

Using Explicit Finite Element Analysis to Simulate Blast Loading on Hazardous Chemical Storage Tanks

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Abstract: *Accurately simulating the blast wave associated with an accidental explosion is extremely valuable in assessing the structural response and potential failure modes of critical process equipment such as storage tanks, piping, or pressure vessels in chemical and petrochemical facilities. Furthermore, assessing the potential damage from a blast wave can provide valuable information about protecting structures from external explosions and developing designs that improve blast damage mitigation. This paper discusses the underlying theory and examines the practical application of multiple finite element based explicit computational techniques for simulating the load acting on a structure due to a chemical explosion. Explicit three-dimensional blast analysis of single and double-walled storage tanks that carry an extremely high consequence of failure is performed. The structural response of the tanks due to postulated accidental explosions is investigated and likely failure modes are quantified and discussed.*

The two explicit computational blast loading methods implemented in Abaqus/Explicit that are discussed and compared in this study are the incident wave loading model and CONWEP. The CONWEP model is appropriate for detonations of conventional explosions, and in this case automates many crucial features of the analysis, such as developing the overpressure time history, defining spatial decay, and accounting for reflection effects. Large vapor cloud explosions are known to behave differently than conventional explosives, and for these cases, the more manual incident wave loading approach permits the user to define their own time-varying overpressure amplitude. These advanced computational methods permit realistic evaluation of complex, three-dimensional process equipment subjected to accidental explosions.

Keywords: *Explicit Finite Element Analysis, CONWEP, Blast Loading, Chemical Storage Tanks, Accidental Explosions, Blast Damage Mitigation, Abaqus/Explicit, Incident Wave Loading, Riks post-buckling analysis, TNT Equivalency*

1. Introduction

A chemical explosion in air creates a blast wave as a result of the atmosphere surrounding the explosion source being pushed back. In general, the pressure of the compressed air at the blast wavefront decays as it moves away from the blast source. As discussed in many widely used books and publications (i.e. Smith and Hetherington, 1994, Kinney and Graham, 1985,

Dusenberry, 2010, Bulson, 1997, ASCE, 1997, and DOD, 2008), a typical blast wave, as observed at a location removed from the center of a given chemical explosion, reaches a peak value of overpressure and begins to decay exponentially (as shown in Figure 1), eventually decreasing below atmospheric pressure. This peak overpressure decreases as the distance from the explosion source increases. The amount of time it takes the blast wavefront to reach a given point is known as the arrival time. The overpressure profile can be divided into the positive pressure portion (positive phase) and negative pressure portion (negative phase). Furthermore, the amount of time it takes the blast wave to decay below atmospheric pressure is known as the positive phase duration. The area under the curve during the positive phase duration is the positive blast wave impulse and is generally closely related to the damage capabilities of a given chemical explosion.

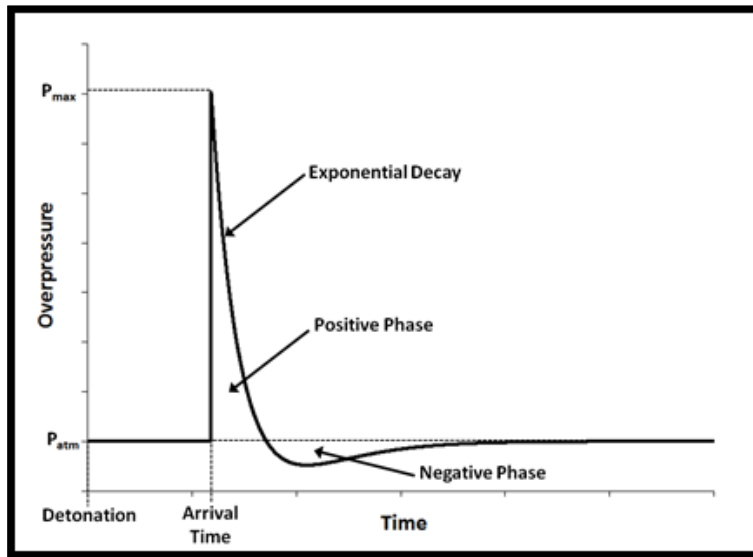


Figure 1. Typical overpressure amplitude for a chemical explosion (Simulia, 2010)

Often times, the positive phase impulse is calculated and an equivalent triangular impulse with the same peak overpressure is used to approximate the realistic overpressure amplitude shown in Figure 1. In many cases, this approximation is appropriate because the positive phase portion of the incident pressure wave is typically the most damaging. Accurately simulating a realistic blast wave acting on a structure for a given explosive scenario is challenging because the peak overpressure, positive phase duration, amount of explosives, and distance from the explosion source all affect the overpressure amplitude. Furthermore, accounting for reflection effects on a loading surface adds further complication to the blast loading model; generally, structural response is fairly sensitive to capturing the correct incident wave reflection.

Two different Abaqus/Explicit finite element techniques used to simulate blast loading due to far-field, external chemical explosions in air are discussed herein; incident wave loading and the conventional weapons effects blast loading model, or CONWEP (Hyde, 1988). CONWEP is well suited for simulating the overpressure wave associated with the detonation of conventional

explosives, while incident wave loading permits reasonable analysis of vapor cloud explosions. The underlying methodology of each approach is discussed in this paper as well as the advantages and applications of each. Furthermore, both computational methods are compared for the explicit dynamic simulations of realistic explosive overpressure waves (from a postulated concentrated explosion source and a vapor cloud) impacting in-service single and double-walled storage tanks that carry extremely high consequences of failure.

2. Blast Curve Generation

In order to develop the blast parameters required to generate realistic overpressure curves for conventional explosives, the equivalent TNT method is most commonly used. TNT equivalency of a given explosive is simply the ratio of the mass of TNT to the mass of explosive such that both yield equal pressure and impulse (Huntington-Thresher and Cullis, 2001). As discussed in (DOD, 2008), the ratio of energy output of a chemical explosive material relative to a given amount of TNT is calculated following

$$W_{effective} = \left[\frac{H_{exp}^d}{H_{TNT}^d} \right] W_{exp} \quad (1)$$

where $W_{effective}$ is the effective charge weight, W_{exp} is the weight of explosive in question, H_{exp}^d is the heat of detonation of a given explosive, and H_{TNT}^d is the heat of detonation of TNT. In order to compare shock wave parameters to available published data, a scaled distance from an explosion source to the loaded structure may be used. As discussed in (Baker, 1987), the most common form of blast scaling is the Hopkinson-Cranz or cube-root scaling method following

$$Z = \frac{R}{W^{(1/3)}} \quad (2)$$

where Z is the scaled distance, R is distance from the explosion source to the loading point, and W is the weight of TNT. This formulation implies that self-similar blast waves are produced at identical scaled distances when two different sized explosive charges (of similar geometry and chemical composition) are detonated in the same atmosphere. Using published empirical data (DOD, 2008), this scaled distance from the explosion source to a loading surface can be used to determine specific blast parameters. The CONWEP blast loading model discussed herein is based on a TNT explosion (assumed surface blast). Thus, when using CONWEP in Abaqus/Explicit, the mass of explosives in question is converted to an equivalent amount of TNT.

As outlined in (Tang and Baker, 1999), a major limitation associated with the equivalent TNT method is that the blast yield is a function of the amount of explosives and not the combustion mode; this makes this method less applicable when analyzing vapor cloud explosions. As discussed in numerous publications (Lees, 1996, Mercx et. al., 1998, Van den Bosch and Weterings, 1997, Woodward, 1998, and AIChE, 1994), vapor cloud explosions differ from conventional explosive detonations because flame accelerations, which can be exacerbated by confinement due to intervening structures, define the overpressure associated with a given explosion more so than simply the amount of fuel ignited. In order to quantify blast curves associated with vapor cloud explosions several widely accepted methods have been developed;

TNO (Van den Bosch and Weterings, 1997) blast curves and Baker-Strehlow (Strehlow et. al., 1979) blast curves among others. In this study, triangular impulses of varying peak overpressures are used for simplicity when analyzing the structural response of a double-walled storage tank subjected to a postulated vapor cloud explosion (discussed below). This also permits evaluation of the structural response sensitivity to varying blast wave parameters, such as impulse duration.

3. CONWEP Blast Loading and Incident Wave Loading

A significant challenge associated with computational blast modeling is appropriately accounting for reflection effects. The peak blast pressure that a structure is subjected to is greater than the peak incident overpressure and is referred to as the reflected pressure. This pressure is a function of the peak incident overpressure and the angle of incidence; that is, the angle between the loading direction and the surface normal of a given point on the loading surface. Generally, neglecting incident wave reflection entirely can yield non-conservative results, particularly for high peak overpressures, while assuming the maximum reflection effect at all points on a structure can potentially be overly conservative (especially for cylindrical geometries).

The CONWEP blast loading model is based on a collection of conventional weapons effects calculations from the equations and curves of TM 5-855-1 (Hyde, 1988) and is implemented into the Abaqus/Explicit through the CONWEP charge property (keyword *CONWEP CHARGE PROPERTY). The main advantage of using CONWEP over the incident wave loading approach is that realistic overpressure amplitudes (including both positive and negative phase) and other blast wave parameters are inherently calculated based on a user-defined amount of TNT at a given distance from the explosion source. Furthermore, the CONWEP blast loading model does not require modeling the fluid medium (air in this case) to account for reflection effects. The reflection formulation employed in the CONWEP charge property is depicted in Figure 2 below.

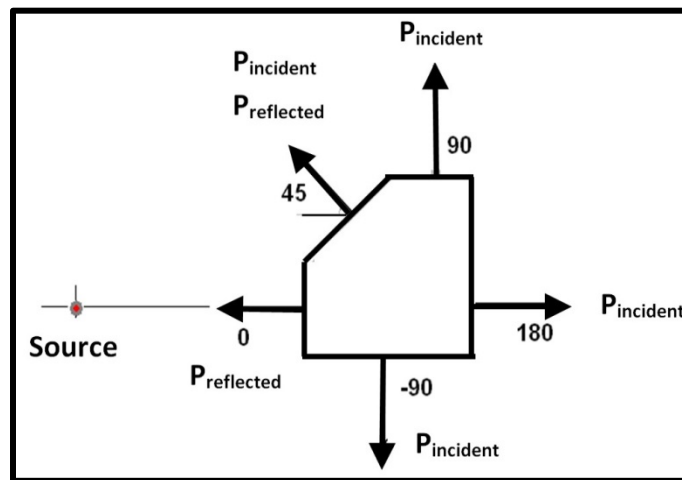


Figure 2. Blast wave reflection formulation built into the CONWEP charge property (Simulia, 2010)

In accordance with Figure 2 and the CONWEP formulation, the overpressure, as a function of angle of incidence and time ($P(t)$), observed on a loading surface is calculated as shown below:

$$P(t) = P_{incident}(t)[1 + \cos\theta - 2\cos^2\theta] + P_{reflected}(t)\cos^2\theta, \quad \text{for } \cos\theta \geq 0$$

$$P(t) = P_{incident}(t), \quad \text{for } \cos\theta < 0$$
(3)

Incident wave loading is an explicit finite element technique in which an incident wave overpressure at a point can be defined as a function of space and time (Abaqus/Explicit keyword *INCIDENT WAVE INTERACTION). This overpressure amplitude is defined at a standoff point, located between the detonation point and the loaded structure. When simulating blast loading, realistic overpressure amplitudes need to be defined by the user. An incident wave can be defined as planar or spherical. A schematic showing the incident wave loading model in Abaqus/Explicit is given in Figure 3 below. For a more rigorous overview of the underlying theory behind both the CONWEP blast loading model and the spatial decay formulation employed in the incident wave loading model, refer to a recent computational study (Prueter et. al., 2012).

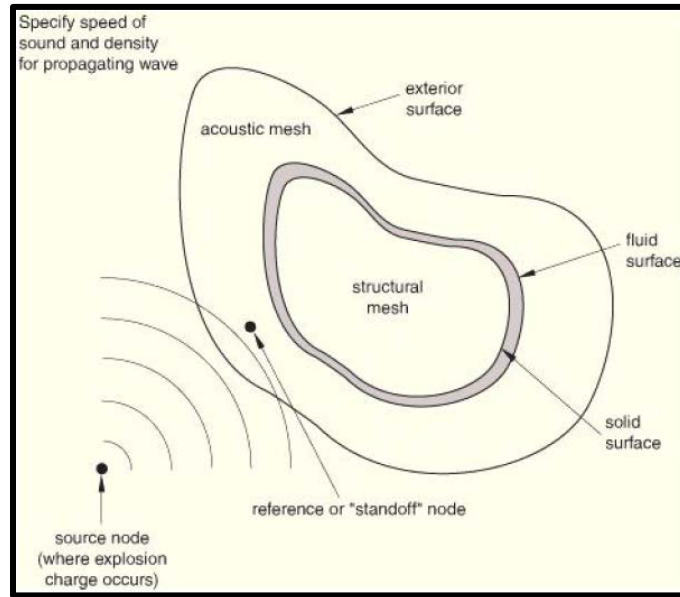


Figure 3. Incident wave loading model (Simulia, 2010)

In the incident wave loading model and as discussed in (Simulia, 2010), overpressure at a given point, x_j , can be defined as a function of space and time (t) following

$$P_I(x_j, t) = P_t(t)P_x(x_j), \quad P_x(x_j) = \left[\frac{R_o}{R_j} \right]^{\xi(R_j, R_o)} \quad (4)$$

where P_i is the incident pressure, P_t is pressure as a function of time, and P_x is pressure as a function of space. The pressure amplitude as a function of time, is defined by the user at a standoff point (keyword *AMPLITUDE), located between the detonation point and the loaded structure. An incident wave can be defined as planar or spherical. Spatial decay can be defined for spherical incident waves as shown above where R_o represents the distance between the source point and the standoff point and R_j represents the distance between the source point and some loaded point in space. The function $\xi(R_j, R_o)$ is used to define the spatial decay of a spherical incident wave.

4. Explicit Analysis of a Tank Subjected to a Vapor Cloud Explosion

As discussed in several case studies (Maremonti et. al., 1999 and Buncefield Investigation Board, 2008), the consequences of storage tank failure in chemical or petrochemical facilities can be catastrophic. To this end, it is estimated that 85 percent of all storage tank accidents are due to fire or explosion (Chang and Lin, 2006). Analyzing the structural response of storage tanks subjected to potential blast loading from conventional detonations or vapor cloud explosions is of great interest to engineers in the chemical and petrochemical industries. The explicit finite element analyses discussed in this paper represent examples of how computational blast simulation techniques can be applied to investigate the dynamic response of in-service process equipment.

The first computational blast analysis examined herein relates to a double-walled storage tank subjected to a postulated external vapor cloud explosion. A complete, elastic-plastic, three dimensional finite element model was constructed in Abaqus/CAE using linear shell elements (Abaqus S4 elements). Figure 3 shows the half-symmetry model with detailed geometric features.

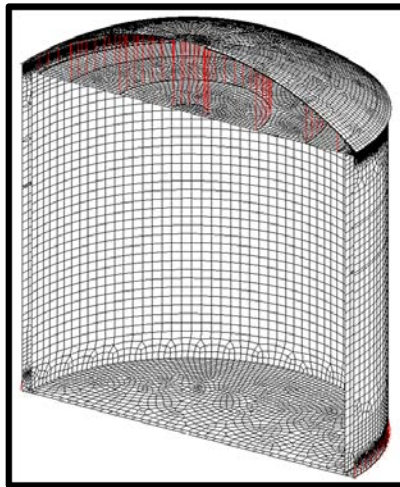


Figure 4. Vapor cloud explosion analysis 3D finite element model.

The baseline finite element model includes all major structural features, including the suspended deck, bracket supports, and the lower support straps. Quadratic beam elements are used to model

the suspended deck hanger rods and the strap supports. Both the inner and outer tanks are modeled for completeness. Contact is defined between the suspended deck and the shell wall.

In this case, because of the range of potential vapor cloud explosive scenarios, iterations are performed using incident wave loading to determine the maximum permissible overpressures and loading durations that predict containment and safe operability. The focus is on establishing a blast rating for the structure, independent of a specific explosion scenario. This provides an essential characteristic of the structure that can be referred to for any future blast loading scenarios. Peak reflected overpressures of 5, 8, and 11 psi are applied for impulse duration of 50 milliseconds to the model. Figure 5 compares maximum deflections and stresses in the domed roof (opposite impact side) for these varying peak overpressures. This figure demonstrates the relatively constant nature of the largest displacements. In the 5 psi case, maximum deflections are generally less than 12 inches with relatively little accumulation in plastic strain.

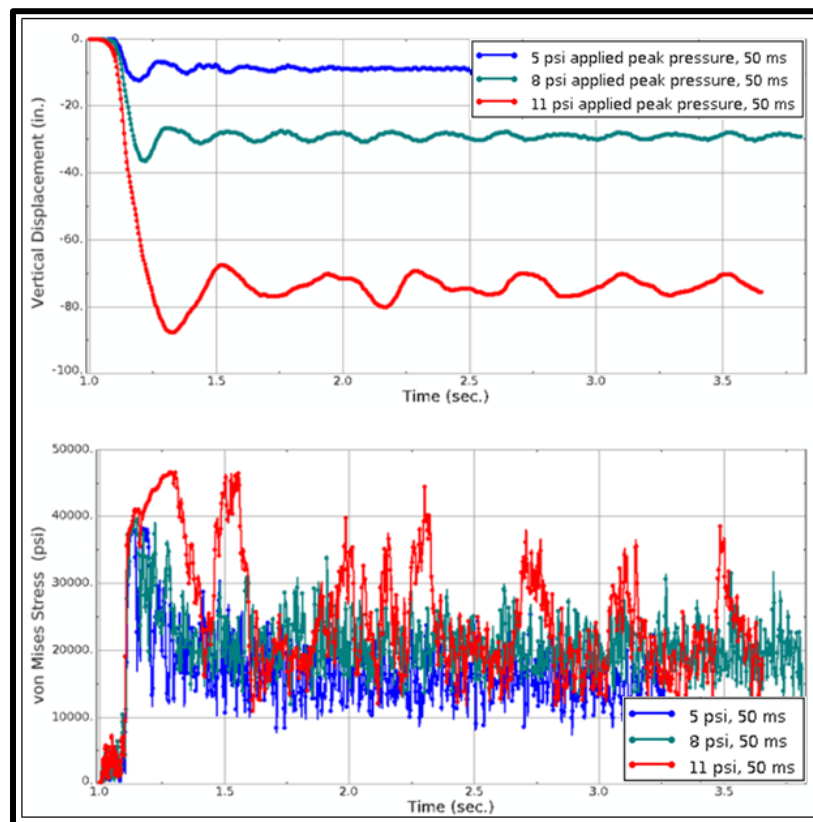


Figure 5. Deflection/stresses in domed roof opposite of impact side for varying peak overpressures

These results indicate that a peak reflected overpressure of 5 psi is near the limit to maintain tank containment following blast loading. Furthermore, for the 8 and 11 psi overpressure cases, results indicate that plastic collapse of the domed roof and tank shell would be likely, and containment of

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the tank contents would likely be jeopardized. This analysis also indicates that the suspended deck is a critical feature of the tank, and is also an indicator of safe operability. The suspended deck is one of the weakest points of the tank internals; results from the series of analyses show that a maximum peak reflected pressure of 2 psi is advisable to ensure safe tank operability (again, impulse duration assumed to be 50 milliseconds). This corresponds to a maximum side-on overpressure of 1 psi with a uniform/constant reflection coefficient of 2.

Additionally, in order to compare the effect of varying blast wave impulse durations, additional iterations are performed where overpressure is held constant and impulse duration is changed. As expected, the duration of the impulse has a significant effect on the overall structural damage. Lower peak overpressures acting at longer durations could also be damaging. Because of the variability in overpressure profiles from vapor cloud explosions, incident wave loading is employed, and offers the flexibility to perform parametric studies for different blast loads.

5. Explicit Analysis of a Doubled-Walled Storage Tank Subjected to a Conventional Explosion

A second double-walled storage tank that carries a high consequence of failure is analyzed; this time the postulated blast loading is due to the accidental detonation of a known amount of concentrated, combustible fuel. Again a complete, elastic-plastic, three dimensional finite element model is constructed in Abaqus/CAE using linear shell elements (Abaqus S4 elements). Figure 6 shows a cutaway view of the model with contours of shell element thickness, and shows the detail of the outer tank roof support structure (also modeled using linear shell elements).

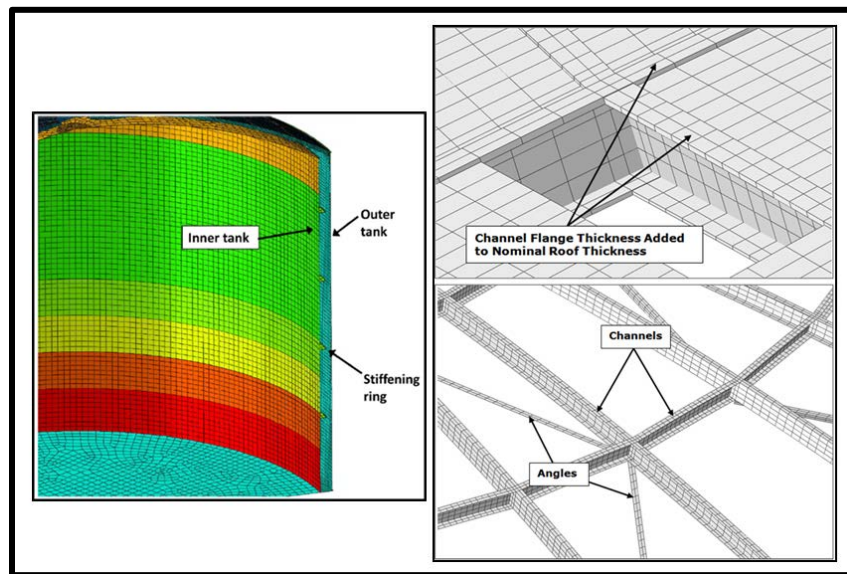


Figure 6. Cutaway view of the complete finite element model with shell thickness contours shown (left) and outer tank roof support structure details (right)

The inner tank has four external stiffening rings that extend into the annular space between the inner and outer tank. The outer tank roof support structure consisting of interconnected channels and angles is also modeled in detail (see Figure 6), and is included in the finite element model. Contact is defined between the tank structures and the effects of self-weight are included.

An initial analysis is performed on just the outer tank (unstiffened shell) to investigate the plastic strains and wall deflections due to the applied blast wave. Both the CONWEP (assumed surface blast) and incident wave loading models are compared. Due to the size of the finite element model and the significant computational requirements, the fluid medium is not explicitly modeled for the incident wave simulation. An overpressure amplitude that accounts for reflection effects is used; that is, the peak reflected overpressure is applied to the entire incident wave model. Furthermore, in order to mimic the behavior of the CONWEP simulation as much as possible, the overpressure profile defined for the incident wave simulation as a function of time does, in fact, consist of positive and negative phases and decays exponentially (obtained from a CONWEP simulation on a single, fixed element). The side-on reflection coefficient for this overpressure magnitude is 2.

Even for the relatively small peak reflected overpressure of roughly 1.9 psi, the outer tank wall deflections prove to be significant, to the point of local collapse. An Abaqus/Standard static post-buckling analysis (using the Riks solver), with surface pressure applied using an analytical field definition to match surface pressure in the dynamic simulations confirms that the outer tank wall buckles before the peak reflected pressure is reached. Riks post-buckling analyses are discussed in more detail below.

For comparison, Figure 7 shows contours of outer tank plastic deformations (identical scale) due to the overpressure wave for blast loading from the CONWEP charge property and incident wave loading.

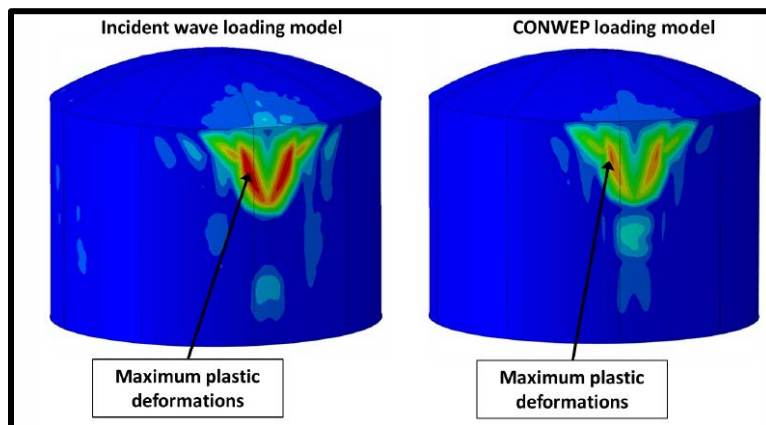


Figure 7. Outer tank plastic deformations due to blast loading using the CONWEP and incident wave loading models (contour scales identical)

As expected, the incident wave approach produces higher deflections than CONWEP because the applied peak reflected overpressure does not decrease as angle of incidence increases (moving

around the circumference of the tank). It is noted that the general agreement between methods is generally quite good. This suggests that the simplification of a single maximum reflection coefficient in this case for the incident wave approach is not excessively conservative, and that reasonable results can be obtained without modeling the entire acoustic domain, in which case reflection effects would be more rigorously accounted for (may not hold true for higher pressures).

For the blast analysis of the complete finite element model that includes both the inner and outer tanks with contact defined between shells, the outer wall deflections are much less significant because the outer tank impacts the inner tank stiffeners. Essentially, the inner tank stiffening rings absorb the impact from the outer tank wall and plastically deform. The resulting deflections in the inner tank shell are fairly minimal. This is demonstrated in Figure 8, which shows the maximum deflection during blast loading from the CONWEP simulation of the inner tank and the outer tank. The contour scale for the inner tank corresponds to 10 percent of the outer tank contour scale, and the maximum inner tank wall deflection is less than 10 percent of the maximum outer tank wall deflection. The maximum outer tank deflections occur in the regions in between the inner tank stiffening rings, and the outer tank shell wall never directly impacts the inner tank shell wall. These relatively minimal inner tank deflections suggest that the sloshing effects of the liquid contained by the inner tank would likely be minimal.

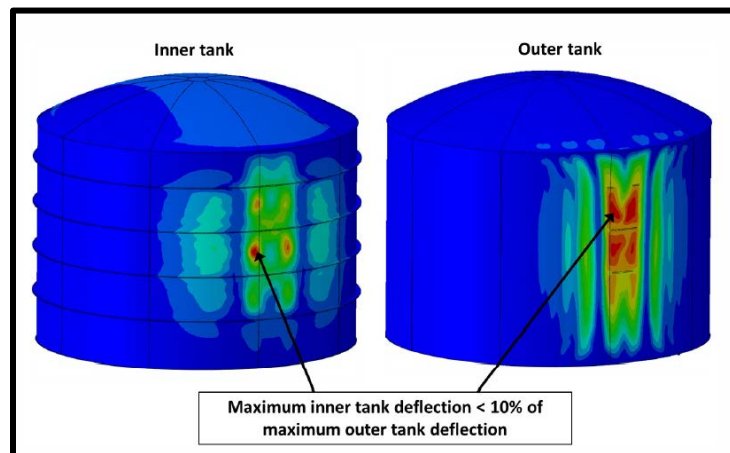


Figure 8. Maximum deflections of the inner and outer tanks due to CONWEP blast loading (inner tank contour scale corresponds to 10 percent of outer tank scale)

These results indicate that from a blast damage mitigation perspective, the four inner tank stiffening rings prove to be very beneficial in reducing the severity of the impact between the inner and outer tanks. While both explicit computational techniques used to analyze this double-walled storage tank give reasonably similar results, from a convenience standpoint, CONWEP proves to be advantageous for conventional detonations because the appropriate overpressure and spatial decay are automatically calculated for the user-defined equivalent amount of TNT. Additionally, due to the built-in formulations that account for overpressure reflection effects, some conservatism is removed in the CONWEP case compared to incident wave loading, making it the natural choice for well-defined, conventional explosive detonation scenarios.

6. Explicit Analysis of Single-Walled Storage Tanks

The postulated blast source in this case is the same source as discussed in the previous example (conventional detonation). However, this cluster of single-walled tanks is located much closer to the blast source, meaning peak overpressures are much higher than the above example. These tanks have self-supporting roofs and are anchored to their respective foundations via hold-down clips and hold-down bolts. As is the case for the above mentioned storage tanks, these tanks carry an extremely high consequence of failure due to their process contents.

Three dimensional, elastic-plastic finite element models of each tank are constructed in Abaqus/CAE using linear shell elements (Abaqus S4 elements) and explicitly analyzed using CONWEP. A node at the center of each hold-down clip is fixed in all degrees of freedom and then coupled to the surrounding bolt hole (keywords `*KINEMATIC` and `*COUPLING`) to simulate the restraint of the bolts as shown in Figure 9. A rigid surface representing the tank foundation is constructed and included in the model, and contact between this rigid surface and the tank bottom is defined. This ensures that the tank will not unrealistically sag due to gravity alone and penetrate the foundation due to self-weight (inducing non-realistic stresses in the tank floor and shell). This modeling technique also permits the tank bottom to physically lift off its foundation when the blast load is applied. In order to account for the weight of the process fluid, an equivalent pressure is applied to the tank bottom that corresponds to the weight of fluid. This pressure is applied throughout the simulation, implying that sloshing effects are neglected.

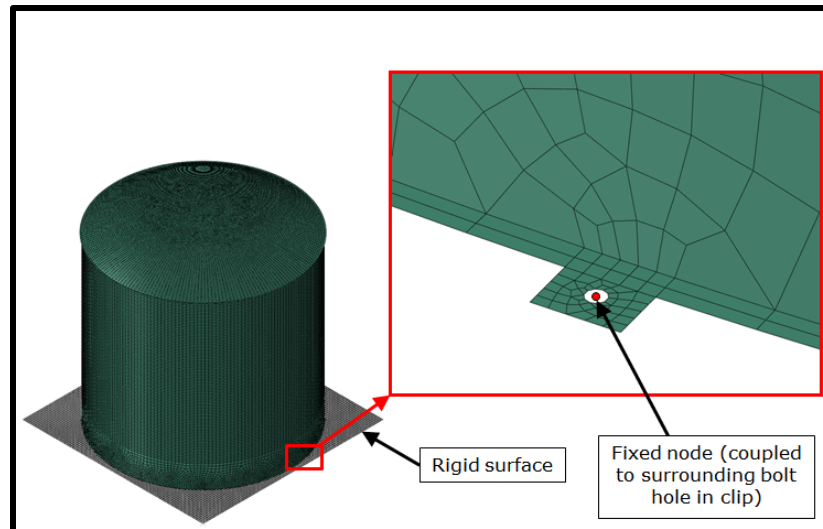


Figure 9. Finite element model of a single-walled storage tank

In this case, after the onset of the blast wave, the wall and the roof of each tank significantly deform. In order to better visualize the tank behavior following the onset of the blast wave impact, Figure 10 shows contours of deflection as time elapses for the tank closest to the blast source (time scale given is seconds after detonation). These large deflections predicted in the shell and roof of the tank are more indicative of plastic collapse-like behavior than a dynamic or

vibratory failure. Furthermore, the stresses observed in the tank shortly after blast wave impact are significant and support the prediction of a plastic collapse failure mode.

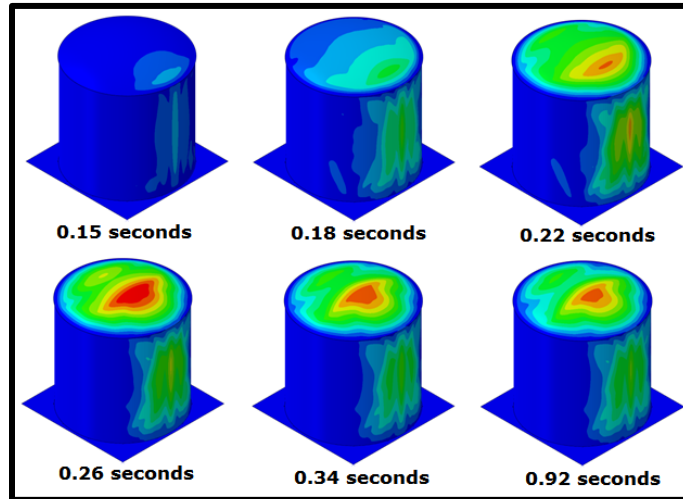


Figure 10. Progression of deformation due to blast loading in Abaqus/Explicit

Additionally, the stresses in the tank at the hold-down clips and reaction forces at the assumed bolt locations predict likely failure of either the bolts themselves or the hold-down clips. Figure 11 shows equivalent plastic strains in the tank closest to the detonation source after the impact of the blast wave (contour scale capped at 5%). The hold-down clips and other portions of the tank wall near the connection with the hold-down clips exceed 100% equivalent plastic strain. Results for the other tanks in the cluster yield similar stresses and plastic strains. In order to further investigate the possibility of plastic collapse or buckling, static Riks post-buckling analyses are performed on each tank using Abaqus/Standard. A static pressure distribution is applied to mimic peak blast loading pressures. This is achieved by defining an analytical pressure distribution in Abaqus/CAE as a function of the global coordinates (higher order polynomial functions are defined in multiple directions).

A Riks analysis is useful for simulating non-linear instability problems, and includes the effects of large deformations and elastic-plastic material behavior. It can also be used to look at post-buckling or collapse shapes. The applied load in a Riks analysis is actually a variable and part of the solution for each increment, and is always relative to the current deformed configuration of the structure. If no converged solution is possible for an incremental increase in load, then the equilibrium solutions can be calculated with a decreased applied load. This is the mechanism that allows post-buckled shapes to be predicted and visualized. In extreme cases, no equilibrium solution can be reached, even with decreased load, and only load reversal is predicted to lead to a stable solution. This is the case for the single-walled tanks discussed herein, where once collapse has initiated, displacements are predicted to be essentially unbounded for any amount of positive load and thus, surface pressure becomes negative before peak overpressure values are achieved (in this case, load reversal occurs at a fraction of peak reflected overpressure).

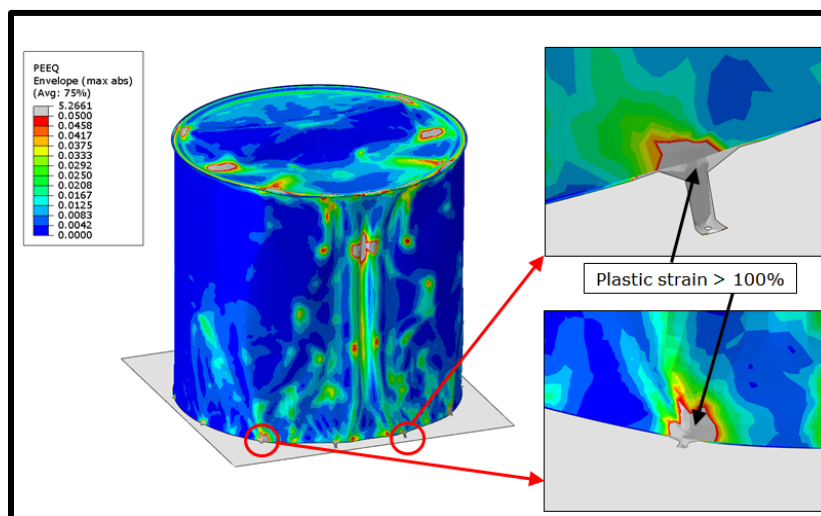


Figure 11. Equivalent plastic strain due to blast loading (contour scale capped at 5%)

Based on the computational results discussed above, the three storage tanks subjected to the assumed postulated blast load are likely to fail via several possible failure modes. The first likely failure mode is plastic collapse of the tank walls and/or roofs. All three tanks see large deflections, and Riks post-buckling analyses confirm that the magnitude of deflections seen in the tank walls would likely result in unstable collapse behavior before the peak blast overpressure is achieved. A second likely failure mode is extreme damage in the tanks at the hold-down bolts and/or regions of the tanks that are connected to the bolts. In all three tanks, equivalent plastic strains exceed 100% in these regions.

Failure of multiple hold-down bolts or hold-down clips could cause gross failure of tank anchorage, and as a result, the tank could slide off its foundation or potentially overturn. Furthermore, sloshing effects of the fluid inside the tanks are neglected in the simulations discussed herein, but would possibly increase the likelihood of failure and possibly contribute to tank collapse or overturning. Essentially, the close proximity of all three tanks to the postulated blast source and corresponding blast wave overpressures indicate that failure would be probable if the given detonation event were to actually occur. Design changes to the tanks to supplement blast damage mitigation would likely have to be drastic in order to achieve a significant reduction in the overall probability of failure.

The analyses discussed herein employ explicit FEA formulations, which in general, are well suited for analyzing highly transient, non-linear behavior and permit evaluation of models with highly discontinuous events with large deformations. Explicit FEA simulations are computationally expensive due to the small time increments generally needed to achieve convergence. It is noted that in order to achieve practical simulation times, all of the explicit analyses discussed herein are conducted across multiple CPUs (often 16 or more) simultaneously. Utilizing parallel computing permits explicit evaluation of complex, three dimensional structures, such as the storage tanks discussed in this paper. Further details of the explicit FEA performed on the hazardous chemical storage tanks discussed herein are available in a recent publication (Prueter and Dewees, 2013).

7. Conclusions

This study compares two different Abaqus/Explicit computational methods for modeling blast loading on structures; incident wave loading (Abaqus/Explicit keyword *INCIDENT WAVE INTERACTION) and the CONWEP charge property (Abaqus/Explicit keyword *CONWEP CHARGE PROPERTY). The conventional weapons effects blast loading model (CONWEP) is well suited for conventional detonations and uses the equivalent TNT method. It also inherently calculates the appropriate blast wave parameters for a given detonation event. Additionally, CONWEP achieves realistic overpressure amplitudes, spatial decay, and reflection effects without having to model the fluid medium, as is the case for incident wave loading. Incident wave loading provides the user with the flexibility to define time-varying overpressure amplitudes. This is useful when performing iterative or sensitivity studies to evaluate blast loading parameters or when attempting to characterize the blast wave associated with a vapor cloud explosion that does not behave like a conventional detonation. The development and implementation of the CONWEP and incident wave blast loading models into Abaqus/Explicit makes accurately analyzing the response of complex, 3D structures subjected to blast loading feasible.

Additionally, explicit, three dimensional finite element analyses of both single and double-walled storage tanks that carry an extremely high consequence of failure are discussed herein. Incident wave loading is used iteratively to determine the maximum permissible overpressure for a double-walled storage tank subject to a postulated vapor cloud explosion. The CONWEP blast loading model is used to analyze single and double-walled storage tanks subjected to a postulated chemical explosion (conventional detonation of concentrated chemical explosives). Gaining a better understanding of the possible failure modes due to blast loading of critical process equipment in the petrochemical and related industries is very beneficial to engineers working in these fields. The explicit computational methods built into Abaqus/Explicit, such as the ones examined herein, can provide valuable insight into the blast resistance of existing structures and can guide design decisions regarding how to mitigate potential blast damage on fixed process equipment.

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