An analysis of TNT equivalencies using AUTODYN

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ABSTRACT

In the analysis of structures under blast loading, it is common practice to express the explosive input or charge weight as an equivalent mass of TNT. TNT equivalencies may be calculated using a variety of methods, including methods based on peak pressure or impulse, however different values may be obtained depending on the method used. In this paper, ANSYS® AUTODYN® is used to calculate TNT equivalencies for three different explosives at varying distances from the explosive charge, using both peak pressure and impulse methods. The TNT equivalency curves were different depending on whether the equivalency was based on peak pressure or impulse. This observation is consistent with experimental results for TNT equivalencies presented in literature. When TNT equivalencies are used, an understanding of how they are calculated and when they are valid is essential for engineers designing against blast loads.

KEYWORDS

AUTODYN; blast; TNT; TNT equivalency.

INTRODUCTION

In the blast resistant design of structures such as buildings, as well as post-blast analysis of explosive events, explosive threats are commonly expressed as an equivalent weight of TNT. TNT equivalence can be calculated based on a number of different parameters using either experimental or theoretical methods. Locking (2011) provides a recent summary of available experimental and theoretical methods, while Cooper (1994) provides details on a number of experimental methods. One method discussed by Cooper is the air blast test, which was used to generate equivalencies reported in Swisdak (1975), which are still commonly used today. In these tests, two different equivalencies are reported, one based on peak blast overpressure and the other on blast impulse. To determine an equivalency, the explosive is detonated with the pressure or impulse measured at set distances from the charge. The explosive mass of TNT required to produce the same pressure or impulse at the same distance is then used to determine the equivalency. Another method discussed by Cooper (1994) is the plate dent test. This test as the name suggests uses the plastic deformation of a plate subjected to a cylindrical explosive charge as the performance measure of the explosive. Cooper (1994) surmises that the plate dent test correlates to the Chapman-Jouguet (CJ) pressure of the explosive and that this is the best equivalency to use for applications relating to "shattering and/or producing plastic deformation of an adjacent material".

The accuracy of TNT equivalences is questionable. Locking states that variations of up to 50% can occur with 20% to 30% being typical. As an example, the difference between TNT equivalencies calculated from air blast tests can differ depending on whether they were calculated using peak pressure or impulse. The air blast experimental equivalency plots reported in Swisdak (1975), show that the equivalency also varies with pressure (or distance from the charge). However, Swisdak reports that for many purposes, it is sufficient to use a single value, which is a linear average of equivalent weights of a range of pressure. For example, C4 pressure equivalencies reported by Swisdak range from below 1 to over 1.5, however the single value quoted is 1.37. Depending on the application, the average value or exact value as read from the curves may be used. Handbooks such as the *Handbook for Blast Resistant Design of Buildings*, by Dusenberry (2010) will often state single values rather than presenting curves. The majority of the equivalency values provided by Dusenberry (2010) are taken from the equivalency values developed by Swisdak (1975). However, it is important to understand the origin of these values and their limitations when using TNT equivalencies in structural design.

In this paper, we use numerical modelling to simulate the air blast test method using bare spherical charges. The TNT equivalencies produced using AUTODN are then compared to values presented in the *Handbook for Blast Resistant Design of Buildings*, by Dusenberry (2010). The explosives considered in this investigation are C4, pentolite and ANFO. The equivalencies for these explosives as taken from Dusenberry (2010) are shown in Table 1. A case study is then used to compare the deformation of a steel container using equivalent values of the selected explosives.

Table 1. TNT equivalencies for selected explosives from Dusenberry (2010).

Explosive	Equivalency for Pressure	Equivalency for Impulse	Pressure Range [MPa]
C4	1.20	1.19	0.07 – 1.38
	1.37	1.19	1.38 – 20.70
Pentolite	1.42	1.00	0.03 – 0.69
	1.38	1.14	0.03 – 4.14
	1.50	1.00	0.03 – 6.90
ANFO	0.87	0.87 (estimated)	0.03 – 6.90

METHODS

Numerical simulations to calculate equivalencies

ANSYS® AUTODYN® was used to simulate spherical free-air bursts of TNT, C4, pentolite and ANFO. The detonation and expansion of the spherical charges were simulated using a one dimensional Euler wedge, which is shown in Figure 1. The wedge was 10.2 m long and had 2,000 elements along its length. The elements were weighted such that there were smaller elements near the detonation point, where the highest pressures were expected. A flow out condition was applied to the end of the wedge at X=10.2 m, to allow the pressure wave to flow out of the grid. The explosives and air were modelled using the numerical models available in the AUTODYN library. The Jones-Wilkins-Lee (JWL) equation of state is used for all four explosives. The JWL values for TNT, C4 and pentolite are taken from Dobratz and Crawford (1985), while the values for ANFO are taken from Davis and Hill (2002). The wedge was filled with an explosive material model to the calculated charge radius (dependent on the mass and density of the explosive being simulated), and the remaining elements were filled with the material model for air. The pressure-time history was documented at 0.5 m intervals within the simulation. The simulations were run for 20 ms to ensure the full blast overpressure history was documented.

Simulations were first run for TNT charges ranging from 6 kg to 25 kg, at 1 kg intervals. This allowed a database of TNT pressures at distances up to 10 m to be recorded. Next, 15 kg charges were simulated using C4, pentolite and ANFO. For each explosive, the peak overpressure and impulse were calculated at each gauge point. The impulse was calculated as the area under the positive phase of the pressure-time graph. A logarithmic interpolation was then used to calculate the explosive mass of TNT which would produce the same peak overpressure or impulse at that distance. The TNT equivalency was then calculated by dividing the mass of TNT (in kg) required to produce the same peak overpressure or impulse at that distance by 15 kg.

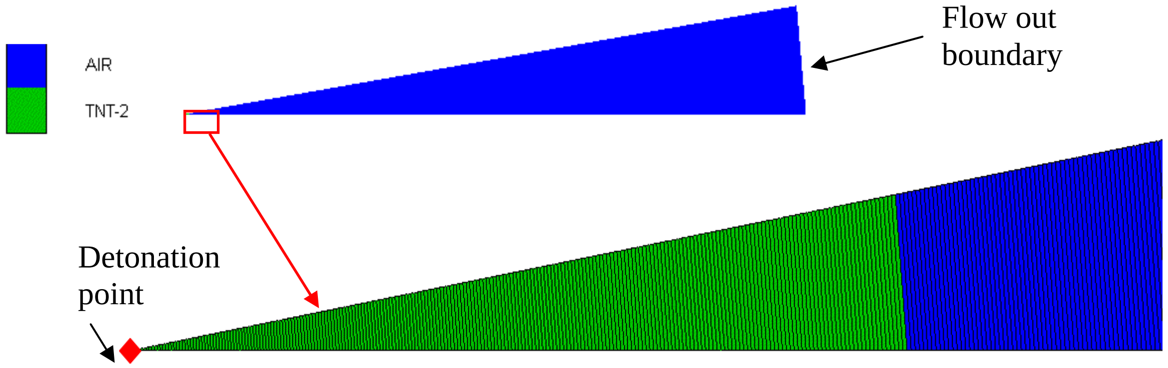

Figure 1. Numerical model setup in AUTODYN. The top image shows the full wedge, while the lower image shows a close up of the mesh in the vicinity of the explosive.

Case study simulations: Blast on a container

Simulations were run to compare the effect of using equivalent TNT values on the deformations of a basic steel container under blast loading. Figure 2 shows the model setup, which used a 2D Euler grid to simulate the explosive loading coupled to a Lagrangian grid to simulate a steel container. The 2D model with axial symmetry represented a donut shaped container with an inner radius of 5 m, an outer radius of 8 m and was 3 m high. The container was constructed using 20 mm thick steel walls and roof, with four elements through its thickness and 600 elements along each 3 m length. The base elements of the container (Y=0) were set such that all velocities and moments were zero. The material model used for the steel (STEEL 4340) was taken from the AUTODYN material library and uses a Johnson-Cook strength model (Johnson and Cook, 1985). The Euler grid used 25,000 elements and was filled with the material model for air. The X=5000 and Y=10,000 Euler grid boundaries were set as flow out boundaries, and axial symmetry was used to simulate a hemispherical charge. In each simulation, the Euler grid was filled with the material model for the explosive over a quarter-circular area to represent a hemispherical charge positioned at the origin. A 500 kg TNT charge was chosen arbitrarily as the baseline. The “equivalent” explosive masses of the C4, pentolite and ANFO charges were calculated using the equivalencies given in Dusenberry (2010). In each simulation, a gauge at the centre of the front wall of the container recorded the displacement of the container wall, which was used for comparison between the models.

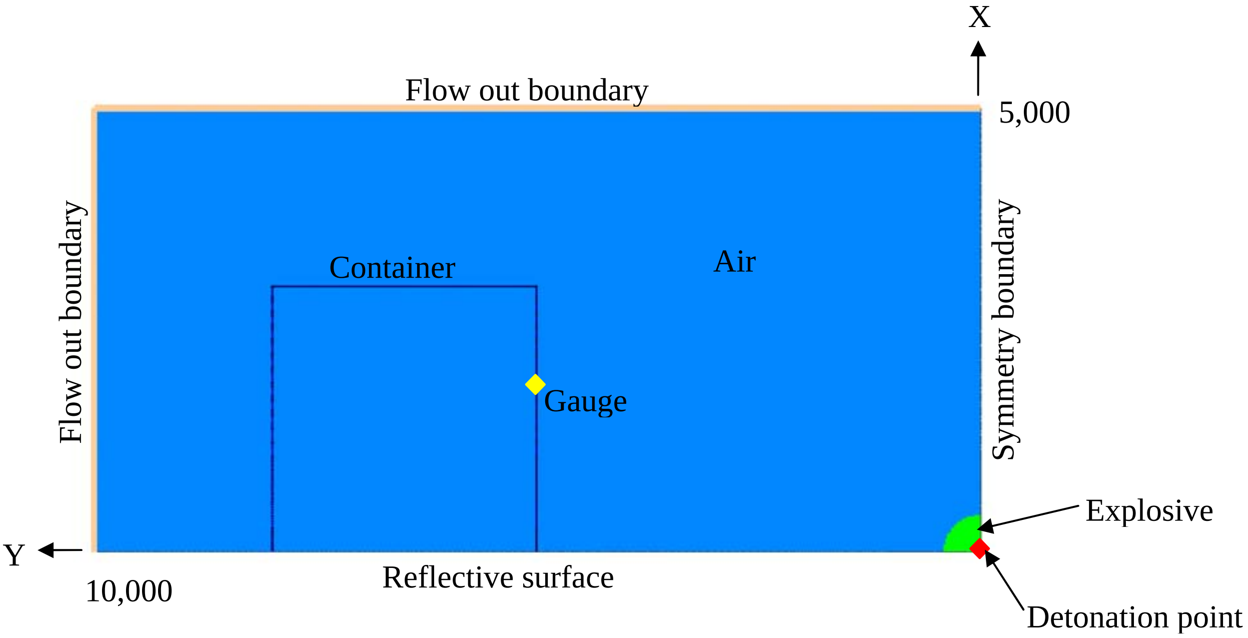

Figure 2. Numerical model setup for the simulation of a hemispherical blast on a steel container. Dimensions are specified in mm.

RESULTS AND DISCUSSION

Numerical simulations to calculate equivalencies

Figures 3 to 5 show plots of the equivalencies determined using AUTODYN, compared with values reported in Dusenberry (2010). For C4 (Figure 3), the values for both impulse and pressure equivalencies below 300 kPa are similar. However, at higher pressures, the AUTODYN calculated impulse and pressure equivalencies deviate from the values proposed by Dusenberry. The AUTODYN impulse equivalency increases and then decreases as the pressure increases, whereas the AUTODYN pressure equivalency increases with increasing pressure. For pentolite (Figure 4), the AUTODYN impulse and pressure equivalencies are similar to each other and the Dusenberry impulse equivalency up to a pressure of around 1000 kPa. Beyond this point, the AUTODYN impulse equivalency increases and then decreases (in a similar manner to the curve seen for C4), whereas the equivalency reported by Dusenberry remains constant before decreasing to 1.0 at 4.14 kPa. The pressure equivalencies from AUTODYN for pentolite do not match the values from Dusenberry over any range; however both sources show an increase in equivalency with pressure. For ANFO (Figure 5), the AUTODYN pressure and impulse equivalency values are lower than the equivalencies reported by Dusenberry. Dusenberry reports an equivalency of 0.87, whereas the AUTODYN simulations result in equivalencies that are less than 0.7. This may be due to the AUTODYN material model not fully capturing the behaviour of the ANFO material. The AUTODYN pressure equivalency for ANFO reduces with increasing pressure, while the AUTODYN impulse equivalency was found to remain fairly constant.

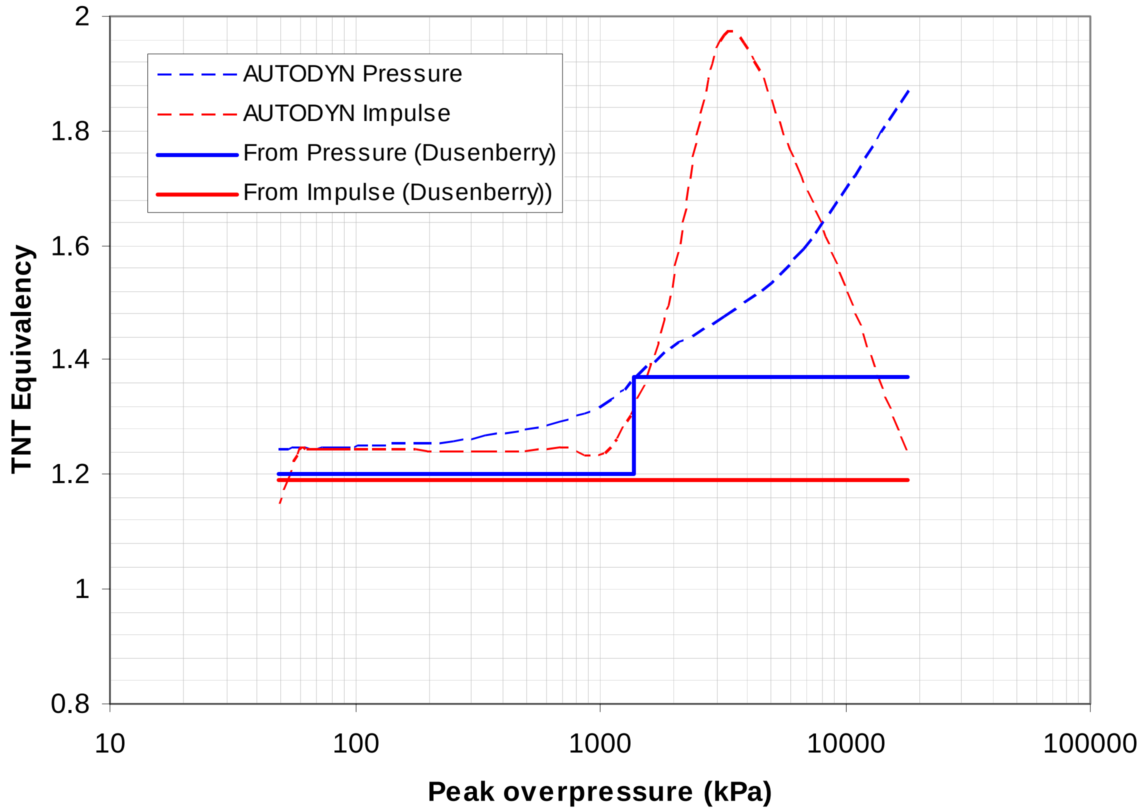

Figure 3. Comparison of TNT equivalencies for C4 using AUTODYN and Dusenberry (2010).

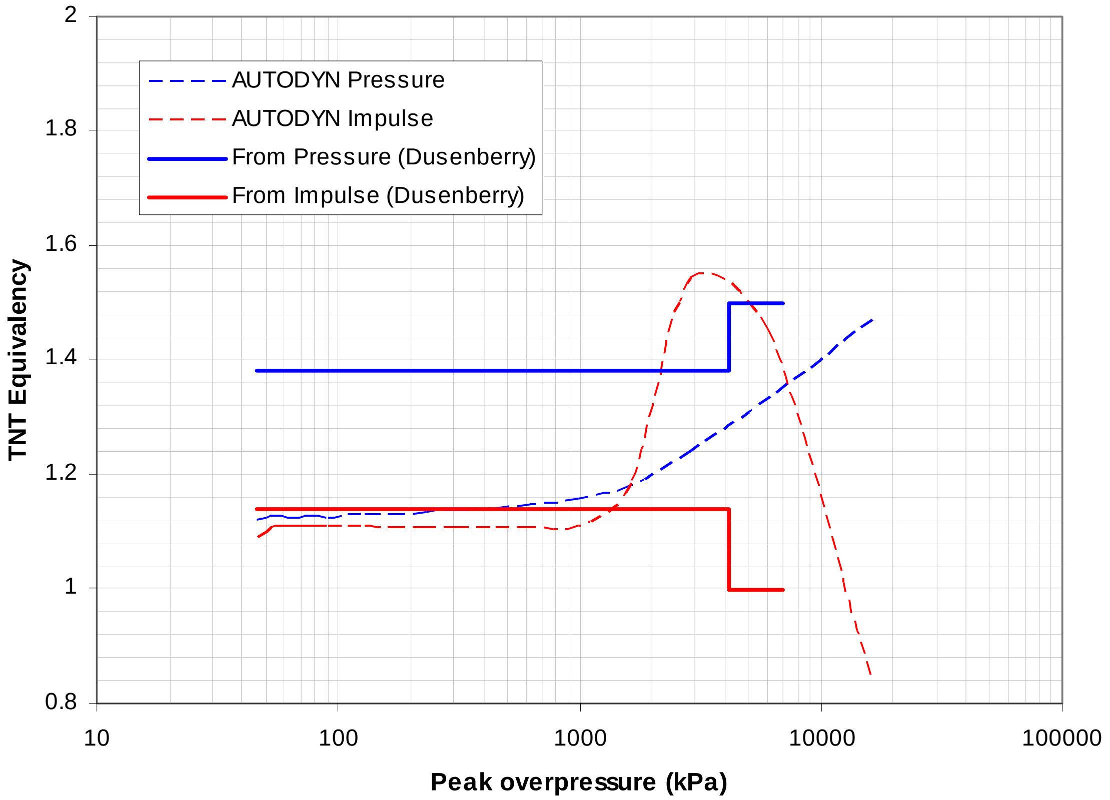

Figure 4. Comparison of TNT equivalencies for pentolite using AUTODYN and Dusenberry (2010).

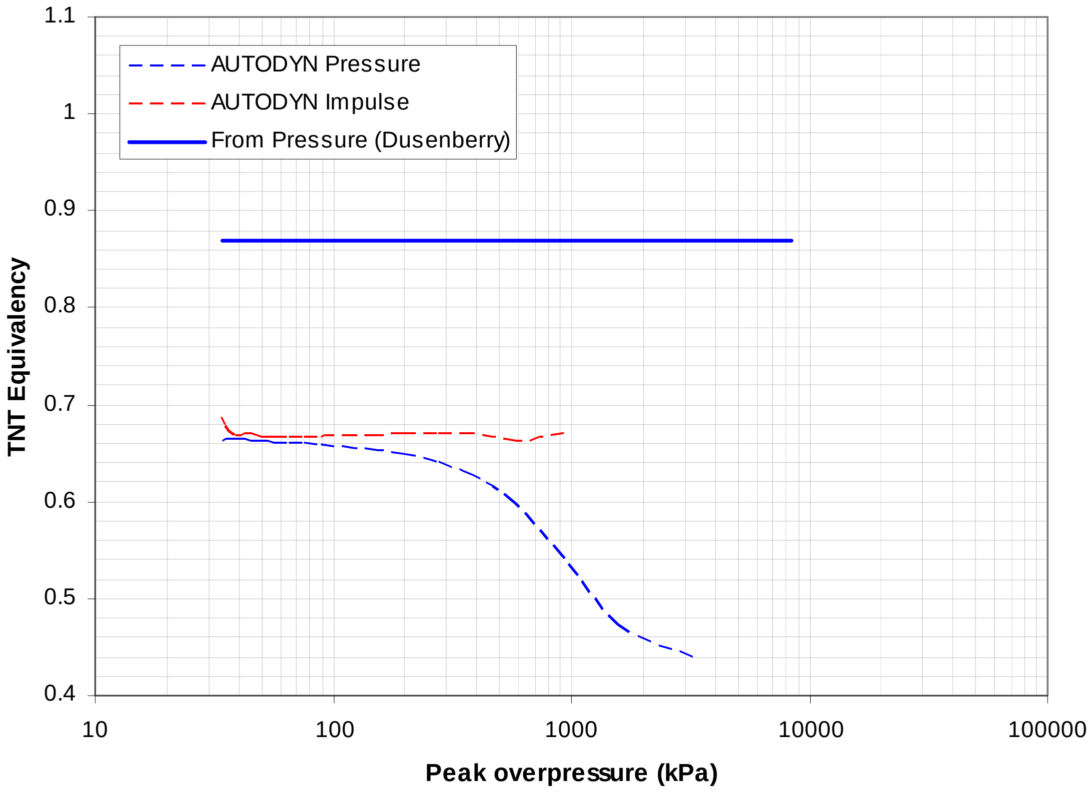

Figure 5. Comparison of TNT equivalencies for ANFO using AUTODYN and Dusenberry (2010).

Case study simulations: Blast on a container

Figure 6 shows a screen capture of the AUTODYN pressure contours during the simulation of a 500 kg charge of TNT, as the blast wave begins to interact with the container. Figure 7 shows the displacements of the container wall for six simulations. Although these simulations all used "equivalent" to 500 kg TNT, variations in the deformation of the container wall were seen. For C4 and pentolite, the impulse equivalencies produced peak deformation results which were close to the 500 kg TNT deformations (within 2%). The peak deformations using pressure equivalencies were 14% and 21% lower for C4 and pentolite, respectively. The peak deformation using ANFO was 24% lower than when using an equivalent weight of TNT.

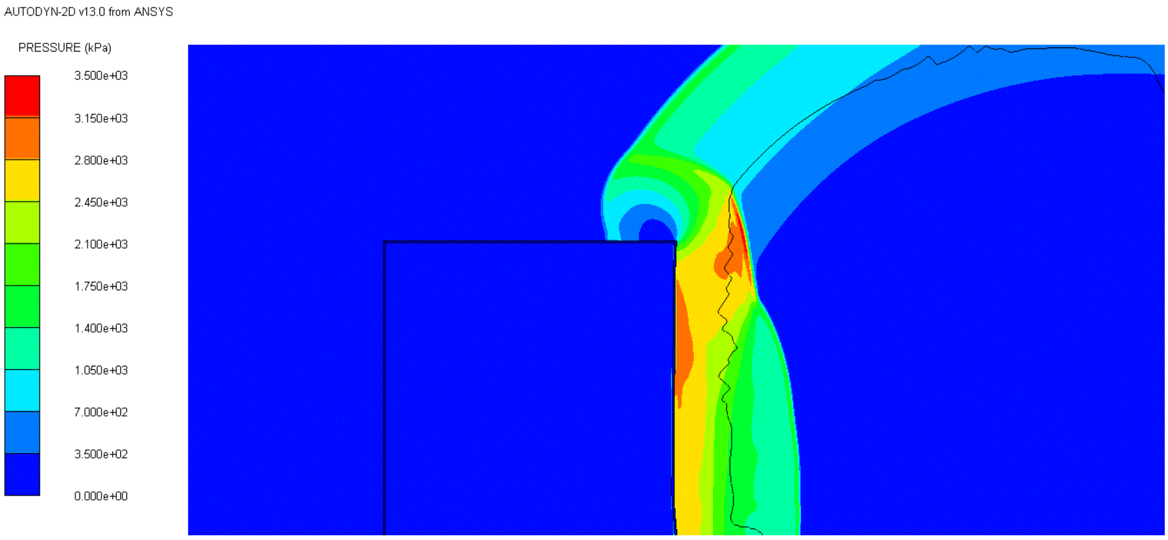

Figure 6. Pressure contours from the simulation of the interaction of the blast wave from a 500 kg hemispherical TNT charge and a 3 m × 3 m steel container.

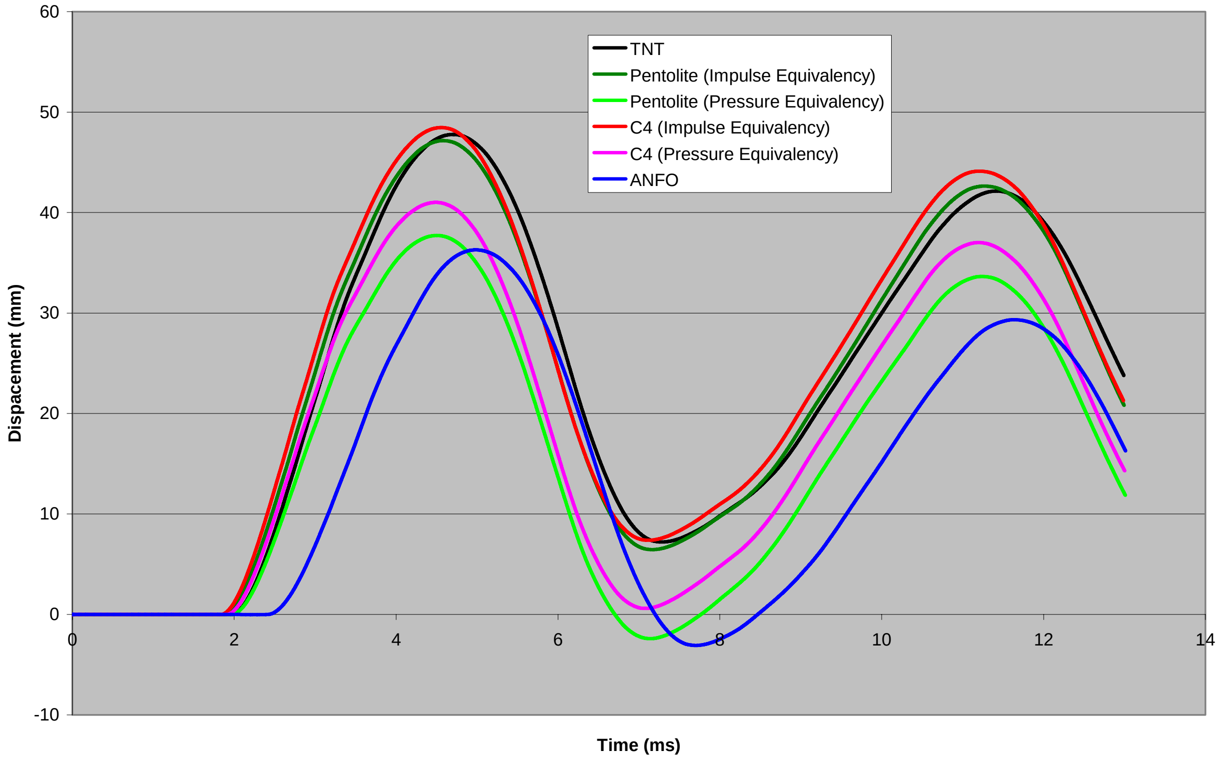

Figure 7. Container wall displacement histories for six 500 kg TNT equivalent charges.

Selection of Appropriate TNT Equivalency

In terms of structural response, impulse equivalencies are expected to be more accurate than pressure equivalencies, as the impulse (rather than pressure) is more representative of the load on the structure. This is supported by the results of the case study shown in Figure 7. However, at close range the transfer of momentum due to the dynamic flow of detonation products also affects the structural response, but is not captured when calculating impulse as the area under the pressure-time curve.

As mentioned previously, Cooper (1994) suggests the use of CJ pressure equivalency when looking at plastic deformation. The CJ pressure equivalency for pentolite and C4 are 1.21 and 1.33 respectively. These are the CJ pressures specified by Dobratz and Crawford (1985). The CJ pressure equivalency for pentolite was found to be similar to the impulse equivalency. However the CJ pressure equivalency for C4 was found to be similar to the air blast pressure equivalency.

If TNT equivalencies are to be used, the most appropriate value is entirely dependent on the situation being assessed, including the pressure range of interest and the measures of performance of the structural response.

CONCLUSIONS

The results presented in this paper highlight the variations in results which can occur when using different values for TNT equivalencies in modelling the interaction of a blast wave with a physical structure. It also highlights the variation in the actual TNT equivalency values when using different methods of derivation. When looking at structural deformation it was found that the impulse equivalency provided the most accurate results. However when using TNT equivalency values in structural design it is essential to have an awareness of the source and an understanding of the limitations of the TNT equivalence values used for blast loading.

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