West Fertilizer Explosion Structural Damage and Source Energy

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Abstract

On April 17, 2013, a fire and explosion occurred at the West Fertilizer facility which resulted in the deaths of twelve first responders and three members of the public, injuries to more than two hundred people, and extensive damage to the facility, surrounding homes, and community facilities. West Fertilizer was a fertilizer storage and distribution facility located in the town of West, TX. The source of the explosion was firmly established prior to ABS Group's arrival on site of West Fertilizer as a catastrophic explosion of Ammonium Nitrate within the Production Building. The explosion projected many pieces of the Process Building and a substantial amount of crater ejecta. The explosion also generated a blast wave that swept across the surrounding area causing significant structural damage to homes and community structures. ABS Group was contracted by the U.S. Chemical Safety Board (CSB) to perform a site survey, collect data pertaining to structural damage and to perform analysis to develop an estimate of the explosion severity and resulting overpressure and impulse contours. This presentation will provide a brief summary of the methodology utilized to determine the explosion energy in pounds of TNT and discuss the observed damage to the community of West, TX from the April 17, 2013 explosion.

1 Introduction

On April 17, 2013, a fire and explosion occurred at the West Fertilizer storage and distribution facility in West, Texas, which resulted in 15 deaths, injuries to more than 200 people, and extensive damage to the facility, surrounding homes, and community facilities [i]. The explosion occurred at approximately 7:51 pm, 22 minutes after being reported to local authorities [i].

The fire and explosion were investigated by the United States Chemical Safety and Hazard Investigation Board (CSB) [i]. ABS Group was contracted by the CSB to perform a site survey, collect data pertaining to structural damage, and perform an analysis to develop an estimate of the explosion severity and resulting overpressure and impulse contours [ii].

2 Background

The town of West is located approximately 20 miles north of Waco, Texas, on Interstate 35. A United States Geological Survey (USGS) map of West is shown in Figure 1. The West Fertilizer Co. site is highlighted in yellow and prominent community structures are noted, including West Intermediate School, West High School, West Middle School, the local nursing home, an apartment complex, and a community playground. Photographs of the West Fertilizer Co. site before and after the event with key features of the West Fertilizer Co. property labeled are provided for reference in Figure 2.

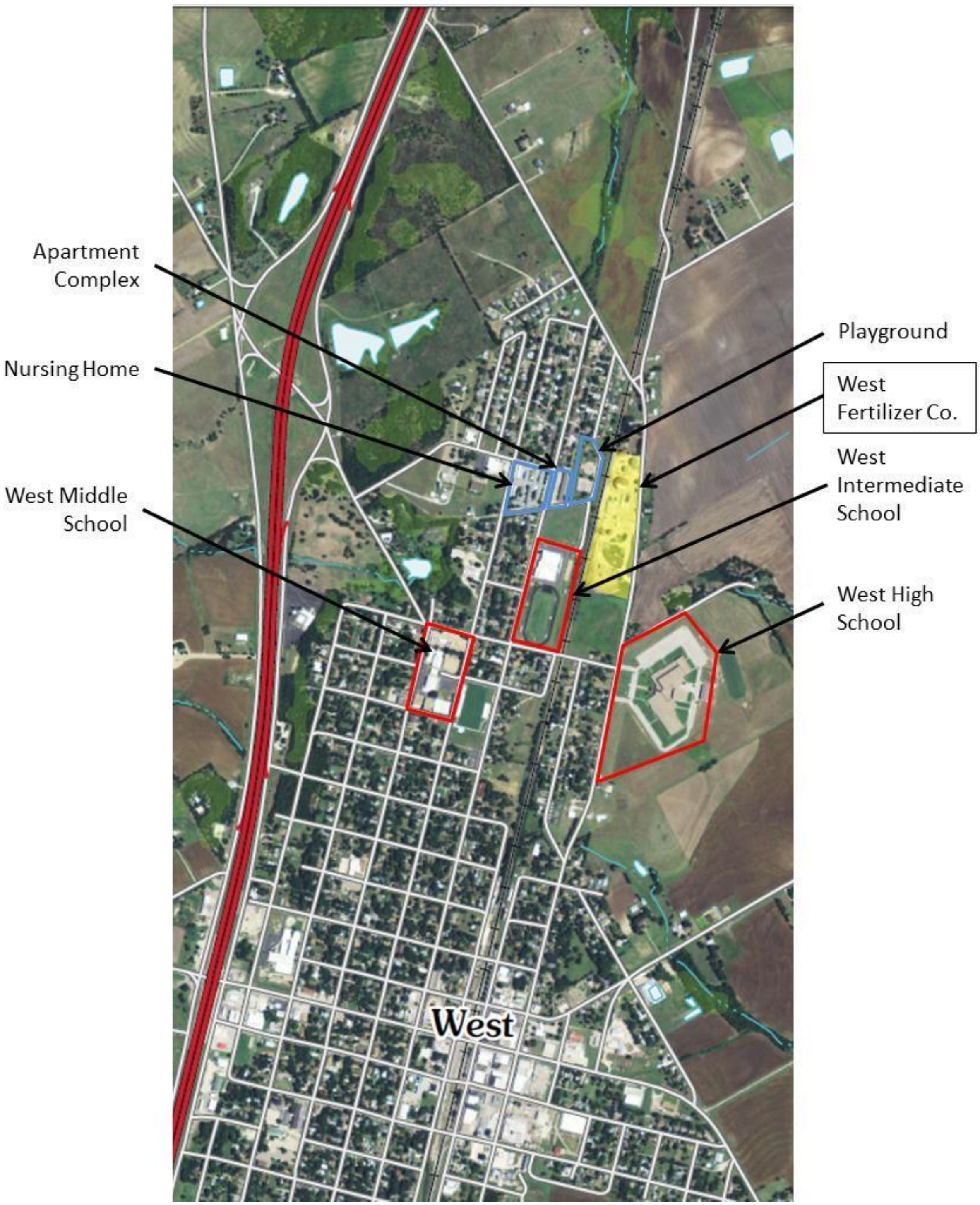

Figure 1. USGS Aerial Map of West, TX

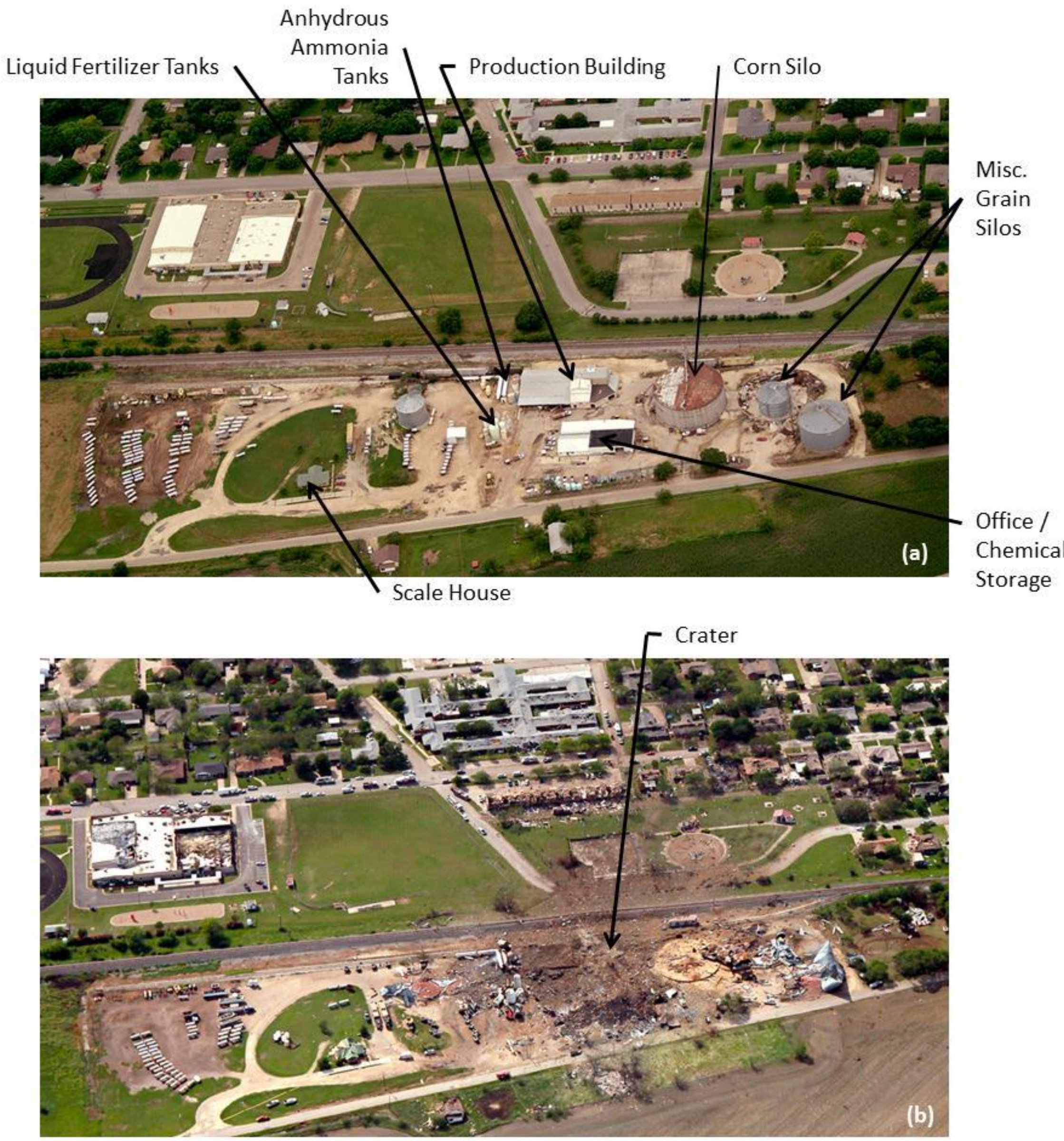

Figure 2. Aerial Photo of West Fertilizer (a) Before Event, (b) Post Event

Figure 3 shows the West Fertilizer crater as observed after the explosion and altered during investigation. The crater lip to lip diameter was approximately 90 feet with an apparent depth of 7.5 feet. [i]

A rail car loaded with fertilizer grade ammonium nitrate (FGAN) was located on the West Fertilizer site, 190 feet to the north of the explosion center. The rail car, shown below in Figure 4, was overturned and heavily damaged by the explosion.

In addition to devastating the West Fertilizer facility and site, the explosion caused extensive damage to the surrounding community. This highlights the importance of understanding potential offsite hazards and community risks posed by fertilizer storage facilities.

Figure 3. West Fertilizer Crater

Figure 4. Rail Car Loaded with Ammonium Nitrate Overturned by Explosion

3 Damage to the Community

ABS Group documented the blast damage to structures in the community of West and performed structural analyses of the blast damage to make an estimate of the explosive yield that was most consistent with the observed damage. A portion of the field observations are summarized in this section to provide a better understanding of the damage caused by the explosion to surrounding areas.

3.1 Community Structures and Facilities

Several structures were in close proximity to the explosion at West Fertilizer and were surveyed to ascertain the level of damage. These facilities, highlighted previously in Figure 1, included:

- Apartment Complex
- Nursing Home
- West Intermediate School
- West High School

3.1.1 Apartment Complex

An apartment complex was located approximately 450 feet (K15) due west from the explosion center. The apartment building was a two-story wood framed structure with wooden roof trusses. The apartment building was heavily damaged by the explosion with failure of all walls and the roof as shown below in Figure 5. There were two fatalities reported in this building.

Figure 5. Apartment Complex East Façade – 450 ft. (K15)

3.1.2 Rest Haven Nursing Home

The Rest Haven Nursing Home was located 650 feet (K22) to the west of the crater and was also heavily damaged by the explosion, as shown below in Figure 6. The nursing home was constructed of load bearing wood stud walls with brick veneer and wood trusses that span from exterior wall to exterior wall.

The Nursing Home was subjected to a large number of debris strikes from the crater ejecta which penetrated the roof, as seen in Figure 7. The size of the crater ejecta debris was large, even at this distance.

Figure 6. Damage to Eastern Entry of Rest Haven Nursing Home– 650 ft. (K22)

Figure 7. Post Incident Aerial View of Rest Haven Nursing Home (Roof Debris Impacts)

3.1.3 West Intermediate School

West Intermediate School was located approximately 700 feet (K24) to the southwest of the explosion center. The building was constructed in sections, which are identified in Figure 8. The first section, located nearest the explosion, was a pre-engineered metal building consisting of lightweight steel frames, cold-formed girts, and purlins supporting lightweight metal decking. The gymnasium and portions of the school were constructed of precast concrete tilt-up, load-bearing walls that supported open web steel joists and a metal roof deck. The school was not in session at the time of the explosion, which occurred at 7:51 pm [i].

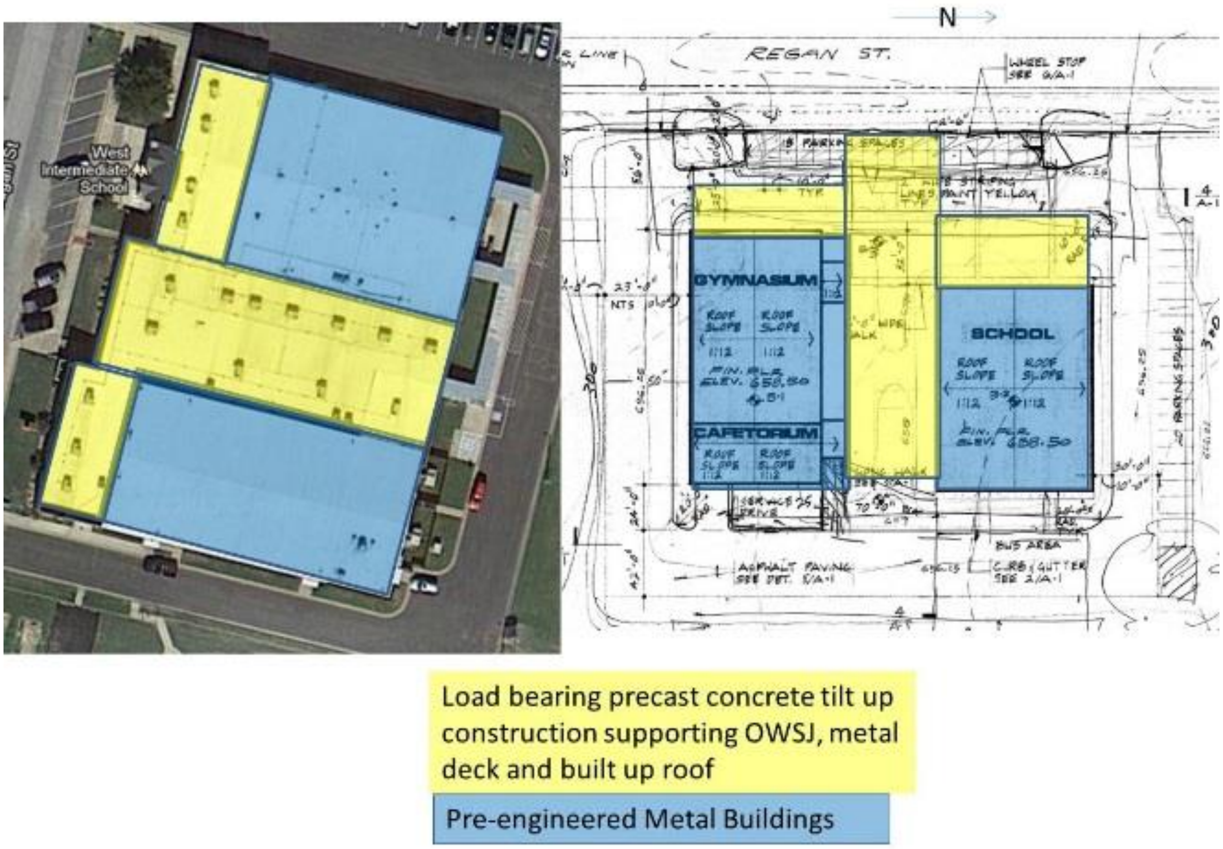

Figure 8. West Intermediate School Building Sections – 700 ft. (K24)

The pre-engineered metal frame/metal clad portion of the school in the northeast corner was heavily damaged by blast overpressure and was also fully involved in a fire. Damage to this portion of the building could not be evaluated due to the excessive damage associated with the fire. An aerial view of the roof is shown in Figure 9 and a view looking east down the hallway of this portion of the school is shown in Figure 10.

Figure 9. West Intermediate School – Original School Northeast Wing Roof

Figure 10. West Intermediate School Interior of Northeast Section that Burned

Classrooms in the center of the school were heavily damaged by the explosion and the interior of a classroom as shown in Figure 11. The acoustic ceiling, light fixtures and insulation have been forced to the floor from a combination of roof motion and air blast entering through the HVAC duct after the roof top air conditioner was displaced by the explosion. The entire ceiling plenum was found on top of the desks.

Figure 11. West Intermediate School – Classroom Nonstructural Debris

3.1.4 West High School

The high school, which was located approximately 1,500 feet (K50) to the southeast of the explosion site, was constructed of concrete masonry unit (CMU) walls supporting open web steel joists and a metal deck with built-up roofing and gravel ballast.

The school was arranged into two wings. The north wing of the high school faced the explosion and was subjected to reflected overpressures. The athletic gymnasium roof, shown overhead in Figure 12, collapsed as a result of the explosion. The joist girders, shown in Figure 13, failed from the in-plane load created by the blast reaction from the reflected wall facing the explosion.

Figure 12. Aerial View of West High School Roof– 1,500 ft. (K50)

Figure 13. West High School Gymnasium 1 Roof Collapse from South Bleachers

3.1.5 Single Family Residences

A total of 190 single family residential buildings were assessed as depicted in Figure 14. Window breakage, façade damage, and structural component failure (i.e. wall, roof system) were documented during the survey. The shock wave caused significant damage by breaking windows, failing roof trusses, and damaging exterior walls. An example of one heavily damaged home observed in the community of West are shown in Figure 15 and Figure 16.

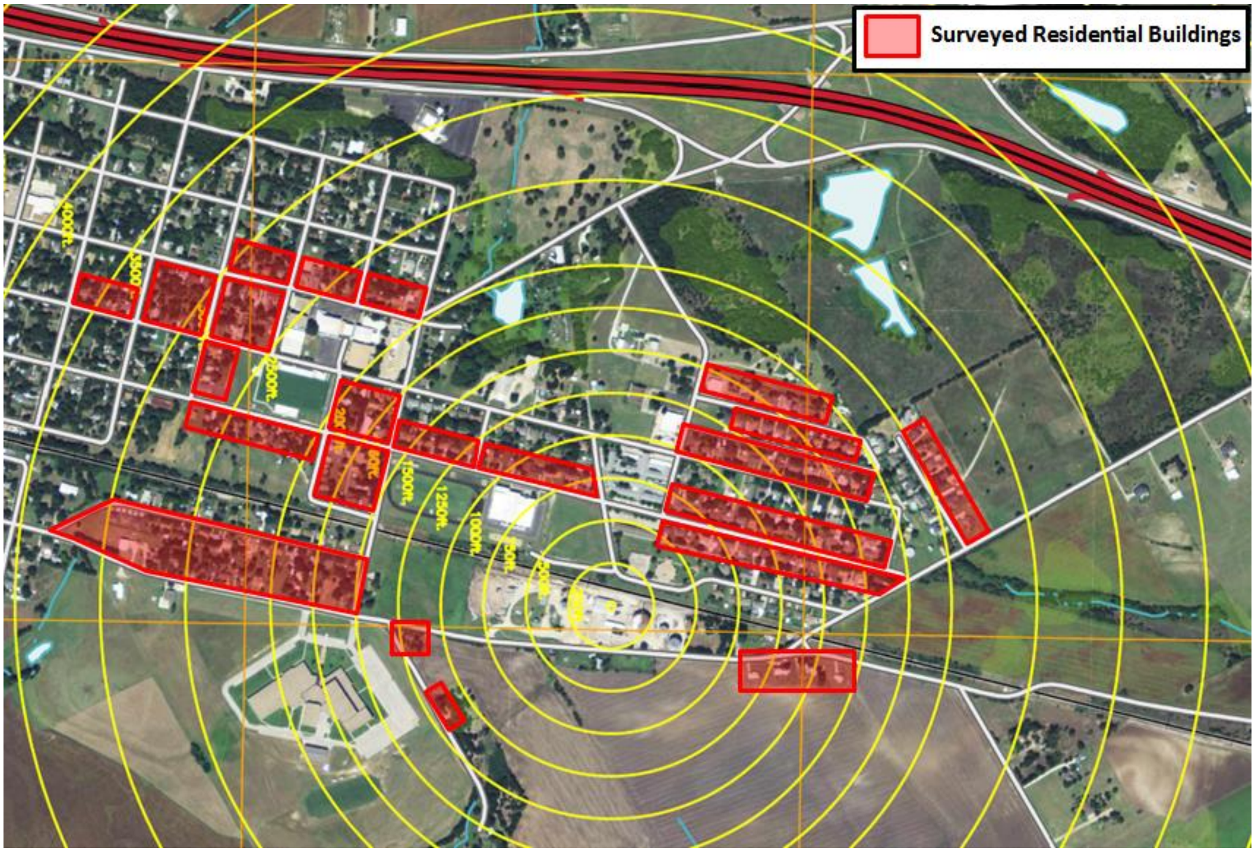

Figure 14. Extent of Surveyed Residential Buildings

Figure 15. Heavily Damaged Residence - – 700 ft. (K24)

Figure 16. Examples of Observed Residential Damage – 700 ft. (K24)

4 Preliminary Estimate of the Explosive Yield

A key objective of the investigation was determination of the TNT equivalence, or energy, of the explosion. This energy is important for evaluating the damage from the West Fertilizer explosion and understanding potential risks of explosive operations through the use of explosives scaling. The effective yield is used to establish a correlation between the actual weight of the energetic material on site and the energy of a potential explosion expressed in weight of TNT.

The estimation of TNT equivalence or net explosive weight (NEW) for the West Fertilizer explosion was performed in phases. First, preliminary upper and lower bounds of the NEW were estimated. The preliminary upper and lower bounds were estimated to be between 20,000 lb_{TNT} and 40,000 lb_{TNT} based on the observed damage to the apartment complex, nursing home, and detailed analysis of observed damage to lightweight metal buildings.

4.1 Apartment Complex and Nursing Home

The apartment complex and nursing home were lightweight wood structures as mentioned previously. These buildings were evaluated utilizing the US Army Corps of Engineers ETL 1110-3-495 [iii]. The document provides information and guidance for estimating the effects of bombs on typical building construction found in government facilities and installations. Standoff vs. charge weight plots allow prediction of the charge weight necessary to produce a selected level of damage. These are commonly referred to as range-to-effect curves and are provided in the reference for a range of charge weights and structure types. The document is For Official Use Only (FOUO) and the plots are not shared in this paper.

4.2 Damage to Lightweight Metal Buildings

Twenty different metal buildings (which are identified in Figure 17) were surveyed during the site inspection, and permanent deformations of building components were documented. The measured permanent deflections of the structural components were analyzed to determine the minimum charge weight necessary to cause the observed damage.

For each component, a standoff distance is measured to its centerline from a scaled aerial map. Using the standoff and angle of incidence, the charge weight is varied in an iterative analysis until the predicted deformation matches the observed deformation. The permanent deformation of a given structural component is obtained from the member’s resistance-deflection curve as shown in Figure 18. Deformations measured in the field were all permanent plastic deformation, which occurs after the member achieves maximum inbound deflection and undergoes elastic rebound. This procedure was repeated for each component and a minimum TNT charge weight required to cause the measured damage was obtained for each structure.

Figure 17. Surveyed Metal Buildings

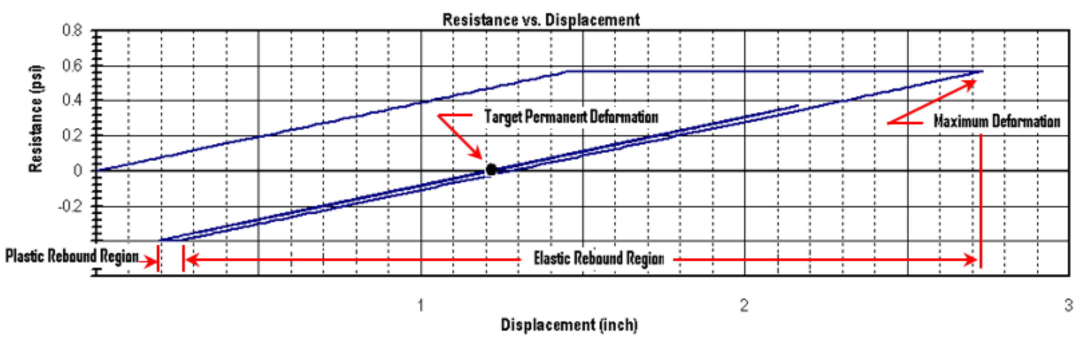

Figure 18. Typical Resistance-Deflection Curve

The statistical analysis that was performed on this data set yielded an average charge weight of 20,000-lb$_{TNT}$. The metal building data have a very large standard deviation and are considered an approximation. Factors affecting the charge weight prediction include (but are not limited to) blast load infiltration into the structure, boundary condition approximations, presence of tension membrane, multiple energy dissipation mechanisms, and clearing of reflected blast loads.

5 Determination of Source Energy

To further refine the charge weight that was most consistent with all of the observed damage, a three dimensional model of the West Community, shown below in Figure 19, was developed. ABS Group software FACET3D TM [iv] was utilized to build the virtual model to evaluate the previously determined potential explosion yields with the observed damage to the single family residences and the community structures. Computational fluid dynamic (CFD) analyses were performed with the software CEBAM [v] and the resulting pressure and impulses were mapped into FACET3D in order to perform the damage assessment to the community. Utilization of CFD provided a more accurate depiction of the shock wave as it wrapped around structures and other obstacles, and it also more accurately predicted the total positive impulse on a building face, including local reflections, clearing, and other blast load phenomena.

FACET3D was built on the methodology from UFC 3-340-02 [vi], which was incorporated into many of the blast prediction tools developed by the US Department of Defense (DOD), such as ConWep, AT Planner, and BEEM. The software allows the user to define threat locations and predicts the peak pressure and impulse applied to each surface defined in the model. For evaluating the NEW of the West Fertilizer explosion, blast loads calculated using CFD simulations were imported into the FACET3D model.

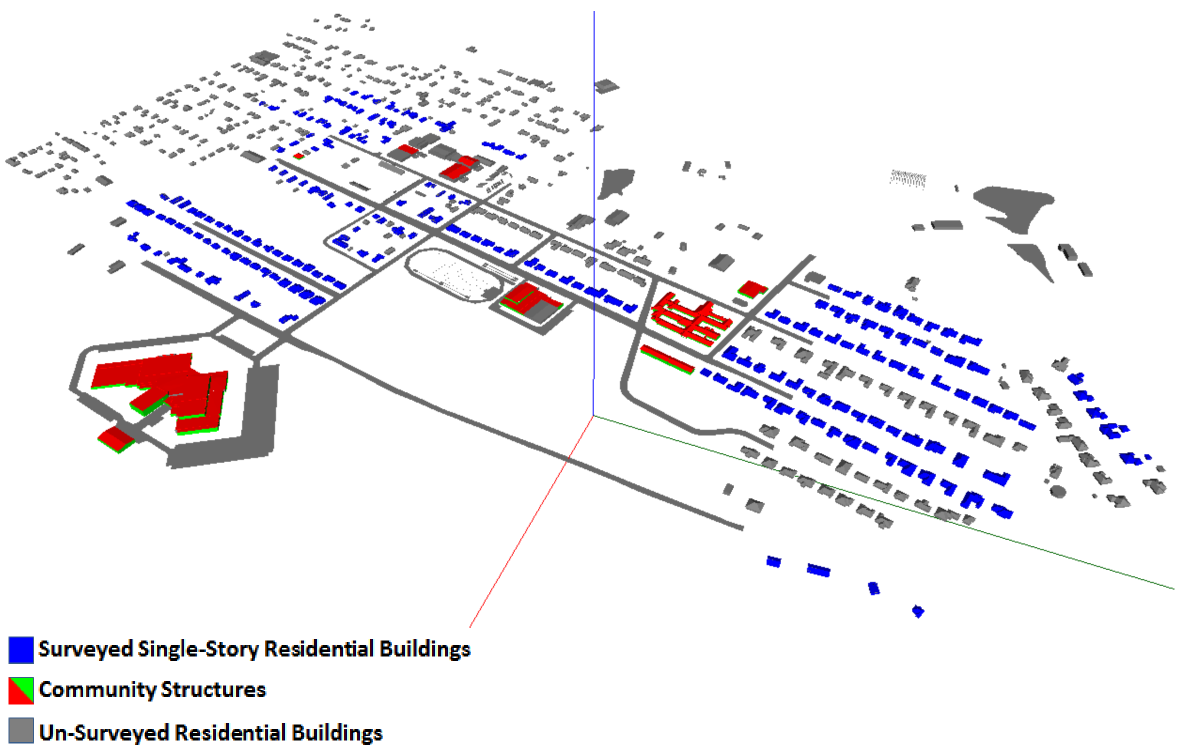

Figure 19. Rendering of the West FACET3D Model

Damage functions in the form of pressure-impulse (P-i) diagrams were developed to determine structural response, or damage, to walls and roof system components utilizing the response limits and damage level definitions developed by the US Army Corps of Engineers in PDC-TR-06-08 [vii] The component damage levels (CDLs) as defined by PDC-TR-06-08 are provided in Table 1 below, and these were correlated to the building damage levels (BDL) defined by ABS Group based on observations of the residential structures in West shown in Table 2. The correlation was performed by assigning a percentage of the residence walls that fall into a given damage category. For instance, at a BDL of 4, which consists of reflected wall failure and significant damage to the remaining walls, 25 percent of the walls are at failure or blowout and the remaining walls (75%) are at varying degrees of damage below failure.

Table 1. Component Damage Level Definitions [viii]

Component Damage Level (CDL)		**Description**
1	Superficial Damage	Component has no visible permanent damage
2	Moderate Damage	Component has some permanent deflection. It is generally repairable, if necessary, although replacement may be more economical and aesthetic
3	Heavy Damage	Component has not failed, but it has significant permanent deflections causing it to be unrepairable
4	Hazardous Failure	Component has failed, and debris velocities range from insignificant to very significant
5	Blowout	Component is overwhelmed by the blast load causing debris with significant velocities

Table 2. Approximate Residential Wall CDL Percentages by BDL

BDL	**Damage Description**	**Percent of Wall Surface Damage**				
		CDL 1 Superficial	**CDL 2 Moderate**	**CDL 3 Heavy**	**CDL 4 Hazardous Failure**	**CDL 5 Blowout**
1	No permanent deformations. The building is immediately usable.	100%	-	-	-	-
2	Onset of visible damage to reflected wall of building. Space in and around damaged area can be used and is fully functional after cleanup and repairs.	0% up to 75%	25% up to 100%	-	-	-
3	Reflected wall components sustain permanent damage requiring replacement, other walls and roof have visible damage that is generally repairable. Progressive collapse will not occur. Space in and around damaged area is unusable.	75%		25%	-	-
4	Reflected wall components are collapsed or very severely damaged. Other walls and roof have permanent damage requiring replacement. Progressive collapse possible. Space in and around damaged area is unusable.	75%			25%	
5	Reflected wall has collapsed. Other walls and roof have substantial plastic deformation that may be approaching incipient collapse.	0% – 25%			75% - 100%	

5.1.1 Single Family Residences

A graphical map showing the building damage levels assigned to the single family residences are provided in Figure 20. Damage levels were previously defined in Table 2. The houses are highlighted to indicate the observed BDL as indicated in the figure legend.

Figure 20. ABS Group BDL Levels of Surveyed Single Family Residences

The single family residences for the analysis were selected for BDL evaluation due to the proximity of the homes to the explosion center and the range of observed BDLs, which ranged from a BDL of 5 in the vicinity of the Rest Haven nursing home to a BDL of 2 farther from the explosion. The residences were divided into two groups based on their location with respect to the approximate explosion source: Group 1 - N. Reagan St. residences located to the North of the Rest Haven nursing home, and Group 2 - the N. Reagan Street residences located to the south of the nursing home. Charge weights, which produced damage that best matched the observe BDLs to these single family residences, were determined for homes grouped by building damage level. The results of the residential BDL assessment are summarized in Table 3. The charge weight that most consistently explained the observed damage from the West Fertilizer explosion was determined to be 25,000 lb_{TNT}.

Table 3. Summary of Yield Assessment based upon Single Family Residence Damage

1100 - 1200 Block of N. Reagan St.					
BDL	**20,000-lb**	**22,500-lb**	**25,000-lb**	**27,500-lb**	**30,000-lb**
2	•	•	•		
3		•	•		
4		•	•		
1400 - 1500 Block of N. Reagan St.					
3			•	•	•
4			•	•	
5		•	•	•	

The West High School roof sustained light to heavy damage from the explosion with the exception of the large gymnasium which collapsed. The failure of the roof over the gymnasium was caused by a combination of out-of-plane blast loading and in-plane diaphragm loading from the wall blast reaction. The damage to the high school predicted by the FACED3D simulation for 25,000 lb_{TNT} is presented below in Figure 21. FACET3D results for the 25,000 lb_{TNT} CEBAM simulation show the predicted damage to the roof of the north wing of the high school. Therefore, the 25,000 lb_{TNT} yield that is consistent with the damage to the single family residences is also most consistent with the observed damage to the high school.

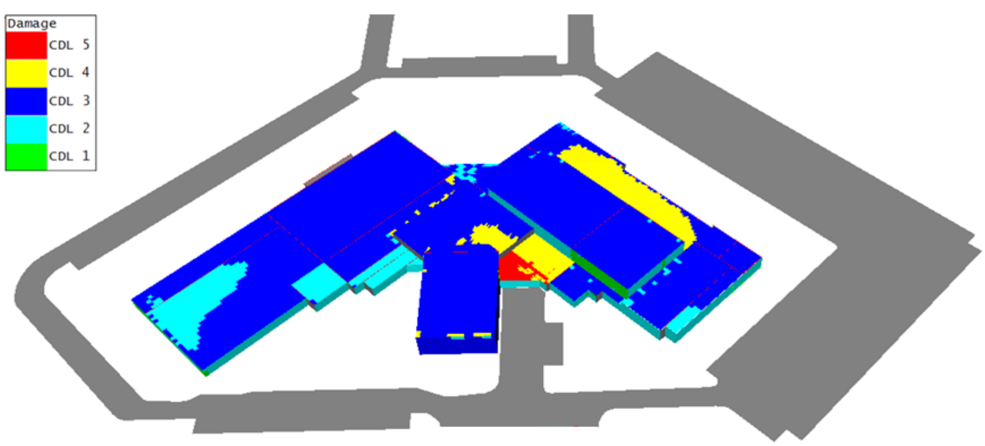

Figure 21. High School FACET3D Model Response – 25,000-lb_{TNT}

6 Findings

Documentation and forensic analysis of the blast damage to the community of West determined that the explosive energy of the West Fertilizer explosion that was most consistent with the observed damage was equivalent to 25,000 lb_{TNT}.

Blast damage in the far field can be an important forensic tool to aid investigators in determining the source energy and magnitude of an event such as the West Fertilizer explosion, where much of the forensic evidence near the center of the explosion is consumed and destroyed by the event. Due to the large NEW of the event there is damage data of interest to the explosives safety community including damage to personal residences, community structures, windows, and power transmission lines.

Pressure contours for the community of West, based on the predicted 25,000 lb_{TNT} equivalent explosive yield, are presented in Figure 22. The apartment complex was at 5 psi free field contour and the nursing home and intermediate school were both at about 2.5 psi free field overpressure.

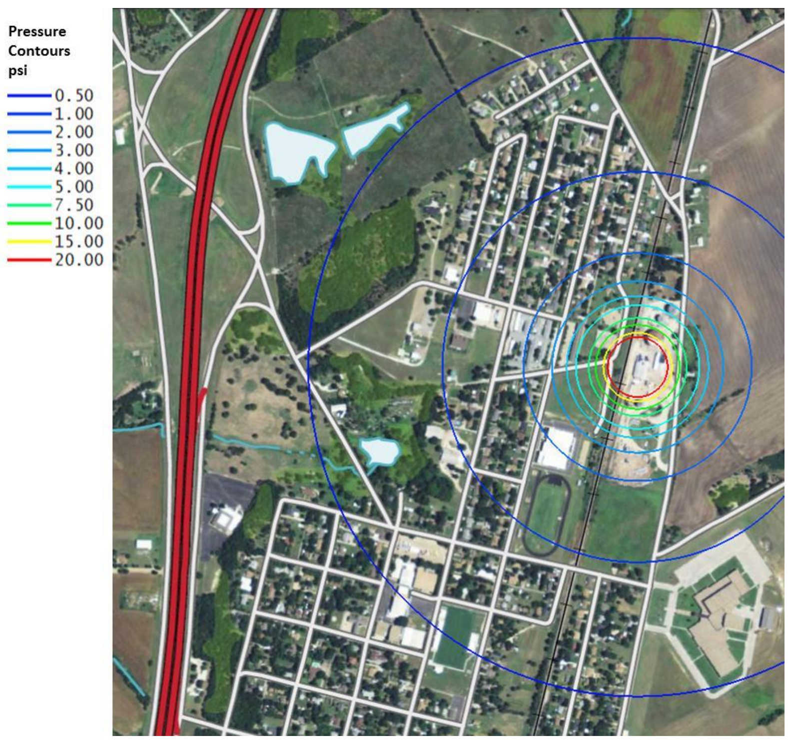

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Figure 22. West Fertilizer Explosion Free-Field K-B Pressure Contours for 25,000 lb_{TNT}

7 References

[i] U.S. Chemical Safety and Hazard Investigation Board, Investigation Report 2013-02-I-TX, "West Fertilizer Company Explosion and Fire", Final Report, January 2016.
[ii] ABS Group Final Report 3087473, "West Fertilizer Incident Support Services Final Report", Issued for public release, 28 August, 2015.
[iii] ETL 1110-3-495, "Estimating Damage to Structures from Terrorist Bombs Field Operations Guide", U.S. Army Corps of Engineers, 14 July 1999.
[iv] Facility Assessment and Consequence Evaluation Tool (FACET3D), ABS Group.
[v] CEBAM, Computational Explosion & Blast Assessment Model, ACENG, San Antonio, TX 2005.
[vi] UFC 3-340-02, "Structures to Resist the Effects of Accidental Explosions", Change 2, 1 September, 2014.
[vii] PDC-TR-06-08, "Single Degree of Freedom Structural Response Limits for Antiterrorism Design", U.S. Army Corps of Engineers PDC, Rev. 1, Jan 2008.
[viii] PDC-TR-06-08, "Single Degree of Freedom Structural Response Limits for Antiterrorism Design", U.S. Army Corps of Engineers PDC, Rev. 1, Jan 2008.