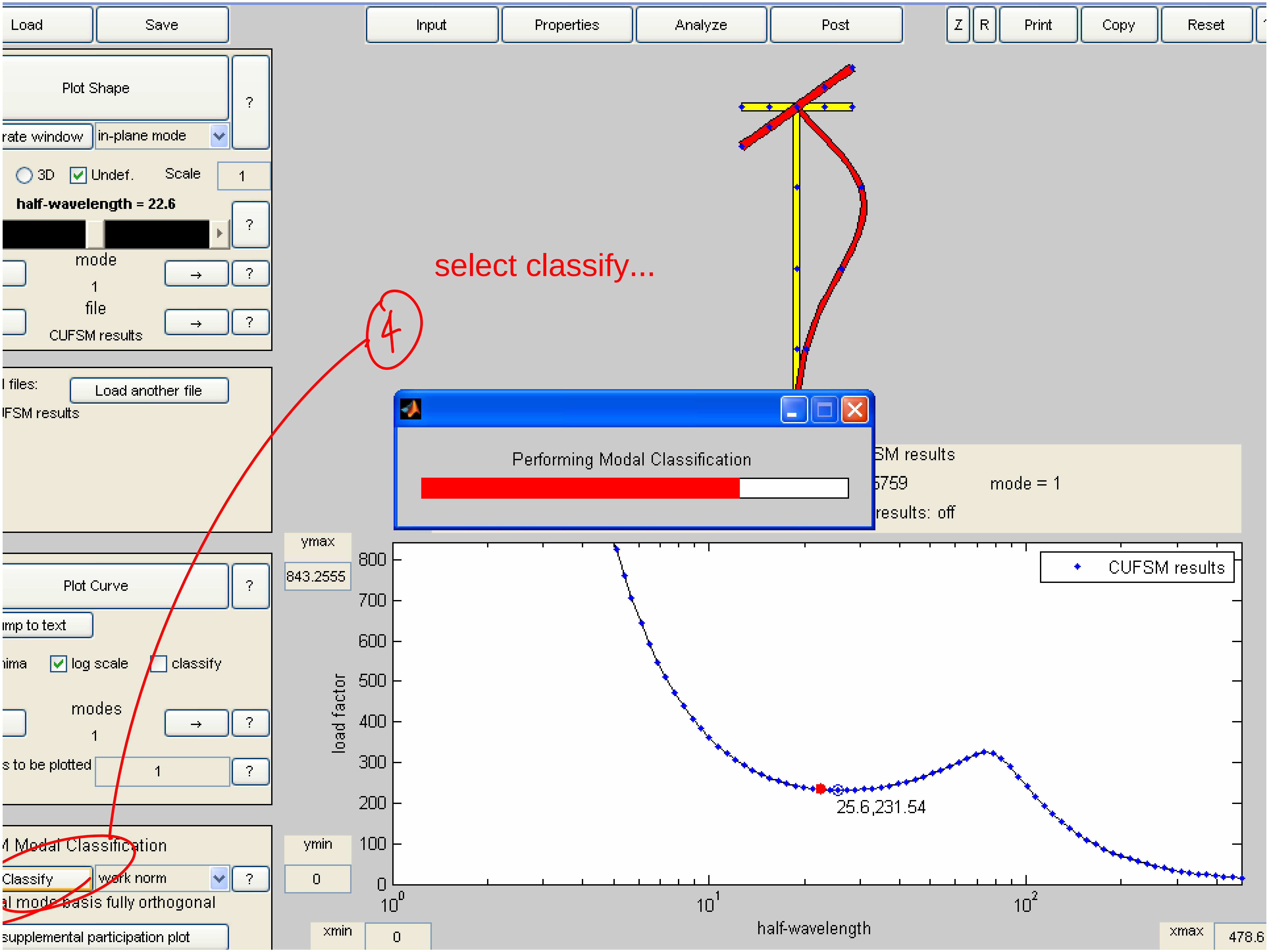
X
Material Properties
mat# | Ex | Ey | vx | vy | Gxy
1 29000.00 29000.00 0.30 0.30 11153.85
Nodes
node# | x | z | xdof | zdof | ydof | qdof | stress
4 9.00 0.00 1 1 1 1 -1.00
5 12.00 0.00 1 1 1 1 -1.00
6 6.00 8.75 1 1 1 1 -0.50
7 6.00 17.50 1 1 1 1 0.00
8 6.00 26.25 1 1 1 1 0.50
9 0.00 35.00 1 1 1 1 1.00
10 3.00 35.00 1 1 1 1 1.00
11 6.00 35.00 1 1 1 1 1.00
12 9.00 35.00 1 1 1 1 1.00
13 12.00 35.00 1 1 1 1 1.00
Elements
elem# | nodei | nodej | thickness | mat#
4 4 5 0.900000 1
5 3 6 0.600000 1
6 6 7 0.600000 1
7 7 8 0.600000 1
8 8 11 0.600000 1
9 9 10 0.900000 1
10 10 11 0.900000 1
11 11 12 0.900000 1
12 12 13 0.900000 1
Update Plot
Plot Options:
node #
element #
material #
stress mag.
stress dist.
coordinates
constraints
springs
origin
C/Z Template
Double Elem.
Divide Elem.
Delete Elem.
Trans. Node
Lengths
8 78.5 83.6 88.9 94.7 100.7 107.2 114.1 121.5 129.3 137.6 146.4 155.9 165.9 176.6 187.9 200.0 212.9 226.5 241.1 256.6 273.1 290.7 309.4 329.3 350.5 373.0 397.0 422.5 449.7 478.6
Springs
node# | DOF(x=1,z=2,y=3,theta=4) | kspring | kflag
0
General Constraints
Master-Slave
node#e | DOFe | coeff. | node#k | DOFk
0
cFSM
Basis for cFSM
View
Natural modes
Axial modes
fully orthogonal O modes
On/Off
Global
Dist.
Local
Other
1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1
go back to the input page
2
turn on cFSM
3
analyze


Load
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Input
Properties
Analyze
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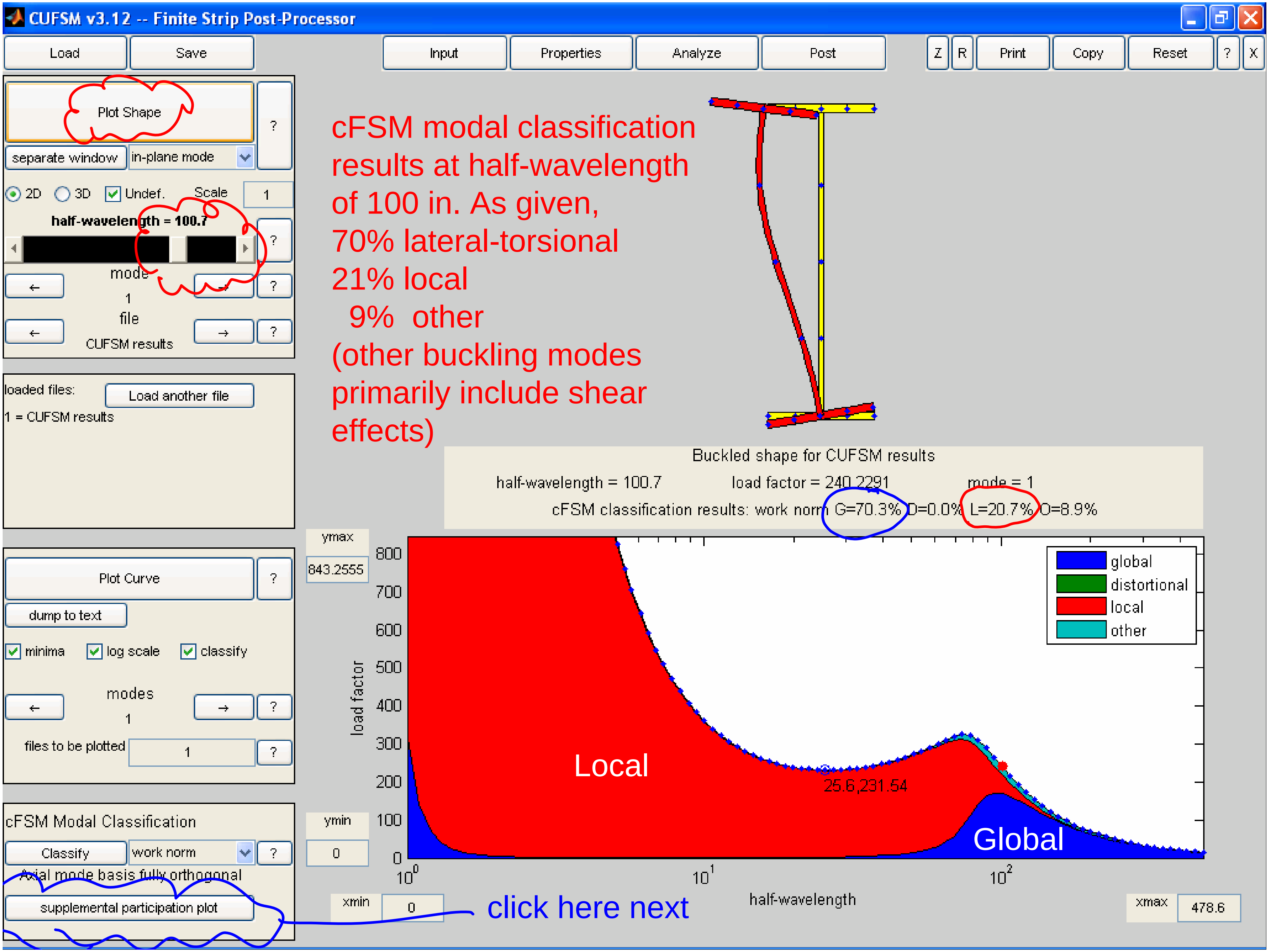
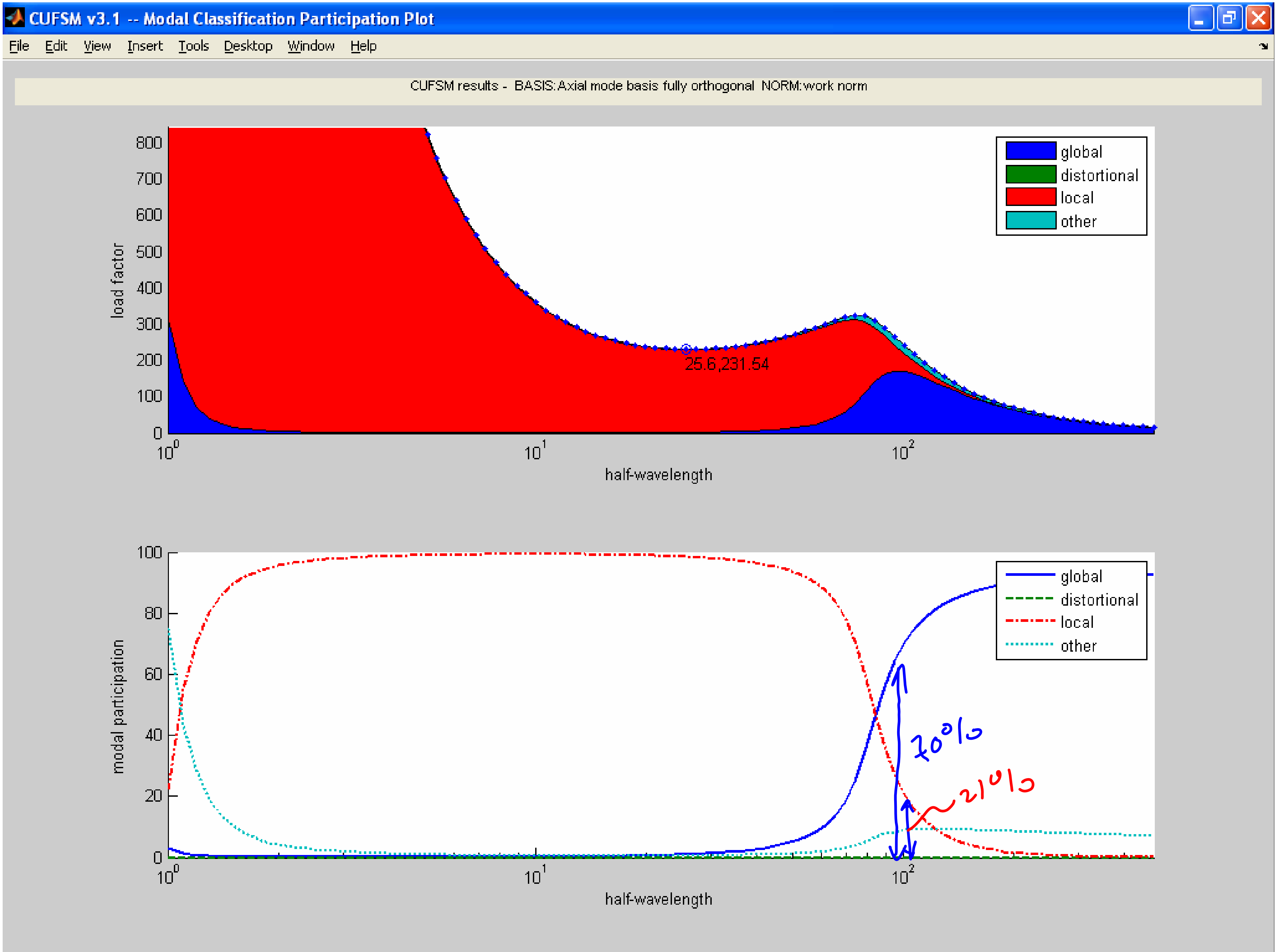
Reset
Plot Shape
?
rate window
in-plane mode
3D
Undef.
Scale
1
half-wavelength = 22.6
mode
1
file
CUFSM results
select classify...
4
l files:
Load another file
IFSM results
Performing Modal Classification
SM results
5759
mode = 1
results: off
ymax
843.2555
Plot Curve
imp to text
nima
log scale
classify
modes
1
s to be plotted
1
M Modal Classification
Classify
work norm
al mode basis fully orthogonal
supplemental participation plot
CUFSM results
25.6,231.54
load factor
half-wavelength
ymin
0
xmin
0
xmax
478.6

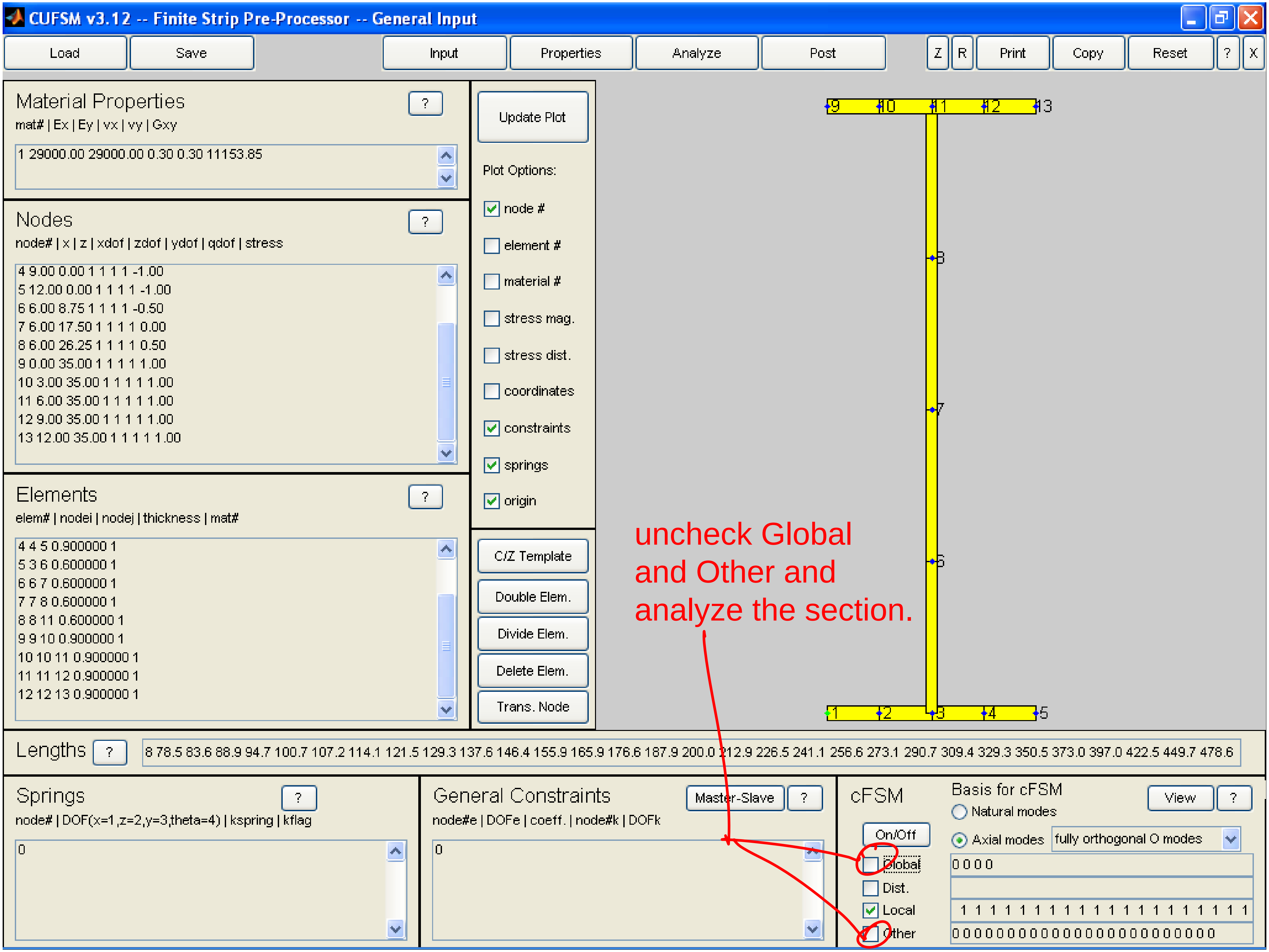

CUFSM v3.12 -- Finite Strip Post-Processor
Load
Save
Input
Properties
Analyze
Post
Z
R
Print
Copy
Reset
?
X
Plot Shape
separate window
in-plane mode
2D
3D
Undef.
Scale
1
half-wavelength = 100.7
mode
1
file
CUFSM results
loaded files:
Load another file
1 = CUFSM results
Plot Curve
dump to text
minima
log scale
classify
modes
1
files to be plotted
1
cFSM Modal Classification
Classify
work norm
Axial mode basis fully orthogonal
supplemental participation plot
cFSM modal classification results at half-wavelength of 100 in. As given,
70% lateral-torsional
21% local
9% other
(other buckling modes primarily include shear effects)
Buckled shape for CUFSM results
half-wavelength = 100.7
load factor = 240.2291
mode = 1
cFSM classification results: work norm G=70.3% D=0.0% L=20.7% O=8.9%
ymax
843.2555
ymin
0
load factor
half-wavelength
xmin
0
xmax
478.6
global
distortional
local
other
Local
Global
25.6,231.54
click here next

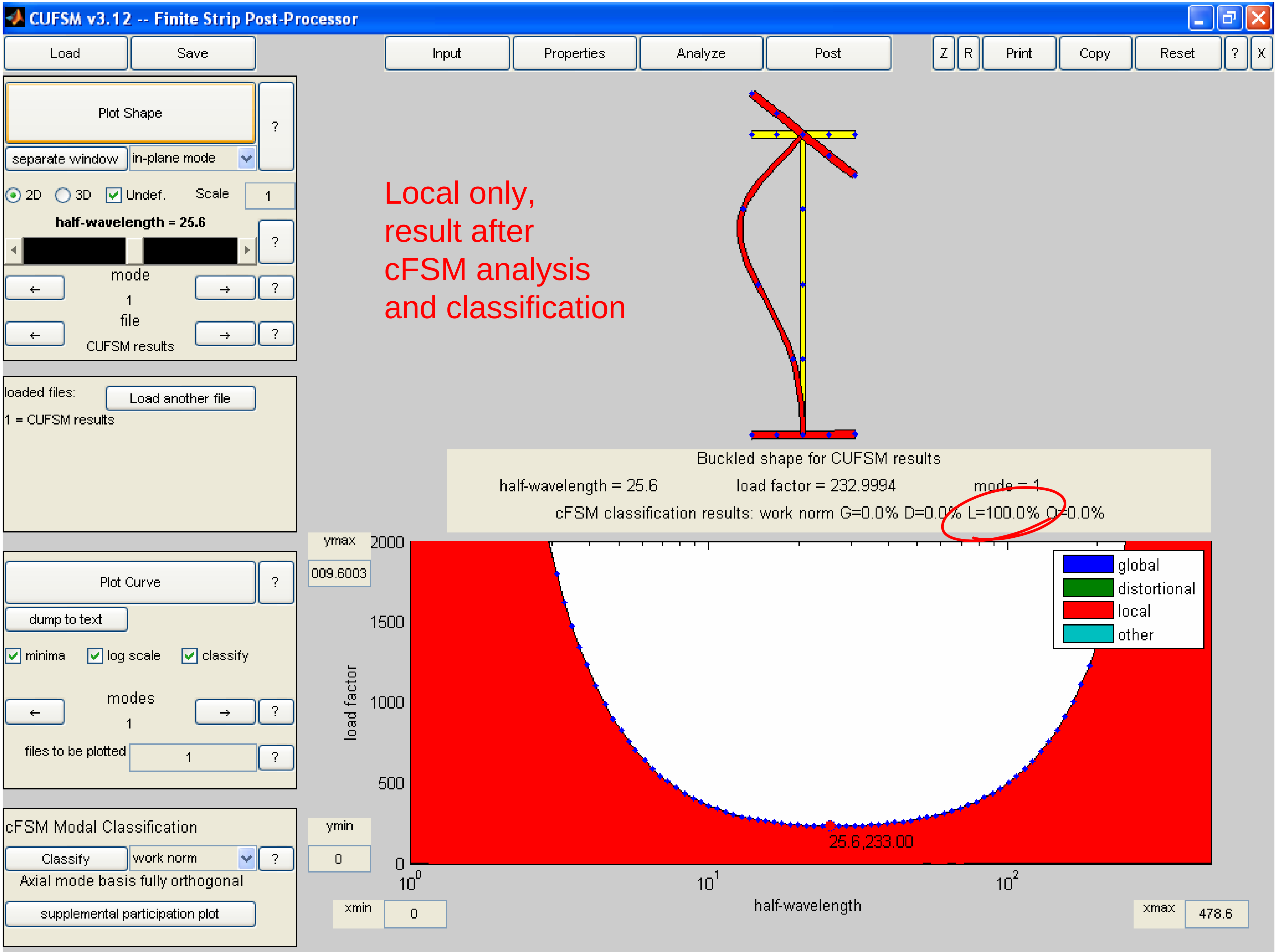


CUFSM v3.1 -- Modal Classification Participation Plot
File Edit View Insert Tools Desktop Window Help
CUFSM results - BASIS:Axial mode basis fully orthogonal NORM:work norm
load factor
800
700
600
500
400
300
200
100
0
global
distortional
local
other
25.6,231.54
10^0
10^1
10^2
half-wavelength
modal participation
100
80
60
40
20
0
global
distortional
local
other
70%
21%
10^0
10^1
10^2
half-wavelength

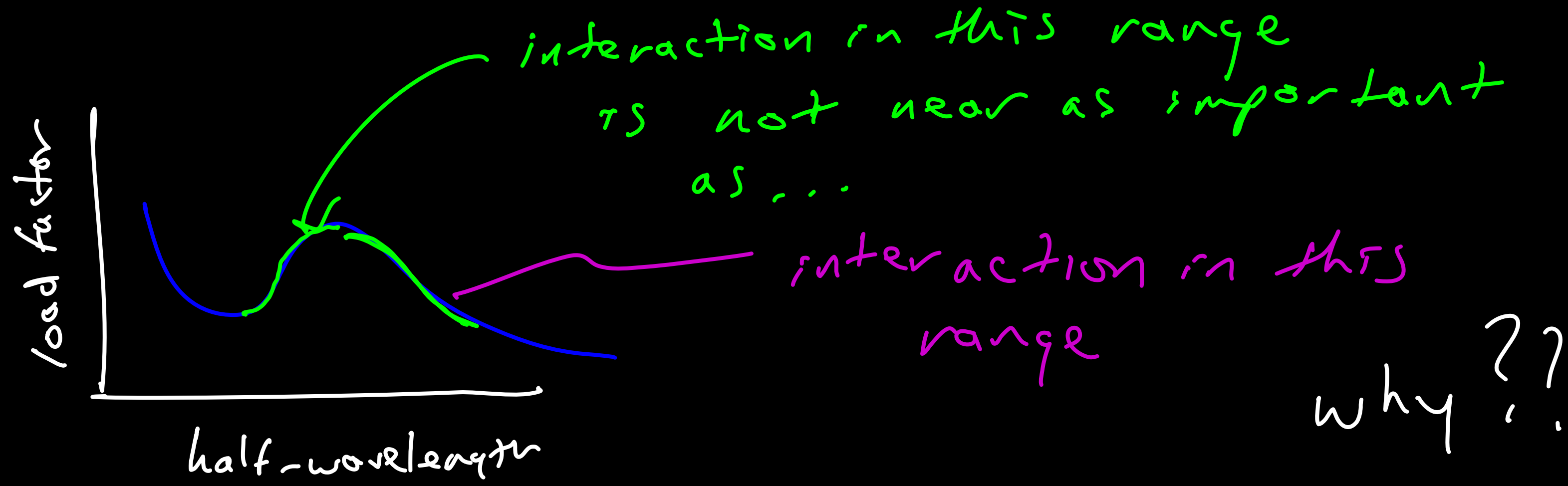
cFSM decomposition

- One of the useful features of cFSM is the ability to focus on only one type of buckling mode at a time, for example, local buckling..

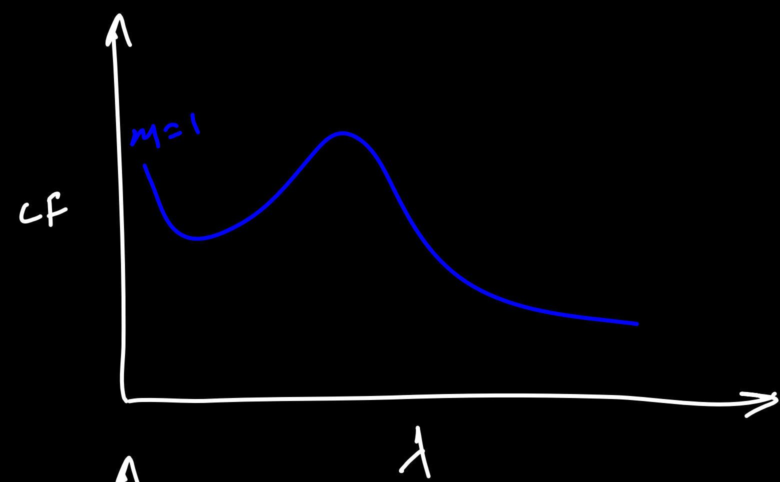

CUFSM v3.12 -- Finite Strip Pre-Processor -- General Input
Load
Save
Input
Properties
Analyze
Post
Z
R
Print
Copy
Reset
?
X
Material Properties
mat# | Ex | Ey | vx | vy | Gxy
1 29000.00 29000.00 0.30 0.30 11153.85
Nodes
node# | x | z | xdof | zdof | ydof | qdof | stress
4 9.00 0.00 1 1 1 1 -1.00
5 12.00 0.00 1 1 1 1 -1.00
6 6.00 8.75 1 1 1 1 -0.50
7 6.00 17.50 1 1 1 1 0.00
8 6.00 26.25 1 1 1 1 0.50
9 0.00 35.00 1 1 1 1 1.00
10 3.00 35.00 1 1 1 1 1.00
11 6.00 35.00 1 1 1 1 1.00
12 9.00 35.00 1 1 1 1 1.00
13 12.00 35.00 1 1 1 1 1.00
Elements
elem# | nodei | nodej | thickness | mat#
4 4 5 0.900000 1
5 3 6 0.600000 1
6 6 7 0.600000 1
7 7 8 0.600000 1
8 8 11 0.600000 1
9 9 10 0.900000 1
10 10 11 0.900000 1
11 11 12 0.900000 1
12 12 13 0.900000 1
Update Plot
Plot Options:
node #
element #
material #
stress mag.
stress dist.
coordinates
constraints
springs
origin
C/Z Template
Double Elem.
Divide Elem.
Delete Elem.
Trans. Node
9
10
11
12
13
8
7
6
1
2
3
4
5
uncheck Global
and Other and
analyze the section.
Lengths
8 78.5 83.6 88.9 94.7 100.7 107.2 114.1 121.5 129.3 137.6 146.4 155.9 165.9 176.6 187.9 200.0 212.9 226.5 241.1 256.6 273.1 290.7 309.4 329.3 350.5 373.0 397.0 422.5 449.7 478.6
Springs
node# | DOF(x=1,z=2,y=3,theta=4) | kspring | kflag
0
General Constraints
Master-Slave
node#e | DOFe | coeff. | node#k | DOFk
0
cFSM
On/Off
Global
Dist.
Local
Other
Basis for cFSM
View
Natural modes
Axial modes
fully orthogonal O modes
0 0 0 0
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0


CUFSM v3.12 -- Finite Strip Post-Processor
Load
Save
Input
Properties
Analyze
Post
Z
R
Print
Copy
Reset
?
X
Plot Shape
separate window
in-plane mode
2D
3D
Undef.
Scale
1
half-wavelength = 25.6
mode
1
file
CUFSM results
loaded files:
Load another file
1 = CUFSM results
Plot Curve
dump to text
minima
log scale
classify
modes
1
files to be plotted
1
cFSM Modal Classification
Classify
work norm
Axial mode basis fully orthogonal
supplemental participation plot
Local only,
result after
cFSM analysis
and classification
Buckled shape for CUFSM results
half-wavelength = 25.6
load factor = 232.9994
mode = 1
cFSM classification results: work norm G=0.0% D=0.0% L=100.0% O=0.0%
ymax
009.6003
2000
1500
1000
500
0
load factor
ymin
0
global
distortional
local
other
25.6,233.00
half-wavelength
xmin
0
xmax
478.6

some more detailed thoughts about when these interactions matter

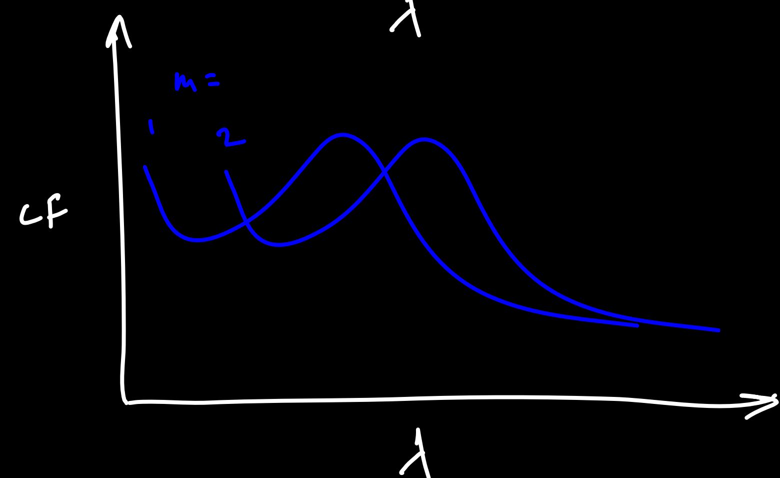


The "up" part of an FSM curve (as shown in green) is typically not the lowest buckling mode because all buckling modes may repeat along the length.

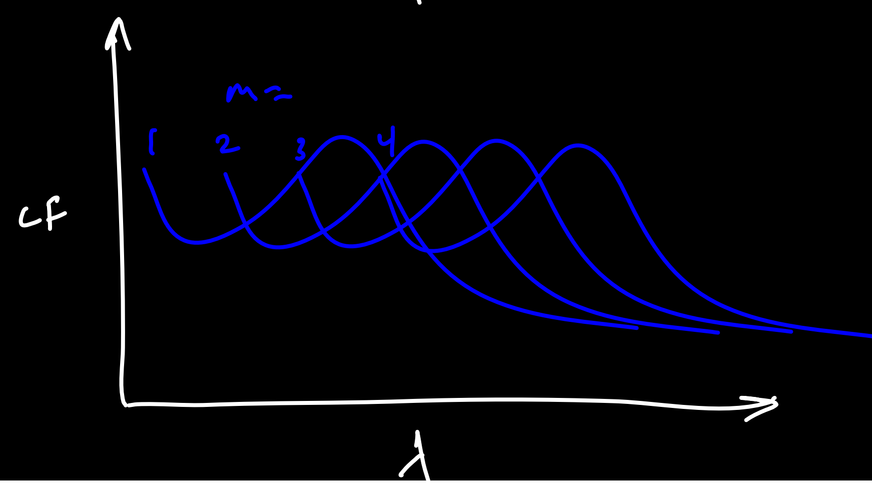


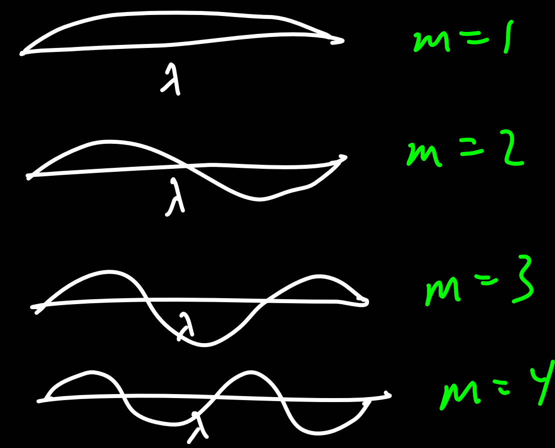
shape $\equiv \sin \frac{m\pi x}{\lambda}$

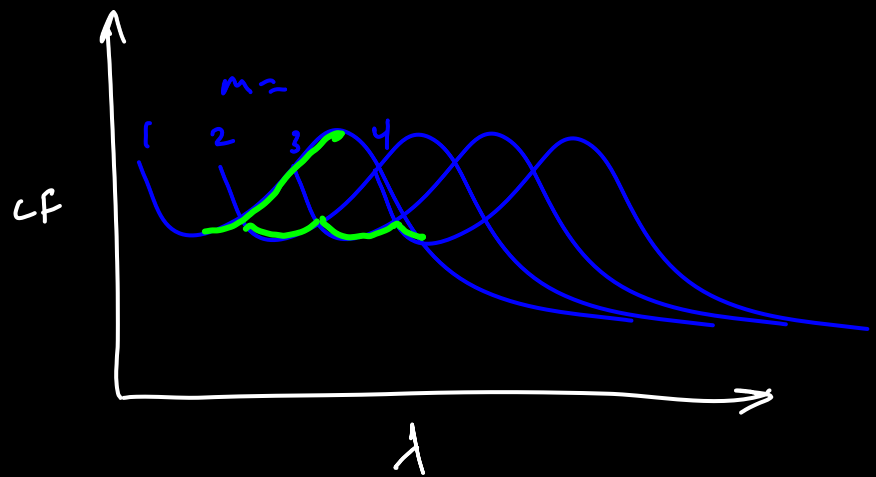
← traditional FSM



here is what we get if we look at two half-waves along the length (compared to 1)







"Green" or up part of the traditional FSM curve does not control, instead the m=2, 3, 4, etc. solutions control (i.e. provide the lowest elastic buckling results.)

conclusion? interaction of the buckling modes is only of serious concern from an FSM analysis when it is identified on the downward slope of a traditional (m=1, single half-wave) finite strip result.

It should also be noted that interactions such as those identified here in these elastic buckling results are not considered in the AISC Spec.