Beirut Port Explosion: Comparison of Field Damage to Explosive Safety Standards

Kevin Mueller[1], PhD, PE, PSP; Elie Hantouche[2], PhD, PE
[1]Thornton Tomasetti, 600 W Fulton, Suite 705, Chicago, Illinois, USA
[2]American University of Beirut, Riad El-Solh 1107 2020, Beirut, Lebanon

Abstract

The city of Beirut sits on a peninsula along Lebanon's Mediterranean coast. The Port of Beirut, opened in 1887, is located directly north of downtown Beirut and mostly separated from the commercial and residential quarters by the Charles Helou highway. Over the years, thousands of tons of ammonium nitrate ended up being stored in Hangar 12, located directly east of the grain silos. For yet unknown reasons, the same hangar stored fuel, acid, fuse spools, and 15 tons of fireworks. Consequently, Hangar 12 was storing everything needed to make a bomb. On 4 August 2020, at around 18:07, a sequence of events started a chain reaction where a fire in the hangar caused the fireworks and subsequently the ammonium nitrate to detonate, resulting in nearly 250 deaths, over 6,000 injuries, around 300,000 people to lose their homes, and between 10-15 billion US dollars in damage throughout the city. The large scale of this event makes the Port of Beirut explosion among one of the biggest non-nuclear explosions in history. In the weeks following the event, the Order of Engineers and Architects of Beirut (OEA) and members of the Civil and Environmental Engineering Department at the American University of Beirut (AUB) mobilized to investigate the structural integrity and safety of many structures throughout the city. As a part of these efforts, more than 150 buildings ranging in distance between 600 m and 4400 m from Hangar 12 (i.e., explosion source) were assessed. In this investigation, the expected and actual damage at select buildings are compared within the framework established by explosive safety standards for munition storage areas, such as the United States Department of Defense Explosive Safety Board, United Kingdom Ministry of Defence, and NATO. The damage comparison discussed in this paper serves to highlight both the accuracies and shortcomings of blast modeling as it relates to the prediction of structural and non-structural damage.

Introduction

The city of Beirut sits on a peninsula along Lebanon's Mediterranean coast. The Port of Beirut, opened in 1887, is located directly north of downtown Beirut and mostly separated from the commercial and residential quarters by the Charles Helou highway. The port contains berths for freight vessels, grain silos, and storage hangars. Over the years, thousands of tons of ammonium nitrate ended up being stored in Hangar 12, located directly east of the grain silos. For yet unknown reasons, the same hangar stored fuel, acid, fuse spools, and 15 tons of fireworks. Consequently, Hangar 12 was storing everything needed to make a bomb [1].

On 4 August 2020 around 18:07, a sequence of events started a chain reaction where a fire in the hangar caused the fireworks and subsequently the ammonium nitrate to detonate, resulting in approximately 250 deaths, over 6,000 injuries, around 300,000 people to lose their homes, and between 10-15 billion US dollars in damage throughout the city. The large scale of this event makes the Port of Beirut explosion among one of the biggest non-nuclear explosions in history [2].

In the weeks following the event, the Order of Engineers and Architects of Beirut (OEA) and members of the Civil and Environmental Engineering Department at the American University of Beirut (AUB) mobilized to investigate the structural integrity and safety of many structures throughout the city [3]. As a part of these efforts, more than 150 buildings ranging in distance between 600 m (0.373 miles) and 4400 m (2.73 miles) from Hangar 12 (i.e., explosion source) were assessed [4]. This paper addresses the field survey conducted in the aftermath of the blast and the interesting findings suggested by the considerable non-structural damage observed. As highlighted in the blast-injury studies discussed, a large percentage of the observed blast injuries were the result of façade, non-structural damage to buildings. In this investigation, the expected and actual damage at select buildings are compared within the framework established by explosive safety standards for munition storage areas of similar TNT equivalency such as the United States Department of Defense Explosive Safety Board and the United Kingdom Ministry of Defence. This detailed comparison serves to highlight both the accuracies and shortcomings of blast modeling as it relates to the prediction of structural damage.

Explosion Magnitude

Given the restrictions on international travel due to the COVID-19 pandemic and limited access allowed by local authorities to the site of the explosion, analysis of the Port of Beirut explosion magnitude proved particularly difficult. To circumvent these challenges, Pilger et al. [5] used publicly available seismological, hydroacoustic, infrasonic, and radar remote sensing data to localize the explosion and to estimate the explosive yield in terms of TNT equivalent mass. This study estimates the Port of Beirut's explosive yield to have a lower bound of around 130 to 340 tons of TNT based on seismic data, and an upper bound between 1000 and 2000 tons of TNT based on infrasound yield relations and radar remote sensing data. This research supports this paper's assumption that around 630 tons of TNT equivalent mass was involved in the Port of Beirut explosion.

Among the variety of buildings and infrastructure affected by the blast were hospitals and other emergency services. Six major hospitals in Beirut were rendered either completely incapacitated or suffered partial disruption to their services due to the blast [6]. The damage suffered by Beirut's healthcare infrastructure rendered the city ill-equipped to handle the nearly 250 deaths and more than 6000 injuries resulting from the explosion. In the aftermath of the blast, Hajjar et al.

[7] investigated the pattern and severity of injuries suffered by blast victims who received care from the American University of Beirut Medical Center. This study found that upper extremity, head and neck injuries and penetrating, blunt trauma (secondary blast injuries) were among some of the most common injuries caused by the blast. In a similar forensic study, Denny et al. [8] investigated the correlation between a victim's blast injuries and their geographical location at the time of the explosion. The researchers found that secondary blast injuries were prevalent at all distances from the blast's epicenter, suggesting that injuries due to flying glass, shrapnel, and other projectiles associated with façade damage were common throughout the city of Beirut.

According to researchers, approximately 2750 tons of ammonium nitrate was stored in Hangar 12 [2, 9, 10, 11]. Based on eyewitness video and estimated shock wave velocity, it was estimated that approximately 1500 tons of ammonium nitrate contributed to the explosion. In practice, explosions are defined based on a TNT-equivalent charge size to better match historical experimental data and utilize industry standard relationships between the TNT charge weight and pressure/impulse for analysis purposes. The explosion resulted in a form of blast wave which, although not unexpected, was considerably different to smaller explosive events. It is assumed for the purposes of this paper that the TNT-equivalent is 630 tons, which equates to approximately 724 tons of ammonium nitrate/fuel oil (ANFO) [12], although current estimates vary from 300 to 960 tons of TNT.

Field Survey Damage Assessment

In the aftermath of the explosion, researchers and engineers at American University Beirut (AUB) set up a hotline for residents or building owners to schedule a structural damage assessment. The initial observations from these assessments show that damage can be classified, and the buildings tagged, using three main categories: destructive (red), partially destructive (yellow), non-destructive (green) damage. The damage classification of over 150 buildings is shown in Figure 1 using appropriately colored circles.

Figure 1. AUB Surveyed Building Locations and Damage Classification

The level of damage is mainly dependent on the type, age, and the location of these buildings. The damage assessment for these buildings was performed to inform the public about the extent of damage that occurred and to assist in the engineering decision between repairing or demolition of the affected buildings.

Approximately a third of the buildings surveyed experienced destructive damage. Those buildings, located within a setback of 1.5 km (0.932 miles) from Hangar 12, were mainly made of masonry blocks dating older than 50 years. The buildings exhibiting destructive damage collapsed, as did the unreinforced masonry bearing wall of the building as shown in Figure 2. This building is located about 1 km (0.621 miles) away from the explosion, and it is classified as a historical masonry building that consists of unreinforced masonry blocks from natural stones with wooden roof trusses. This type of building is designed to resist gravity and wind loads only; it cannot resist lateral loads (i.e., earthquake or blast loading). This is due to the absence of seismic structural systems and horizontal diaphragms that can help in resisting shock waves due to an explosion.

Figure 2. Historical Building Total Collapse

A reinforced-concrete building located near the collapsed historical building, as shown in Figure 3, withstood the blast load without any severe damage recorded. It is assumed that the gravity reinforced-concrete building frame provided adequate stiffness capable of resisting the blast shock waves.

Figure 3. Reinforced Concrete Building without Severe Damage

The buildings identified as having partially destructive damage are not totally collapsed but were still severely affected by the explosion. Figure 4 shows a building identified as having partially destructive severe damage. The building is classified as a historical building that consists of natural stone masonry bearing walls with wooden roof trusses. This building is located around 1.2 km (0.746 miles) away from the explosion. The traditional balconies with thin cantilever slabs collapsed and the top timber roof truss failed. This is because the timber roof trusses, as constructed, cannot act as diaphragms to resist any lateral load. The third floor of the exterior wall of this building also experienced severe damage.

Figure 4. Natural Stone Masonry Historical Building with Partial Collapse

Reinforced concrete buildings primarily from the 1950s (Figure 5) did not encounter any structural damage even though they were close to the explosion location (within 1 km (0.621 miles) from the explosion); this is mainly due to their location being surrounded by tall new buildings reducing the explosion intensity. Only non-structural damage was observed such as partition walls (CMU), doors, and windows.

Figure 5. 1950's Reinforced Concrete Building Non-Structural Damage

Near the Beirut port (facing the port to the south) is an 11-story reinforced concrete building constructed post-2010. The building's high stiffness in both directions due to the reinforced concrete shear wall system was able to resist the blast-induced lateral loads. Despite the substantial impact, no severe structural damage occurred. The entire aluminum double-glazed façade facing the explosion site exhibited a convex curvature as shown in Figure 6 (aligned with the blast shock wave impact), exerting compressive forces on the supporting partition walls (CMU). This led to the development of cracks along the CMU wall joint. The building façade, composed of double-glazed glass, experienced complete damage, with all its elements affected. At higher floors, the partition walls (CMU) increasingly exhibit both horizontal and diagonal cracks; this is mainly due to some foundation movement resulting from a 3.3 magnitude earthquake from the blast [13] with the blast shock waves.

Figure 6. Post-2010 Reinforced Concrete Building Non-Structural Damage

This building was designed following seismic codes to resist earthquakes using reinforced-concrete shear wall systems that provide the building with very high stiffness in both directions, which was able to resist the blast-induced lateral loads. While this damage may seem minor with respect to the structural damage experienced by other types of buildings, it can severely impact a community's ability to recover and occupy buildings damaged in this manner.

Explosive Safety Standards

Another way to assess the field survey data is to utilize explosive safety standards, which have been developed by organizations such as the United States Department of Defense Explosive Safety Board [14], the United Kingdom Ministry of Defence [15], and North Atlantic Treaty Organization [16] over the past several decades. As shown in Figure 7, the siting requirements include minimum distances between the stored explosives (Hangar 12) and inhabited buildings, public traffic routes, electrical systems, and other explosive storage locations.

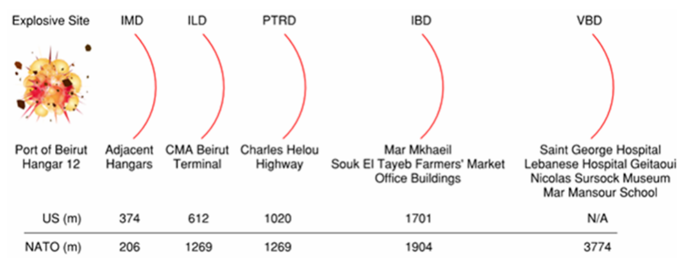

Figure 7. QD Summary from Hangar 12

The goal of explosive safety siting is two-fold: public life-safety and to mitigate the propagation of explosives between storage locations. Quantity-Distance (QD) arcs – for vulnerable buildings (VBD), inhabited buildings (IBD), public traffic routes (PTRD), munitions-related occupied buildings (defined as intraline distance, ILD), and related unoccupied munitions storage magazines (defined as intermagazine distance, IMD), which are listed in order of decreasing radius to the explosive source – are developed to establish minimum setback distances based on the net explosive weight (NEW) stored in Hangar 12. The expected damages, injuries, and fatalities at each QD are provided in Table 1.

Table 1. Expected Blast Pressure and Damage at each QD

QD	Blast Pressure (kPa)	Structural Damage	Façade Damage	Injuries	Fatalities
VBD	< 6.9	Superficial	Very Minor	Very Few	None
IBD	8.3	Very Minor	Minor	Very Few	Very Few
PTRD	11.7	Minor	Moderate	Few	Very Few
ILD	24.0	Major	Major	Moderate	Few
IMD	55.3	Destruction	Destruction	Major	Major

The critical parameter most applicable to the city of Beirut is the inhabited building distance (IBD). The IBD reflects the minimum permissible distance between a quantity of explosives and any building inhabited by the public or where people are accustomed to assembling. From a US perspective, this includes all apartment/condo buildings, offices, markets, schools, hospitals, and shopping centers. From a NATO perspective, this only includes apartment/condo buildings, offices, markets, and shopping centers, while schools and hospitals are classified as vulnerable buildings. Meeting this minimum distance provides a high degree of protection against structural damage based upon blast or shock wave effects to frame or masonry buildings. It does not necessarily provide protection against glass breakage. Personnel injury from flying glass is possible even when in compliance with government regulations due to its high failure potential under low blast pressure (5kPa [0.73 psi] peak pressure). The IBD for the assumed 630 tons TNT-equivalent explosion is between 1700m (1.06 miles) and 1900m (1.18 miles) based on US and UK standards, respectively.

The observations from the field survey assessments show that damage can be classified, and the buildings tagged, using three main categories: destructive (red), partially destructive (yellow), non-destructive (green) damage. The damage classification of over 150 buildings is shown in Figure 8 using appropriately colored circles and with the US (red) and NATO (yellow) IBD arcs overlayed. Figure 9 shows one mid-rise residence building with widespread façade failure such as that expected in a building located within an IBD arc.

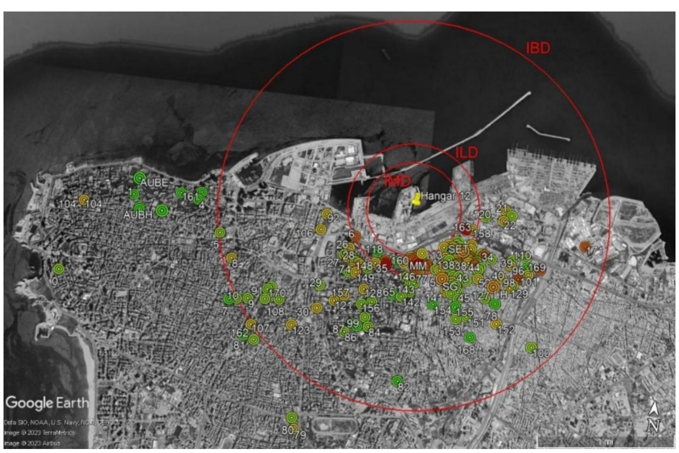

Figure 8. AUB Surveyed Building Locations and Revised QD Arcs

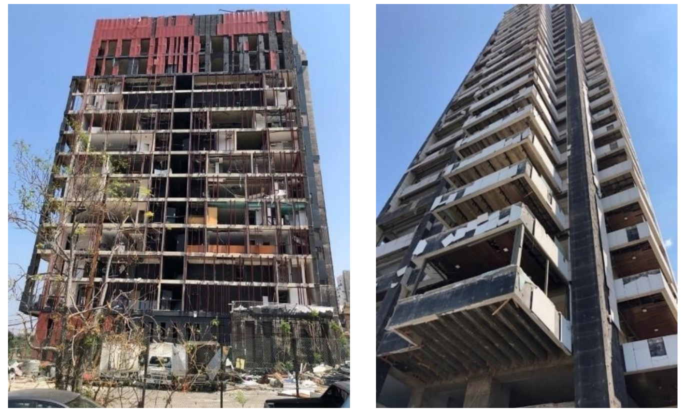
Figure 9. Post-2010 Reinforced Concrete Building Façade Damage

Given the lack of use of these siting standards in the storage of the explosives in Hangar 12, many buildings that would be classified as either inhabited or vulnerable buildings were located well within these IBD standoff distances. For example, the apartment building considered in the Façade Detailed Analysis herein was located only 517.18 m (1697 ft) from the blast source, subjecting it to anticipated ILD-level damages, which include major structural and façade damage. In contrast to these predicted damages, the building did not exhibit structural damage, as discussed. The discrepancies between the damages predicted by explosives safety criteria (Figure 7 and Table 1) and those observed in the field survey (Figure 8) can be used to produce an updated estimate of the net explosive weight (NEW) involved in the ammonium nitrate explosion.

As summarized in Table 2, these revised QD arcs result in a TNT equivalent net explosive weight between 1406 and 2288 tons, as compared to the initial assumption of 630 tons. PTRD is not shown as it is calculated as 60% of IBD, and damage to vehicles was not specifically investigated as part of the field assessment to use for comparison. Using the TNT equivalency of ANFO from ASCE/SEI 59-22, the total quantity of stored explosives based on the explosives safety standards is estimated to be between 2000-3000 tons. Based on the field assessment and damage witnessed throughout the city, the actual quantity of ammonium nitrate contributing to the explosion in Hangar 12 would have to had been closer to the total stored amount, meaning that almost all material contributed to the explosion. This highlights the conservative nature of explosive safety standards and assumptions on how the blast load develops.

Table 2. Hangar 12 Net Explosive Weight based on Field Survey

QD	Survey Distance (m)	TNT (tons)	ANFO (tons)
IBD	2400	1772	2340
ILD	800	1406	1858
IMD	575	2288	3023

Summary and Conclusions

Traditionally, the storage of high explosives near populated areas is tightly controlled, particularly with respect to munition storage areas of military bases. The urban nature of the Port of Beirut explosion, however, contributed to widespread damage and injury. Additionally, given that this explosion occurred in such a structurally diverse, urban setting, common blast modeling practices and relevant predictive software appear to have shortcomings as highlighted herein. The following considerations are of particular importance to the development of more accurate modeling practices for use in the field of protective design consulting:

- UFC 3-340-02 assumes all explosive charge weight is located as a single point. This can lead to the underestimation of damages as compared to if the explosives were treated as spread-out over a larger surface area. The sizable diameter of the crater produced by the Port of Beirut explosion suggests that the explosives were distributed throughout Hangar 12. Consequently, this simplifying assumption led to an underestimation of the damages observed.

- The Port of Beirut blast led to widespread non-structural damage (shattered glass and façade damage) throughout the city. The prevalence of non-structural damage, rather than structural damage, was not expected given the extremely large TNT equivalent and suggests both the possibility of overly conservative modeling practices in the field of protective design and the unaddressed complexity of urban explosions. This non-structural damage was a major contributor to the secondary blast injuries suffered by many blast-victims during the event, thus suggesting that hospitals located near explosives storage facilities – especially those that are sited in or near urban settings – should be prepared to respond to such secondary blast injuries.

- Using the explosive safety standards outlined by the US Department of Defense and NATO, the observed damages and their retrospectively associated QD arcs can be used to provide an alternative (albeit conservative) estimate on the TNT equivalency of an explosion.

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Contact Information

Kevin Mueller, PhD, PE, PSP
Thornton Tomasetti
600 W Fulton St, Suite 705
Chicago, Illinois 60661, USA
+1-312-788-7032
kmueller@email.tt

Elie Hantouche, PhD, PE
American University of Beirut
Riad El-Solh 1107 2020
Beirut, Lebanon
+961-1-350000 (Ext.: 3474)
eh12@aub.edu.lb

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