Proceedings of Conference
ASME International Offshore Pipeline Forum
October 29-30, 2008, Houston, Texas USA

Paper No. IOPF2008-903

EVALUATING THE PERFORMANCE OF A PIPELINE PROTECTION SYSTEM TO PREVENT DAMAGE TO SUBSEA PIPELINES FROM DROPPED OBJECTS

Chris Alexander
Stress Engineering Services, Inc.
Houston, Texas
chris.alexander@stress.com

Larry Stubbs
Chevron
Houston Texas
aeek@chevron.com

Yesudas Manimala
Chevron Energy Technology Company
Houston Texas
ymanimala@chevron.com

Dan Spikula
Geoscience Earth & Marine Services, Inc.
Houston Texas
dspikula@gemsinc.com

ABSTRACT

One of the primary concerns for subsea pipeline involves damage from dropped objects. Using risk analysis modeling, it is possible to estimate the likelihood of impact, as well as the consequence of damage. Chevron Energy Technology Company, Stress Engineering Services, Inc. (SES) and Geoscience Earth & Marine Services, Inc. (GEMS) conducted a study to evaluate the effectiveness of a pipeline protection system (PPS) designed to protect a subsea 16-inch products pipeline off the coast of Angola in West Africa in approximately 400 feet of water beneath the South Nemba platform. The plan prior to the study was for platform upgrades to be made and concerns existed regarding the potential for dropped objects. Chevron specified that the PPS be designed to withstand a minimum impact of 3 MJ, with the possibility for extending this to 5 MJ if possible.

The work involved a combination of testing and analysis methods. Chevron developed the basic design of the PPS that included a large diameter upper (60-inch diameter) and a lower (72-inch diameter) half-pipe assemblies placed over the top of the 16-inch diameter pipeline. Preliminary analyses calculated the potential energy absorption capacity of the design considering variations in thickness of the PPS structural members. Using insights gained from the preliminary analysis, full-scale drop tests were performed on prototype PPS pieces fabricated from rolled and welded steel plate. These drop tests released a 23,850 lbs weight dropped from 25.2 feet, resulting in impact energies of 815 kJ. Significant deformation was inflicted to the PPS tests pieces during the drop tests; however, the 16-inch diameter pipe placed beneath the protection was untouched for all tests except the one that did not include the upper half-pipe shell.

Once the full-scale testing efforts were completed, finite element modeling was used to evaluate the PPS to soil interaction. The West Africa soil is rather compliant and concerns existed prior to the final phase of this study regarding the level of rigidity that could be expected from the soil. The ABAQUS Explicit finite element software was used to simulate impact with a dropped object having energy levels up to 5 MJ. Results showed that with contribution from the surrounding soil the system design, including the PPS pieces and the mud mats, can withstand impact energies of 5 MJ when the thickness of the upper shell is 1.25 inches. The results of this study demonstrate that the Chevron energy design requirement can be satisfied using the appropriate PPS design.

INTRODUCTION

This paper details findings from a study that was performed for Chevron to assess the performance capacity of a pipeline protection system for a 16-inch diameter products pipeline off the coast of Angola in West Africa [1] . This pipeline is located in approximately 400 feet of water and is beneath the South Nemba platform. Planned platform upgrades required that Chevron consider the effects of dropped objects on the integrity of the pipeline. The study had two principal aims. The first was to assess the energy capacity of a protection system, fabricated from rolled and welded steel plate, through testing and finite element modeling efforts. The second was to model the soil-structure interaction and determine if sufficient energy capacity existed to absorb 5 MJ.

A multi-phased approach was used to accomplish the principal aims of this study that included both analysis and testing work. **Figure 1** is a flowchart that shows the major phases involved in this effort. Readers are encouraged to note the details shown in this flow chart. Fundamentally, each successive phase of work provided information about how the system would respond to impact loading. Without this iterative phased approach, it is unlikely that this work could have been completed. A good example is how the initial quasi-static phase of testing demonstrated that the initial design did not have the rigidity required to absorb an impact load even equal to 1 MJ (much less the target 3 MJ to 5 MJ). Using these insights, the PPS design was modified and the next phase of testing generated favorable results.

It is appropriate in this portion of the paper to discuss the principal purpose for each phase of the study. Refer to the **Figure 1** flowchart for how each phase fits within the overall study. The testing efforts serve as a means for validating the analysis work. The experimental results served as benchmarks for how the PPS would respond relative to impact loading. Measurements such as displacement and load can be directly related to analysis results. It is also important to note that full-scale testing of a long assembly of PPS pieces is impractical due to the significant time and expense, as well as issues relating to the inclusion of West Africa soil; however, it is completely feasible to construct a finite element model that completely represents the actual protection system. By validating the response and behavior of the PPS under scaled loading conditions, confidence in the methodology and future results is achieved.

The use of finite element methods (FEA) is a central element of this study. The use of FEA permits an assessment of different PPS geometries (i.e. steel plate thicknesses and overall dimensions), as well as modeling interactions with soil and the mud mats placed beneath the PPS. The finite element models were also used to determine the energy absorbed by the respective PPS design. This was especially important for determining the length of the PPS required to withstand impact energies on the order of 3 MJ to 5 MJ. The dimensions of the mud mat required to support the impact load were an important variable of interest. The ABAQUS Explicit finite element code was used specifically to perform the dynamic assessment that included the soil (with time-dependant properties), PPS, mud mats, and pipeline. Animation files were created to show the overall response of the system subject to impact.

In addition to the work performed by SES, GEMS performed preliminary soil mechanics work in addition to performing impact testing to assess the mechanical response of soil. GEMS provided technical guidance and soil properties used in the finite element modeling work. The soil properties provided as a function of time (i.e. time-dependant properties) were critical for proper modeling of the PPS impact response and determining the maximum vertical reaction force on the soil along with the required mud mat area [2].

One of the important features of this study was the reliance on both analytical and experimental work. While finite element modeling provides a vehicle for studying the effects of a wide range of variables, the experimental results are used to validate the analysis findings. A good example is how the finite element model results were compared to the load-deflection data from the quasi-static crush tests. The comparison revealed that it is possible to model the response of the PPS subject to external loads that include the effects of soil-structural interaction.

This paper represents a volume of work spanning a seven month period. The *Background* section provides documentation on previous dropped object studies, an initial study performed by SES on dropped object protection schemes for Chevron, background information on work performed by GEMS on soil mechanics, and the Atkins [3] work on energies associated with the Nemba major lifts. The *Testing Efforts* section provides details on the purpose and scope of work, basic principles of testing, description of tests and measurements, and the corresponding results. The testing work performed by SES includes the quasi-static crush tests, full-scale dropped object tests, drop tests on PVC pipe, and compression crush testing to determine energy absorbed by the concrete mats. The *Analytical Efforts* section provides a brief introduction on limit analysis methods and how they were used to calculate impact energy by numerically integrating the finite element load-deflection curves. Included in this section are detailed discussions on the wide range of finite element models, including the initial quasi-static analysis, assessment of soil response, and the final analysis efforts that used ABAQUS Explicit to determine the dynamic response of the PPS in conjunction with the soil and mud mats in three dimensional space. The final sections, *Discussion* and *Conclusions*, detail how the overall study was used to design and optimize a pipeline protection system for the 16-inch products line.

BACKGROUND

Prior to starting the work that is reported herein, preliminary concepts for a pipeline protection system were developed. The assessment methodology used to determine the amount of energy that can be absorbed by a given structure are based on limit analysis. A finite element model with elastic-plastic material properties is loaded using either a controlled force or displacement. The response of the structure was recorded and the load-deflection data was numerically integrated to determine the work done on the structure. Due to conservation of energy and assuming minimum loss of energy during deformation (i.e. due to heat loss), the work done on the object is equivalent to the impact energy imparted to the structure. In this manner, the limit analysis method can be used to calculate the amount of energy absorbed by a structure during an extreme loading event such as impact with a dropped object.

Another significant body of work performed prior to this study was done by Atkins. Chevron contracted Atkins to determine the impact energy associated with a range of potential dropped objects from the upgrade of the South Nemba platform. Provided in **Table 1** are a summary of the energies associated with major Nemba lifts. **Figure 2** is a map showing the potential locations for dropped objects. Note on the lower left hand side of this figure the position of the pipeline. Protecting this pipeline is the focus of the present study.

In addition to prior studies using finite element limit analysis, work has also been performed using full-scale testing to capture both energy from applied static loads and dropped objects. Prior testing involved dropping 24,000 lbs from 30 feet to determine the impact energy capacity for a 12-inch flowline pipe. One of the insights gained from this previous study was the importance of making high speed measurements and taking high speed video (i.e. 2,000 frames per second) during testing. These insights were used in developing the full-scale test program for this study [4].

As will be demonstrated in this paper, the response of the soil during impact with the pipeline protection system contributes significantly to the amount of absorbed energy. GEMS performed a study based on classical mechanics to assess the response of the soil. Furthermore, sub-scale testing was performed to determine the response of dropped objects in soil for objects dropped from 15 feet into actual soil from West Africa. High speed data were recorded including acceleration and soil penetration.

TESTING EFFORTS

As discussed previously, the testing work was important to validate the modeling efforts. This relationship between testing and analysis is especially important considering that dynamic finite element modeling efforts are required to perform a complete assessment of the protection system that integrates the PPS members, mud mats, soil, and pipeline. Confidence in the analysis methodology is achieved using insights from the full-scale testing efforts. The testing program involved the following phases of work:

- Quasi-static tests involving compressive force loading applied to PPS pieces placed in a soil box.
- Full-scale drop tests involving a 23,850 lbs weight dropped from a height of 25.2 feet onto fabricated PPS test samples.
- Additional testing:
    - Compression tests on concrete blocks to assess the energy absorption of these members.
    - Small-scale drop tests on gel-filled PVC pipe originally considered for filling the space between the pipeline and the lower shell of the PPS.

The sections that follow provide specific details on the above phases of testing.

Quasi-static Compression Tests

SES constructed a load frame to permit testing 5-ft long PPS pieces fabricated from rolled and welded plate. **Figure 3** provides photographs of the vertical load frame that was constructed that was attached to an existing platform table used by SES on a previous project. As noted in these photographs, a wooden box was positioned at the base of the load frame to integrate soil response into the test program. This particular load frame was designed to generate 1 million lbs of compression load. Prior to construction of the load frame, Chevron provided drawings for the proposed PPS system. The original design was modified based on results from three different quasi-static tests, where less than favorable results from the first test.

Before providing specific details on the test program, a brief discussion is provided regarding the purpose of testing, basic principles of testing, and test set-up including measurements. At the beginning of the study, it was clear that full-scale drop tests would be required. However, it was realized from previous experience that one important piece of information missing from large scale drop tests was the ability to capture load-deflection data. The basis for this observation is the inability to obtain load cells that record loads exceeding 1 million lbs. In a prior study, SES performed drop tests involving a 150 lbs weight. Even this relatively small static load generated dynamic impact forces measuring 9,000 lbs. Using this same thought process, drops involving more than 20,000 lbs would necessitate load cells capable of measuring more than 1 million lbs and capable of withstanding extreme shock load conditions. <u>Therefore, one of the primary purposes of the quasi-static load test was to capture load-deflection data, which was numerically integrated to calculate the deflection energy. A secondary purpose was to capture the overall deflection of the PPS considering a vertical load that included soil-structure interaction.</u>

The quasi-static tests involved making measurements that included vertical displacement and compression load. **Figure 4** is a schematic diagram of the set-up for quasi-static tests that includes five displacement measurement locations. Measurements were made using potentiometer-based displacement transducers, along with a calibrated 2.5 million lbs hydraulic cylinder, and recorded using a computer data acquisition system. The following configurations were tested.

- Sample #1 (PPS original design).
- Sample #2 (PPS with only 72-inch lower shell).
- Sample #3 (PPS modified design with external gusset and removed internal gusset).

The last quasi-static test was performed using the modified PPS design having external gussets. The design for this test piece was modified by removing the internal reinforcing plate and adding external gussets to improve load transfer between the upper and lower shells and more fully engage support from the bottom support structure (i.e. W-sections).

Figure 5 provides photographs of the testing for Test #3, while **Figure 6** shows the load-deflection data for this particular test (as well as data included from a calibrated finite element model). An energy absorption level of 229 kJ was calculated from the compressive load-deflection data. As shown in **Figure 6**, minimal deflection occurred in the lower shell, while significant deformation occurred in the top shell. The success of this test was an important lead-in to the full-scale dropped object phase of work. It should also be noted that the results only considering loading a 5-ft long PPS test sample. Additional lengths would be expected to increase the PPS load capacity.

Full-scale Drop Tests

Using insights gained from the quasi-static tests and preliminary finite element work, efforts were focused on full-scale drop tests. The drop tests used a forging weighing 23,850 lbs dropped from a height of 25.2 feet (measured from top of the PPS to dropped object center of mass) resulting in an impact energy of 815 kJ. A photograph of the dropped object is shown in **Figure 7**. <u>The primary objectives of the full-scale drop tests were to demonstrate several important elements:</u>

- Confirmation that the energy capacity predicted by the finite element analysis was accurate.
- Demonstrate the failure mode associated with collapse of the upper shell and that the PPS had sufficient rigidity to withstand the imparted impact loads.
- Observe the soil-structure interaction and assess the level of residual deformation in both the soil and PPS after impact.
- Use high speed data acquisition to capture displacement (i.e. velocity) and acceleration as functions of time.
- Assess the overall benefit of the concrete mattress on energy absorption.

A total of four drop tests were performed. **Figure 8** provides a schematic showing the four different configurations. As noted, one of the test variables included location of impact relative to the internal reinforcing gusset. The four tests included the following configurations:

- Test #1 - Standard PPS with drop offset from gusset approximately 3 feet.
- Test #2 - Standard PPS with drop on top of gusset end.
- Test #3 - Standard PPS with concrete mat (drop at axial center).
- Test #4 - No upper shell PPS with concrete mat (drop at axial center).

Measurements played an important role in evaluating the overall response of the PPS design. Measurement devices included strain gages, displacement transducers, and accelerometers. **Figure 9** shows the location of the four displacement transducers. Also shown in this figure is the viewpoint used for the high speed video camera. From previous studies, SES knew the contribution that high speed video would have for assessing the overall response of the PPS test pieces to the impact loading. Studio Works of Houston, Texas was contracted to provide this service. High speed video was captured in digital format at a rate of 2,000 frames per second. This rate corresponds to a period of 0.0005 seconds for every captured image on the video. Digital video files (mpeg format) were produced after testing was completed that included a counter showing elapsed time during the period of impact.

Figure 10 provides a set of photographs showing the set-up for the full-scale testing. As shown, a gantry crane capable of lifting objects to heights up to 35 feet was used. The spacing between the gantry jacks was deemed sufficient to prevent contact with the dropped object after impact. The PPS test pieces were also oriented in such a way as to increase the likelihood that their post-impact response would direct them away from the gantry crane jacks.

Figure 11 through **Figure 14** provide photographs for Tests #1 through #4, respectively. The following observations are made in viewing the visual aspects of the drop tests:

- Tests involving the full PPS design (Tests #1, #2, and #3) demonstrate that the design had sufficient rigidity to prevent the prevent damage to the pipe.
- The PPS design without the upper shell (Test #4) clearly demonstrates the importance of the upper shell. Contact with the pipe was made in this test.
- The concrete mats act to distribute load to the overall PPS structure as shown in comparing the damage shown in **Figure 13** (Test #3) to **Figure 11** (Test #1).

One of the questions posed during the study concerned the velocity imparted to the upper shell at impact. The displacement data for Test #1 were post-processed to determine the calculated velocity. Results for this calculation are based on the plotted data in **Figure 15**. As noted, the calculated velocity over the first 0.040 seconds was 33 feet per second (fps). Considering a drop height of 25 feet, the velocity at impact was 40.1 fps. The calculated velocity of 33 fps is acceptable considering an instantaneous deceleration occurs once the dropped object impacts the PPS. Using this same procedure, SES calculated that the velocity of the lower shell to be 12.5 fps during initial impact and 7.6 fps during the subsequent deceleration as shown in **Figure 16**. Displacement and velocity results for the lower shell are also provided in this figure.

Based on these calculations, it is clear that different members of the PPS exhibit different velocities. The ability to delineate component velocities is important in terms of understanding the overall response of the PPS to impact loading. These results also show that different regions of the PPS absorb different percentages of the impact energy.

ANALYTICAL EFFORTS

Prior to starting work on this study, it was recognized that both testing and analysis would play an important role in evaluating the energy capacity of the PPS. The analysis work was used to assess the effects of different variables including geometry of the PPS (i.e. thickness) and time-dependant soil response. Addressing the effects of changes in these variables would be difficult to evaluate experimentally (and in some circumstances not possible), especially in terms of attempting full-scale drops up to 5 MJ. However, the items below relate to how test results were specifically used in conjunction with the analysis results.

- The quasi-static tests were useful in showing how the PPS deforms in response to vertical loading and support from the soil. Once several tests had been completed, finite element models were used to show how thickness increases in the upper and lower shells could increase the energy absorption capacity of the PPS.
- One of the important observations from testing was the progression of deformation during impact. The upper shell deforms first and displacement of the lower shell only occurs after appreciable deformation has taken place.
- Due to the magnitude of the full-scale drop tests, it was not possible to measure the actual impact load. However, the accelerometers provided insights as to the magnitude of impact force relative to the static weight of the dropped object. Additionally, the high speed data were used to show the duration of impact, which served an important role in validating the ABAQUS Explicit analysis results and that the initial peak impact occurs in a period not more than 0.20 seconds.

Provided in **Table 2** are the dynamic amplification factors, *f*, as functions of axial strain rate for the soil used in the ABAQUS Explicit models. It is noted that at the highest strain rate, a magnification factor of 1.5 is present. This implies that at an extremely high rate of loading, the soil has a yield strength that is 50 percent greater than at quasi-static loading conditions. To incorporate this rate dependency, a dynamic finite element model is required that loads the soil as a function of time. **Figure 17** is a schematic that shows the arrangement for the dynamic models.

Figure 18 is a contour plot from ABAQUS Explicit corresponding to impact energies of 3 MJ with a PPS having a 0.75-inch thick top shell. As noted in this figure, no contact with the pipe occurred for this PPS configuration. Building on the results from this model, an additional analysis was executed that evaluated impact energies of 5 MJ with the 0.75-inch thick top. **Figure 19** shows the results for this configuration in which contact between the dropped object, PPS, pipeline was made. **Figure 20** provides a series of plots showing force-displacement results for the dynamic FEA models that include the following configurations.

- 3 MJ with 0.75-inch top shell.
- 4 MJ with 0.75-inch top shell.
- 4 MJ with 1.0-inch top shell.
- 4 MJ with 0.75-inch top shell.

As noted in **Figure 20**, contact was made for the 4 MJ case with the 0.75-inch top shell and 5 MJ case with the 0.75-inch top shell. If the top shell thickness is increased to 1.0 inches, even with an impact energy of 4 MJ the PPS does not make impact with the pipeline and a resulting gap of 8.19 inches remains between the lower shell and top surface of the pipeline.

The final series of ABAQUS Explicit dynamic finite element analyses verified that the optimum thickness for the upper and lower shells is 1.25 inches and 1.00 inches, respectively, for the 5 MJ case. Under these conditions, the pipeline is protected from the respective impact energy levels.

Table 3 provides a summary of the results associated with the above list. As noted, the maximum capacity of the current PPS design is achieved by increasing the upper shell thickness to 1.25 inches. The maximum impact energy of 5 MJ occurs with an increase in the upper shell thickness and results in a space between the lower shell and top of the 16-inch pipeline equaling 6.34 inches. Also included in **Table 3** are the stresses in the upper and lower shells extracted at Locations 1 and 2 taken at 0.30 seconds. Correspondingly, **Table 4** provides displacements for each of the six load cases extracted from the finite element models. Note that Load Cases 2, 3, and 6 are for conditions where contact between the lower shell and 16-inch diameter pipeline occurred.

DISCUSSION

Results have been presented for the experimental and analytical phases of this dropped object study. In completing the desired objective of developing a pipeline protection system, the following recommendations are provided in relation to the final design of the system.

- The structural requirements for the PPS require that the system possess the ability to absorb up to 5 MJ of energy. As shown from the dynamic analysis work, at this energy level an impact force on the order of 1.6 million lbs is expected. Another important requirement concerns the ability of certain sections of the PPS to collapse without actually making contact with the pipe during impact. The use of both an upper and lower shell provides an effective means for satisfying this design requirement.

- In terms of actual geometry of the PPS, the diameters of the upper and lower shells (as designated by Chevron) were selected to be 60 inches and 72 inches, respectively. The ABAQUS Explicit dynamic finite element analysis verified that the optimum thicknesses for the upper and lower shells are 1.25 inches and 1.00 inches, respectively, for the 5 MJ case.
- The mud mats considered in the analysis were 12 feet wide, 20 feet long, and 8 inches thick. The surface area associated with the geometry of these mud mats proved to be acceptable with sufficient capacity to support the peak impact force.
- If the maximum impact force is imparted to a connection between two adjacent PPS sections, the eight (8) connecting pins can be expected to experience 1.6 million lbs for the 5 MJ case. This corresponds to a shear stress of 15.9 ksi considering force divided by cross-sectional area. If 100 ksi yield material is used to fabricate the pins, this shear stress state is acceptable.
- From the ABAQUS Explicit FEA model considering Case 3 (5 MJ with 0.75 inch top), the membrane stress in the pins was calculated to be 6.2 ksi, while the membrane plus bending stress was computed to be 10.9 ksi. These results consider the total response of the system including the mud mats, soil, pins, and contact interaction between the PPS pieces.

CONCLUSIONS

This paper has provided details on the testing and analysis work performed to evaluate the energy capacity of a pipeline protection system for a 16-inch products line. The intent was to develop a protection system that prevented significant damage from being imparted to the pipeline during a dropped object event.

Initial efforts focused on quasi-static and full-scale drop tests. The intent was to develop a greater level of understanding on the level of energy absorption afforded by the PPS and supporting soil. The PPS design utilized a top shell that sacrificially deformed, while a lower shell prevented contact with the pipeline (internal to the PPS). The full-scale drop tests demonstrated the effectiveness of this design based on the observed deformation. Additionally, instrumentation used during the full-scale testing phase revealed that different portions of the PPS had different velocities, indicating that certain regions of the PPS were absorbing different levels of energy than others. Although significant insights were gained during the course of the testing phases, important questions were raised regarding the capacity of the soil to provide sufficient rigidity for the potential impact loads. To address these concerns, numerical modeling using finite element analyses were conducted.

The analysis phase of this study involved both quasi-static and dynamic modeling techniques. Initial analysis efforts considered geometry variations (primarily wall thickness changes in the upper and lower shells) on the energy absorption capacity of the PPS design. After having developed some understanding about the mechanics of deformation and energy capacity, follow-on efforts focused on the contribution of soil. A two-dimensional plane strain model demonstrated how soil along the length of the pipeline engaged to provide resistance to impact. Building on this insight, a detailed three-dimensional finite element model was constructed to assess the dynamic response of the system. This model used ABAQUS Explicit and integrated contact surfaces and time-dependant soil properties where elevated strain rates induced greater rigidity in the soil. Significant insights were gained as a result of this modeling effort. The model showed that the current PPS design has the capacity to absorb up to 3 MJ of energy and not make direct contact with the pipeline. A subsequent analysis considering impact energies of 5 MJ with an increase in the upper shell thickness from 0.75 inches to 1.25 inches showed that it is possible to achieve greater energy levels. Unlike the previous analyses that considered an upper shell thickness of 0.75 inches, this particular analysis demonstrated that by optimizing the thickness of the upper shell, greater impact energies can be achieved. Due to limitations on the size of the mud mat, it is not possible with the current geometry to achieve energy levels on the order of 6 MJ as loads are transferred to the pipeline due to contact between the PPS and pipe.

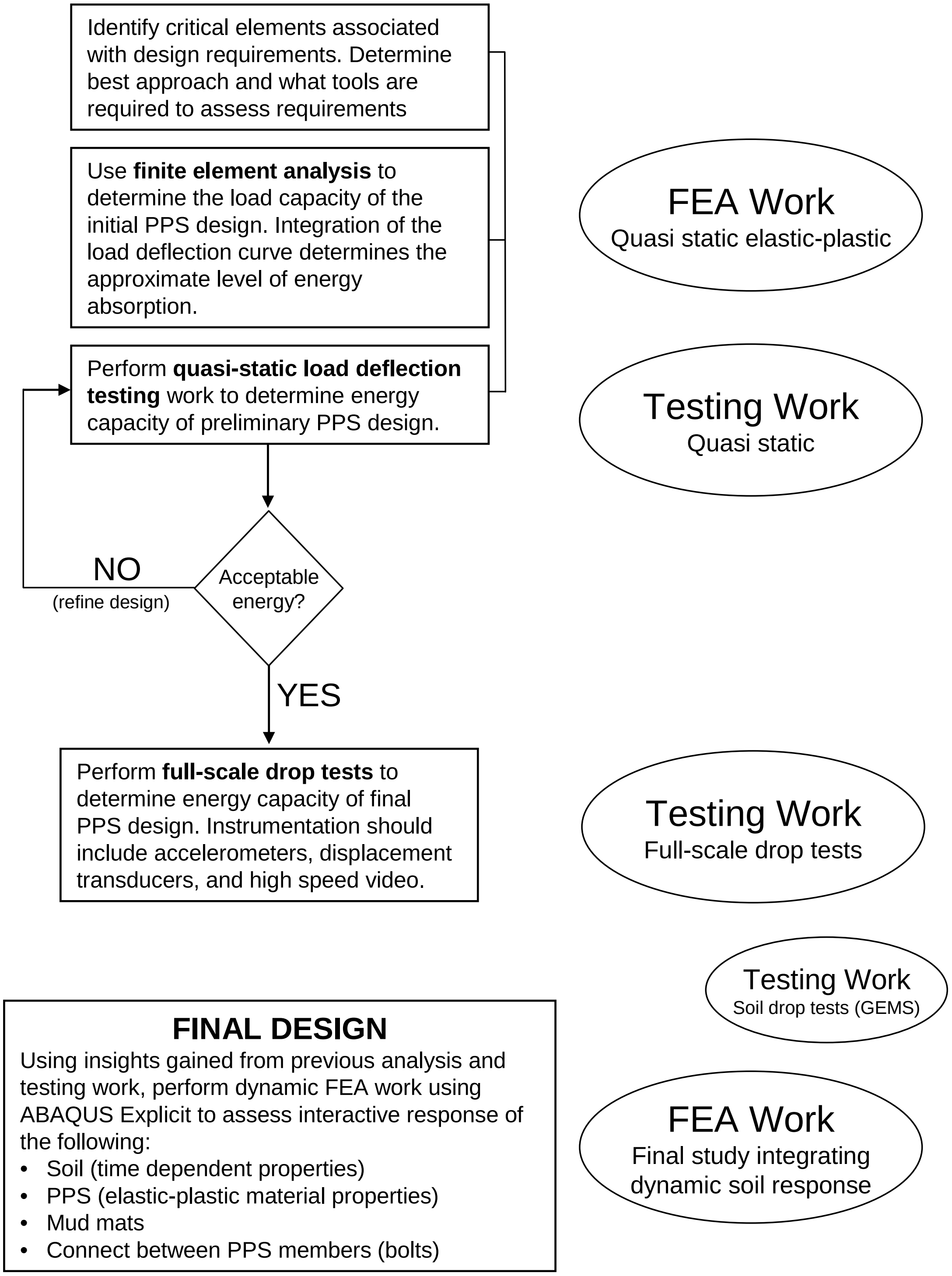
The primary conclusion from this in-depth study is that a properly-designed pipeline protection system can prevent damage to a subsea pipeline considering impact energies up to 5 MJ. This conclusion is predicated on several important observations:

- The properties of the soil are based upon data provided to SES by GEMS.
- A sufficient mud mat area must be present to resist the impact load.
- The thickness of the top shell must be at least 1.25 inches. Increasing the thickness of the top shell beyond this value does not guarantee an increase in energy capacity as there are limitations on what the soil can absorb.

REFERENCES

1. Alexander C.R. et al, *Study to Assess the Performance of a Subsea Pipeline Protection System*, SES Report to Chevron Energy Technology Company (SES PN116307CRA), Houston, Texas, October 2007.
2. Spikula, D.R. et al, *Geotechnical Study of a Pipeline Protection System*, Project No. 0107-1287, October 19, 2007.
3. *South Nemba Subsea Dropped Objects Risk Assessment*, Atkins Doc. No.: OG002-07-RPT-002, July 2006.
4. Alexander, C.R., *Assessing the Effects of Dropped Objects on Subsea Pipelines*, Paper No. IOPF2007-110, Proceedings of the ASME International Offshore Pipeline Forum, October 23-24, 2007, Houston, Texas.

Assessment Process



Identify critical elements associated with design requirements. Determine best approach and what tools are required to assess requirements

Use **finite element analysis** to determine the load capacity of the initial PPS design. Integration of the load deflection curve determines the approximate level of energy absorption.

Perform **quasi-static load deflection testing** work to determine energy capacity of preliminary PPS design.

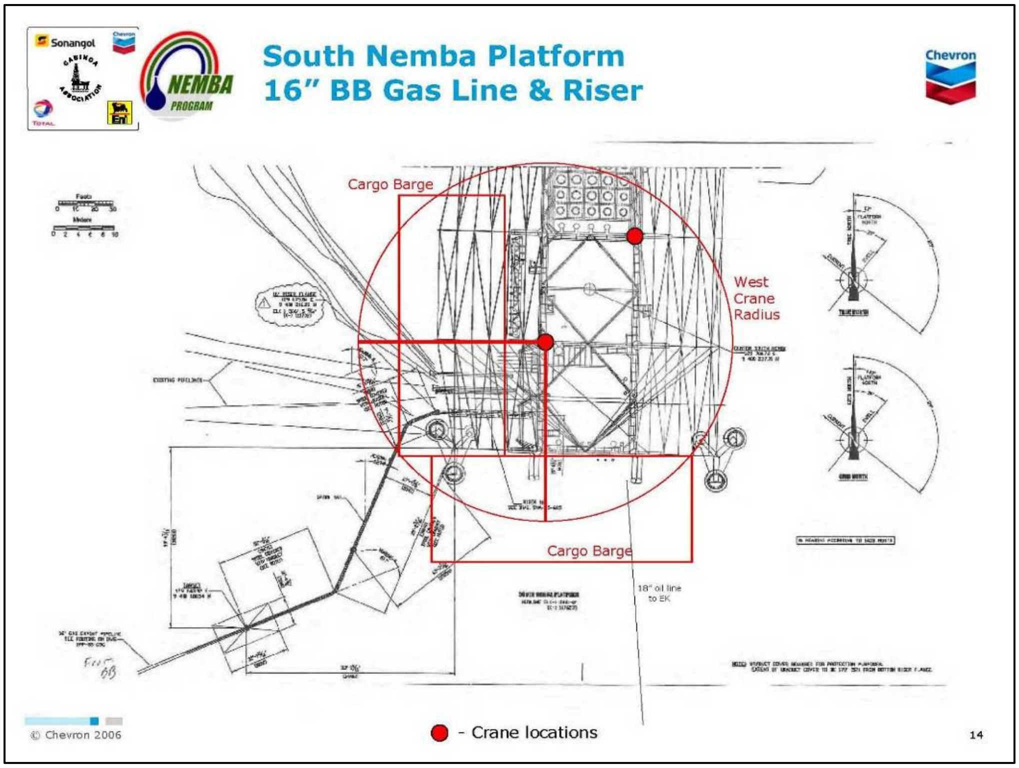
Perform **full-scale drop tests** to determine energy capacity of final PPS design. Instrumentation should include accelerometers, displacement transducers, and high speed video.

FINAL DESIGN

Using insights gained from previous analysis and testing work, perform dynamic FEA work using ABAQUS Explicit to assess interactive response of the following:

- Soil (time dependent properties)
- PPS (elastic-plastic material properties)
- Mud mats
- Connect between PPS members (bolts)

Figure 1 – Flowchart showing phases of study



South Nemba Platform

16" BB Gas Line & Riser

● - Crane locations

14

Figure 2 – Map showing layout of potential drop zones

Figure 3 – Photographs showing vertical load frame

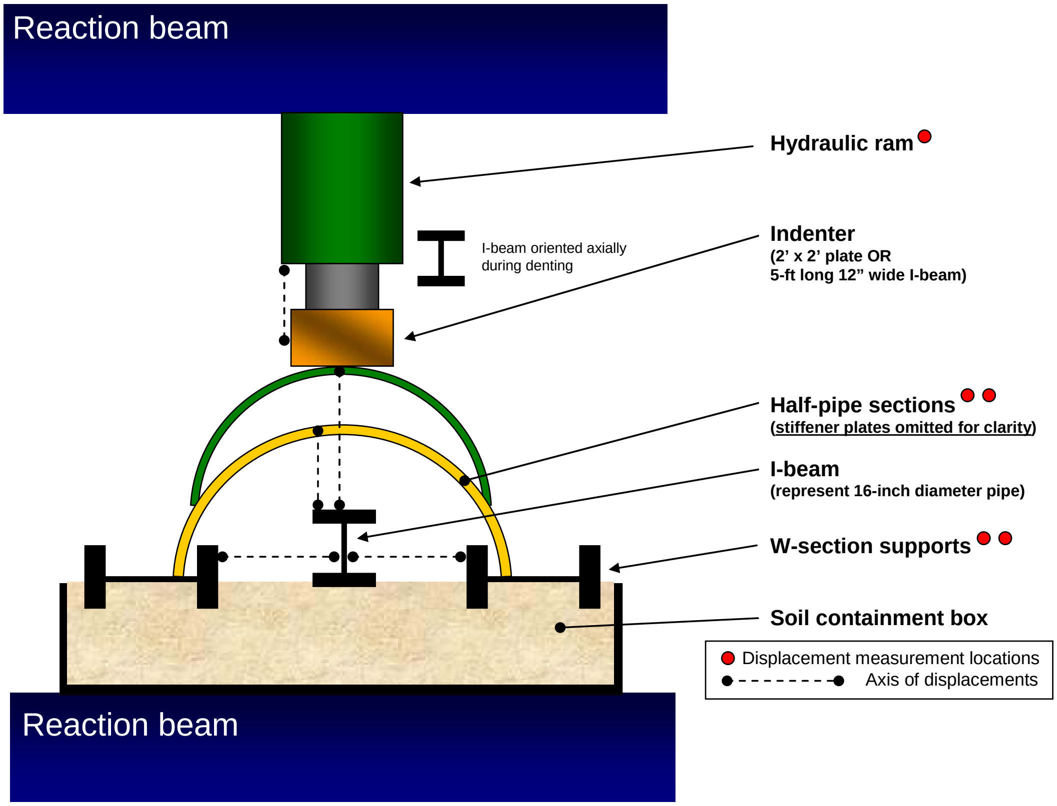


Figure 4 – Schematic diagram showing set-up for quasi-static tests
(reinforcing gussets not included in drawing for clarity of presentation)

Figure 5 – Photograph from Test #3 (before and after testing)

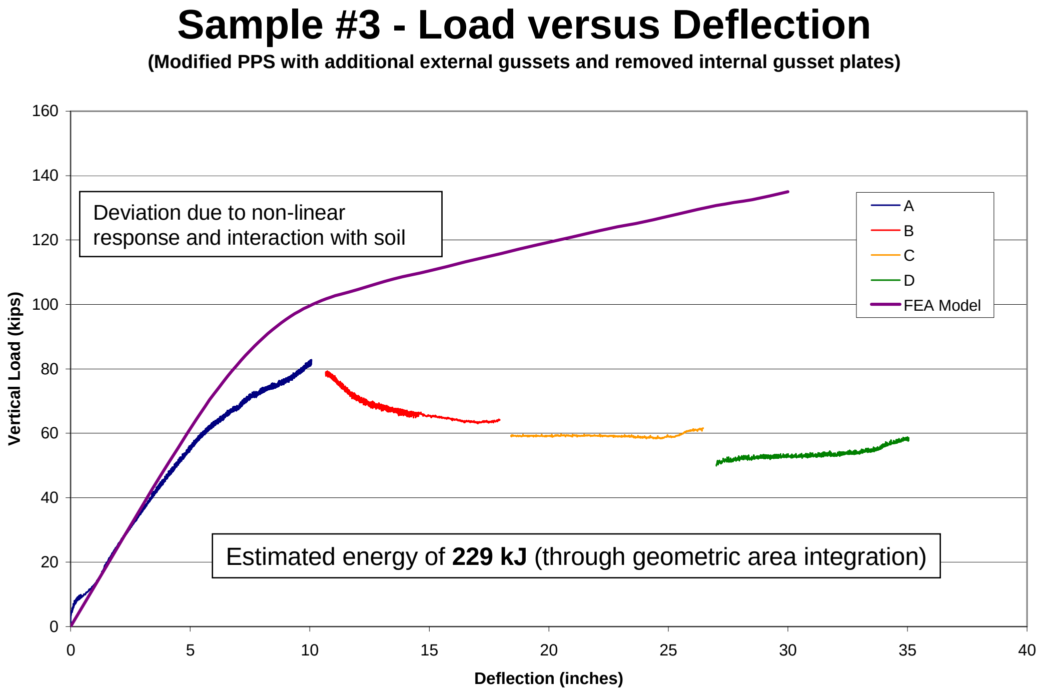


Figure 6 – Load versus deflection for quasi-static Test #3
(different colors in plot represent subsequent loading phases during testing)

Figure 7 – Photograph of weight serving as dropped object

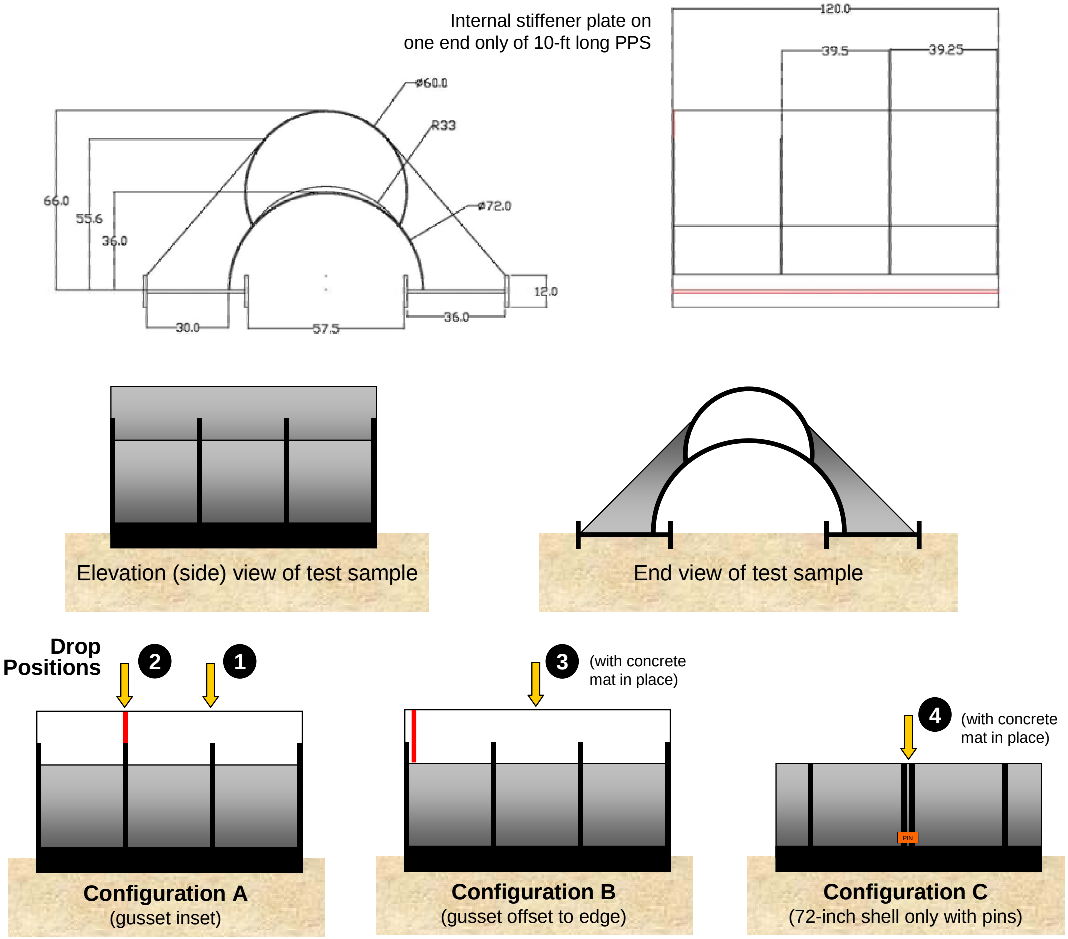


Figure 8 – Schematic diagram showing four drop test configurations

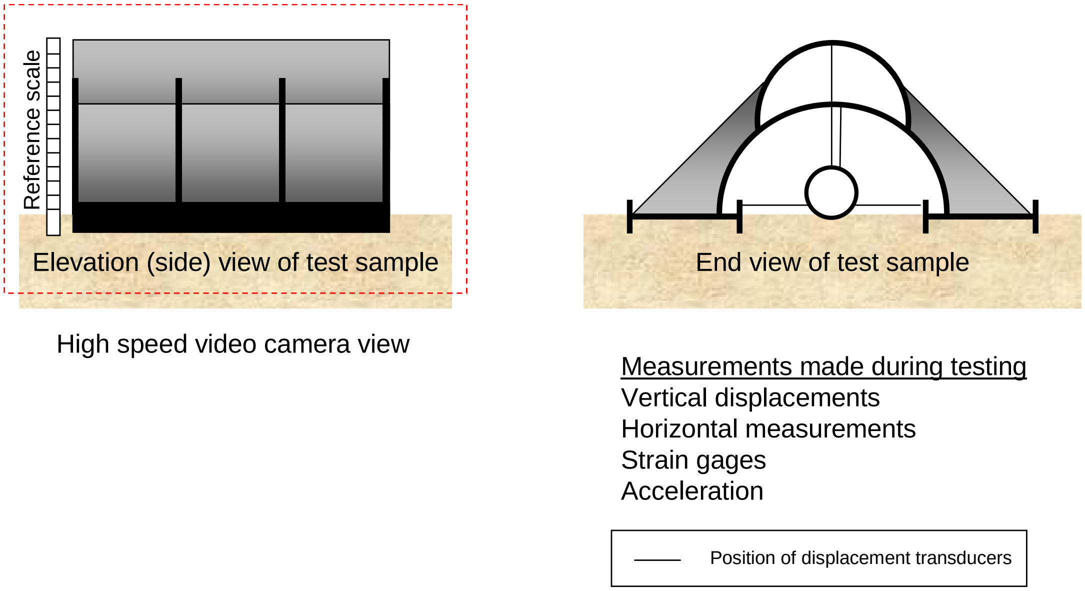


Figure 9 – Measurements devices used in full-scale drop testing

Figure 10 – Photographs of full-scale drop test set-up

Figure 11 – Photographs from Test #1 drop test

Figure 12 – Photographs from Test #2 drop test

Figure 13 – Photographs from Test #3 drop test

Figure 14 – Photographs from Test #4 drop test

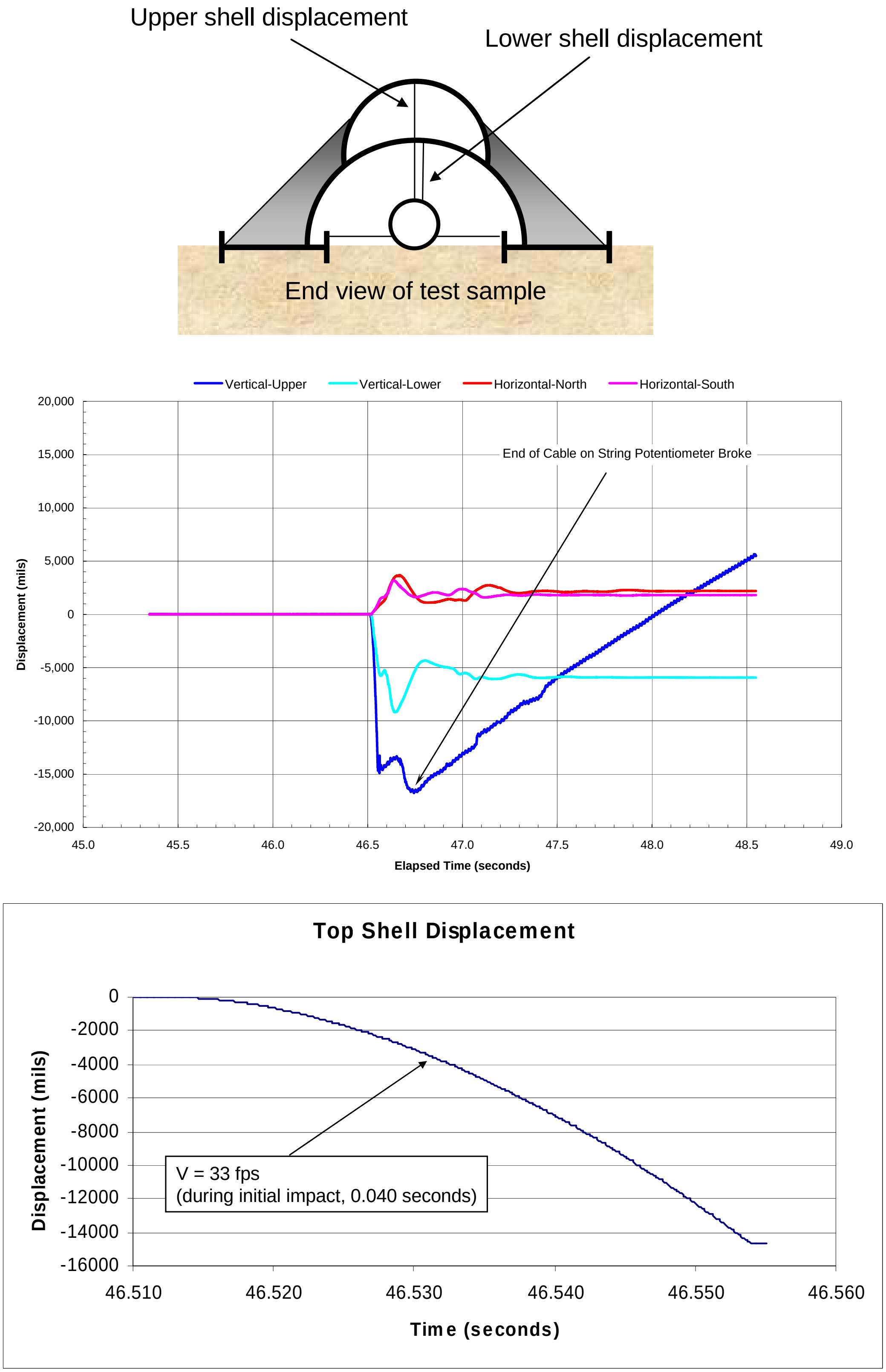


Figure 15 – Velocity of top shell based on displacement measurements for Test #1

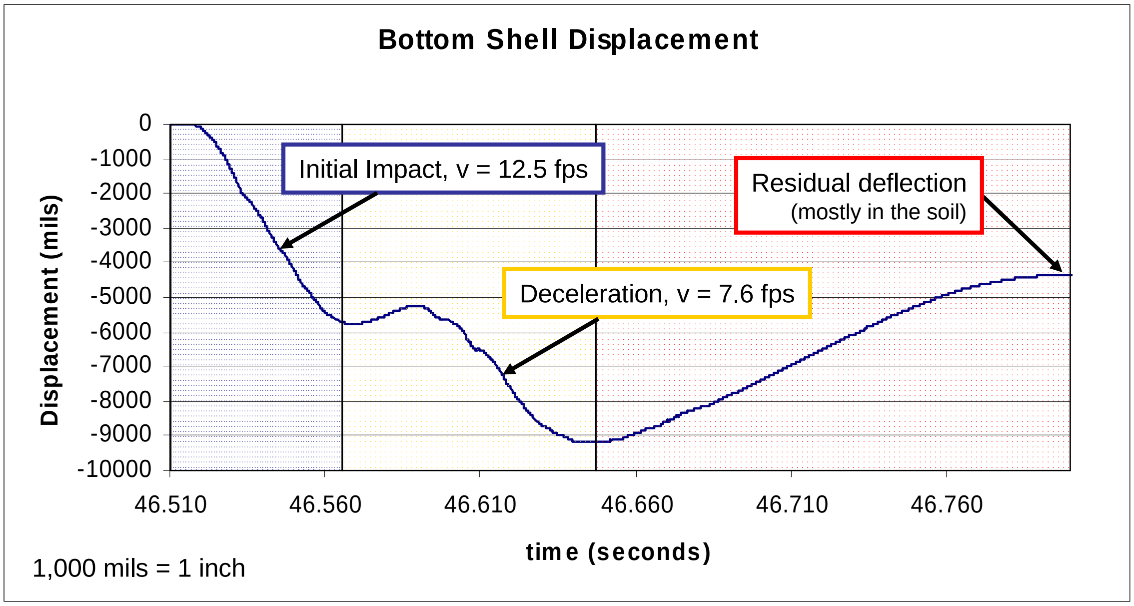


Figure 16 - Velocity of lower shell based on displacement measurements for Test #1

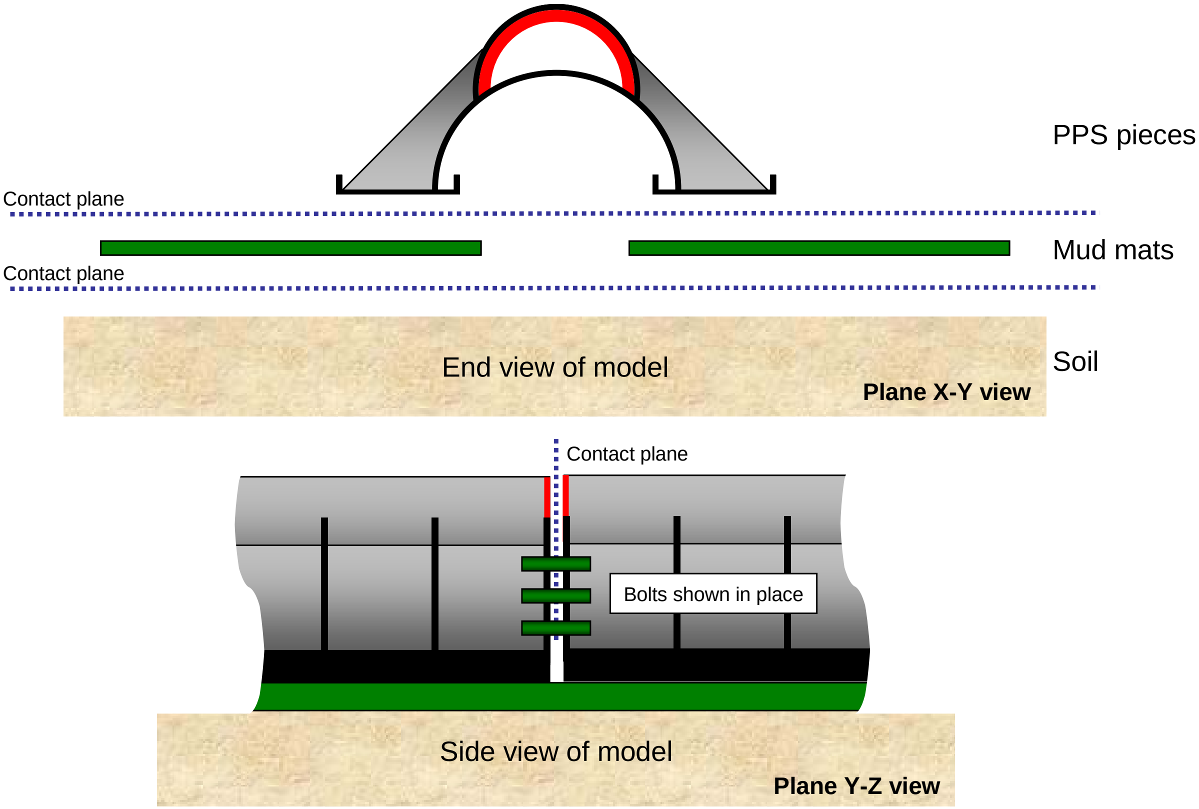


Figure 17 – Arrangement of contact surfaces for dynamic ABAQUS Explicit models

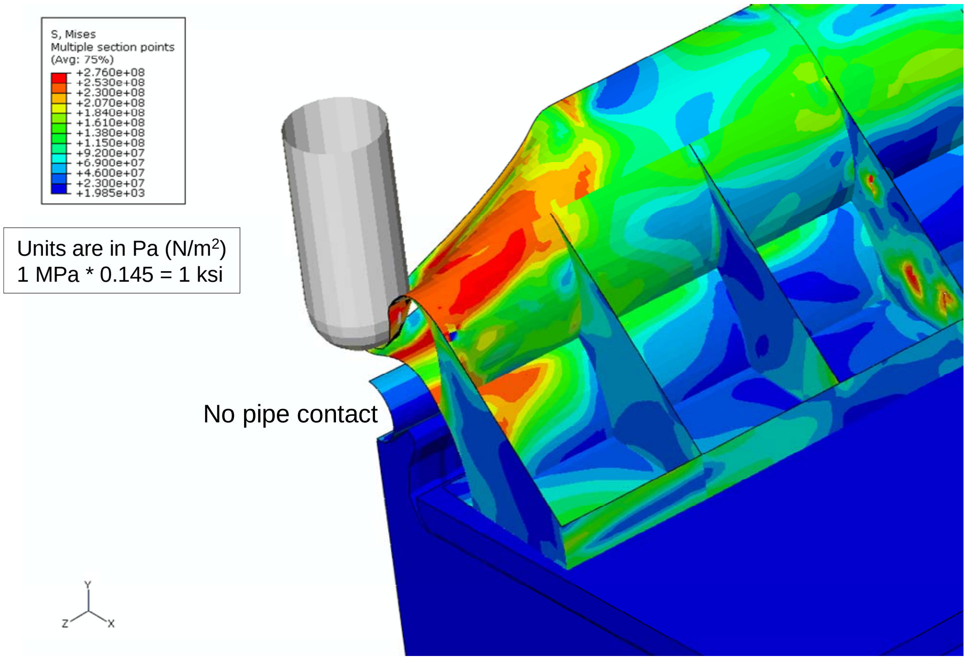


Figure 18 - 3 MJ with 0.75-inch thick top shell with no pipe contact

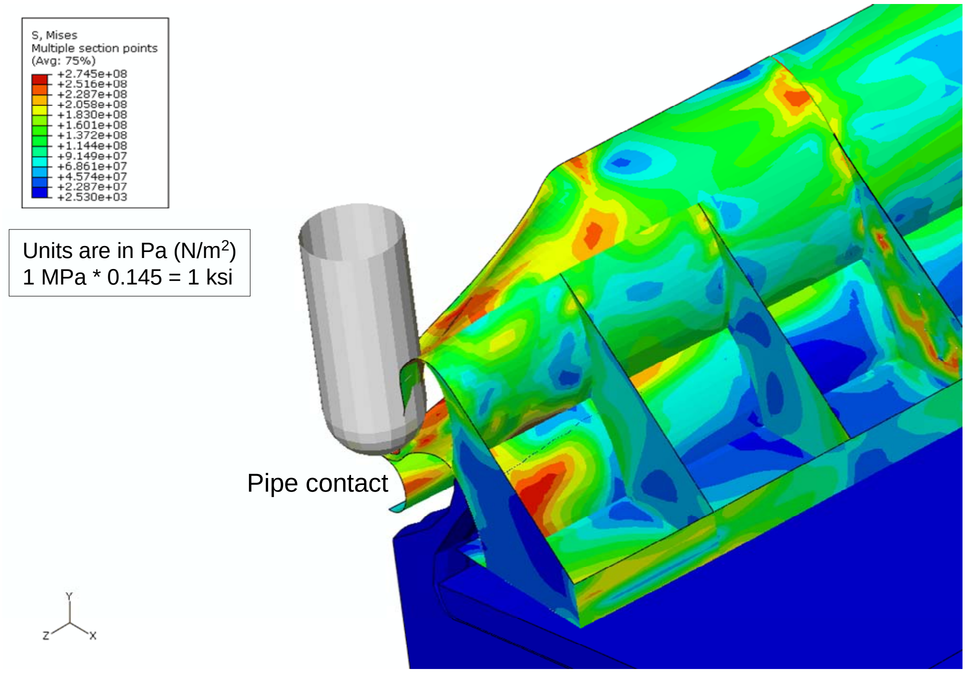
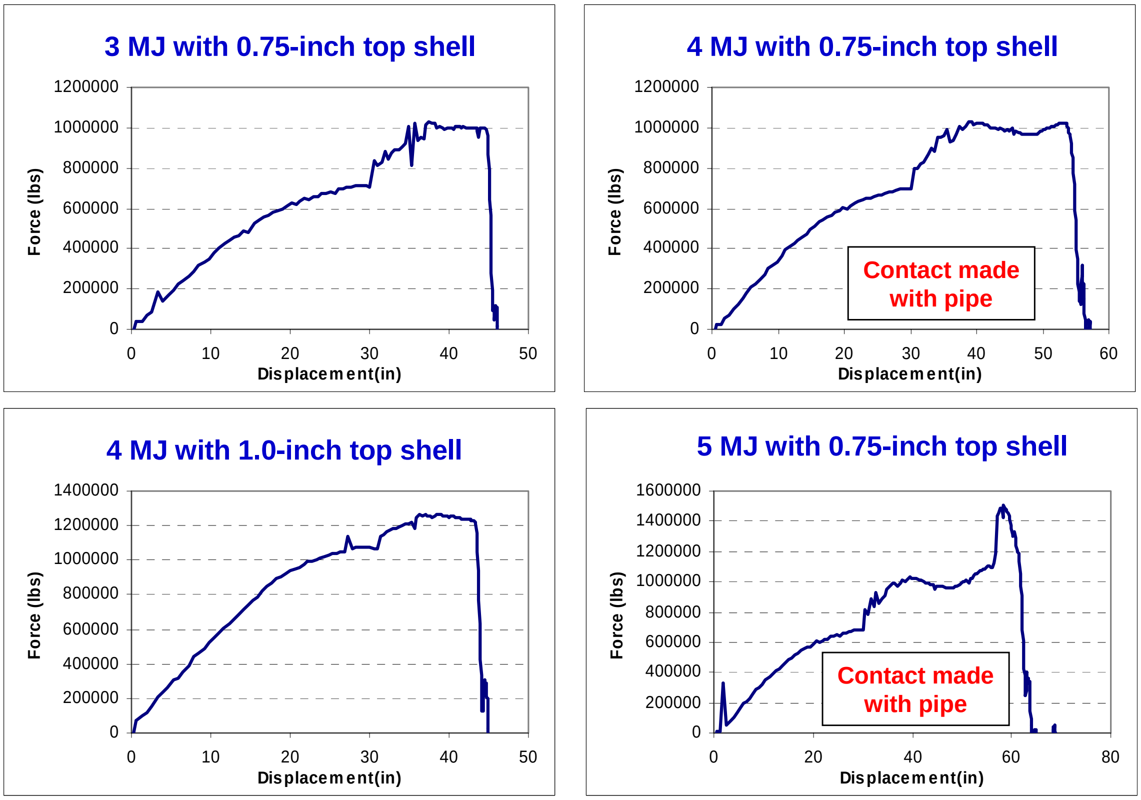


Figure 19 - 5 MJ with 0.75-inch thick top shell with pipe contact


3 MJ with 0.75-inch top shell

4 MJ with 0.75-inch top shell

4 MJ with 1.0-inch top shell

5 MJ with 0.75-inch top shell

Figure 20 – Summary force-displacement results for dynamic FEA models

Table 1 - Nemba Major Lifts and Dropped Object Energies

Lift No.	Item	Weight (lbs)	Reference in Lift Manifest Tables	Impact Energy (kJ)	Reference in Imact Energy Tables
1	HPC Filter Separator	145000	Hazid No. 3.3 in Table 3.3	4077	Hazid No. 3.3 in Table 4.3
2	Helideck Lifts	180000	Hazid No. 1.10 & 1.16 in Table 3.3	5446	Hazid No. 1.10 & 1.16 in Table 4.3
3	New Glycol Regeneration Package	200000	Hazid No. 3.10 in Table 3.5	7720	Hazid No. 3.10 in Table 4.5
4	Existing Quarters Building	500000	Hazid No. 4.1 in Table 3.3	22351	Hazid No. 4.1 in Table 4.3
5	Existing Contactor	200000	Hazid No. 2.4 in Table 3.3	27234	Hazid No. 2.40 in Table 4.3
6	ESR Module	4600000	Hazid No. 6.1 in Table 3.6	300000	Hazid No. 6.1 in Table 4.6

Table 2 – Soil dynamic amplification factors

Axial strain rate, %/hr	Ratio of undrained shear strength to undrained shear strength at a strain rate of 1 %/hr
0.00001	0.970
0.5	0.970
1	1
10	1.1
100	1.2
1000	1.3
10000	1.4
100000	1.5

Table 3 – Effects of upper shell thickness on impact response of PPS

Load Case	Impact Energy	Lower Shell Thickness	Upper Shell Thickness	Position of Lower Shell Relative to Pipe	Location 1 (ksi)	Location 2 (ksi)
1	3 MJ	1.00 inches	0.75 inches	8.87 inch gap	31.8	30.5
2	4 MJ	1.00 inches	0.75 inches	No gap (contact)	38.4	28.4
3	5 MJ	1.00 inches	0.75 inches	No gap (contact)	33.6	23.5
4	4 MJ	1.00 inches	1.00 inches	8.19 inch gap	38.0	33.1
5	5 MJ	1.00 inches	1.25 inches	6.34 inch gap	37.1	30.3
6	6 MJ	1.00 inches	1.25 inches	No gap (contact)	30.7	14.2

Table 4 – Displacements of locations in PPS after impact

Load Case	Location 1 (inches)	Location 2 (inches)	Location 3 (inches)	Location 4 (inches)	Location 5 (inches)	Location 6 (inches)
1	-47.4	-19.1	0.1	0.1	-17.9	-3.7
2	-57.3	-29.0	-0.9	-0.9	-7.6	-3.0
3	-69.3	-41.2	-12.5	-12.5	-33.4	-5.7
4	-46.5	-18.2	1.6	1.6	-21.2	-4.4
5	-50.6	-22.3	-0.7	-0.7	-37.0	-9.8
6	-57.2	-28.9	-1.3	-1.3	-40.4	-9.1

Notes:

1. Highlighted ROWS correspond to cases where contact was made between the lower shell and pipe.
2. Refer to figure below for location of extracted displacements.
3. Differences in displacements at Locations 5 and 6 indicative of mud mat rotation.