Virtual Simulation to Drive Product Designs for Wellbore Construction

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Abstract: *Today's design community uses virtual simulations to design and optimize new or existing products. Most of the time design engineers use virtual simulations to verify or improve the product design when performance issues are observed at critical PDM (Product Development Management) reviews or during prototype tests. Using virtual simulation in later phases of the design cycle to correct or improve the design, leads to increased development time and cost. The power of virtual simulations can be effectively used in the front end of the design project cycle before building costly prototypes to drive optimized product designs and develop a product "Right First Time" to effectively minimize the development time and cost.*

This paper summarizes how Baker Hughes uses FEA based virtual simulations using Abaqus to drive the product designs for wellbore constructions tools used in oil and gas industry in the early design phase. Next generation wellbore constructions tools such as expandable liner hangers, packers, solid expandables and setting tools designs in multiple sizes are driven using virtual simulations to meet the desired performance requirements. Virtual simulation is tightly integrated in all the PDM phases of design and development from feasibility study to product launch. Using virtual simulations in the front end of the design cycle during feasibility studies or concept development helped to capture most of the design failure modes and design limitations with improved product performance before building costly prototypes.

In summary, using virtual simulation in early phases of design cycle to drive designs helped us to achieve significant reduction in product development time and cost.

Keywords: *Virtual Simulation, PDM, Expandable, Liner Hanger, Oil and Gas, FEA, DOE, Reliability, Validation*

1. Introduction

Product reliability, safety, speed to market, and cost control are vital to succeed in the oil and gas industry. To remain competitive, oil and gas service companies must ensure that the right products are built reliably and meets customer expectations ahead of competitors. The key to develop optimized products at minimum development cost is to design, simulate, test, and verify the product performance in virtual environments by applying various simulation tools in the early phases of the product design cycle and then validate only the final design(s) with physical prototypes to confirm performance. The power of virtual simulations can be effectively used in the front end of the design project cycle before building costly prototypes to drive optimized product designs with "Right First Time" design strategy to minimize the development time and cost. Next generation wellbore construction tools such as expandable liner hangers, packers, solid expandables and setting tool designs used within the oil and gas industry are complex mechanical systems. Because of the mechanical complexity and inherent nonlinearity, developing wellbore constructions tools presents a challenge to engineers. Virtual Simulation can be used to understand the complex tool behavior under complex loading scenarios to allow the engineer to tackle technical challenges before manufacturing prototypes.

2. Virtual Simulation and "Right First Time" Design Strategy

Virtual Simulation is the process of creating and analyzing a digital prototype to predict its performance in the real world. Oil and gas service companies cannot afford to ignore a "Right First Time" strategy to design products in order to stay competitive. Ideally, only the final design(s) needs to be validated with physical prototypes to confirm the performance. The design community can avoid or minimize the high costs, schedule delays and lost opportunities associated with the failure of physical prototype test. The design community must use virtual simulations in the early phases of the design cycle to test various design concepts using virtual prototypes. Virtual prototyping enables design engineers to learn and understand the design limitations, constraints, interactions and helps to improve the design to meet required design performance criteria. Simulating multiple design ideas concurrently, design teams can identify dramatic engineering improvements early in the design process, prior to and more effectively before the more costly physical prototyping. Once the design team gets enough confidence with the final design based on a series of virtual simulations, the team can proceed with the physical prototype to confirm the design. Tight integration of virtual simulation in all the Product Development Management (PDM) phases of the design cycle, from feasibility study to product launch, will maximize the probability that the product will be designed "Right First Time".

Structural simulation models are built using commercially available major FEA simulation software's such as ABAQUS, ANSYS, NASTRAN, LS-Dyna, or Hyperworks, or in-house software programs.

Simulation models enables designers and engineers to avoid replicating multiple physical prototypes to analyze the new or existing parts. Before creating the physical prototype, analysts can virtually investigate many digital prototypes.

3. Integrating Virtual Simulation with Product Development Process

Virtual simulation can be tightly integrated with typical Product Development Management (PDM) Processes to evaluate and improve the product design performance from concept to Product Life cycle Management as illustrated in **Figure 1**.

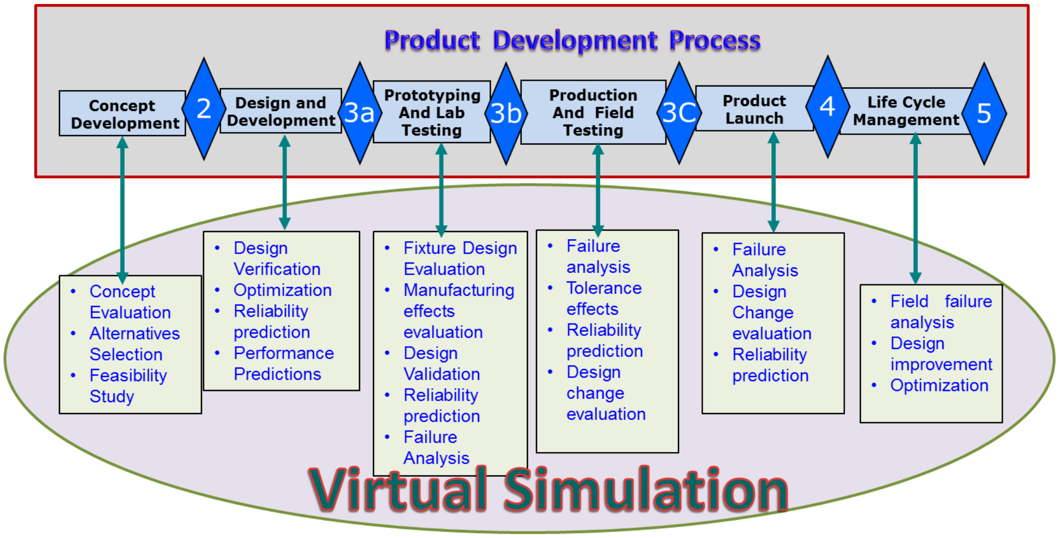


Figure 1. Tight Integration of Virtual Simulation with typical PDM Process

At the concept phase, the number of concepts with varied features, geometry, material etc. can be evaluated using virtual simulation under various loading scenarios to choose the best concept among alternatives and set the design direction. Also virtual simulation can be used to carry out feasibility studies to justify and understand the technological limits, manufacturing constraints, and economic viability of planned products.

Once a design concept is selected, virtual simulation can be used for design verification, performance evaluation, design improvement, optimization, and reliability predictions. Multiple design iterations can be performed at minimal simulation cost to study alternatives. Design sensitivity studies are carried out to check the effect on design performance before building costly physical prototype. The Seven-Step Methodology described in reference 4 can also be used to verify and validate a design.

Once a satisfactory design is finalized, a physical prototype is built and tested if needed to validate the final design performance under intended field conditions to meet customer requirements and regulatory needs. Making a physical prototype is always costly and time consuming. So if enough historical test data is available from similar products to correlate virtual simulation model, one can use virtual simulation to validate product design performance instead of building costly physical prototypes. Virtual simulation also can be used to evaluate test fixture design performance to ensure it can withstand test setup and actual test loading conditions, to aid in failure analysis; to study effects of manufacturing short comings on design performance, and reliability predictions.

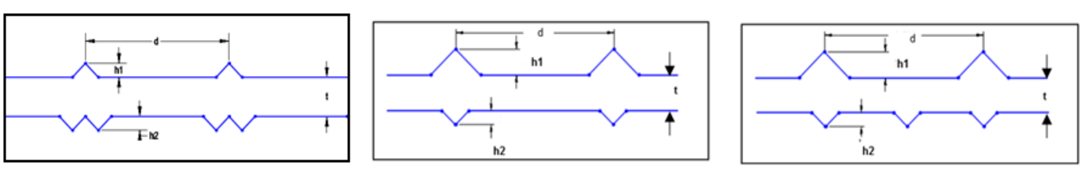
At the production and field testing phase virtual simulation can be very effective way to perform failure analysis, to study the effect manufacturing tolerance variations, and any assembly issues without need of physical prototype.

Before a product gets launched, a simulation model can be used to verify the effects of any minor design changes (made based on physical test data) on overall design performance. During the life cycle of the product, simulation can be very useful to study the effect of any design changes, warranty issues, reliability study, manufacturing variations, environmental conditions changes, and further design improvements.

Tight integration of virtual simulation with the product development cycle enables organizations to develop products faster, cheaper and have a higher degree of reliability. Baker Hughes uses FEA based virtual simulations with tight integration within the PDM process to drive product designs for wellbore constructions tools used in the oil and gas industry from the early phases of development cycle. Later sections of this paper discusses how Baker Hughes used virtual simulations using Abaqus in various phases of PDM to develop and drive wellbore construction product designs such as expandable liner hangers, packers, solid expandables, and various down-hole setting tools.

4. Virtual Simulation in Concept Development Phase

Varied features, geometry, material etc. can be evaluated using virtual simulations under various loading scenarios to choose the best design concept among the alternatives to set the design direction during concept phase of PDM. Multiple design iterations can be performed at minimal simulation cost to evaluate alternatives. **Figure 2** shows an example of the concept design configurations for a slip ring used in liner hanger applications. Slip ring shown in **Figure 4** has triangular wickers all around the slip ring body on both OD and ID as shown in **Figure 2**. During setting of liner hanger it gets expanded and penetrates the wickers in casing ID and Hanger body OD which permanently locks the hanger body with cemented casing, hence hangs the liner weight. The slip ring thickness, wicker geometry and position drive the hanging capacity of the liner hanger. Multiple design configurations with variation in dimensional parameters were studied during the concept phase to find the best and optimum slip ring design to hang maximum liner weight during wellbore construction. The Design of Experiments (DOE) was performed to find the optimum design. **Figure 3** shows the full factorial DOE setup details.



(a) (b) (c)

Figure 2. Slip Ring Concept Design Configurations

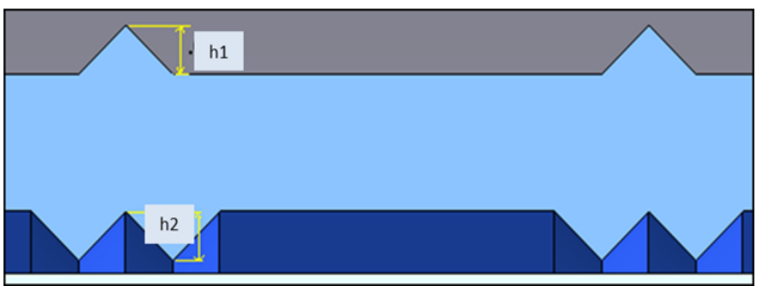
Typical FEA model comprises the liner hanger assembly and setting tool as shown **Figure 6.** Design of Experiments (DOE) based optimization of the slip ring geometry was performed using HyperStudy and Abaqus/explicit software. Full factorial DOE was used for approximation using least squares regression. Design variables such as slip ring thickness, ID and OD wicker height and spacing between wickers were with 3 level of variation used to perform DOE. FEA consists of setting the liner hanger by expanding the slip ring and then finding out the hanging capacity of liner hanger by measuring the reaction force when liner is pulled down. The goal was to increase hanging capacity. Typical results consists hanging capacity as shown in **Figure 12**.

Full Factorial DOE

3 design factors and 3 levels ,

# of experiments = s^3 =27

Design Factors\Levels	High	Center	Low
h1	1	2	3
h2	1	2	3
s1	1	2	3



Full Factorial run Matrix

Full Factorial DOE Run Matrix
(3 factors, 3 levels)

Run #	h1	h2	s1
1	1	1	1
2	1	1	2
3	1	1	3
4	1	2	1
5	1	2	2
6	1	2	3
7	1	3	1
8	1	3	2
9	1	3	3
10	2	1	1
11	2	1	2
12	2	1	3
13	2	2	1
14	2	2	2
15	2	2	3
16	2	3	1
17	2	3	2
18	2	3	3
19	3	1	1
20	3	1	2
21	3	1	3
22	3	2	1
23	3	2	2
24	3	2	3
25	3	3	1
26	3	3	2
27	3	3	3

Figure 3. Slip Ring Design Concept - DOE

Based on DOE, the optimum slip ring geometry was selected based on highest hanging capacity. The final design based on DOE showed 40% improvement over the original concept design.

5. Virtual Simulation in Design and Development Phase

Design verification, performance evaluation, design improvement, design optimization, and reliability prediction can also be done using virtual simulation during the design and development phase. Design change sensitivity also can be studied to ensure desired performance before building costly physical prototypes. One can follow the Seven-Step Methodology as mentioned in the paper, reference 4, to verify and validate the design. The discussion in section 5.1 deals with the application of virtual simulation to design and develop an expandable liner hanger.

5.1 Expandable Liner Hanger Development

The expandable liner hanger is a liner hanger system capable of hanging liner weight under extreme conditions thereby enabling wellbore construction in problematic environments. The expandable liner hanger uses pipe expansion, in place of conventional mechanisms for making contact with the casing wall to support the weight of the liner and seal off the annulus.

Figure 4 shows the expandable liner hanger system, which comprises a hanger body, slip ring, and packer. A special running tool with an adjustable swage carries the system into the well; through applied hydraulic pressure, the adjustable swage moves and plastically deforms the hanger body to activate the slips and packer. The hanging slips and packer are forced outward during expansion, causing them to make contact with the parent casing wall. Following expansion, the running tool is removed from the wellbore, leaving the liner hanger and the suspended liner in the well.

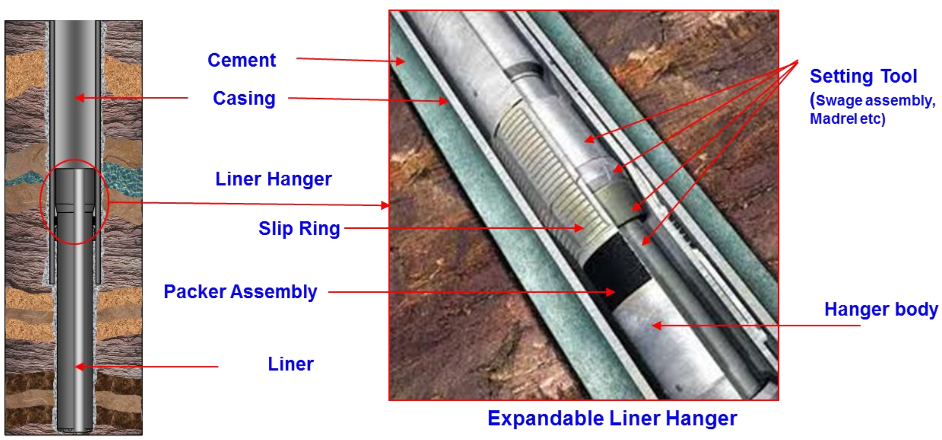


Figure 4. Expandable Liner Hanger System

A finite element (FE) model of an expandable liner hanger system comprises an adjustable swage assembly to expand the hanger body, slip ring to hang the liner load, and a packer to seal in a variable-diameter casing. The expandable liner hanger is set in the well bore by application of hydraulic pressure, a swage moves inside the hanger body while expanding the hanger body, slip ring and packer into the casing. As the expansion occurs, the slip ring wickers bite into the casing wall and hanger body providing permanent attachment of hanger body with casing. The hanging capacity depends upon the slip ring design of the hanger packer assembly. The packer is squeezed between the hanger body and the casing wall creating an annular, pressure-tight seal.

Figure 5 illustrates a half section of a 3D Finite Element (FE) model of the expandable liner hanger. A typical FE model can have more than six to seven million elements because of its size and the need of a refined mesh in slip wicker zone.

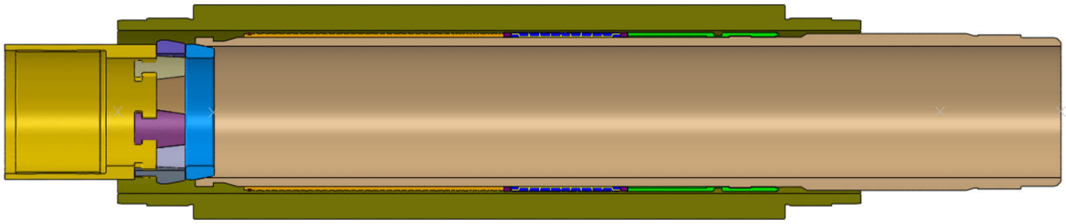


Figure 5. Pre expansion Finite Element Model

Figure 6 shows the mesh illustration of 3D FE model

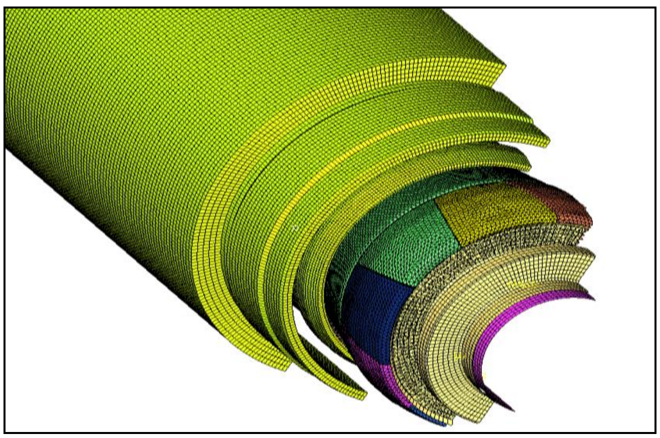


Figure 6. FE Mesh illustration

Figure 7 shows the sample simulation results like stresses on various parts of hanger packer assembly and swage assembly, plastic strain on swage segment, and contact pressure for seal integrity for the expandable liner hanger. Liner hanger design development was an iterative process and the design was modified multiple times based on simulation results.

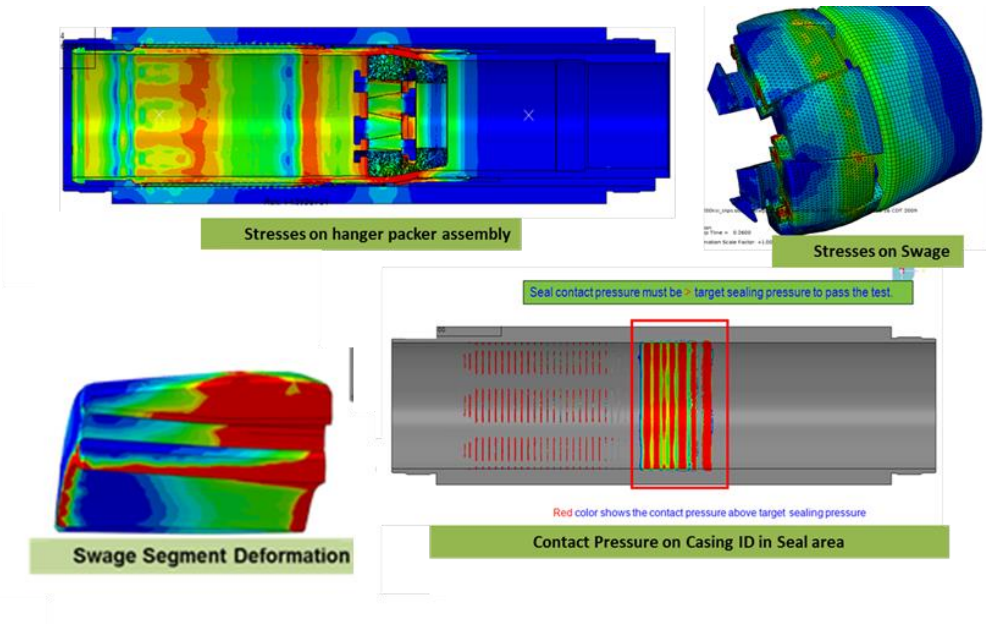


Figure 7. Simulation results

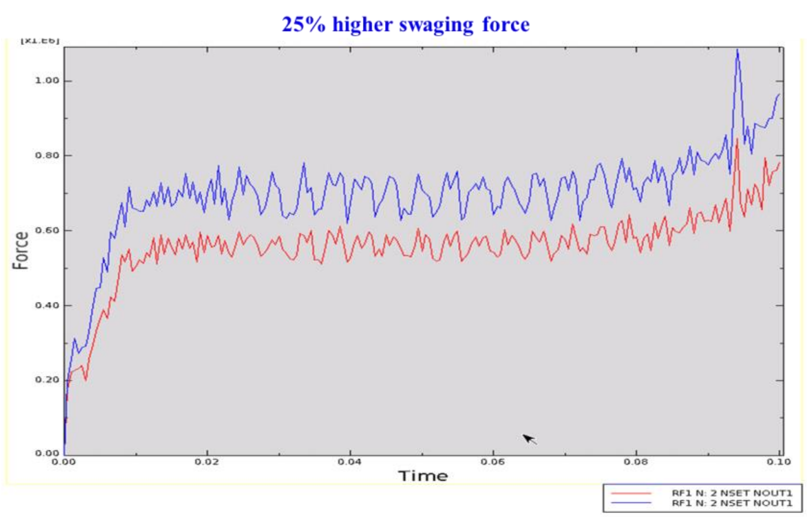


Figure 8. Effect of material strength on expansion force

Figure 8 shows the effect of material strength on expansion force. The expansion force was increased by 25% with changing material strength from 125ksi to 140ksi.

A reliability assessment was also performed early during design and development phase. The reliability assessment process comprises performing the stochastic analysis using the DOE based response surface to predict the reliability. **Figure 9** shows the sample response surface for reliability assessment of liner hanger based on slip design DOE.

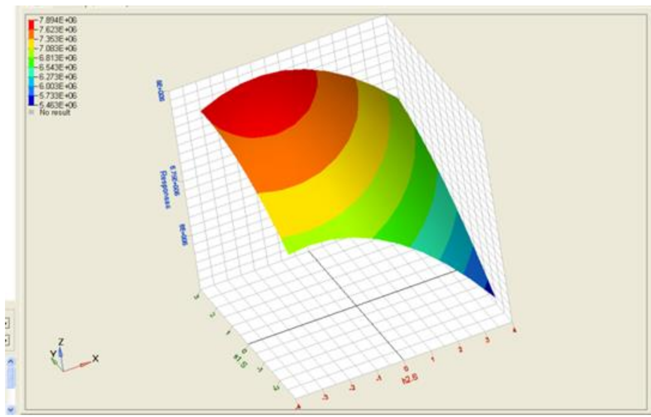


Figure 9. Response Surface

Extensive use of virtual simulations in design and development phase helped to develop an optimum and reliable design for the expandable liner hanger.

6. Virtual Simulation in Testing Phase

Once a satisfactory design is finalized, the physical prototype can be built and tested if needed to validate the final design performance under intended environmental conditions to meet customer requirements and regulatory needs. Making a physical prototype is always costly and time consuming. So if enough historical test data is available from similar products to correlate to the virtual simulation model, one can use the virtual simulation to validate product design performance instead of building costly physical prototypes. Virtual simulation also can be used to evaluate test fixture design performance to ensure it can withstand test setup and actual test loading conditions, to aid in failure analysis; to study the effects of manufacturing short comings on design performance, and reliability predictions.

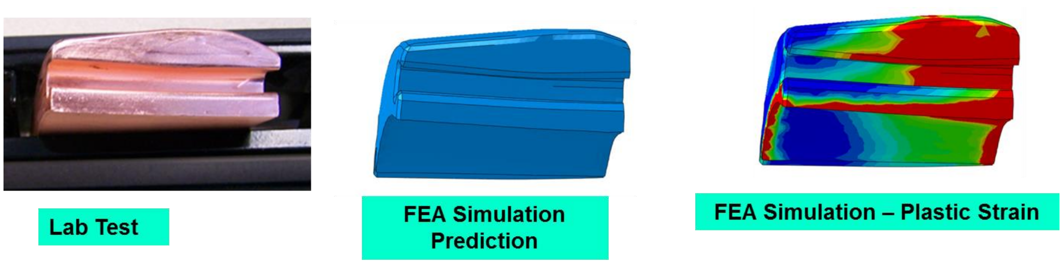


Figure 10. Test Correlation with FEA – Swage Segment Deformation

Figure 10 shows the comparison of virtual simulation results for a swage segment deformed during lab testing. Virtual simulation helped to investigate the causes of the swage segment deformation and take corrective actions.

Figure 11 shows the comparison of the slip ring penetration on the hanger body OD with lab test data to validate the behavior and performance.

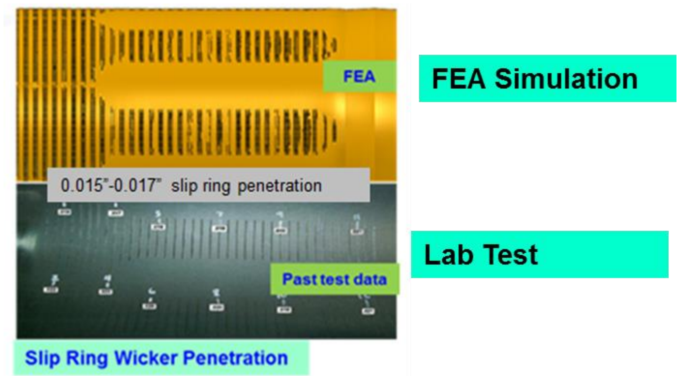


Figure 11. Test Correlation with FEA – Slip Ring Penetration

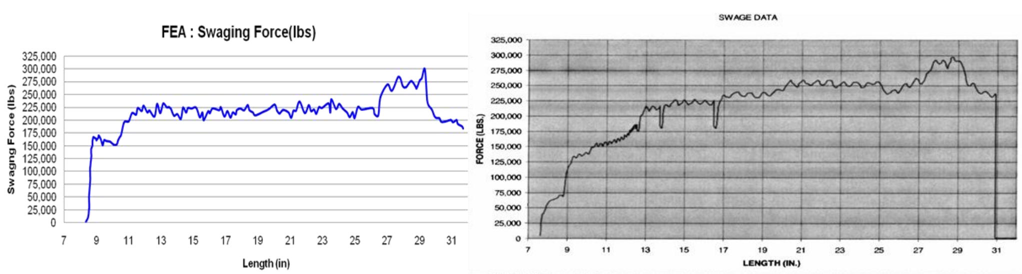


Figure 12. Test Correlation with FEA – Expansion Force

Figure 12 shows the comparison of FEA and a test for the expansion force. Virtual simulation can help to avoid unnecessary prototype tests if it is used effectively with good correlation.

7. Virtual Simulation in Product Launch Phase

Before product gets launched, simulation models can be used for verify any minor design changes resulting from the physical test results to ensure the product still meets the desired performance. **Figure 13** shows an example of an existing backup ring extrusion issue observed during a laboratory test. The existing backup ring was made with a thermoplastic material and extruded because of the extreme expansion force. Virtual simulation was used to reproduce the same issue as observed in the test and take corrective action by trying different thermoplastic materials for the backup ring. Finally a different thermoplastic material with stronger shear properties was selected based on the virtual simulation predictions and product was launched on time without waiting for further physical prototype results with the new material.

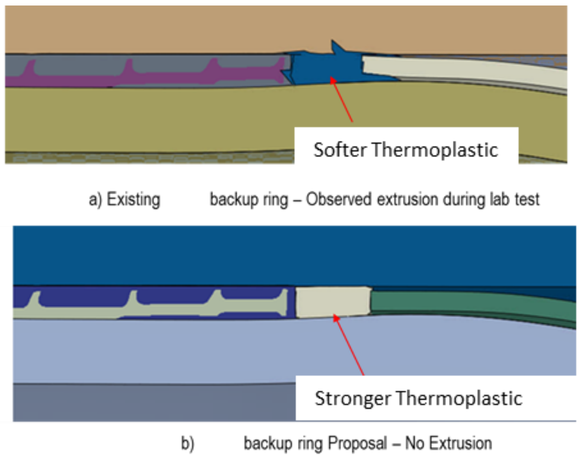


Figure 13. Backup Ring Material Performance

8. Virtual Simulation in Product Life Cycle Management Phase

During the life cycle of the product, simulation can be very useful to perform failure analysis, to study the effect of any design changes, warranty issues, reliability analysis and for further design improvements to meet customer needs. The example of the adjustable express cone design described in this section is an application of virtual simulation for a failure analysis and verifying a design change to correct a problem that occurred due to unanticipated loading conditions. This adjustable cone is used to expand the screen used in sand control applications.

One of the segment rails of the adjustable cone was broken and the segment came off from the adjustable swage assembly during a pullback test as shown in **Figure 14**.

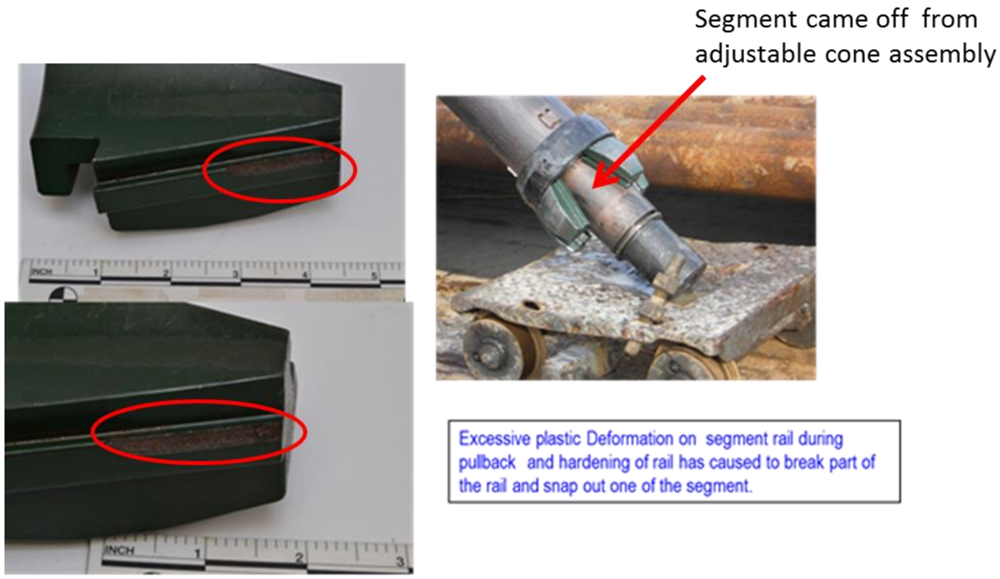


Figure 14. Adjustable Cone Segment Field Failure

FEA was used to reproduce the failure and identify the loading condition which caused the failure of adjustable cone. Simulation identified that the unsupported shear ring in the existing design caused the shear ring to tilt during expansion as shown in **Figure 15**. This shear ring tilting changed the dynamics of the segment behavior during pullback and loaded the cone segment excessively. This caused the excessive plastic deformation and subsequent breaking of the segment rail as shown in **Figure 16**. Because of segment damage, it snapped out of the cone assembly. The design was corrected to overcome this issue using virtual simulation.

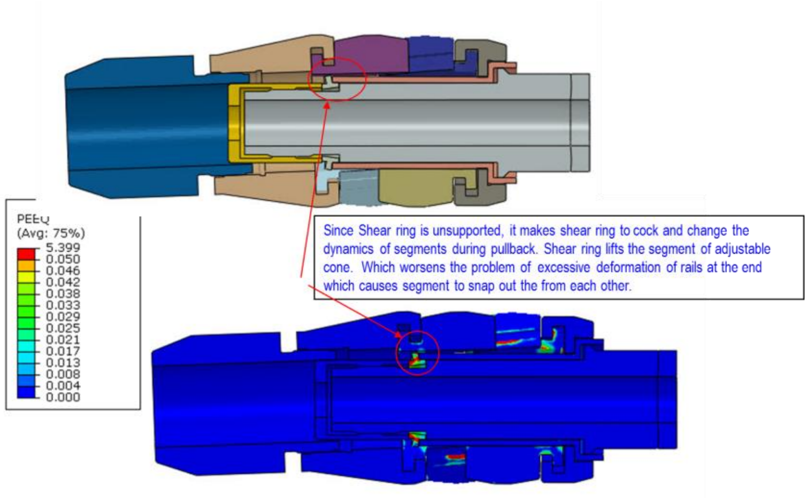


Figure 15. FEA of Adjustable Cone Segment Failure

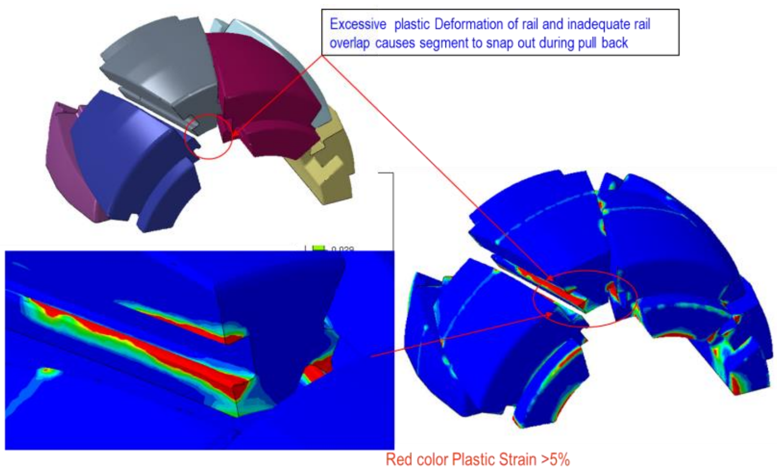


Figure 16 Excessive Plastic deformation of Adjustable Cone Segment

9. Cost – Benefits of tight integration of Virtual Simulation with PDM

Significant returns can be achieved over investment (ROI) by integrating simulation with PDM through the cost savings in overall development cost and time. Table 1 shows the cost–benefits of integrating virtual simulation with PDM through saving in prototype cost and development time.

Table 1. Cost - Benefit Analysis of integrating Virtual Simulation with PDM

	Project A : where FEA based optimization and Reliability simulation were not used	Project B : where FEA based optimization and Reliability simulation were used	Project C : where FEA based optimization and Reliability simulation were used
No of Prototype Tests	35	9	8
% reduction in # of prototype	0%	74%	77%
Development Time (months)	65	30	26
% reduction in Development Time	0	54%	60%
Cost per test (Material + Labor)	$33,200	$58,000	$63,840
Total Test cost	$1,162,000	$522,000	$510,720
FEA Simulation Cost ($8000/test)	$0	$280,000	$280,000
Total Test cost If no FEA simulation would have used to develop	$1,162,000	$2,030,000	$2,234,400
Cost Savings with using FEA Simulation to develop	$0	$1,228,000	$1,443,680
% Cost Savings with using Simulation to develop	0%	60%	65%

10. Summary

Effective Integration of virtual simulation during all the PDM phases helped us to develop next generation wellbore construction tools such as expandable liner hangers, packers, solid expandables and setting tools designs in multiple sizes with improved performance at lower costs. Using virtual simulations in the front end of the design cycle during feasibility studies or concept development helped to capture most of the design failure modes and design limitations with improved product performance before building costly prototypes. In summary, using virtual simulation in early phases of design cycle to drive designs helped us to achieve significant reduction in product development time and cost.

11. References

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15. Acknowledgements

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