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Exploring the design space of aluminium tubing using knowledge objects and FEM

Mr. Aniket Chandrakant Patil.

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This thesis work is performed at Jönköping Institute of Technology within the Mechanical Engineering Department. The work is a part of the university's master's degree in mechanical engineering specialisation in Product development and Industrial design. The authors are responsible for the given opinions, conclusions and results.

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Abstract

There are great possibilities to cut lead time in product development process by automation of the routine work. Finite Element Analysis (FEA) is often used to test product properties virtually. But the process of setting up FEA is manual most of the times and not properly structured. By exploring a design space with the help of FEA-application, we can automise that process. FEA includes lots of predictions and validations and it would be beneficial to formalise and automate the process of developing such calculation. LS-DYNA was used as FEM application and a semiautomatic KBE system to explore the design space. By integrating KBE, FEM and CAD we can implement Design Automation.

Key Words

Design Automation, Knowledge objects, FEM, LS-DYNA, CATIA, Rotary Draw Bending, Parametric model, Knowledge design studio, Knowledge based engineering (KBE)

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1 Introduction

In today's world of intense competition, Design Automation could be the way to cut lead time. In many product development processes there are some design calculations where design engineer repeatedly does. Finite element methods (FEM) are often used to test product properties virtually. But the major workload is on the pre-processing setup of FEM. Rotary draw bending is the most commonly used manufacturing processes out of all bending process. Here a semi-automatic Knowledge based engineering (KBE) system was used to explore design space of rotary draw bending. Also a design automation technique based on KBE, FEM and CAD was used.

1.1 Background

FEM is the most common method use to test product properties virtually. But the setting up procedure of pre-processing step of FEM process is time consuming. In order to cut lead time we have to use Design automation technique. Rotary draw bending is most commonly used bending method of all bending methods. Despite its simplicity, it has some serious defects.

1.2 Purpose and aims

The aim of this thesis is to explore a design space of Rotary Draw Bending of aluminium tubing using Knowledge Based Engineering (KBE) system.

By integrating Parametric CAD model and KBE system it is possible to automate the Pre-processing step of FEM. A small design space is explored with the help of FEM simulations to set guidelines for numerical calculations.

1.3 Outline

The report is structured in four parts. A first part gives theoretical aspects of rotary draw bending and general tube bending. It also says about governing rules of the process and knowledge based engineering. In second part implementation part is covered. It suggests how design automation is applied with the help of KBE system. Third part gives results obtained. One sample graph of each condition is shown and all graphs are attached at the end. All Conclusions and discussion are given in the fourth part.

1.4 Delimitations

This work does not present the mathematical details of the FE method. No details about how to build Knowledge based engineering system are intended to be provided in this work. The Knowledge based engineering system that we have used is provided by our guide Mr. Joel Johansson.

2 Theoretical background

In many product development process same type of data, formulas and rules are applied over and over again to design the product with new specifications. There are many possibilities to cut lead time in product development process by automation of “routine” work. All this design knowledge related to product can be stored in various format e.g. spreadsheet, databases or algorithmic programs, MATHCAD files, MATLAB files etc. These pieces of knowledge should be captured and secured. Knowledge based engineering (KBE) system can be used to automate the Design process with all the pieces of knowledge linked in it. A parametric model of product is needed which responds to changes in design specification. In simple words parametric model is geometric entities that contain intelligence.

2.1 Design Rules for metal forming process

In the metal forming process there are four different types of design rules applied, namely knowledge based on heuristics (rules of thumb), Knowledge based on analytics (rules derived from fundamental physical laws), data from numerical calculations (e.g. FEM) and empirically developed data (Actual manufacturing data). [1]

2.1.1 Heuristic rules

Heuristic rules are typically found in different handbooks, company standards and skilled engineer’s experience. Biggest advantage of this rule is that they are accurate enough and can be faster if automated. They have easy to use relationships which are only valid for small range of design space and are not able to explain fundamental principals related to the process. In reality many design processes are built on this kind of knowledge.

2.1.2 Analytical rules

Analytical rules are derived from fundamental physical laws and are more complex than heuristics. But they are capable of explaining why things happen. They can give faster results when implemented properly in a computer system.

2.1.3 Numerical rules

Finite Element Method (FEM) is the most common numerical method for solving different engineering problems. But results are mainly dependant on Mesh Density, Element type, Boundary conditions, Material model, and Time step. If used properly FEM can give highly reliable data.
Comparing to the above rules, FEM is costly to use in terms of both money and time. Also it is not able to answer why things happen. The benefit is that FEM

allows full control over the process so it is easy to scroll in time and space, doing sections and plotting different parameters. One thing is to keep in mind that simulation tools are like instruments for measurements, i.e. they must be calibrated. This calibration is done via result feedback. With time, accurate model can be developed.

2.1.4 Empirical rules

Trial manufacturing offers reliable data. It’s not possible to perform experiments for each and every design specification as they are very expensive. Also they have limited range and do not answer why things happen. To make empirical data usable, experiment planning has to be done beforehand to isolate interesting parameters. The empirical data plays two different roles. Firstly it can be used to directly evaluate or verify a single setup. Secondly it can also be used to develop heuristic rules.

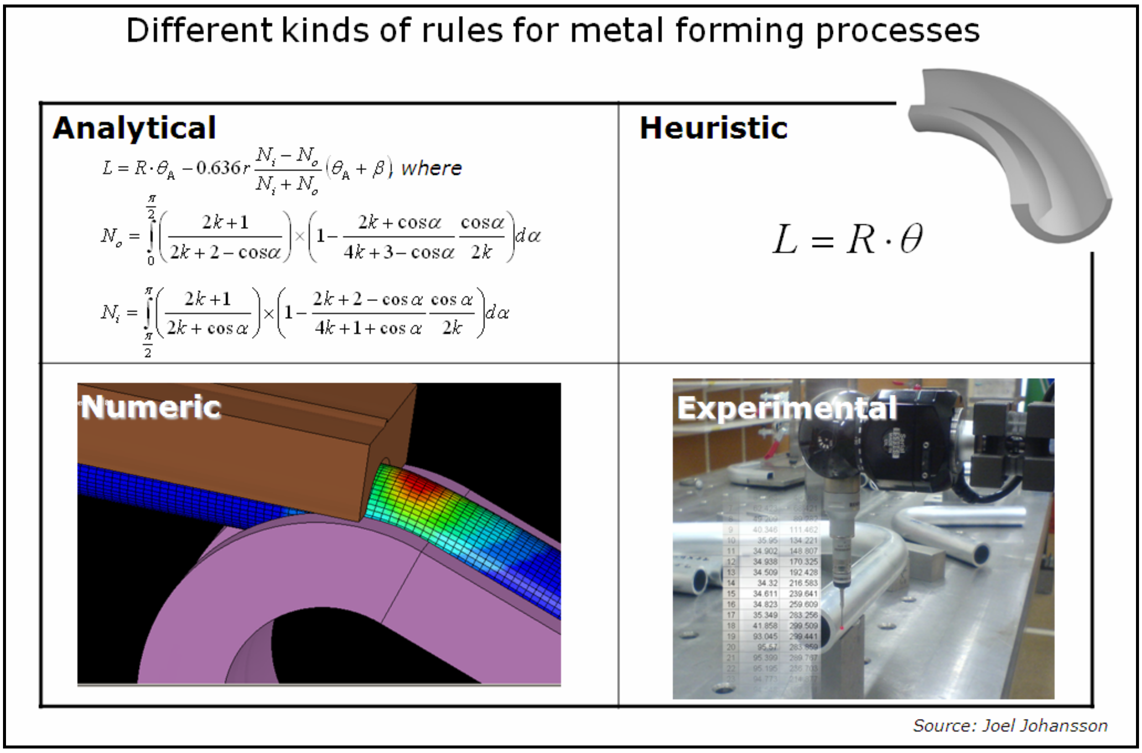


Figure 1- Rules in Metal Forming Processes [1]

2.2 Rotary Draw Tube Bending

Rotary draw tube bending is the most flexible bending method and is used immensely in industry on account of its tooling and low cost. The tooling consists of a bend die, clamp die, pressure die and wiper die. In this bending technique the tube is securely clamped to the bend die by using the clamp die. The bend die rotates and draws the tube along with it. The pressure die prevents the tube from rotating along with the bend die. The pressure die may be stationary or it may move along with tube. The pressure die provides a boost (pushes the material at the extrados of the tube) to reduce the thinning of the tube and can be very helpful when the bending angle is large and the bending radius is small. A mandrel along with wiper die may be used to prevent the wrinkling and collapsing of the tube. But the use of mandrel should be avoided if possible since it increases the production cost. Figure 2&3 shows the internal and external tooling of rotary draw bending process. Rotary draw tube bending provides close control of metal flow necessary for small radius and thin walled tube [2]. Following figures 2 and 3 shows the tooling of rotary draw bending process.

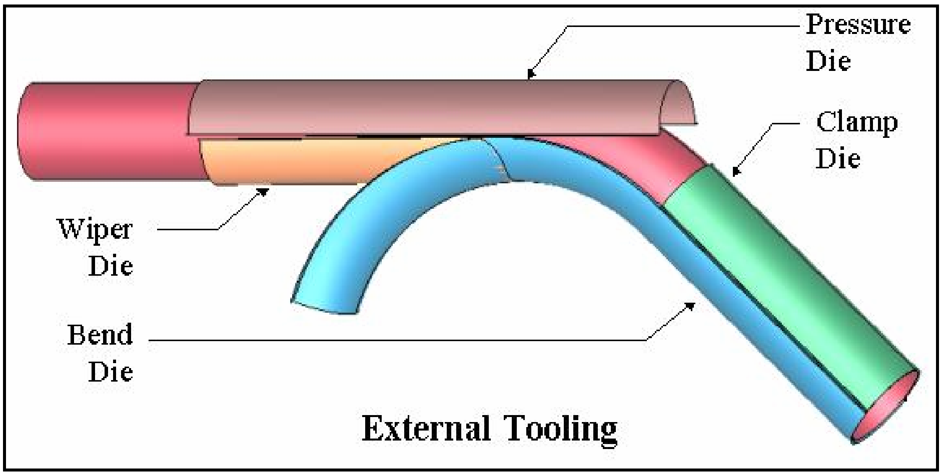


Figure 2-External tooling for Rotary Draw Tube Bending [3]

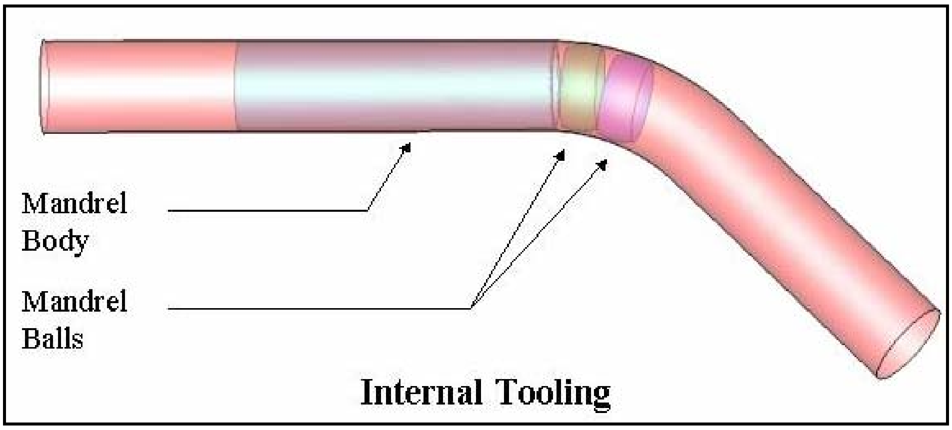


Figure 3-Internal tooling for Rotary Draw Tube bending [3]

2.3 Defects in Rotary Draw Bending

Despite its simplicity, rotary draw bending gives some defects if not properly used. Due to these defects it's hard to match tight dimensional tolerances. Also it causes corrosion and spoils the surface finish. But out of these, there are three serious defects discussed below and which are the main focus area of the entire work.

2.3.1 Variation in wall thickness

When a tube is bent, two things happen to metal. The outside wall is reduced in thickness due to stretching of the material and the inside wall becomes thicker due to compressing of the material. The material that forms the outside of the bend has to further travel and therefore is stretched; the inside of the bend has less distance to travel and is compressed. [4]

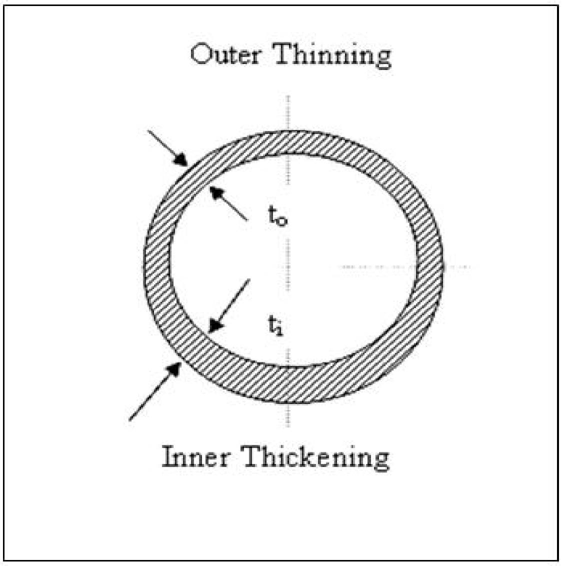


Figure 4-Variation in wall thickness

During the bending process the bending moment induces axial forces in the inner and outer fibers. The inner and outer fibers are subjected to compressive and tensile stresses respectively. This results in thinning of the tube wall at the outer section (extrados) and thickening of the tube wall at the inner section (intrados). The wall thickness variation is shown in Figure (4). This is called as variation in wall thickness.

2.3.2 Tube Wrinkling

As the tube is bent, the inner surface of the tube, the intrados is subjected to compressive stress. When the tube is bent into a tight radius, it is subjected to high compressive stress in the intrados which leads to Bifurcation instability or buckling (wrinkling) of the tube. Figure (5) shows tube wrinkling.

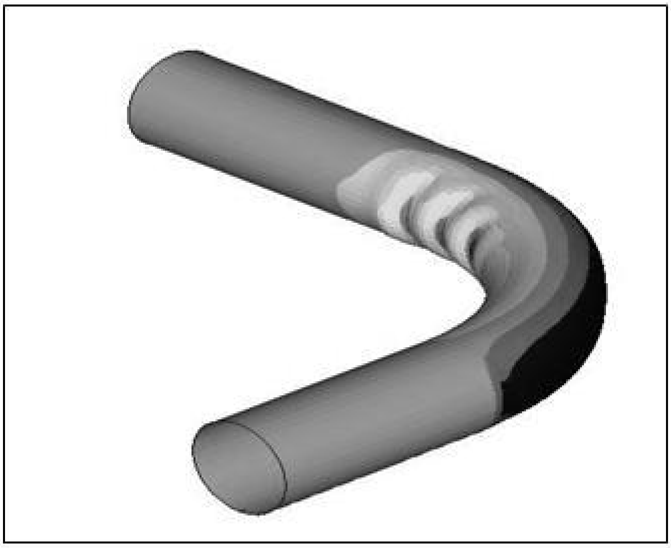


Figure 5-Wrinkling in tube

Wrinkles are wavy types of surface distortions. As tubes are used as parts in many applications where tight dimensional tolerances are desired, wrinkles are unacceptable and should be eliminated. Furthermore, wrinkles spoil the aesthetic appearance of the tube.

2.3.3 Springback

After the bending process is complete and the toolings have been withdrawn the bent tube tries to get back to its original shape due to the elastic nature of the tube material. This is called spring back or the elastic recovery of the tube. Springback is the term used to describe the tendency of metal that has been formed to return to its original shape. During the bending process internal stresses which are developed in the tube do not vanish even upon unloading. After bending the extrados is subjected to residual tensile stress and the intrados is subjected to residual compressive stress. These residual stresses produce a net internal bending moment which causes spring back. The tube continues to spring back until the internal bending moment drops to zero.

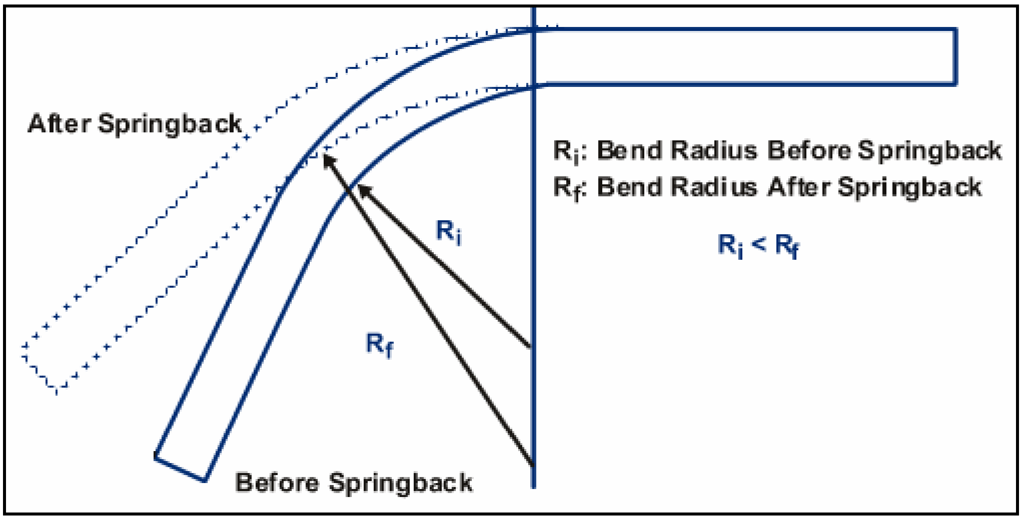


Figure 6-Springback

The spring back angle depends on the bend angle, tube material, tube size, plug or mandrel, machine and tooling. In actual practice the amount of spring back is calculated and the tube is over bent by that amount.

Spring back is excessive when a mandrel is not used. This should be considered when selecting a bend die. Springback will cause the tube to unbend from two to ten degrees depending on the radius of bend, and may increase the bend radius of the tube. Smaller the radius of bend the smaller will be the springback.

2.4 Availability of rules

These three different phenomenons' can be solved with three different rules. Here the data is taken from the paper [1].

PHENOMENON	HEURISTIC RULES	ANALYTICAL RULES	EMPIRICAL RULES
WRINKLING	Low Precision	Low Precision	Best For Small Range
SPRINGBACK	Low Precision	Moderate Precision	Best For Small Range
VARIATION IN WALL THICKNESS	Low Precision	Moderate Precision	Best For Small Range

From above table it is clear that these rules have some limitations. It can be seen that Heuristic rules have low precision but can be applied over a large range in Design space. Heuristic rules are based on empirical data, while Analytical rules has low precision for wrinkling and has moderate precision for other two phenomenons. Empirical rules always gives correct data but cannot be applied over the whole design space as they are costly and trial manufacturing cannot be performed for each and every design configuration.

The heuristic rules and analytical rules are only applicable when the bending factor is quite high and wall factor is large. The assumption with perfectly-elastic plastic material behavior makes the rules applicable only on large bending angles (ideally > 90). [1]

2.5 Design space

As we know that these rules have their own limitations, sometimes they conflict between different sources of knowledge. Also they lose precision between two distinct points in design space. Heuristic knowledge is applicable within a narrow design space with low precision. The analytically derived knowledge, on the other hand, is applicable on a wide design space. However, due to simplifications and assumptions made in order to make the expression usable, the precision is moderate. [1]

Here a small design space is selected just on the edges of those assumptions. Numerical rules were applied to explore that design space and use that knowledge for future development of product. Following figure (7) shows the design space which was selected.

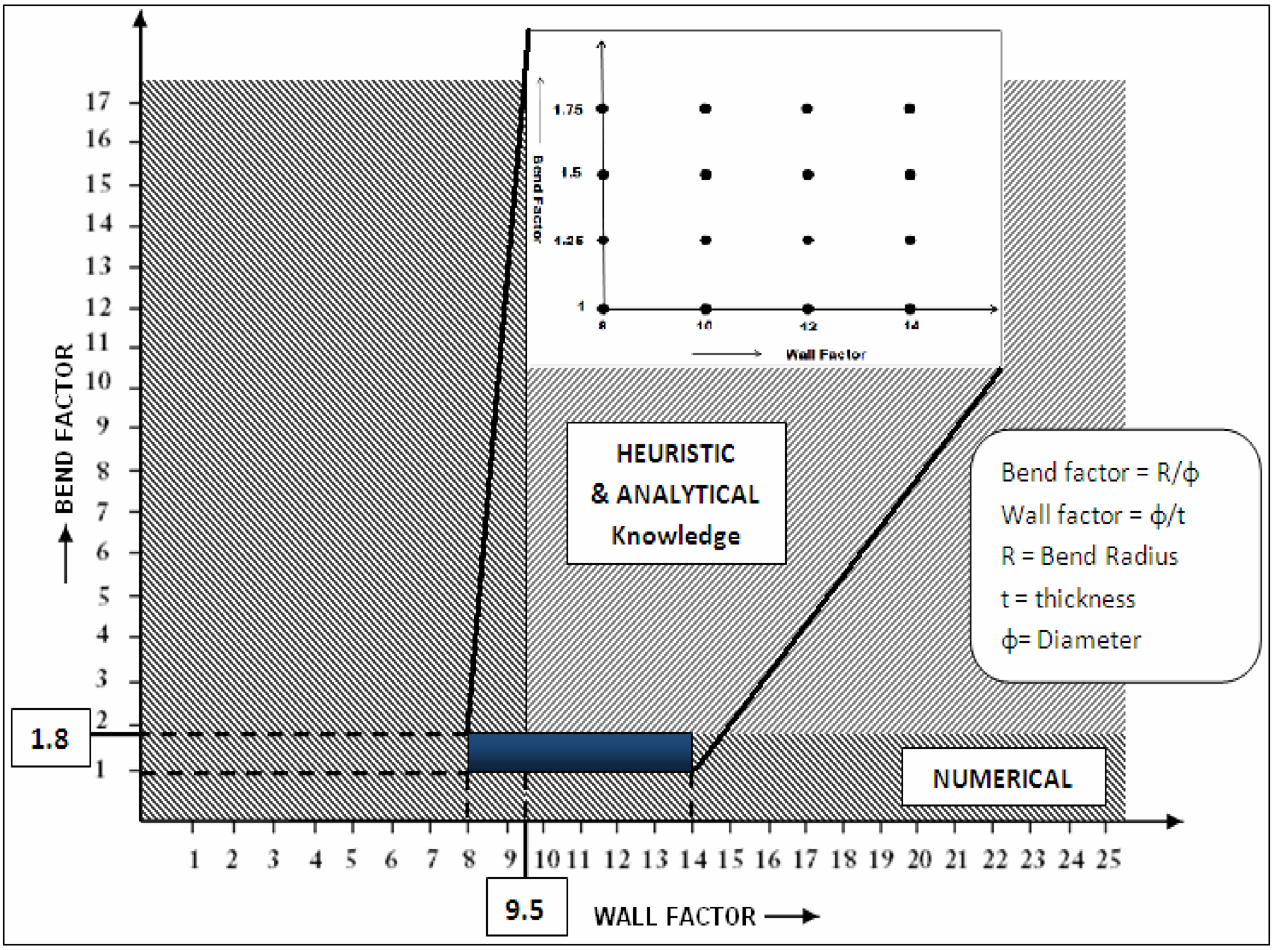


Figure 7-Design space

2.6 Knowledge based engineering (KBE)

In many organizations, information at every stage in the life-cycle of the product is stored in various forms such as spreadsheets, databases or algorithmic programs, thumb rules etc. A lot of knowledge is stored in all these files. This knowledge is used by the companies developing various products and hence is highly valuable. Therefore it becomes very necessary that this knowledge should be collected and secured.

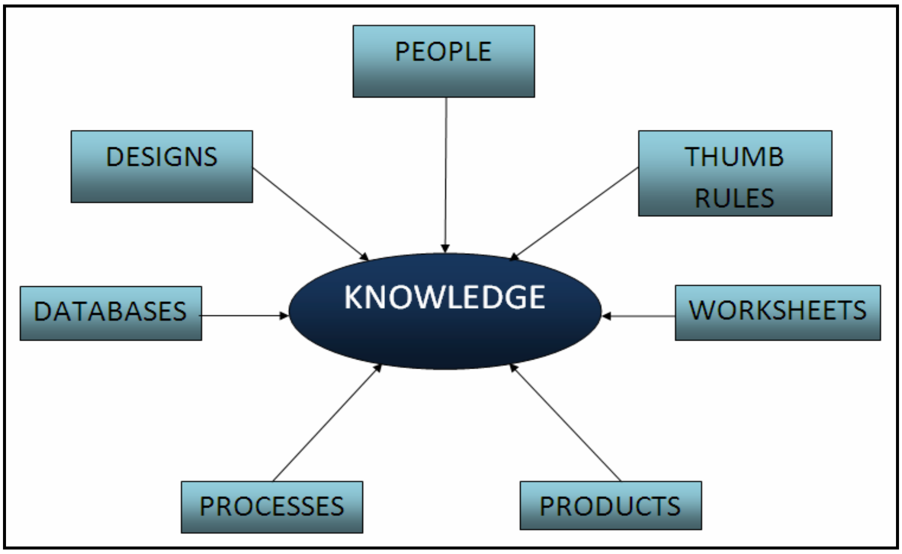


Figure 8-Sources of knowledge

Knowledge-Based Engineering is the process or system that collects all the information available in the life-cycle of a product, and makes it re-usable. It captures existing company information and engineering knowledge to help engineers automate certain design processes and thus concentrate on engineering rather than repetitive tasks. A simplified KBE system architecture would be as follows given by HOPGOOD [5].

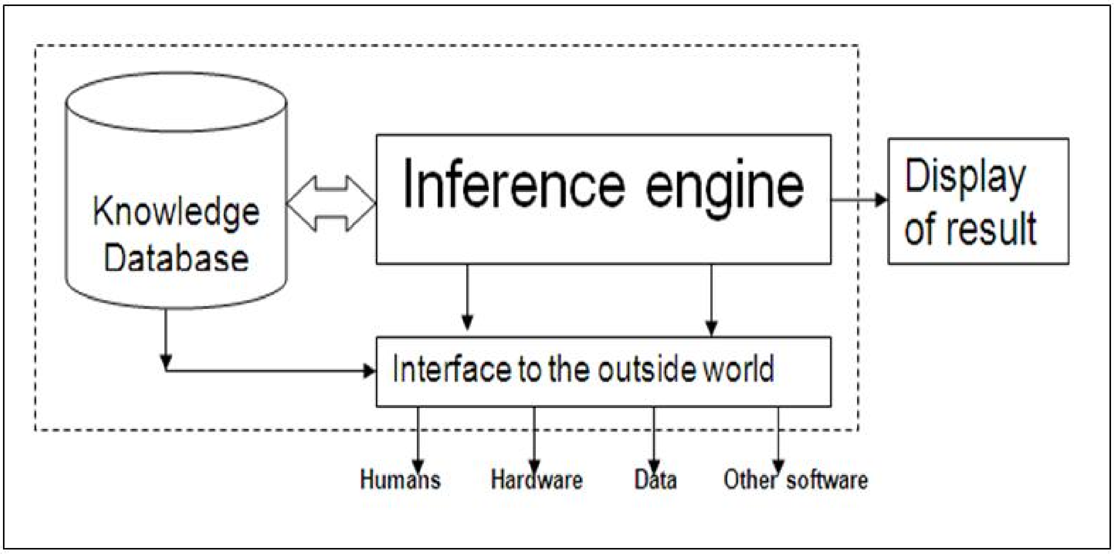


Figure 9-KBE system with essential components

There are some requirements for capturing knowledge both on system architecture and knowledge itself.

The guidelines for KBES given by Cederfeldt [6] should be as follows –

1. Low effort of development
2. Low level of investment
3. User reachable and understandable knowledge
4. Transparency and Longevity
5. Scalability
6. Flexibility and Ease of use

In this thesis work building a system is not focused rather how to use it to automate FEM is mentioned.

2.6.1 Knowledge objects

The KBE system used here is semi-automatic. It means user interference is needed. This KBE system works on Knowledge objects containing information on inputs, outputs and what software's are used to implement the knowledge pieces. Knowledge objects for FEM could be as per given in section 2.7. When Numerical calculations e.g. FEM is wanted, the system is set to run applicable knowledge objects for presented input data.

2.7 FEM as knowledge objects

FEM (Finite Element Method) is the most common procedure adopted to solve many engineering problems. There are many readily available FEM software packages. We have used LS-DYNA as FEM application in the simulation of Rotary Draw bending of Aluminium Tube. Traditional FEM is divided into three steps: pre-processor, solver, post processor as shown in figure (10) below.

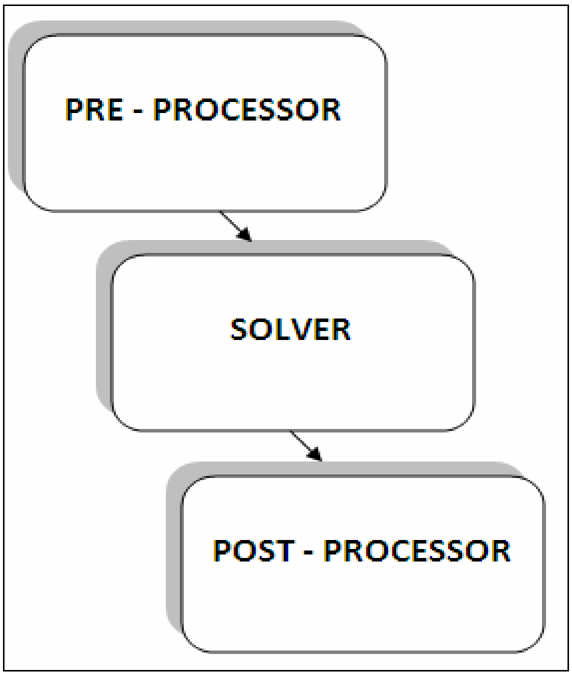


Figure 10-Traditional FEM procedure

Many times design engineer has to manually carry out the Pre-processing setup. Pre-processing includes problem definition, geometry definition, defining constraints and assumptions and finally the mesh generation. Solver stage is comparatively automatic. Results are interpreted in post processing at the end. The most time consuming process is pre-processing of FEM model. Results of FEM are greatly dependant on mesh size, Element type, and material model [7]. LS-DYNA was used as FEM application. Descriptions of parameters in FEM are mentioned below. These parameters works together as Knowledge objects of KBE based on FEM calculations.

1. Mesh size- Larger the mesh size less time is required to perform FE analysis. But results will not be accurate enough. Smaller mesh size will give accurate results but again FE analysis will take long time. The design engineer has to find out the best compromise between accuracy of result and time taken by analysis. Many time selection of mesh size is based on past experience or gut feeling. So there are chances of misleading results. Here the FE analysis was first performed by taking firstly 5 as initial mesh size.

Then same analysis was performed with finer mesh size of 2 for comparison. This helped to set a guideline for selection of the mesh size.

2. Element type- Various types of elements are available for meshing. Each Finite element software package has its own element library. Selection of element type is normally based on geometry and the type of process. Shell elements are used to model curved bodies in which the thickness of the shell is much smaller than the other dimensions. Shell element w selected as it requires less memory and CPU time than the triangular elements.

3. Material model- Lots of material model [8] are available and it's hard to select the correct one. There is a need of FEA specialist to do that. The main aim of developing this system is to develop rules to automat the FEA process and free the FEA specialist to work on their problem. In this research work two material models were compared. Comparative simulations (See table 6) would help to find out best suited material model.

4. Boundary condition- It depends on which type of analysis is conducted and type of process. In this research dynamic type metal forming analysis was carried out.

5. Solver- It is the last procedure to set a solver for analysis in pre-processing step of FEM. There are mathematical equations involved to determine the unknown variables (here displacements) at each node in FEM. Specially adapted solvers that can considerably reduce the computational time and storage requirements are often used in FE codes. Two types of solver are available to solve them in LS-DYNA namely double precision and single precision.

Above are the parameters in FEM used as knowledge objects used in KBE system. By running simulation in selected Design space one could find out the best possible combination of different parameters mentioned above. This one set of all parameters is called as Knowledge objects. By selecting the proper knowledge objects we can run the system for optimal accuracy. Thus it is possible to cut lead time in product development.

2.8 Design Automation

To use the design space a parameterized CAD model is needed which would respond to changes in design. A parametric FE model was used and created by some built in function of CATIA. This model is made up of shell element and was developed by our Guide Mr. Joel Johansson [8]. Shell elements are used to model structures in which one dimension (the thickness) is significantly smaller than the other dimensions and in which the stresses in the thickness direction are negligible. Shell element consumes less CPU time while performing analysis than any other [7]. This parametric approach saves great amount of time. Following figure (11) shows screenshot of parametric model built in CATIA

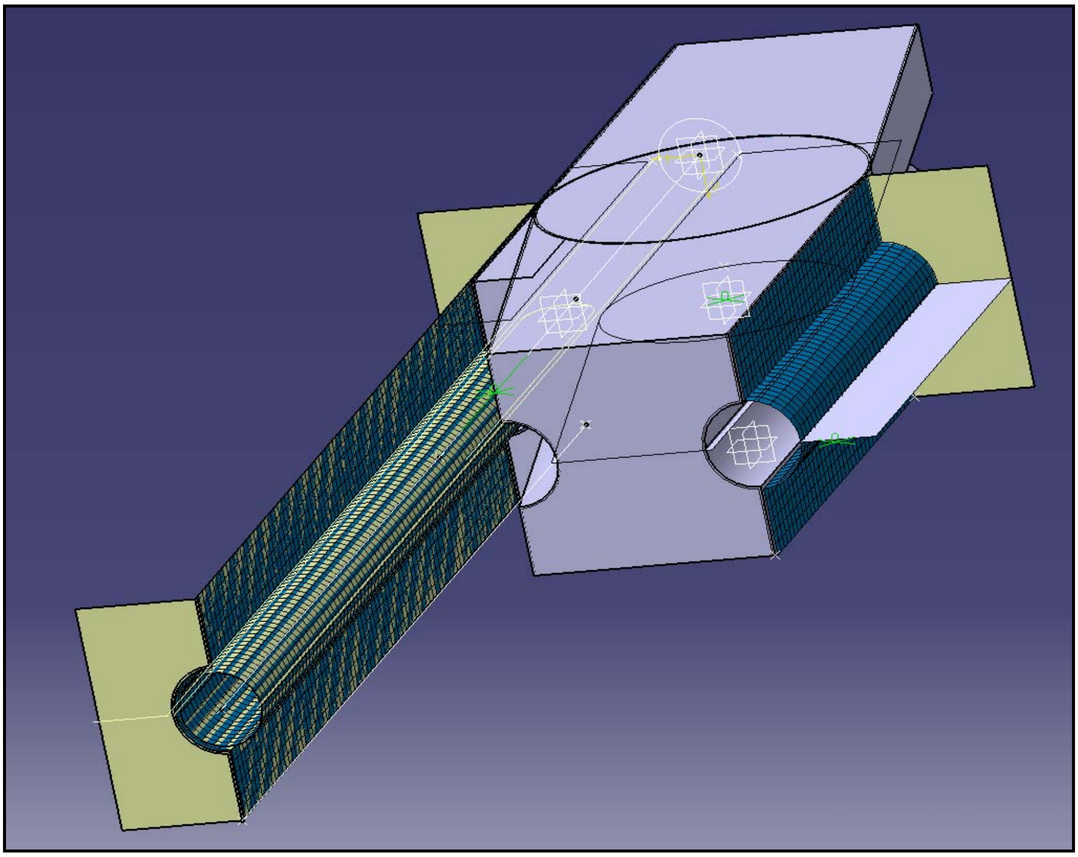


Figure 11-Parametric CAD model built in CATIA

In this thesis work it was focused to apply Design Automation technique in pre-processing area of FEM with the help of Knowledge based Engineering (KBE) system concept.

Smart searching a design space for feasible or optimal solutions using software applications is called as Design Automation. Design automation includes storage and retrieval of Product development knowledge whenever necessary. Finite element methods are often used to test product properties virtually. The major workload in the FEM process is in the pre-process. So it is necessary to automate that procedure.

There are two ways to automate the pre-process, one is to use parameters in the FEA applications and the other is to use parameterized CAD model. Adding parameters in the FEM application usually includes programming and hence it is limited to FEA specialist. Also it's hard to interpret such FEA models. Whereas parameterized CAD models are simple and can be controlled easily by outside programming. A program written in Microsoft VB called as text converter was used. This text converter is part of Knowledge based engineering system; called as KDS (Knowledge Design studio) [9].
Following figure (12) shows the role of KBE in Design automation.

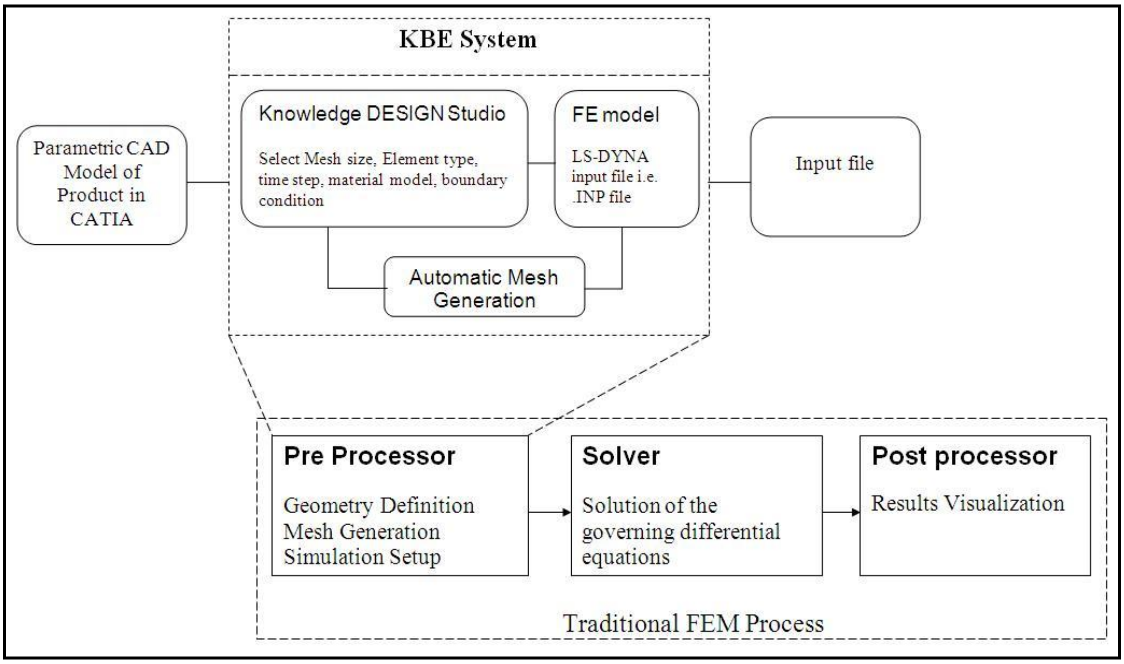


Figure 12-Design automation in FEM

To automate the Pre-processing of FEM, KBE system is most probably used. This KBE system is semi automatic and needs user interference to execute knowledge objects. Final results are again displayed back into KBE system. It works on sophisticated programming done in Microsoft VB and in connection with various readily available software packages. A small string in programming could be used to execute each knowledge object.

3 Implementation

The present research focuses on how numerical calculations should be performed by exploring a design space for rotary draw tube bending. As mentioned earlier, Heuristic and Analytical knowledge are applicable within a narrow design space with low precision. For detailed design proposal we have to move towards and carry out advanced calculations such as FEM. FEM data could be reliable if it is achieved by a proper FEM technique. In this research a small design space was selected in numerical calculation range. The implementation flowchart is given below.

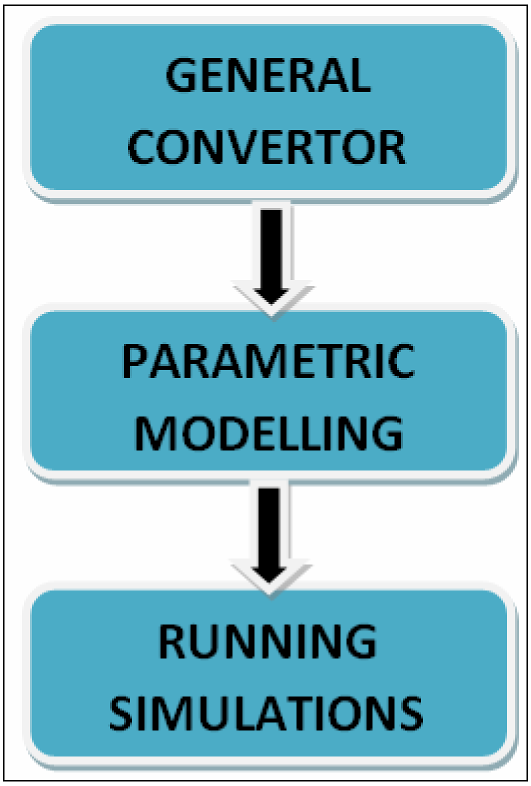


Figure 13-Implementation Steps

3.1 General converter

A basic geometry of 100-100 mm Cube in CATIAV5 was generated and a surface mesh having mesh size of 5 was used. There were two options for the element shape, i.e. triangular and quadrilateral. Quadrilateral element was selected as it requires less memory and CPU time than the triangular elements. Hence the selected element type for CATIA was CQUAD4. After completing the mesh generation, .DAT file (CATIA FEM DATA) was exported and created. A similar geometry with same parameters in ABAQUS was created to compare it with the .DAT file in CATIA and meshed it with the global element size of 5. Referring to various books and articles it was found that the equivalent ABAQUS element for CQUAD4 is the S4R5, also a quadrilateral shell element. .INP file which is the input file for ABAQUS was created.

Next step was to create a converter between CATIA and ABAQUS. A general purpose text convertor written in MICROSOFT VISUAL BASIC (VB) was used. By comparing the above results of .DAT and .INP file modifications were done in the program which read each line in .DAT file and tried to convert it into equivalent ABAQUS .INP file.

These experiments were run for only one part. The main objective was to create a converter for a Rotary draw bending model having various parts and assemblies. Hence again a basic model having two parts assembled together were created and by following the same procedure mentioned above, .DAT file and .INP file for CATIA and ABAQUS respectively were created.

It was observed that in .DAT file the node numbering was taken as a whole for different parts in an assembly and element order and positioning were divided and bifurcated for different parts according to their element type, whereas in ABAQUS .INP file the node numbering and element order and positioning was divided according to different parts in an assembly. This made it more difficult to convert .DAT file into equivalent .INP file through Visual Basic. It was found that .k file of LS-DYNA uses the same kind of positioning system as used in CATIAV5. The equivalent LS-DYNA element for CQUAD4 of CATIA was the Shell element. Hence the text convertor between CATIA and LS-DYNA which was created in VB, built by our Guide Mr. Joel Johansson to convert CATIA mesh files into LS-DYNA format was used. The following figure explains the node and element positioning for CATIA, ABAQUS and LS-DYNA. The following figure explains the difference in the extracted data from CATIA (.DAT), ABAQUS (.INP) and LS-DYNA (.k).

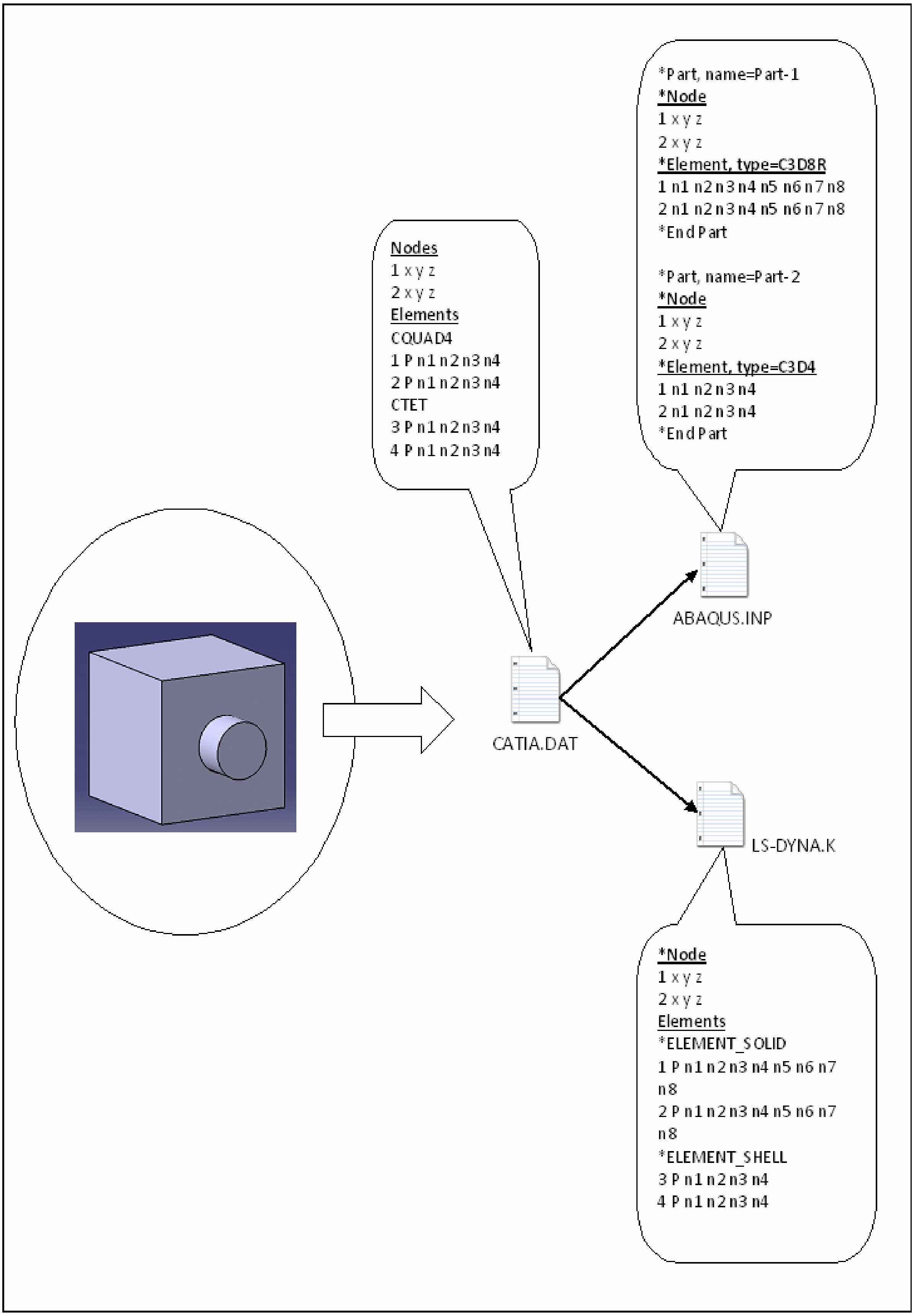


Figure 14-Arrangements of elements and nodes in input files of ABAQUS and LS-DYNA

3.2 Parametric modelling

Next step was to build a parametric model of a Rotary draw tube bending tooling setup for aluminum in CATIA. The most common apparatus was used consisting of the following parts: -

- Clamp
- Follower
- Form Die
- Plug and Mandrel
- Tube
- Wiper

For running the simulations in LS-DYNA without errors and to get precise results, certain adjustments were made to the tooling setup. A mirror image of Form Die and Clamp were created to get accurate results. A Parametric CATIA model with some built in publication was used, provided by our guide Mr. Joel Johansson. [3]

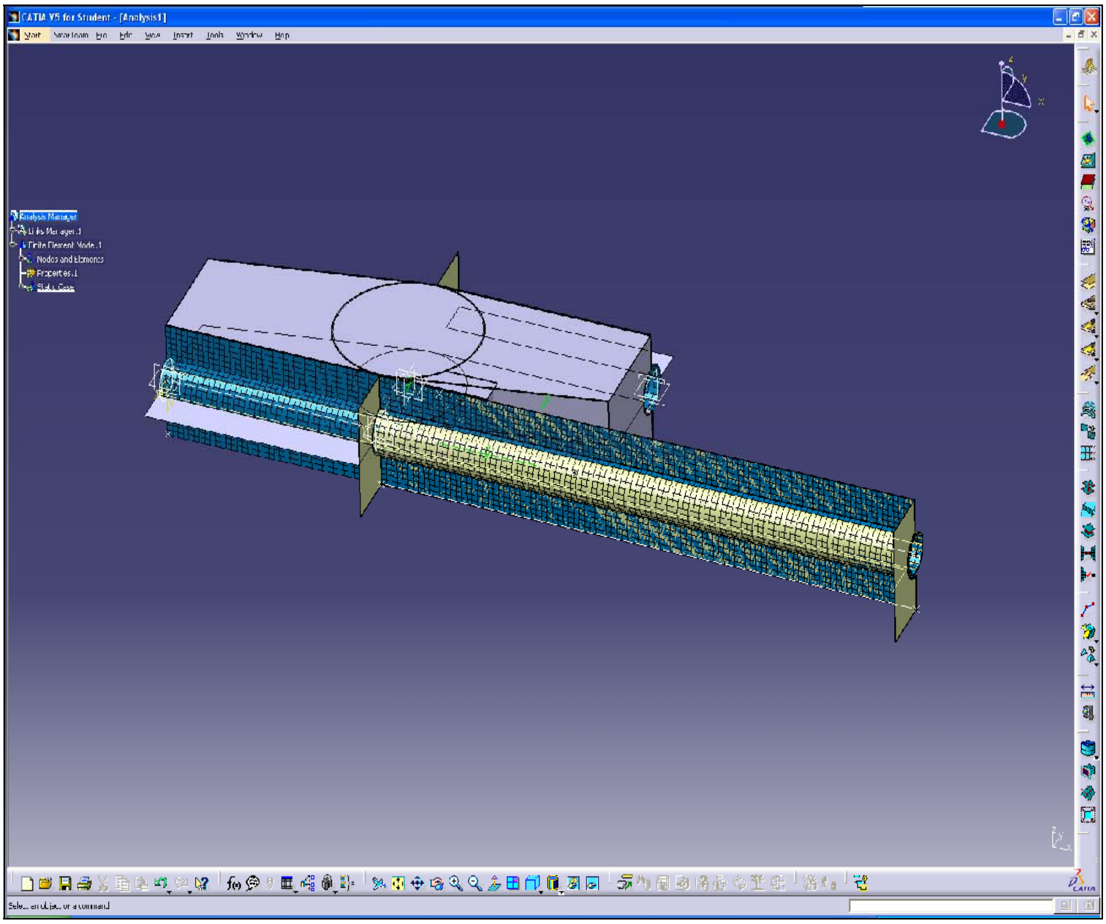


Figure 15-Screen shot of parametric CAD model made up of shell element in CATIA

3.3 Running Simulations

The Wall Factor in the range of 8-14 mm i.e. (8, 10, 12 and 14) and Bend Factor in the range of 1-1.75 mm i.e. (1, 1.25, 1.5 and 1.75) were taken by keeping the diameter of the pipe constant i.e. 38 mm. Hence 16 factors were used to work on as shown in the Figure (16) below.

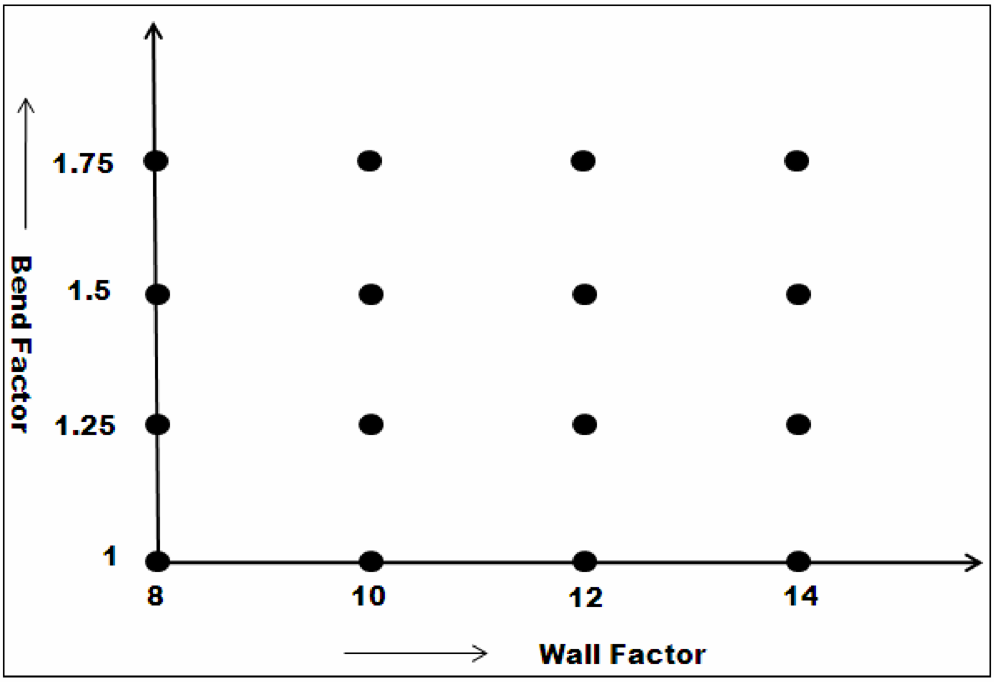


Figure 16-selected design space

From the formula Wall Factor = (Diameter of Tube D / Tube Thickness t) and Bend Factor = (Bending Radius r / Tube Diameter D), tube thickness and bending radius were calculated for each of the 16 factors.

For convenience the simulations were divided into 2 categories –

NO.	Type	Total no of simulation
1	PRELIMINARY SIMULATIONS (Coarse Simulations and Fine Simulations)	32
2	COMPARATIVE SIMULATION	8

3.3.1 Preliminary Simulations – (Coarse Meshing)

The mandrel was de-activated and the plug was activated to get simplified results from the CATIA model. Some necessary changes were made to bending radius and tube thickness by keeping the tube diameter constant. Knowledge Design Studio (Converter between CATIA and LS-DYNA) was used to mesh all the 16 toolsets to the mesh size of 5. After mesh generation, .DAT CATIA file was created and converted to LS-DYNA .k format using the same interface of Knowledge Design Studio. Following is the screenshot of knowledge design studio that was used to create all setup files for LS-DYNA simulation.

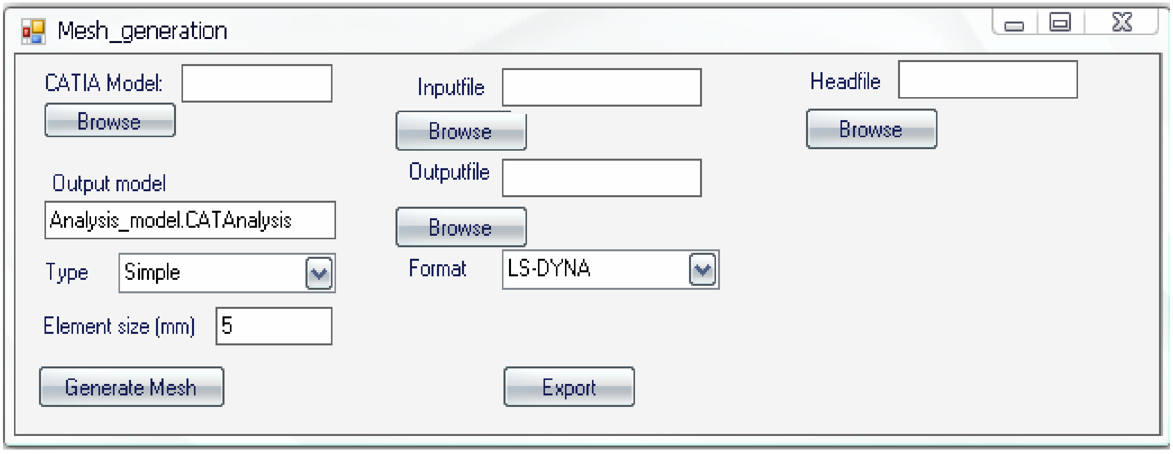


Figure 17-Screenshot of knowledge design studio

After successfully creating the LS-DYNA header files, necessary changes were made to the same. Simulations were run by using Single Precision solver in LS-DYNA post-processor for all the 16 files. When this simulation result was run in LS-DYNA pre-processor by using the 'd3plot' output file some defects were observed by naked eye which are shown in Table No 1.

It was essential to calculate the Spring-back angle for all the dimensions. For that some files were needed to be created to carry out Spring-back simulations. Hence the Spring-back header files were generated for each of the 16 dimensions and the 'dynain' file was used from their respective simulation output. After making necessary changes to the two files (Spring-back header file and corresponding 'dynain' file) for each dimension, the Spring-back simulations were run separately in a different folder this time using the Double Precision solver in LS-DYNA post processor.

Using the data available from the simulation output the following parameters were calculated

- SPRINGBACK ANGLE
- MAXIMUM BENDING MOMENT
- MAXIMUM & MINIMUM WALL THICKNESS

The observations are shown in table No 2 (Preliminary Simulations - Coarse) To be conclusive about the results observed in Table No 1, graph of Time V/S Moment was plotted which are shown in GRAPH (1) and GRAPH (2). From the graph it was observed that in the dimensions having no wrinkles there is no sudden dip or rise in the curvature (i.e. it is approximately constant) and also the oscillations also were constant. Whereas in the dimensions having wrinkles the graph showed sudden dip and rise in the curvature and oscillations were variable.

All these simulations were carried out with a coarse mesh size of 5. To refine and clarify the conclusions fine mesh size of 2 was used to compare these results.

3.3.2 Preliminary Simulations – (Fine Meshing)

For creating database for these types of simulation the same procedure was followed as was done in previous coarse simulations. To calculate Spring Back angle the same procedure was followed by using double precision solver in the LS-DYNA post processor.

Using the data available from the simulation output calculations were made for

- SPRINGBACK ANGLE
- MAXIMUM BENDING MOMENT
- MAXIMUM & MINIMUM WALL THICKNESS

The observations are shown in Table No 3 (Preliminary Simulations - Fine) and plotted graph of Time V/S Moment shown in GRAPH (3) and GRAPH (4).

The same phenomenon was observed for the all the dimensions which were seen in Coarse Simulations i.e. dimensions having no wrinkles there is no sudden dip or rise in the curvature (i.e. it is approximately constant) and also the oscillations also were constant. Whereas in the dimensions having wrinkles the graph showed sudden dip and rise in the curvature and oscillations were variable.

Table No 4 shows the dimensions showing no wrinkling and wrinkling tendency.

3.3.3 Comparative Simulations

The data from real experiments were available as shown in Table No 5. It was required to compare these real experiment calculations with the calculations observed by running various simulations using different parameters and then to make comments which one closes matches to the real data. The following Design configurations which were taken in the real experiments were used to run the simulations.

Tube outside diameter (D)	38mm
Wall thickness (t)	4mm
Bend radius (r)	69mm
Nominal Bending Angle	120^o

While running simulation for this configuration all possible combinations of mesh size, solver and material model were taken. The various Simulation Parameters are shown as follows.

- Mesh Size 5, Single Precision Solver, Piecewise Linear
- Mesh Size 5, Double Precision Solver, Piecewise Linear
- Mesh Size 5, Single Precision Solver, Barlat [8]
- Mesh Size 5, Double Precision Solver, Barlat [8]
- Mesh Size 2, Single Precision Solver, Piecewise Linear
- Mesh Size 2, Double Precision Solver, Piecewise Linear
- Mesh Size 2, Single Precision Solver, Barlat [8]
- Mesh Size 2, Double Precision Solver, Barlat [8]

Time study was conducted for each of the simulation, calculations of Spring back angle, Maximum and Minimum wall thickness were made and graph of Time V/S Moment was also plotted following the same procedure used in previous simulations which are shown in Table No 6. These simulation data were compared with the real experiment data and some important observations were made which are mentioned later.

4 Results

4.1 Preliminary Simulations

Table (1) Preliminary Simulations (Coarse)

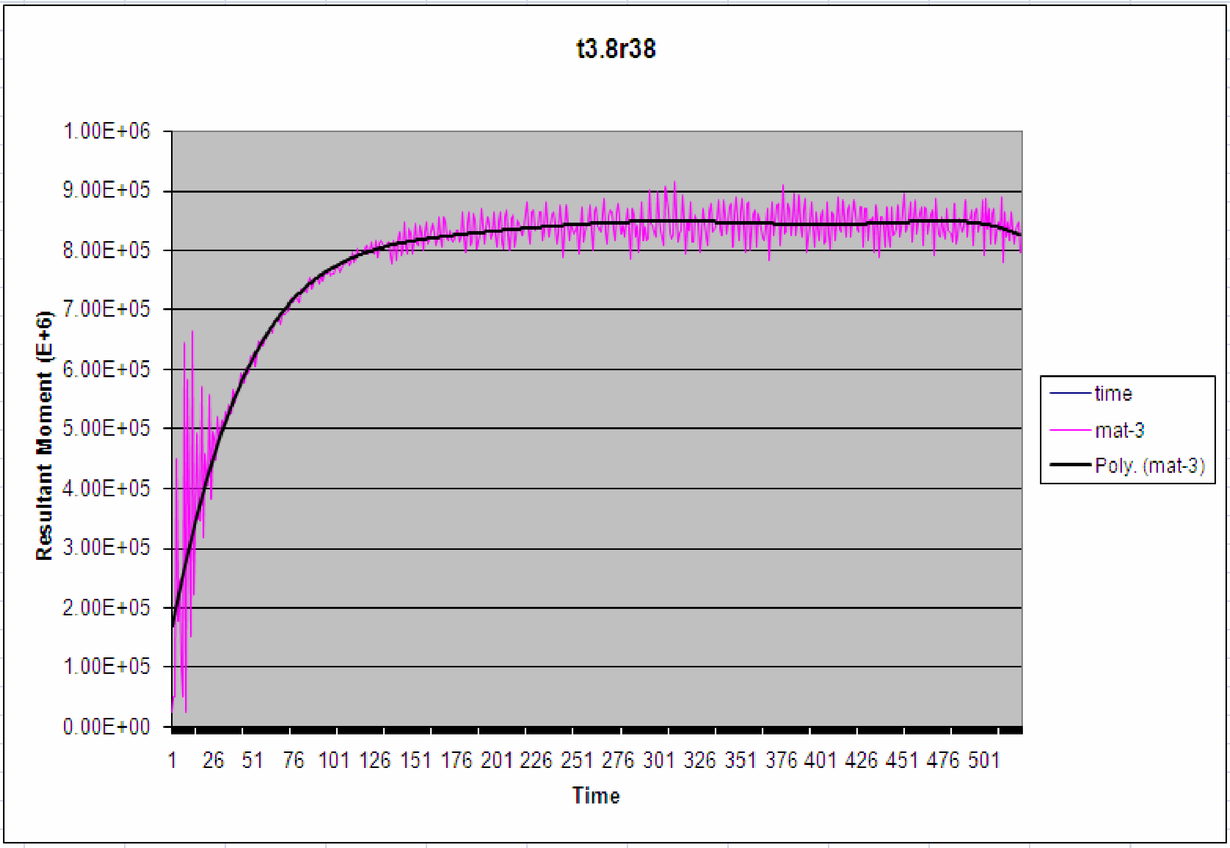
SERIAL NO.	DIMENSIONS	MESH SIZE	WRINKLES	FLATTENING & THINING
1	**t2.71r38**	5	YES	YES
2	**t2.71r47.5**	5	YES	YES
3	**t2.71r57**	5	YES	YES
4	**t2.71r66.5**	5	YES	YES
5	**t3.17r38**	5	YES	YES
6	**t3.17r47.5**	5	YES	YES
7	**t3.17r57**	5	YES	YES SMALL
8	**t3.17r66.5**	5	YES	VERY SMALL
9	**t3.8r38**	5	NO	YES
10	**t3.8r47.5**	5	NO	YES
11	**t3.8r57**	5	NO	YES SMALL
12	**t3.8r66.5**	5	NO	VERY SMALL
13	**t4.75r38**	5	NO	YES SMALL
14	**t4.75r47.5**	5	NO	VERY SMALL
15	**t4.75r57**	5	NO	NO
16	**t4.75r66.5**	5	NO	NO

TABLE (2) Preliminary Simulations (Coarse)

Index	**Dimensions with Bending angle 120**	**Mesh size**	**Material model**	**Solver**	**Results**			
					Springback angle	**Max Bending moment**	**Variation in wall thickness**	
							Max. thickness	**Min. thickness**
1	**T2.71r38**	**5**	**PL**	**SP**	118.694	638200	3.86213	2.26199
2	**T2.71r47.5**	**5**	**PL**	**SP**	118.737	686900	3.71196	2.33033
3	**T2.71r57**	**5**	**PL**	**SP**	118.365	726200	3.53098	2.38749
4	**T2.71r66.5**	**5**	**PL**	**SP**	119.862	679900	3.31328	2.41859
5	**T3.17r38**	**5**	**PL**	**SP**	118.713	751200	4.48063	2.63428
6	**T3.17r47.5**	**5**	**PL**	**SP**	118.667	780800	4.19142	2.71763
7	**T3.17r57**	**5**	**PL**	**SP**	118.477	787700	3.96889	2.77419
8	**T3.17r66.5**	**5**	**PL**	**SP**	118.518	747500	3.76528	2.81881
9	**T3.8r38**	**5**	**PL**	**SP**	118.654	913700	4.97803	3.11773
10	**T3.8r47.5**	**5**	**PL**	**SP**	118.571	957100	4.66713	3.23212
11	**T3.8r57**	**5**	**PL**	**SP**	118.357	892800	4.48981	3.30577
12	**T3.8r66.5**	**5**	**PL**	**SP**	118.329	894200	4.36998	3.3589
13	**T4.75r38**	**5**	**PL**	**SP**	118.697	1263000	6.21737	3.89329
14	**T4.75r47.5**	**5**	**PL**	**SP**	118.775	1296000	5.86248	4.01765
15	**T4.75r57**	**5**	**PL**	**SP**	118.418	1311000	5.60177	4.09156
16	**T4.75r66.5**	**5**	**PL**	**SP**	118.717	1292000	5.58247	4.18229

PL = Piecewise linear
SP = Single Precision
DP = Double Precision

GRAPH (1) COARSE MESHING - No Wrinkles Observed On the Tube



GRAPH (2) COARSE MESHING - Wrinkles Observed On The Tube

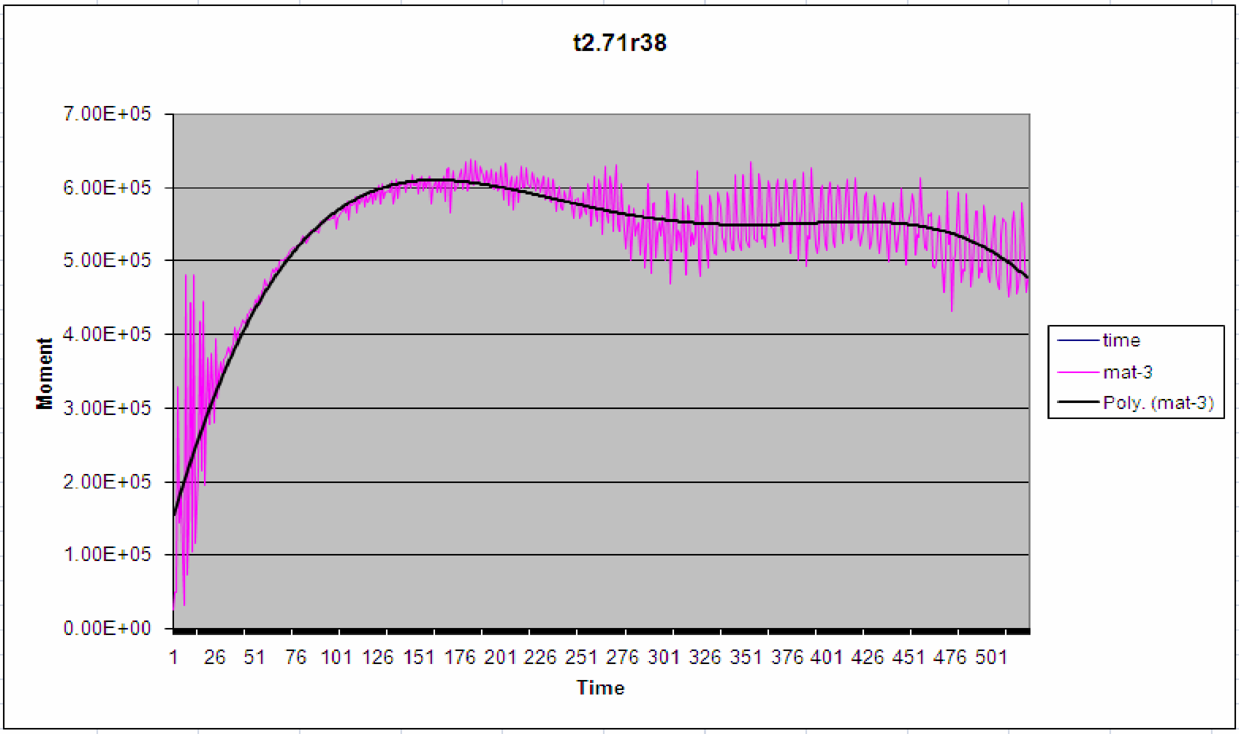
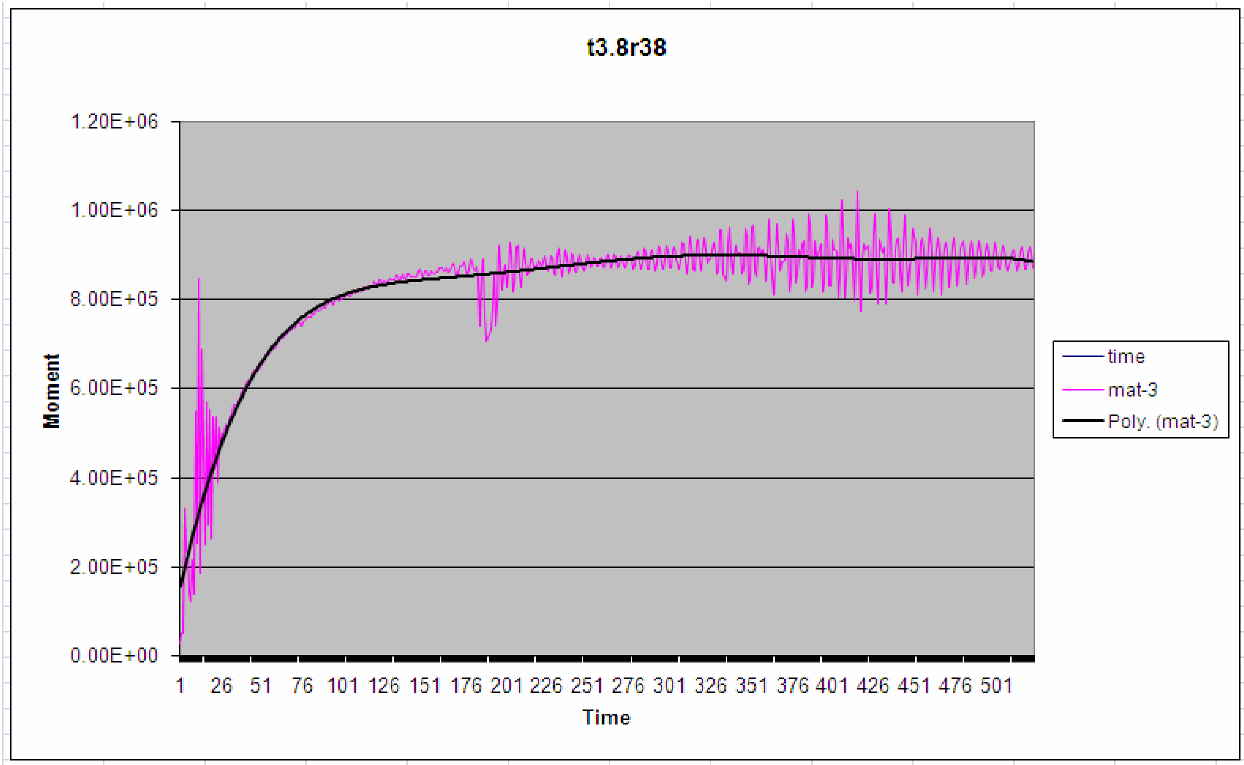


TABLE (3) Preliminary Simulations (Fine)

Index	Dimensions with Bending angle 120	Mesh size	Material model	Solver	Results			
					Spring back angle (DP)	Max Bending moment	Variation in wall thickness	
							Max. thickness	Min. thickness
1	**T2.71r38**	**2**	**PL**	**SP**	118.19	818300	4.20739	2.21322
2	**T2.71r47.5**	**2**	**PL**	**SP**	118.66	781700	4.22376	2.31944
3	**T2.71r57**	**2**	**PL**	**SP**	117.393	757300	4.22376	2.31944
4	**T2.71r66.5**	**2**	**PL**	**SP**	118.546	818300	3.70256	2.38633
5	**T3.17r38**	**2**	**PL**	**SP**	118.551	838900	5.0048	2.56243
6	**T3.17r47.5**	**2**	**PL**	**SP**	118.02	858800	4.45353	2.66269
7	**T3.17r57**	**2**	**PL**	**SP**	118.479	1074000	4.78223	1.68229
8	**T3.17r66.5**	**2**	**PL**	**SP**	118.318	809600	4.55221	2.74813
9	**T3.8r38**	**2**	**PL**	**SP**	117.994	1043000	5.25587	3.0434
10	**T3.8r47.5**	**2**	**PL**	**SP**	118.326	1024000	5.27358	3.19658
11	**T3.8r57**	**2**	**PL**	**SP**	118.045	1029000	6.60578	2.66002
12	**T3.8r66.5**	**2**	**PL**	**SP**	118.563	948600	4.44392	3.32193
13	**T4.75r38**	**2**	**PL**	**SP**	-	-	-	-
14	**T4.75r47.5**	**2**	**PL**	**SP**	-	-	-	-
15	**T4.75r57**	**2**	**PL**	**SP**	119.026	1461000	7.17846	3.88839
16	**T4.75r66.5**	**2**	**PL**	**SP**	118.616	1493000	5.82927	4.12812

PL = Piecewise linear
SP = Single Precision
DP = Double Precision

GRAPH (3) FINE MESHING - No Wrinkles Observed On The Tube



GRAPH (4) FINE MESHING - WRINKLES OBSERVED ON THE TUBE

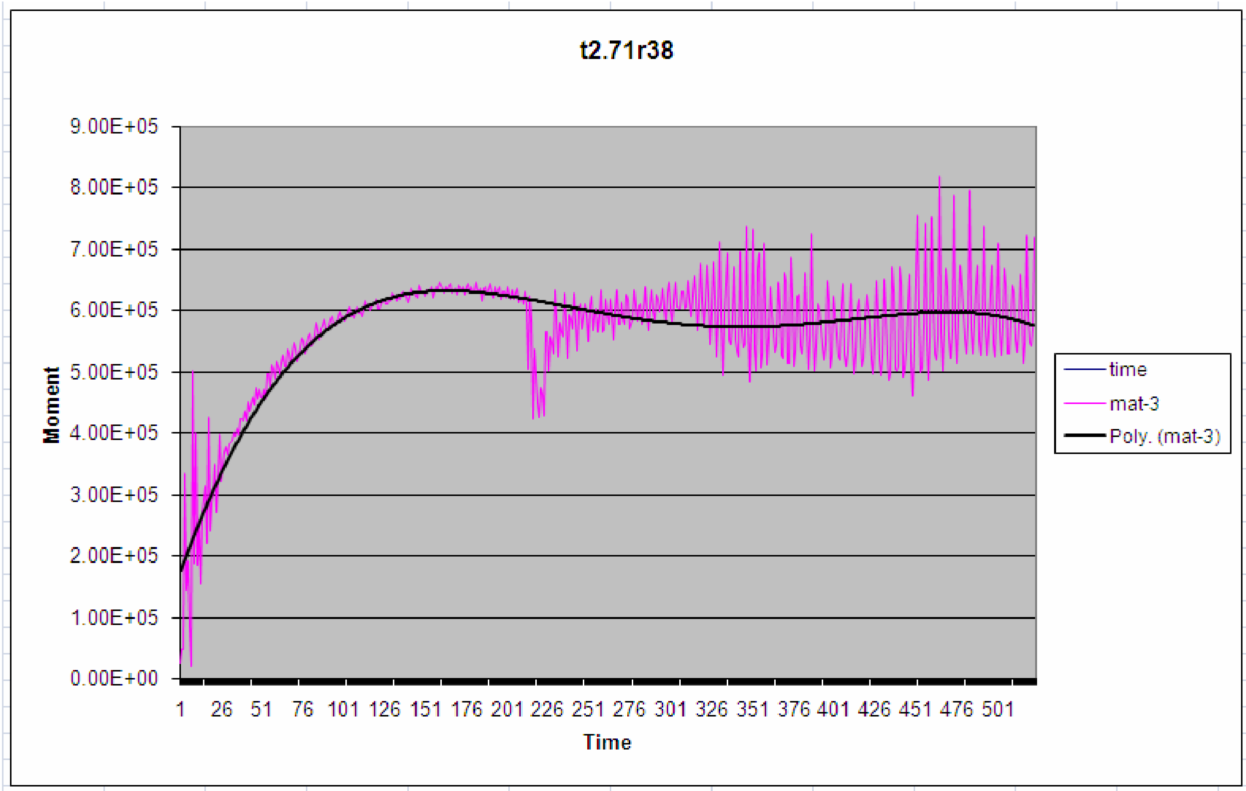


TABLE (4) Dimensions showing no wrinkling and wrinkling tendency

Dimensions with No Wrinkles	Dimensions with Wrinkles
T3.8r38	**T2.71r38**
T3.8r47.5	**T2.71r47.5**
T3.8r57	**T2.71r57**
T3.8r66.5	**T2.71r66.5**
T4.75r38	**T3.17r38**
T4.75r47.5	**T3.17r47.5**
T4.75r57	**T3.17r57**
T4.75r66.5	**T3.17r66.5**

4.2 Comparative Simulations

TABLE (5) EXPERIMENTAL DATA

Reading No	**Springback angle**		**Variation in wall thickness**			
			Min. thickness		**Max. thickness**	
1	115,9166667	115.8666667	3,235	3.2617	4,72	4.71
2	115,8333333		3,2725		4,63	
3	115,9166667		3,2675		4,7125	
4	115,75		3,251		4,77	
5	115,9166667		3,2825		4,7175	

TABLE (6) COMPARATIVE SIMUALTIONS

No	**Mesh size**	**Material Model**	**Solver**	**RESULTS**				
				Springback angle	**Max Bending moment**	**Variation in wall thickness**		**Appro.Time in Minutes**
						Max. thickness	**Min thickness**	
1	**Coarse 5**	**PL**	**SP**	118.331	948800	4.57616	3.55103	36
2	**Fine 2**	**PL**	**SP**	118.304	1022000	4.66768	3.51715	720
3	**Coarse 5**	**Barlat**	**SP**	118.073	1443000	4.59751	3.68858	60
4	**Fine 2**	**Barlat**	**SP**	118.001	1590000	4.84988	3.63485	1035
5	**Coarse 5**	**PL**	**DP**	118.335	974700	4.57754	3.55116	135
6	**Fine 2**	**PL**	**DP**	118.282	1028000	4.81153	3.5204	2242
7	**Coarse 5**	**Barlat**	**DP**	118.107	1464000	4.57347	3.68259	130
8	**Fine 2**	**Barlat**	**DP**	117.841	1603000	4.93223	3.63981	2783

5 Conclusions and discussion

5.1 Preliminary Simulations –

- Mesh Size – Preliminary simulations were carried out to find out the appropriate mesh size. Two simulations at each test point in design space were compared in order to evaluate which mesh size is best suited. To get desired results Coarse Mesh (5) is sufficient instead of Fine Mesh (2), which saves a lot of simulation run time.
- Wrinkles – By looking at the Time V/S Moment graph it can easily be predicted whether the bent tubes have wrinkles or no wrinkles.

5.2 Comparative Simulations –

- By using Coarse Mesh (5), Barlat model and Single Precision Solver results can be achieved which closely match to the experimental data. This again saves a lot of simulation run time.

6 References

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7 Search words

ABAQUS

Barlat

Bending factor

Bending moment

CATIA V5

CQUAD4

Coarse

Converter

Design space

Design Automation

Double precision

dynain

Elements

Fine

FEM

Header file

Input file

Knowledge design studio

Knowledge objects

Knowledge Based Engineering

LS-DYNA

Material model

Mesh size

Numerical rules

Nodes

Parametric modeling

Piecewise Linear

Pre-processor

Post-processor

Rotary Draw Tube Bending

Shell element

Simulations

Single precision

Springback

Solver

Wall factor

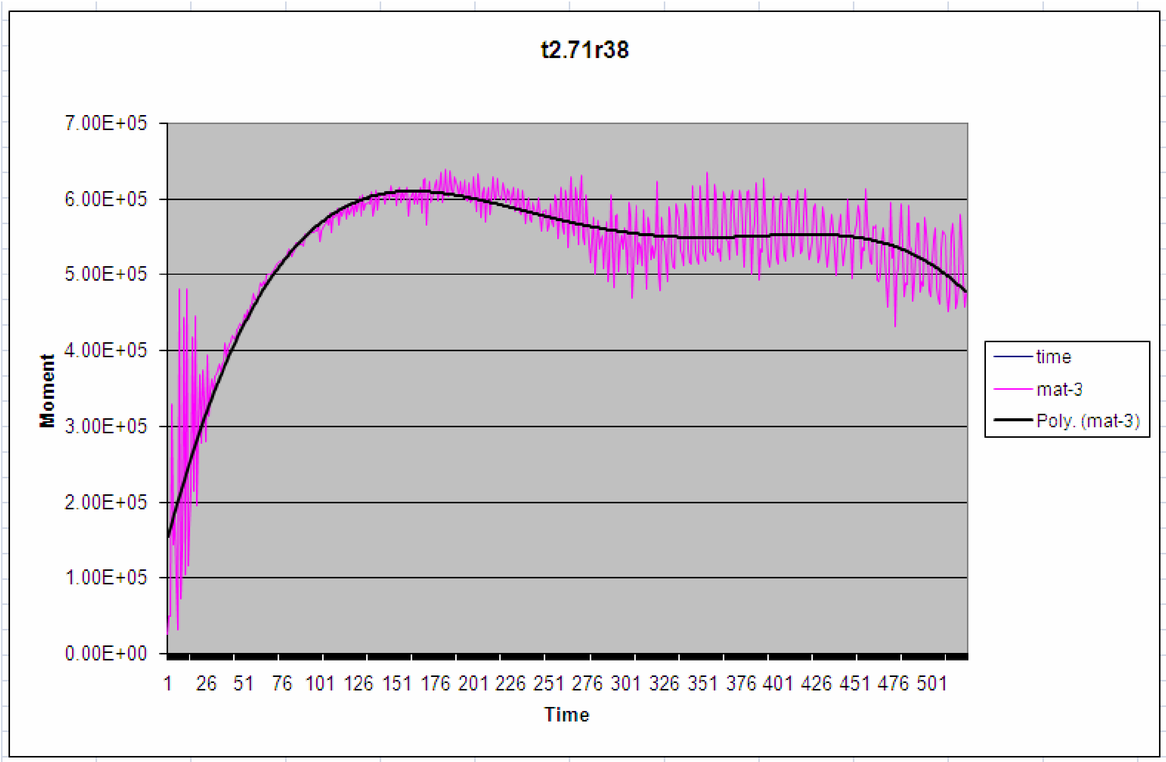
Wall thickness

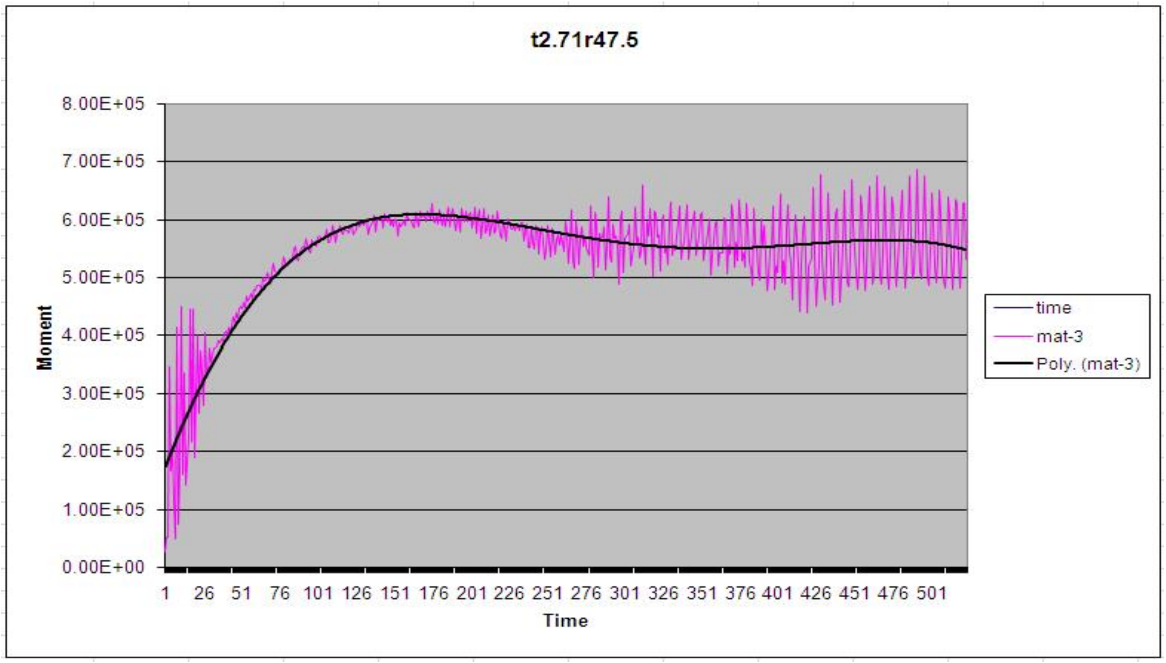
Wrinkles

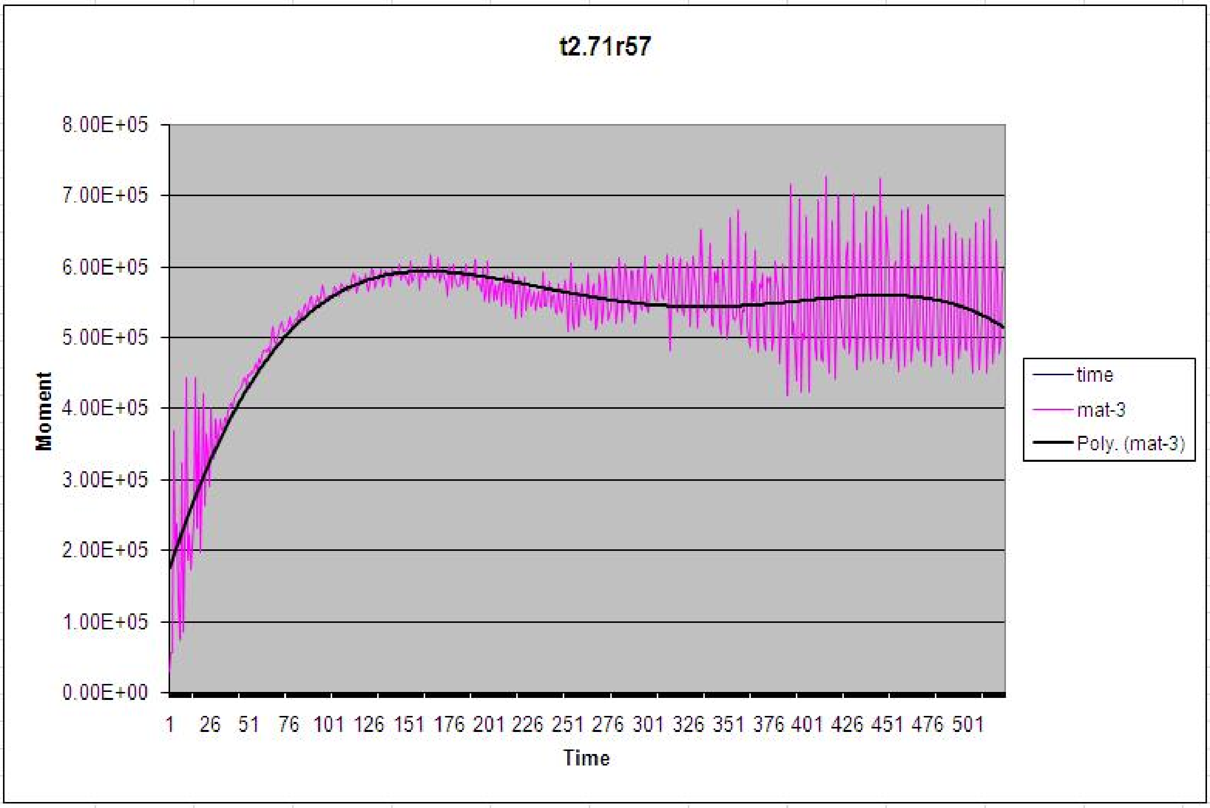
8 Attachment

8.1 Preliminary Simulations (Coarse Mesh)

8.1.1 With Wrinkles



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4.00E+05
3.00E+05
2.00E+05
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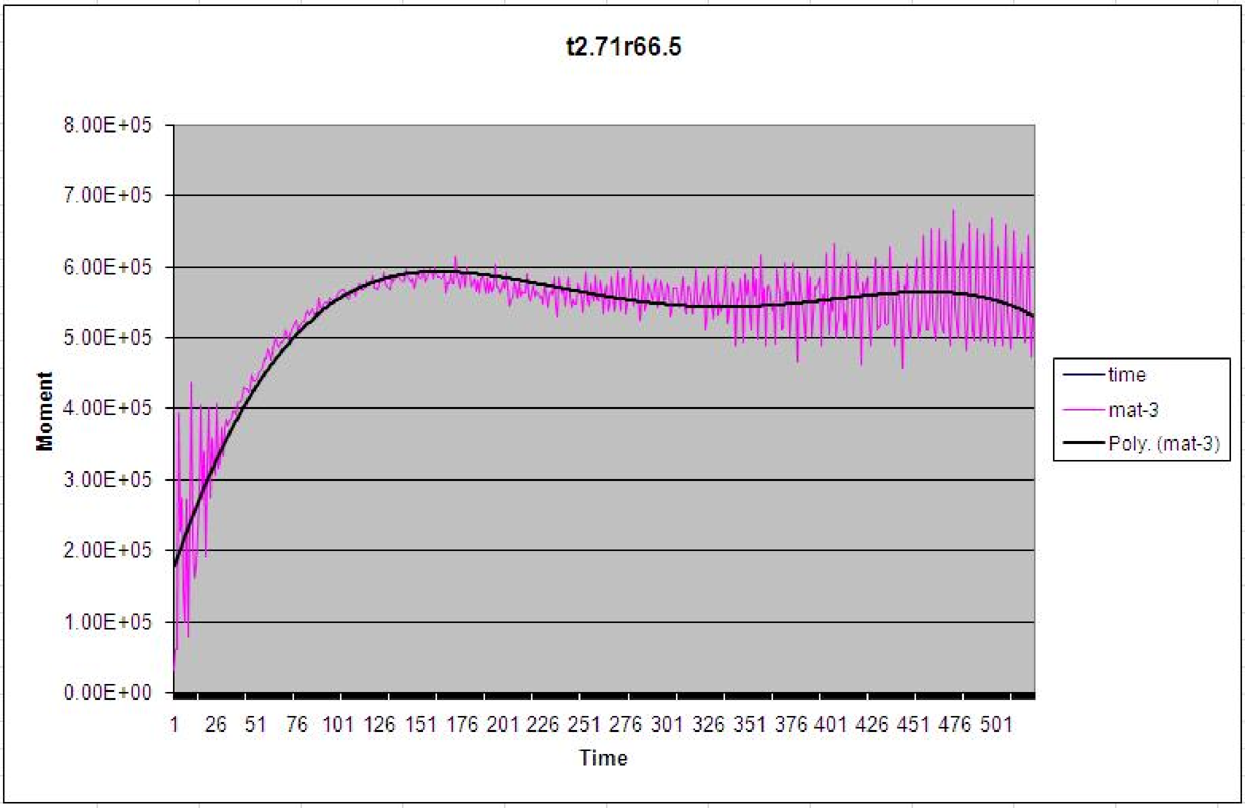
Time
time
mat-3
Poly. (mat-3)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Moment
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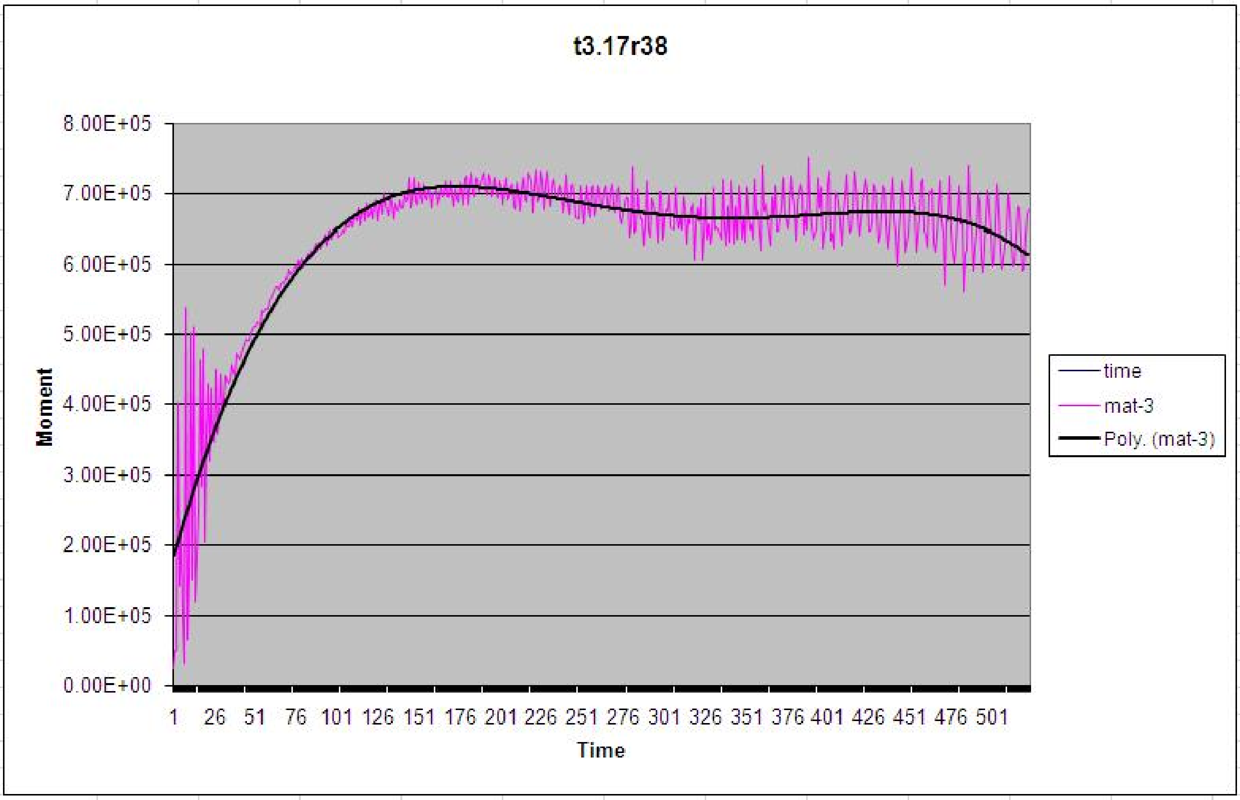
Time
time
mat-3
Poly. (mat-3)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Moment
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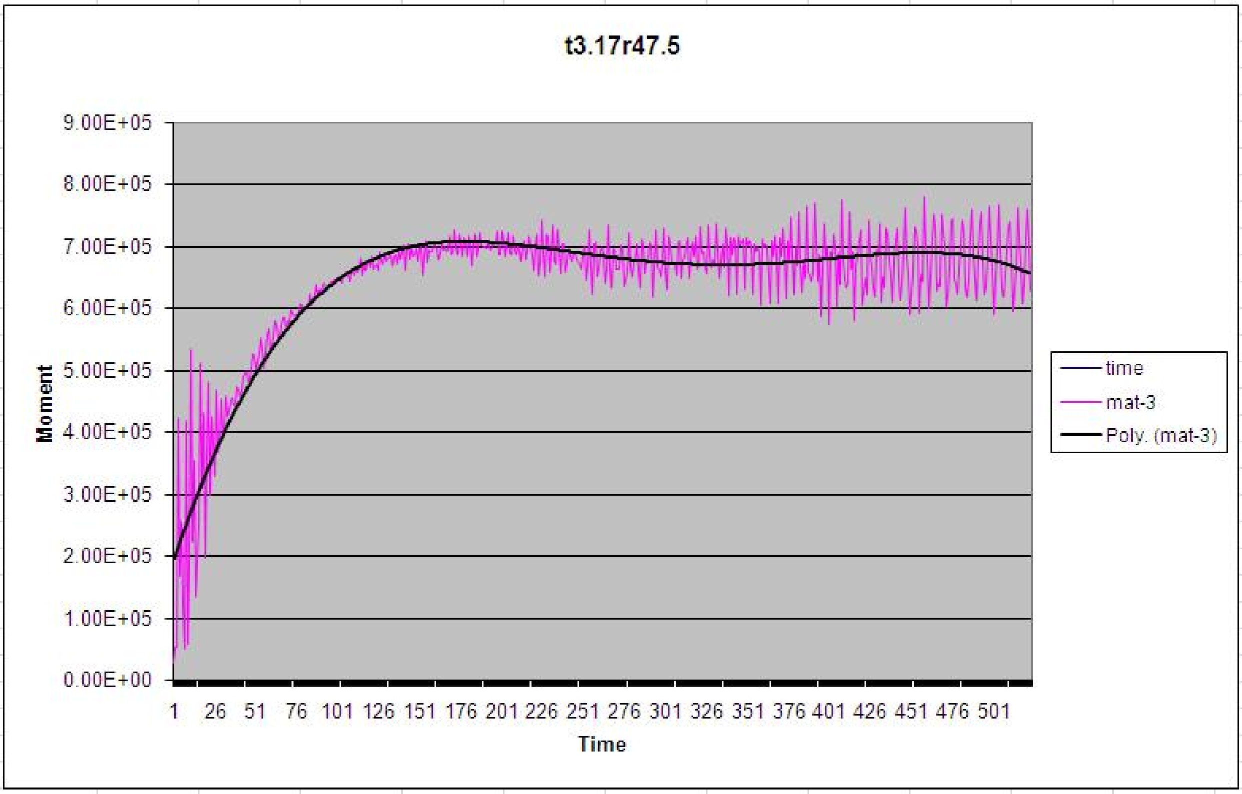
Time
time
mat-3
Poly. (mat-3)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2.00E+05
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Moment
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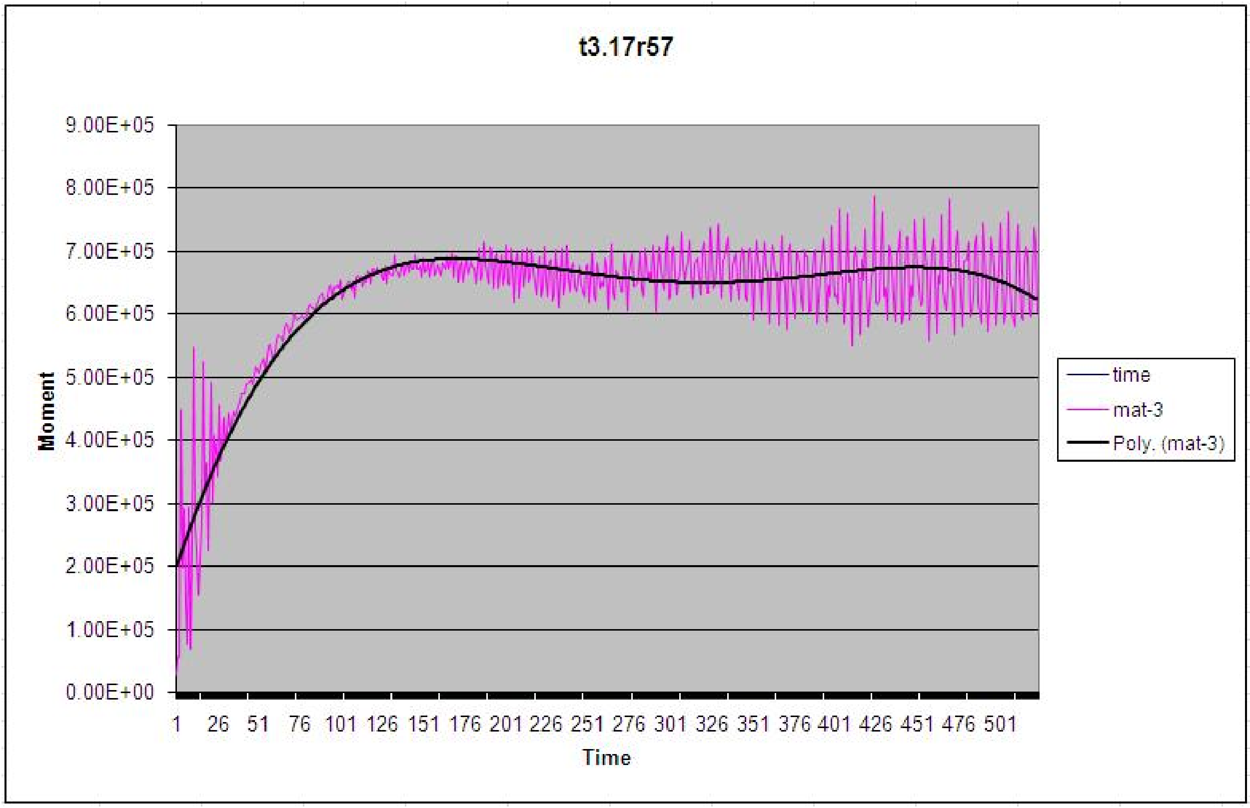
Time
time
mat-3
Poly. (mat-3)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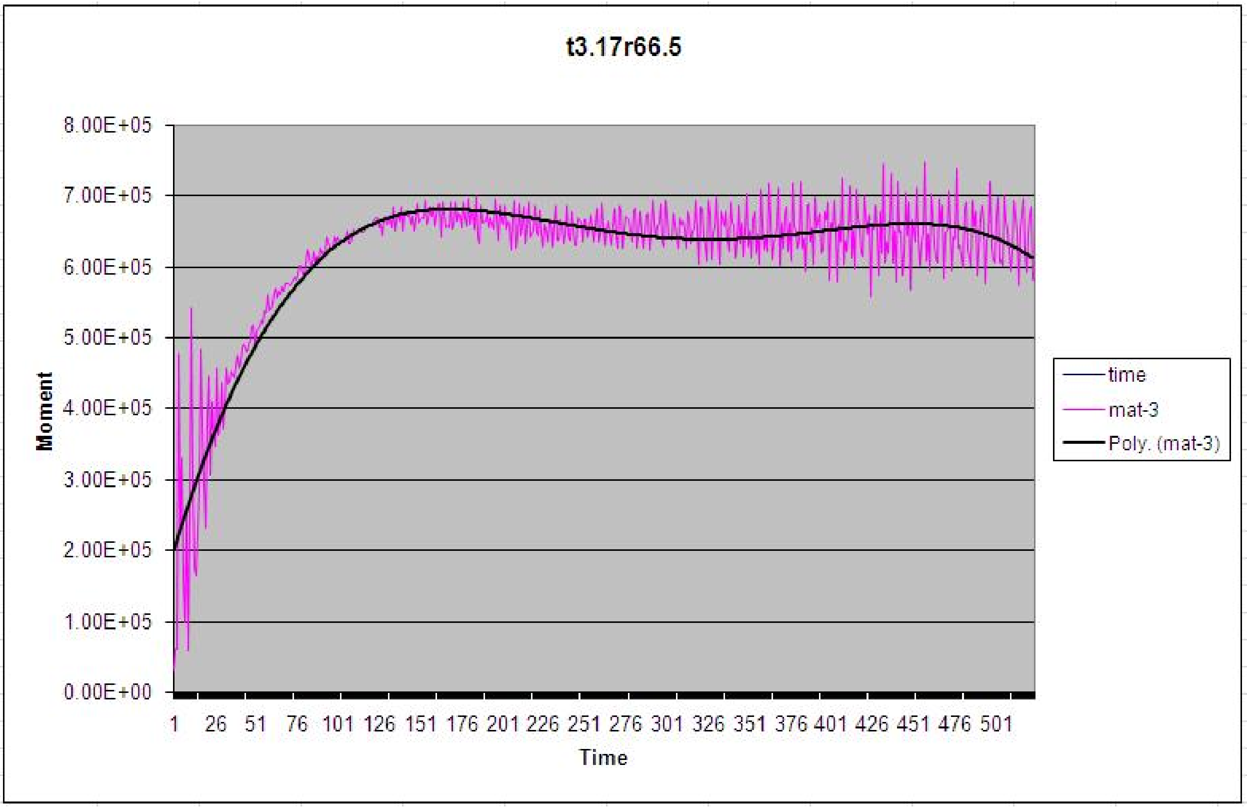
Time
time
mat-3
Poly. (mat-3)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1.00E+05
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Moment
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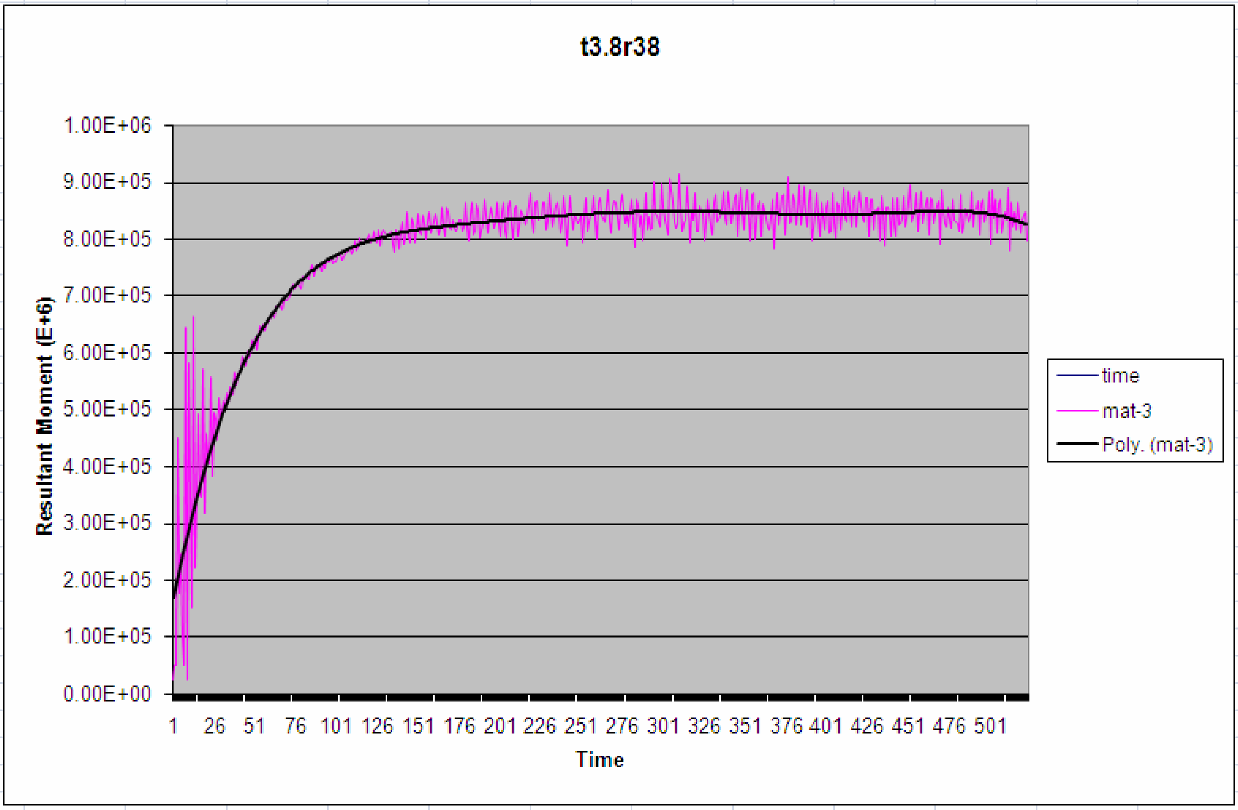
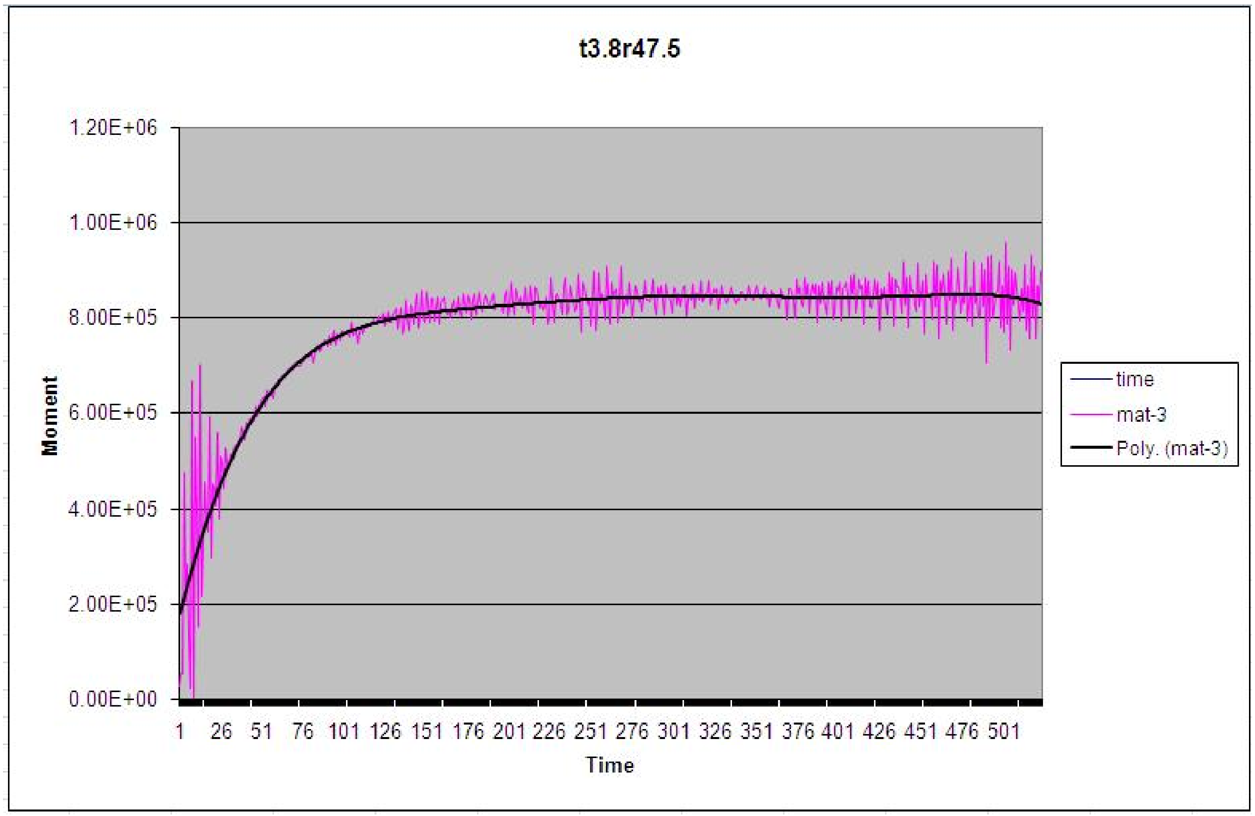
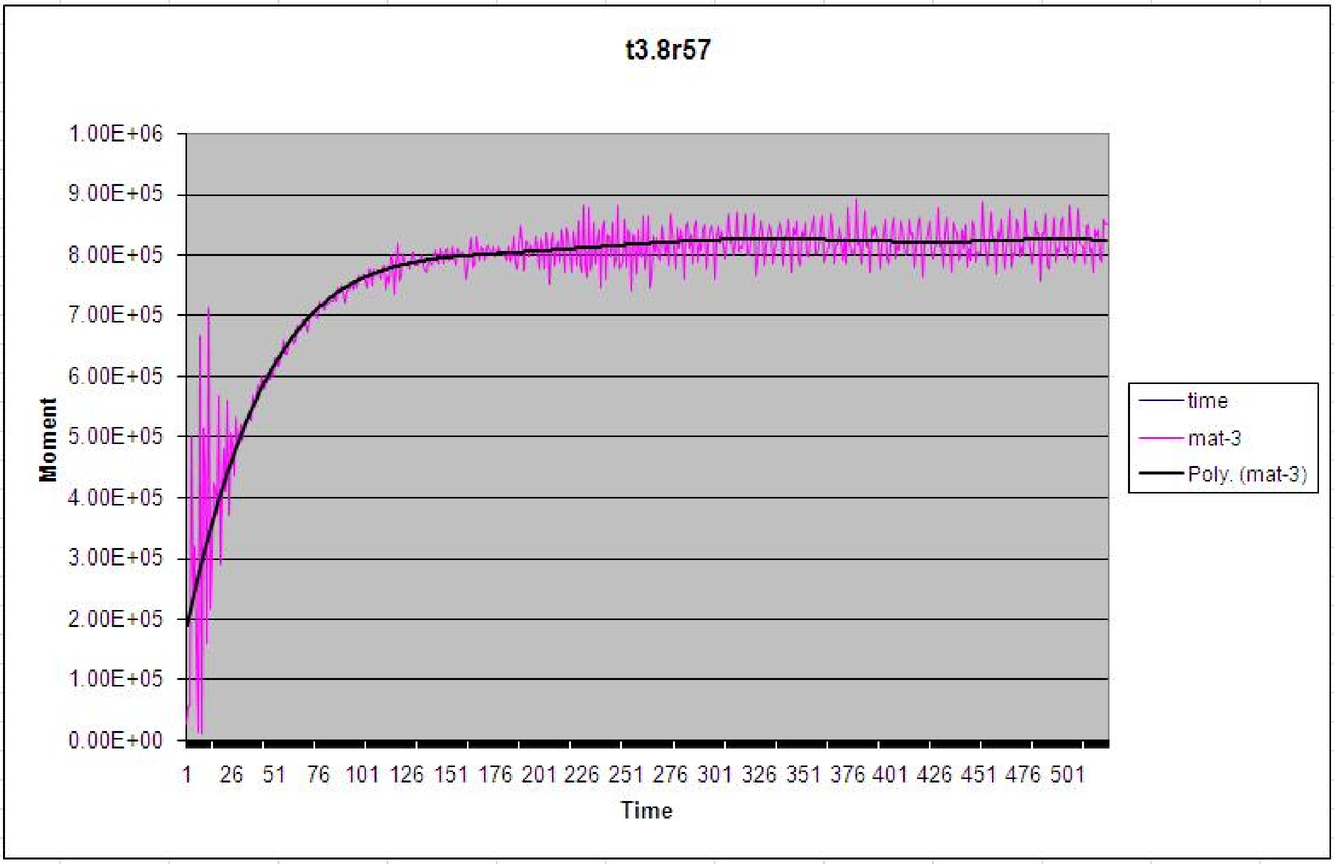
Time
time
mat-3
Poly. (mat-3)

8.1.2 Without Wrinkles



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Time
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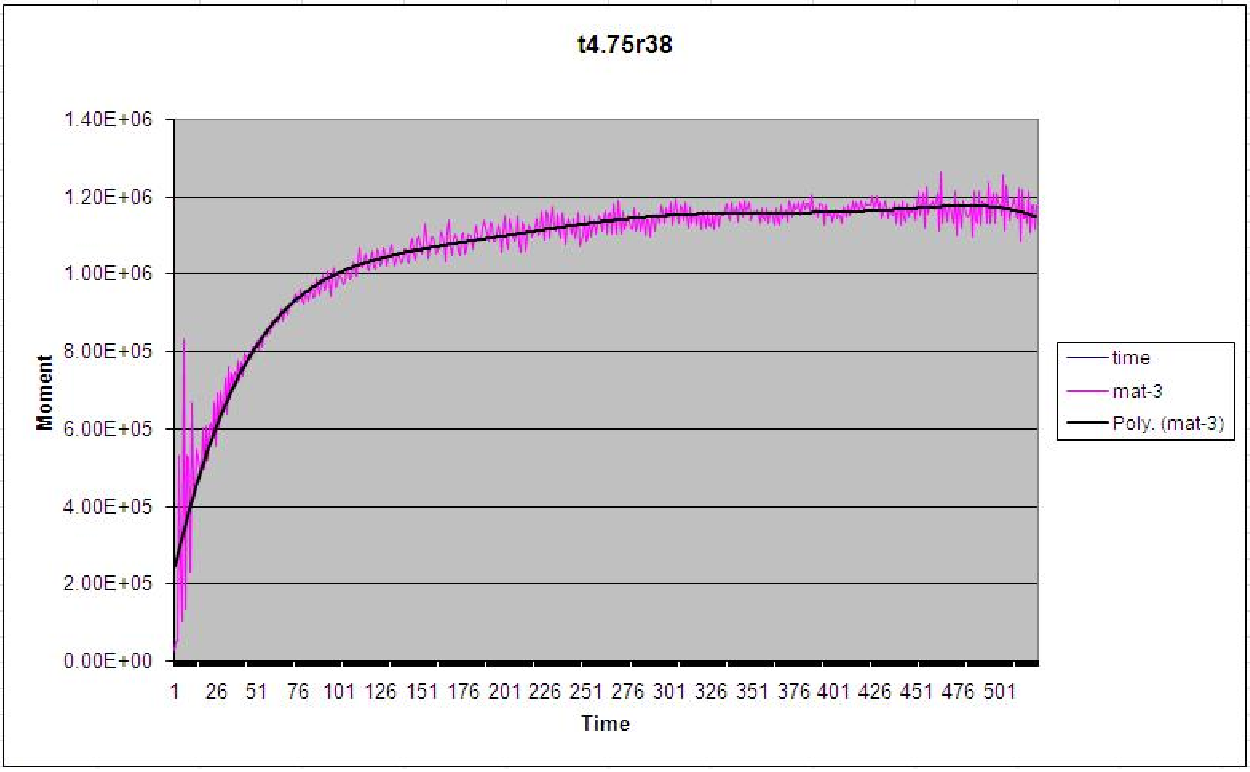
mat-3
Poly. (mat-3)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Moment
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Time
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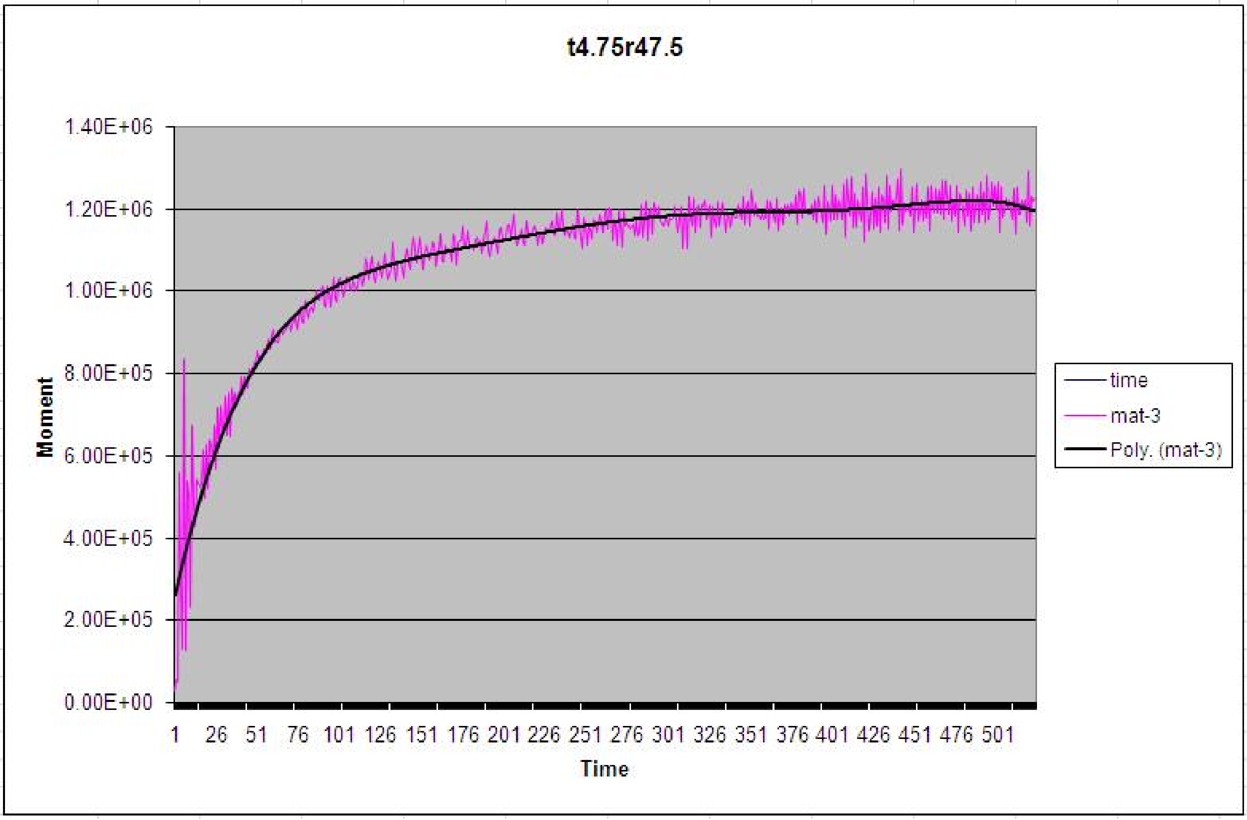
mat-3
Poly. (mat-3)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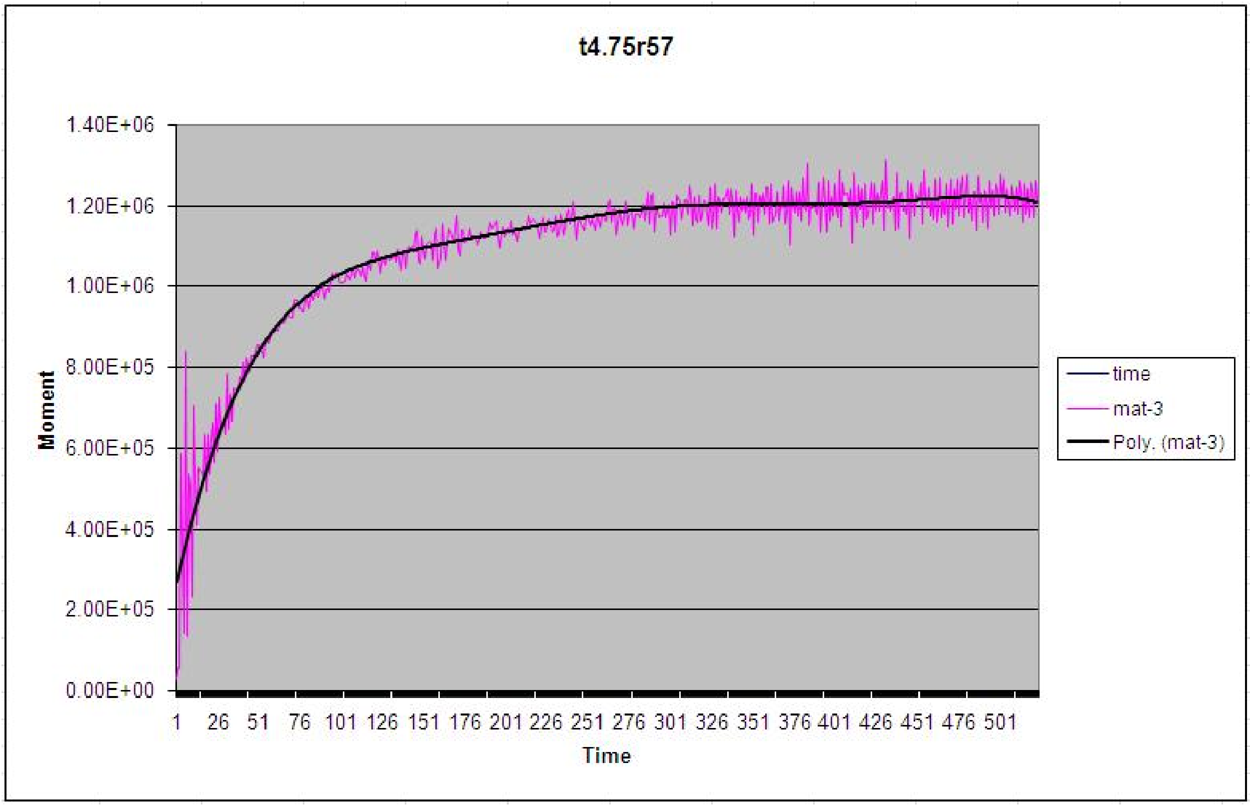
Time
time
mat-3
Poly. (mat-3)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Moment
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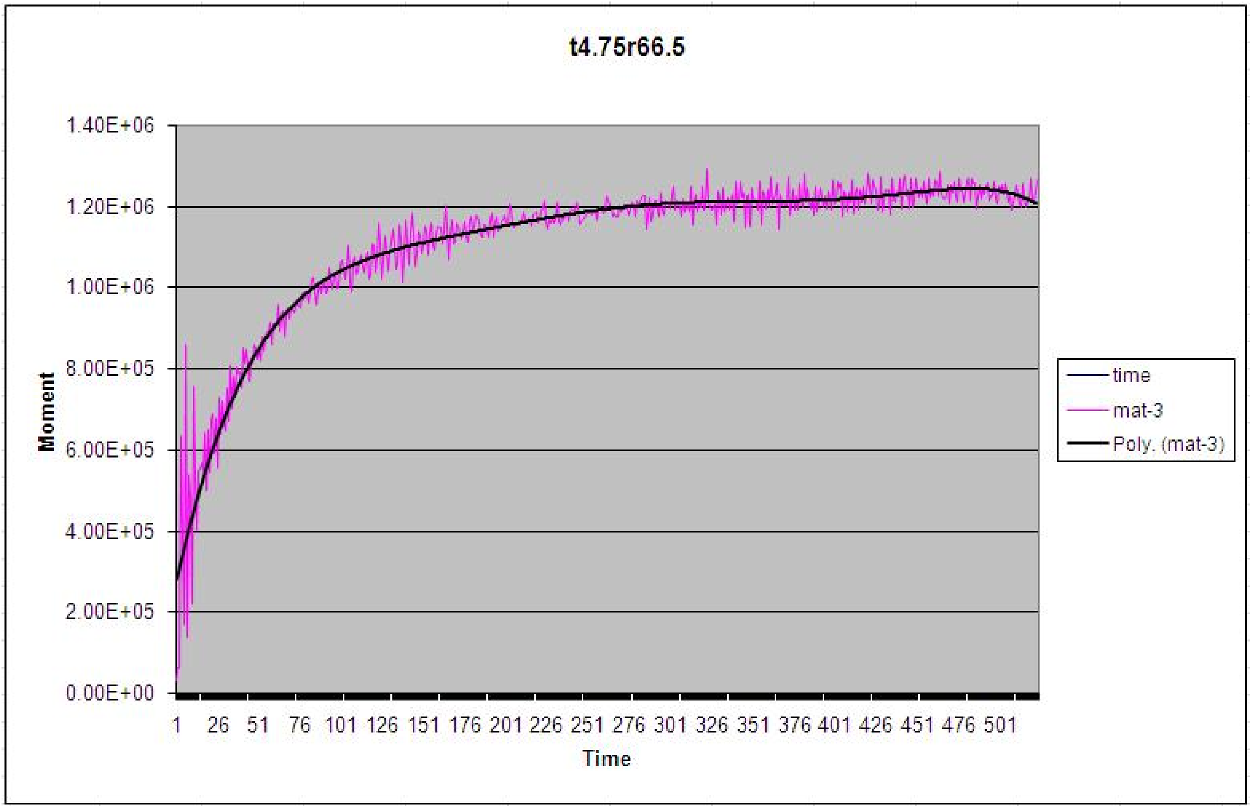
Time
time
mat-3
Poly. (mat-3)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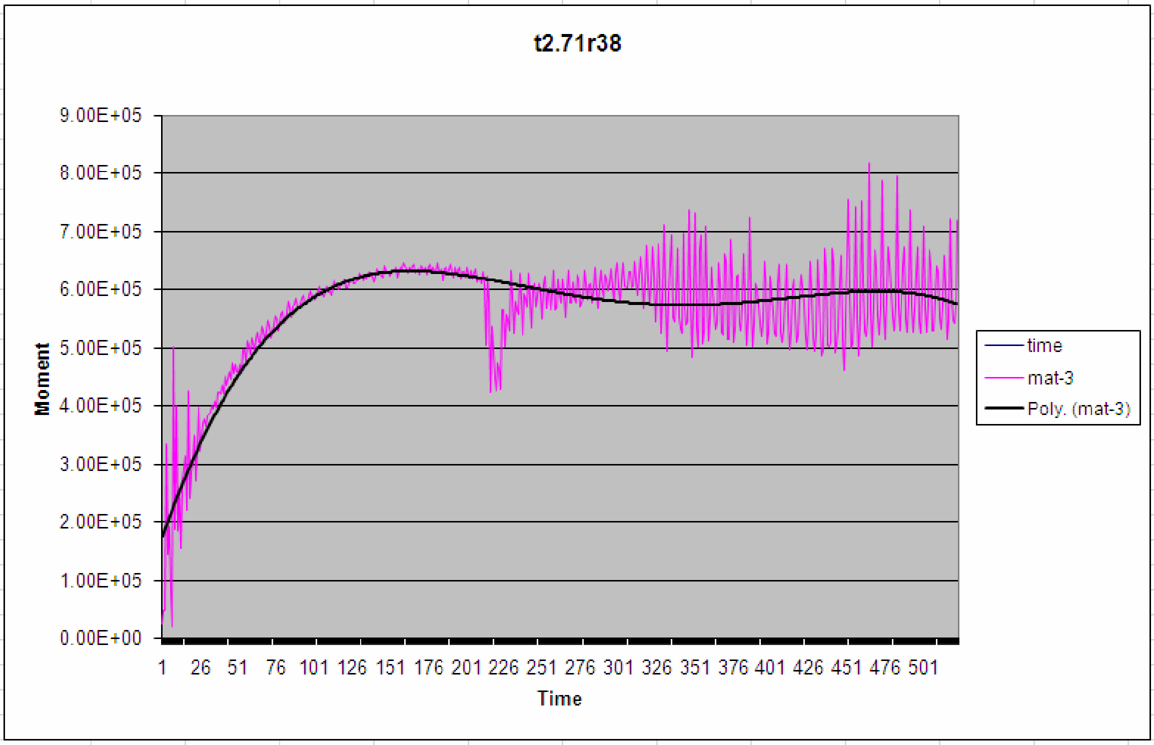
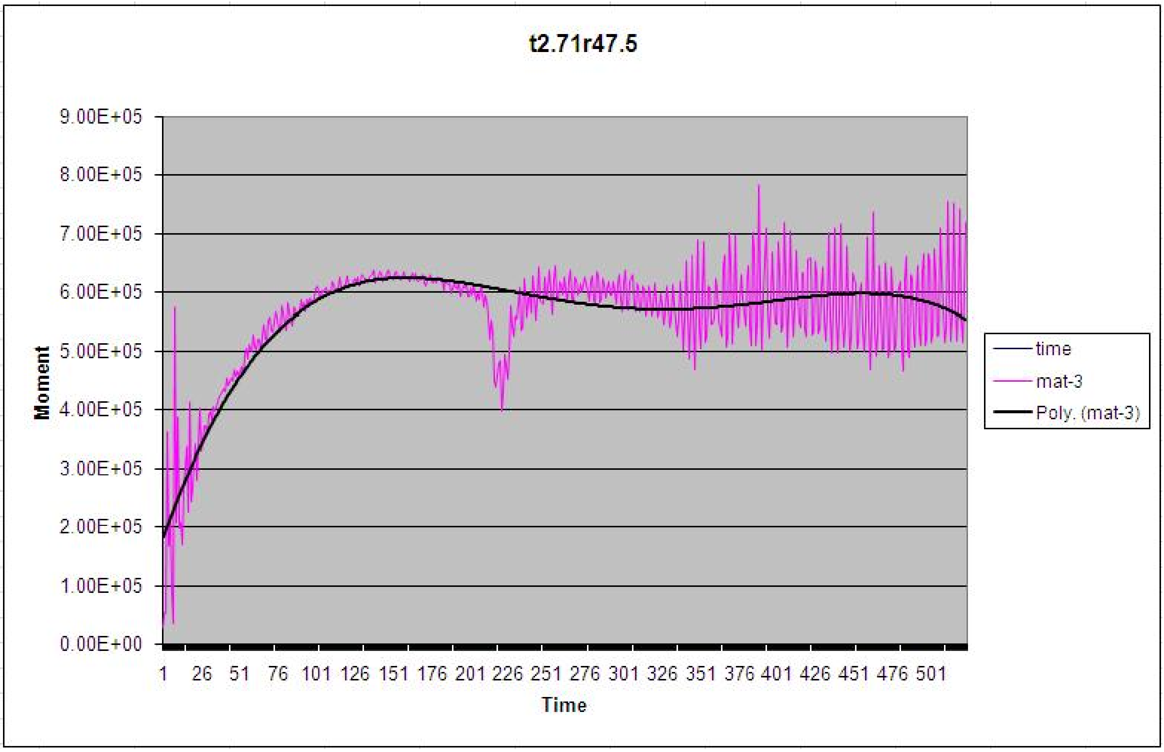
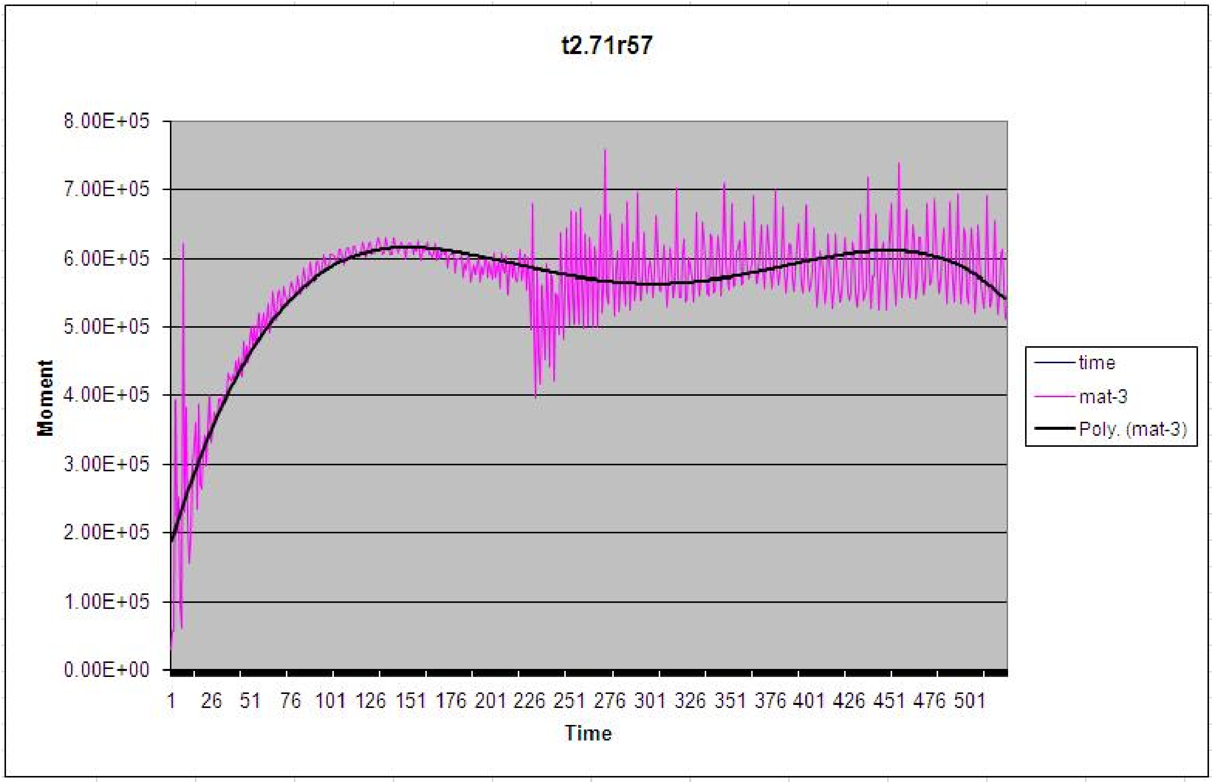
4.00E+05
2.00E+05
0.00E+00
Moment
1
26
51
76
101
126
151
176
201
226
251
276
301
326
351
376
401
426
451
476
501
Time
time
mat-3
Poly. (mat-3)

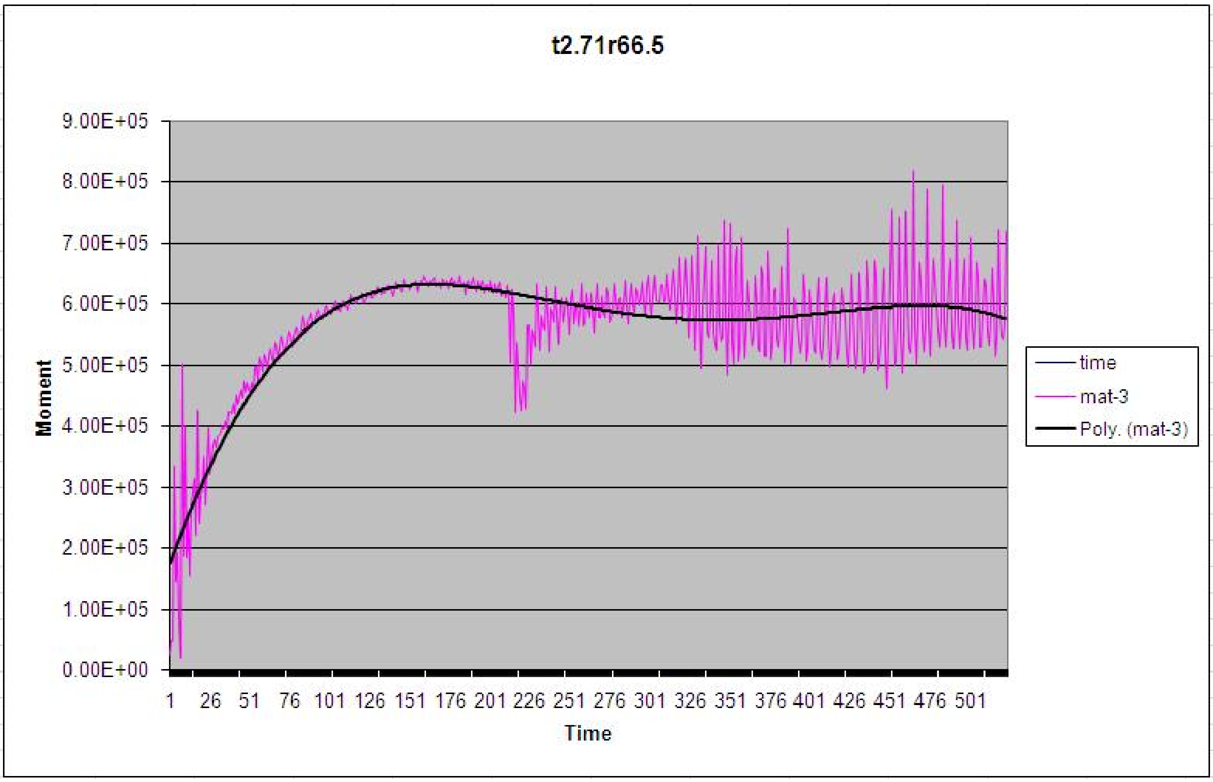
8.2 Preliminary Simulations (Fine Mesh)

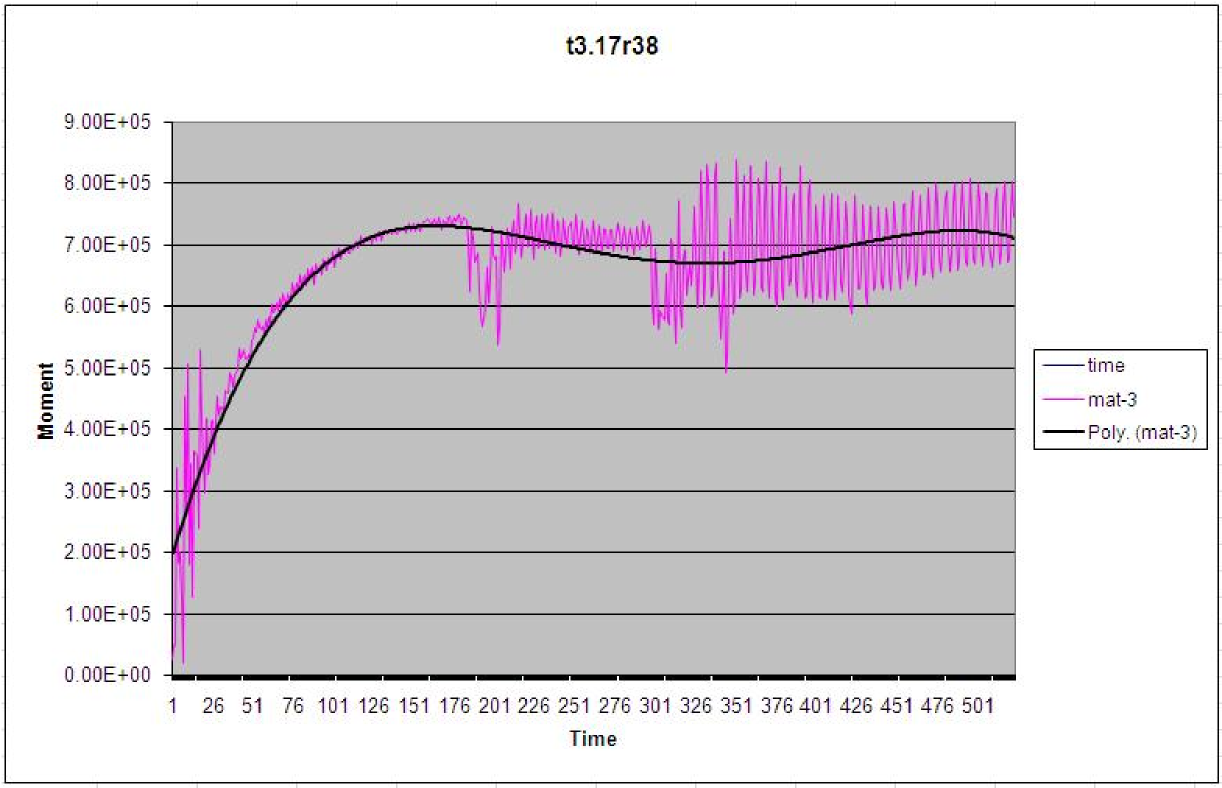
8.2.1 With Wrinkles

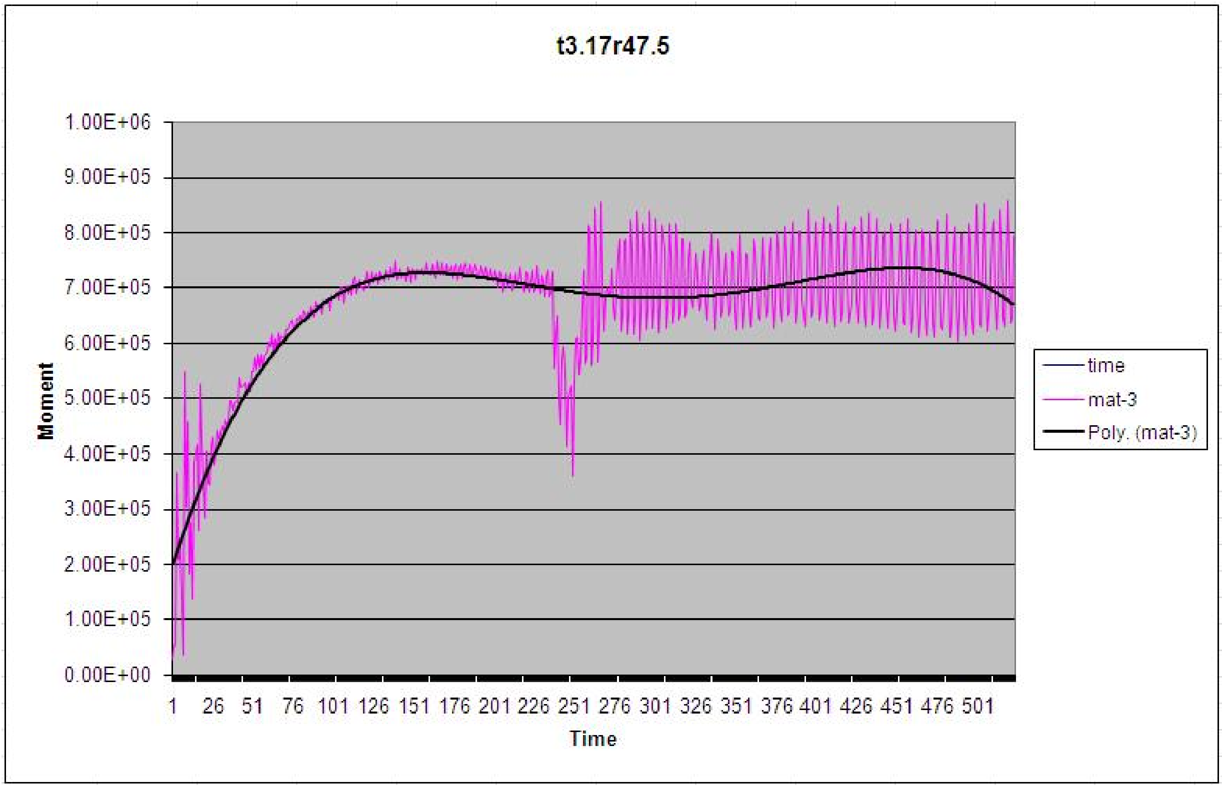


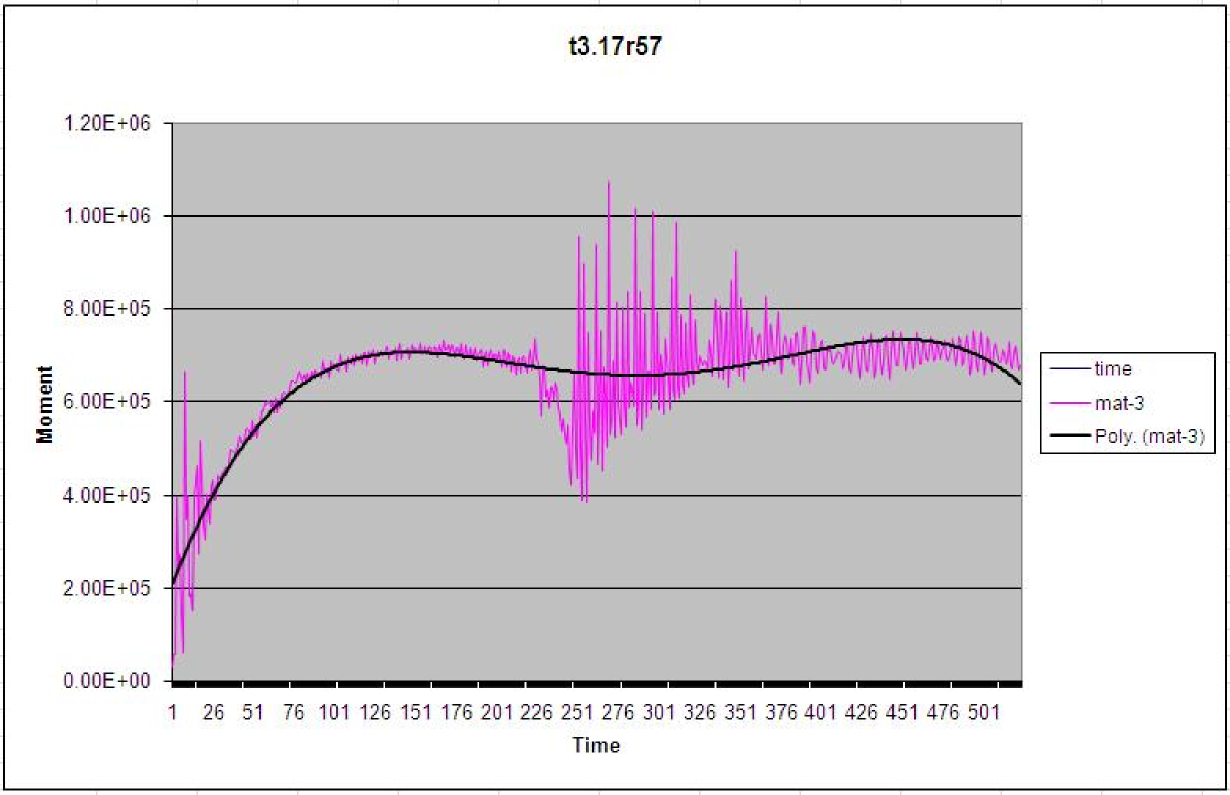


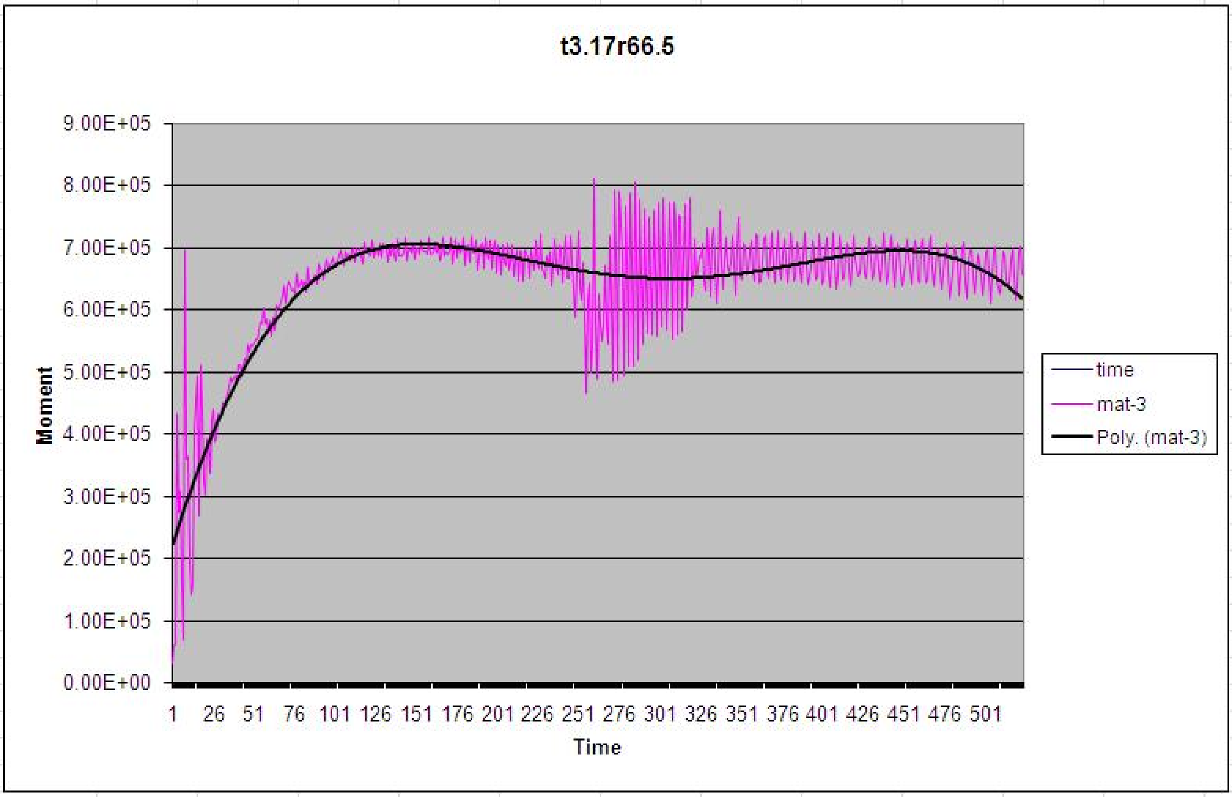

t2.71r57
Moment
8.00E+05
7.00E+05
6.00E+05
5.00E+05
4.00E+05
3.00E+05
2.00E+05
1.00E+05
0.00E+00
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)


t2.71r66.5
Moment
9.00E+05
8.00E+05
7.00E+05
6.00E+05
5.00E+05
4.00E+05
3.00E+05
2.00E+05
1.00E+05
0.00E+00
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)

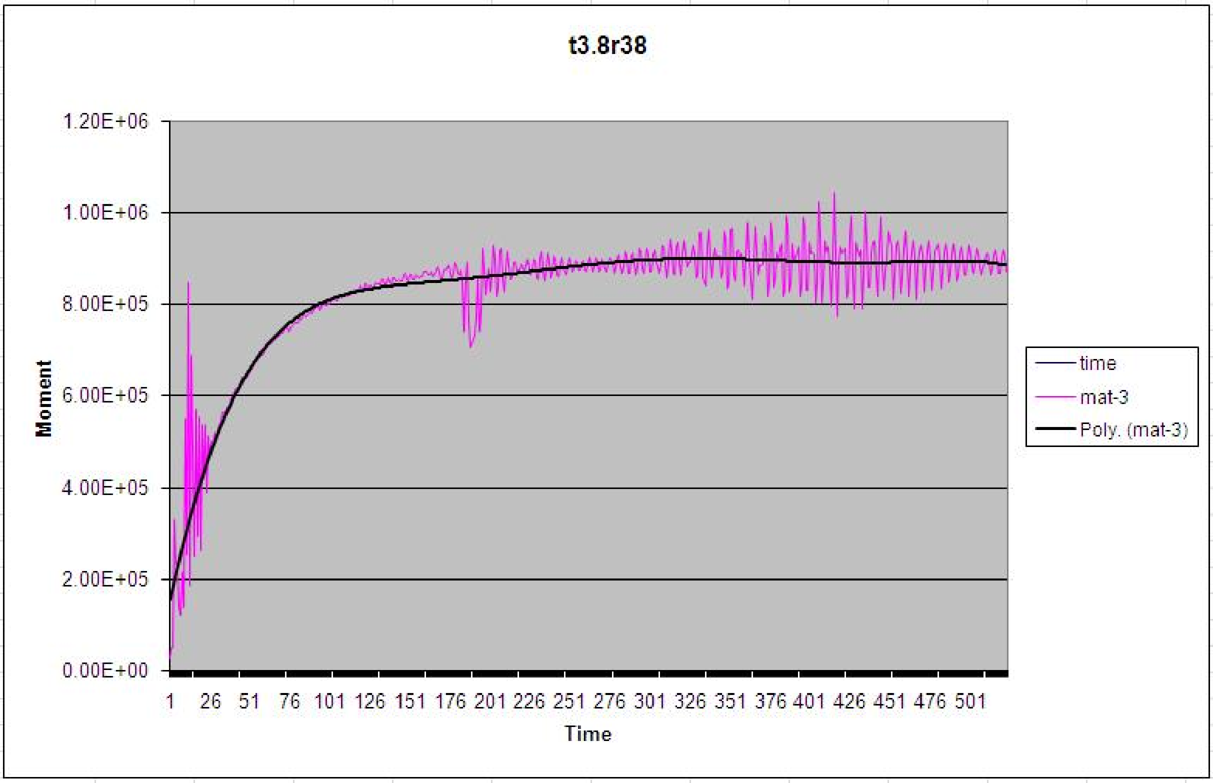

t3.17r38
9.00E+05
8.00E+05
7.00E+05
6.00E+05
5.00E+05
4.00E+05
3.00E+05
2.00E+05
1.00E+05
0.00E+00
Moment
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)

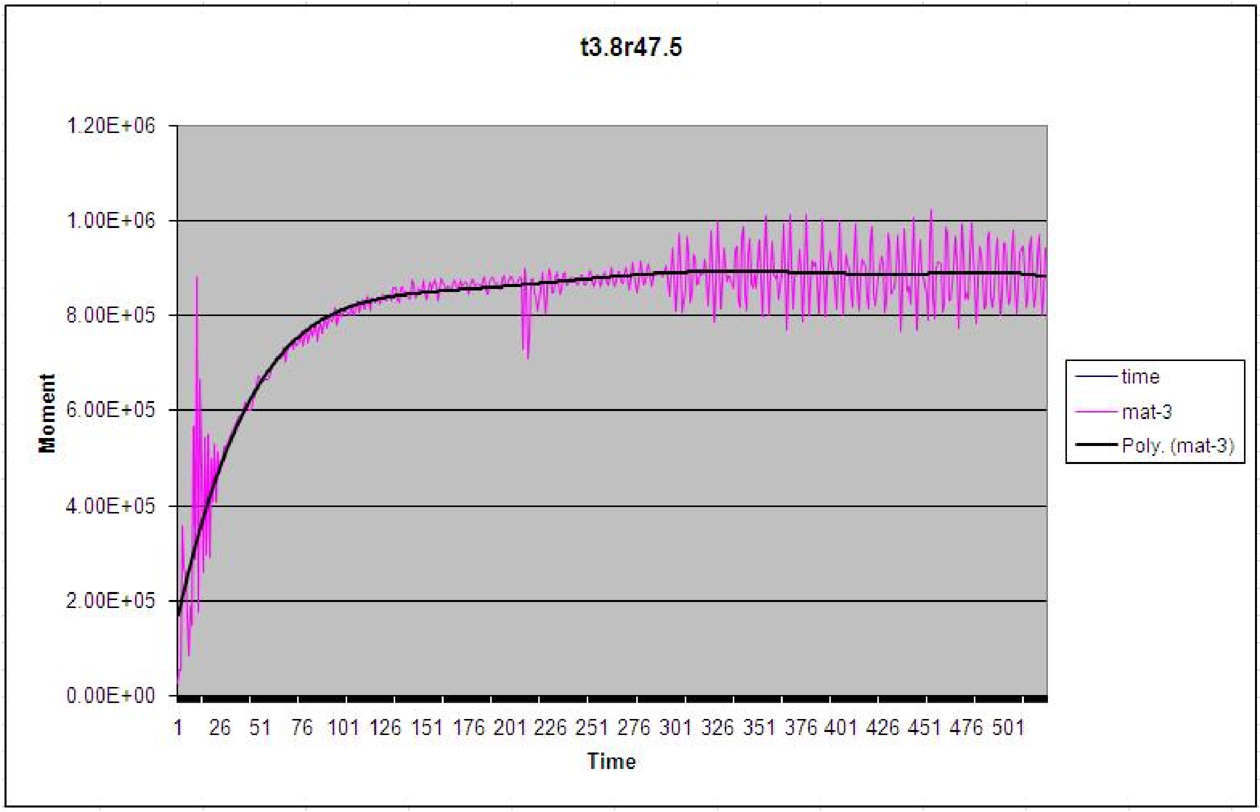

t3.17r47.5
1.00E+06
9.00E+05
8.00E+05
7.00E+05
6.00E+05
5.00E+05
4.00E+05
3.00E+05
2.00E+05
1.00E+05
0.00E+00
Moment
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)

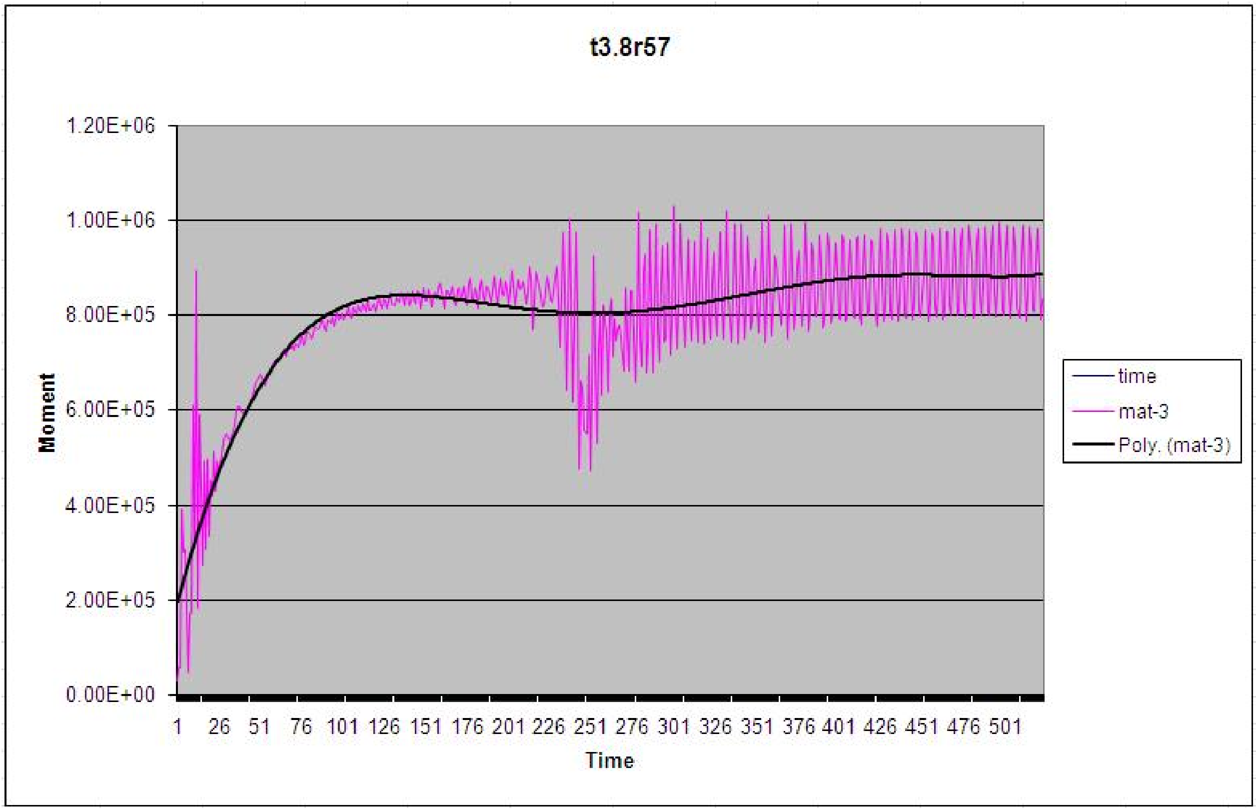

t3.17r57
1.20E+06
1.00E+06
8.00E+05
6.00E+05
4.00E+05
2.00E+05
0.00E+00
Moment
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)

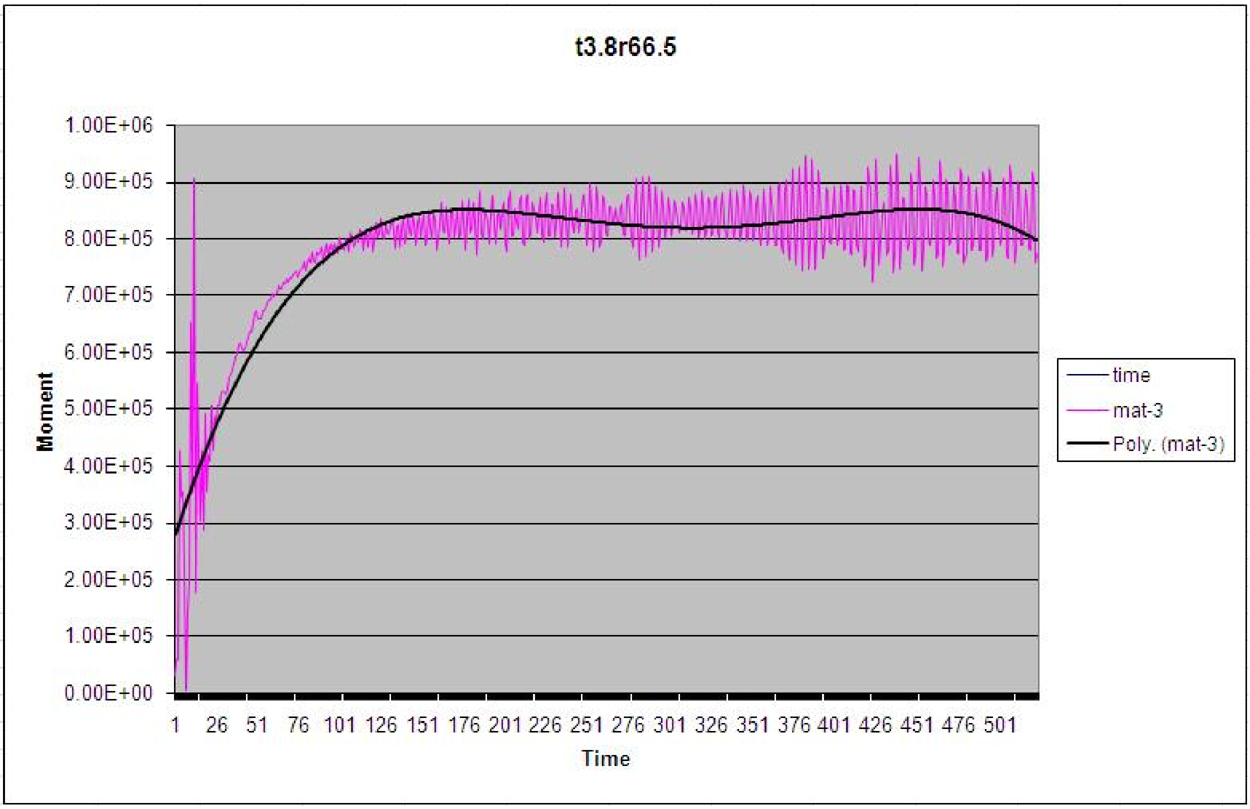

t3.17r66.5
9.00E+05
8.00E+05
7.00E+05
6.00E+05
5.00E+05
4.00E+05
3.00E+05
2.00E+05
1.00E+05
0.00E+00
Moment
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)

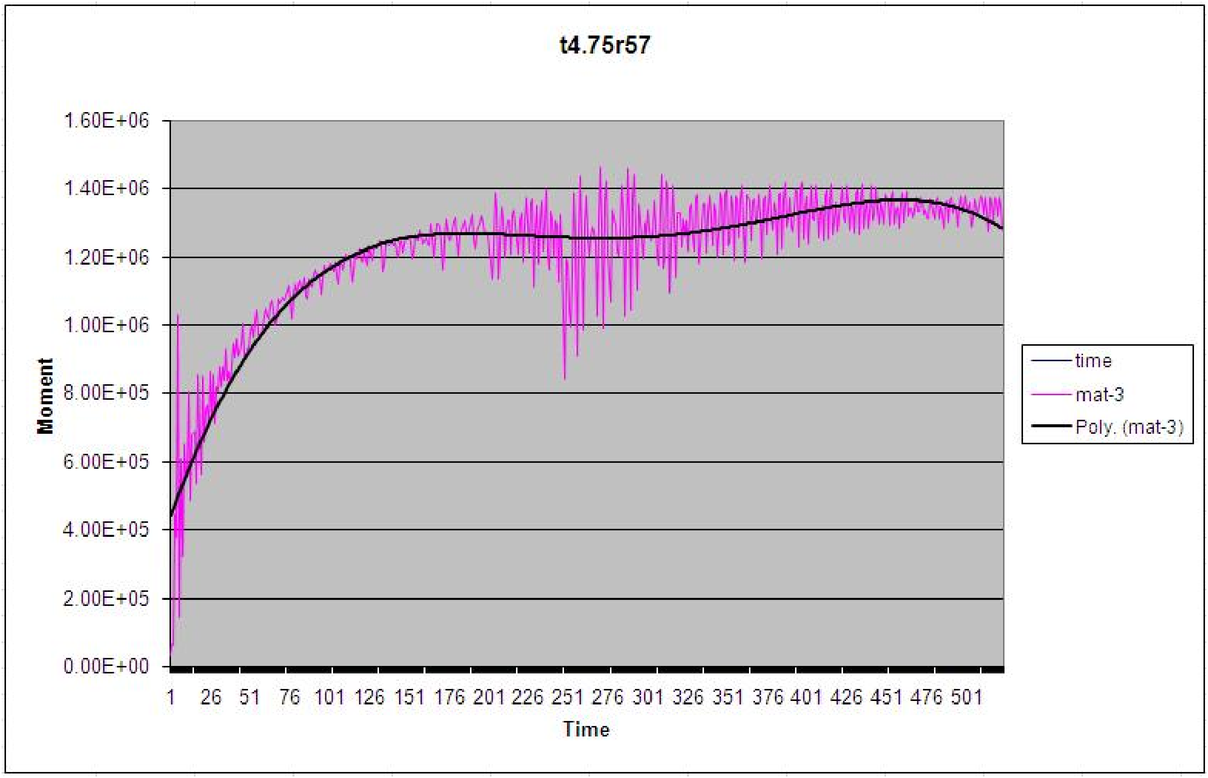
8.2.2 Without Wrinkles

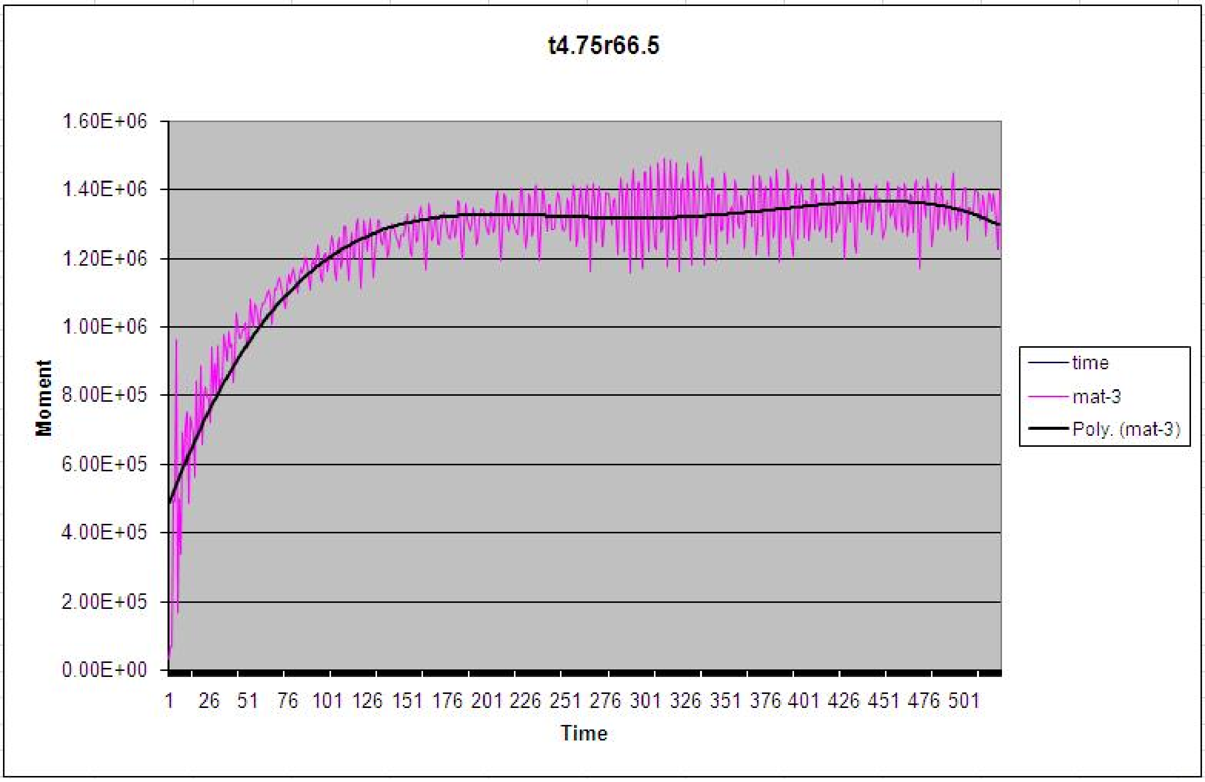




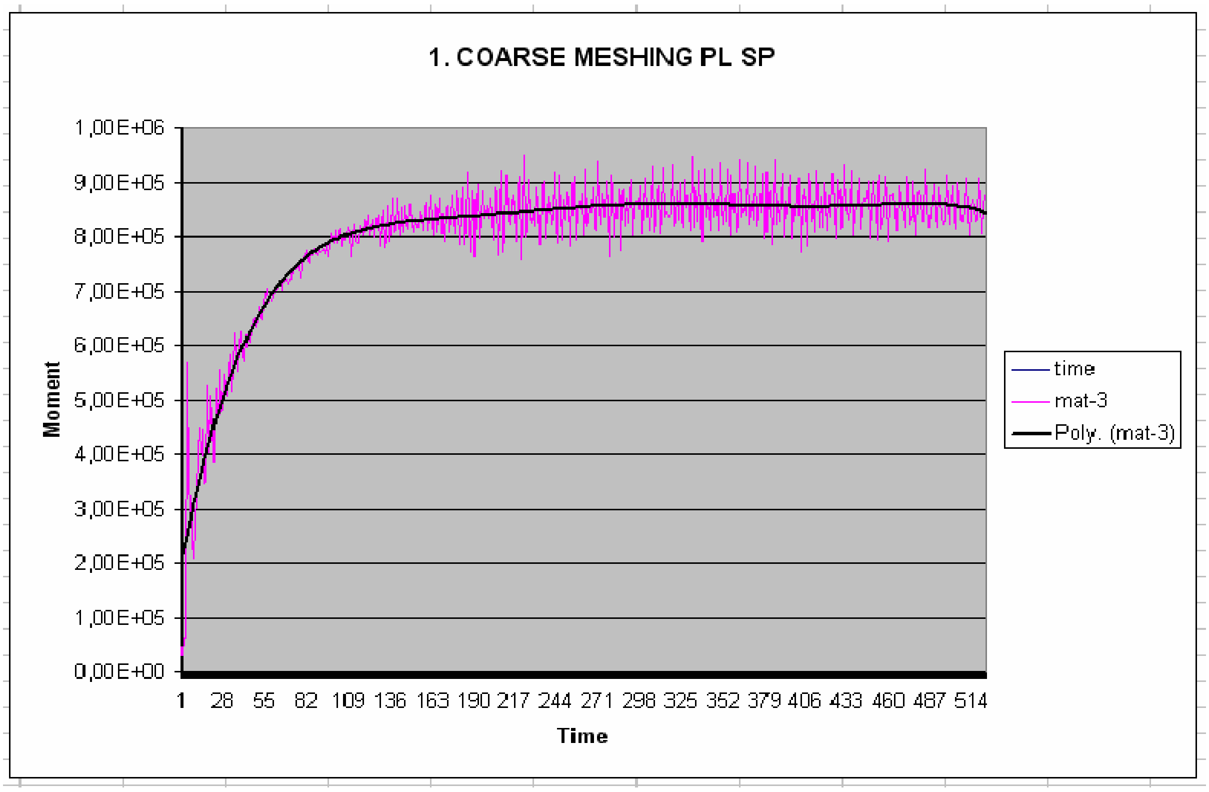

t3.8r57
1.20E+06
1.00E+06
8.00E+05
6.00E+05
4.00E+05
2.00E+05
0.00E+00
Moment
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)

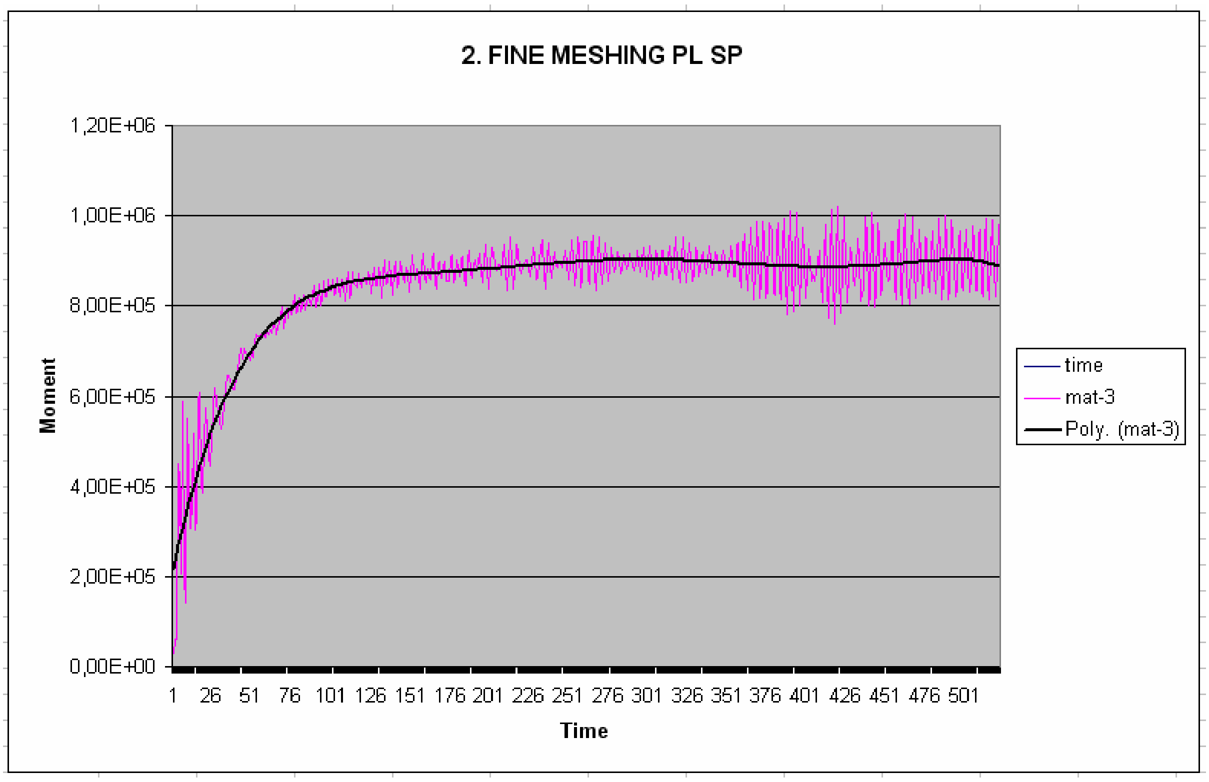

t3.8r66.5
1.00E+06
9.00E+05
8.00E+05
7.00E+05
6.00E+05
5.00E+05
4.00E+05
3.00E+05
2.00E+05
1.00E+05
0.00E+00
Moment
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)

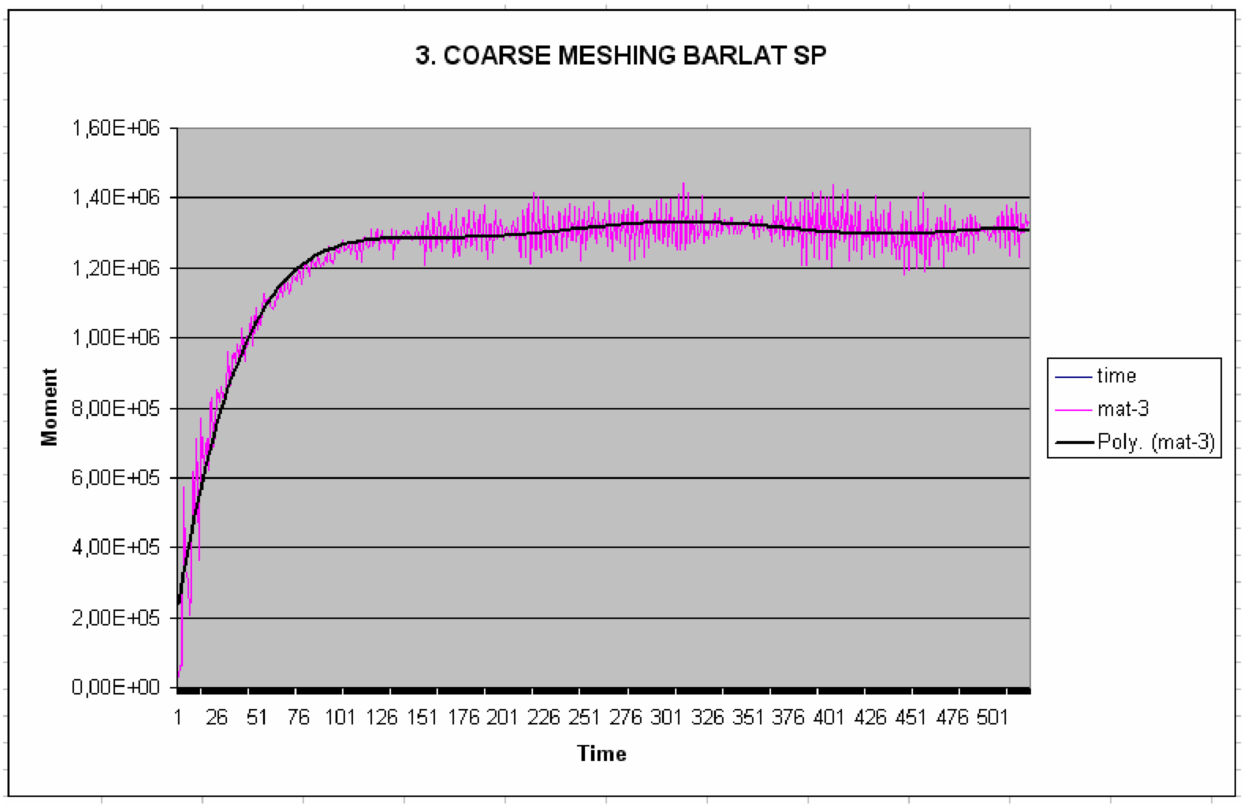

t4.75r57
1.60E+06
1.40E+06
1.20E+06
1.00E+06
8.00E+05
6.00E+05
4.00E+05
2.00E+05
0.00E+00
Moment
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)

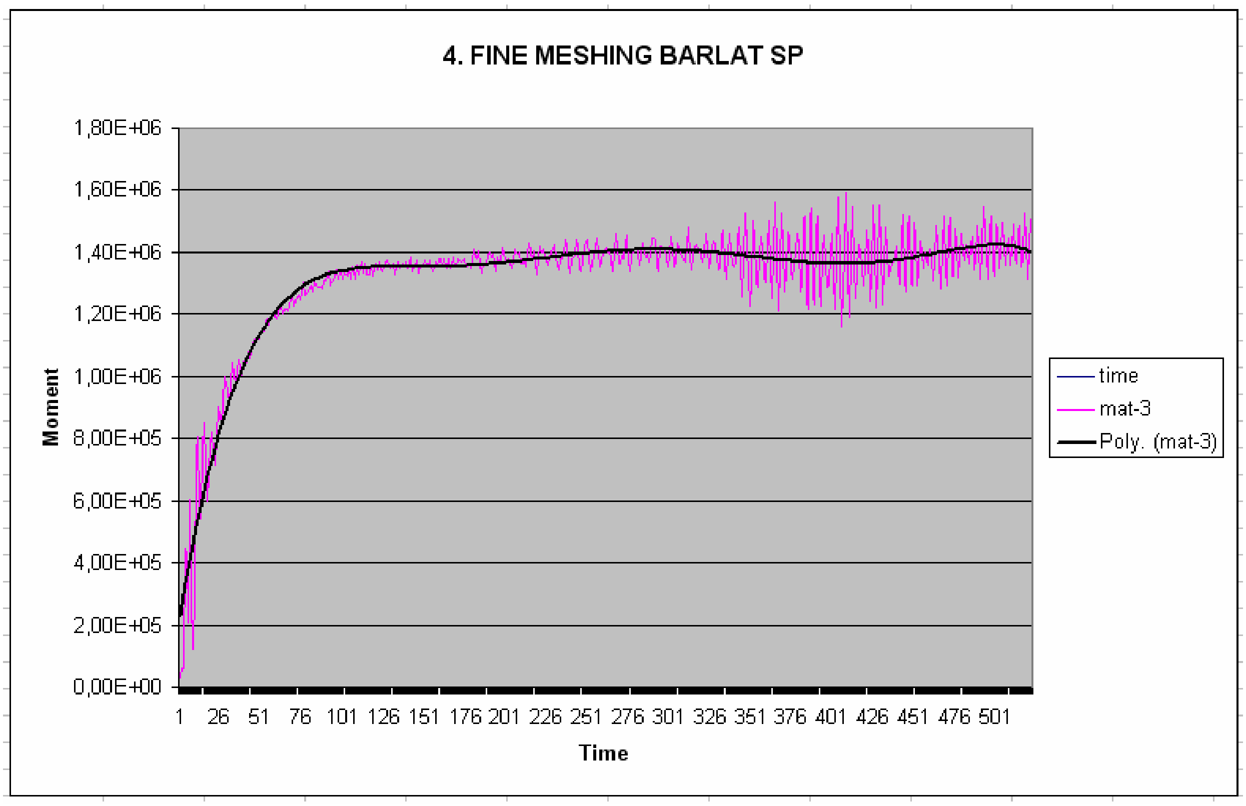

t4.75r66.5
1.60E+06
1.40E+06
1.20E+06
1.00E+06
8.00E+05
6.00E+05
4.00E+05
2.00E+05
0.00E+00
Moment
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)

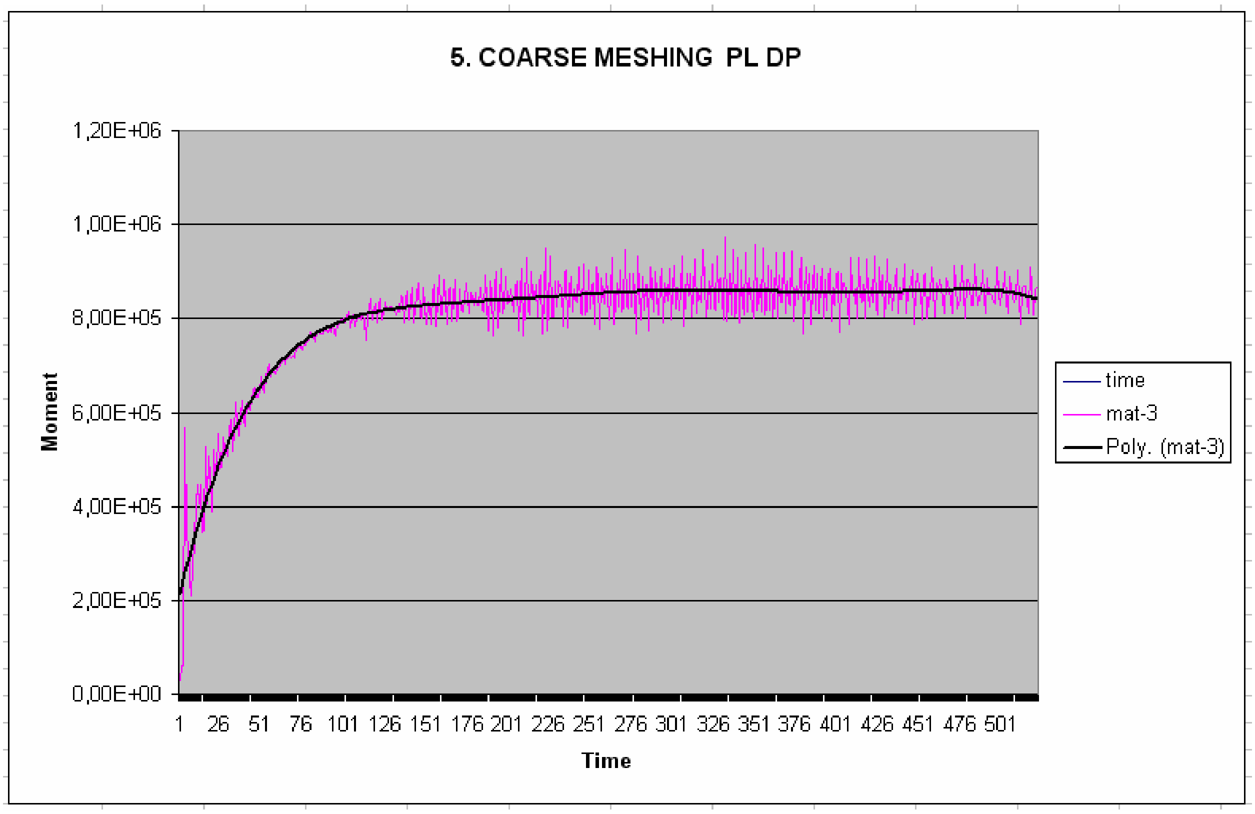
8.3 Comparative Simulations

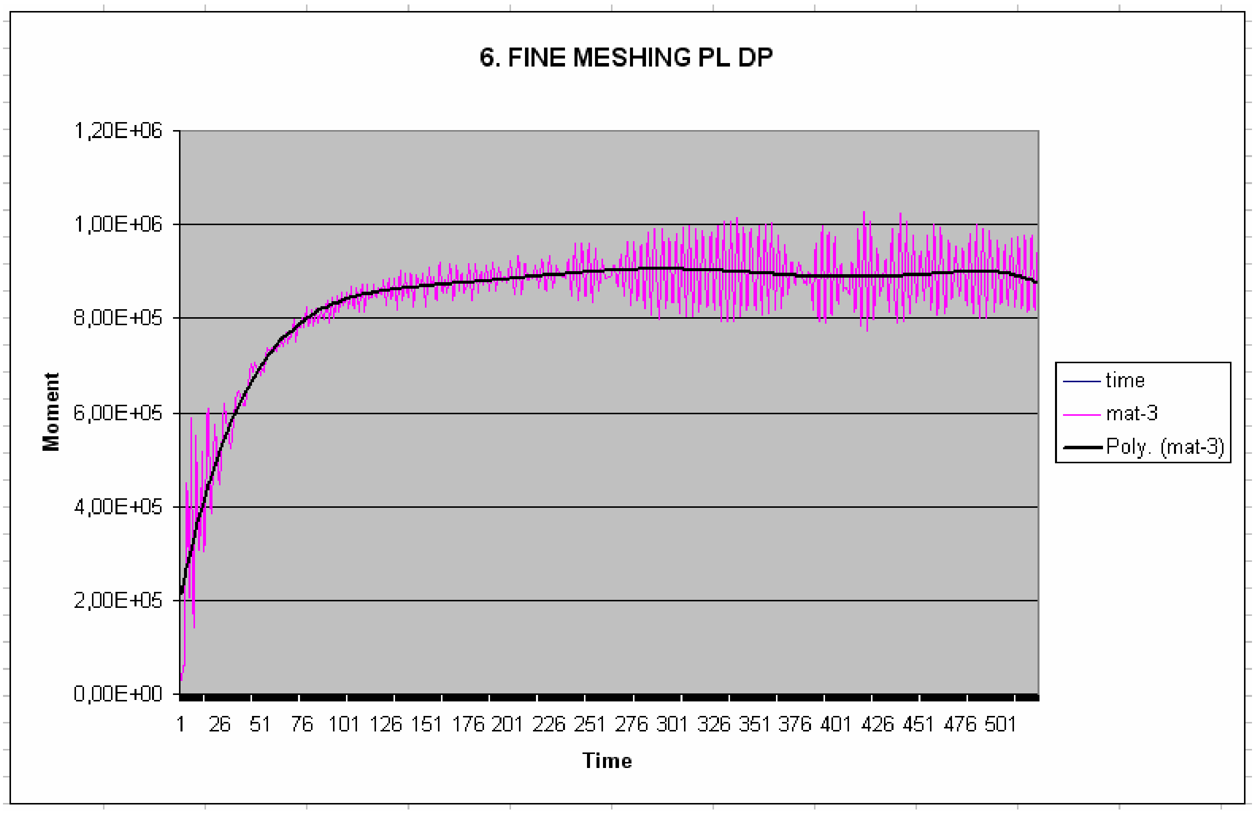


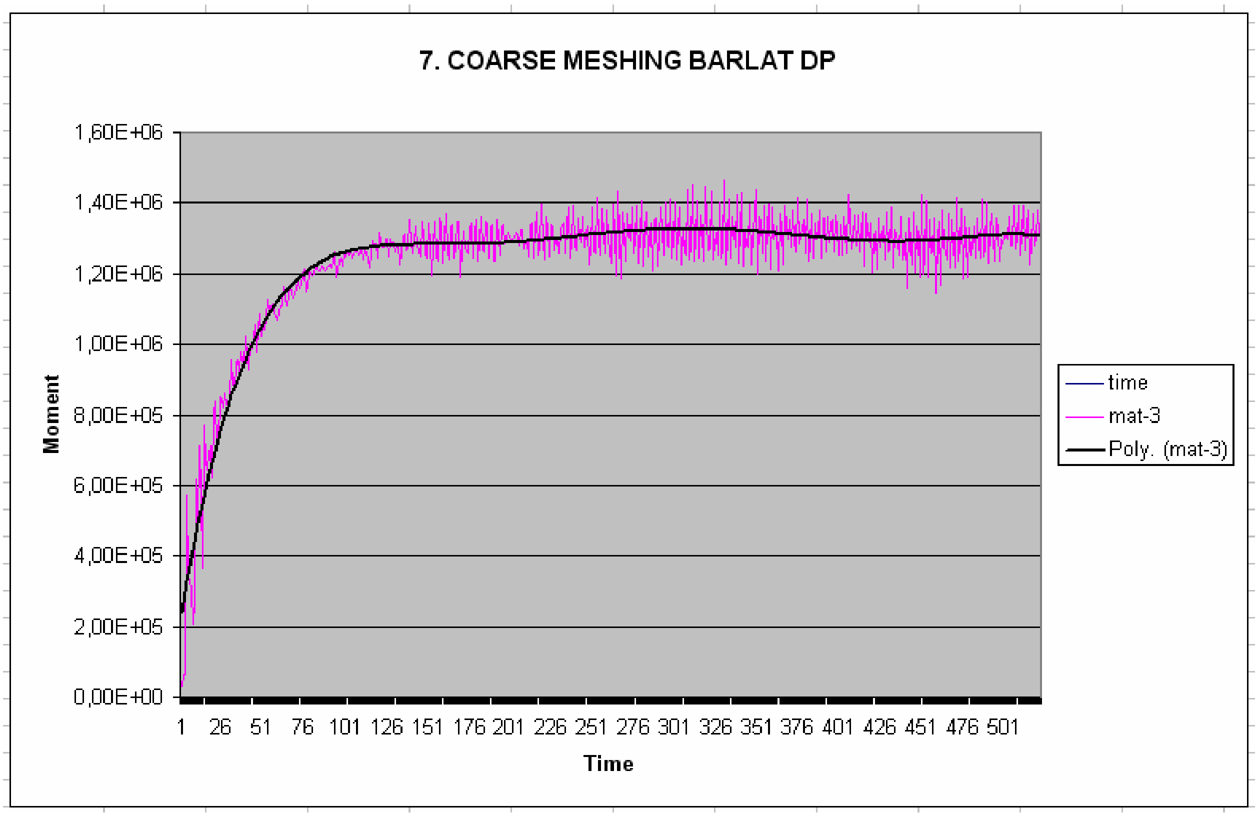


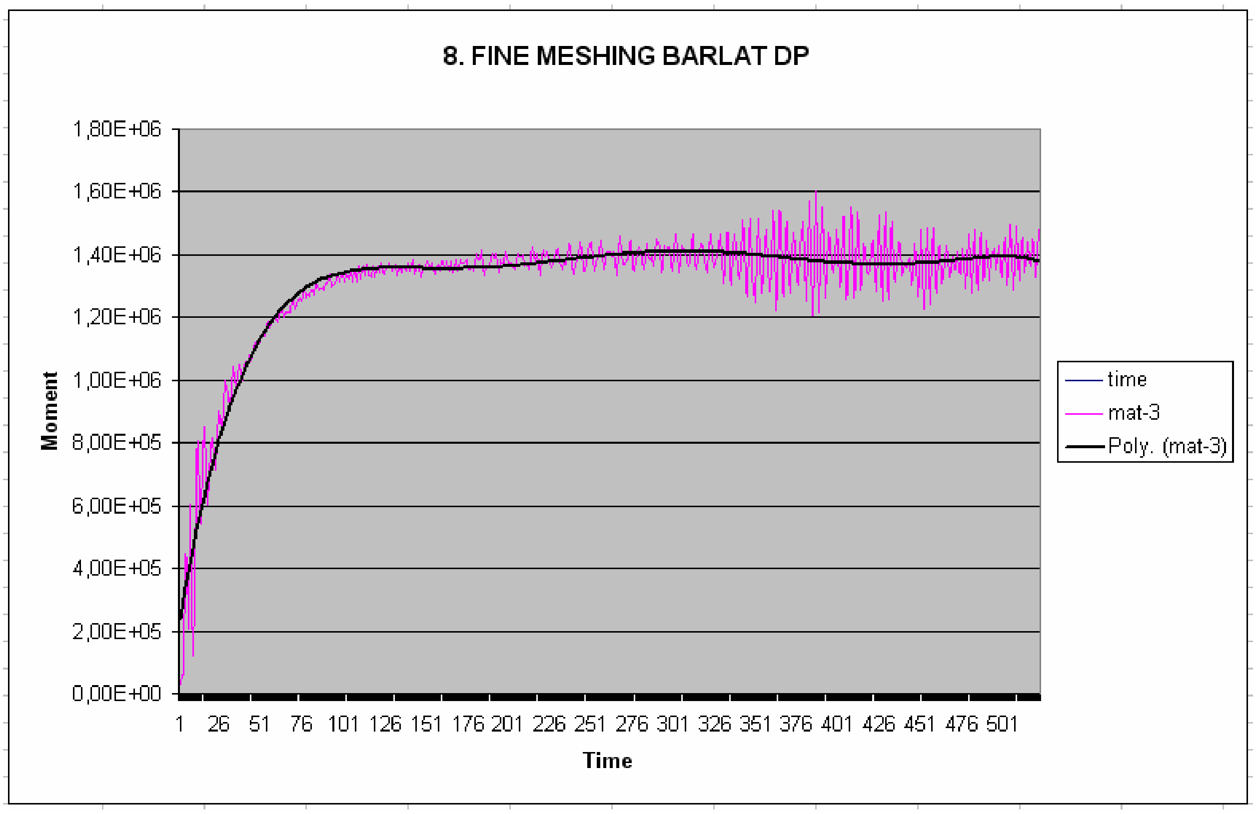

3. COARSE MESHING BARLAT SP
Moment
1,60E+06
1,40E+06
1,20E+06
1,00E+06
8,00E+05
6,00E+05
4,00E+05
2,00E+05
0,00E+00
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)


4. FINE MESHING BARLAT SP
Moment
1,80E+06
1,60E+06
1,40E+06
1,20E+06
1,00E+06
8,00E+05
6,00E+05
4,00E+05
2,00E+05
0,00E+00
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)


5. COARSE MESHING PL DP
1,20E+06
1,00E+06
8,00E+05
6,00E+05
4,00E+05
2,00E+05
0,00E+00
Moment
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)


6. FINE MESHING PL DP
1,20E+06
1,00E+06
8,00E+05
6,00E+05
4,00E+05
2,00E+05
0,00E+00
Moment
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)


7. COARSE MESHING BARLAT DP
Moment
1,60E+06
1,40E+06
1,20E+06
1,00E+06
8,00E+05
6,00E+05
4,00E+05
2,00E+05
0,00E+00
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)


8. FINE MESHING BARLAT DP
Moment
1,80E+06
1,60E+06
1,40E+06
1,20E+06
1,00E+06
8,00E+05
6,00E+05
4,00E+05
2,00E+05
0,00E+00
1 26 51 76 101 126 151 176 201 226 251 276 301 326 351 376 401 426 451 476 501
Time
time
mat-3
Poly. (mat-3)