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Inherently Safer Design for Process Plant Piping and Equipment Exposed to Accidental Explosion Loads

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Abstract
Recent statistics have indicate that it is not uncommon to have an accidental explosion on an offshore platform. The design and assessment of process piping systems against blast events are of importance and require advanced analysis capabilities. They are important because during an explosion rupture of a piping and vessel system leads to the leakage or release of hydrocarbons which will likely cause another explosion or fire, and can eventually leads to a disastrous event. On an offshore platform where availability of escape, shelter, and evacuation is limited, the consequences are worse because explosion escalation into severe scenarios can have more detrimental effects in addition to direct damages such as injuries, fatalities and asset losses. A safe design should be driven by the ultimate goal of no accidents, no harm to people, and no damage to the environment. In order to have such design for process piping systems, advanced nonlinear analysis is required to properly capture the dynamic response of the piping and vessels subjected to blast loadings. This type of analysis, in general, should take into account (1) Blast drag load and blast overpressure; (2) Nonlinear material properties, i.e. thermal and strain-rate dependence; (3) Effects of non-structural masses and adjacent piping systems; (4) Pipe supports; (5) Failure of flanges and piping detail; (6) Effects of operating temperature on material properties; (7) Blast direction/ignition location/attenuation sensitivity; (8) Shielding effect, e.g. pipes behind large objects such as vessels; and (9) Effects of pipe insulation, i.e. increased pipe diameters. This paper first discusses the methodology/techniques to account for such effects in nonlinear advanced analysis for a safe design. The paper then uses case studies to demonstrate the methodology we developed to show how advanced simulation techniques are applied as tools for piping blast response to minimize the risk of failure. These case studies involve a process piping system that is simulated from global to detailed modeling. The goal of the paper is to discuss how to achieve a safe design for process piping systems by using advanced analysis.

Introduction

Recommended practice for the design of piping against explosions was documented in FABIG Technical Note [1] and API 2006 [2]. The methodology of performance based design of blast resistant offshore piping has also been described in recent studies including a report produced for HSE by SCI in 2005 [3] and a paper by Yasseri and Ocraft [4] in 2010. However, up to date, there is little discussion on an advanced approach that includes all aspects of a piping blast analysis. This paper attempts to give an overview of considerations that should be included in the analysis. The first part of the paper discusses these considerations. The second part serves as demonstration of the methodology by case studies. This part of the paper includes ABAQUS simulations involving a piping system modeled at different detail levels. An FE model was developed for a piping system that included two piping branches connecting to a Wet Oil Tank. In the FE model, the first piping branch and its supports were modeled using nonlinear beam elements; the second branch, its supports, and the Wet Oil Tank were model using shell elements. In a more detailed model, we sub-modeled a pipe flange on the first piping branch using solid elements. In this sub-model, the flange's boundary conditions were fed from the global model, in which the flange was modeled as shell elements. More details of modeling are followed.

Methodology

Piping blast analysis in general should take into account the following considerations:

1. Drag load versus blast overpressure effects
2. Nonlinear material model
3. Effects of non-structural masses and adjacent piping systems
4. Pipe supports
5. Flange failure
6. Effects of operating temperature on material properties
7. Effects of pipe insulation
8. Effects of shielding effect
9. Blast direction/ignition location sensitivity

Blast Drag Loading versus Blast Overpressure Effects

Two types of loading that must be considered in the piping blast analysis are:

- Overpressure
- Drag

It is commonly believed that building structures respond principally to the overpressure effects of explosions whereas pipes respond mostly to drag loading.

The distribution of pressure around a cylinder results in a time varying force in the stream-wise and the crosswise direction. The hydrodynamic force is calculated by integrating the normal and shear stresses over the surface of the obstacle. The following equation presents a phenomenological splitting of the hydrodynamic force [3]:

$$F_h = \frac{1}{2} C_d \, A|U(t)|U(t) + (\rho V + m)\frac{\partial}{\partial t}(U) + \frac{\partial \rho}{\partial t} V U(t) + F_{DP(M)} + F_{HE}$$

The first term is the quasi-static form of drag depending on obstacle shape, surface roughness, fluid density and Reynolds Number. The second term is the inertia force which is proportional to the acceleration. The third term is a combustion contribution originating from the change of mass per unit volume in a generalized version of Newton's law. The fourth term is the differential pressure, which is a function of the Mach number (U/c), where c is the velocity of sound. The last term is the hydro-elastic component.

Blast Overpressure

Overpressure is the pressure caused by a shock wave over and above normal atmospheric pressure. Blast overpressure results from explosions which can be classified into two types: detonation and deflagration. *Detonation*, e.g. generated with TNT, occurs when the combustion is driven by shock heating and pressurization of the unburned fuel to the point of auto-ignition. *Deflagration*, e.g. vapor cloud explosions, is a subsonic combustion event where the hot burning material preheats the subsequent layer of cold unburned gas or dust and ignites it. Figure 1 shows typical overpressure time history for two types of explosions.

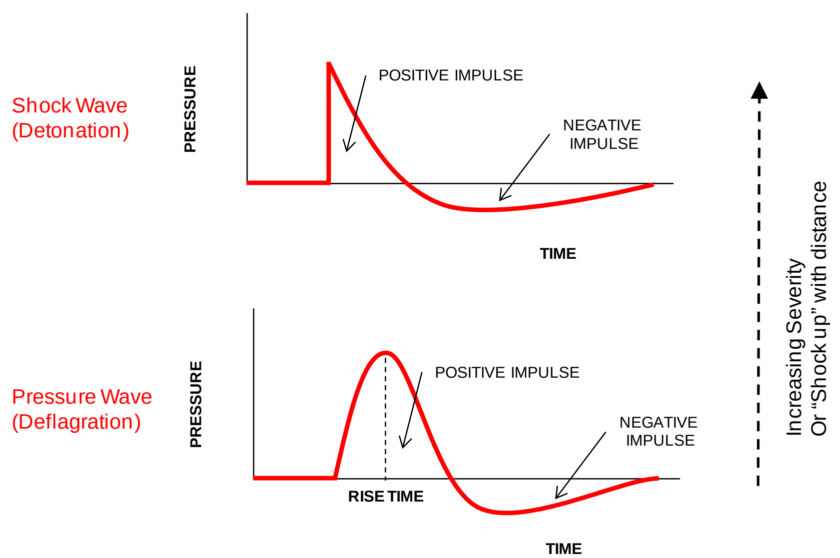


Figure 1 – Typical Overpressure Time History for Two Types of Explosions

Blast Drag Loading

The drag force, a combination of the skin friction (tangential stresses) and the form drag (normal stresses), is commonly written as follows:

$$F_D = \frac{1}{2}\,\rho\, A\, C_d\, |v| v$$

where ρ is the fluid density, A is the maximum cross sectional area of the object in a plane normal to v , C_d is the drag coefficient and v is the large scale fluid velocity ignoring spatial fluctuations in the vicinity of the object.

To allow the drag loading to be applied in the finite element models, blast pressure must be converted to an equivalent distributed load, i.e. drag force. The drag force is rewritten using the formula below:

$$F_D = C_d\, P_d\, OD \tag{1}$$

where

F_D	=	Drag Force
C_d	=	Drag coefficient
P_d	=	Drag Pressure [psi]
OD	=	Outer Diameter of the pipe

In summary, with the drag pressure known, a line load was computed by multiplying the drag pressure by outer diameter of the pipe/tube being loaded. The force is then multiplied by a drag coefficient, C_d, to get the drag line load. The drag coefficient, C_d, depends on the shape of the obstacle and on the Reynolds number of the flow. The nature of C_d has been studied extensively for various standard shaped objects in steady flow. Figure 2 presents the drag coefficient for different shapes which suggests a value of 1.2 for pipes. Dependence of C_d on the Reynolds number is summarized in Figure 4 [13], for flow transverse to a cylinder.

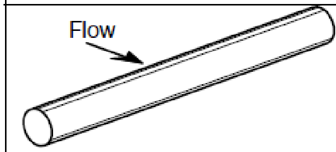
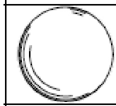
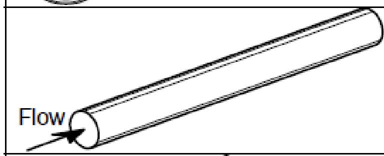
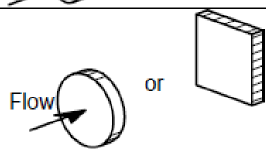
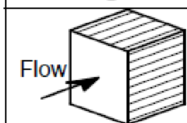
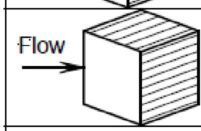
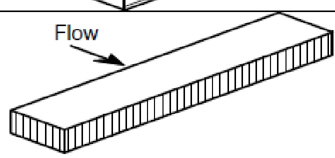
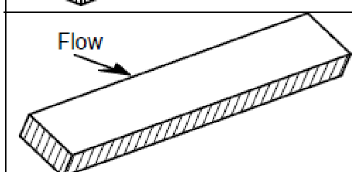
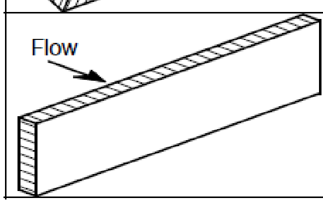
Sketch	Shape	C_D
	Circular cylinder (long rod), side on	1.20
	Sphere	0.47
	Rod, end-on	0.82
	Disc, face-on	1.17
	Cube, face-on	1.05
	Cube, edge-on	0.80
	Long rectangular member, face-on	2.05
	Long rectangular member, edge-on	1.55
	Narrow strip, face-on	1.98

Figure 2 – Drag coefficients, C_d, for various shapes [7]

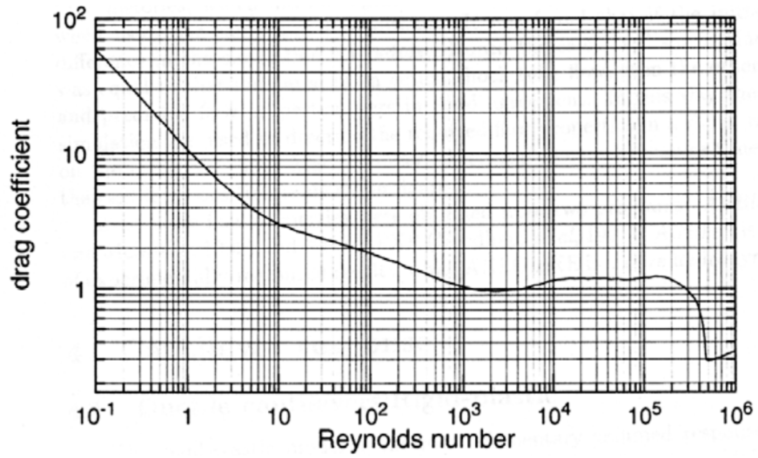


Figure 3 – Drag Coefficient of a cylinder as a function of Reynolds Number [13]

In Equation 1, the drag pressure is often computed as approximately 1/3 of the blast overpressure (OP). This gives conservative drag pressure up to an overpressure of approximately 2 bars (one bar is 14.5 psi). Figure 4 shows a CFD-based empirical relation between blast drag pressure on piping and overpressure calculated using CFD analysis for a typical offshore module [4].

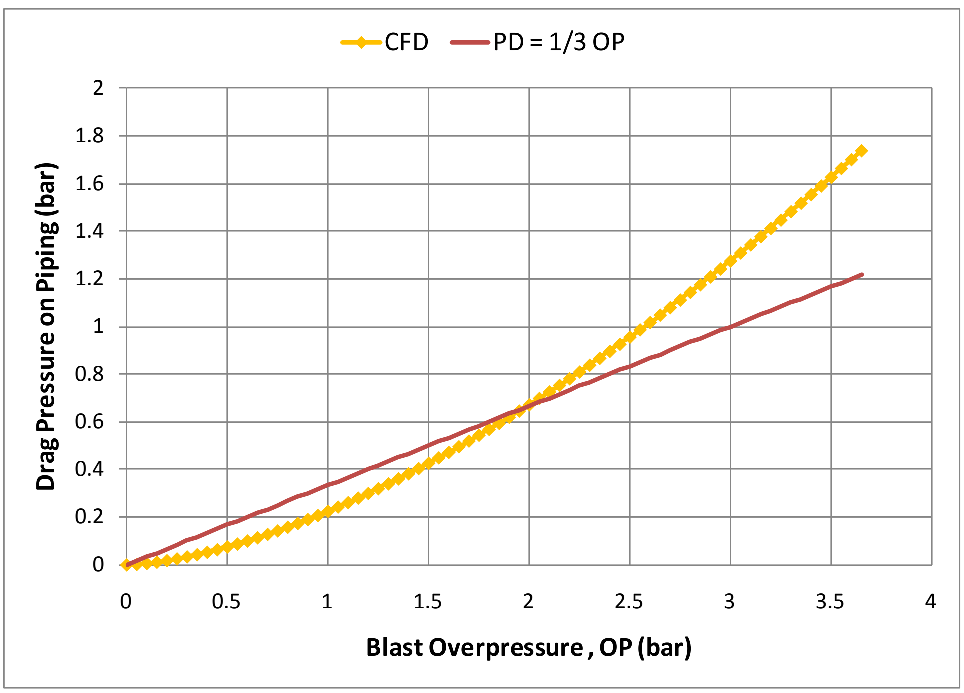


Figure 4 – Blast drag pressure versus overpressure for a typical offshore module [**4**]

Ideally, a CFD (Computational Fluid Dynamics) analysis should be performed first to computer the blast loads on a pipe system. Results of the CFD analysis is then fed into a FEA (Finite Element Analysis) which predicts structural response of the pipe system through a nonlinear transient dynamics solver. However, the main problem with CFD approach is that in order to capture drag load around a pipe section properly, fine mesh is often required; hence expensively computational cost. The question is how one should overpressure in piping analysis. With small pipes, response to explosion wind (drag pressure) is dominant to response to overpressure. In other word, overpressure (direct shock loading) is small compared to drag pressure (explosion wind). This is mainly due to the speed with which shock fronts can pass piping systems, allowing rapid equalization of upstream and downstream pressures [1]. Drag pressure might be calculated conservatively using the 1/3 factor given overpressure is less than 2 bars. However, this might not be true with pipes or vessels with one-foot diameter or larger [3]. With these large pipes, pressure does not wrap around pipe section quick enough to establish equalization. As a result, upstream and downstream pressures are not in balance and there are time delay and attenuation in terms of pressure as shown in Figure 5. In other words, effects of overpressure might not be negligible and should be considered in analysis.

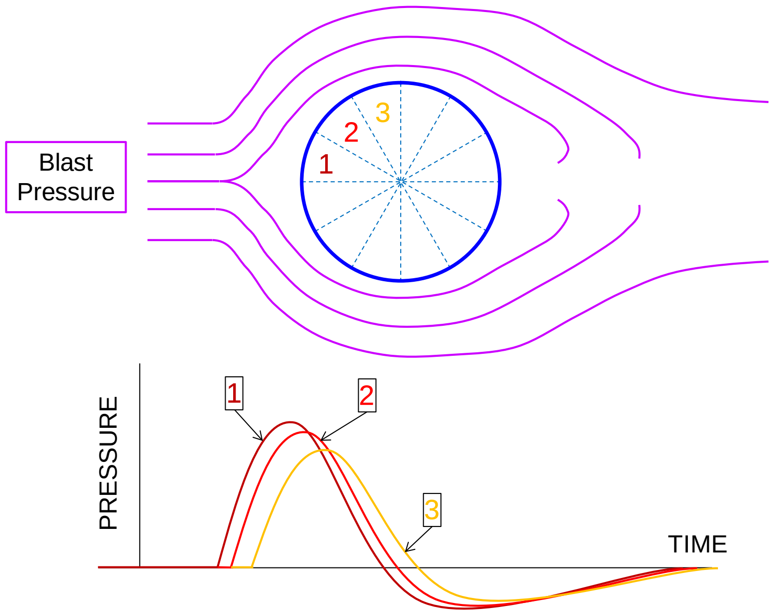


Figure 5 – Pressure Time delay and Attenuation with Large Pipes

The phenomena of time delay and attenuation with large pipes is similar to the way blast wave propagates in space. Figure 6 illustrates how blast wave travels toward objects A, B, and C. Given the ignition location, each object experiences blast pressure differently. Being closest to the ignition location, object A experiences blast loads first. Blast wave comes to object C last with less pressure compared to blast wave at A and B. Blast drag pressure time history at A, B, and C will look similar to those shown in Figure 5 but at a larger magnitude of difference. These effects should also be considered in a piping blast analysis.

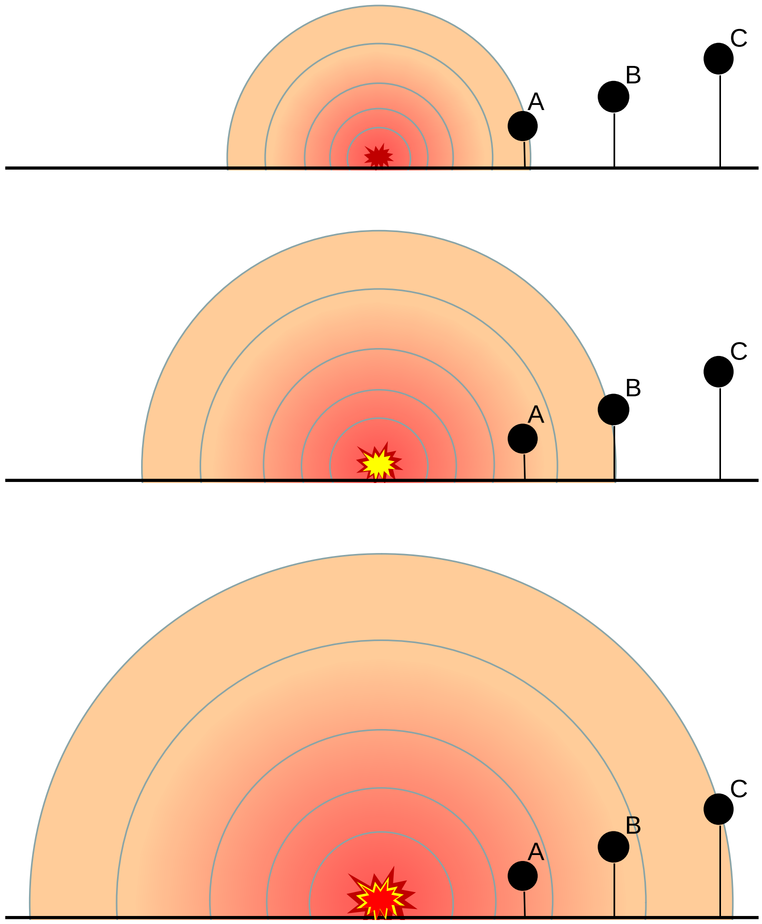


Figure 6 – Blast wave propagation

Nonlinear Material Model

Excessive deformation of pipes is expected during a blast event. It is likely that structural components undergo large plastic deformation, even failure. Hence material plasticity/failure must be modeled to capture these nonlinear effects. Since blast loading happens in very short duration of time, rate-dependent plasticity should be taken into account. Figure 7 presents stress-strain relationships up to fracture for low-carbon mild steel at different strain rates [10]. Yielding stress is also sensitive to strain rates, especially for high strength steels. Increase in yield strength due to strain rate effects is characterized by a dynamic increase factor. In Figure 8, the dynamic increase factor for yield strength versus strain rate is plotted for a mild steel (ASTM A36 steel with static yield stress of 250 MPa) and for a high strength, quenched and tempered steel (ASTM A514 steel with yield stress approximately 760 MPa) [11].

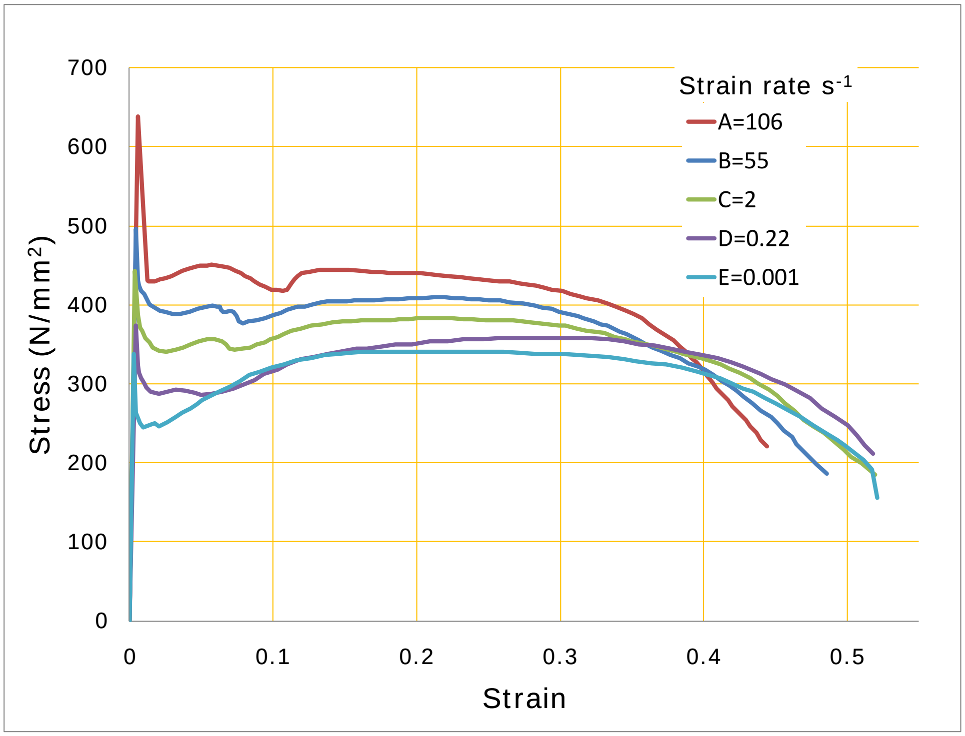


Figure 7: Effect of strain rates on behavior of mild steel [10]

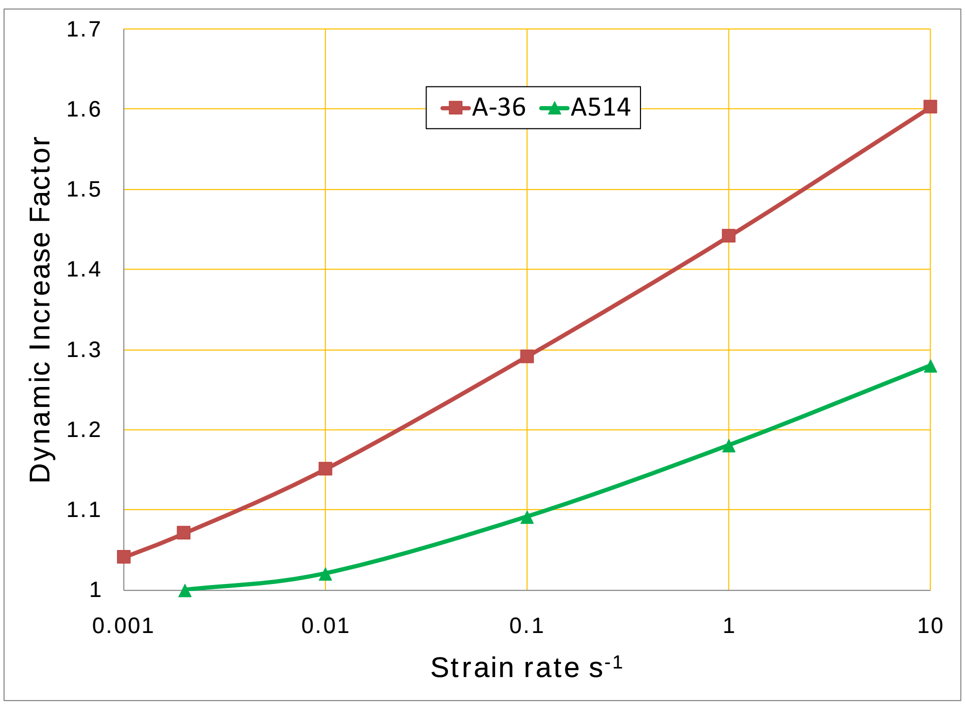


Figure 8: Dynamic increase factor for yield strength of mild and high strength steel versus strain rate [11]

Cowper and Symonds [12] proposed a relationship which can be used to calculate the enhancement of stresses due to strain rate effects. The relationship is given as follows:

$$\frac{\sigma_D}{\sigma_S} = 1 + \left(\frac{\dot{\epsilon}}{D}\right)^{\frac{1}{q}}$$

where

σ_D	=	Dynamic stress at a particular strain rate
σ_S	=	Static stress
$\dot{\epsilon}$	=	Uniaxial plastic strain rate
D and q	=	Constants associated with steel

Values of D and q are strain-dependent. For example, D = 40.4 s^{-1} and q =5 could be used to describe the behavior up to 4% strain of mild steel. Despite its popular use, recent tests [14] indicate that Cowper and Symonds model might be un-conservative as shown in Figure 9.

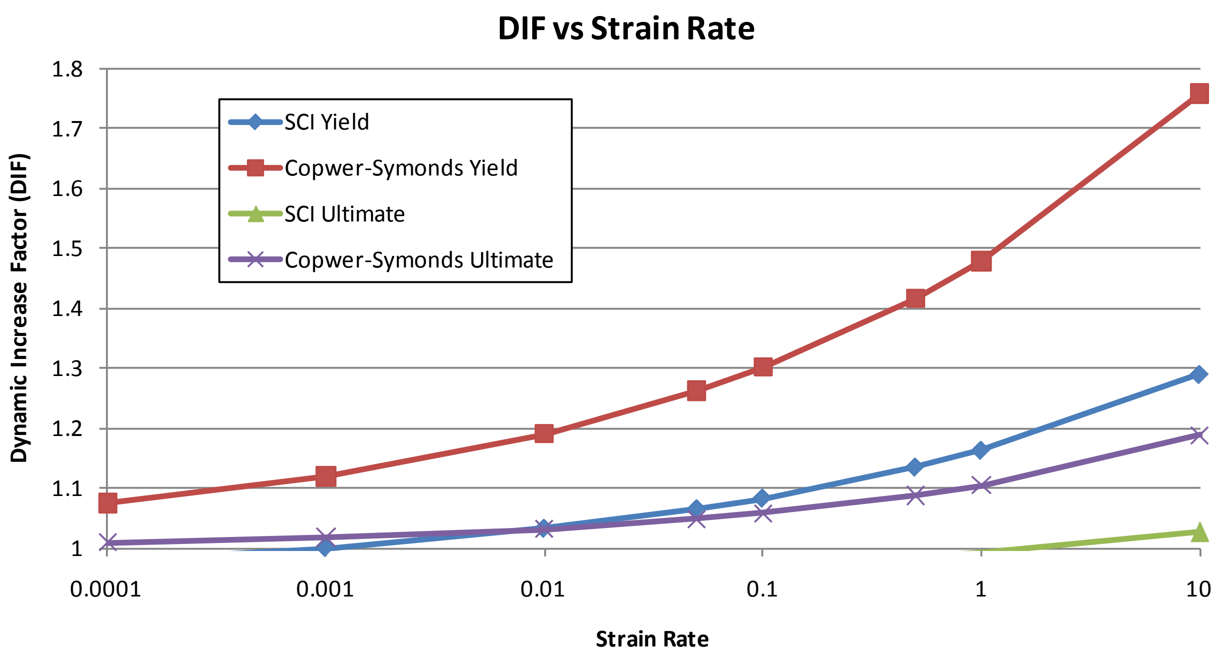


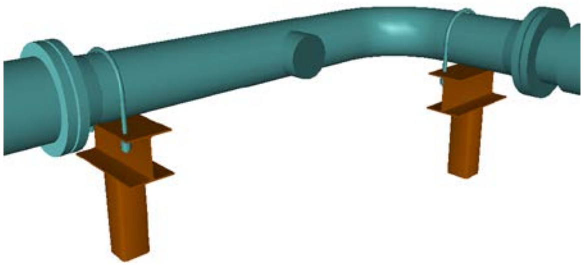
Figure 9: Dynamic increase factor of 50 ksi mild steel versus strain rate

Effects of Non-Structural Masses and Adjacent Piping Systems

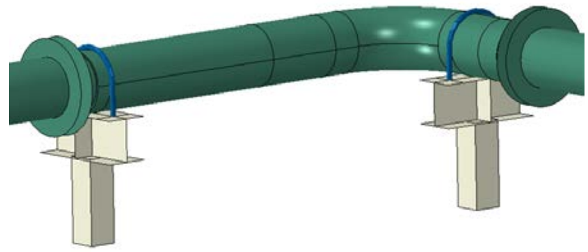
It is common that pipe systems are designed to run parallel to each other sharing the same support or run along a wall. A piping blast analysis should take into account the possibility that a pipe can impact other pipes or walls because of excessive deformation of pipes that can occur. Flanges, valves, and fittings should be taken into account as nonstructural masses. Non-structural masses can also come from adjacent piping system sharing the same supports. It is desirable to include these effects in analysis.

Pipe Supports

Interaction among pipe and support and anchor bolts should be considered. Assumptions on supports in piping blast analysis can significantly affect analysis results. Pipe supports can fail during a blast. Assuming pipes are fixed or pinned at supports then using corresponding reactions to analyze supports can be fallacious. In other words, in blast analysis, care should be taken when modeling pipe supports. Whenever possible, they should be modeled explicitly. Figure 10 shows an example of pipe supports and U-bolts from a 3D view and corresponding FE model in which pipe supports and U-bolts are modeled as shell and beam element, respectively.



(a) 3D View



(a) View from Abaqus FE model

Figure 10 – Example of pipe supports and U-bolts

Flange Failure

In a blast event, pipes might deform excessively without rupture. However, details such as flanges and fittings can fail because they may have less strength in bending than the pipe in which they are located. Such failure can lead to an escalation of an initial explosion event to the failure of larger vessels and/or pipes. This is discussed later in some more details in the Solid Model.

Effects of Operating Temperature on Material Properties

Material properties in general are temperature dependent. For pipe systems, steel Young modulus is reduced when operating temperature is high. This stiffness reduction should be included in a piping blast analysis. Figure 11 shows an example of carbon steel properties as a function of temperature (known as degradation curves). It is indicated from Figure 11 that Young modulus is more sensitive to temperature than yielding stress.

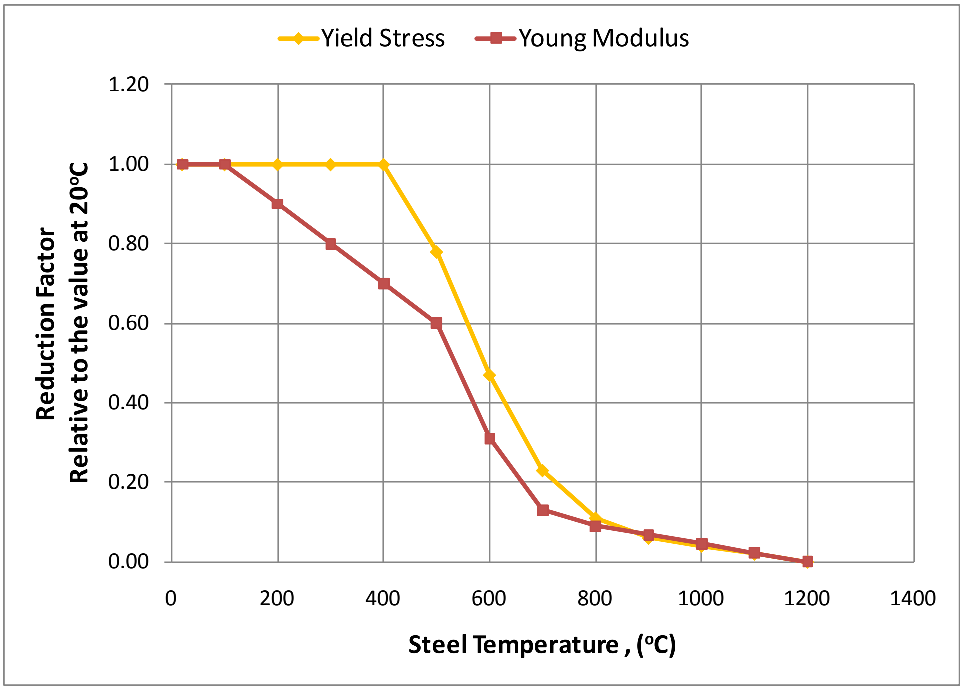


Figure 11: Reduction factors for stress-strain relationship of carbon steel at elevated temperatures [8]

Blast Direction/Ignition Location Sensitivity

Blast loading is directional. However, it is common practice that blast loading is assumed principal directions with respect to the piping systems provided information on blast loading is not known [1]. However, a sensitivity study on blast direction/ignition location should be conducted to check if other directions can be more critical to the pipe system response.

Shielding Effects

In an explosion, a certain amount of blast pressure reduction may be gained by having any large and substantial object between the object of interest and the ignition location. For example, in a blast event, a vessel between a pipe and the explosion center will shield the pipe from the explosion, partially reducing the blast pressure on the pipe. This shielding effect should be included in a piping blast analysis.

Pipe Insulation

Pipe insulation help protect pipes from freezing and condensation when operating at low temperatures. Very hot pipe systems should also be insulated to avoid potential human injuries. In terms of loading, insulation leads to larger pipe outer diameter, which technically attracts more drag loads in a blast event. As shown in Equation (1), the blast drag force is linearly proportional to the outer diameter of the pipe. In general, pipe insulation thickness is a function of pipe temperature and pressure. Drag pressure should be calculated based on effective outer diameter which takes into account pipe coatings.

The case studies were to illustrate the methodology that we developed. In the following specific simulations, we addressed the following aspects of the blast piping problems as discussed in the methodology sections:

1. Drag load versus blast overpressure effects
2. Nonlinear material model
3. Effects of non-structural masses
4. Pipe supports
5. Flange failure
6. Effects of operating temperature on material properties
7. Blast direction/ignition location sensitivity
8. Effects of pipe insulation

FE Model of the Piping System

The piping system considered in this study consists of a Wet Oil Tank, a 10-inch pipe branch, a 24-inch pipe branch, and U-bolt pipe supports. As discussed earlier, small pipes respond mostly to drag loading while big diameter pipes and vessels respond principally to the overpressure effects of explosions. To address the effects of drag load versus blast overpressure effects, in the FE model, the 10-inch pipe and its supports were modeled as beam elements while the Wet Oil Tank and the 24-inch pipe and its supports were modeled using shell elements. The FE model, which was constructed of nonlinear beam and shell elements having approximately a one-inch length per element, is shown in Figure 12. Connecting elements (U-bolts) attaching piping segments to pipe supports were modeled explicitly. Figure 12 also shows that a flange whose details are presented in Figure 13, was modeled explicitly using shell elements in the 10-inch pipe branch. In this global model, twelve pre-tensioned bolts were modeled using springs. The response, i.e., displacements, at the shell-beam element interface was used later as boundary conditions in the detailed sub-modeling of the flange, which is shown in Figure 14. In this sub-model, the pipe portion, the flange, and the pre-tensioned bolts were all modeled using solid elements. The goal of the sub-modeling was to examine the response of a pipe flange under blast loadings.

Table 1 summarizes pipe sizes and materials used in simulations. Figure 15 shows the normalized blast load time history. The blast was assumed to last 100 milliseconds with no negative phase. Blast peak pressure was assumed 44 psi. Figure 16 indicates the scenario considered which shows the blast loading in +Y direction of the FE model.

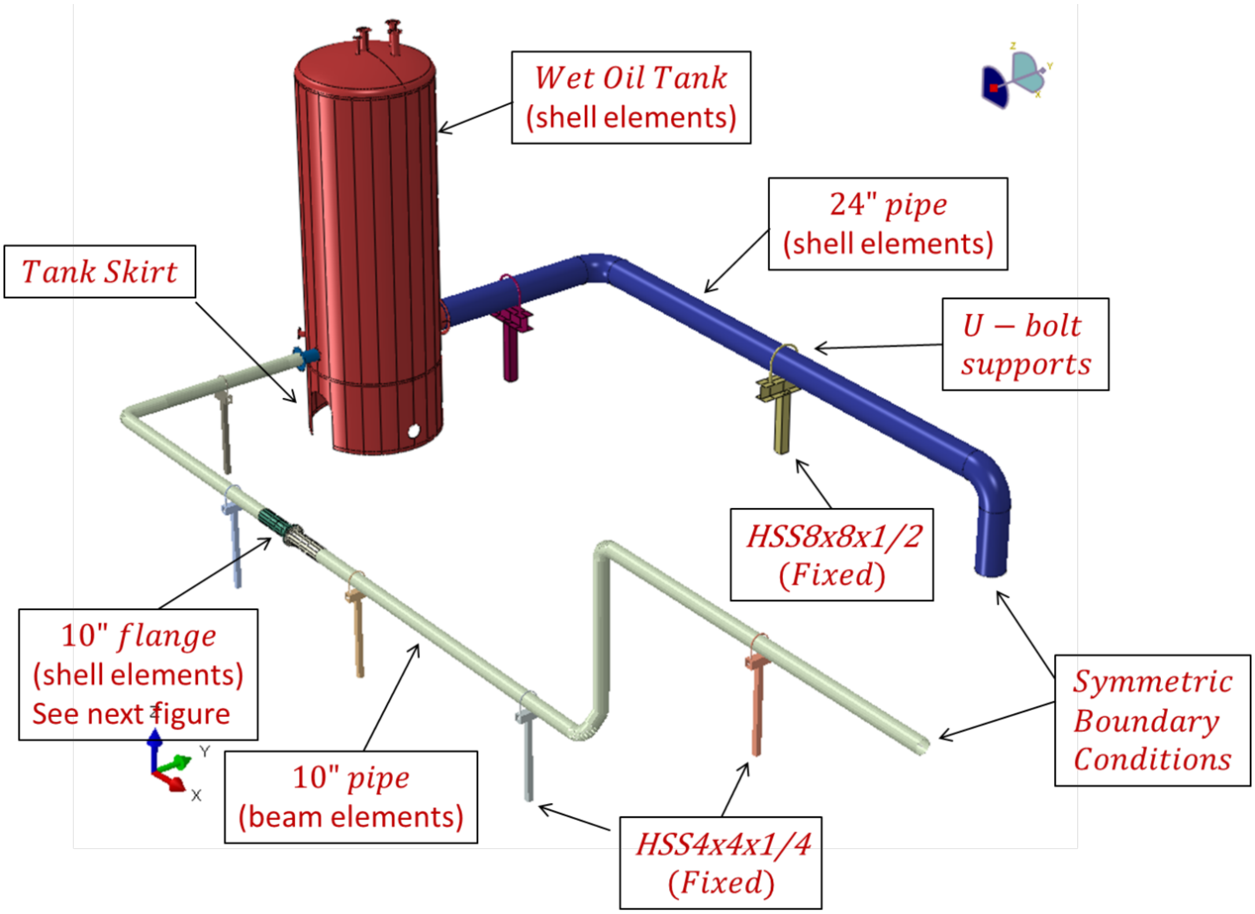


Figure 12 – FE model showing pipes, vessel, and supports

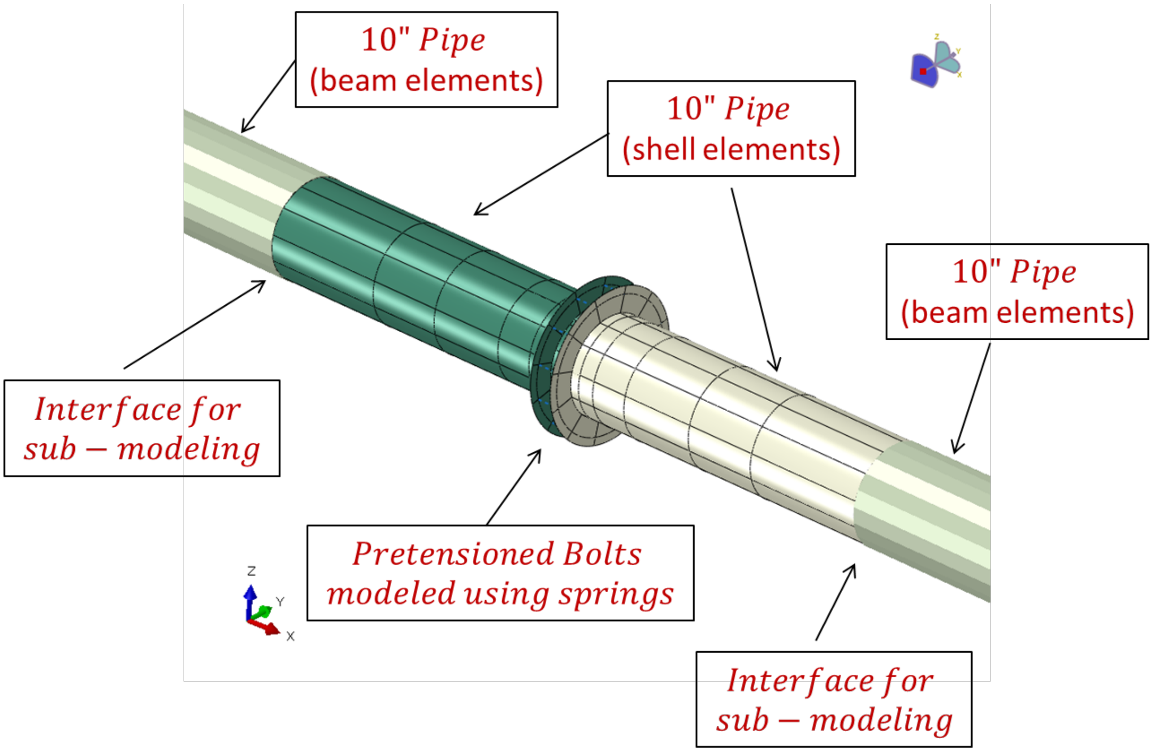


Figure 13 – FE Model of 10” Flange for Sub-modeling

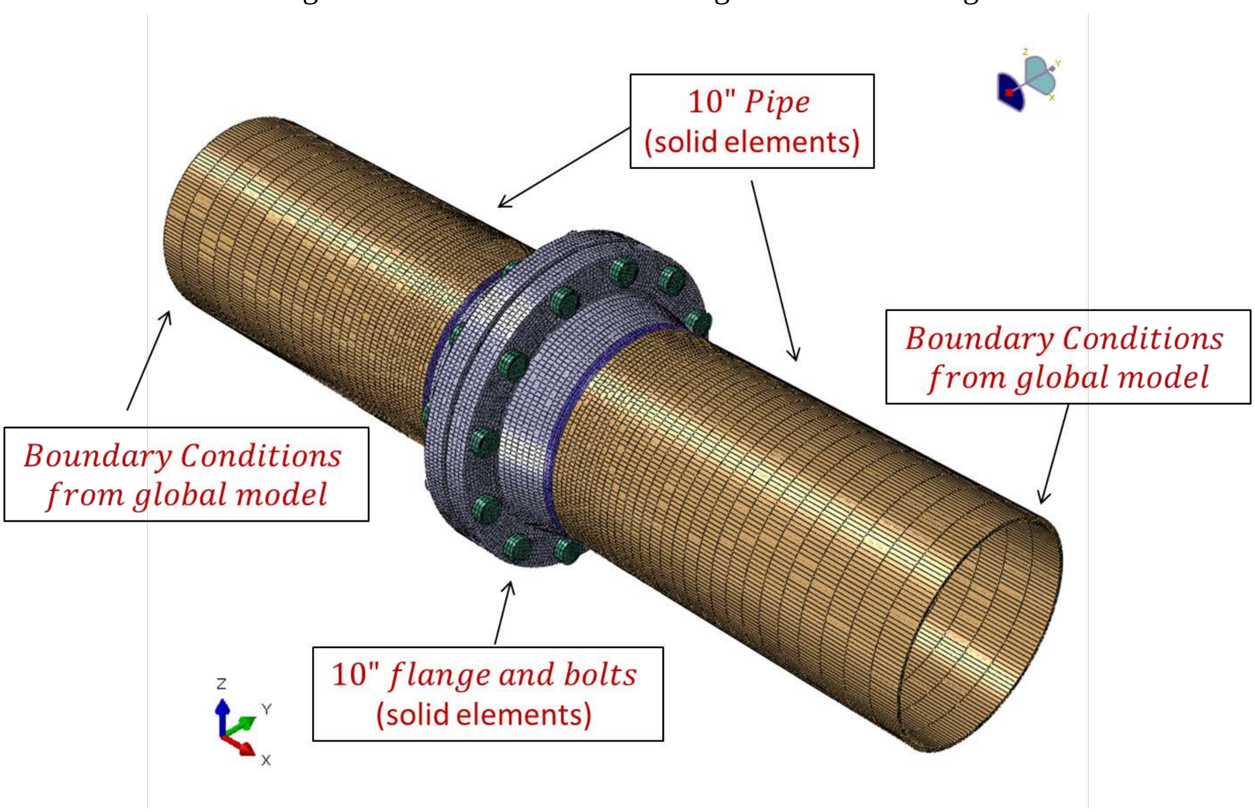


Figure 14 – FE Sub-model of 10” Flange (Solid Elements)

Table 1 – Pipe Size and Material Properties

Item	Outside Diameter (inches)	Thickness (inches)	Material
NPS 10	10.75	0.165	Stainless Steel, Yield Strength = 50 ksi
NPS 24	24	0.25	Stainless Steel, Yield Strength = 50 ksi
Wet Oil Tank	108	0.75	Stainless Steel, Yield Strength = 36 ksi
U-bolt Supports			Carbon Steel, Yield Strength = 36 ksi

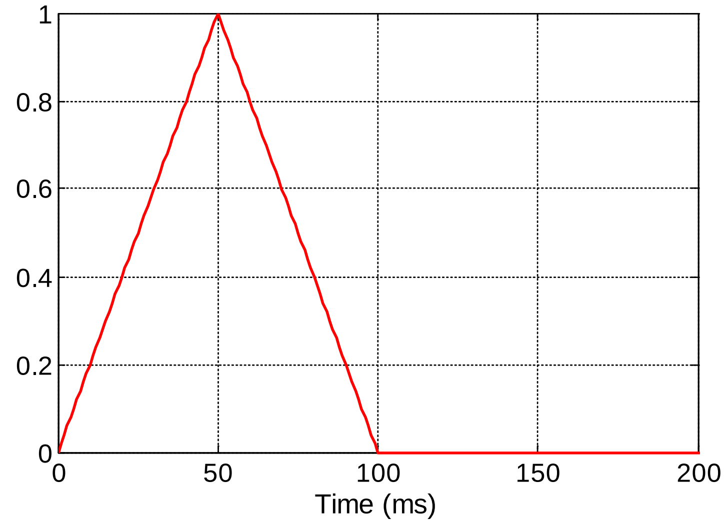


Figure 15 – Normalized Blast Loading Time History

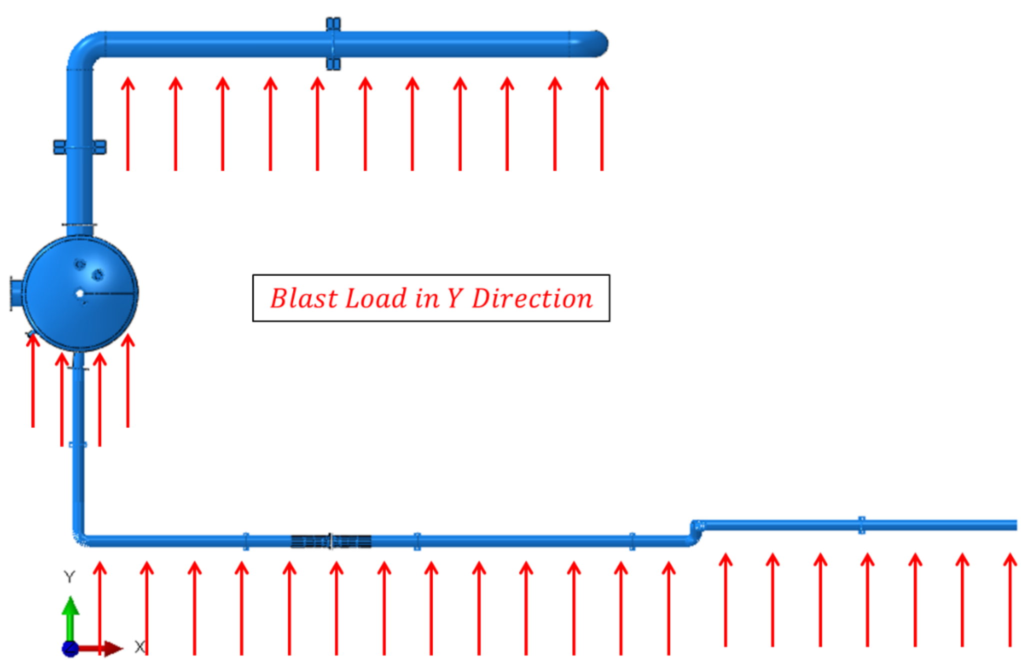


Figure 16 – Plan View indicating 44 psi Blast Pressure Loading in +Y Direction

Results – Global Model Response

Figure 17, Figure 18, and Figure 19 present the contour plots of von Mises stress, plastic strain, and deflection of the piping system at the peak of the blast, t = 50 ms. Figure 17 and Figure 18 indicate high stresses, plastic strains at pipe connections and supports. It is seen that the supports can fail due to excessive bending moments and shears induced by blast loadings. Pipe supports are often designed to sustain gravity loads and expected to fail during a blast event. The failure of pipe supports might lead to excessive deflections of the pipes and escalations. The pipes at connections and supports might rupture due to the high stresses and strains; leakage would follow. Figure 19 indicates that high deflections were observed at the 24-inch branch as a result of the applied blast loading and lack of supports; a maximum value of 46.21 inches was observed at the time of 50 ms.

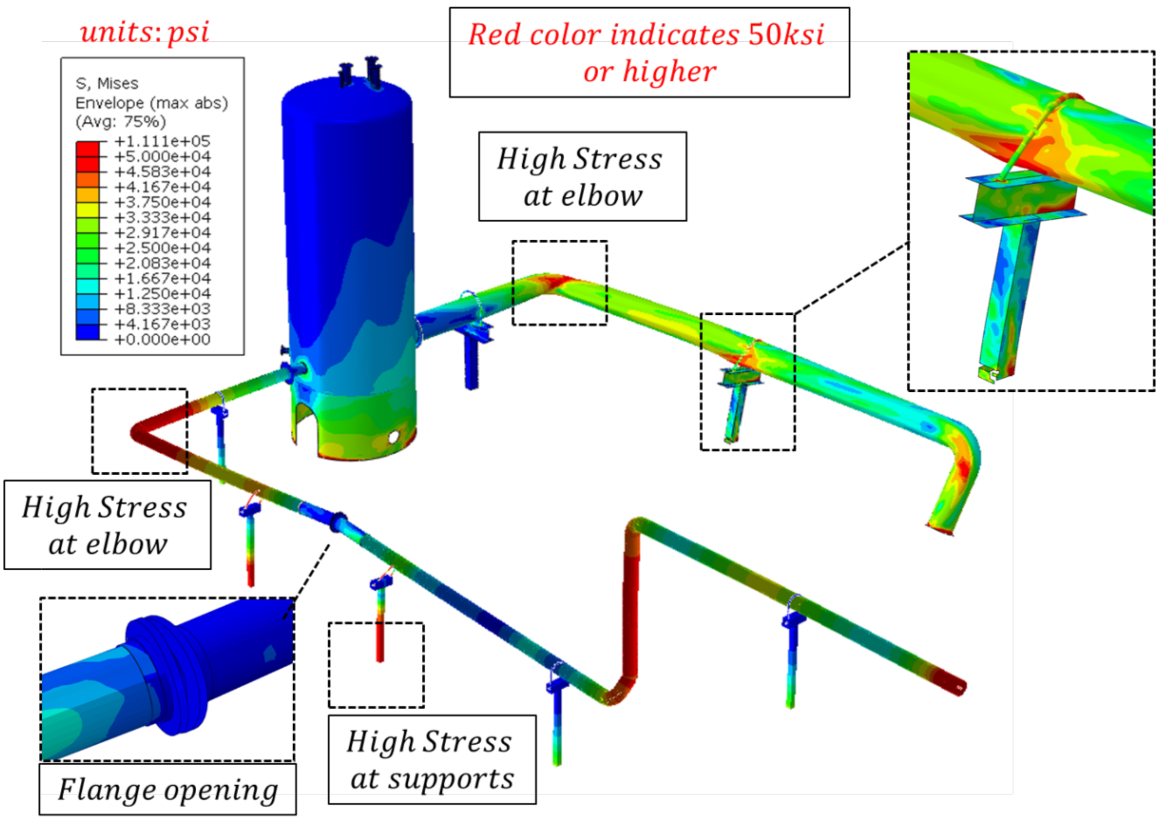


Figure 17 –Stress contours at time = 50 ms

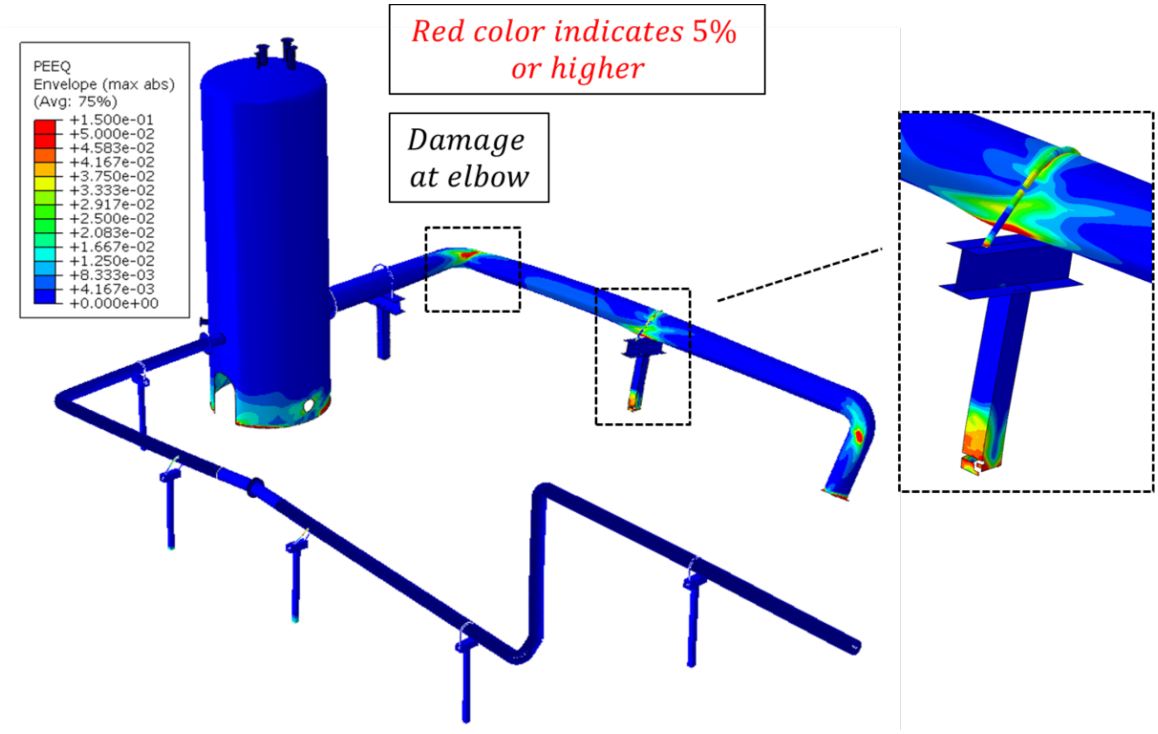


Figure 18 – Plastic Strain contours at time = 50 ms

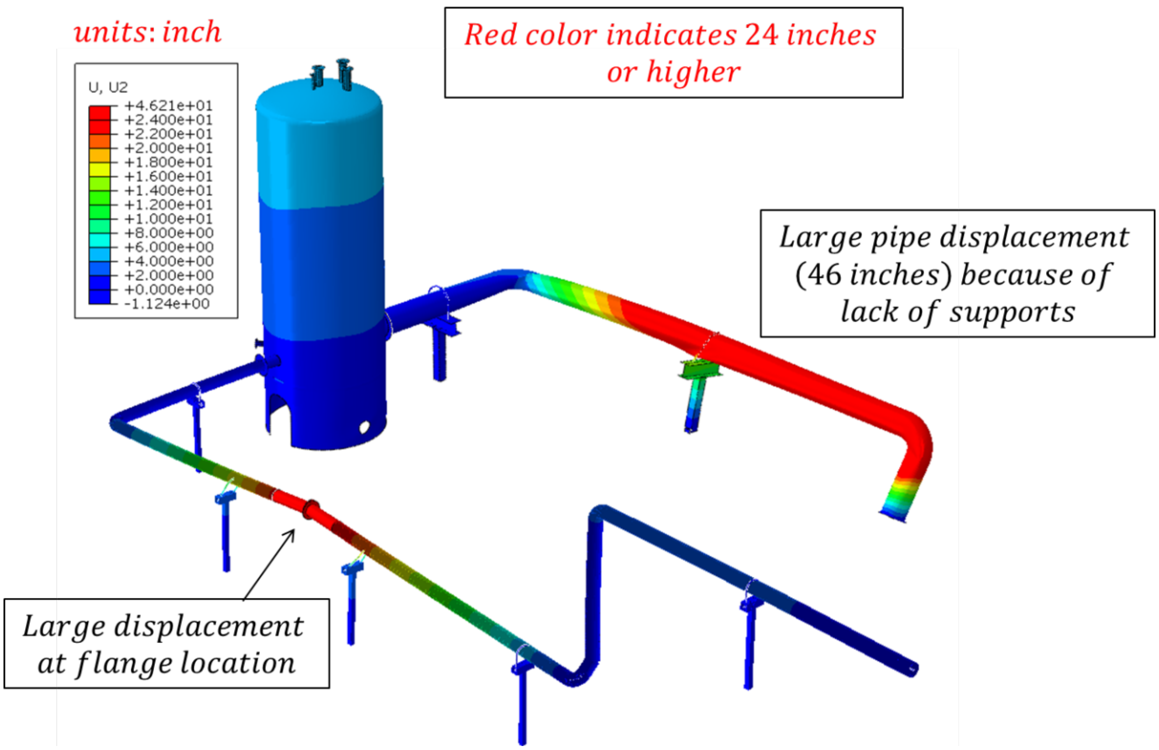


Figure 19 – Deflection contours at time = 50 ms

Results – Wet Oil Tank

Figure 20 shows the contour plots of stress, plastic strain, and deflection contours for the Wet Oil Tank at the end of the blast, time = 100 ms. Excessive stresses and strains were observed at the supports (tank skirt) and pipe connections. The tank displaced more than 3 ft at top; it might lose stability due to excessive damage at the base skirt. Leakage might happen at the nozzle-pipe connections and might lead to escalations.

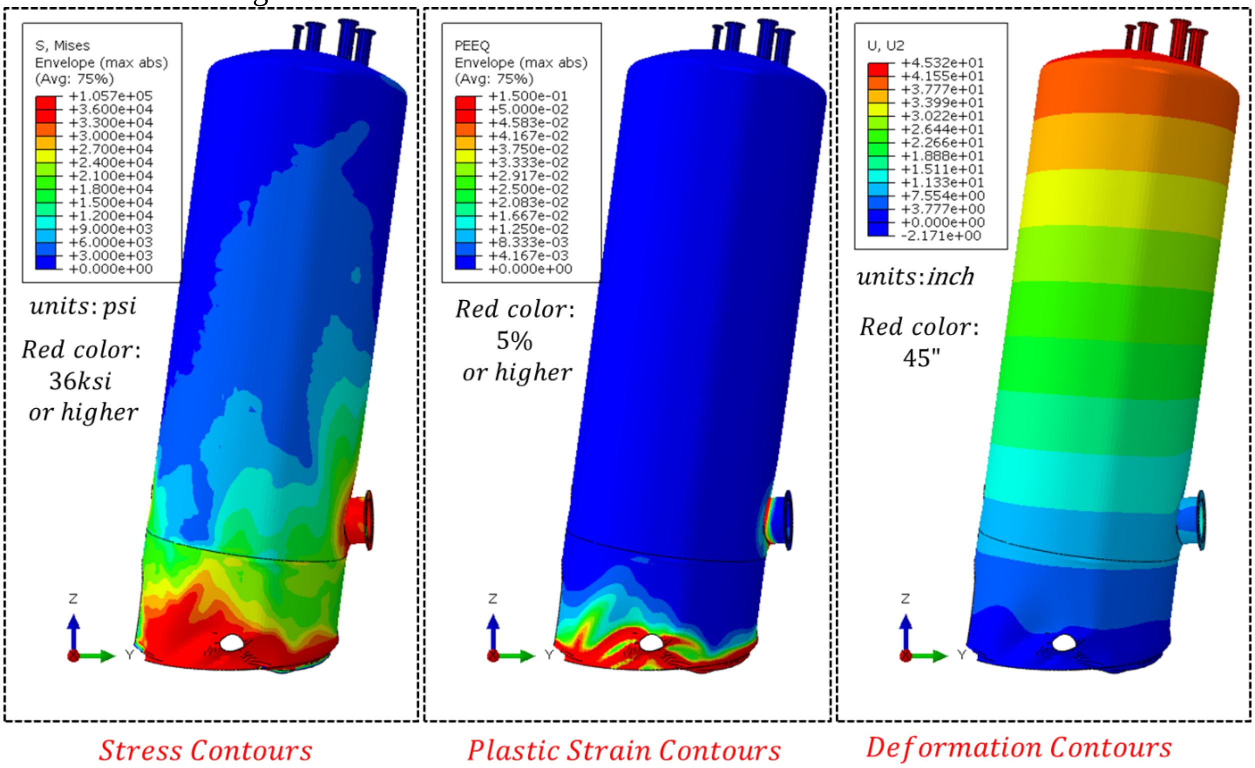


Figure 20 – Wet Oil Tank Stress, Plastic Strain, and Deformation Contours at time = 100 ms

Results – Flange Detailed Sub-modeling

In a blast event, it is concerned that flanges can open or even fail, and then leakage is an issue. This section examines flange behavior in detail. To this end, in the global model, a flange connection was assumed and modeled explicitly using shell elements, as shown in Figure 12 and Figure 13. Bolts were modeled as connectors with pretension forces. This global model was then fed into a detailed sub-model which is shown in Figure 14, where the flange connection was modeled explicitly using solid elements.

Figure 21 presents the contact pressure at the peak of the blast. Note that in the sub-model, the bolts were pre-tensioned to 2,585 pounds before the blast loads were applied. During the blast, the pre-tensioning forces helped prevent the opening of the flange. However, when the demand from the blast loading became higher than the yield capacity of the bolts, the opening would follow due to the inelastic response of the bolts. Since the blast was in the positive Y direction, as shown in Figure 21, the bolts in the front (more positive Y direction, see Figure 16) experienced more tension forces and were over-stressed while the bolts in the back experienced lower levels of loading.

Figure 22 shows the contour plots of stress, plastic strain, and deflection contours for the flange at the peak of the blast, time = 50 ms. It is indicated that the flange connection had opened and a leak might occur. The results were good indication that the bolts might eventually fail and leakage and/or escalations would follow. It is recommended that flanges at critical locations (e.g. large bending moment, high differential movements) should be modeled explicitly in blast piping analysis.

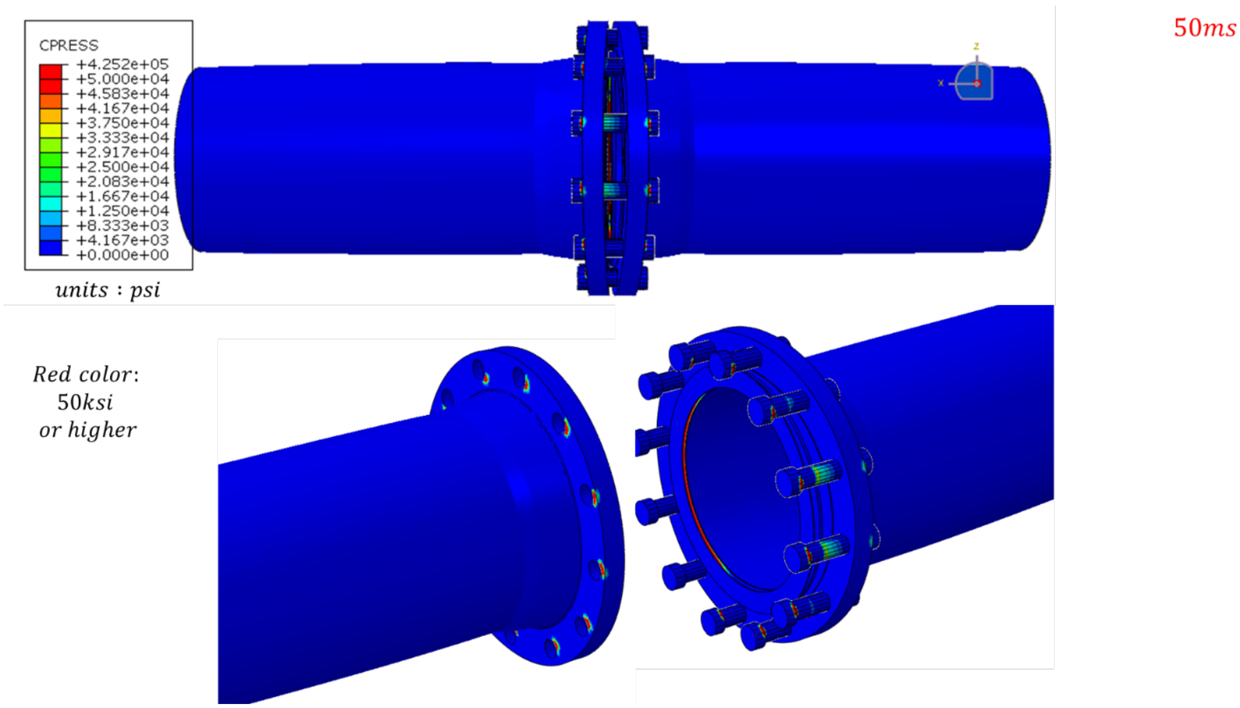


Figure 21: Contact Pressure Contours, t = 50ms

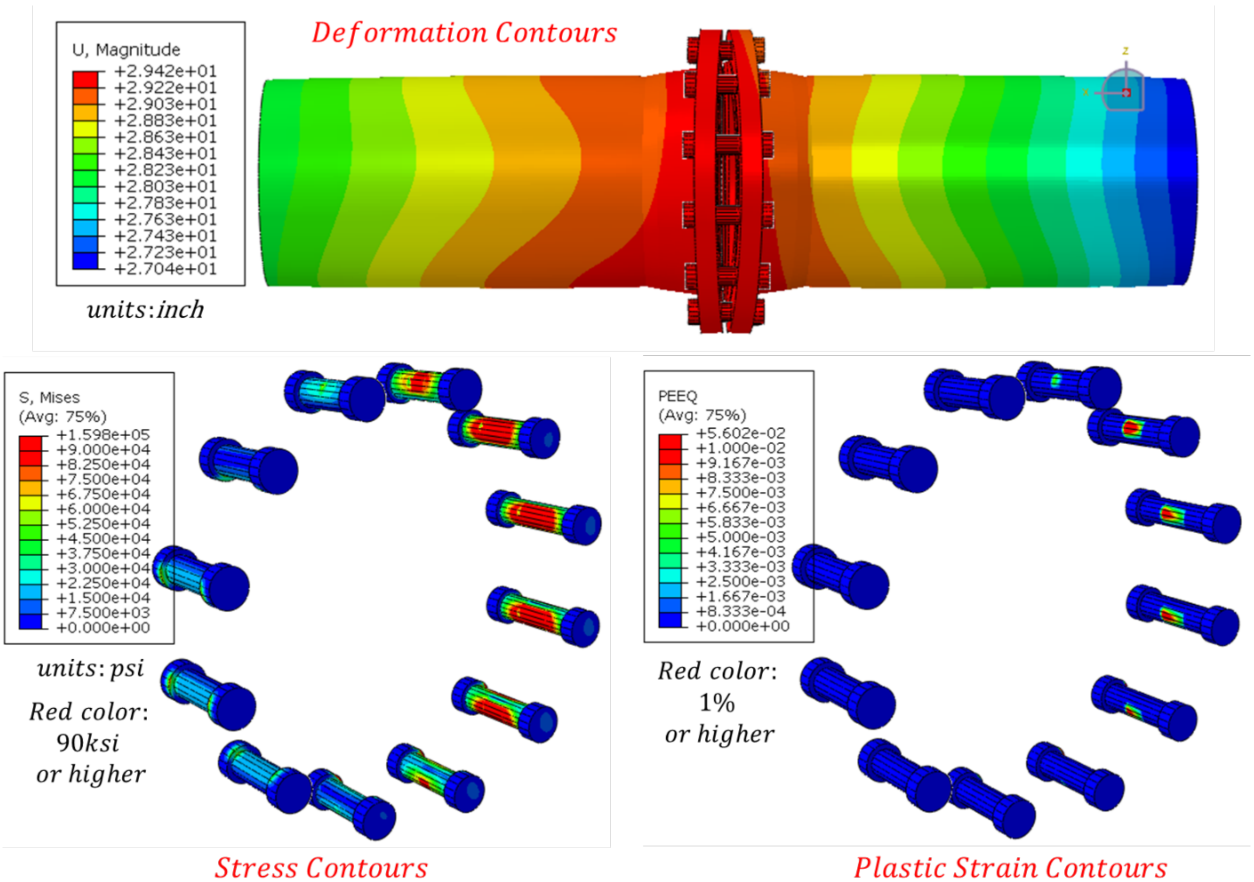


Figure 22: Stress, Plastic Strain, and Deformation Contours at time = 50 ms

Conclusions

Offshore piping subjected to blast is a complex problem. There are many factors that can affect the response of a piping system to blast loading. The ability to perform an advanced numerical analysis such as that described in this paper allows for a safer design of process piping systems. Advancements in technology allow detailed numerical studies to become increasingly feasible where physical testing is often not. The carried-out advanced FE analyses allowed the following conclusions and observations to be made for case studies presented in this paper:

- Support configuration, flexibility, and capacity affect the blast response of a piping system significantly.
- Non-structural components (masses) and piping details (elbows, flanges) affect the overall response of the piping system.
- Detailed sub-modeling is recommended for critical piping locations.
- Bolt rupture might control the failure of a piping system. Flange opening/damage should be modeled.

References

1. FABIG/SCI, Protection of Piping Systems Subject to Fires and Explosions, Technical Note 8.

2. API 2FB, Recommended practice for the design of offshore facilities against fire and blast loading, 2006
3. HSE report 285, Protection of piping systems subject to fires and explosion, Prepared by the Steel Construction Institute, 2005
4. Yasseri, S. and Ocraft, M., Blast resistant design of process piping: The State of Practice, FABIG Newsletter Issue 55, May 2010
5. ASME Code for Pressure Piping, B31, ASME B31.3, Process Piping, 2002.
6. Dassault Systèmes Simulia Corp, "Abaqus 6.12 Analysis User's Manual", 2012
7. Baker W E, Cox P A, Westine P S, Kulesz J J and Strehlow R A 1983. Explosion Hazards and Evaluation, Elsevier Scientific Publishing Company
8. Eurocode 3: Design of steel structures —Part 1-2: General rules — Structural fire design, BS EN 1993-1-2:2005
9. FABIG/SCI, Design Guide for Steels at Elevated Temperatures and High Strain Rates, Technical Note 6.
10. Campbell, J.D. and Cooper, R.H. Yield and flow of low-carbon steel at medium strain rates. Proceedings of the Conference on the physical basis of yield and fracture. Institute of Physics and Physical Society, London, 77-87 (1966)
11. Smith, P.D. and Hetherington, J.G. Blast and ballistic loading of structures, Butterworth Heineman, 1994
12. Cowper, G.R. and Symonds, P.S. Strain hardening and strain rate effects in the impact loading of cantilever beams, Brown University Division of Applied mathematics Report No. 28, September 1957
13. Schlichting H., 1960, Boundary layer Theory, McGraw-Hill, New York.
14. Burgan, B., "Elevated temperature and high strain rate properties of offshore steels", Offshore Technology Report 2001/020, SCI