LIGO Laboratory / LIGO Scientific Collaboration

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Quadruple Suspension Dynamics Model with Finite Elements (Advanced LIGO)

Dennis Coyne

Distribution of this document:
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This is an internal working note
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California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW17-161
175 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

http://www.ligo.caltech.edu/

Change Record:

Revision –00: Initial Release. Written 6 Dec 2005 (issued 26 June 2006). Note that this was work performed, and documented (to the extent given below) late last year but not completed. The work was started when neither the Matlab nor the Mathematica suspension models of the quadruple pendulum were matching initial response of the controls quadruple suspension. Eventually it was found that the largest discrepancy was the position of the effective wire flexure point. With beam elements modeling the wires, this was not a limitation of this finite element approach. The finite element model of the suspension was relatively successful, except that the lowest frequency pitch mode was at times found to be negative. This is either a model parameter problem or a numerical problem in the eigensolver.

1 Introduction

There are currently three models used for dynamics modeling of suspensions:

- A Mathematica Model[1] created by Mark Barton. This model has been used to model the Mode Cleaner triple suspension and the quadruple suspension[2].
- A Matlab Model[3] created by Calum Torrie. This model has been extended and applied in design for the triple and the quadruple suspensions[4].
- A Maple Model[5] created by Mathew Husman.

All three of these models are based on closed form equations.

So why yet another approach to modeling? Recent measurements on the quadruple, controls prototype suspension did not (initially) match eigenfrequency predictions. Questions arose about the proper modeling of the effective wire flexure distance[6] and the effect of non-vertical wires, blade spring stiffnesses other than in the principal bending direction (in-plane longitudinal, lateral and torsional stiffness), off-diagonal mass moments of inertia, non-flat blade spring geometry, geometry faithful to the CAD, blade tip mass, etc. All of these factors can be included in a finite element based numerical model.

There are (at least) two basic approaches to developing the finite element model:

- Geometry derived from the CAD 3D model. The virtue of this approach is that the model can be keyed to the CAD files used to create the physical parts. In principle a parametric 3D CAD model can be dynamically linked to the finite element model so that updates to the

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[1] M. Barton, Models of the Advanced LIGO Suspensions in Mathematic, LIGO-T020205-00.

[2] N. Robertson, M. Barton, J. Greenhalgh, Cross-Coupling in Quadruple Suspension, T040143-00.

[3] C. Torrie, "Development of Suspensions for the GEO600 Gravitational Wave Detector",

PhD Thesis, University of Glasgow, 2000. Description of the design of the GEO suspensions,

with particular reference to an analytical model of them in Matlab.

[4] N. Robertson, et. al., Advanced LIGO Suspension System Conceptual Design, T010103-04.

[5] M. Husman, "Suspension and Control for Interferometric Gravitational Wave Detectors", PhD Thesis, University of Glasgow, 2000. Description of the design and control of the GEO suspensions, with particular reference to an analytic model of them in Maple.

[6] N. Robertson, M. Barton, Technical Note on the Effects of Stiff Wires on the Behaviour of Suspensions, LIGO number pending, 9 Sep 2005.

CAD can propagate to the model; In practice this level of interoperability can be difficult to achieve.[7]

- Geometry generated from a command script with parameter values. The virtue of this approach is that the model can be updated quickly with a simple text edit (similar to editing the input parameters for either the Mathematica or Matlab models). Generating the eigensolution or transfer function for perturbations in parameter values is quick and easy.

I've describe both approaches in the following sections. The first approach was accomplished with I-DEAS and the second approach was attempted with ANSYS. However, either finite element tool could be used for either approach.

2 Approximations

Linear

Pre-stress, not geometrically nonlinear pre-load – assuming ideal loading to intended location

Etc.

Note approximations that are inherent & not inherent in the FEA approach

3 Geometry Derived from CAD

The quadruple suspension parts were developed as 3D parts and assemblies in SolidWorks. Since I-Deas does not directly import SolidWorks files, I converted. Of the available conversions[8], I found IGES to work best. However it is essential to minimize the complexity of the assembly; Only include those parts essential for developing the model. Hidden parts in SolidWorks are not converted.

Once the geometry is imported into I-Deas, use the wireframe attach function to associate the finite element mesh with the assembly (or part). The following idealizations of the suspension were made in developing the mesh:

- Blade springs are modeled as plates (shells): The top surfaces of each blade spring solid part were selected for auto-meshing of shell elements (with bending, membrane and torsional stiffnesses). The thicknesses and material properties were keyed in manually.
- Wires are modeled as beams: The intersections of the wires with the clamp faces were 'found' by adding line and point features keyed to the imported geometry. Then beam elements (bending, torsion and extensional stiffness) were auto-meshed between the wire/clamp interface points. The cross-sectional geometry of each wire and the wire material properties were then keyed in manually.
- Suspension masses modeled as "lumped masses": The essentially rigid parts that comprise the suspension masses (upper mass, upper intermediate mass, penultimate mass and test

[7] This seamless updating of CAD and FEM is possible within I-DEAS, but does not appear possible between our chosen CAD tool, SolidWorks, and ANSYS.

[8] Of flavors generated by SolidWorks 2005 and read by I-Deas v9, STEP203 had 3 of the 6 blades facing the wrong way, STEP214 didn't work.

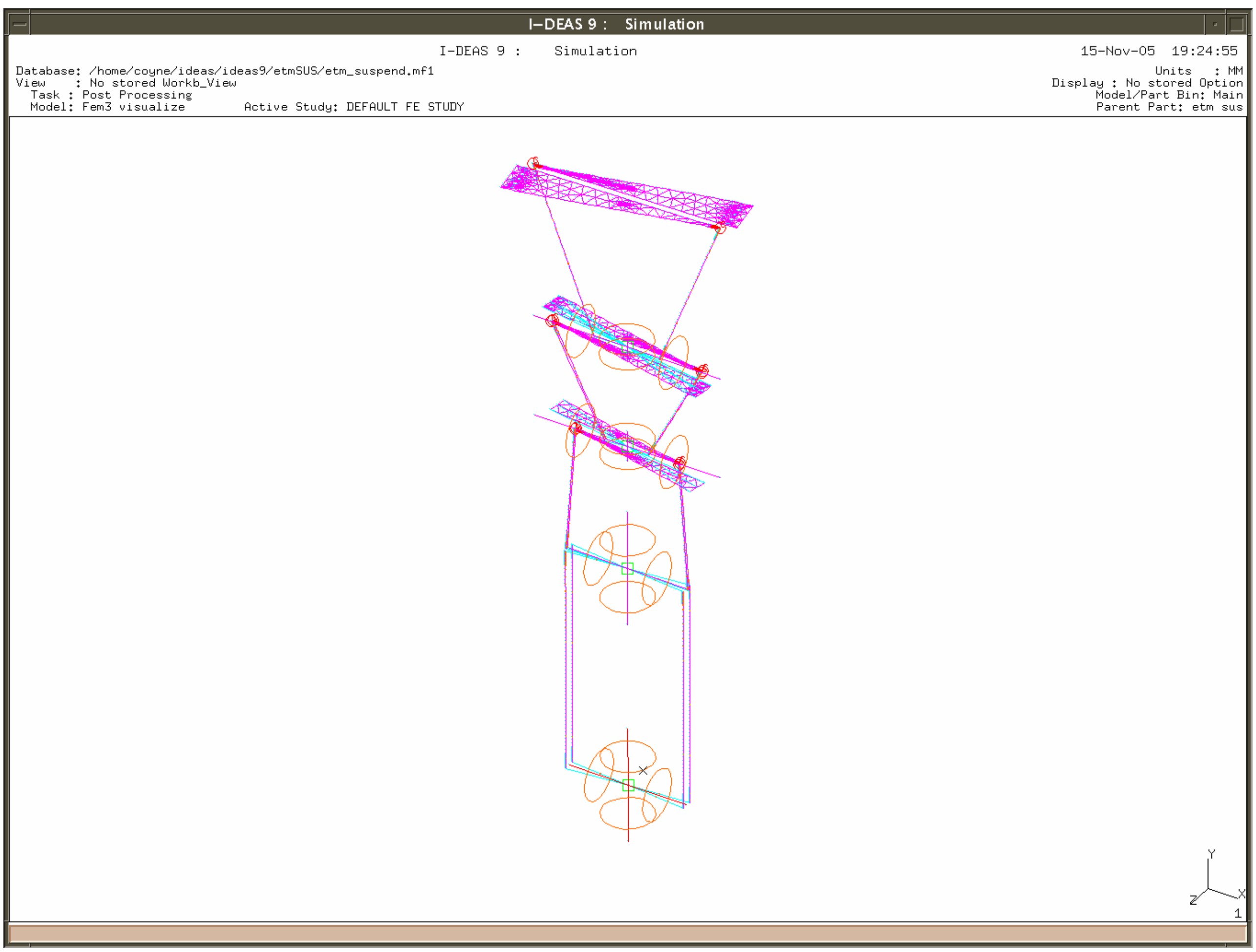
mass) are modeled as “lumped” (point) masses with a full mass moment of inertia matrix. The matrix was calculated in SolidWorks for each suspension mass, with the blade springs removed, and then keyed into I-Deas manually. The locations were established from the imported geometry.

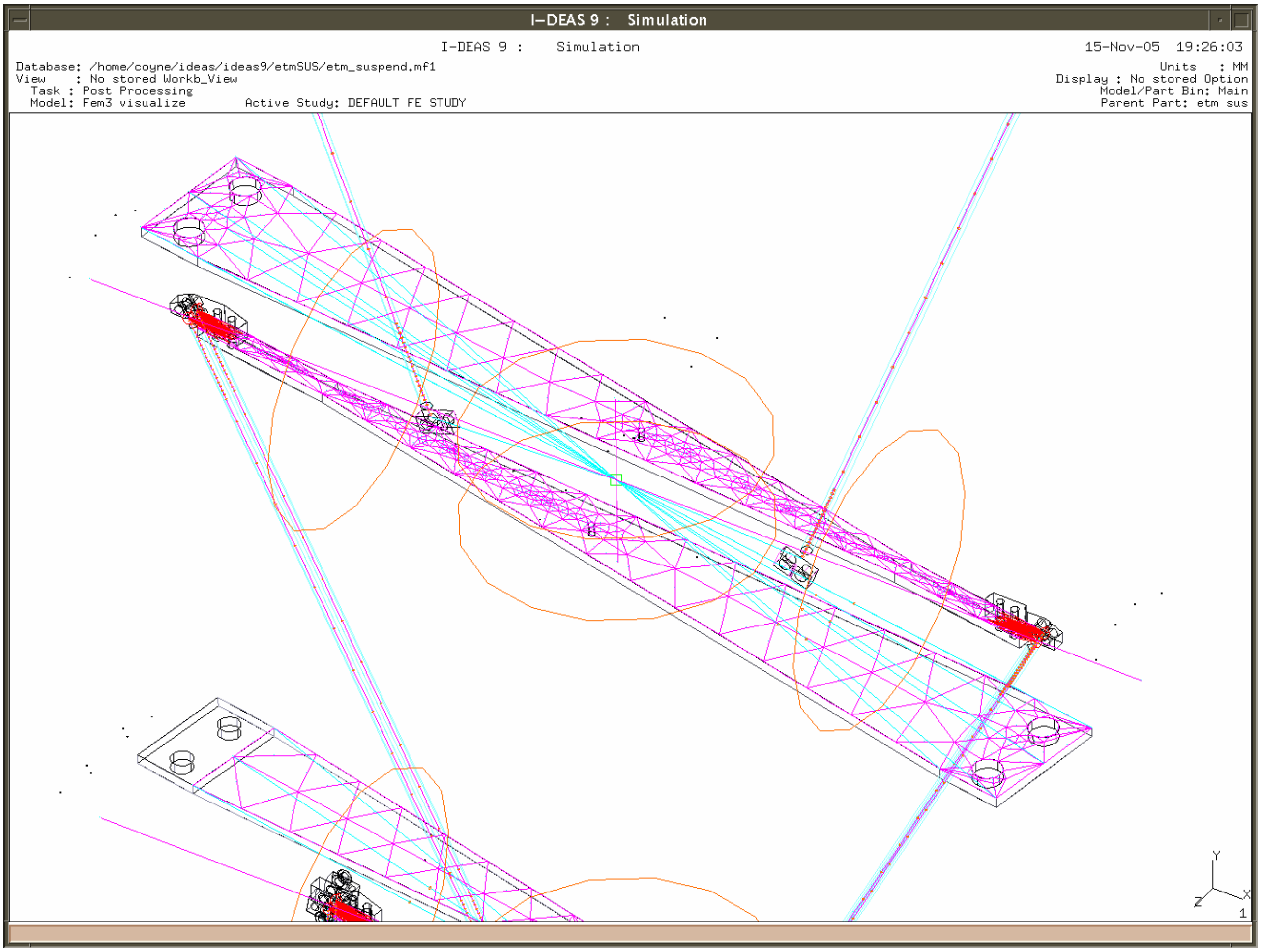
- Multipoint constraints (MPC): The point mass elements representing the suspension masses were then tied rigidly to the flexible elements (spring blade bases and wire ends) using multipoint rigid constraints which ensured that all 6 degrees of freedom of the suspension masses are imposed on the attachments. Since the MPC elements do not appear in any mode shape plots in I-Deas, stiff, low mass beams were added vertically and horizontally to each point mass (with dimensions equal to the physical extent of the actual suspension mass) to help visualize the motion of each suspension mass.

3.1 Model

The model is depicted in the following Figures. More explanation and description …

Figure 1: CAD Derived Finite Element Model

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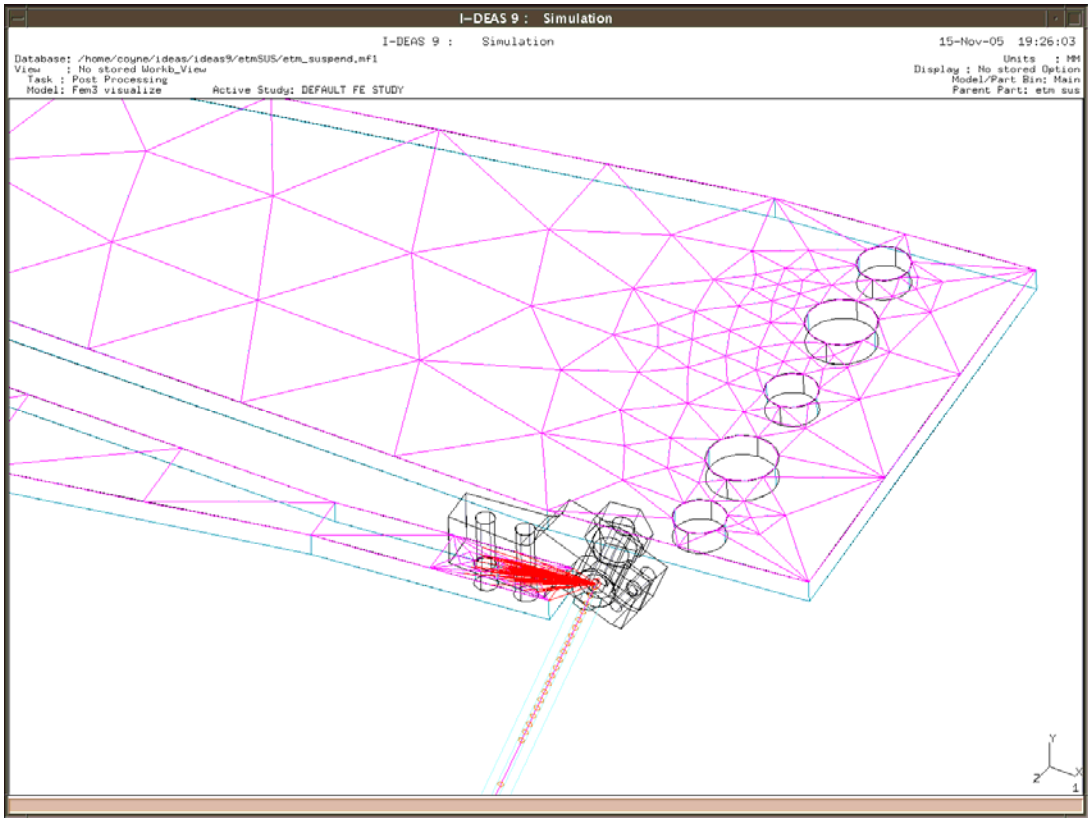
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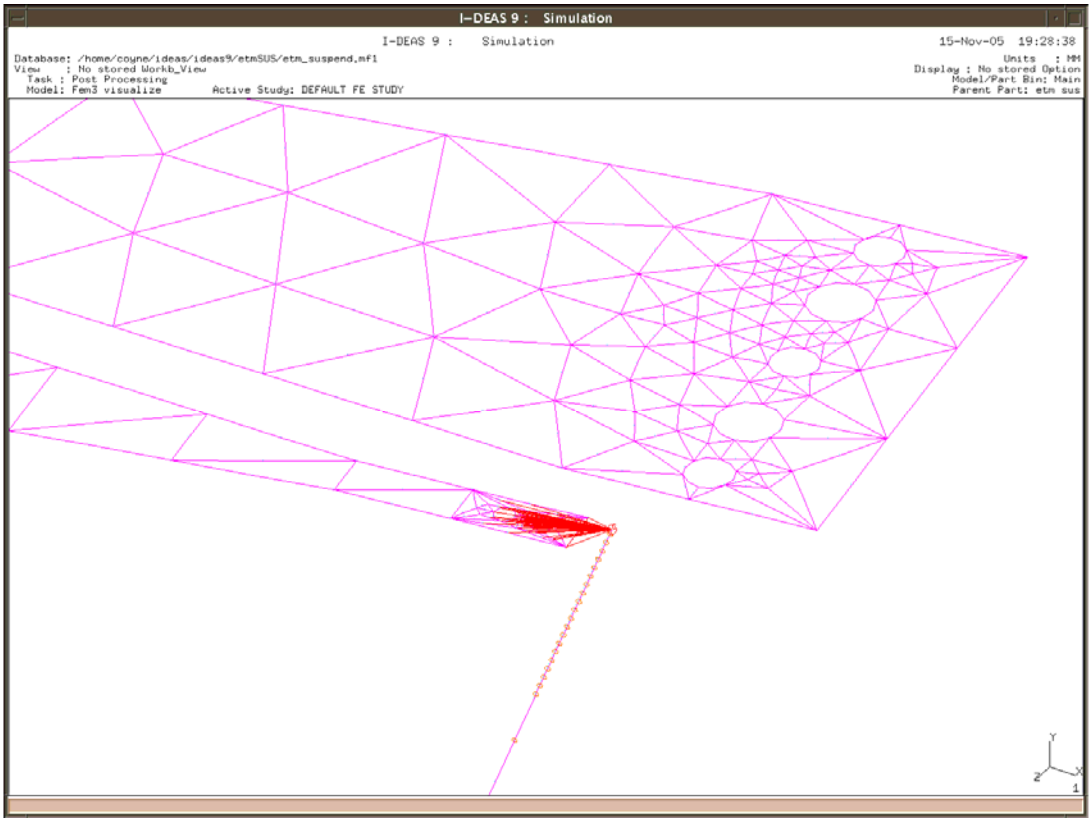
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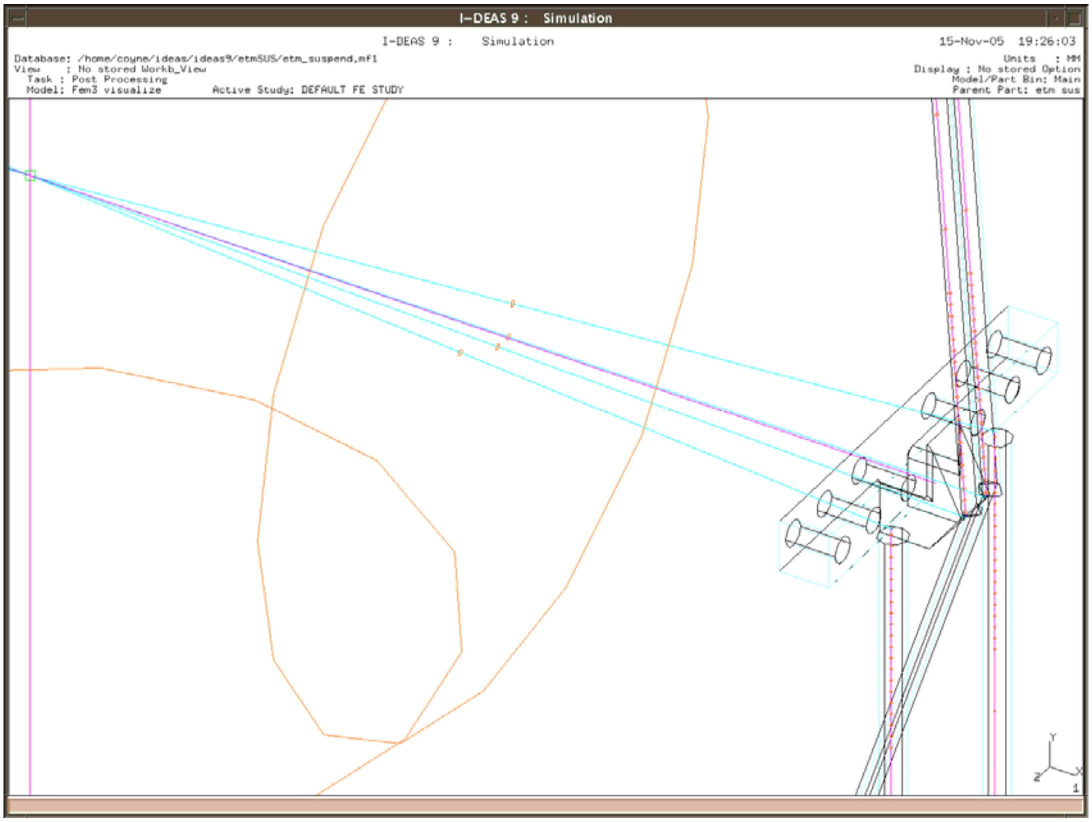
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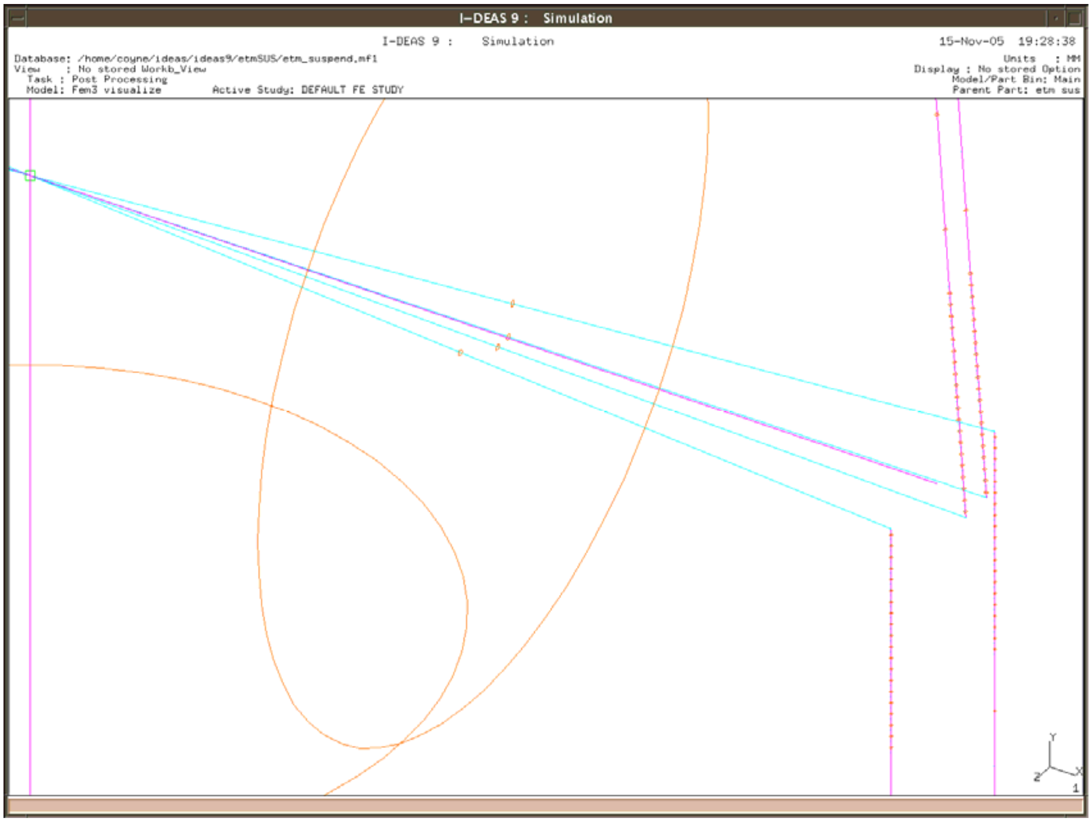
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3.2 Eigensolution

Explain concerns with low frequency solutions – may have a numerical eigensolver problem.

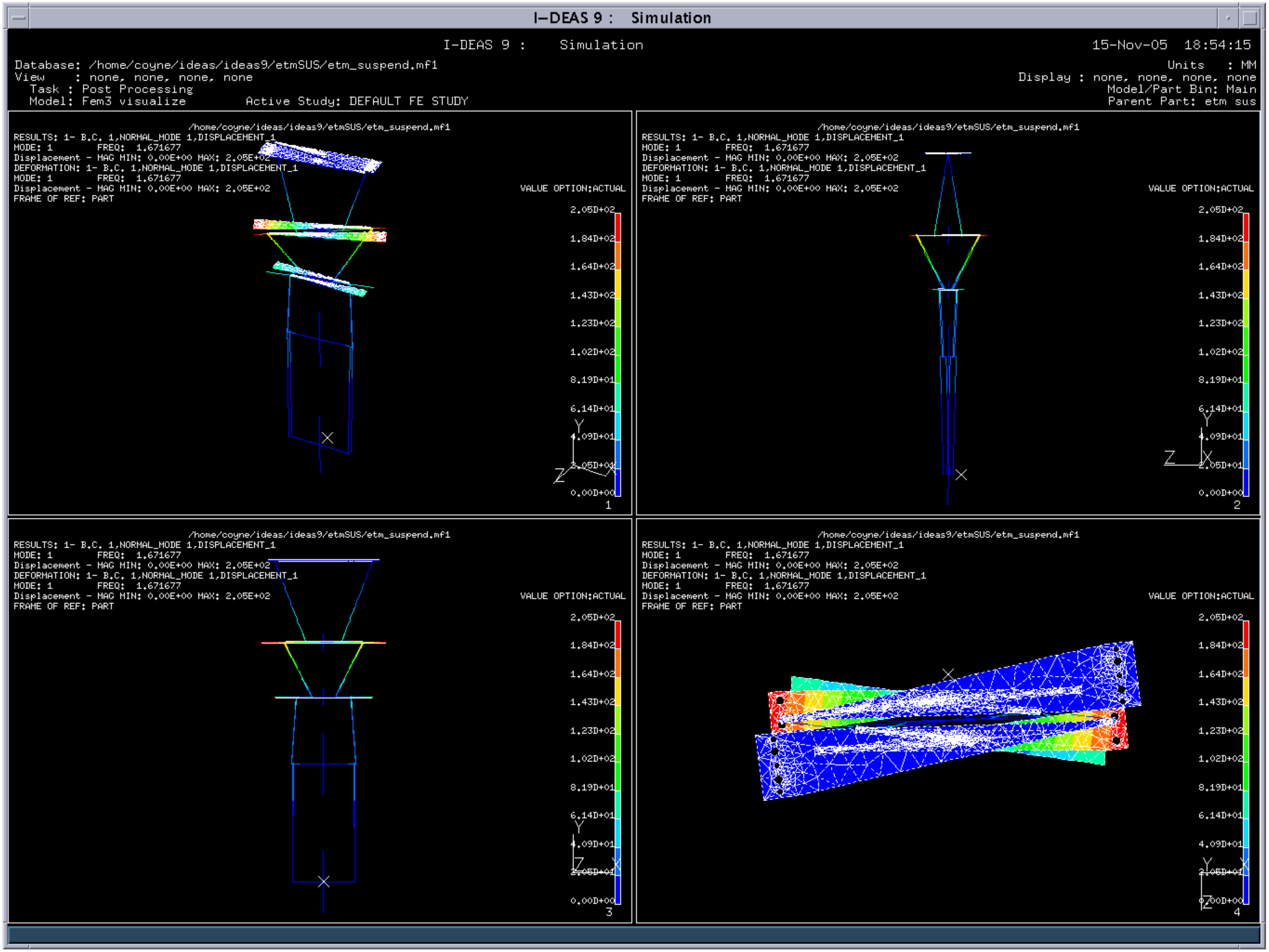
Table 1: Modal Frequencies

Mode #	Frequency(Hz) Undamped	Modal Prop. Mass	% X-Mass	% Y-Mass	% Z-Mass
*2	0.2549	1.32767e+06	3.58	0.00	0.00
*3	0.4358	4.73684e+07	0.00	0.00	77.20
*4	0.4707	2.41062e+07	68.87	0.00	0.00
*5	0.5408	525608	0.02	0.00	0.18
*6	0.5611	3.33127e+07	0.00	93.22	0.00
*7	0.9530	354642	0.00	0.00	0.00
*8	0.9879	9.72652e+06	0.00	0.00	15.25
*9	1.0346	9.75084e+06	17.46	0.00	0.00
*1	1.6717	342382	0.00	0.00	0.00
*10	1.7018	1.03984e+06	0.00	0.00	0.00
*11	1.7843	259162	1.04	0.00	0.01
*12	1.9703	2.59522e+06	0.05	0.00	5.05
*13	2.0580	676561	6.68	0.00	0.03
*14	2.1440	236195	0.27	0.00	0.01
*15	2.2637	2.22979e+06	0.00	5.22	0.00
*16	2.7155	271473	0.00	0.00	0.00
*17	2.8448	593596	0.01	0.00	0.00
*18	3.0861	400200	0.00	0.00	0.00
*19	3.2241	186502	0.14	0.00	0.01
*20	3.3555	843797	0.00	0.00	0.78
*21	3.6121	615741	0.00	0.43	0.00
*22	4.5777	1.03667e+06	0.38	0.00	0.00
*23	15.2017	3.3333e+06	0.00	0.00	0.00
*24	22.0533	908453	0.00	0.00	0.00
*25	64.6838	5238.6	0.01	0.00	0.00
*26	64.7360	5182.54	0.00	0.42	0.00
*27	93.4493	1746.49	0.00	0.00	0.00
*28	93.6721	1753.28	0.00	0.00	0.00
*29	112.9465	1153.3	0.00	0.00	0.00
*30	113.1198	1156.63	0.00	0.00	0.00

*26	64.7360	5182.54	0.00	0.42	0.00
*27	93.4493	1746.49	0.00	0.00	0.00
*28	93.6721	1753.28	0.00	0.00	0.00
*29	112.9465	1153.3	0.00	0.00	0.00
*30	113.1198	1156.63	0.00	0.00	0.00
*31	198.3211	940.398	0.00	0.02	0.00
*32	198.3726	945.893	0.00	0.16	0.00
*33	238.2189	25.3292	0.00	0.00	0.00
*34	238.2189	42.044	0.00	0.00	0.00
*35	238.2189	38.9075	0.00	0.00	0.00
*36	238.2189	77.564	0.00	0.00	0.00
*37	238.2189	25.3374	0.00	0.00	0.00
*38	238.2225	52.3369	0.00	0.00	0.00
*39	238.2225	52.3368	0.00	0.00	0.00
*40	238.2317	52.7298	0.00	0.00	0.00

Mode shape plots are given in the following figures.

Mode shape movies for the first 33 modes follow.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MODE: 1 FREQ: 1.671677
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1.84D+02
1.64D+02
1.43D+02
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1.02D+02
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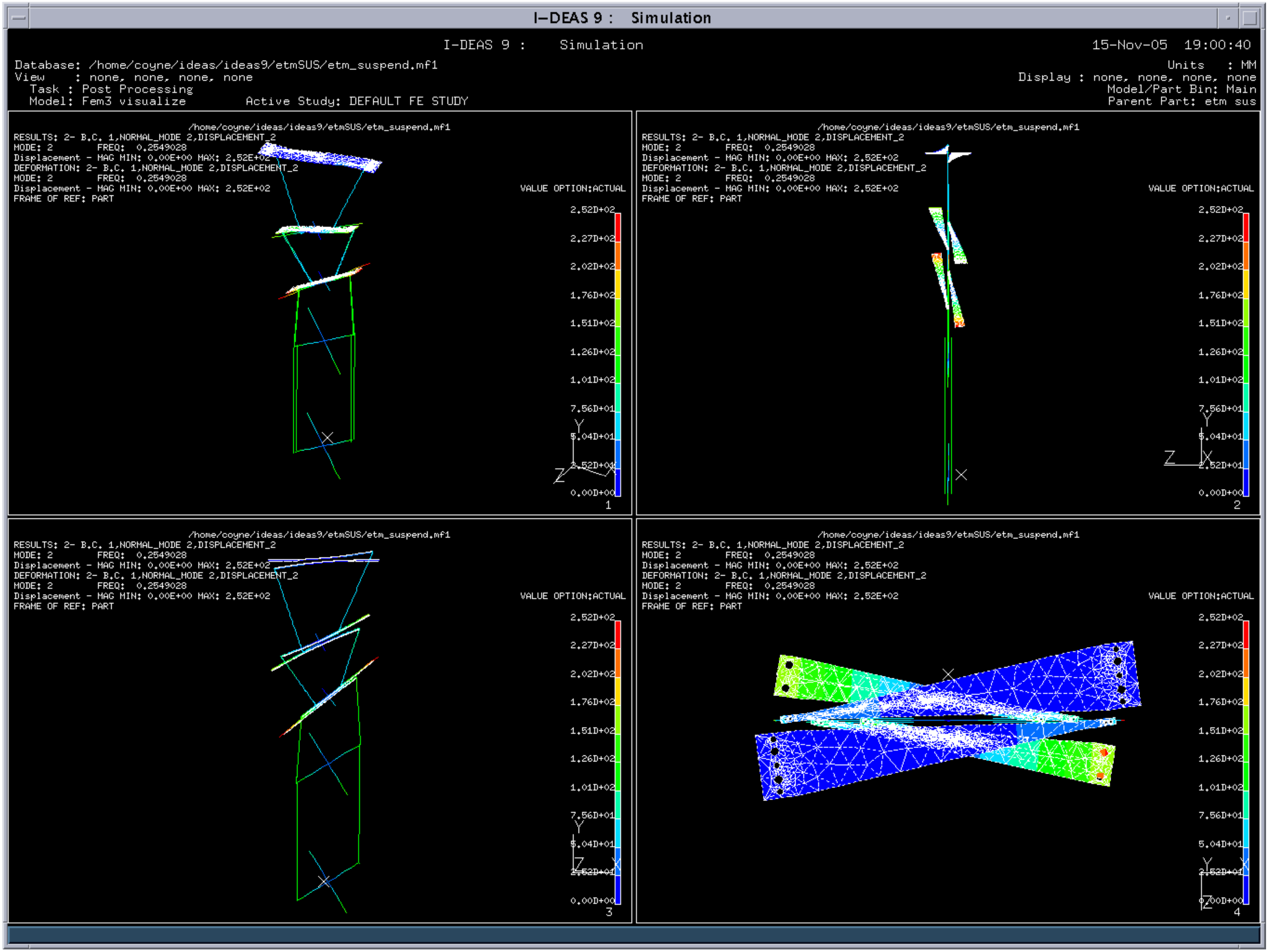
4.09D+01
2.05D+01
0.00D+00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Units : MM
Display : none, none, none, none
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Parent Part: etm sus
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MODE: 2 FREQ: 0.2549028
Displacement - MAG MIN: 0.00E+00 MAX: 2.52E+02
DEFORMATION: 2- B.C. 1,NORMAL_MODE 2,DISPLACEMENT_2
MODE: 2 FREQ: 0.2549028
Displacement - MAG MIN: 0.00E+00 MAX: 2.52E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
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2.27D+02
2.02D+02
1.76D+02
1.51D+02
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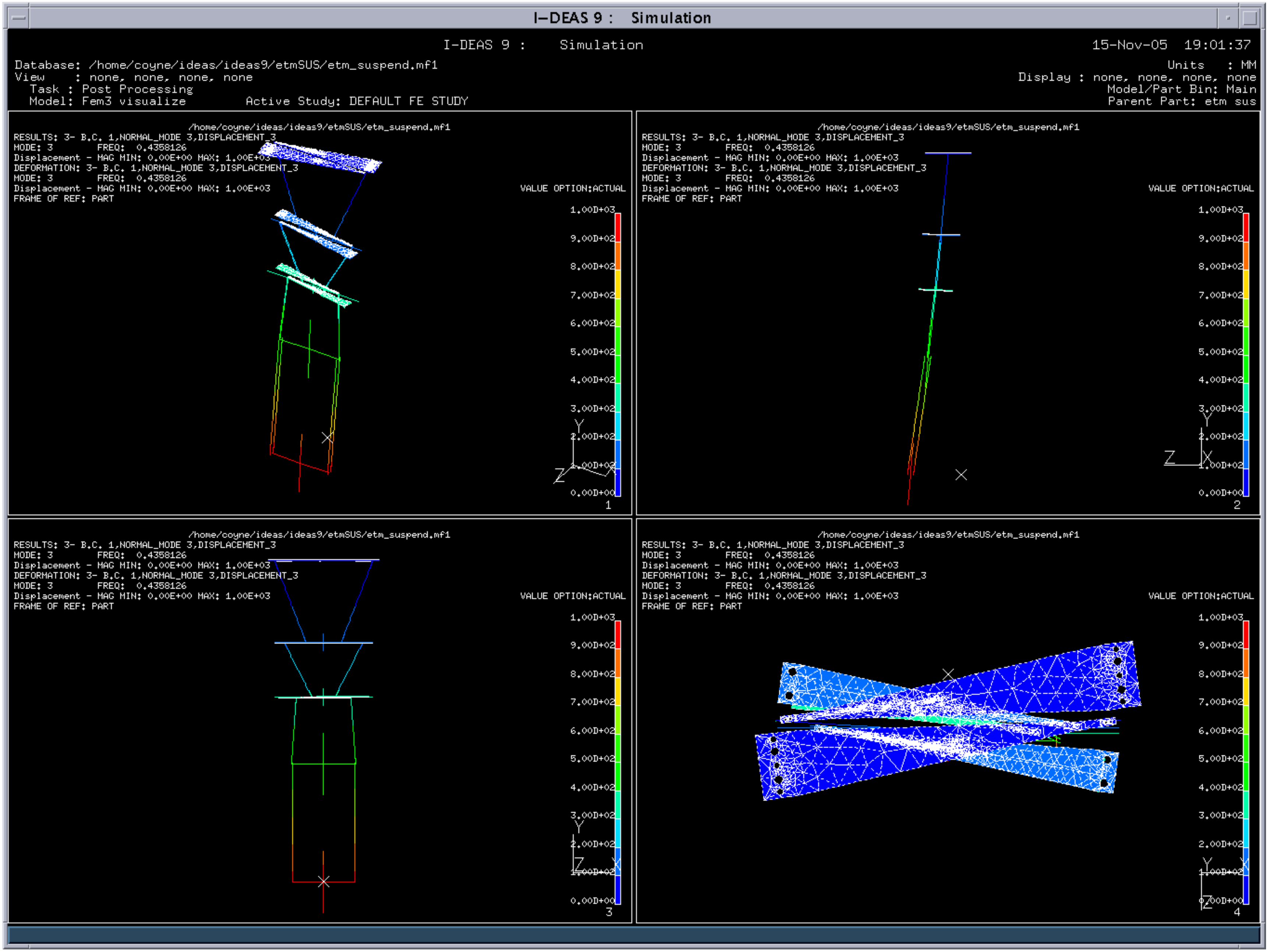
1
2
3
4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Displacement - MAG MIN: 0.00E+00 MAX: 1.00E+03
FRAME OF REF: PART
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9.00D+02
8.00D+02
7.00D+02
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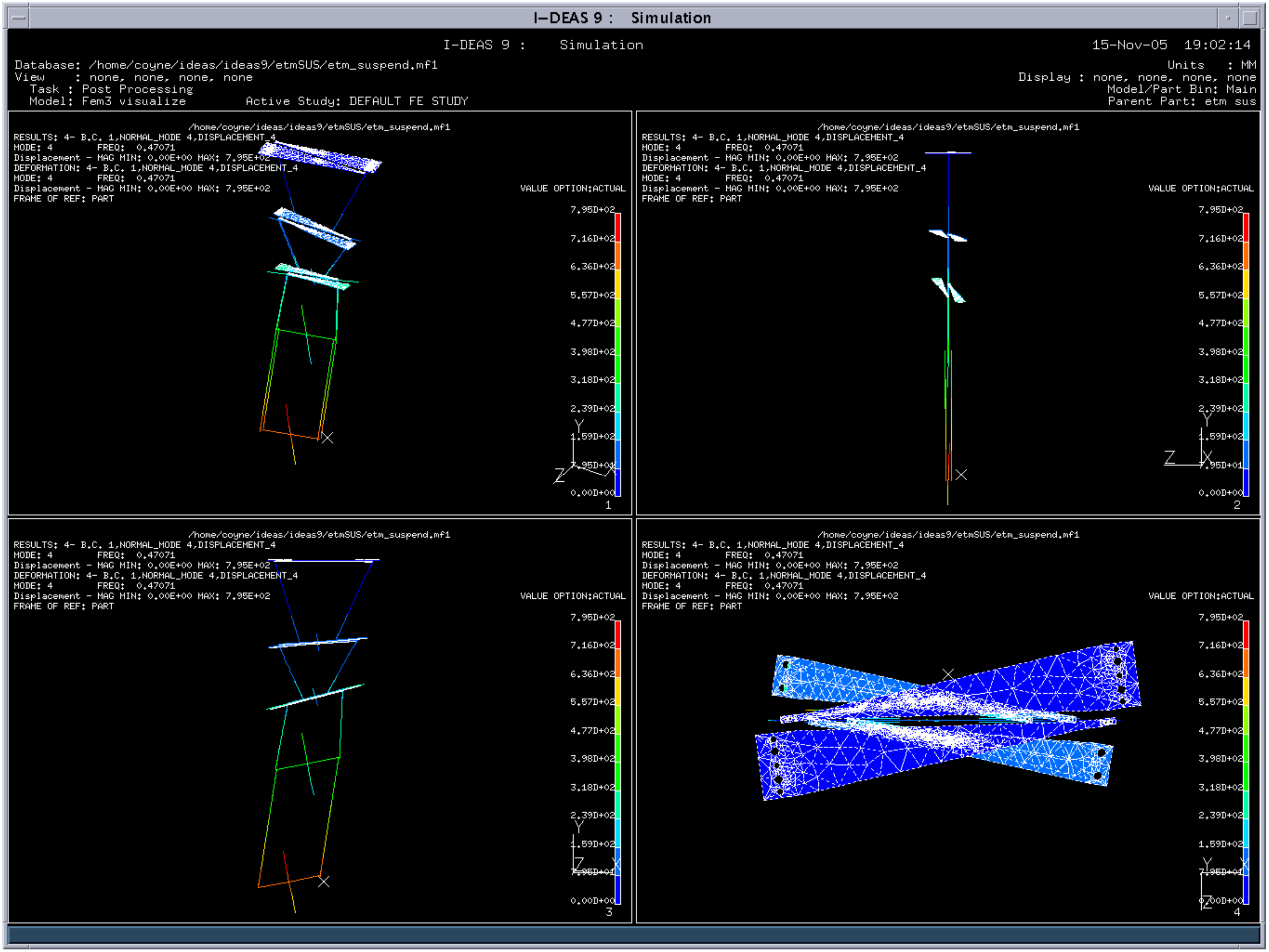
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MODE: 4 FREQ: 0.47071
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6.36D+02
5.57D+02
4.77D+02
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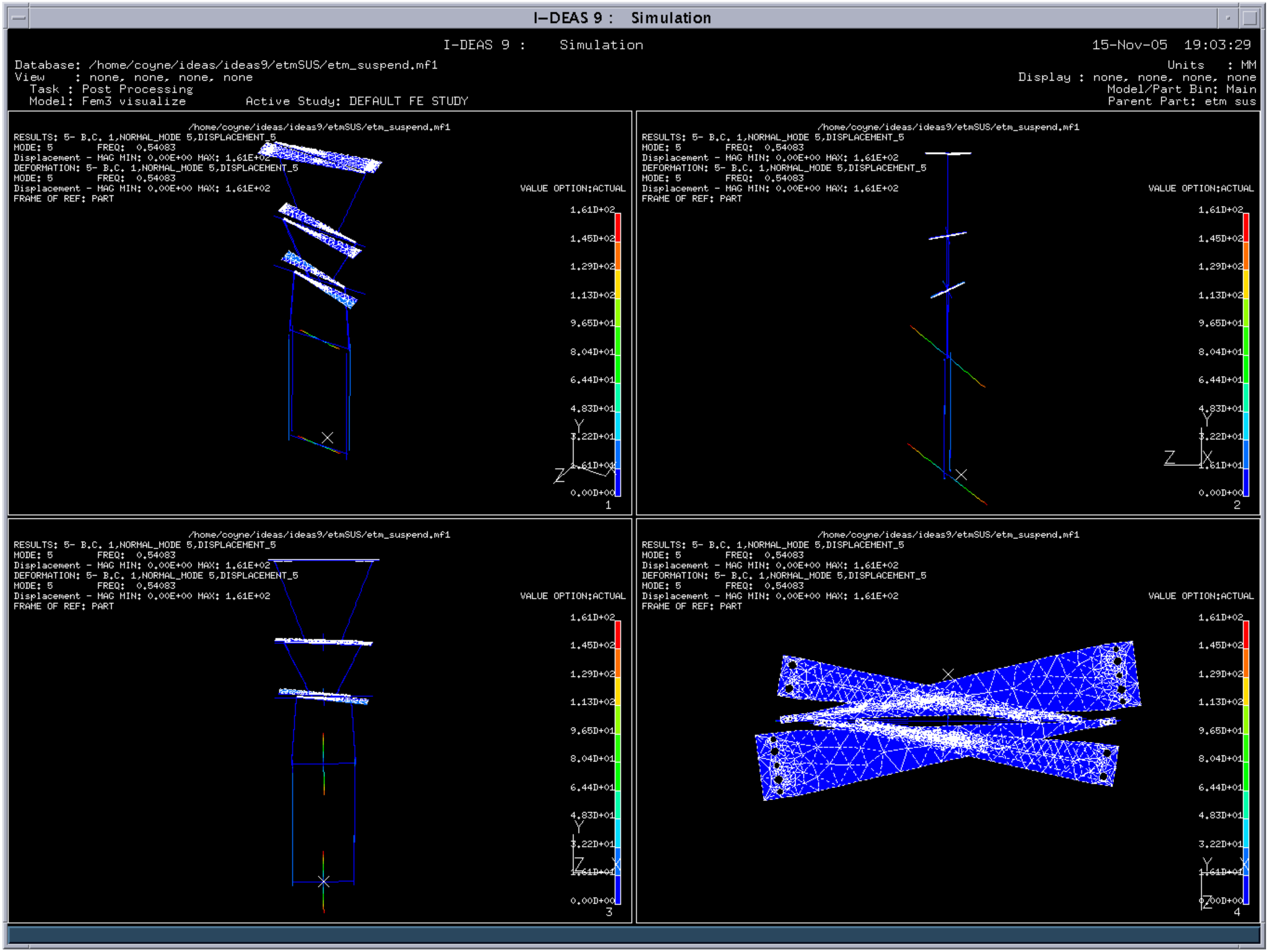
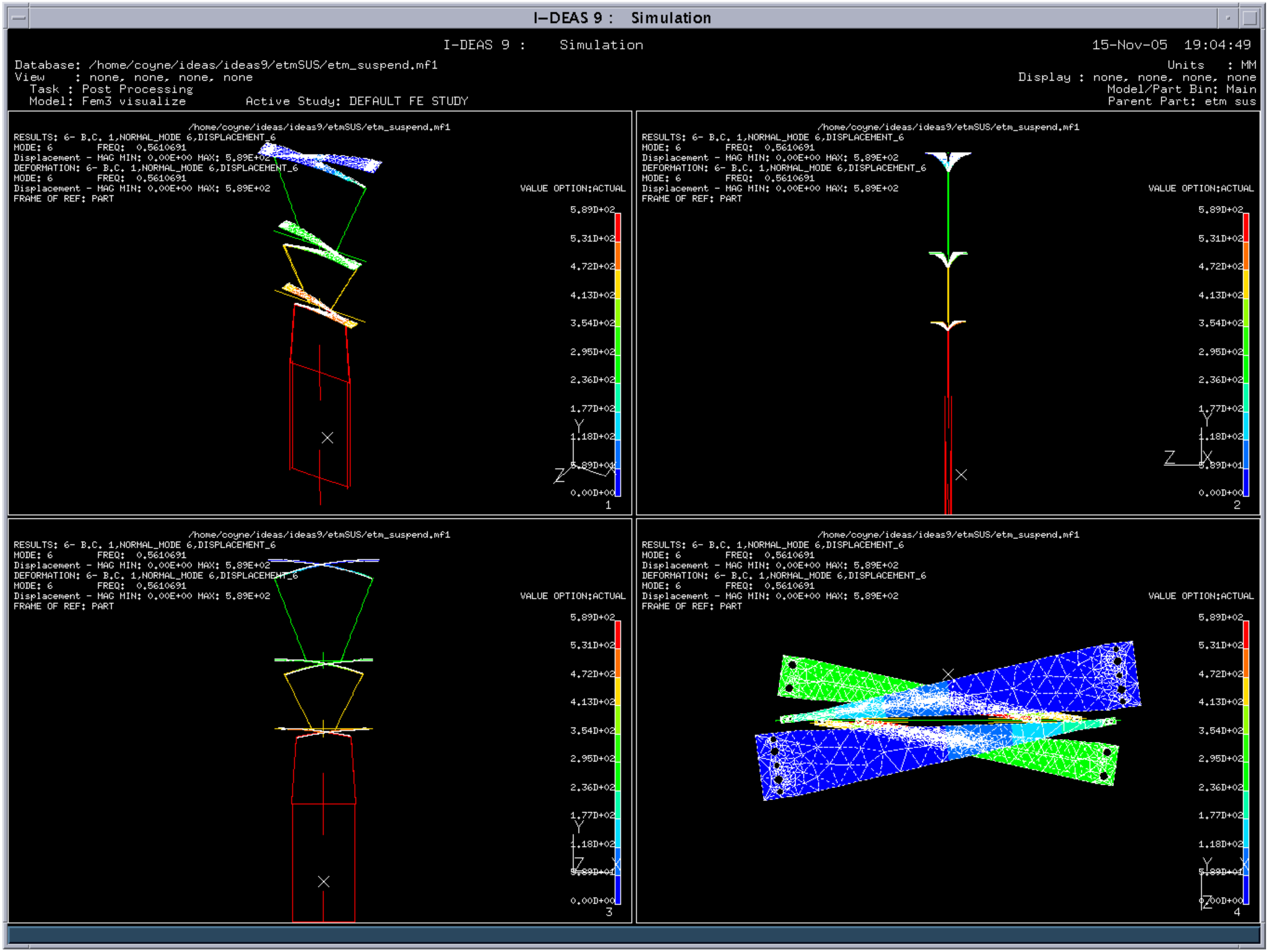
7.95D+01
0.00D+00
1
2
3
4

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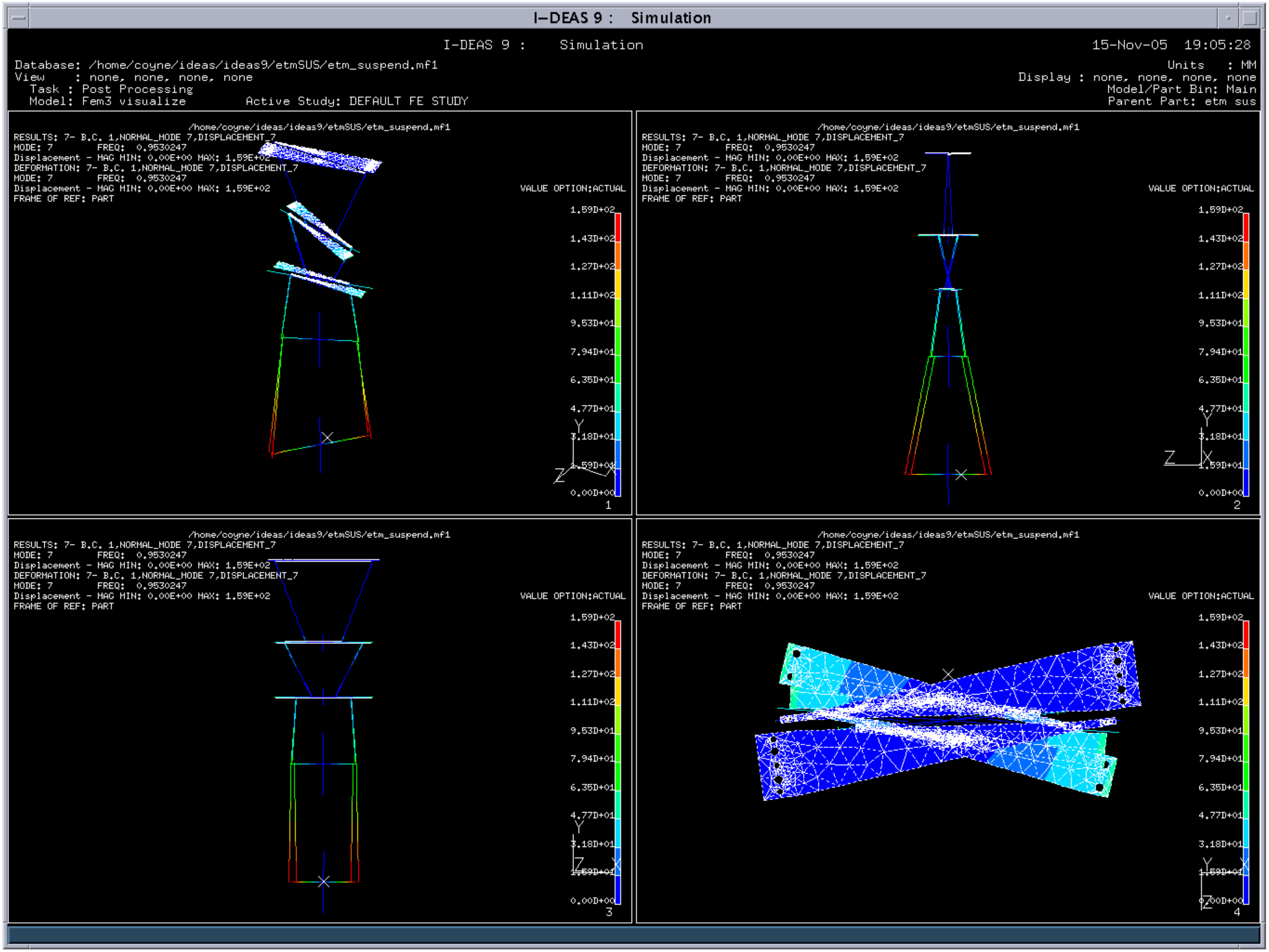
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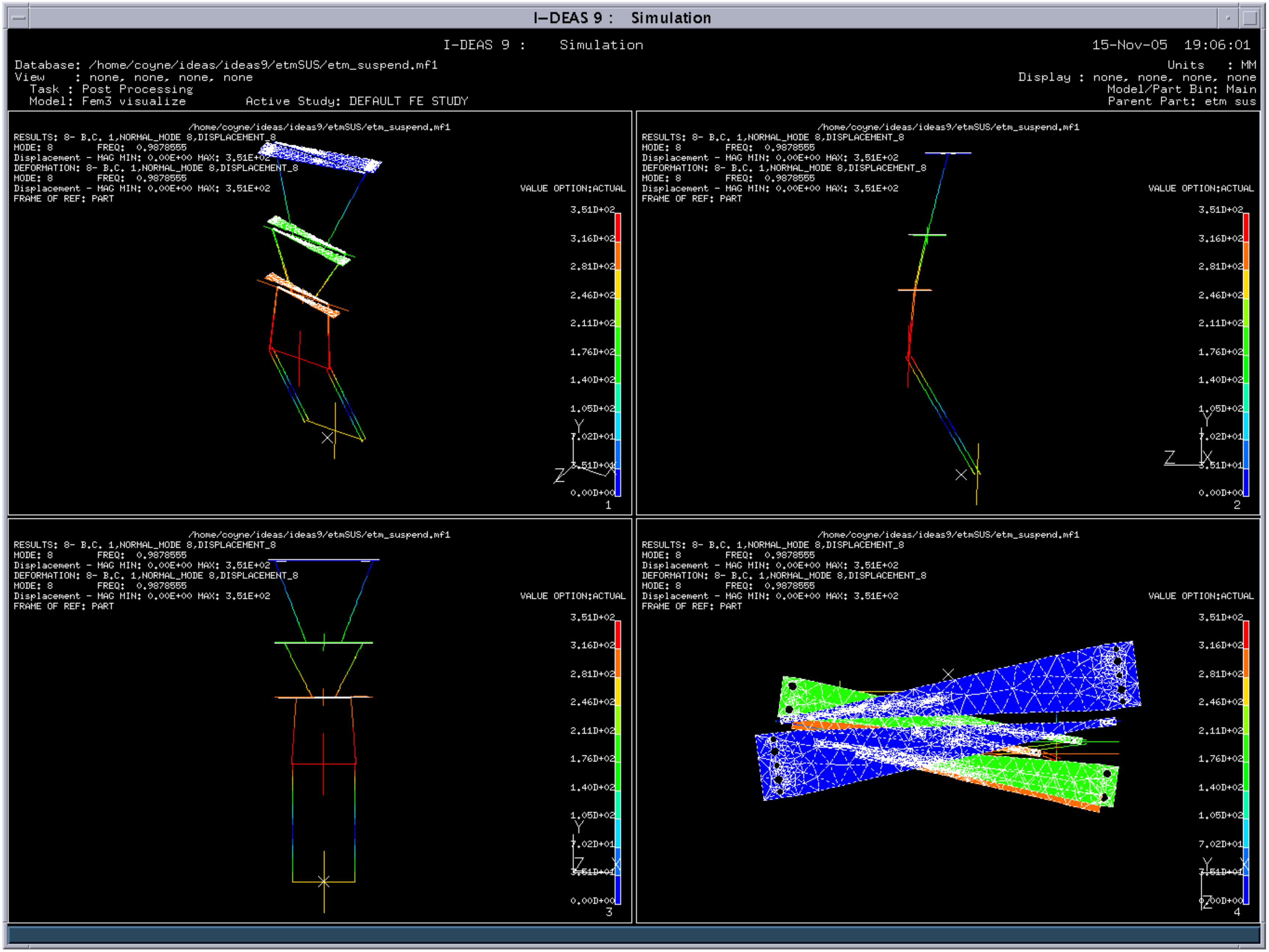
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MODE: 8 FREQ: 0.9878555
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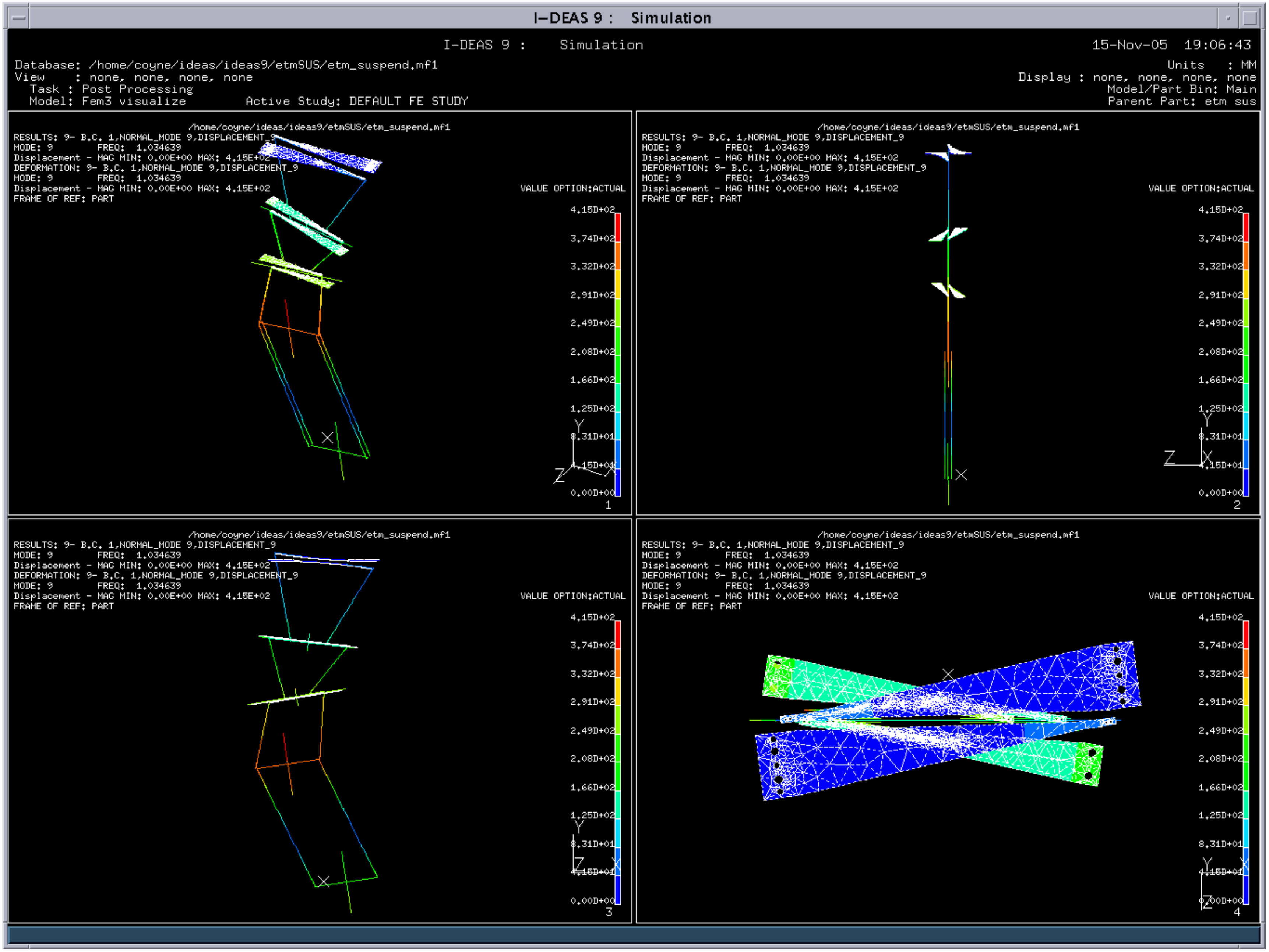
1
2
3
4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Parent Part: etm sus
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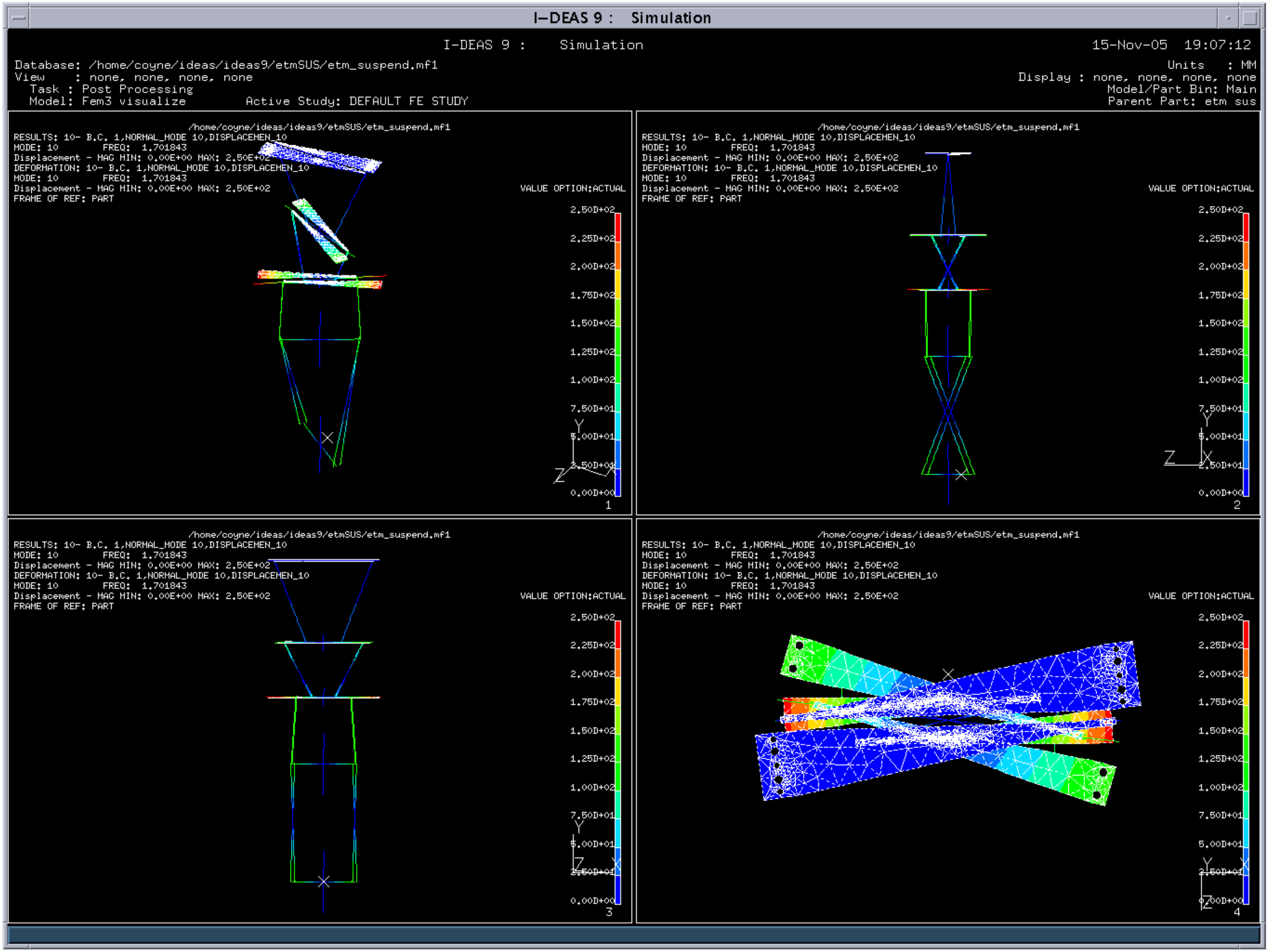
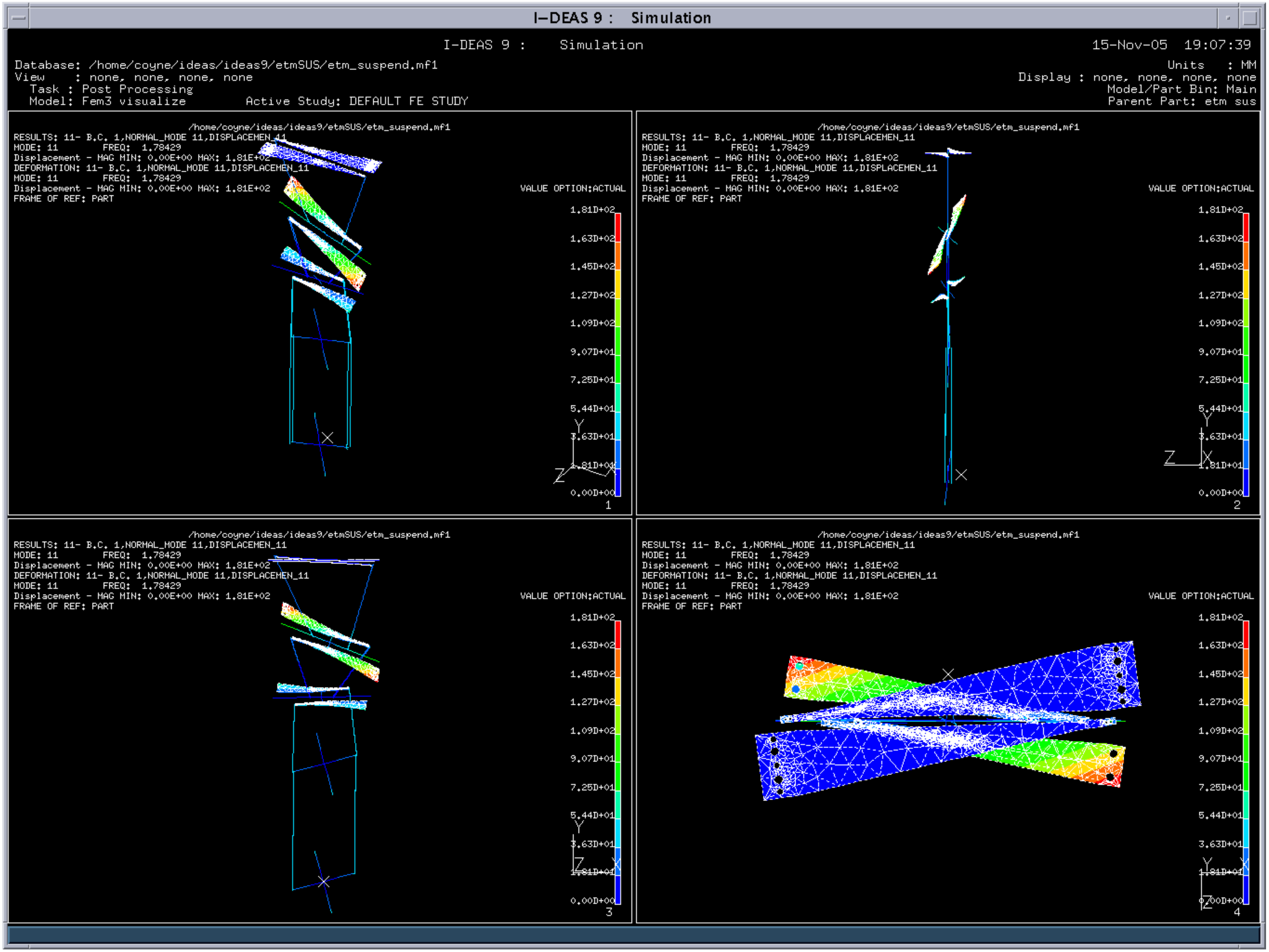
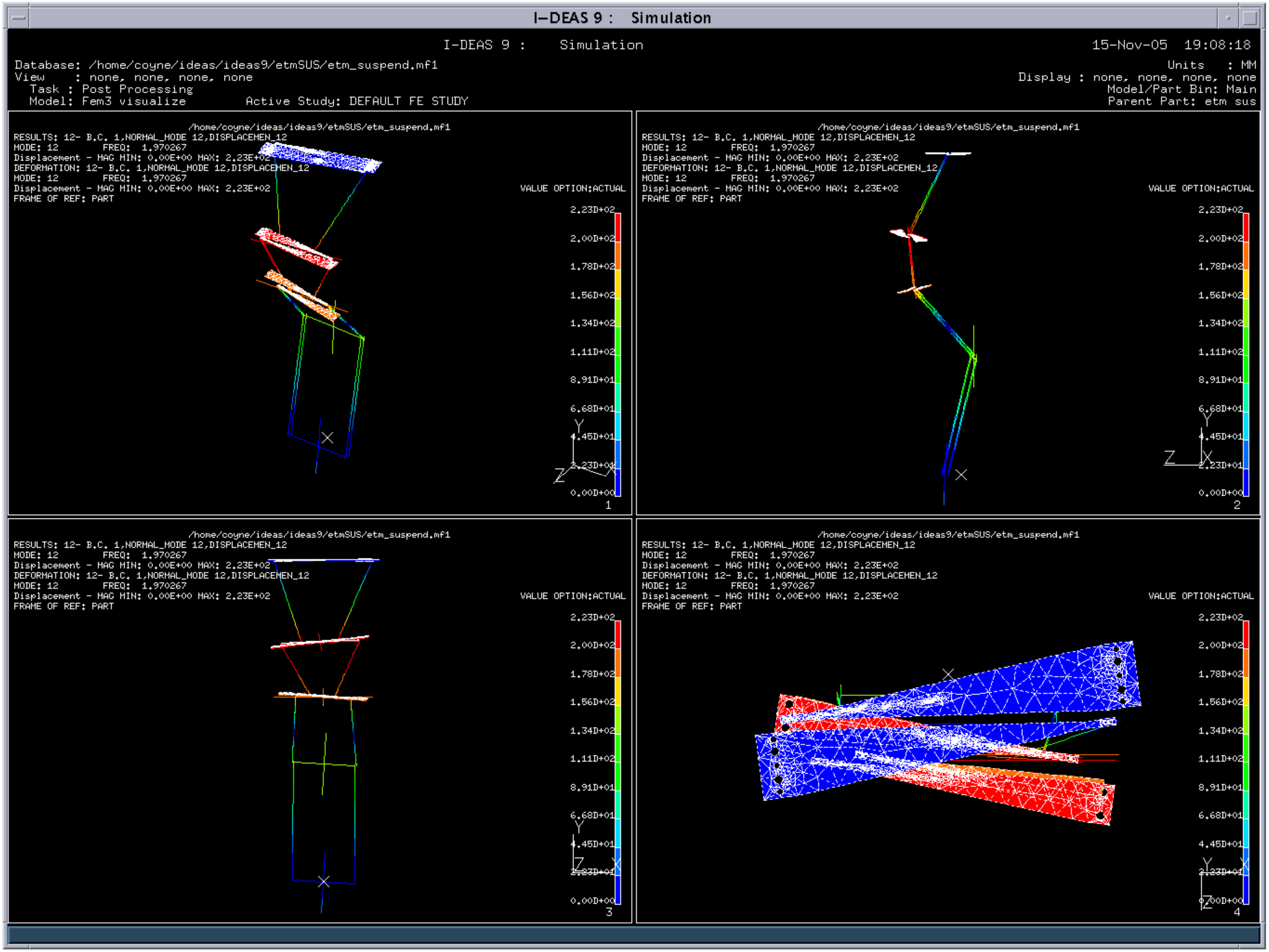
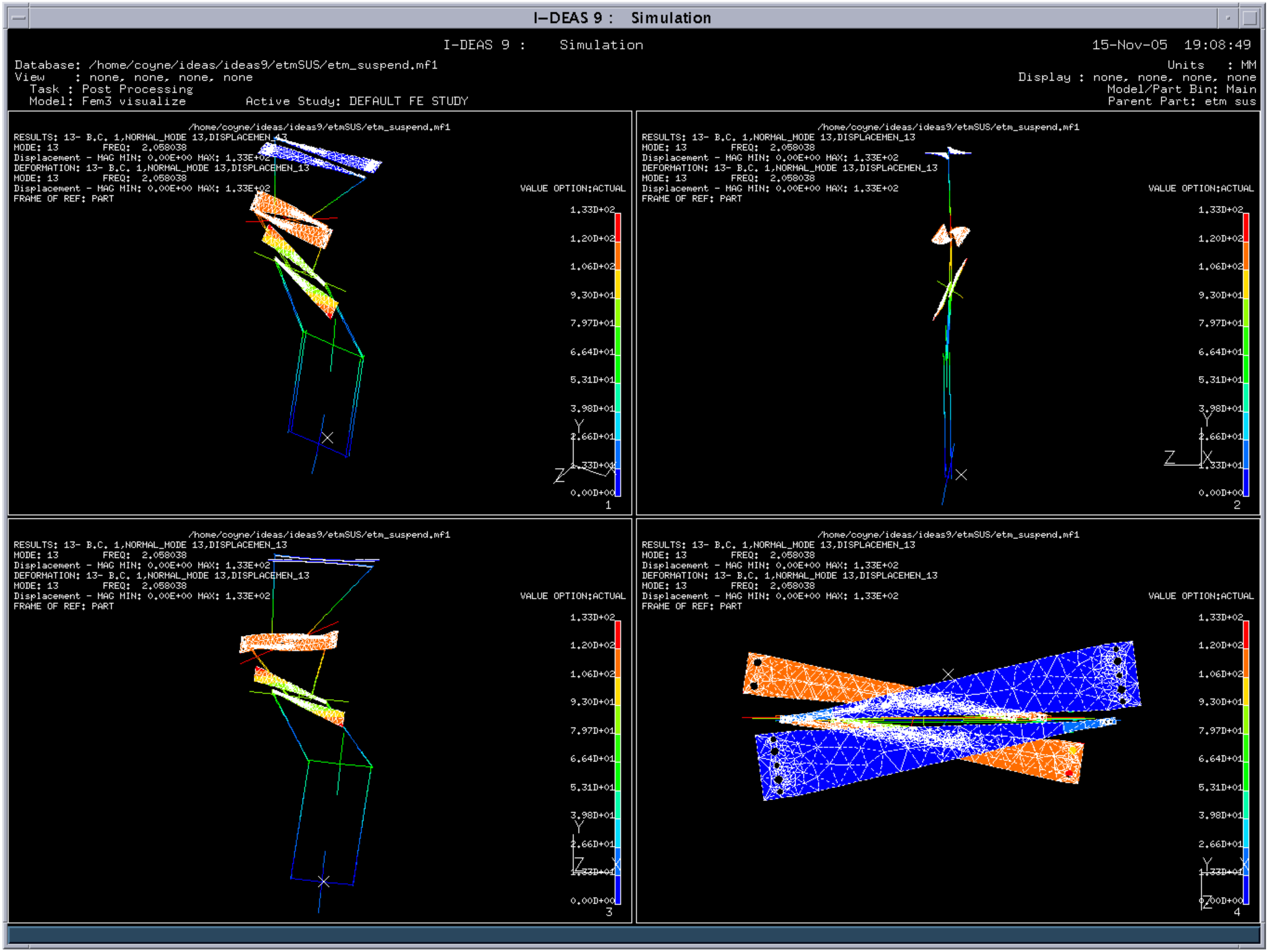
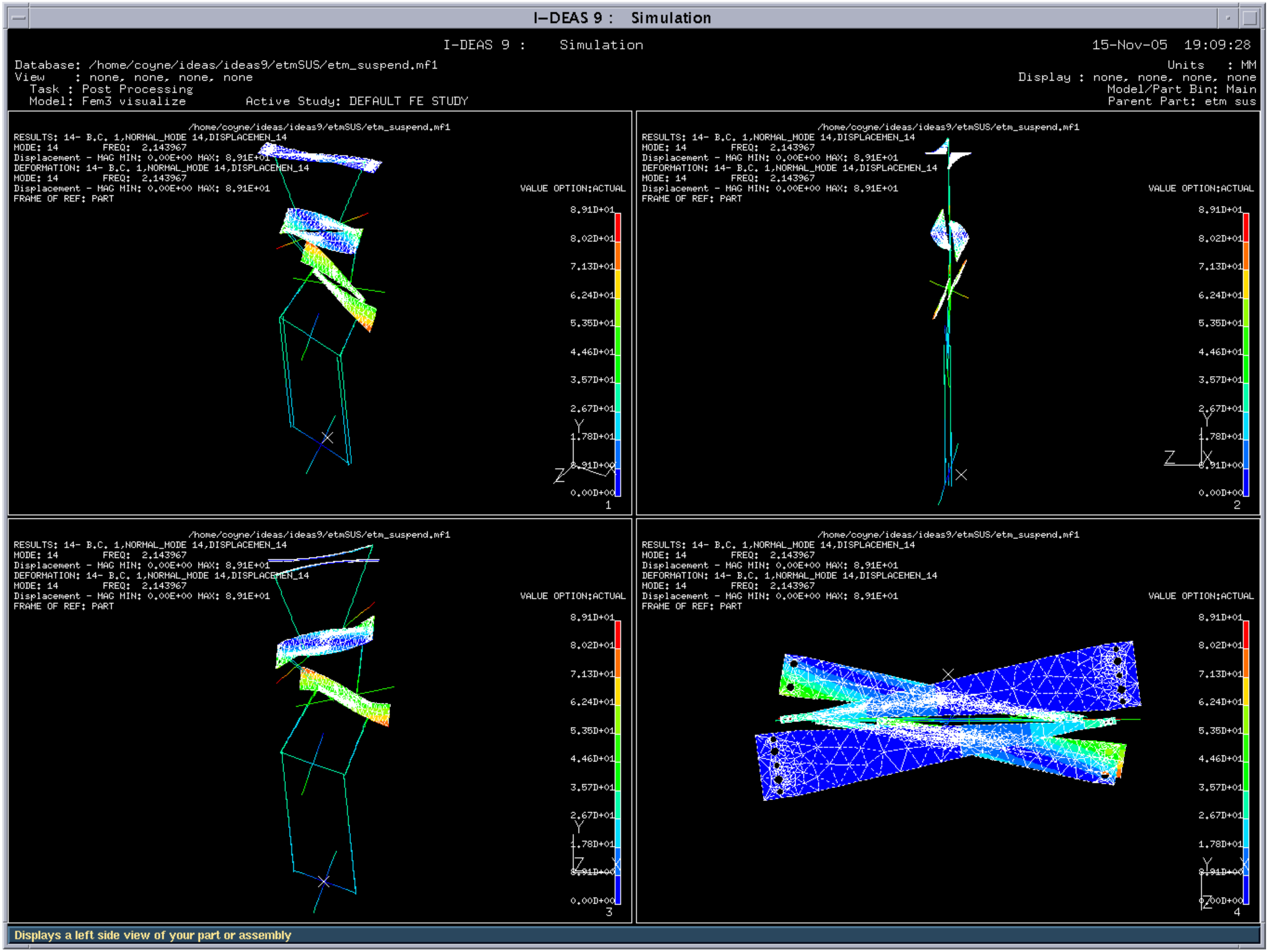
MODE: 9 FREQ: 1.034639
Displacement - MAG MIN: 0.00E+00 MAX: 4.15E+02
DEFORMATION: 9- B.C. 1,NORMAL_MODE 9,DISPLACEMENT_9
MODE: 9 FREQ: 1.034639
Displacement - MAG MIN: 0.00E+00 MAX: 4.15E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
4.15D+02
3.74D+02
3.32D+02
2.91D+02
2.49D+02
2.08D+02
1.66D+02
1.25D+02
8.31D+01
4.15D+01
0.00D+00

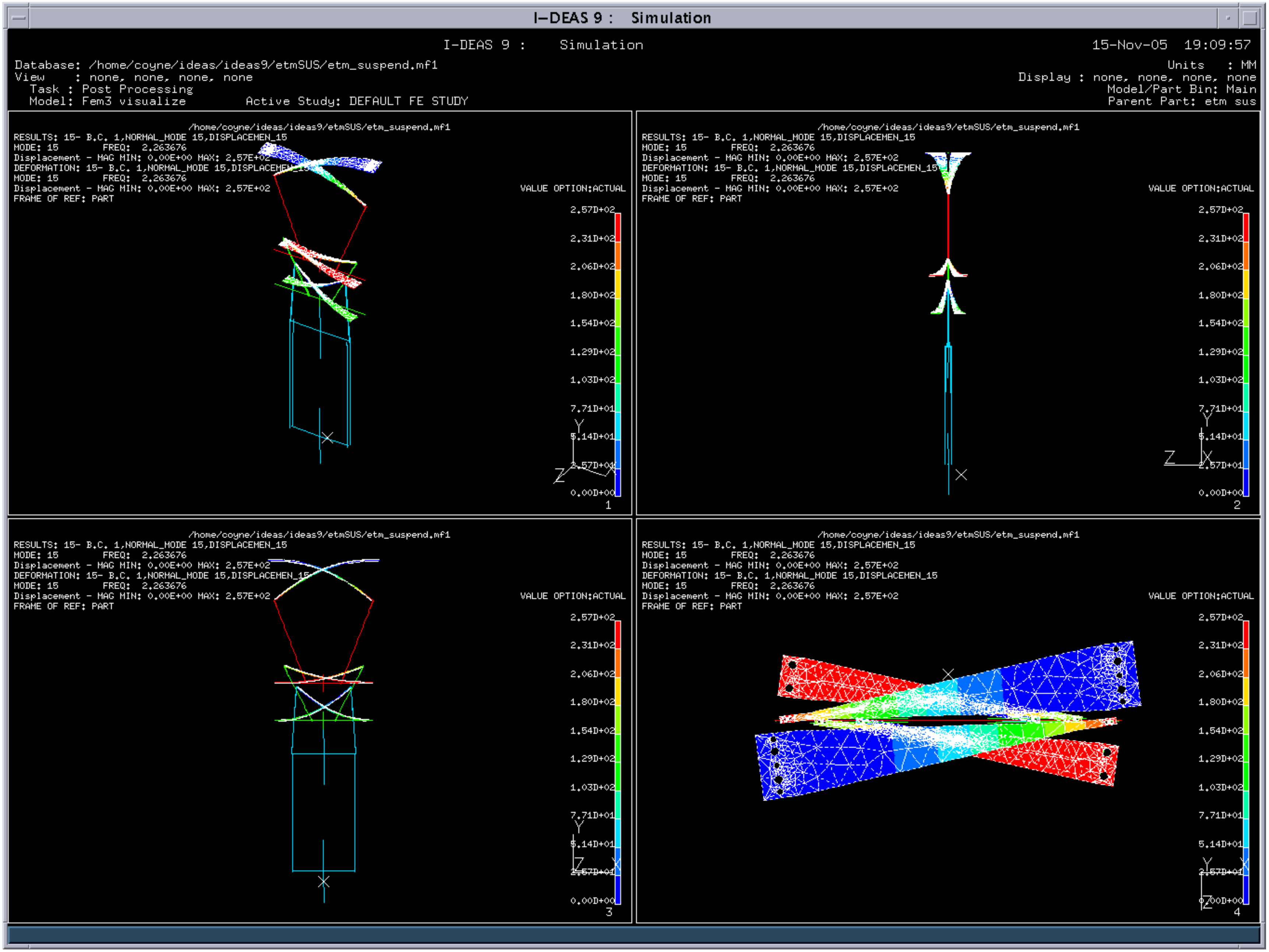

I-DEAS 9 : Simulation
15-Nov-05 19:07:12
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 10- B.C. 1,NORMAL_MODE 10,DISPLACEMEN_10
MODE: 10 FREQ: 1.701843
Displacement - MAG MIN: 0.00E+00 MAX: 2.50E+02
DEFORMATION: 10- B.C. 1,NORMAL_MODE 10,DISPLACEMEN_10
MODE: 10 FREQ: 1.701843
Displacement - MAG MIN: 0.00E+00 MAX: 2.50E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL

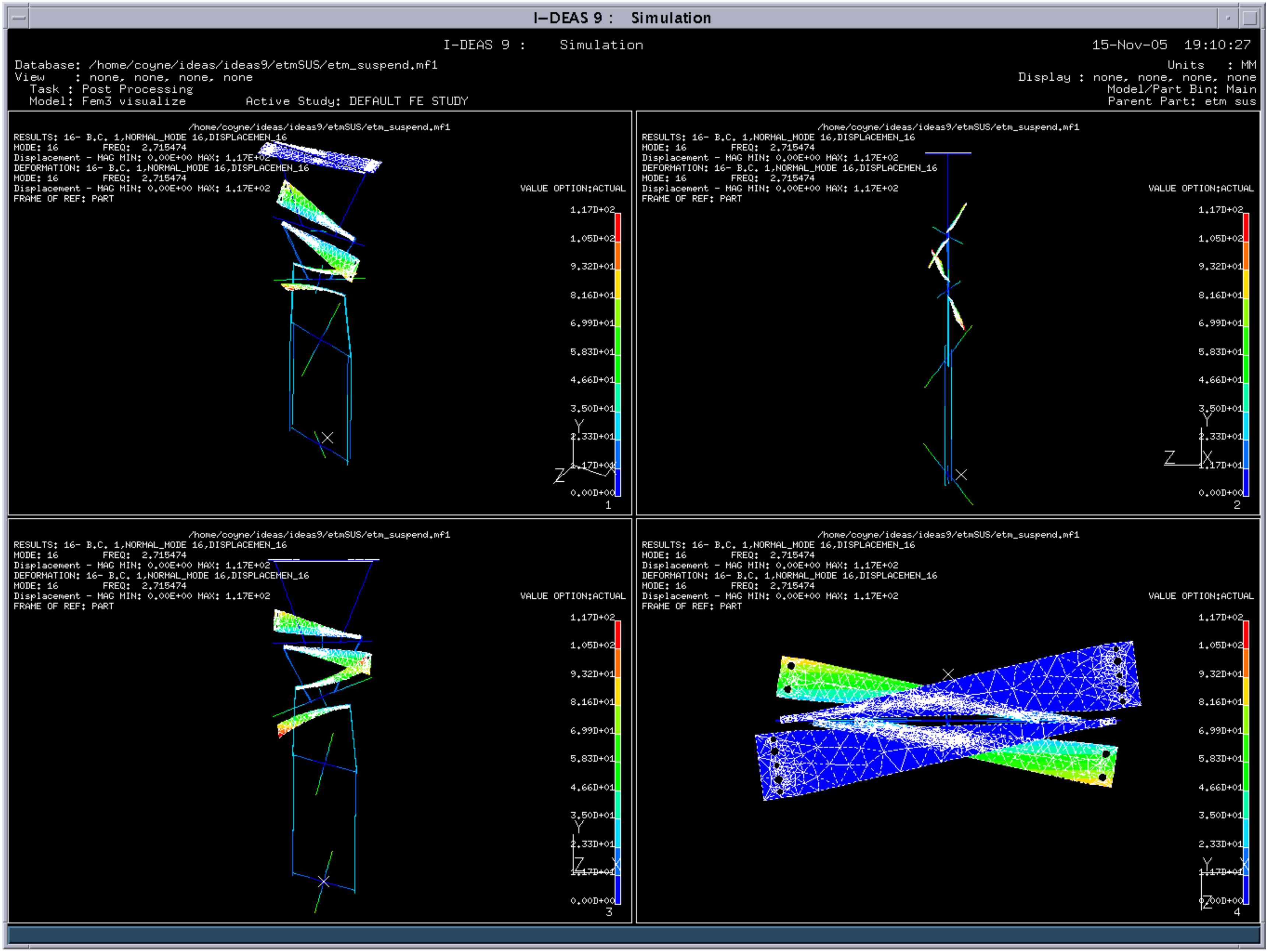

I-DEAS 9 : Simulation
15-Nov-05 19:07:39
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
RESULTS: 11- B.C. 1,NORMAL_MODE 11,DISPLACEMEN_11
MODE: 11 FREQ: 1.78429
Displacement - MAG MIN: 0.00E+00 MAX: 1.81E+02
DEFORMATION: 11- B.C. 1,NORMAL_MODE 11,DISPLACEMEN_11
FRAME OF REF: PART
VALUE OPTION:ACTUAL

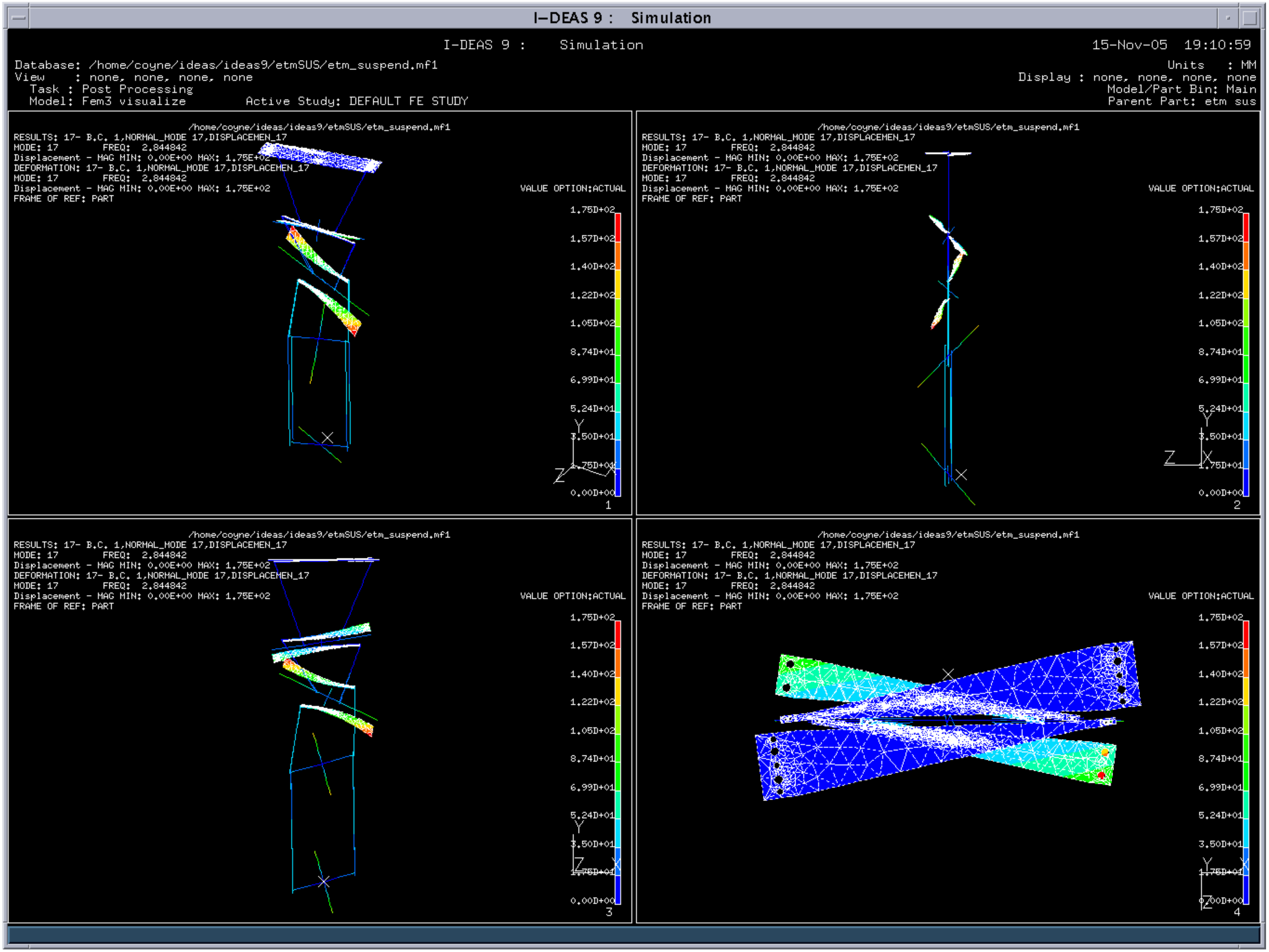

I-DEAS 9 : Simulation
15-Nov-05 19:08:18
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 12- B.C. 1,NORMAL_MODE 12,DISPLACEMEN_12
MODE: 12 FREQ: 1.970267
Displacement - MAG MIN: 0.00E+00 MAX: 2.23E+02
DEFORMATION: 12- B.C. 1,NORMAL_MODE 12,DISPLACEMEN_12
MODE: 12 FREQ: 1.970267
Displacement - MAG MIN: 0.00E+00 MAX: 2.23E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
2.23D+02
2.00D+02
1.78D+02
1.56D+02
1.34D+02
1.11D+02
8.91D+01
6.68D+01
4.45D+01
2.23D+01
0.00D+00

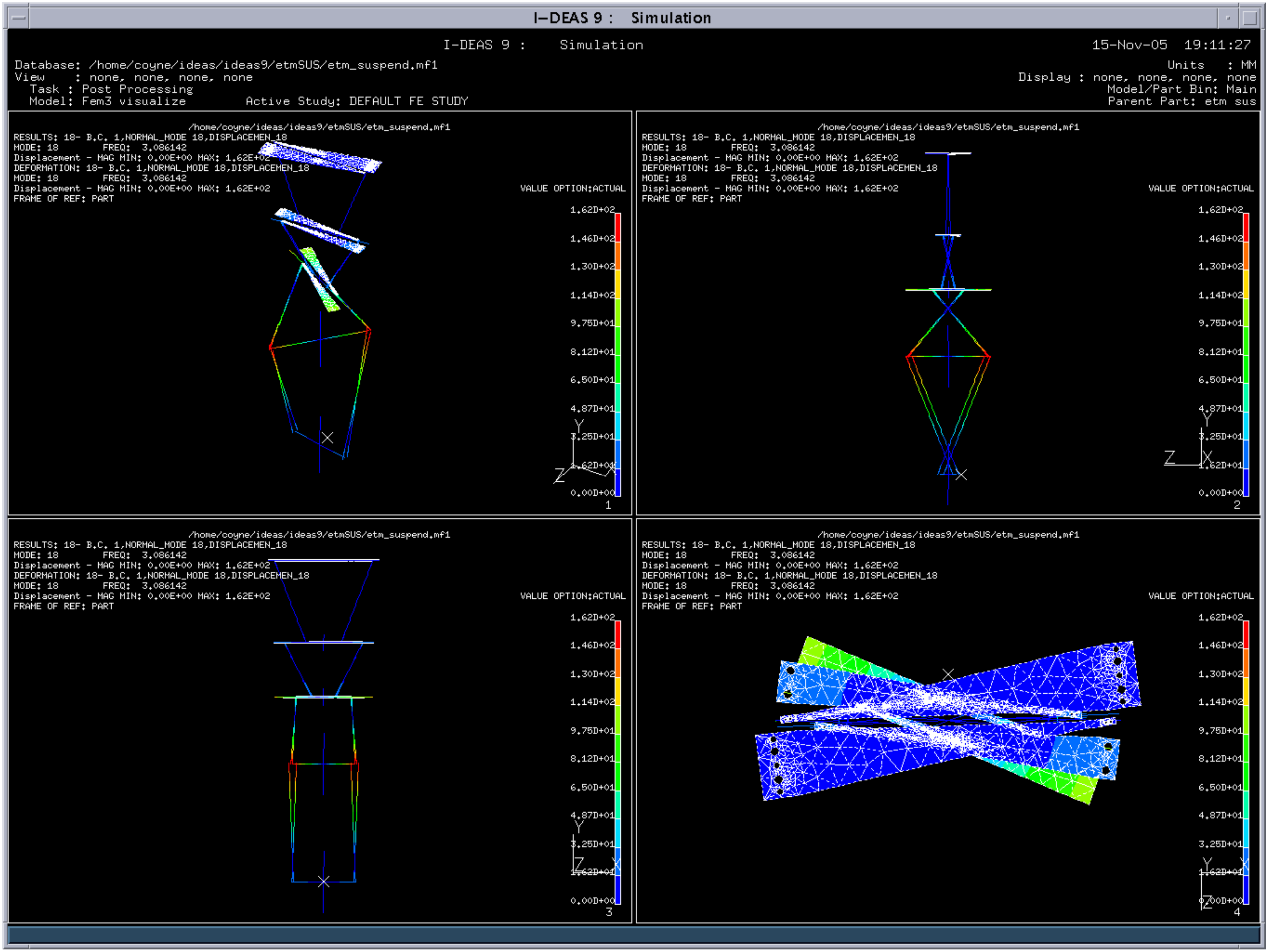

I-DEAS 9 : Simulation
I-DEAS 9 : Simulation
15-Nov-05 19:08:49
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 13- B.C. 1,NORMAL_MODE 13,DISPLACEMEN_13
MODE: 13 FREQ: 2.058038
Displacement - MAG MIN: 0.00E+00 MAX: 1.33E+02
DEFORMATION: 13- B.C. 1,NORMAL_MODE 13,DISPLACEMEN_13
MODE: 13 FREQ: 2.058038
Displacement - MAG MIN: 0.00E+00 MAX: 1.33E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
1.33D+02
1.20D+02
1.06D+02
9.30D+01
7.97D+01
6.64D+01
5.31D+01
3.98D+01
2.66D+01
1.33D+01
0.00D+00

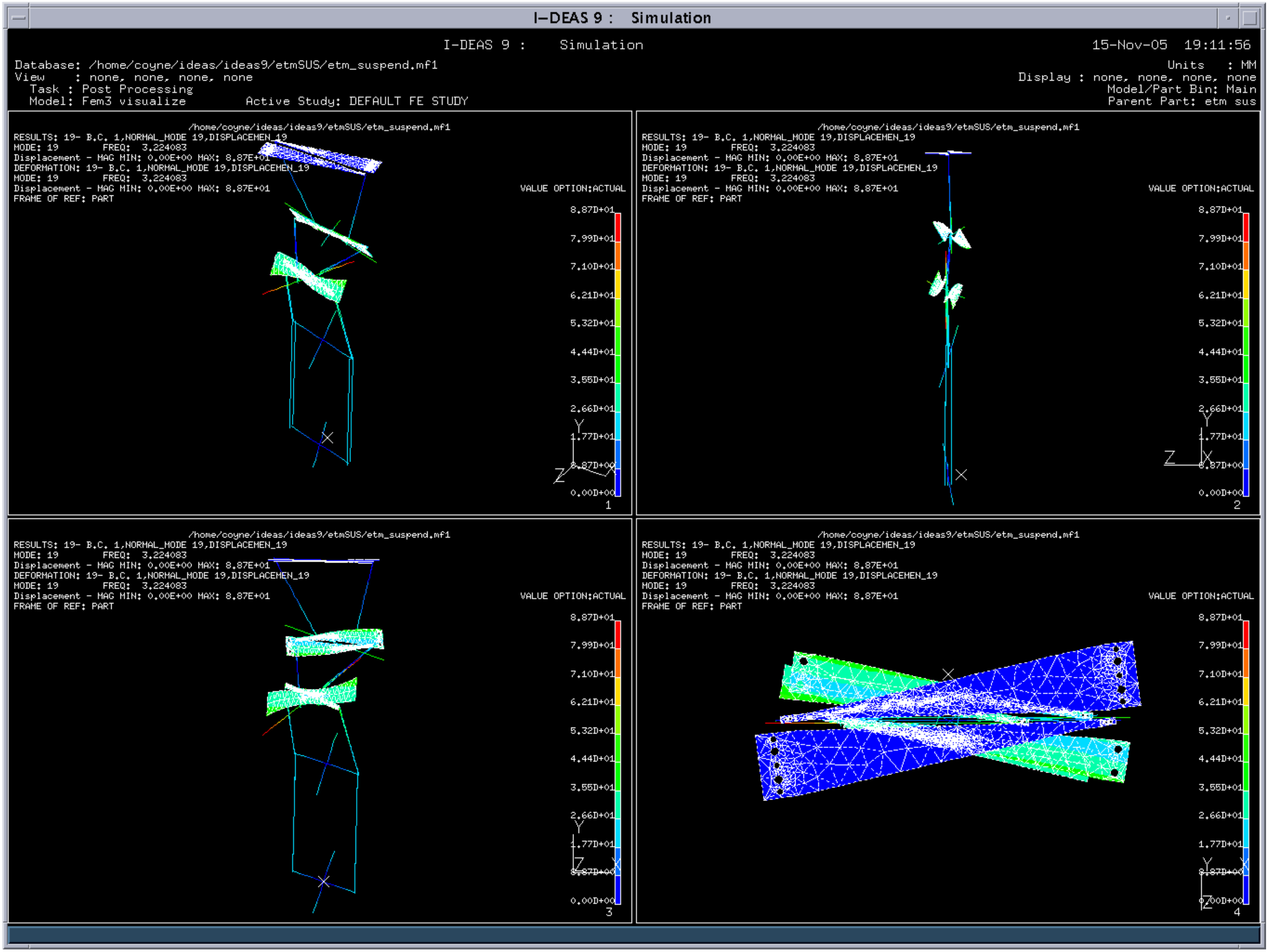

I-DEAS 9 : Simulation
I-DEAS 9 : Simulation
15-Nov-05 19:09:28
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 14- B.C. 1,NORMAL_MODE 14,DISPLACEMEN_14
MODE: 14 FREQ: 2.143967
Displacement - MAG MIN: 0.00E+00 MAX: 8.91E+01
DEFORMATION: 14- B.C. 1,NORMAL_MODE 14,DISPLACEMEN_14
MODE: 14 FREQ: 2.143967
Displacement - MAG MIN: 0.00E+00 MAX: 8.91E+01
FRAME OF REF: PART
VALUE OPTION:ACTUAL
8.91D+01
8.02D+01
7.13D+01
6.24D+01
5.35D+01
4.46D+01
3.57D+01
2.67D+01
1.78D+01
8.91D+00
0.00D+00
Displays a left side view of your part or assembly

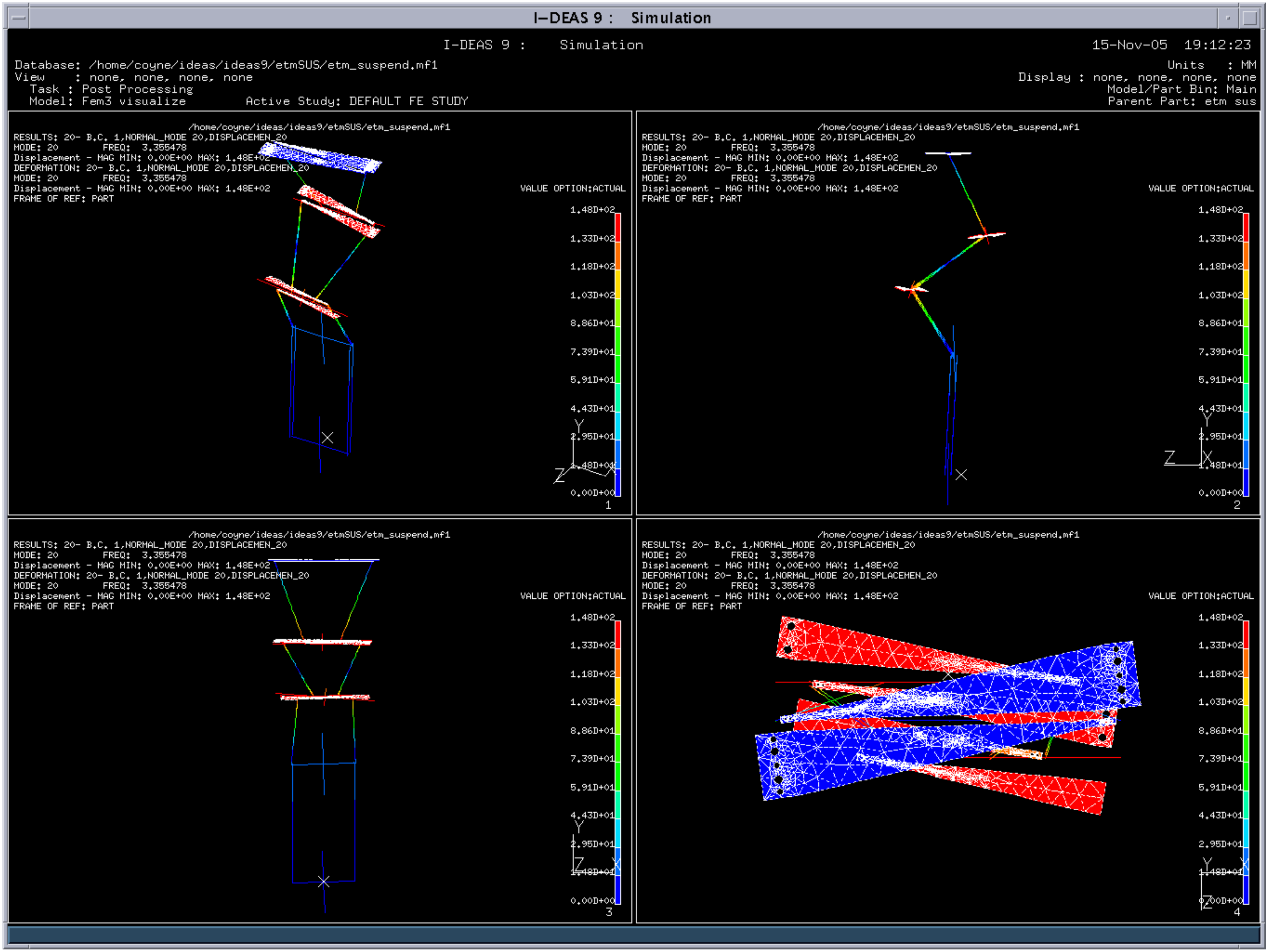

I-DEAS 9 : Simulation
I-DEAS 9 : Simulation 15-Nov-05 19:09:57
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 15- B.C. 1,NORMAL_MODE 15,DISPLACEMEN_15
MODE: 15 FREQ: 2.263676
Displacement - MAG MIN: 0.00E+00 MAX: 2.57E+02
DEFORMATION: 15- B.C. 1,NORMAL_MODE 15,DISPLACEMEN_15
FRAME OF REF: PART
VALUE OPTION:ACTUAL
2.57D+02
2.31D+02
2.06D+02
1.80D+02
1.54D+02
1.29D+02
1.03D+02
7.71D+01
5.14D+01
2.57D+01
0.00D+00

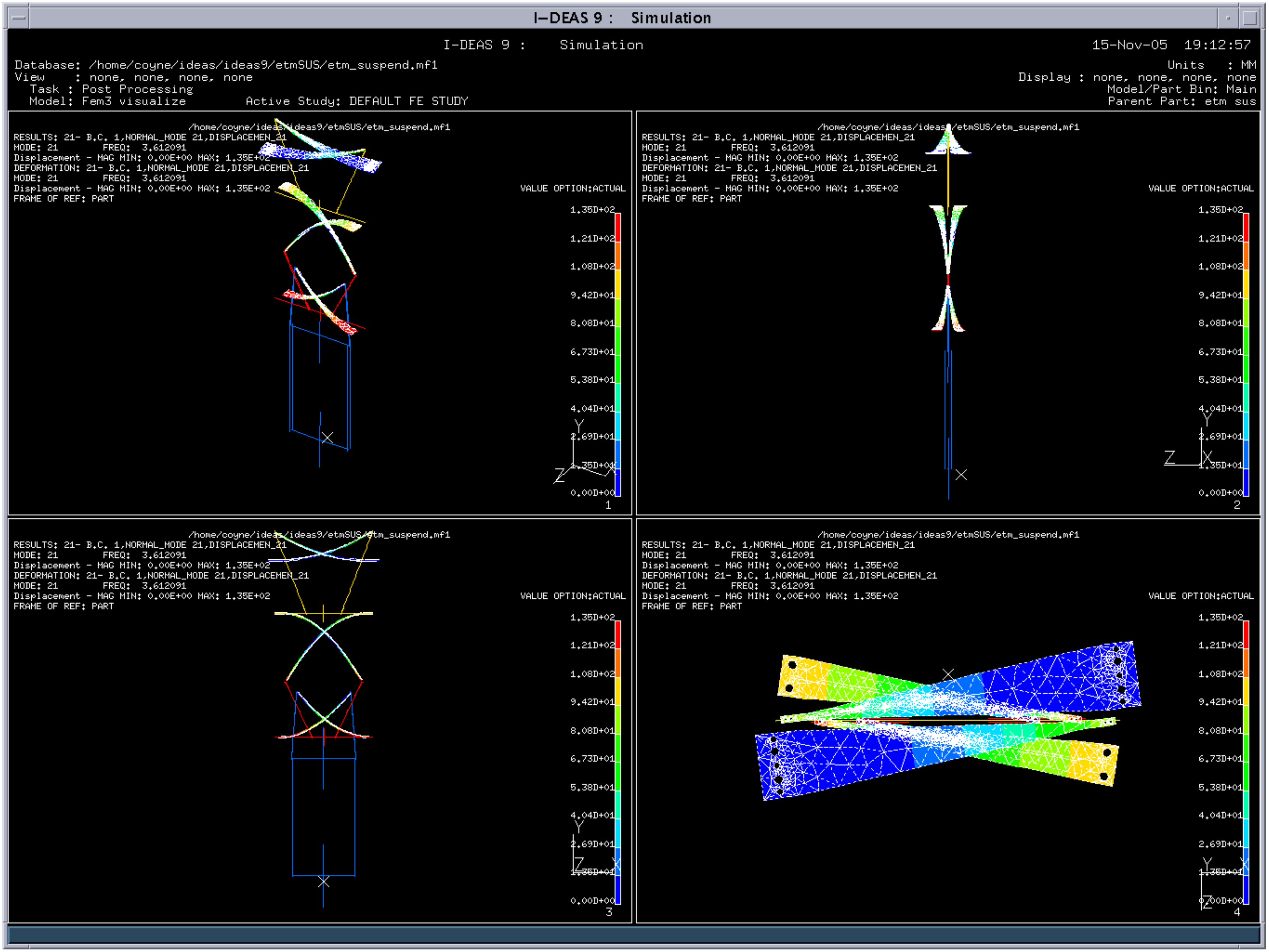

I-DEAS 9 : Simulation
15-Nov-05 19:10:27
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
RESULTS: 16- B.C. 1,NORMAL_MODE 16,DISPLACEMEN_16
MODE: 16 FREQ: 2.715474
Displacement - MAG MIN: 0.00E+00 MAX: 1.17E+02
DEFORMATION: 16- B.C. 1,NORMAL_MODE 16,DISPLACEMEN_16
FRAME OF REF: PART
VALUE OPTION:ACTUAL

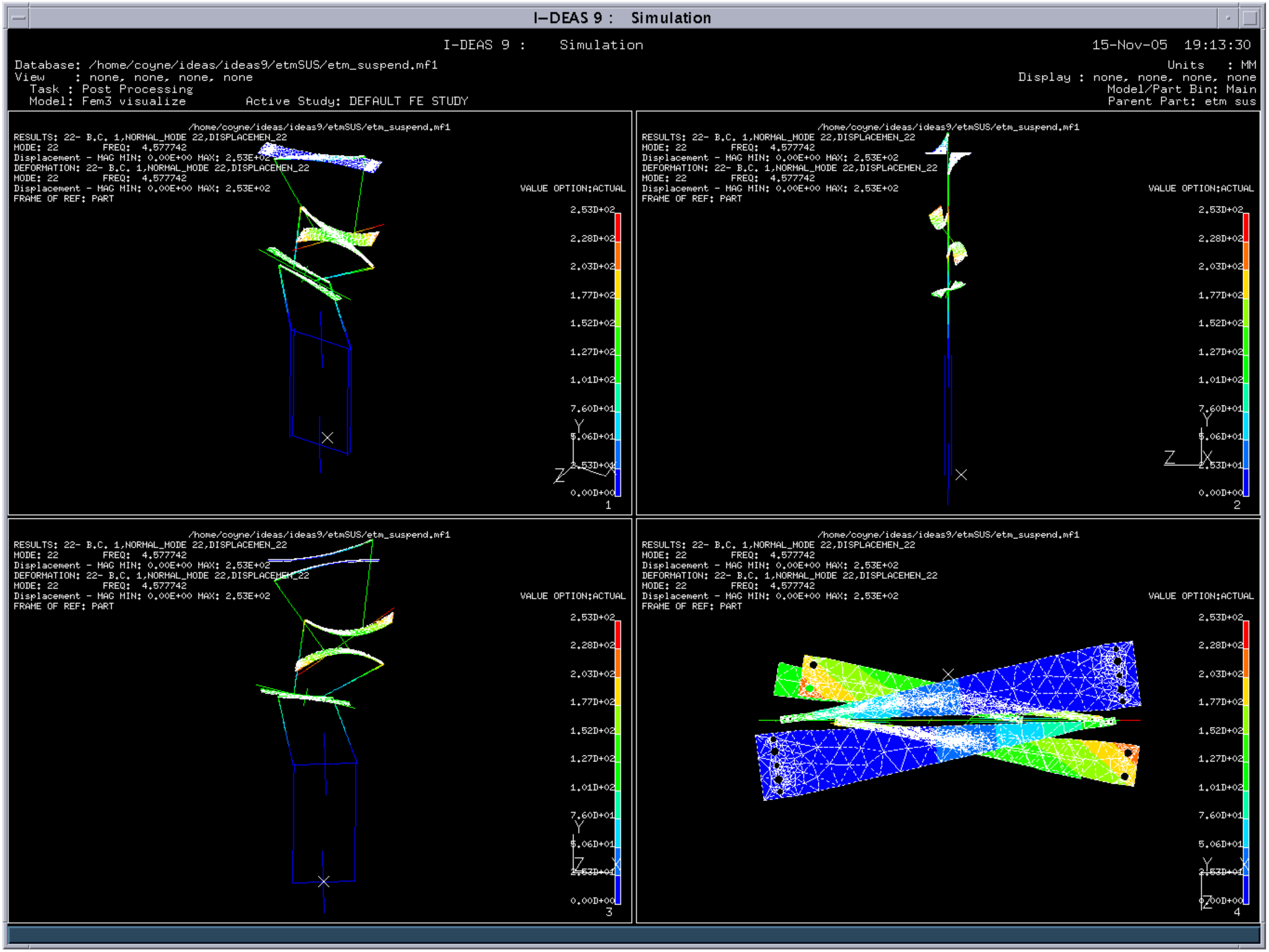

I-DEAS 9 : Simulation
15-Nov-05 19:10:59
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 17- B.C. 1,NORMAL_MODE 17,DISPLACEMEN_17
MODE: 17 FREQ: 2.844842
Displacement - MAG MIN: 0.00E+00 MAX: 1.75E+02
DEFORMATION: 17- B.C. 1,NORMAL_MODE 17,DISPLACEMEN_17
MODE: 17 FREQ: 2.844842
Displacement - MAG MIN: 0.00E+00 MAX: 1.75E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
1.75D+02
1.57D+02
1.40D+02
1.22D+02
1.05D+02
8.74D+01
6.99D+01
5.24D+01
3.50D+01
1.75D+01
0.00D+00

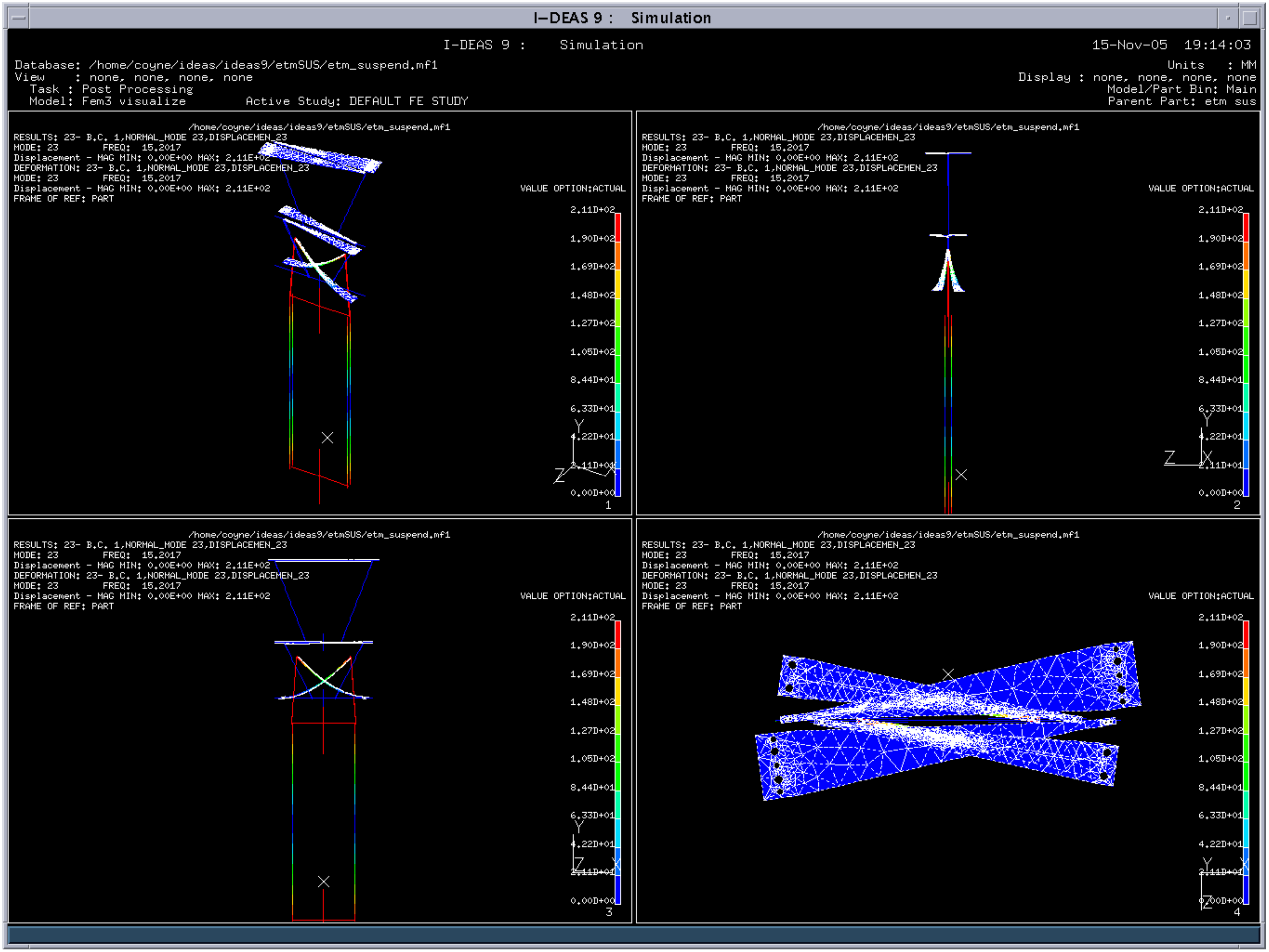

I–DEAS 9 : Simulation
I-DEAS 9 : Simulation
15-Nov-05 19:11:27
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 18- B.C. 1,NORMAL_MODE 18,DISPLACEMEN_18
MODE: 18 FREQ: 3.086142
Displacement - MAG MIN: 0.00E+00 MAX: 1.62E+02
DEFORMATION: 18- B.C. 1,NORMAL_MODE 18,DISPLACEMEN_18
MODE: 18 FREQ: 3.086142
Displacement - MAG MIN: 0.00E+00 MAX: 1.62E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
1.62D+02
1.46D+02
1.30D+02
1.14D+02
9.75D+01
8.12D+01
6.50D+01
4.87D+01
3.25D+01
1.62D+01
0.00D+00
1
2
3
4

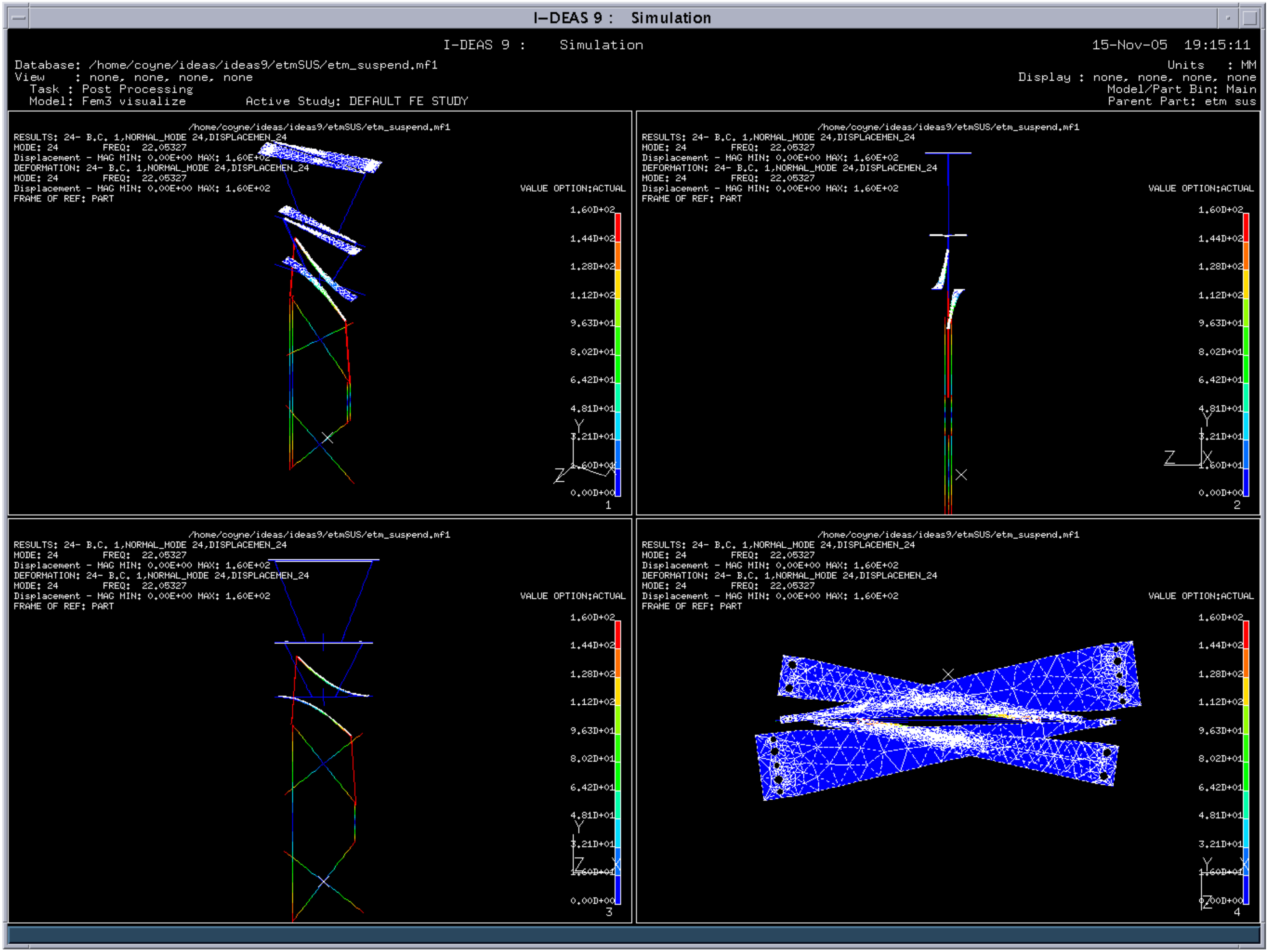

I-DEAS 9 : Simulation
I-DEAS 9 : Simulation 15-Nov-05 19:11:56
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 19- B.C. 1,NORMAL_MODE 19,DISPLACEMEN_19
MODE: 19 FREQ: 3.224083
Displacement - MAG MIN: 0.00E+00 MAX: 8.87E+01
DEFORMATION: 19- B.C. 1,NORMAL_MODE 19,DISPLACEMEN_19
MODE: 19 FREQ: 3.224083
Displacement - MAG MIN: 0.00E+00 MAX: 8.87E+01
FRAME OF REF: PART
VALUE OPTION:ACTUAL
8.87D+01
7.99D+01
7.10D+01
6.21D+01
5.32D+01
4.44D+01
3.55D+01
2.66D+01
1.77D+01
8.87D+00
0.00D+00
1
2
3
4


I-DEAS 9 : Simulation
15-Nov-05 19:12:23
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 20- B.C. 1,NORMAL_MODE 20,DISPLACEMEN_20
MODE: 20 FREQ: 3.355478
Displacement - MAG MIN: 0.00E+00 MAX: 1.48E+02
DEFORMATION: 20- B.C. 1,NORMAL_MODE 20,DISPLACEMEN_20
MODE: 20 FREQ: 3.355478
Displacement - MAG MIN: 0.00E+00 MAX: 1.48E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
1.48D+02
1.33D+02
1.18D+02
1.03D+02
8.86D+01
7.39D+01
5.91D+01
4.43D+01
2.95D+01
1.48D+01
0.00D+00

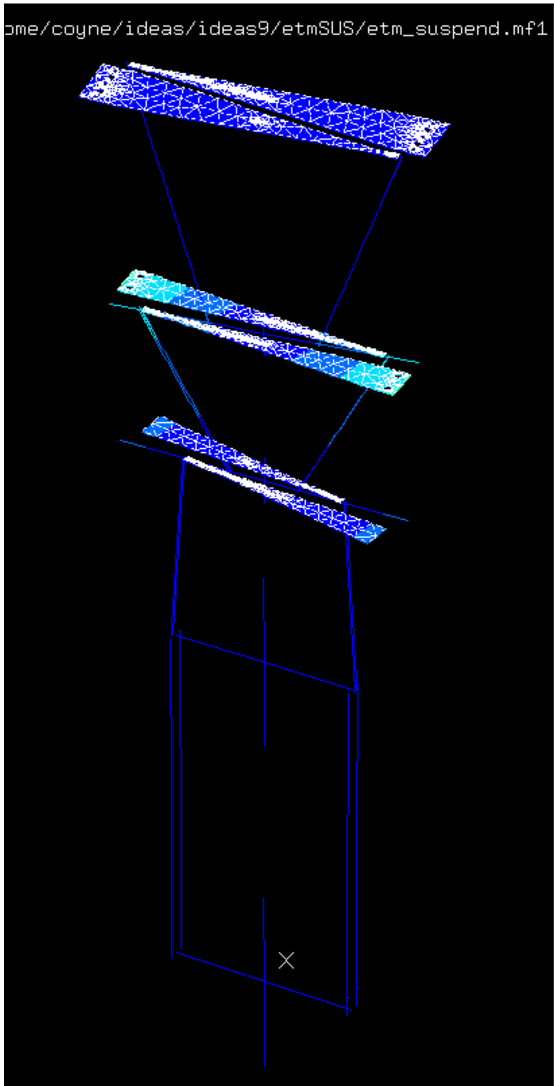

I-DEAS 9 : Simulation
15-Nov-05 19:12:57
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 21- B.C. 1,NORMAL_MODE 21,DISPLACEMEN_21
MODE: 21 FREQ: 3.612091
Displacement - MAG MIN: 0.00E+00 MAX: 1.35E+02
DEFORMATION: 21- B.C. 1,NORMAL_MODE 21,DISPLACEMEN_21
MODE: 21 FREQ: 3.612091
Displacement - MAG MIN: 0.00E+00 MAX: 1.35E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
1.35D+02
1.21D+02
1.08D+02
9.42D+01
8.08D+01
6.73D+01
5.38D+01
4.04D+01
2.69D+01
1.35D+01
0.00D+00


I-DEAS 9 : Simulation
15-Nov-05 19:13:30
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
RESULTS: 22- B.C. 1,NORMAL_MODE 22,DISPLACEMEN_22
MODE: 22 FREQ: 4.577742
Displacement - MAG MIN: 0.00E+00 MAX: 2.53E+02
DEFORMATION: 22- B.C. 1,NORMAL_MODE 22,DISPLACEMEN_22
FRAME OF REF: PART
VALUE OPTION:ACTUAL

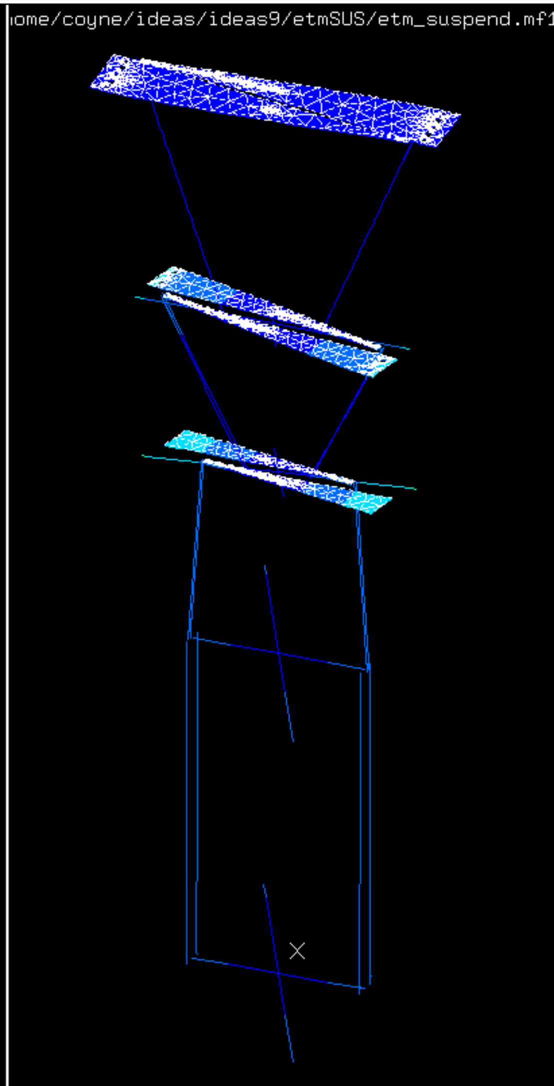

I-DEAS 9 : Simulation
I-DEAS 9 : Simulation
15-Nov-05 19:14:03
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 23- B.C. 1,NORMAL_MODE 23,DISPLACEMEN_23
MODE: 23 FREQ: 15.2017
Displacement - MAG MIN: 0.00E+00 MAX: 2.11E+02
DEFORMATION: 23- B.C. 1,NORMAL_MODE 23,DISPLACEMEN_23
MODE: 23 FREQ: 15.2017
Displacement - MAG MIN: 0.00E+00 MAX: 2.11E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
2.11D+02
1.90D+02
1.69D+02
1.48D+02
1.27D+02
1.05D+02
8.44D+01
6.33D+01
4.22D+01
2.11D+01
0.00D+00
1
2
3
4


I-DEAS 9 : Simulation
15-Nov-05 19:15:11
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 24- B.C. 1,NORMAL_MODE 24,DISPLACEMEN_24
MODE: 24 FREQ: 22.05327
Displacement - MAG MIN: 0.00E+00 MAX: 1.60E+02
DEFORMATION: 24- B.C. 1,NORMAL_MODE 24,DISPLACEMEN_24
MODE: 24 FREQ: 22.05327
Displacement - MAG MIN: 0.00E+00 MAX: 1.60E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
1.60D+02
1.44D+02
1.28D+02
1.12D+02
9.63D+01
8.02D+01
6.42D+01
4.81D+01
3.21D+01
1.60D+01
0.00D+00

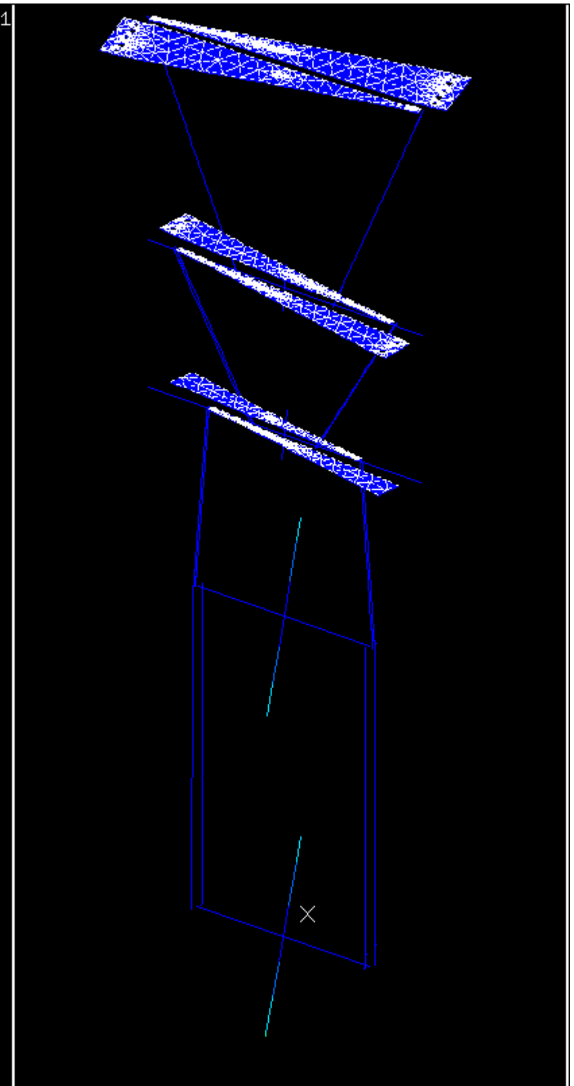
Mode shape movies are given in the following figures (just double click to launch viewer).



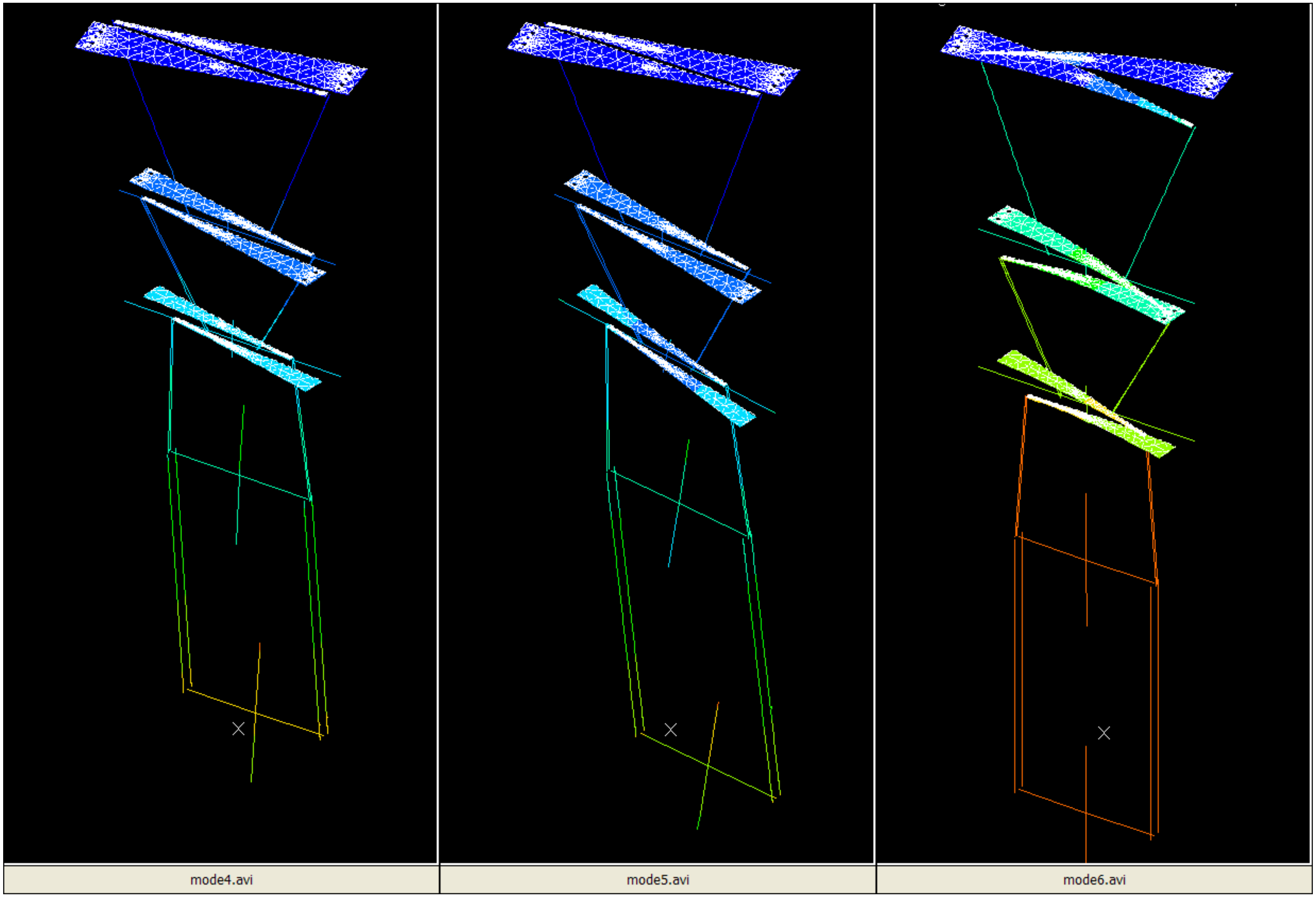
mode1.avi

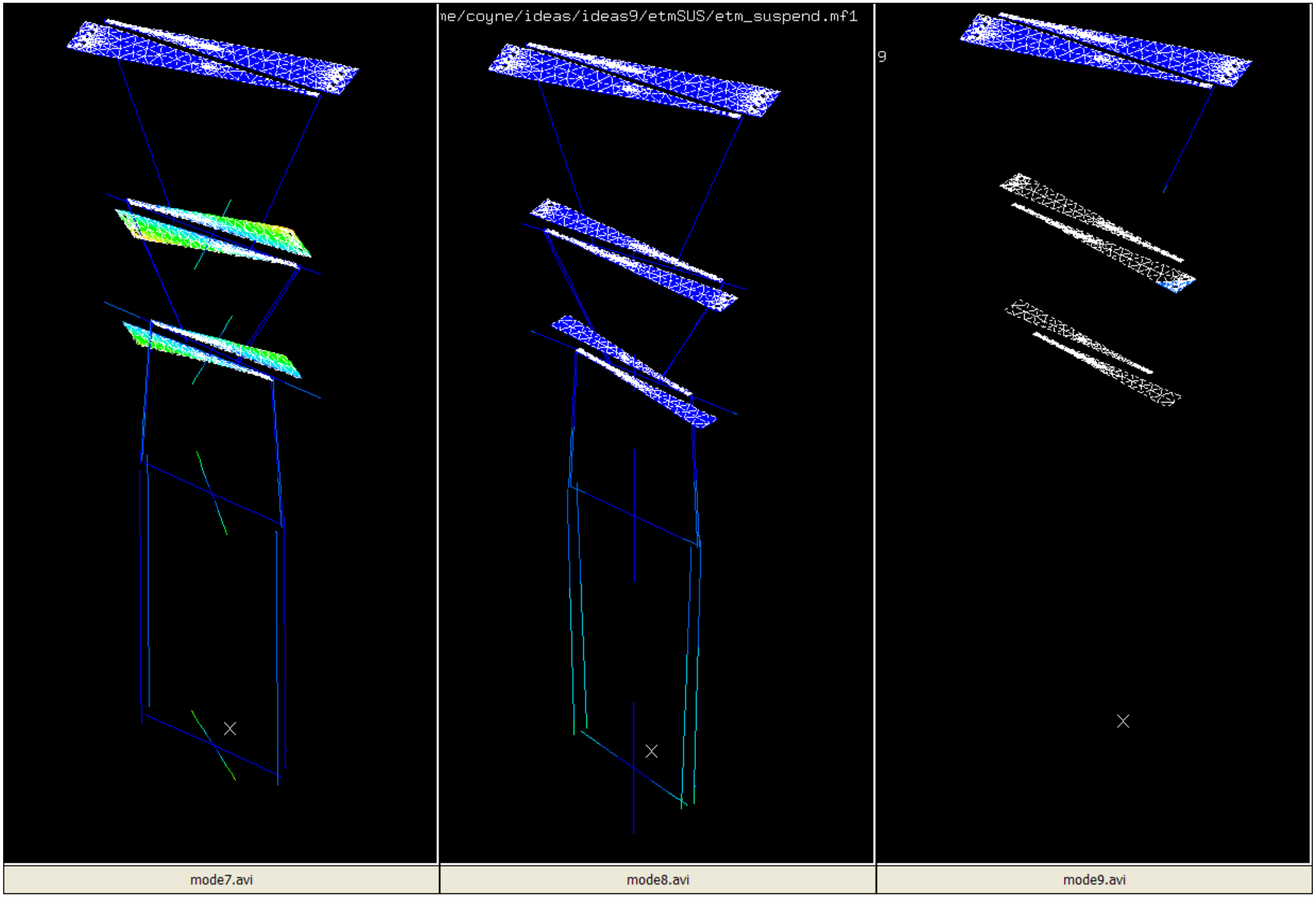


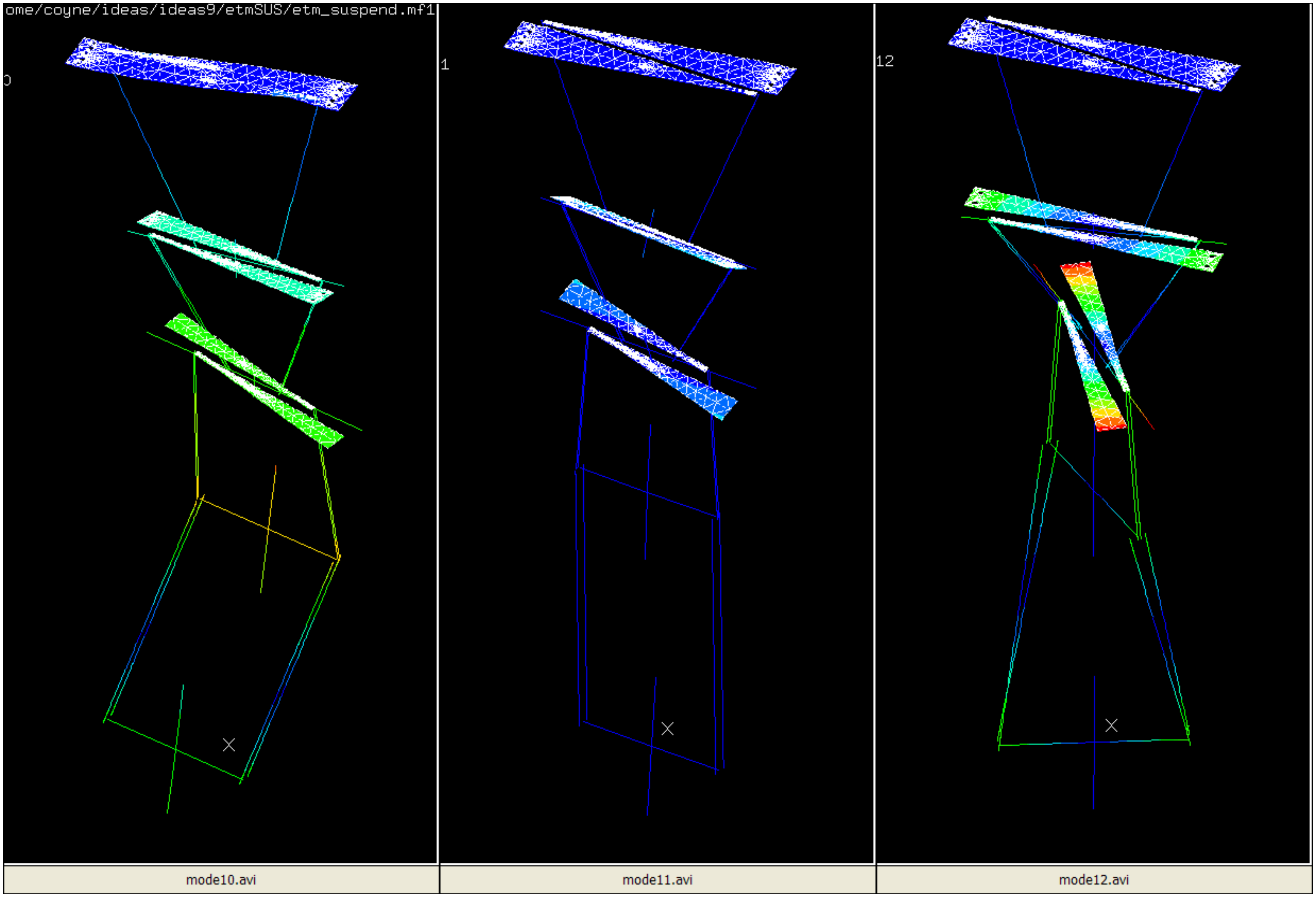
mode2.avi

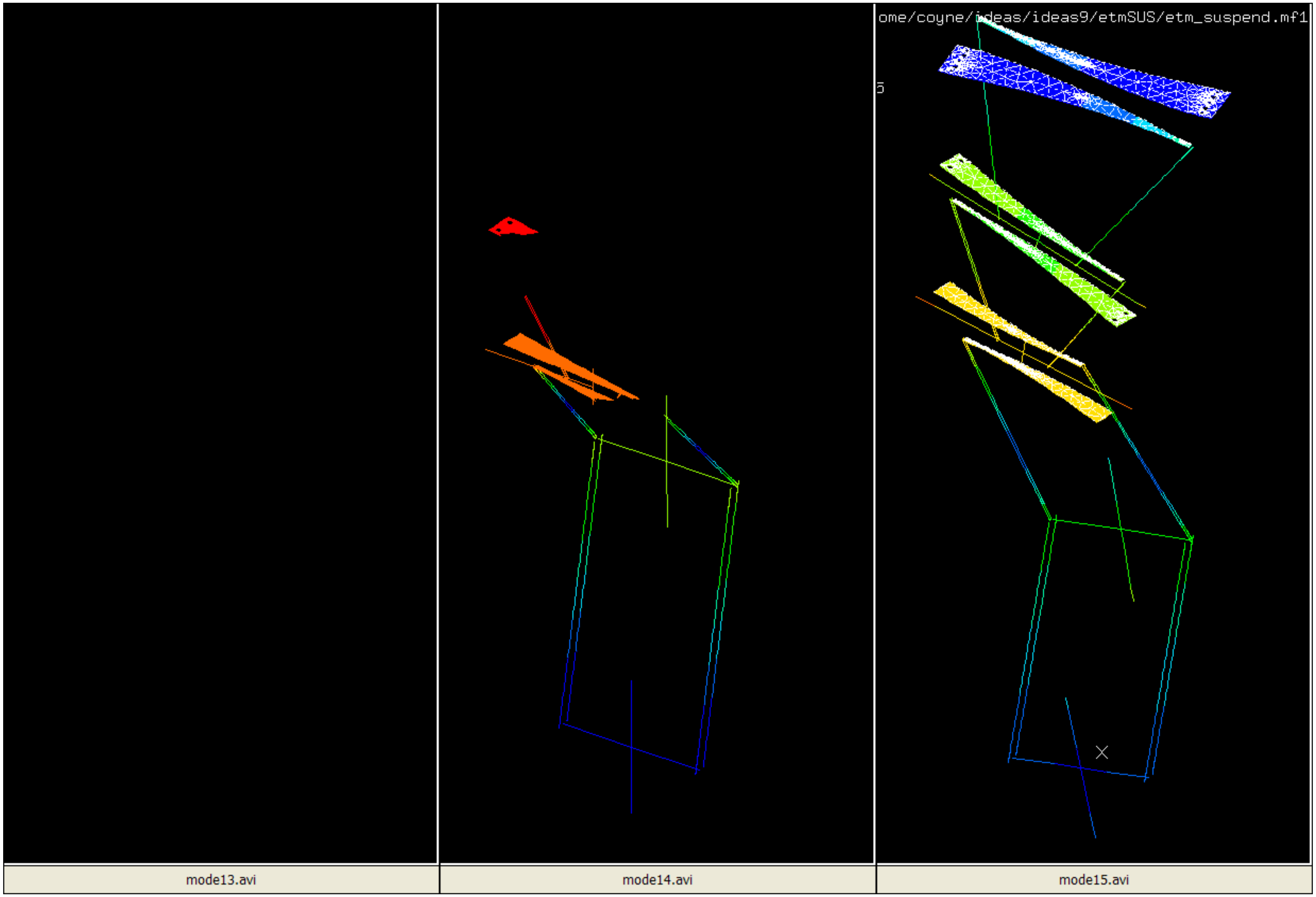


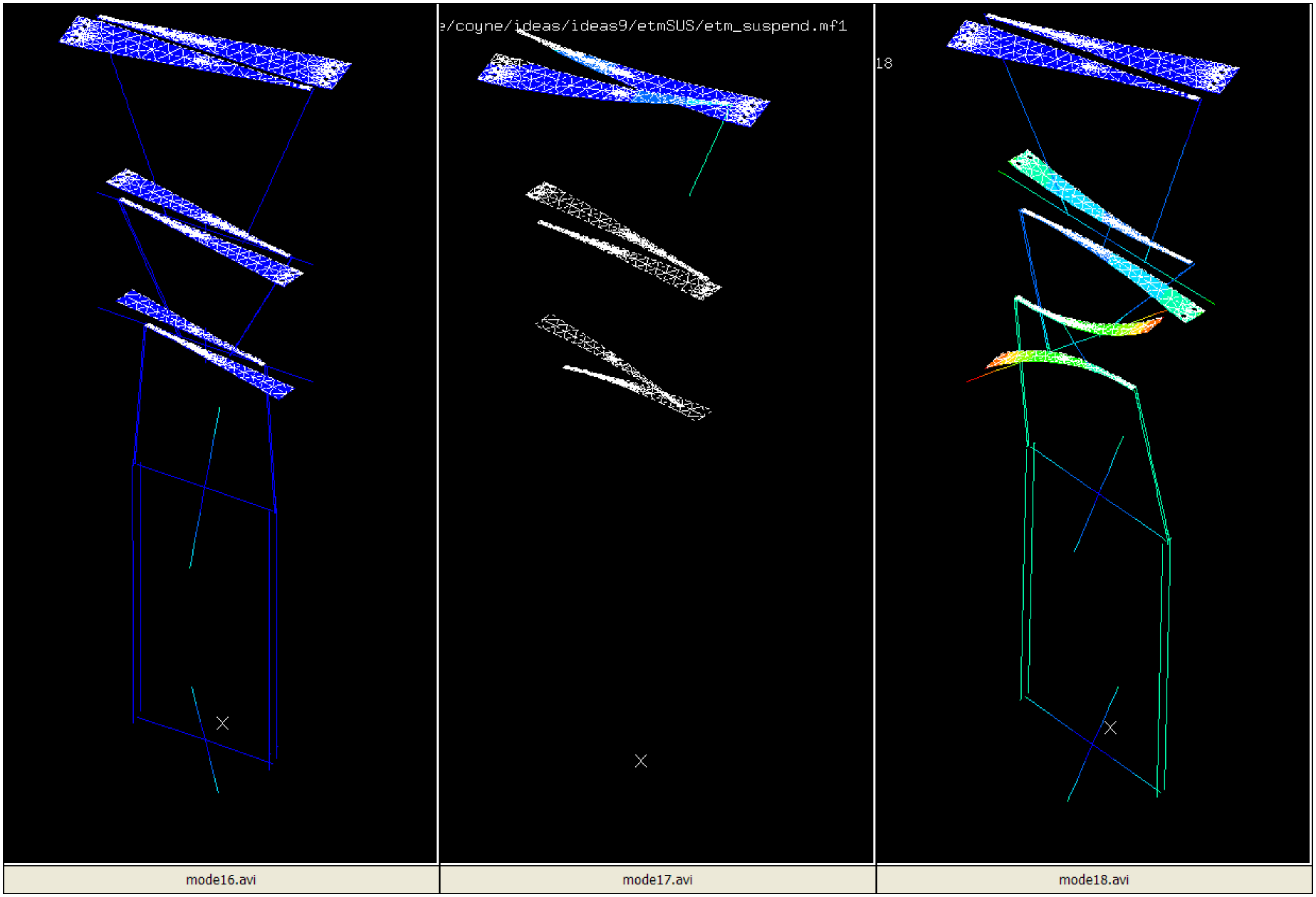
mode3.avi

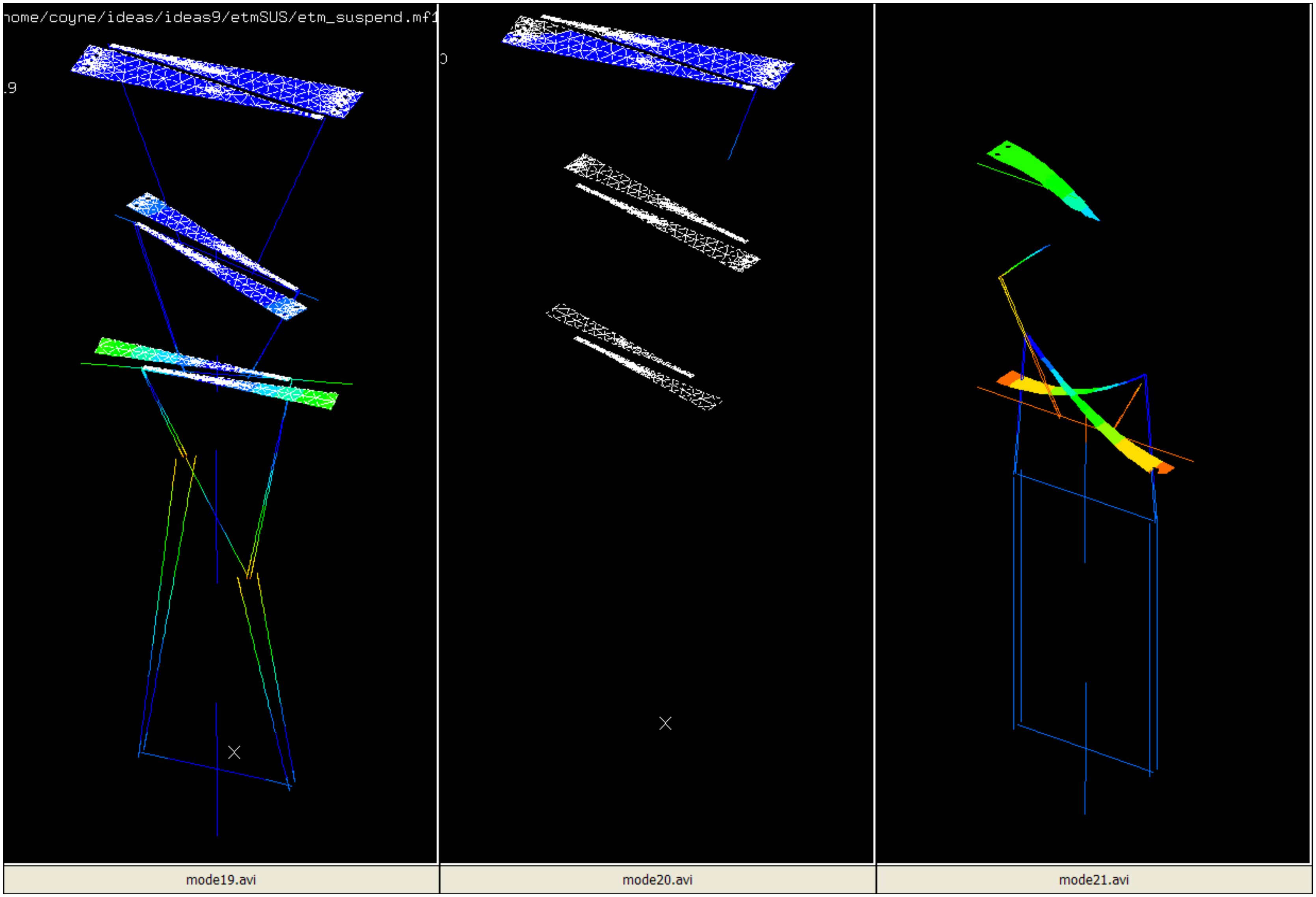

mode4.avi
mode5.avi
mode6.avi


me/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
9
mode7.avi
mode8.avi
mode9.avi

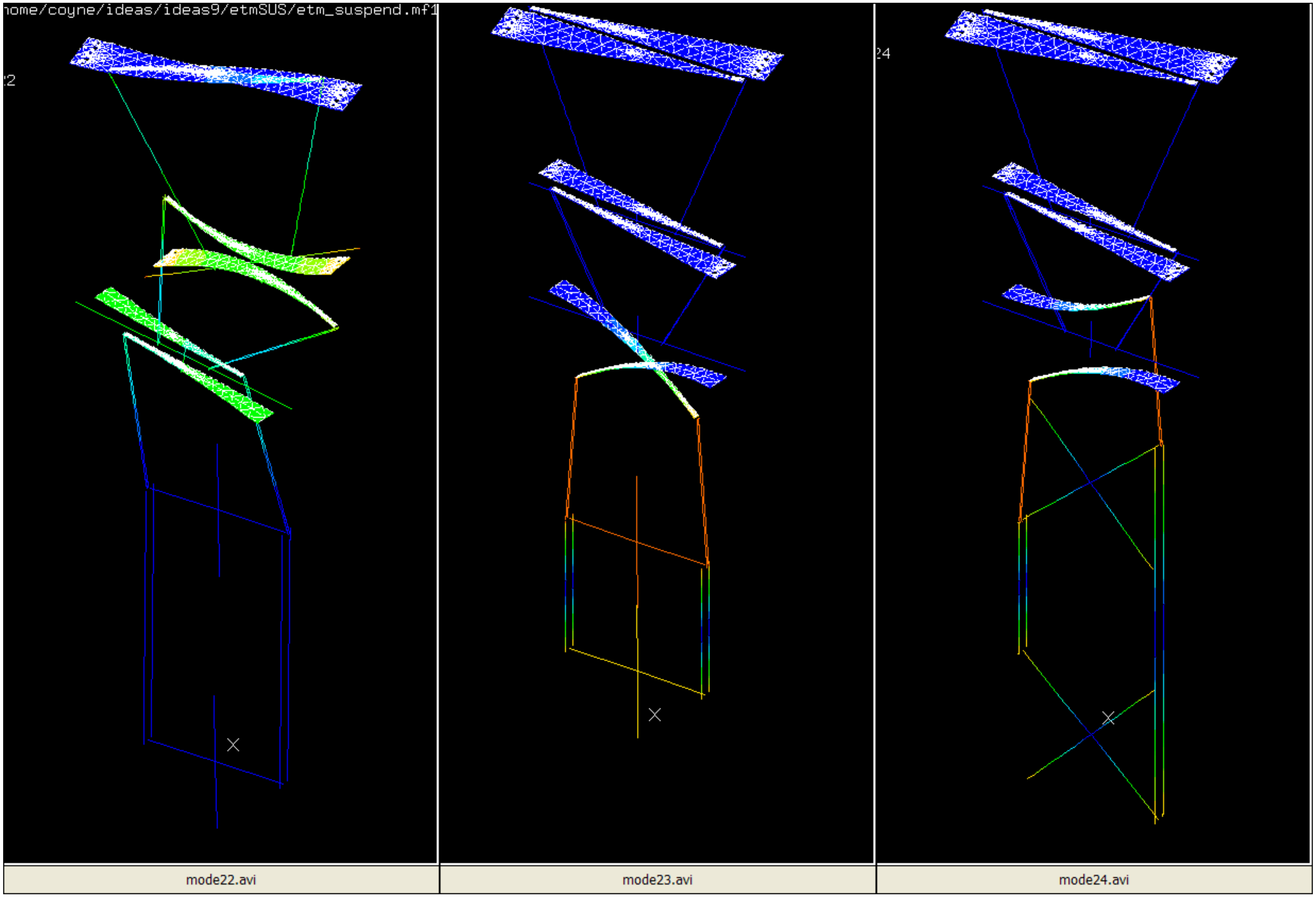

ome/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
1
12
mode10.avi
mode11.avi
mode12.avi

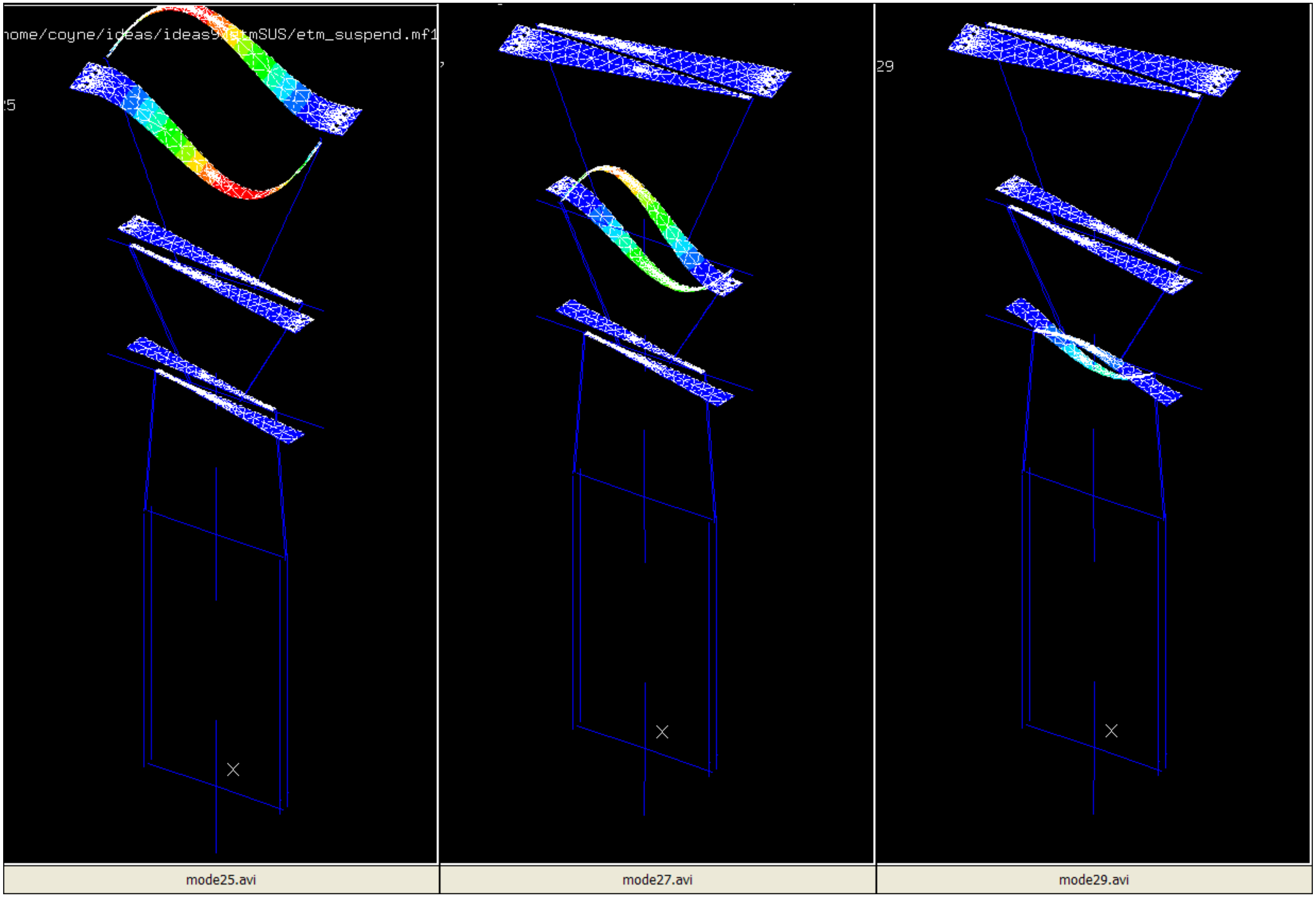

ome/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
mode13.avi
mode14.avi
mode15.avi

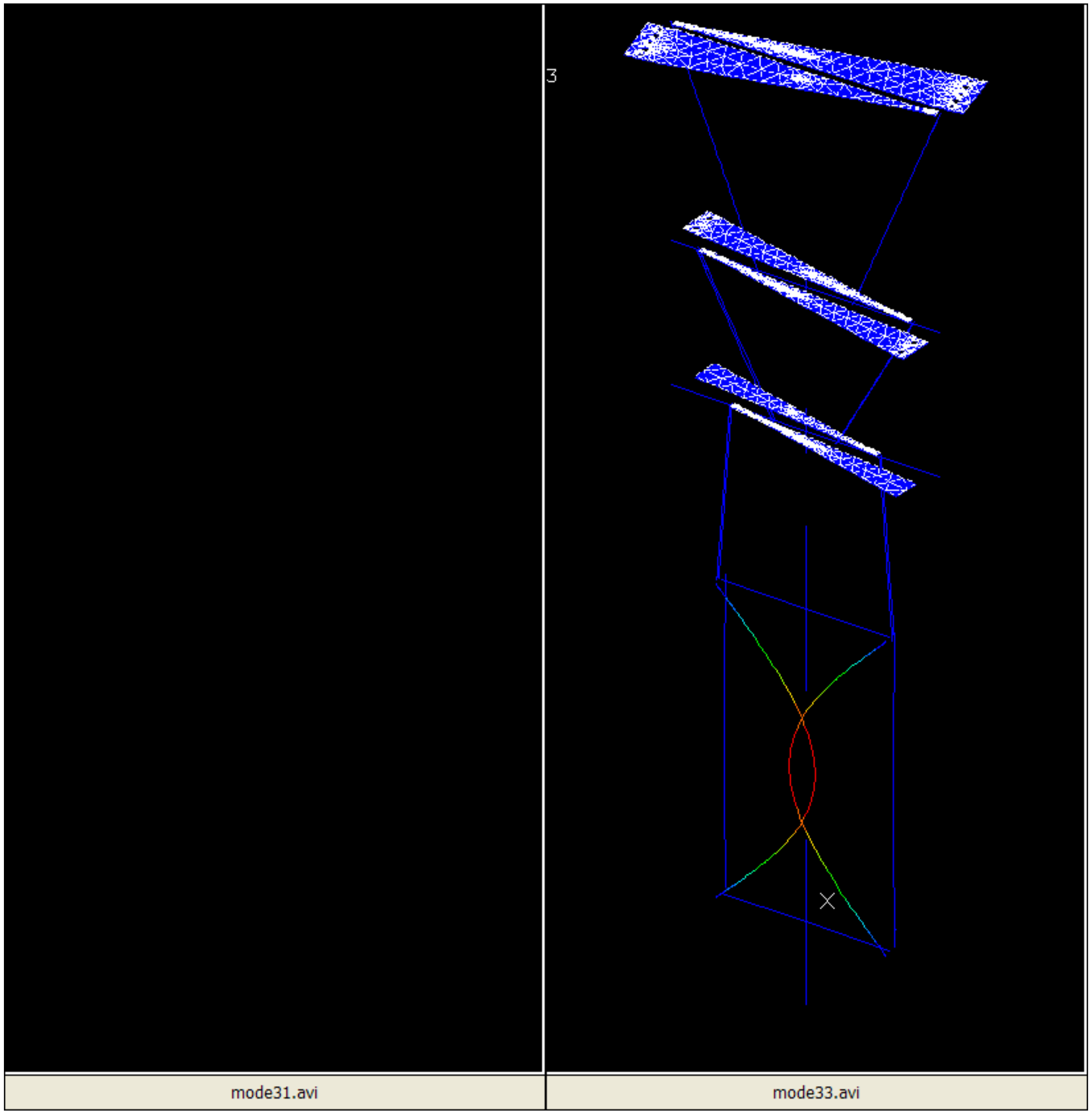

e/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
18
mode16.avi
mode17.avi
mode18.avi

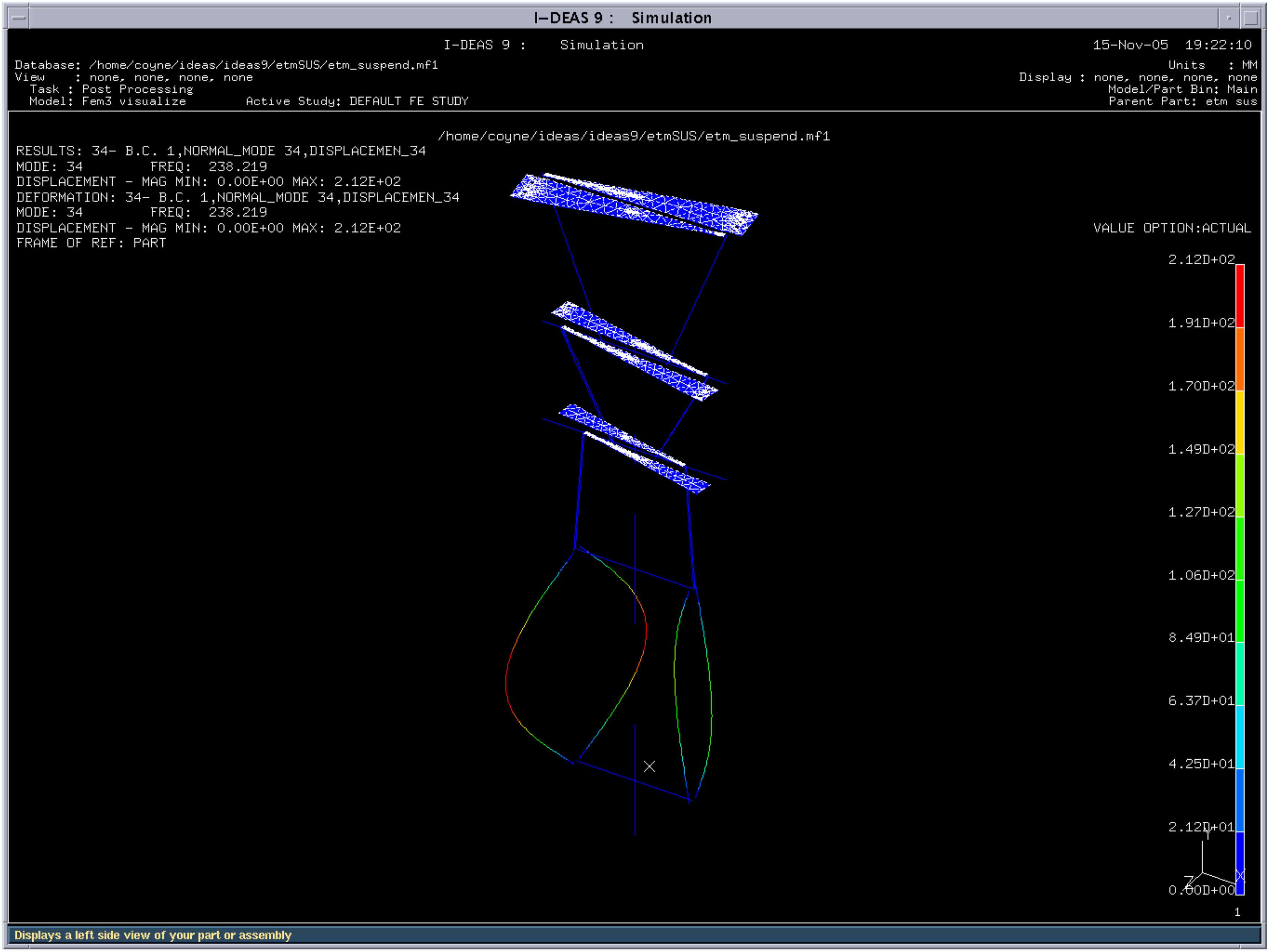


ome/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
mode19.avi
mode20.avi
mode21.avi

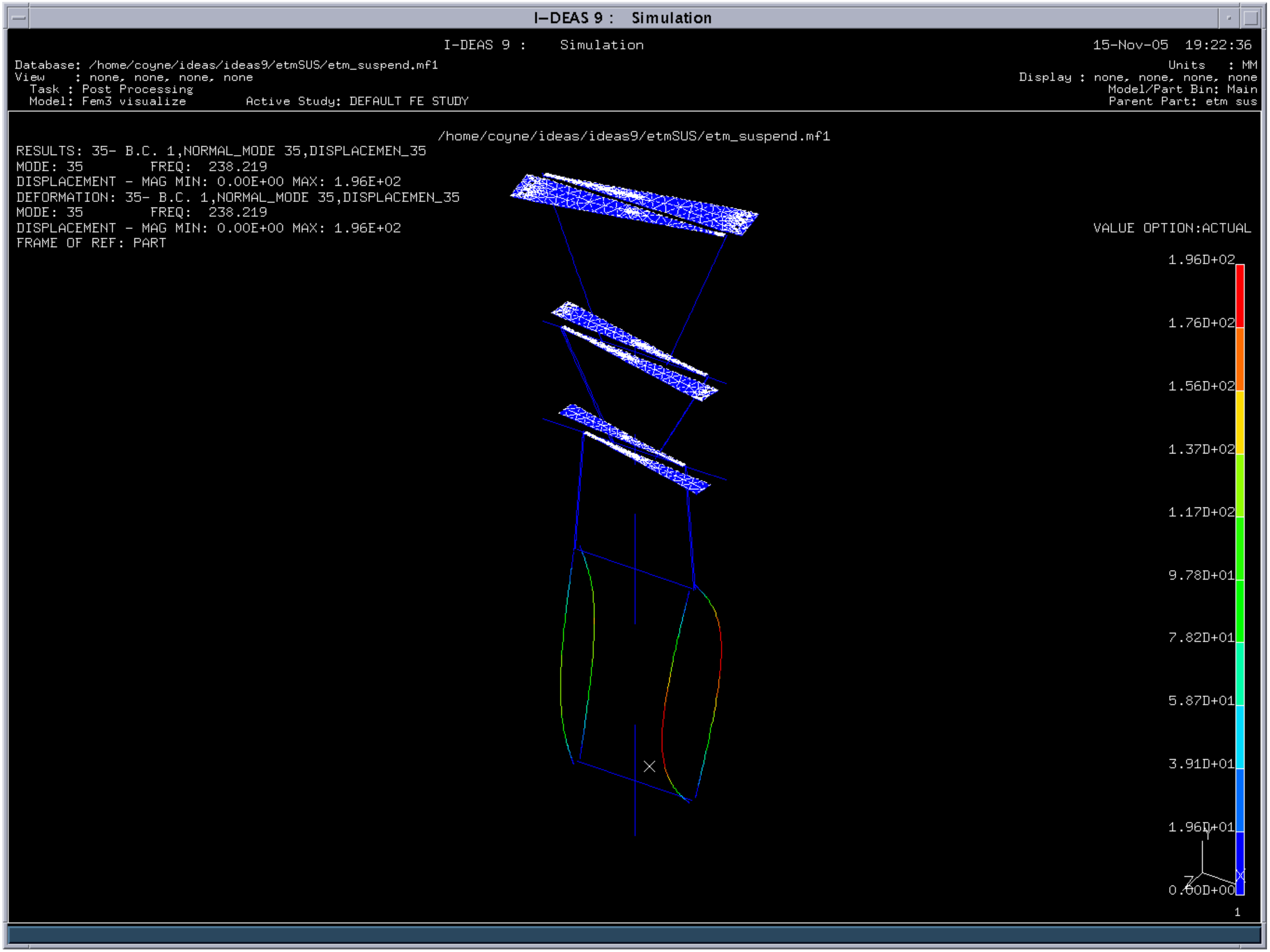

home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
mode22.avi
mode23.avi
mode24.avi


ome/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
mode25.avi
mode27.avi
29
mode29.avi

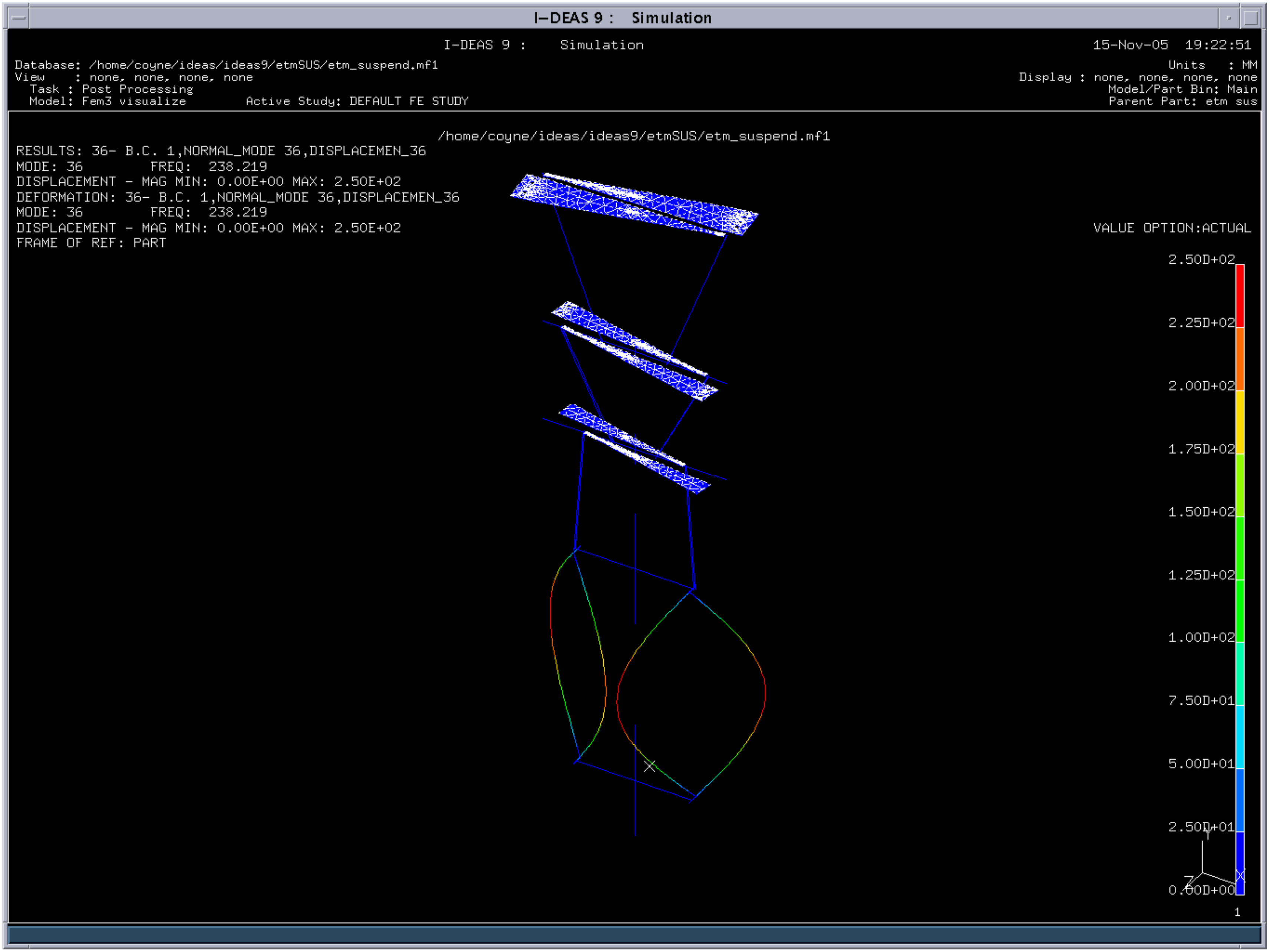

3
mode31.avi
mode33.avi

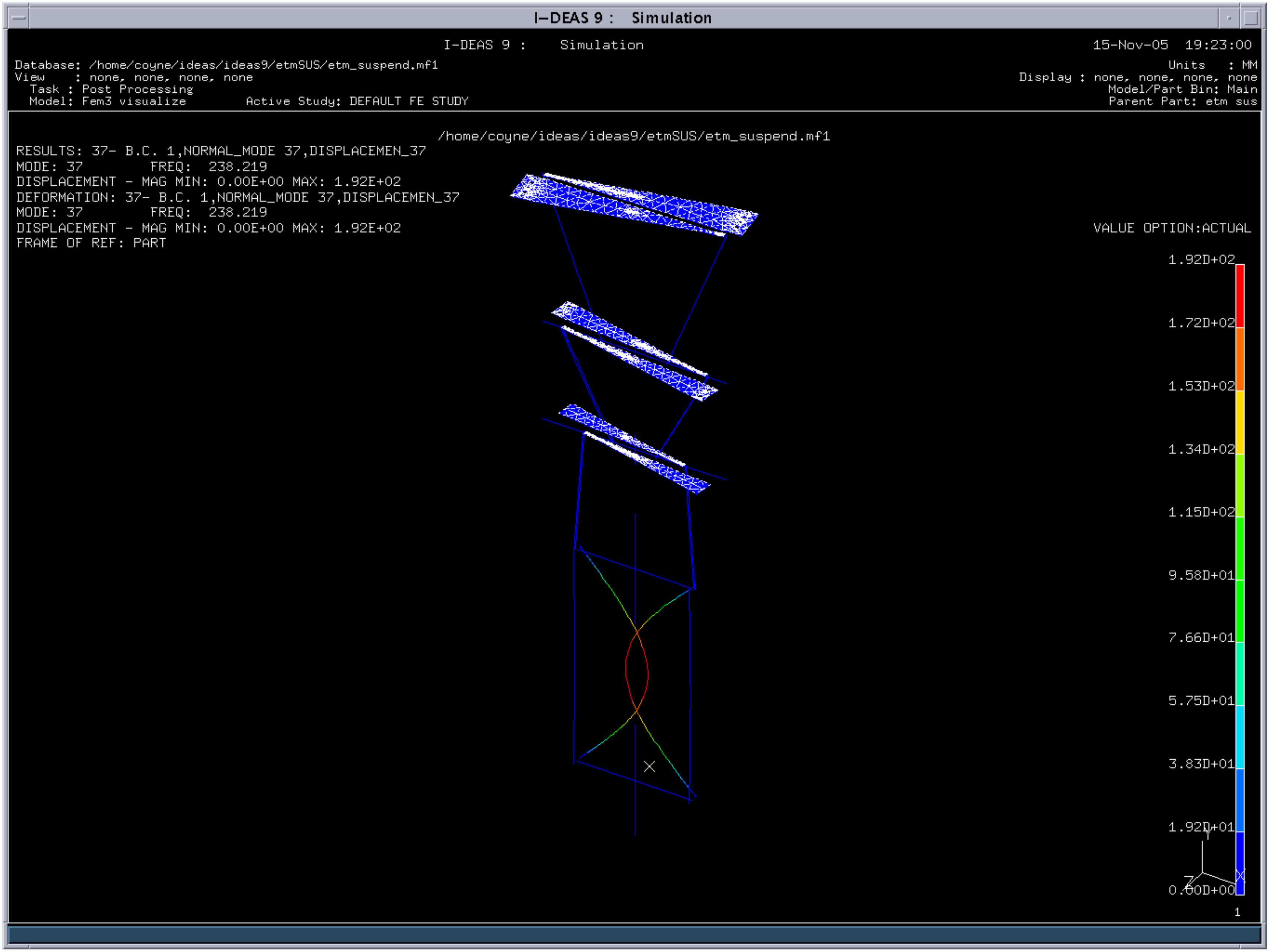


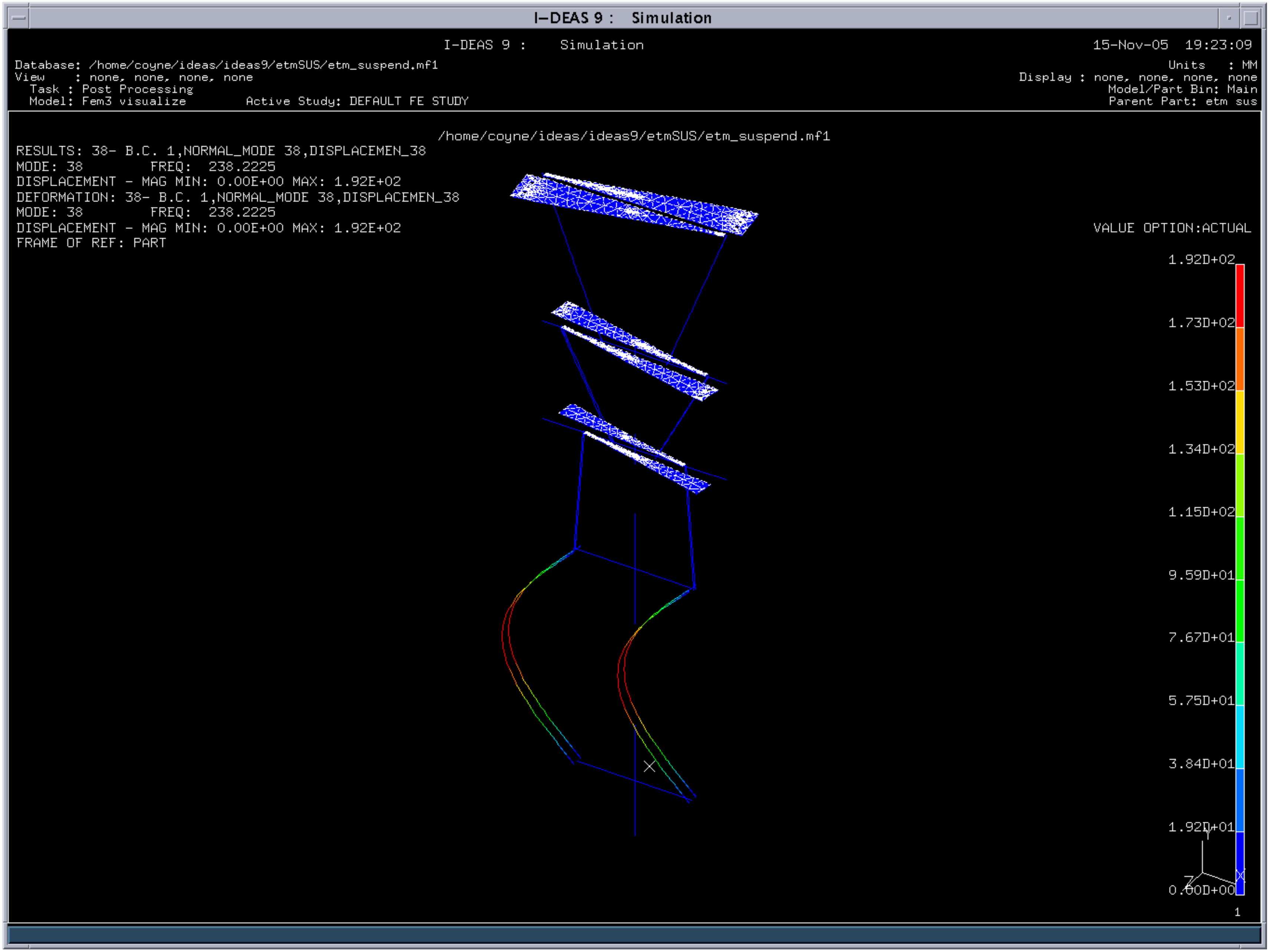
I-DEAS 9 : Simulation
I-DEAS 9 : Simulation
15-Nov-05 19:22:10
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 34- B.C. 1,NORMAL_MODE 34,DISPLACEMEN_34
MODE: 34 FREQ: 238.219
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 2.12E+02
DEFORMATION: 34- B.C. 1,NORMAL_MODE 34,DISPLACEMEN_34
MODE: 34 FREQ: 238.219
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 2.12E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
2.12D+02
1.91D+02
1.70D+02
1.49D+02
1.27D+02
1.06D+02
8.49D+01
6.37D+01
4.25D+01
2.12D+01
0.00D+00
1
Displays a left side view of your part or assembly

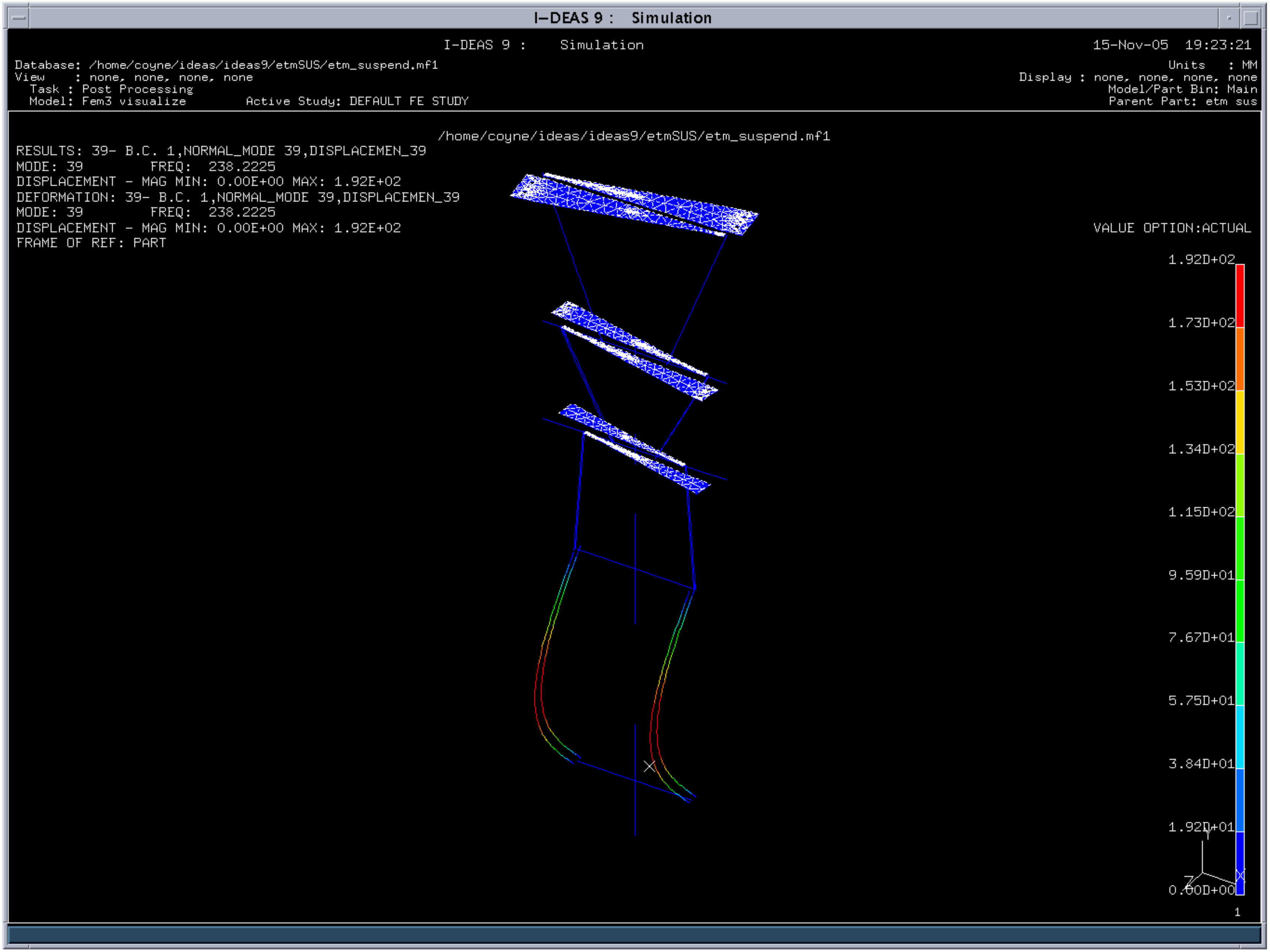


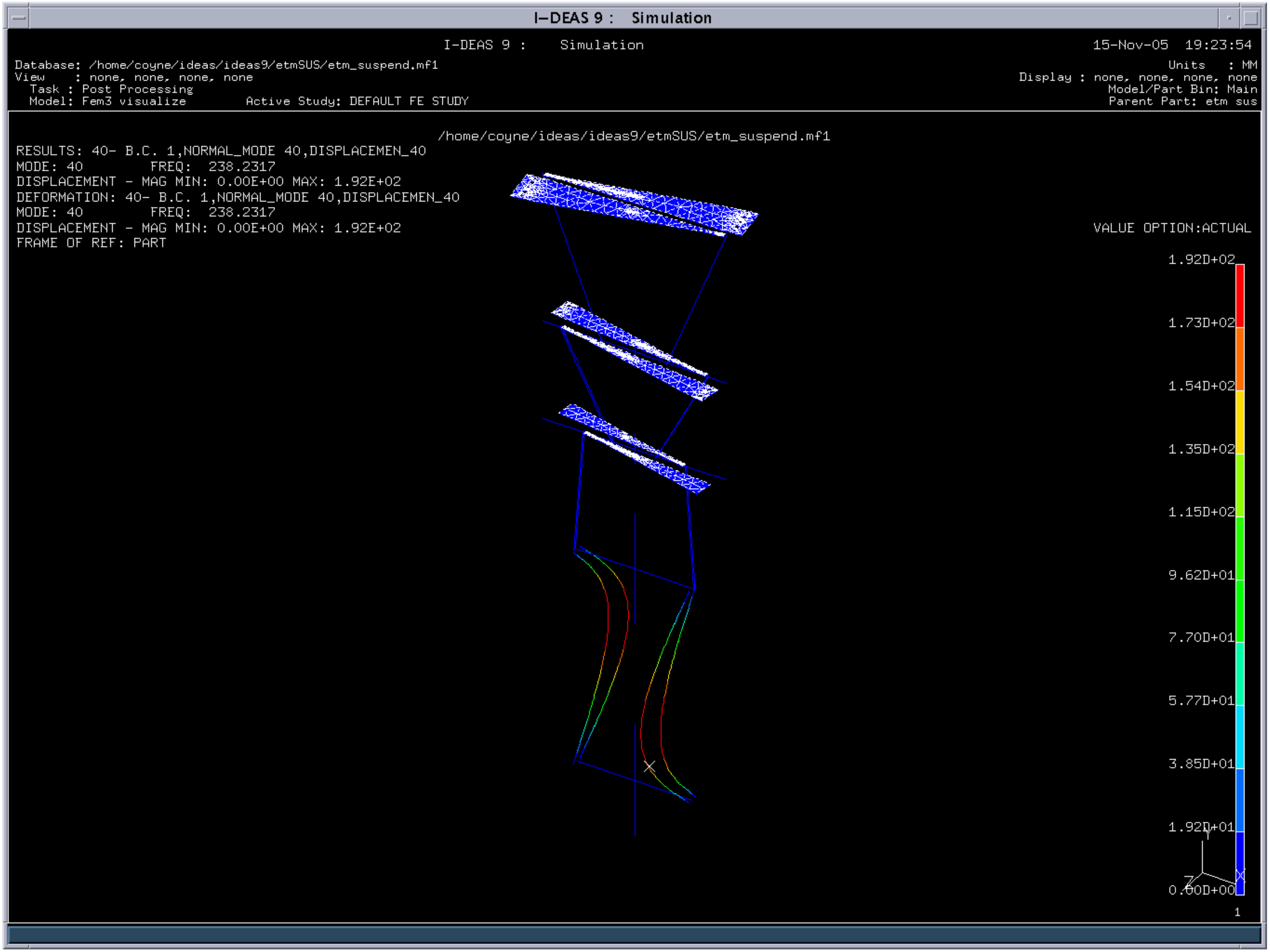
I-DEAS 9 : Simulation
I-DEAS 9 : Simulation
15-Nov-05 19:22:36
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 35- B.C. 1,NORMAL_MODE 35,DISPLACEMEN_35
MODE: 35 FREQ: 238.219
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.96E+02
DEFORMATION: 35- B.C. 1,NORMAL_MODE 35,DISPLACEMEN_35
MODE: 35 FREQ: 238.219
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.96E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
1.96D+02
1.76D+02
1.56D+02
1.37D+02
1.17D+02
9.78D+01
7.82D+01
5.87D+01
3.91D+01
1.96D+01
0.00D+00


I-DEAS 9 : Simulation
I-DEAS 9 : Simulation
15-Nov-05 19:22:51
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 36- B.C. 1,NORMAL_MODE 36,DISPLACEMEN_36
MODE: 36 FREQ: 238.219
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 2.50E+02
DEFORMATION: 36- B.C. 1,NORMAL_MODE 36,DISPLACEMEN_36
MODE: 36 FREQ: 238.219
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 2.50E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
2.50D+02
2.25D+02
2.00D+02
1.75D+02
1.50D+02
1.25D+02
1.00D+02
7.50D+01
5.00D+01
2.50D+01
0.00D+00


I-DEAS 9 : Simulation
I-DEAS 9 : Simulation
15-Nov-05 19:23:00
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 37- B.C. 1,NORMAL_MODE 37,DISPLACEMEN_37
MODE: 37 FREQ: 238.219
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.92E+02
DEFORMATION: 37- B.C. 1,NORMAL_MODE 37,DISPLACEMEN_37
MODE: 37 FREQ: 238.219
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.92E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
1.92D+02
1.72D+02
1.53D+02
1.34D+02
1.15D+02
9.58D+01
7.66D+01
5.75D+01
3.83D+01
1.92D+01
0.00D+00


I-DEAS 9 : Simulation
I-DEAS 9 : Simulation
15-Nov-05 19:23:09
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 38- B.C. 1,NORMAL_MODE 38,DISPLACEMEN_38
MODE: 38 FREQ: 238.2225
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.92E+02
DEFORMATION: 38- B.C. 1,NORMAL_MODE 38,DISPLACEMEN_38
MODE: 38 FREQ: 238.2225
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.92E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
1.92D+02
1.73D+02
1.53D+02
1.34D+02
1.15D+02
9.59D+01
7.67D+01
5.75D+01
3.84D+01
1.92D+01
0.00D+00
1


I-DEAS 9 : Simulation
I-DEAS 9 : Simulation
15-Nov-05 19:23:21
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 39- B.C. 1,NORMAL_MODE 39,DISPLACEMEN_39
MODE: 39 FREQ: 238.2225
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.92E+02
DEFORMATION: 39- B.C. 1,NORMAL_MODE 39,DISPLACEMEN_39
MODE: 39 FREQ: 238.2225
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.92E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
1.92D+02
1.73D+02
1.53D+02
1.34D+02
1.15D+02
9.59D+01
7.67D+01
5.75D+01
3.84D+01
1.92D+01
0.00D+00

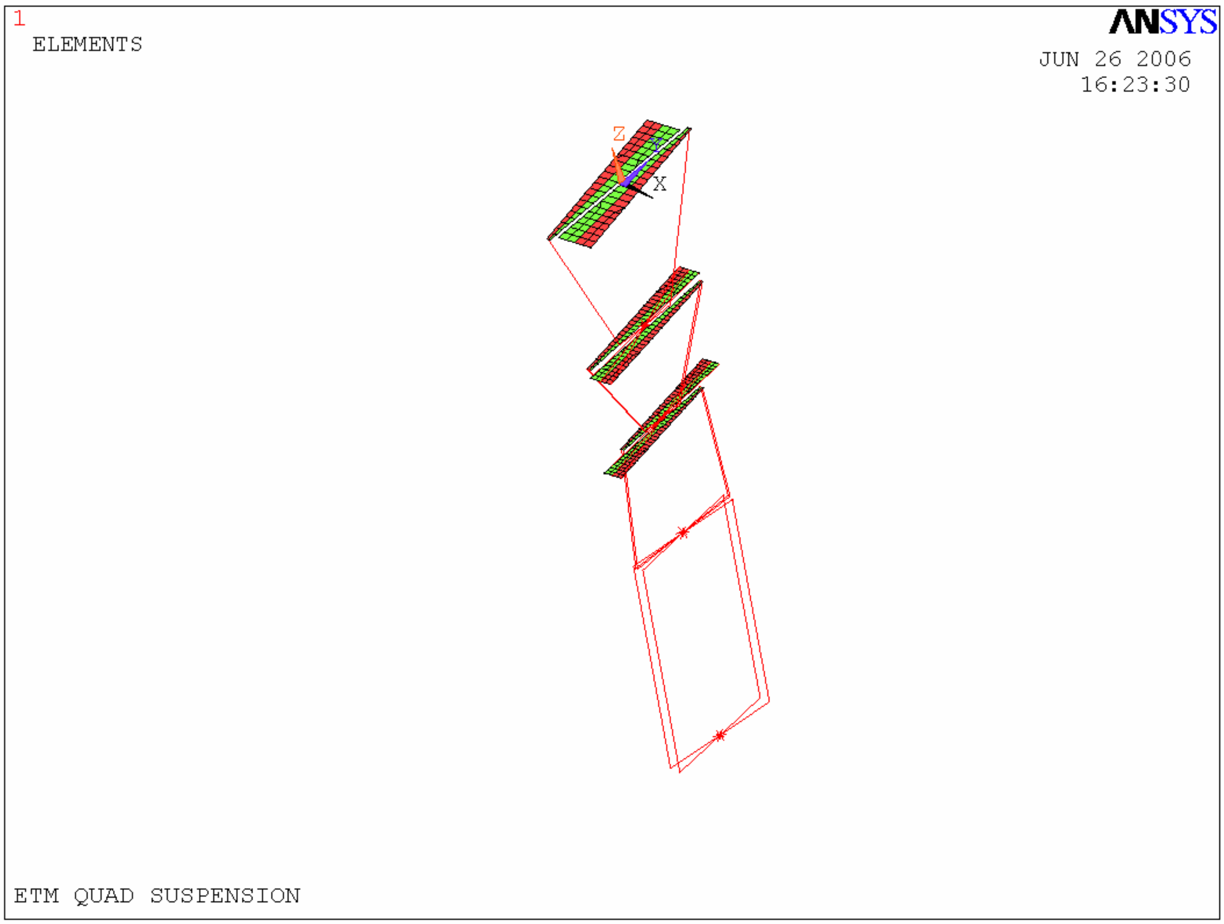

I-DEAS 9 : Simulation
I-DEAS 9 : Simulation
15-Nov-05 19:23:54
Database: /home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
View : none, none, none, none
Task : Post Processing
Model: Fem3 visualize
Active Study: DEFAULT FE STUDY
Units : MM
Display : none, none, none, none
Model/Part Bin: Main
Parent Part: etm sus
/home/coyne/ideas/ideas9/etmSUS/etm_suspend.mf1
RESULTS: 40- B.C. 1,NORMAL_MODE 40,DISPLACEMEN_40
MODE: 40 FREQ: 238.2317
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.92E+02
DEFORMATION: 40- B.C. 1,NORMAL_MODE 40,DISPLACEMEN_40
MODE: 40 FREQ: 238.2317
DISPLACEMENT - MAG MIN: 0.00E+00 MAX: 1.92E+02
FRAME OF REF: PART
VALUE OPTION:ACTUAL
1.92D+02
1.73D+02
1.54D+02
1.35D+02
1.15D+02
9.62D+01
7.70D+01
5.77D+01
3.85D+01
1.92D+01
0.00D+00
1

Include a Table of mass 6dof participation factors here

4 Script and Parameter Generated Geometry

The key parameters used were consistent with the values reported in the mode identification report[9] for the quadruple controls prototype. These parameters and the terminology used in the script are consistent with the pendulum naming conventions[10].

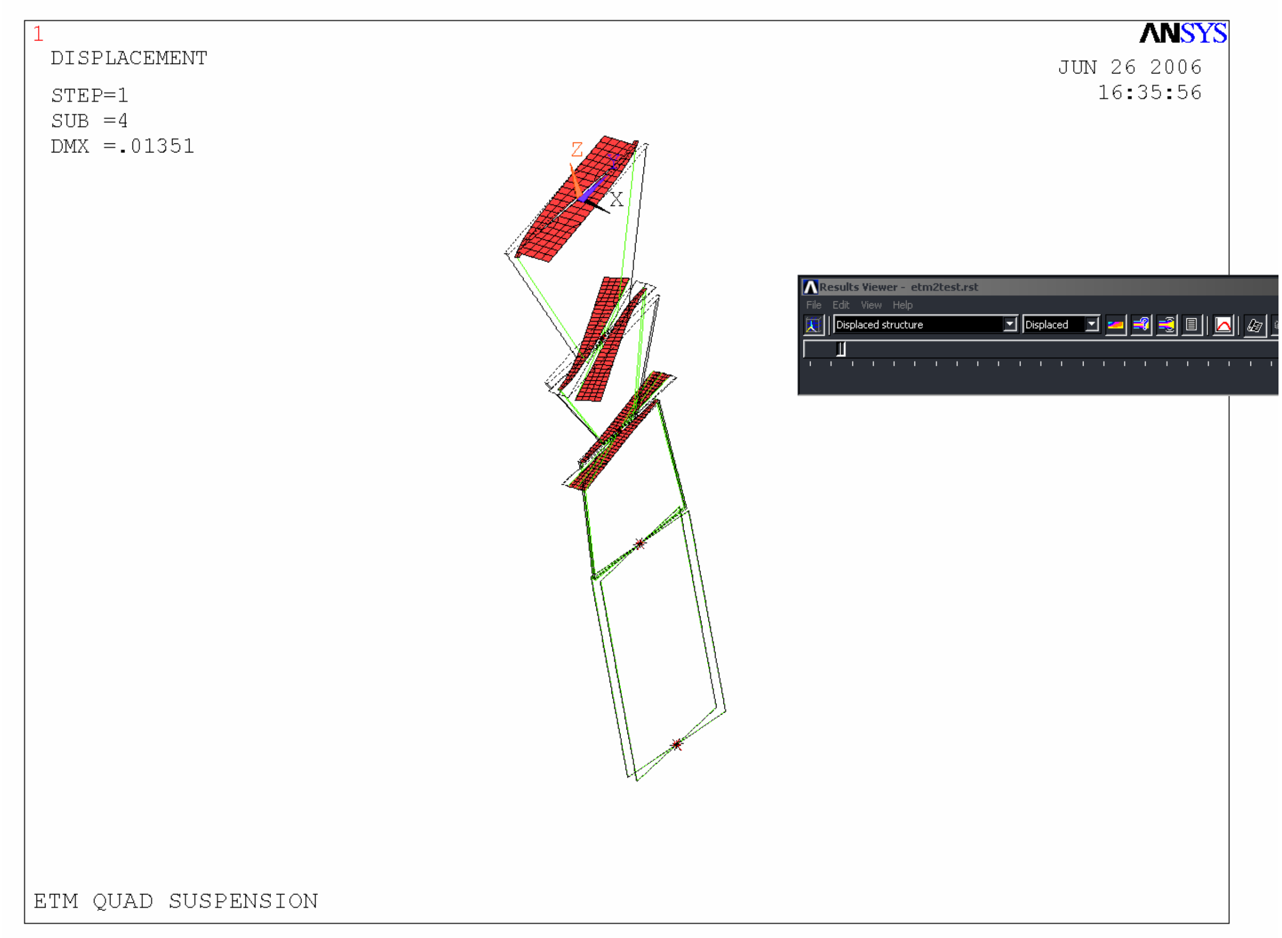
Using the Ansys macro script in Appendix A, the suspension model shown in the following figure was created.



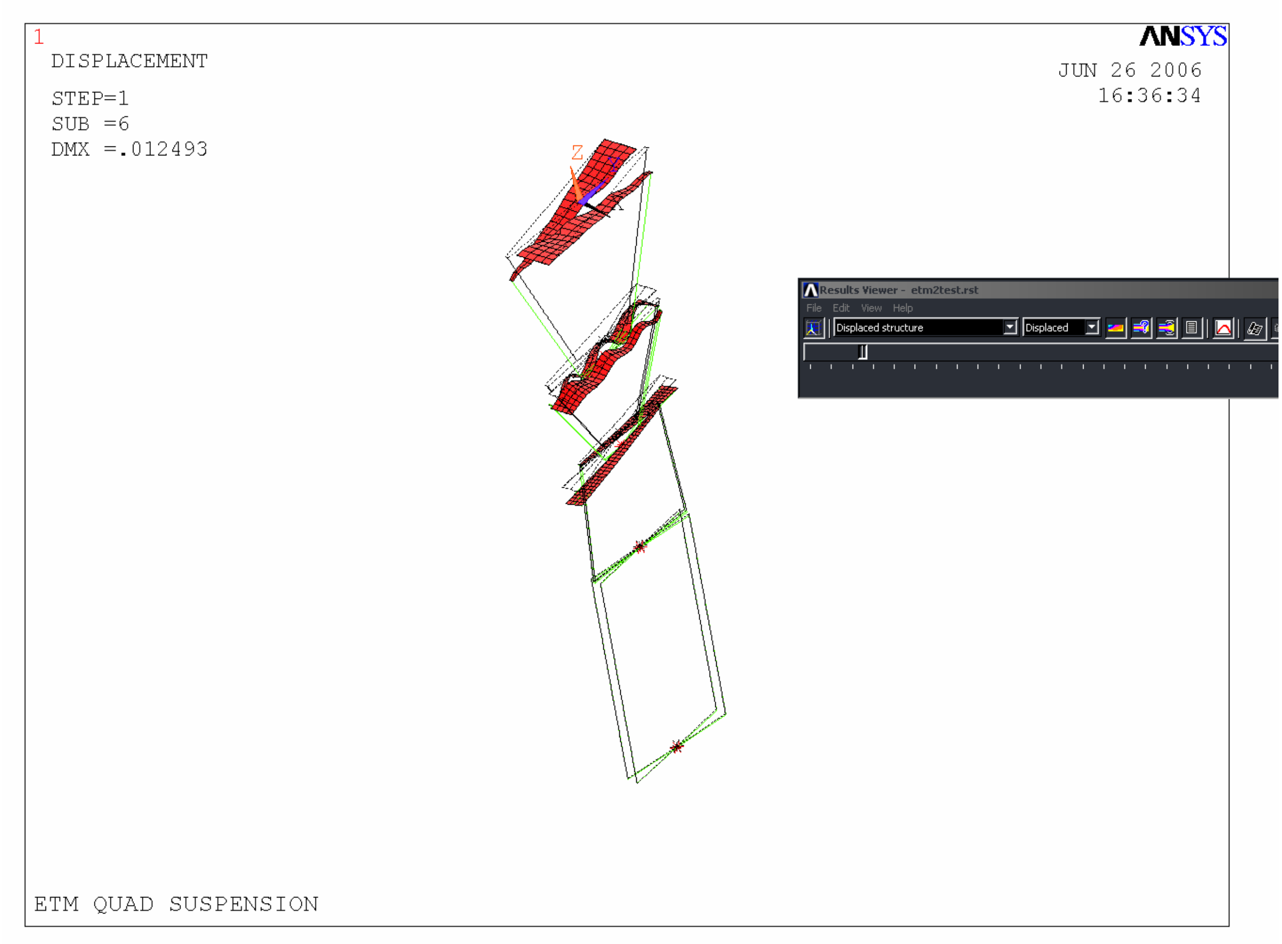
When pre-loaded and then the eigenvalue analysis is preformed, some of the modes seem reasonable, such as the one in the following figure (although in-plane blade spring compliance seems higher than actual).

[9] M. Barton, Quad Pendulum Conrols Prototype – Identification of Modes, LIGO-pending number, 3 Nov 2005.

[10] M. Perreur-Lloyd, Pendulum Parameter Descriptions and Naming Convention, LIGO-T040072-01.



However some of the modes, such as the one in the following figure, have high bending modes in the blades at low frequencies, which is not realistic. Either there is a model error or the eigensolver is having difficulties.



5 Appendix: Ansys Macro to generate Quadruple Pendulum Suspension

```
!**********************************************************************
! etmsus.mac
!**********************************************************************
! macro to analyse natural frequencies of an ETM quad suspension
!
!Dennis Coyne 28-nov-2005
!
finish
/CLEAR,START
/COM,ANSYS MODEL OF A SINGLE ETM QUAD SUSPENSION CHAIN
/PREP7
/TITLE,ETM QUAD SUSPENSION
!**********************************************************************
!*     GEOMETRIC PARAMETERS
!**********************************************************************
! values of parameters
! SI units (m,N)
! naming per T040072-01, plus extensions explained below
! coordinate system per T040072-02 with origin at center of top blades

! top blades (D040298)
lnb=0.480
anb=0.095
bnb=0.010  ! blade tip width
cnb=7.5*3.14159/180  ! blade centerline angle to y-axis (rad)
hnb=0.00429
nn0=0.25
!*
! middle blades (D040297)
l1b=0.4207
a1b=0.059
b1b=0.010  ! blade tip width
c1b=7.5*3.14159/180  ! blade centerline angle to y-axis (rad)
h1b=0.0046
n0=0.200
!*
! bottom blades (D040296)
l2b=0.370
a2b=0.049
b2b=0.010  ! blade tip width
c2b=7.5*3.14159/180  ! blade centerline angle to y-axis (rad)
h2b=0.0042
n2=0.140
!*
! Top Wires
! zw1 is the height coordinate of the top wire attachment to the top mass
! zcg1 is the height coordinate of the c.g. of the top mass
! zb1 is the height coordinate of the neutral axis of the middle blades
nn1=0.090
ln=0.450
```

```
rn=0.00052
dm=0.001
dn=0.001
zw1=-SQRT(ln**2-(nn0-nn1)**2)
zcg1=zw1-dm
zb1=zcg1-dn
!*
! Middle Wires
! zw2 is the height coordinate of the middle wire attachment to the UI mass
! zcg2 is the height coordinate of the c.g. of the UI mass
! zb2 is the height coordinate of the neutral axis of the bottom blades
n1=0.060
l1=0.3085
r1=0.00035
d0=0.001
d1=0.001
su=0.003
zw2=zb1-SQRT(l1**2-(n0-n1)**2)
zcg2=zw2-d0
zb2=zcg2-d1
!*
! Penultimate Wires
! zw3 is the height coordinate upper (penultimate) wire attachment to the PM
! zcg3 is the height coordinate of the c.g. of the PM
! zb3 is the height coordinate of lower (TM) wire attachment to the PM
n3=0.1635
l2=0.3400
r2=0.00031
d2=0.001
d3=0.001
si=0.003
zw3=zb2-SQRT(l2**2-(n2-n3)**2)
zcg3=zw3-d2
zb3=zcg3-d3
!*
! Test Mass Wires/Ribbons
! zw4 is the height coordinate TM wire attachment to the TM
! zcg4 is the height coordinate of the c.g. of the TM
n4=0.1585
n5=0.1585
l3=0.6020
r3=0.00022
d4=0.001
sl=0.015
zw4=zb3-SQRT(l3**2-(n4-n5)**2)
zcg4=zw4-d4

!***********************************************************************
!*     MASS PARAMETERS
!***********************************************************************
```

```
!* N.B.: The moments of inertia below (Inx, Iny, Inz) are values without
!        the blade springs included.
!  Top Mass
mn=22.1
Inx=0.0670
Iny=0.4289
Inz=0.4309
!*
!  UI Mass
m1=21.8
I1x=0.0581
I1y=0.5005
I1z=0.4988
!*
!  PM
m2=38.4
I2x=0.2765
I2y=0.2752
I2z=0.4704
!*
!  TM
m3=39.61
I3x=0.2692
I3y=0.2679
I3z=0.4556

!***************************************************************************
!*     MATERIAL PROPERTIES
!***************************************************************************
maryoung=1.76e11
marpoiss=0.3
mardens=7800
wireyoung=2.0e11
wirepoiss=0.3
wiredens=7800

!MPTEMP,,,,,,,,
!MPTEMP,1,0
!MPDATA,EX,1,,maryoung
!MPDATA,PRXY,1,,marpoiss
!MPDATA,DENS,1,,mardens
!MPTEMP,,,,,,,,
!MPTEMP,1,0
!MPDATA,EX,2,,wireyoung
!MPDATA,PRXY,2,,wirepoiss
!MPTEMP,,,,,,,,
!MPTEMP,1,0
!MPDATA,DENS,2,,wiredens
MP,EX,1,maryoung
MP,EY,1,maryoung
```

```
MP,EZ,1,maryoung
MP,PRXY,1,marpoiss
MP,DENS,1,mardens
MP,EX,2,wireyoung
MP,EY,2,wireyoung
MP,EZ,2,wireyoung
MP,PRXY,2,wirepoiss
MP,DENS,2,wiredens

!***********************************************************************
!*     GENERATE GEOMETRY
!***********************************************************************
!*          BLADES
!***********************************
! Top Blade, Right
K,1,0,nn0,0,
K,2,-bnb*cos(cnb)/2,nn0-bnb*sin(cnb)/2,0,
K,3,bnb*cos(cnb)/2,nn0+bnb*sin(cnb)/2,0,
K,4,lnb*sin(cnb),nn0-lnb*cos(cnb),0,
K,5,lnb*sin(cnb)-anb*cos(cnb)/2,nn0-lnb*cos(cnb)-anb*sin(cnb)/2,0,
K,6,lnb*sin(cnb)+anb*cos(cnb)/2,nn0-lnb*cos(cnb)+anb*sin(cnb)/2,0,
LSTR, 1, 4 ! line 1
LSTR, 4, 6 ! line 2
LSTR, 6, 3 ! line 3
LSTR, 3, 1 ! line 4
LSTR, 4, 5 ! line 5
LSTR, 5, 2 ! line 6
LSTR, 2, 1 ! line 7
AL,1,2,3,4 ! area 1
AL,1,5,6,7 ! area 2
!*
! Top Blade, Left
K,7,0,-nn0,0,
K,8,bnb*cos(cnb)/2,-nn0+bnb*sin(cnb)/2,0,
K,9,-bnb*cos(cnb)/2,-nn0-bnb*sin(cnb)/2,0,
K,10,-lnb*sin(cnb),-nn0+lnb*cos(cnb),0,
K,11,-lnb*sin(cnb)+anb*cos(cnb)/2,-nn0+lnb*cos(cnb)+anb*sin(cnb)/2,0,
K,12,-lnb*sin(cnb)-anb*cos(cnb)/2,-nn0+lnb*cos(cnb)-anb*sin(cnb)/2,0,
LSTR, 7,10 ! line 8
LSTR,10,12 ! line 9
LSTR, 9,12 ! line 10
LSTR, 7, 9 ! line 11
LSTR,10,11 ! line 12
LSTR, 8,11 ! line 13
LSTR, 7, 8 ! line 14
AL,8,9,10,11 ! area 3
AL,8,12,13,14 ! area 4
!*
! Middle Blade, Right
K,13,0,n0,zb1,
```

```
K,14,-b1b*cos(c1b)/2,n0-b1b*sin(c1b)/2,zb1,
K,15,b1b*cos(c1b)/2,n0+b1b*sin(c1b)/2,zb1,
K,16,l1b*sin(c1b),n0-l1b*cos(c1b),zb1,
K,17,l1b*sin(c1b)-a1b*cos(c1b)/2,n0-l1b*cos(c1b)-a1b*sin(c1b)/2,zb1,
K,18,l1b*sin(c1b)+a1b*cos(c1b)/2,n0-l1b*cos(c1b)+a1b*sin(c1b)/2,zb1,
LSTR, 13,16 ! line 15
LSTR, 16,18 ! line 16
LSTR, 18,15 ! line 17
LSTR, 15,13 ! line 18
LSTR, 16,17 ! line 19
LSTR, 17,14 ! line 20
LSTR, 14,13 ! line 21
AL,15,16,17,18 ! area 5
AL,15,19,20,21 ! area 6
!*
! Middle Blade, Left
K,19,0,-n0,zb1,
K,20,b1b*cos(c1b)/2,-n0+b1b*sin(c1b)/2,zb1,
K,21,-b1b*cos(c1b)/2,-n0-b1b*sin(c1b)/2,zb1,
K,22,-l1b*sin(c1b),-n0+l1b*cos(c1b),zb1,
K,23,-l1b*sin(c1b)+a1b*cos(c1b)/2,-n0+l1b*cos(c1b)+a1b*sin(c1b)/2,zb1,
K,24,-l1b*sin(c1b)-a1b*cos(c1b)/2,-n0+l1b*cos(c1b)-a1b*sin(c1b)/2,zb1,
LSTR, 19,22 ! line 22
LSTR, 22,24 ! line 23
LSTR, 21,24 ! line 24
LSTR, 19,21 ! line 25
LSTR, 22,23 ! line 26
LSTR, 20,23 ! line 27
LSTR, 19,20 ! line 28
AL,22,23,24,25 ! area 7
AL,22,26,27,28 ! area 8
!*
! Bottom Blade, Right
K,25,0,n2,zb2,
K,26,-b2b*cos(c2b)/2,n2-b2b*sin(c2b)/2,zb2,
K,27,b2b*cos(c2b)/2,n2+b2b*sin(c2b)/2,zb2,
K,28,l2b*sin(c2b),n2-l2b*cos(c2b),zb2,
K,29,l2b*sin(c2b)-a2b*cos(c2b)/2,n2-l2b*cos(c2b)-a2b*sin(c2b)/2,zb2,
K,30,l2b*sin(c2b)+a2b*cos(c2b)/2,n2-l2b*cos(c2b)+a2b*sin(c2b)/2,zb2,
LSTR, 25,28 ! line 29
LSTR, 28,30 ! line 30
LSTR, 30,27 ! line 31
LSTR, 27,25 ! line 32
LSTR, 28,29 ! line 33
LSTR, 29,26 ! line 34
LSTR, 26,25 ! line 35
AL,29,30,31,32 ! area 9
AL,29,33,34,35 ! area 10
!*
! Bottom Blade, Left
```

```
K,31,0,-n2,zb2,
K,32,b2b*cos(c2b)/2,-n2+b2b*sin(c2b)/2,zb2,
K,33,-b2b*cos(c2b)/2,-n2-b2b*sin(c2b)/2,zb2,
K,34,-l2b*sin(c2b),-n2+l2b*cos(c2b),zb2,
K,35,-l2b*sin(c2b)+a2b*cos(c2b)/2,-n2+l2b*cos(c2b)+a2b*sin(c2b)/2,zb2,
K,36,-l2b*sin(c2b)-a2b*cos(c2b)/2,-n2+l2b*cos(c2b)-a2b*sin(c2b)/2,zb2,
LSTR, 31,34 ! line 36
LSTR, 34,36 ! line 37
LSTR, 33,36 ! line 38
LSTR, 31,33 ! line 39
LSTR, 34,35 ! line 40
LSTR, 32,35 ! line 41
LSTR, 31,32 ! line 42
AL,36,37,38,39 ! area 11
AL,36,40,41,42 ! area 12
!***********************************
!*          MASSES
!***********************************
!*
! Top Mass
K,100,0,0,zcg1,
K,101,0,nn1,zw1,
K,102,0,-nn1,zw1,
K,103,su,n0,zb1,
K,104,-su,n0,zb1,
K,105,su,-n0,zb1,
K,106,-su,-n0,zb1,

!*
! Upper Intermediate (UI) Mass
K,200,0,0,zcg2,
K,201,su,n1,zw2,
K,202,-su,n1,zw2,
K,203,su,-n1,zw2,
K,204,-su,-n1,zw2,
K,205,si,n2,zb2,
K,206,-si,n2,zb2,
K,207,si,-n2,zb2,
K,208,-si,-n2,zb2,

!*
! Penultimate Mass (PM)
K,300,0,0,zcg3,
K,301,si,n3,zw3,
K,302,-si,n3,zw3,
K,303,si,-n3,zw3,
K,304,-si,-n3,zw3,
K,305,sl,n4,zb3,
K,306,-sl,n4,zb3,
K,307,sl,-n4,zb3,
```

```
K,308,-sl,-n4,zb3,

!*
! Test Mass (TM)
K,400,0,0,zcg4,
K,401,sl,n5,zw4,
K,402,-sl,n5,zw4,
K,403,sl,-n5,zw4,
K,404,-sl,-n5,zw4,

!***********************************
!*           WIRES
!***********************************
!*
! Top Wires
LSTR,1,101      ! line 43
LSTR,7,102      ! line 44
!*
! UI Wires
LSTR,103,201    ! line 45
LSTR,104,202    ! line 46
LSTR,105,203    ! line 47
LSTR,106,204    ! line 48
!*
! PM Wires
LSTR,205,301    ! line 49
LSTR,206,302    ! line 50
LSTR,207,303    ! line 51
LSTR,208,304    ! line 52
!*
! TM Wires
LSTR,305,401    ! line 53
LSTR,306,402    ! line 54
LSTR,307,403    ! line 55
LSTR,308,404    ! line 56

!***********************************
!*           RIGID LINKS
!***********************************
!*
! Top Mass
LSTR,100,101    ! line 57, top wire 1
LSTR,100,102    ! LINE 58, top wire 2
LSTR, 15,103    ! LINE 59, middle blade to wire 1
LSTR, 14,104    ! LINE 60, middle blade to wire 2
LSTR, 20,105    ! LINE 61, middle blade to wire 3
LSTR, 21,106    ! LINE 62, middle blade to wire 4
LSTR,100, 16    ! LINE 63, c.g. to blade root 1
LSTR,100, 17    ! LINE 64, c.g. to blade root 2
LSTR,100, 18    ! LINE 65, c.g. to blade root 3
```

```
LSTR,100, 22   ! LINE 66, c.g. to blade root 4
LSTR,100, 23   ! LINE 67, c.g. to blade root 5
LSTR,100, 24   ! LINE 68, c.g. to blade root 6
!*
! UI Mass
LSTR,200,201   ! line 69, UI wire 1
LSTR,200,202   ! LINE 70, UI wire 2
LSTR,200,203   ! LINE 71, UI wire 3
LSTR,200,204   ! LINE 72, UI wire 4
LSTR, 27,205   ! LINE 73, bottom blade to wire 1
LSTR, 26,206   ! LINE 74, bottom blade to wire 2
LSTR, 32,207   ! LINE 75, bottom blade to wire 3
LSTR, 33,208   ! LINE 76, bottom blade to wire 4
LSTR,200, 28   ! LINE 77, c.g. to blade root 1
LSTR,200, 29   ! LINE 78, c.g. to blade root 2
LSTR,200, 30   ! LINE 79, c.g. to blade root 3
LSTR,200, 34   ! LINE 80, c.g. to blade root 4
LSTR,200, 35   ! LINE 81, c.g. to blade root 5
LSTR,200, 36   ! LINE 82, c.g. to blade root 6
!*
! PM
LSTR,300,301   ! LINE 83, c.g. to PM wire 1
LSTR,300,302   ! LINE 84, c.g. to PM wire 2
LSTR,300,303   ! LINE 85, c.g. to PM wire 3
LSTR,300,304   ! LINE 86, c.g. to PM wire 4
LSTR,300,305   ! LINE 87, c.g. to TM wire 1
LSTR,300,306   ! LINE 88, c.g. to TM wire 2
LSTR,300,307   ! LINE 89, c.g. to TM wire 3
LSTR,300,308   ! LINE 90, c.g. to TM wire 4
!*
! TM
LSTR,400,401   ! LINE 91, c.g. to TM wire 1
LSTR,400,402   ! LINE 92, c.g. to TM wire 2
LSTR,400,403   ! LINE 93, c.g. to TM wire 3
LSTR,400,404   ! LINE 94, c.g. to TM wire 4
!*
! Plot Areas
aplot

!***********************************************************************
!*     MESH GEOMETRY
!***********************************************************************
!*
!***********************************
!           Blade Springs
!***********************************
!ET,1,SHELL63,0,0,1,,0,0
!ET,1,SHELL43,,,2
!ET,1,SHELL181,1
!ET,1,SHELL93
```

```
ET,1,SHELL63
TYPE,1     ! shell elements
MAT,1      ! maraging steel
!     Top Blades
R,1,hnb               !for the blade
REAL,1
ESIZE,anb/4,0
amesh,1,4
!     Middle Blades
R,2,h1b               !for the blade
REAL,2
ESIZE,a1b/4,0
amesh,5,8
!     Bottom Blades
R,3,h2b               !for the blade
REAL,3
ESIZE,a2b/4,0
amesh,9,12

!***********************************
!           Suspension Masses
!***********************************
ET,2,MASS21,0,0,0
TYPE,2     ! discrete mass elements
!     Top Mass
R,4,mn,mn,mn,Inx,Iny,Inz
REAL,4
KMESH,100
!     UI Mass
R,5,m1,m1,m1,I1x,I1y,I1z
REAL,5
KMESH,200
!     PM
R,6,m2,m2,m2,I2x,I2y,I2z
REAL,6
KMESH,300
!     TM
R,7,m3,m3,m3,I3x,I3y,I3z
REAL,7
KMESH,400

! Wire Clamps
!R,8,mc,mc,mc,Icx,Icy,Icz
!REAL,8
!kmesh,?

!***********************************
!           Wires
!***********************************
ET,3,BEAM4,,0,,,,0
```

```
TYPE,3     ! beam elements
MAT,2
!     Top Wires
wAn=3.14159*rn**2
wIn=(3.14159*rn**4)/4
wJn=(3.14159*rn**4)/2
R,9,wAn,wIn,wIn,rn,rn,0
RMORE,0,wJn
REAL,9
ESIZE,0.005
LMESH,43,44
!     UI Wires
wA1=3.14159*r1**2
wI1=(3.14159*r1**4)/4
wJ1=(3.14159*r1**4)/2
R,10,wA1,wI1,wI1,r1,r1,0
RMORE,0,wJ1
REAL,10
ESIZE,0.005
LMESH,45,48
!     PM Wires
wA2=3.14159*r2**2
wI2=(3.14159*r2**4)/4
wJ2=(3.14159*r2**4)/2
R,11,wA2,wI2,wI2,r2,r2,0
RMORE,0,wJ2
REAL,11
ESIZE,0.005
LMESH,49,52
!     TM Wires
wA3=3.14159*r3**2
wI3=(3.14159*r3**4)/4
wJ3=(3.14159*r3**4)/2
R,12,wA3,wI3,wI3,r3,r3,0
RMORE,0,wJ3
REAL,12
ESIZE,0.005
LMESH,53,56

!***********************************
!           Rigid Links
!***********************************
ET,4,MPC184,1,0
TYPE,4      ! rigid body constraint elements
ESIZE,,1
LMESH,57,94

NUMMRG,NODE,0.00001

!***********************************************************************
```

```
!*     BOUNDARY CONDITIONS
!***********************************************************************
!*
! Clamp the upper blade roots
DL, 2, ,ALL,0
DL, 5, ,ALL,0
DL, 9, ,ALL,0
DL,12, ,ALL,0
EPLOT

FINISH

!***********************************************************************
!   Static Preload Analysis
!***********************************************************************
/SOL
ANTYPE,STATIC
PSTRES,ON
G=9.84
ACEL,0,0,G
SOLVE
FINISH
!/POST1
!PLDIST,0
!FINISH
!***********************************************************************
!   Eigenvalue Analysis
!***********************************************************************
/SOL
ANTYPE,MODAL
MSAVE,0
!*
MODOPT,LANB,60
EQSLV,JCG
!MXPAND,0, , ,0
LUMPM,OFF
PSTRES,ON
!*
/STATUS,SOLU
SOLVE
FINISH
/POST1
/output,etmsus,out,,
!*Status,argx
SET,LIST
/output
*get,freq1,mode,1,freq
*get,freq2,mode,2,freq
*get,freq3,mode,3,freq
```