Validation of Abaqus Virtual Simulation Model for an Expandable Liner Hanger

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Abstract: Expandable liner hangers used for wellbore construction within the oil and gas industry are complex mechanical systems. The consumable nature of the expandable products makes the accuracy and reliability of virtual simulation predictions important for reducing the time and cost to introduce a reliable and robust product to the competitive marketplace. This paper summarizes the seven-step methodology for validation of Abaqus virtual simulation model used for the performance predictions of an expandable liner hanger. The virtual simulation model of the liner hanger system comprises an adjustable swage to expand the hanger body, a slip ring to hang, and a packer to seal in a variable-diameter casing. The Abaqus/Explicit solver is used to evaluate and predict performance parameters such as required expansion force, hanging capacity, and seal integrity. The methodology presents the steps taken and challenges faced to validate the Abaqus simulation model from its initial build and refinement to the final model. Also included is how the validated simulation model helped us to study and optimize the effect of the various design parameters and investigate diverse design iterations with increased confidence. The seven-step validation methodology can be used as guideline by the simulation community to apply simulated predictions with confidence to achieve significant reductions in product development time and cost.

Keywords: Expandable, Liner Hanger, Oil and Gas, FEA, DOE, Reliability, Validation

1. Introduction

The deep waters of the Gulf of Mexico, the frigid regions of Russia, and the hot, dusty, undeveloped deserts of the Middle East are some of the geographic challenges facing today's oil and gas industry. The environment has many technical challenges because extreme depth, pressures and temperatures. Safety is the top priority of oil and gas service companies while designing and developing innovative tools and equipment to solve technological challenges. Stricter environmental and safety regulations around the world have increased the urgency to develop advanced tools and equipment faster and more reliably while keeping costs at a minimum.

Product reliability, safety, speed to market and cost control are vital success 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 is to design, simulate, test, and verify the product performance in virtual environments and then validate only the final design(s) with physical prototypes to confirm performance. In virtual environments, the accuracy and reliability of the virtual simulation model is extremely important to introduce a robust product design with confidence in less time and at a lower cost.

Expandable liner hangers used for wellbore construction within the oil and gas industry are complex mechanical systems. Because of the mechanical complexity and inherent nonlinearity, developing an expandable liner hanger system presents a challenge to engineers. The consumable nature of the expandable products makes the accuracy and reliability of the virtual simulation predictions necessary to introduce a robust product in the competitive marketplace.

2. Simulation Model

Simulation modeling is the process of creating and analyzing a digital prototype of a physical model to predict its performance in the real world. Simulation modeling is used to help designers and engineers understand under what conditions, and in which ways a part could fail and what loads it can withstand. Simulation modeling also helps predict fluid flow and heat transfer patterns.

Structural simulation models are built using commercially available major FEA simulation software's such as ABAQUS, ANSYS, NASTRAN, LS-Dyna, or Hyperworks, or writing your own software program. Simulation system models are built by modeling each part of the system, the interaction between parts, assigning physical properties such as material, temperature, heat treatment, etc., and then applying specific loading and boundary conditions. The simulation program runs the simulation model and delivers various performance outputs. Simulation accuracy of simulation predictions depends on the quality and accuracy of the assumptions used to build the simulation model. Understanding, knowledge, experience, and engineering judgment of FEA analysts play an important role in producing accurate simulation models.

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

- Optimize geometry for performance improvement, weight and strength
- Select materials that meet performance and budget requirements
- Simulate part failure and identify the loading conditions that caused them
- Assess extreme environmental conditions or loads not easily tested on physical prototypes, such as earthquake shock load
- Verify hand calculations
- Validate the likely safety and survival of a physical prototype before testing

3. Typical Simulation Modeling Process

Analysts usually follow distinctive simulation modeling processes:

- Build 2D or 3D CAD model to develop a virtual simulation model (digital prototype).
- Generate 2D or 3D FE mesh for analysis calculations. Analysts create structured meshes to maintain control over element quality.
- Define finite element analysis data (loads, constraints, or materials) based on analysis type (thermal, structural, or fluid). Apply boundary conditions to the model to represent how the parts are being restrained.
- Perform finite element analysis.

- Review results, and make design recommendations.

To ensure simulation model predictions are accurate and reliable, analysts must verify and validate the simulation model before making final design decisions. Baker Hughes' Liner Hanger FEA group developed a *seven-step methodology for verification and validation* of the virtual simulation model based upon extensive liner hanger analysis and laboratory correlation work.

4. Expandable Liner Hanger

The expandable liner hanger is a liner hanger system capable of hanging liner weight under extreme conditions thereby enabling wellbore construction during 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 1 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 1. Expandable Liner Hanger System

5. Seven-Step Methodology for Verification and Validation

Figure 2 shows a graphical representation of the seven-step methodology to verify and validate an expandable liner hanger virtual simulation model.

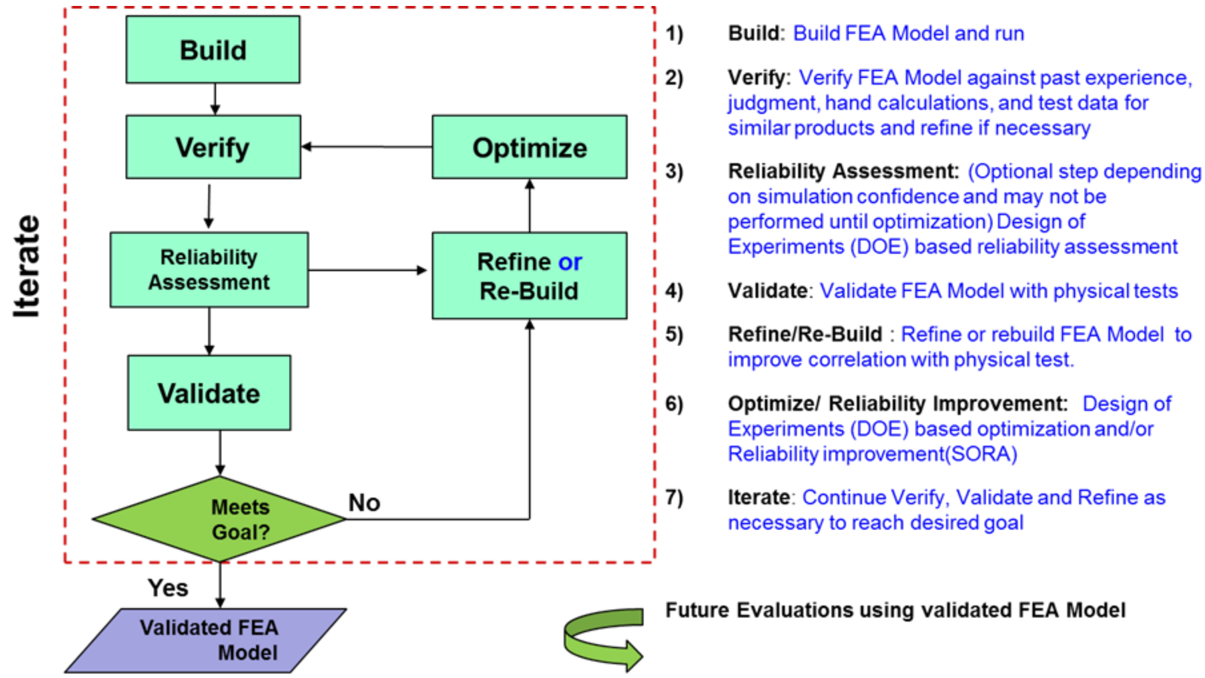


Figure 2. Seven-Step Methodology for Verification and Validation

The methodology begins by building an initial FEA model and verifying the model behavior with past experience, engineering judgment, hand calculations, and any previous test data for similar products. The model is refined as necessary. The next step includes performing the reliability assessment, optimization and iterates if analysts feel confident about the model's validity. Simulation model results are validated against physical prototype test data. Analysts progress back and forth between steps to build, verify, and validate data until results represent real behavior and obtaining high quality correlations with physical prototype tests. Simulation models may have to be refined or rebuilt to improve correlation and minimize error (with respect to physical test data).

Once a simulation model shows enough confidence, the analysts use model to optimize the design as necessary to meet the design goal and run reliability assessment to predict the reliability of design based on the identified design variables. The last step includes an iterative process whereby the analysts may have to repeat the steps multiple times until the simulation model accurately represent the physical behavior. Once the validated simulation model is prepared, further design evaluations and performance predictions are completed with confidence.

6. FE Model Building for Expandable Liner Hanger

The first step to build a good simulation model is ensuring accurate material models, realistic load and boundary conditions, proper considerations of effect of manufacturing processes on structure, and accurate geometry representation in the area of interest. 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. During setting of expandable liner hanger in well bore by application of hydraulic pressure, 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. This mechanical attachment hangs the hundreds of feet's heavy liner attached to the hanger body in down hole. The hanging capacity depends upon the slip ring design of the hanger packer assembly. The packer is squeezed in between the hanger body and the casing wall creating an annular, pressure-tight seal.

Figure 3 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 need of a refined mesh in slip wicker zone. Arbitrary Lagrangian-Eulerian (ALE) adaptive meshing maintains a high quality mesh in the area of large material deformation throughout the analysis. The large material deformation occurs because of slip ring wicker penetration into the casing and hanger body after expansion (as shown in Figure 4).

Modeling contact interactions was a challenge because friction values among swage segments, swage and the hanger body depends on coating, lubrication, material, surface finish, and heat treatment effects. Therefore, measuring friction for all the variations is often cumbersome and sometimes impractical. Abaqus/Explicit is used to run the analysis.

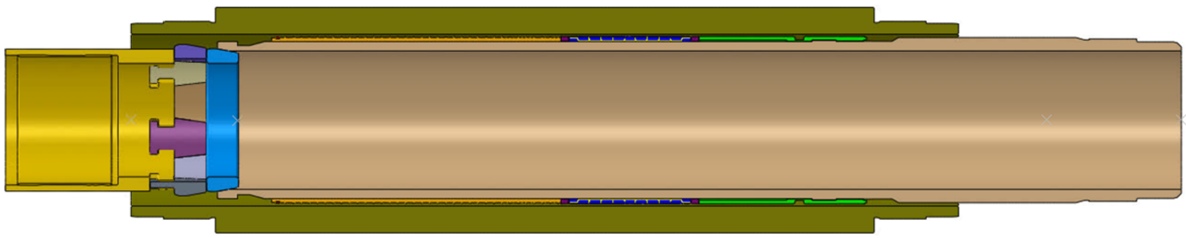
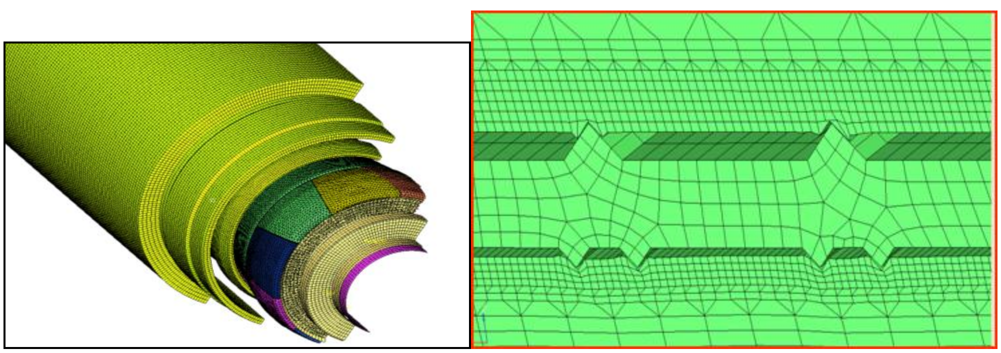


Figure 3. Finite Element Model before expansion



(a) **(b)**

Figure 4. FE Mesh illustration

7. Verification of Simulation Model

The next step is verifying the simulation model behavior with past experience, engineering judgment, hand calculations, and previous test data for similar products and refining the model if necessary. **Figure 5** represents the verification of a simulation model with hand calculation and past test data.

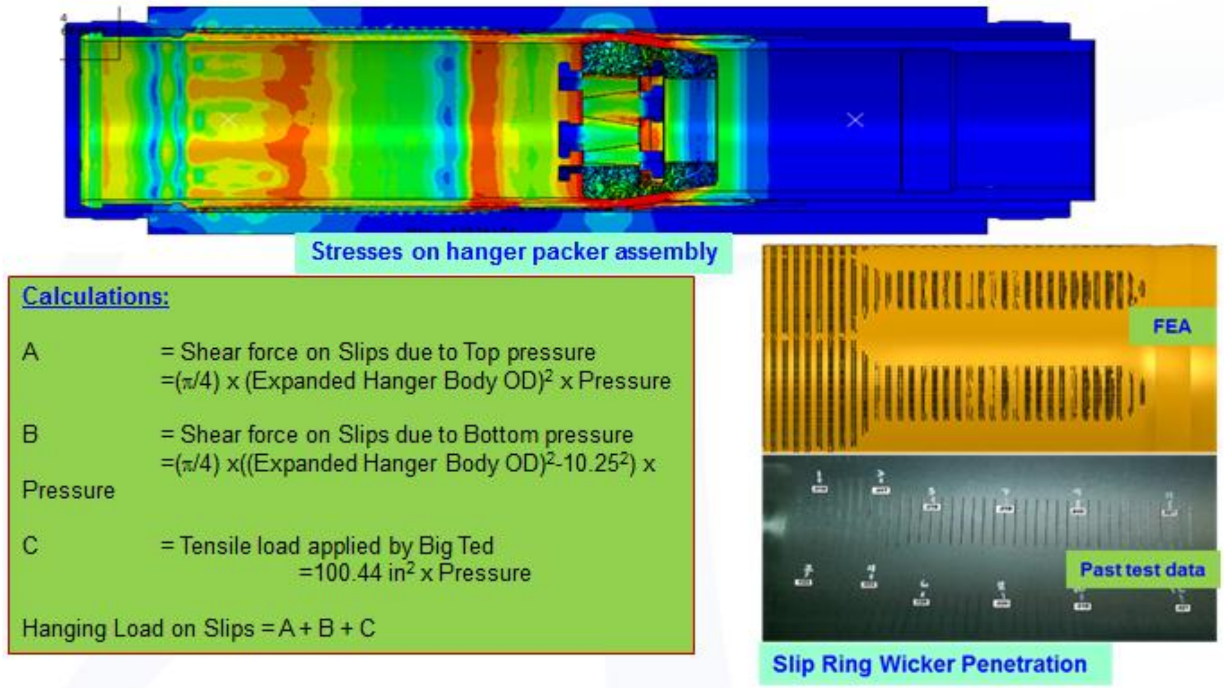


Figure 5. Simulation model verification

8. Initial Validation of Simulation Model

After verification, if there is not enough confidence in the simulation model, analysts can skip the optional step of reliability assessment and perform validation with the physical prototype. **Fig. 6** presents validation for a swage segment comparing the plastic deformation with actual deformation observed on the segment during a physical prototype test. The comparison shows deformation on the simulation model and the actual test part is very similar, is an indication of model validity. Hanging capacity results based on the simulation model are 25% higher than prototype test results (as shown in Figure 7). Therefore, the simulation model must be refined to correlate the hanging capacity more accurately. Friction, material properties, and casing conditions are factors which affect the hanging capacity.

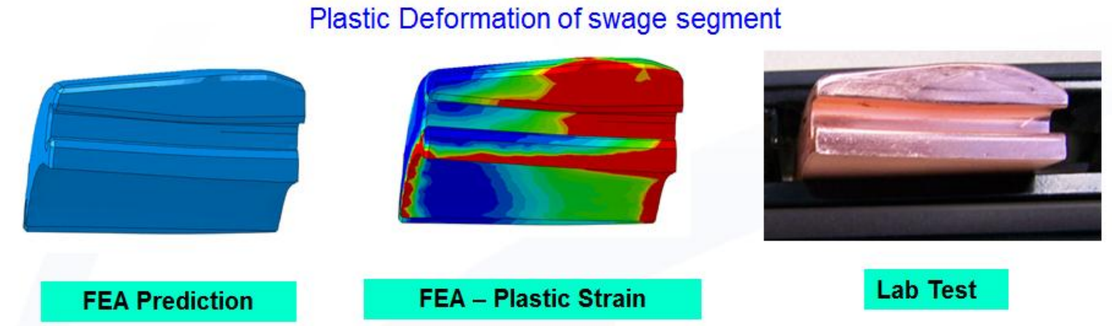


Figure 6. Plastic deformation of Swage Segment – initial test validation

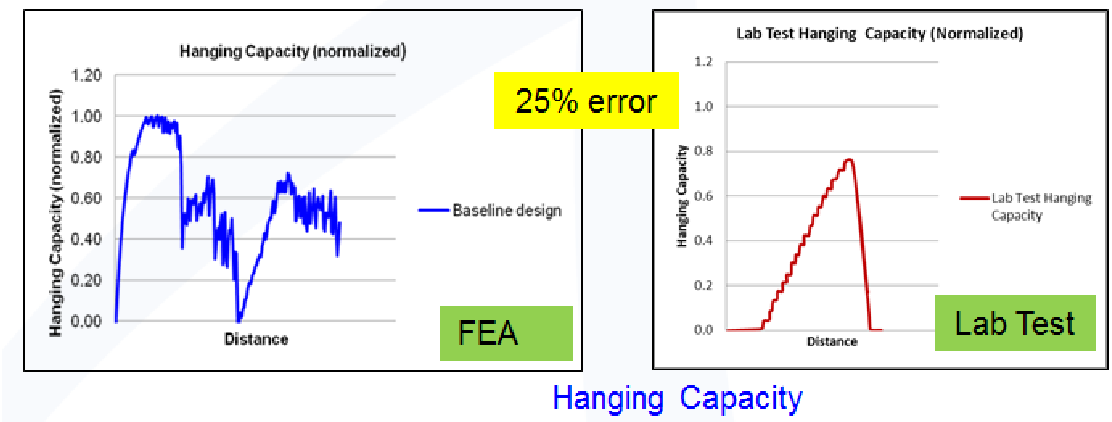


Figure 7. Hanging capacity - initial test validation

9. Refine or Re-Build Simulation Model

Analysts make certain assumptions very often regarding geometry, tolerances, material models, heat treatment affected zones, friction, environmental exposure, loading data, and constraints. Depending upon the system model interaction, each assumption can have significant effect on the predictions. In expandable liner hangers, diametrical tolerances and friction between various contact areas (especially between swage segments themselves and swage to hanger body) are important for representing the swage behavior correctly and reducing errors in predicting performance.

Analysts may have to refine the FEA model to improve correlation with physical test data to minimize error in simulation predictions. For expandable liner hangers, the FE model was refined with the necessary coefficient of friction between swage, hanger body, and swage segments to improve expansion force correlation with test data. **Figure 8** illustrates how significant the effect a slight change in friction values has on the expansion force.

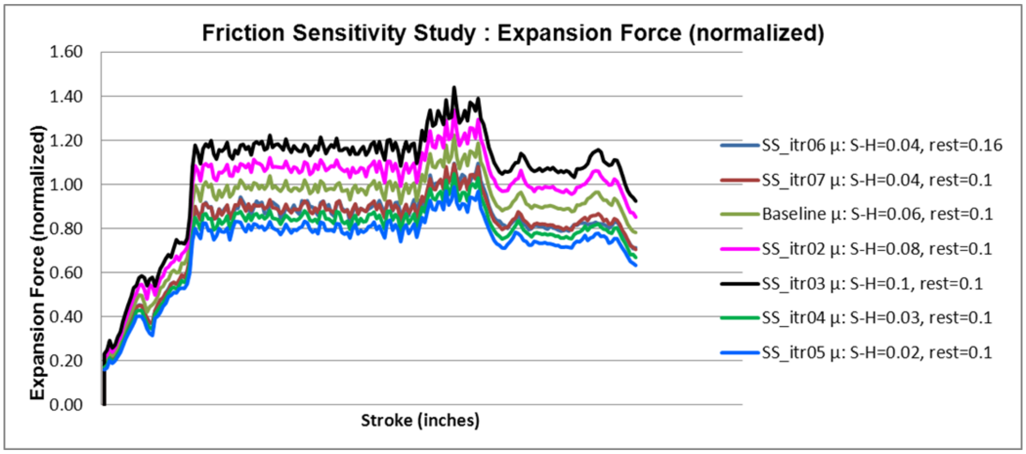


Figure 8. Effect of friction on expansion force

10. Reliability Assessment and Optimization

A reliability assessment can be performed early on the initial model, depending on how much confidence there is in the validity of the initial model. For expandable liner hangers, initial models are verified against known data and validation is done without performing reliability assessment. After refining FEA model, predictions were much closer to test data. The reliability assessment was performed on the baseline design to ensure it meets the reliability target. Hyperstudy software is used to perform reliability assessment. Reliability assessment process comprises performing Design of Experiments Study (DOE) based on identified design variables, and then performing the stochastic analysis using DOE based response surface to predict the reliability. **Figure 9** shows the sample response surface, variable distribution and reliability assessment. The baseline liner hanger slip design obtained 95% reliability which is lower than the target. Therefore, reliability-based design optimization (RBDO) can be performed to improve design reliability by optimizing design variables.

10.1 Computational Summary

Typical computational summary for an expandable liner hanger DOE study:

Model Size: 6.3 million elements; *number of design variables= 3 and levels* = 3
Number of DOE runs= 27 (Full factorial); *Cores per Analysis job* = 16 cores
Computational wall-clock time per analysis job: 26h:47m:40s; Memory: 12GB

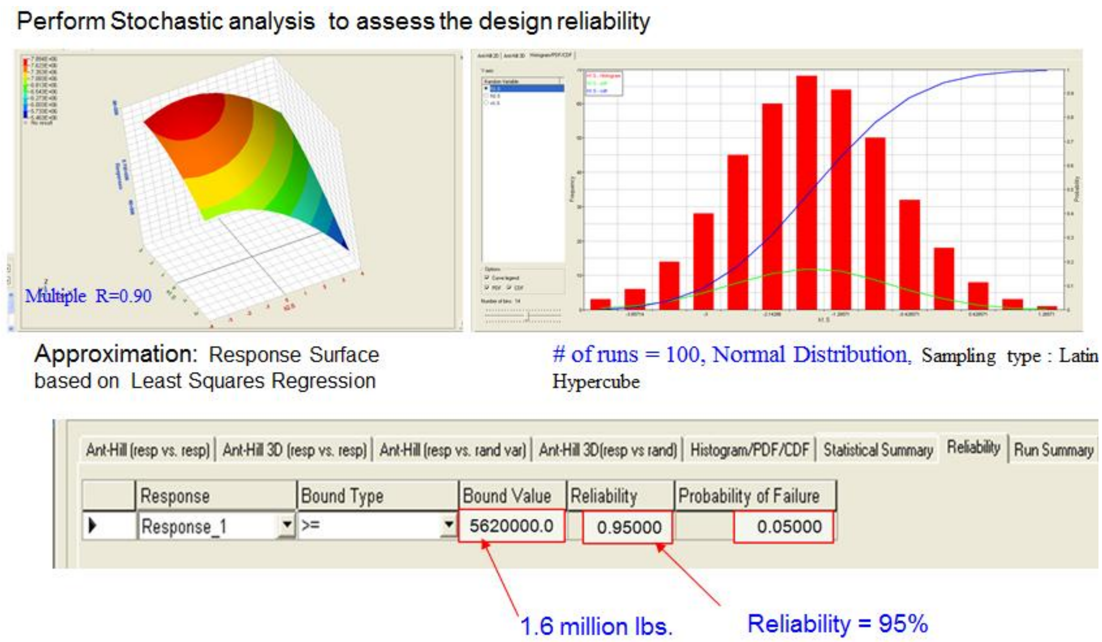


Figure 9. Reliability assessment

11. Iterate

The seven-step methodology for validation of simulation models is an iterative process and analysts sometimes repeat the steps multiple times (until the simulation model represents real physical behavior). When the validated simulation model is available, further design evaluations and performance predictions can be performed with confidence.

12. Final Validation- Examples

Figure 10 presents example of swage and backup ring simulation model validation results with test data. Local deformation mode on the swage and stress concentrations predicted by the simulation model are similar to the swage used in prototype test. Backup ring extrusion showed directionally similar behavior; however, tests showed softer behavior than FEA because the material model assumption for the thermoplastic backup ring. **Figure 11** shows the close correlation of setting forces for small and large size expandable liner hanger. The overall correlation of the Abaqus simulation model with test data was within 4% for most performance parameters (which was good enough to run future design evaluations using the validated virtual simulation model).

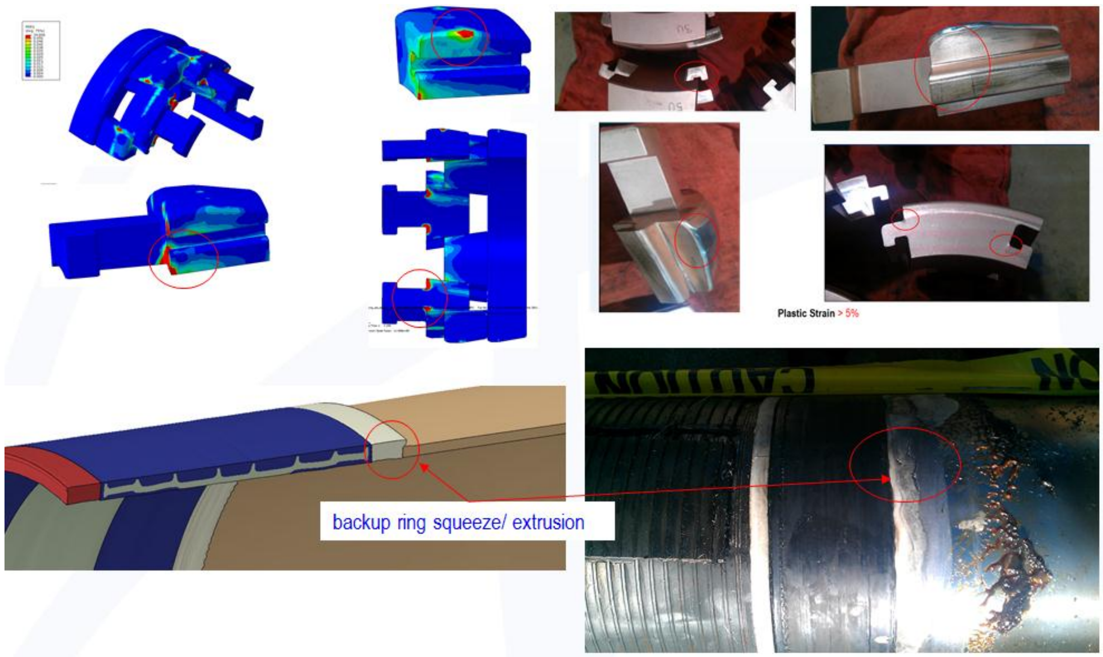


Figure 10. Validation of Swage and backup ring

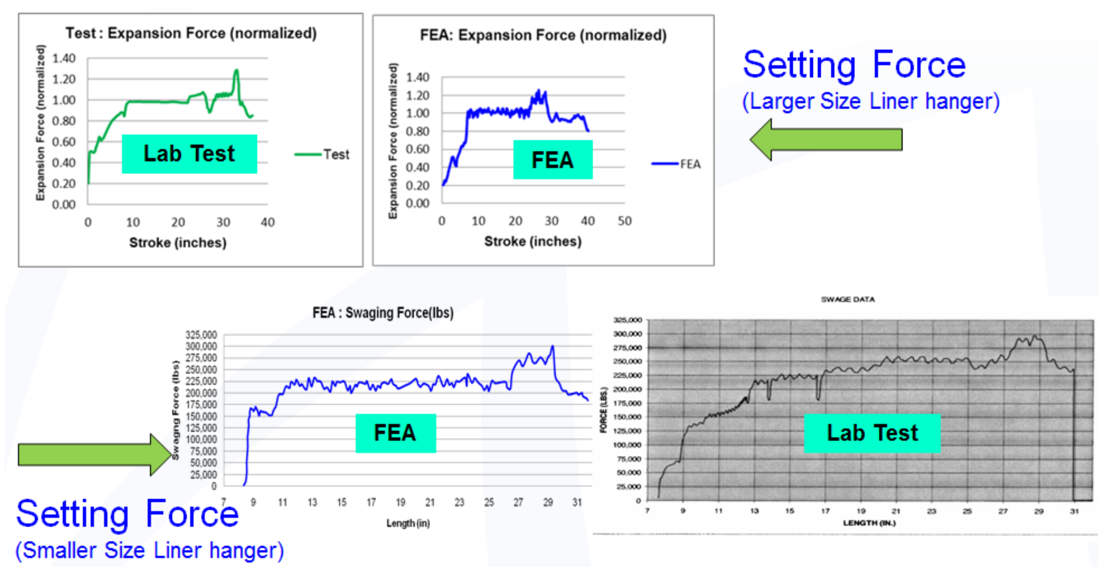


Figure 11. Validation of Setting (Expansion) Force

13. Conclusion

The seven-step methodology facilitated the study, optimization and investigation of the effects of various design parameters on the expandable liner hanger's performance. Despite modeling challenges, this iterative methodology was helpful in identifying proper friction values based on types of coating, grease and surface conditions. The seven-step methodology improved the reliability and robustness of expandable liner hanger design while reducing development time and cost. The numbers of prototype tests were reduced by 60% to70% and overall development time was reduced from 65 months to 26 months.

In summary, the seven-step validation methodology is useful as a guideline for the simulation community to apply simulated predictions with confidence to significantly reduce product development time and cost.

14. References

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15. Acknowledgements

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