PERFORMANCE OF STRUCTURES SUBJECTED TO WEST FERTILIZER COMPANY EXPLOSION

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ABSTRACT

The West Fertilizer Company (WFC) explosion, which occurred on April 17, 2013, resulted in varying degrees of damage to many residential and commercial structures. The author's firm performed evaluations of 35 structures reportedly damaged by the explosion, with locations ranging from approximately .1 miles to over 5.5 miles from ground zero. The evaluations were collectively reviewed for identification of consistent distress mechanisms at the structures and global patterns of distress propagation in relation to distance from the explosion origin. This paper studies the respective performance of the evaluated structures subjected to the WFC explosion, particularly in relation to distance from the explosion site. In addition, the distress patterns from the WFC explosion evaluations are compared to published data referencing expected distress to building components relative to superimposed pressure. The comparison is used as a basis to establish a methodology of explosion investigations considering "damage indicators" in relation to relative distance from an explosion source.

OVERVIEW OF SUBJECT EXPLOSION AND AUTHOR'S INVESTIGATIONS

The West Fertilizer Company (WFC) explosion occurred in West, Texas, on April 17, 2013. A fire broke out at the fertilizer plant during the evening of April 17, and at 7:50 P.M., stored ammonium nitrate ignited, causing 15 fatalities and over 200 injuries. The explosion reportedly created a crater 93 feet wide and 10 feet deep (NPR 2015). The explosion registered as a magnitude 2.1 event with a Modified Mercalli Intensity of IV, which was recorded approximately 30 miles away from the explosion origin (USGS 2015).

The author's firm was enlisted to evaluate a total of 35 residential and commercial structures reportedly damaged by the WFC explosion. Evaluations of the structures offered the opportunity to study the effects of this explosion over a widespread area due to the relatively large magnitude of the blast. As a result, a sufficient sample size was able to be studied for patterns of distress mechanisms and the propagation of these mechanisms in relation to distance from the blast origin. While observations from these evaluations are event-specific, the observed patterns can be applied to distress evaluations related to many explosion sources.

The majority of the evaluated structures were wood-framed, single-family residences with 2x wood roof rafters. The foundations of the residences constructed after 1970 were primarily concrete slabs-on-grade, and the residences constructed prior to 1970 were generally supported by shallow-bearing pier-and-beam systems.

Extensive data collection was performed by the author's firm during the structural evaluations, including photographic documentation of the sites, exteriors, interiors, attics, roofs, and accessible portions of the foundations; distress mapping; relative elevation surveys performed at the structures' floors/foundations; plumbness measurements obtained at the structures' exterior walls; and deflection profiling at select structural members.

DISCUSSION OF EXPLOSION EVENTS

Explosion events have the potential to cause significant damage to property and people. In order to discuss the distress patterns observed during the WFC explosion evaluations, it is first necessary to gain a basic understanding of explosions and the forces they impart on structures. This section contains a brief descriptive background on explosions; however, it is not intended to be an all-inclusive discussion of all types and effects of explosions. The 1977 Glasstone and Dolan reference is a particularly comprehensive resource for gaining an understanding of explosion events and their effects on structures.

Explosions result in an almost instantaneous rise in pressure that decays rapidly with distance from the origin and time. Generally, affected structures are damaged by three potential mechanisms: heat, air pressure waves, and ground waves.

Mechanisms of air blast loading on structures are typified by overpressure, reflected pressure, and dynamic pressure. Overpressure, also referred to as "side-on" overpressure or "incident pressure," engulfs a structure within a "bubble" of elevated pressure. When a structure is fully encompassed by the elevated pressure bubble, the overpressure can positively load all surfaces of a structure at once. Due to the rapid decay of blast waves with increasing distance from the explosion origin, proportional to $1/d^3$ where d = distance from the blast origin (Noon 1995), the overpressure at the blast-facing end of a structure may be much larger than the overpressure on the "leeward" side. When the blast wave from an explosion impacts a surface, the pressure wave is reflected from the impacted surface, resulting in loading on the reflecting surface that is typically much greater than that of the side-on overpressure loading. For this reason, the most severe blast-related damage is often found on the blast-facing components of structures.

Dynamic pressure, or "blast wind," results from air movement as the blast wave propagates outward from the origin. Dynamic pressures for overpressure ranges that do not result in collapse of wood-framed structures do not affect enclosed structures as significantly as the two previously described mechanisms; however, dynamic pressure can contribute to the overall positive loading on a blast-loaded surface.

Ground motions induced through blast loading decay slower than overpressures and, therefore, can propagate farther out from the explosion origin than the above-surface blast wave. The decay of ground motions is typically considered to occur proportional to $1/d^2$ (Stachura, Sisking, and Kopp 1984). As such, at some distance from the explosion origin, the ground waves can become more significant than the air blast wave.

DAMAGE INDICATORS

In order to establish a methodology of using damage indicators to estimate expected pressures and associated distress mechanisms at explosion sites, similar to methodologies that have been used for determining wind speeds in the aftermath of tornadic events (Texas Tech 2004), the authors conducted a review of published distress mechanisms in relation to superimposed pressures. The authors compared these distress mechanisms to the distress patterns observed during the WFC evaluations. The observations were studied to establish if correlation existed with the published data.

Damage Indicators In Literature

Damage indicators for explosion-related distress were obtained from multiple references. The data was consolidated to include all ranges of overpressures published in the consulted sources for the respective indicators. A summary of the damage indicators and associated incident overpressures is shown in Table 1. The incident overpressure for the "heavy damage to ceilings" indicator was inferred from commentary in the 1977 Glasstone and Dolan reference.

Table 1. Summary of Published Damage Indicators*.

Damage Indicator	Incident Overpressure (psi)
Typical window glass breakage	0.15 – 1.0
Room doors dislodged	0.3 – 0.4
Heavy damage to ceilings	~1.7
Panels of sheet metal buckled	1.1 – 1.8
Brick walls (unreinforced) toppled	1.0 – 2.1
Damage to roofs	1.7 – 2.0
Collapse of wood-framed buildings	Over 5.0

* Sources of data include FEMA 2003; Glasstone and Dolan 1977; Kennedy and Kennedy 1990; Kinney and Graham 1985; and Noon 1995

WFC Brick Veneer Observations

Significant brick veneer distress observed during the WFC evaluations included diagonal brick fractures, separations and fractures at exterior corners, and collapsed portions of the veneer. These forms of distress were localized to structures with significant structural framing distress.

The failure planes of significant diagonal fractures and stair-step veneer separations were typically oriented in a direction consistent with the travel of the shock front and are consistent with shear failures due to rapid and severe loading. The near-vertical separations and fractures were observed at the corners of structures (see Figure 1) are consistent with both in-plane and out-of-plane deformation of the veneer.

The failure modes of localized collapsed areas of brick veneer indicated that the veneer was subjected to a variety of loading mechanisms related to the explosion. Reflected and side-on overpressures can directly cause displacement in the veneer, both in plane and out of plane. In addition, the interaction between the veneer and structural framing during explosion loading can also contribute to the distress.

Due to the rapid and significant loading on the structural framing induced by explosion overpressures, the structure and its framing members can undergo significant displacement and deformation, even before rupturing of framing, which can lead to unanticipated transfer of load to "non-loadbearing" components. Large areas of collapsed veneer were often located adjacent to significant structural distress to roof eave framing and at locations where brick ties were not installed and/or engaged (see Figure 2). In general, the presence of severe and widespread veneer distress correlated with structures exhibiting severe structural damage.

WFC Roof Framing Observations

Rafters were fractured on both blast-facing and "leeward" roof planes (see Figure 3). The fractured rafters were permanently displaced inward on both of these planes, indicating dominance of positive loading throughout the roof. In addition to rafter fractures, many instances of fractured and detached purlins, and fractured and displaced struts, were observed within the attics.

A pattern of shingle distress was not evident at the evaluated structures and is evidence of the relatively minimal contribution of dynamic pressures to the observed distress. Distortion of the shingles was limited to areas of fractured and permanently displaced roof framing and decking (see Figure 4). The lack of distress to shingles within high wind pressure zones and to nearby trees at evaluated sites is not indicative of influence of high winds, according to published wind damage indicators (Texas Tech 2004).

Figure 1. Near-Vertical Fractures at Exterior Corners

Figure 2. Buckled and Collapsed Veneer at Structure Exhibiting Severe Structural Damage

Figure 3. Fractured Roof Framing

Figure 4. Shingle Distortion Isolated to Areas of Structural Roof Damage

WFC Ceiling Finish Observations

One of the more unique distress patterns related to explosion loading is the collapse of interior gypsum board ceiling finishes (see Figure 5 and Figure 6). This indicator has been repeated in other explosion events investigated by the author's firm. Pressurization of the attic space, which occurs due to openings in the attic envelope and displacement of the roof framing/decking, creates an unbalanced load on the gypsum board ceiling panels, ultimately causing failure of the panels. Openings in the attic envelope can occur due to attic venting and severe structural distress to the roof framing and decking.

The instantaneous reduction in attic volume due to deflection of the roof framing and decking can lead to pressurization of the attic. Boyle's Law (i.e., $P_1V_1 = P_2V_2$) can be used to illustrate this effect. For discussion purposes, the following conditions can be assumed for input into the Boyle's Law equation: the configuration of an attic resembles a triangle with a base of 40' and a height of 5' ($V_1 = 100 ft^3/ft$); P_1 in the attic is atmospheric pressure (14.7 psi); and an instantaneous 1" deflection of the rafters in a parabolic pattern occurs, causing a reduction in the attic volume ($V_2 = 97.7 ft^3/ft$). Inputting these values into the original equation, the increase in attic pressure due to the sudden rafter deflection approximates 50 psf. While there are many unaccounted-for variables that alter the value of this calculation, the result illustrates the potential for increase in the attic pressure due to sudden deflection of the roof system.

Figure 5. Collapsed Ceiling Finish

Figure 6. Collapsed Ceiling Finish

WFC Window/Door/Glazing Observations

Distress to windows and doors were observed farthest out from the blast, relative to other damage indicators. Closer to the blast origin, window glass planes were fractured on both blast-facing and "leeward" elevations of the structure. Farther out, the instances of fractured glazing decreased, and fractured glazing was primarily located on blast-facing elevations of the buildings. Additional observations included displacement of interior and exterior door units as well as deformation of garage overhead doors, which have a relatively large unreinforced surface area.

WFC Diaphragm Displacement Observations

One isolated structure located approximately 1.65 miles from ground zero exhibited evidence of diaphragm displacement. The residence was a two-story structure with a shallow-bearing pier-and-beam foundation. A pattern of separations at the wall/ceiling corners were concentrated at the second-floor level, consistent with a ground vibration or "seismic" form of distress.

Separations were reportedly present before the explosion occurred. However, new separations reportedly appeared, and previous separations were exacerbated. As damage is a function of not only loading, but also the structure's resistance to the loading, this isolated instance of diaphragm displacement is consistent with ground vibration or "seismic" loading resulting from the explosion. Although difficult to completely rule out blast-related cosmetic distress to some structures, the evaluated structures did not respond with permanent lateral racking.

WFC Foundation Observations
No instances of discrete foundation damage attributable to air-blast waves or ground vibrations were observed at the evaluated structures. Evidence of long-term foundation movement, as evidenced by repaired, weathered, and/or dull-edged finish separations at locations typically indicative of differential foundation movement were typical at the structures. Additionally, the majority of the structures were located on soils with high to very high shrink/swell potential, as classified by the United States Department of Agriculture (USDA 2015).

ANALYSIS OF DATA
The data obtained from the WFC explosion evaluations was analyzed to determine the extents of the distress mechanism propagation from the explosion origin. The extents were determined based on the distance data points at which the mechanism patterns became inconsistent. The extents are intended to be considered as relative numbers rather than actual values, as significant potential for skew in the data resulted from the gaps in available distance data points.

A pattern of significant and widespread brick veneer distress, including diagonal fractures, separations/fractures at exterior building corners, and/or collapsed portions of the veneer, occurred up to approximately .35 miles from the explosion origin. A significant gap of over .1 miles existed in the distance data points farther out than .35 miles, which may have caused error in the extent estimate for the brick veneer damage indicator.

A pattern of structural roof distress was consistent at structures located within approximately .5 miles of the explosion origin, but some structures exhibited roof framing distress up to approximately .7 miles from ground zero. Due to the inconsistency in the framing distress for structures farther than .5 miles from the blast origin, the authors assumed an extent of .5 miles. One structure located more than .6 miles from the origin exhibited fractured framing. This structure had a clear line of site to the origin and, consequently, was likely subjected to increased loading relative to structures at a similar distance from the blast origin but in more densely developed areas.

A pattern of collapsed ceiling finishes was evident up to approximately .6 miles from the explosion origin. A significant sample size of data points from sites farther than .6 miles exists to support the estimated extent for this damage indicator.

A pattern of distress to windows, doors, and/or glazing was evident up to approximately .8 miles from the explosion origin. The pattern became less consistent farther than .8 miles from the origin; however, a significant cluster of window/door damage data points was evident up to 1.0 miles from the origin.

Table 2 shows the observed patterns of distress, the approximate distance from the explosion origin that the observed instances of the damage indicator became inconsistent, and an estimated incident pressure at that distance. The estimated incident pressures were calculated by assuming a value of .50 psi for window/door/glazing damage at .80 miles from the origin and back-calculating pressures based on a $1/d^3$ ratio. Altering the initial pressure/distance assumption significantly influences the estimated incident overpressure calculation.

Table 2. Observed Damage Indicators vs. Distance and Estimated Pressure

Damage Indicator	Distance from Origin (miles)	Estimated Incident Overpressure (psi)	Published Incident Overpressure (psi)
Severe Brick Veneer Distress	.35	6.0	1.0 – 2.1
Fractured Wood Rafters	.50	2.0	1.7 – 2.0
Heavy Damage to Ceilings	.60	1.2	~1.7
Window/Door/Glazing Damage	.80	.5 (Assumed)	0.15 – 1.0

With the exception of the severe brick veneer distress, the estimated incident overpressures correlated with the published values. The estimated overpressure for severe brick veneer distress was significantly higher than the published pressure range; however, the estimated overpressure was of sufficient magnitude to be indicative of veneer distress related to substantial structural distress. The 5.0 psi published threshold for the collapse of wood-framed buildings indicator is estimated at approximately .37 miles from the explosion origin, based on the initial assumed values. This distance correlates with observations of severe and widespread structural distress within .35 miles to the blast origin; however, full collapse of wood-framed structures was not typical.

The general correlation between the damage indicators observed during the WFC evaluations and the published damage indicator data supports the use of damage indicators in evaluations of explosion-related distress. While the use of damage indicators can facilitate an estimation of blast pressures at a site of interest, this estimation cannot be relied on solely for damage evaluation. Distress propagation is a function of not only load but resistance. Resistance is a function of multiple variables, including but not limited to, age, design, construction, materials, pre-existing damage, and maintenance (Nelson, DeLeon, and Schober 2011). The most extreme damage indicator at a site can be used to determine other expected forms of distress based on the relative published pressure thresholds for the respective damage indicators.

Figure 7 shows the locations of select structures evaluated by the author's firm. Radial distance markers are overlaid on Figure 7 to show the extents of distress mechanism propagation as determined by the authors from the collective review of the 35 evaluations. Table 3 summarizes key observations from the 35 evaluations and can be correlated to the structure numbers in Figure 7.

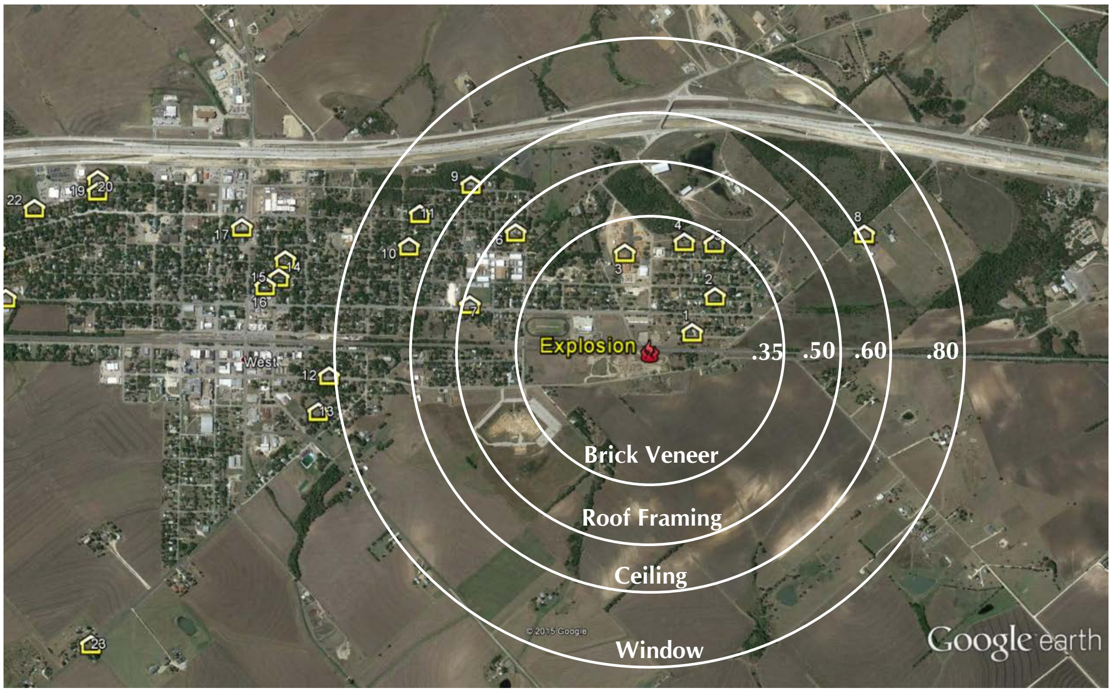

Figure 7. Overview of Evaluated Structures and Extents of Distress Propagation

Table 3. Summary of West Fertilizer Company Distress Evaluations.

File Number	Structure #	Type	Construction				Year Built	Distance From Blast	Direction from Explosion	Veneer Damage		Fractured Roof Framing			Displaced/Collapsed Ceilings		Windows/Doors/Glazing			Other Distress
			Roof	Walls	Foundation	Veneer				Extent	Remarks	Facing	Leeward	Remarks	Extent	Remarks	Facing	Leeward	Remarks	Remarks
12388	1	Residential	Wood	Wood	Slab	Brick/Wood	1997	0.1	NNW	Widespread	Collapsed veneer at all elevations, brick ties not engaged, gables displaced inward, diagonal brick fractures at leeward side in direction of blast wave	Y	Y	-	Widespread	-	Y	Y	-	
12373	2	Residential	Wood	Wood	Slab	Brick	1977	0.21	NW	Severe	Corner fractures, severe distress concentrated at blast facing half of structure	Y	Y	-	Widespread	-	Y	Y	Overhead doors on facing side displace inward	Front porch (facing) soffit displaced upward
12345	3	Medical	Wood Truss	Wood	Slab	Brick	2006	0.26	W	Severe	Diagonal brick fractures; Fractures at corners; Inward displacement at facing gable and compression from roof (both side elevations); Fractures at two-story façade	Y	Y	Truss web and top members fractured	Widespread	-	Y	Y	Displaced doors on side elevation; Interior partitions distorted near breached windows	Fencing blown down in direction of blast; Impact in facing veneer; Soffits blown out
12344	4	Residential	Wood	Wood	Slab	Brick	1993	0.29	W	Severe	Diagonal brick fractures; Fractures at corners; Wedge chip fracture at brick veneer fracture	Y	Y	All faces, permanent downward deformation on facing side	Widespread	-	Y	Y	Deformed windows and overhead doors on facing side	
12412	5	Residential	Wood	Wood	Slab	Brick	1979	0.32	NW	Widespread	Continuous horizontal separation along elevations at soldier course, separations/fractures minor but widespread	Y	Y	-	Widespread	-	Y	Y	-	
12391	6	Residential	Wood	Wood	Pier-and-Beam	Vinyl	1951	0.45	SW	Minor	Slight displacement of gable siding	Y	N	Multiple fractured rafters	Isolated	-	Y	Y	-	
12347	7	Residential	Wood	Wood	Pier-and-Beam	Wood	1920	0.46	SW	Minor	-	Y	N	Fractured struts, no fractured rafters	Minor	Some minor displacement and nail pops; No collapsed panels	Y	Y	Displaced window units on side elevation; Displaced door on facing elevation	Upward displacement at carport
12361	8	Residential	Wood	Wood	Slab	Brick	1990	0.61	NNW	Isolated	Widening of previous separation on facing elevation	Y	N	Multiple fractured rafters	Moderate	Collapsed ceilings and nail pops throughout	Y	Y	Minor fractures on leeward windows	Clear line of site to ground zero; lead flashing popped off vent
12362	9	Residential	Wood	Wood	Pier-and-Beam	Vinyl	1930	0.62	SW	Minor	Fractures at stucco crawlspace skirt	N	N	-	Isolated	Sag at isolated location where strut bears	Y	N	-	
12354	10	Residential	Wood	Wood	Pier-and-Beam	Wood	1925	0.66	SW	None	-	N	N	-	None	-	Y	N	One fractured glass plane and minor displacement of a unit on facing elevations	
12417	11	Residential	Wood	Wood	Pier-and-Beam	Brick/Wood	1955	0.68	SW	None	-	Y	N	Minor fracturing/displacement of isolated struts	None	-	Y	Y	Minor fractures	Displacement of wall due to lack of bracing at top
12390	12	Residential	Wood	Wood	Slab	Brick/Wood	1976	0.8	S	Isolated	Newer in appearance brick veneer separations	N	N	Isolated separated struts	None		N	N	-	4" foundation out-of-levelness
12371	13	Residential	Wood	Wood	Pier-and-Beam	Wood	1950	0.84	S	Minor	Distorted metal foundation skirt	N	N	1 split 2x4 roof rafter	None	-	N	N	-	Reportedly displaced attic gable vent
12360	14	Residential	Wood	Wood	Pier-and-Beam	Wood/Stone	1940	0.95	SSW	None	-	N	N	-	None	-	N	N	-	Deformation of roll-up door at workshop
12392	15	Residential	Wood	Wood	Pier-and-Beam	Wood	1930	0.95	SSW	None	Exterior under remodel	N	N	-	None	Sporadic ceiling separations; interior under remodel	N	N	-	
12339	16	Commercial - Postal Office	Steel	CMU	Slab	Brick	1968	0.97	SW	None	-	N	N	-	None	-	Y	N	Reported crack at glazing facing explosion	Displacement of battens suspended from ceiling grid
12434	17	Residential	Wood	Wood	Pier-and-Beam	Wood	1900	1.05	SSW	None	-	N	N	-	None	-	Y	Y	Rear door reportedly blown in	Nail pops at north and east walls; High walls on Victorian style home
13010	18	Commercial	Steel	Steel	Slab	Metal	2001	1.3	NNW	None	-	N	N	-	None	-	N	N	-	Clear line of site to ground zero
12364	19	Residential	Wood	Wood	Slab	Brick/Stone	2011	1.43	SSW	None	-	N	N	-	None	-	N	N	-	
12423	20	Residential	Wood	Wood	Pier-and-Beam /Slab	Brick	1968	1.45	SW	None	-	N	N	Isolated dislocated purlin struts	None	-	N	N	-	
12477	21	Residential	Wood	Wood	Slab	Brick	1997	1.48	ESE	None	-	N	N	-	None	-	N	N	-	Clear line of site to ground zero
12474	22	Residential	Wood	Wood	Pier-and-Beam	Brick	1958	1.57	SSW	None	-	N	N	Fracture through partial depth of rafter on east plane	None	-	N	N	-	
12478	23	Residential	Wood Truss	Wood	Slab	Brick	1971	1.57	SSE	None	-	N	N	-	None	-	N	N	-	Clear line of site to ground zero
12700	24	Commercial	Steel	Steel	Slab	Metal/Brick	2008	1.61	S	None	-	N	N	-	None	-	N	N	-	
12420	25	Residential	Wood	Wood	Pier-and-Beam	Wood	1960	1.66	SSW	None	-	N	N	-	None	-	N	N	-	Separations of interior corners throughout structure
12426	26	Residential	Wood Truss	Wood	Slab	Brick	1979	1.79	SW	None	-	N	N	Isolated fractured purlin struts	None	-	N	N	-	
12379	27	Residential	Wood	Wood	Slab	Brick/Wood	1979	1.82	SSW	None	-	N	N	-	None	-	N	N	-	
12473	28	Residential	Wood	Wood	Pier-and-Beam	Vinyl	1964	1.84	SE	None	-	N	N	-	None	-	N	N	-	Separations at interior finishes, deteriorated foundation with relatively tall piers, clear line of site to ground zero
12421	29	Residential	Wood	Wood	Slab	Brick	1992	1.98	SW	None	-	N	N	-	None	-	N	N	-	
12416	30	Residential	Wood	Wood	Slab	Brick	1986	2.57	NE	None	-	N	N	-	None	-	N	N	-	
14904	31	Residential	Wood	Wood	Slab	Brick	1994	3.04	SW	None	-	N	N	-	None	-	N	N	-	
13380	32	Residential	Wood	Wood	Slab	Stone	2005	3.18	SW	None	-	N	N	-	None	-	N	N	-	
13446	33	Residential	Wood	Wood	Slab	Brick/Wood	1979	3.18	SE	None	-	N	N	-	None	-	N	N	-	Clear line of site to ground zero
13445	34	Residential	Wood	Wood	Slab	Brick/Wood	1974	3.28	SE	None	-	N	N	-	None	-	N	N	-	Clear line of site to ground zero
13458	35	Residential	Wood	Wood	Slab	Brick/Wood	1984	5.65	S	None	-	N	N	-	None	-	N	N	-	

CONCLUSIONS

Observations from 35 WFC explosion distress evaluations performed by the author's firm were compared to published damage indicator data to establish correlation between the two and to support a methodology of using damage indicators to evaluate explosion distress. The WFC observations correlated with the published values and, therefore, confirm that damage indicators can be used to estimate the overpressures and associated expected distress at a site of interest subjected to an explosion event.

The use of damage indicators to estimate blast pressures cannot be used as a sole determinant of distress causation, as the propagation of distress is a function of loading and resistance. Both variables of this equation have multiple sub-variables, and individual site evaluations are necessary to delineate blast damage for structures that are not completely destroyed by the explosion.

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