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.

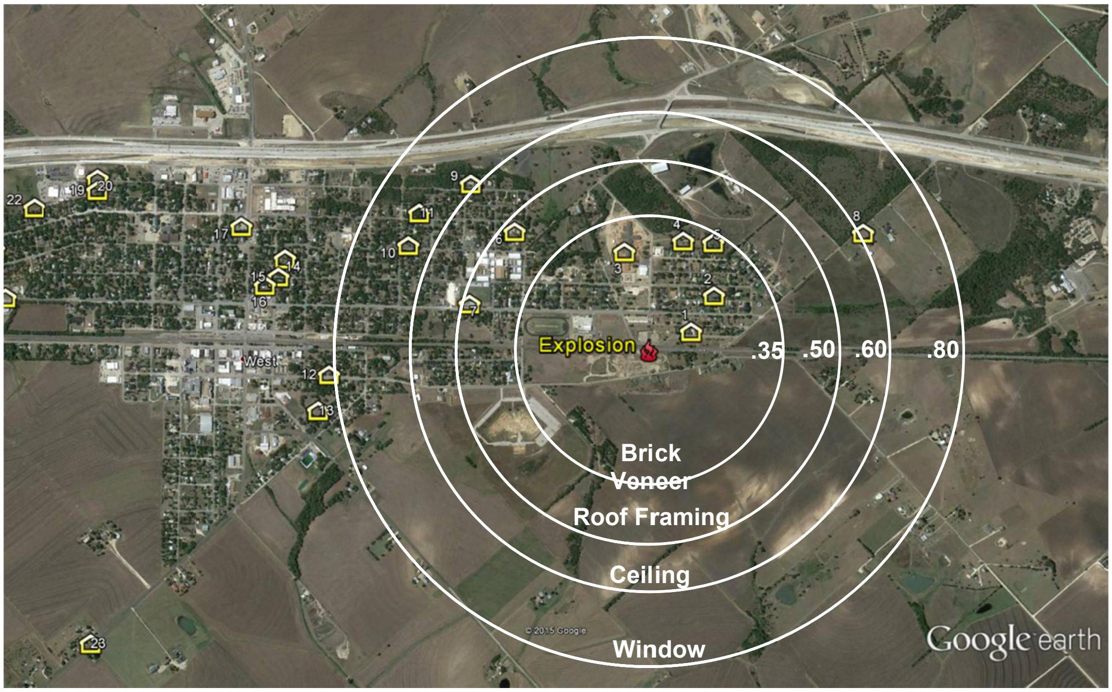

Figure 7. Overview of Evaluated Structures and Extents of Distress Propagation

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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Investigation of the Fragment Impact and Blast Shock Wave on Window Breakage

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Abstract

A natural gas explosion in East Harlem, NY destroyed two buildings and caused breakage of windows on a building across the street from the explosion. The equivalent TNT charge of the explosion is estimated and used to develop an explosion-fragment model (EFM) of the explosion event. The EFM is employed to investigate the potentiality of the window breakage as being caused by fragment impact or by the blast shock wave itself. Sections of the building facade predicted to be vulnerable to a combination of fragment impact and the shock wave are found to correlate with slightly higher rates of window breakage than sections predicted to be vulnerable only to the shock wave.

INTRODUCTION

A natural gas explosion occurred on March 12th, 2014 in East Harlem, NY causing deaths of several people and wounding numerous others (Kiger, 2014). The explosion resulted in the progressive collapse of two five-story brick buildings (see Figure 1), and neighboring buildings sustained different levels of damage from the reflection of the blast wave and fragment impact.

Natural gas is composed primarily of methane along with smaller percentages of other combustible gases such as ethane, propane and butane (NaturalGas.org, 2014). The high combustibility of natural gas is attributed to the exothermic reaction between methane and oxygen. Natural gas can leak through cracks in underground transmission pipes, permeate the surrounding soil and ignite resulting in an uncontrolled explosion with catastrophic effects as was the case in the East Harlem explosion. The combustion results in a rapidly expanding hemispherical wave of high pressure gas called a shock wave. The shock wave itself can directly cause damage to neighboring buildings. In addition, the shock wave can cause building components to fly off and impact surrounding buildings causing additional damage.

A seven-story brick building located across the street from the East Harlem explosion sustained facade damage from the event. Specifically, numerous windows on the west wall of the building were shattered. A study is conducted to investigate the potentiality of the window breakage as being caused by fragment impact or by the blast shock wave itself or a combination of both. The equivalent TNT charge of the explosion is estimated based on an existing video recorded by a surveillance camera near the explosion site. An explosion-fragment model (EFM) of the explosion is developed using the equivalent TNT charge and the properties of the collapsed five-story brick buildings. Using the EFM, the flight radii of assumed fragment sizes are calculated and mapped to predict if the west wall of the building across the street from the explosion was vulnerable to damage from fragment impact. Finally, the damage effect of the west wall windows from the fragment impact is compared to that caused by the shock wave. Conclusions are drawn on the lethality of fragment impact versus the shock wave for the west wall.

Figure 1. Buildings prior to explosion and after collapse (Mullings, 2014).

PREDICTION OF EQUIVALENT TNT CHARGE

Debris flying off the west wall of the seven-story brick building across the street from the East Harlem explosion was captured by a surveillance camera installed on the sidewalk. The camera view is angled in a southerly direction and the west wall at street level facing the epicenter of the explosion can be seen. Upon explosion numerous chunks of debris were recorded flying off of the west wall and landing onto the sidewalk and street (see Figure 2).

The explosion epicenter is assumed to be located at the center of the site covered by the two collapsed buildings. The estimated range and incident angle between the epicenter and the origin of the west wall debris are determined from a plan view taken from Google maps (see Figure 2). The difference in elevation between the blast epicenter and the debris is assumed to be negligible with respect to the horizontal range. The range is found to be approximately 50 m and the incident angle is effectively zero degrees.

Figure 2. Plan of East Harlem natural gas explosion.

The reflected impulse at the origin of the flying debris can be predicted given the estimated mass and velocity of one of the fragments observed in the video. The larger chunk of debris indicated in Figure 3 appears to be a glass shard shaped in the form of a trapezoid. Its dimensions are estimated by scaling in Bluebeam the shard size with respect to the width of the sidewalk in the background. The width of the sidewalk is determined from a plan view taken from Google maps. The windows on the west wall are assumed to be composed of 6 mm annealed glass (ASTM E1300-12a, 2012) as it was the typical facade construction for the year when it was built. As a result, the shard thickness is assumed to be 6 mm. Given the dimensions measured in Figure 3a along with the density of glass taken as 2.579 g/cm^3, the mass of the shard is estimated to be 1.25 kg.

Figure 3. (a) Glass shard flying off west wall showing estimated dimensions and (b) the same shard shown two frames later.

The glass shard appears to fly off the building in a direction normal to the west wall. Also, the video recording is found to have a frame rate of 30 frames per second, or 1/30 seconds between each frame. The distance traveled by the shard over three frames is estimated by scaling in Bluebeam that distance with the width of the sidewalk. This distance is found to be approximately 1.68 m. Dividing this distance by 1/15 seconds results in an estimated shard velocity of 25 m/s.

The momentum of a fragment is given by $\rho = Mv$, where M is the fragment's mass and v is its velocity. The impulse of the fragment is defined as its change in momentum. Since the glass shard is initially stationary its impulse is equal to its momentum in this case. Substituting the estimated shard mass and velocity into the momentum equation results in an impulse of 31.25 N-s. Converting the impulse into units of pressure and time requires an estimation of the target area of the shard facing the blast front. This area is taken to be the area of the trapezoidal-shaped shard and is calculated to be approximately 763 cm^2. Finally, dividing 31.25 N-s by the target area results in an impulse of 0.41 kPa-s. This impulse represents an estimation of the reflected impulse at the west wall due to the explosion.

The energy released from the gas explosion can be estimated by employing equivalent TNT charge. Based on the range of 50 m and reflected impulse of 0.41 kPa-s, the equivalent TNT charge weight for the gas explosion is found to be 680 kg by using Figure 2-15 in UFC 3-340-02 (2008). An explosion-fragment model is developed to analyze the effects from the blast wave and fragment impacts upon the detonation of the equivalent TNT.

EXPLOSION-FRAGMENT MODEL

Fragments resulting from an explosion can be categorized into primary fragments and secondary fragments (UFC 3-340-02, 2008). Primary fragments are typically defined as fragments from the encasement of the explosive. In the case of the East Harlem explosion the primary encasement is presumed to be the cracked natural gas transmission pipe buried beneath the site of the collapsed buildings. Secondary fragments are defined as fragments that are compelled into motion by the shock wave due to being in the near vicinity of the blast epicenter. Examples of secondary fragments include various building components such as bricks, stone, lumber, and glass. This study focuses upon secondary fragments on account of the blast epicenter being enclosed by the brick walls of the two collapsed buildings.

Secondary Fragment Launch Velocity and Range

The interaction of a shock wave with fragments must be first evaluated to predict the velocity of fragments excited by the explosive detonation. In essence, a portion of the shock wave is reflected from the surface of the fragment facing the blast front while the remaining wave diffracts around the fragment (UFC 3-340-02, 2008). The reflected pressure imparts a net force upon the fragment described by the following equilibrium equation:

$$p(t)A = a(t)M \qquad (1)$$

where $p(t)$ is the pressure-time history imparted upon the fragment by the shock wave, A is the area of the fragment facing the blast front and $a(t)$ is the acceleration of the