Beirut Explosion
Structural Assessment of the Explosion Magnitude

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Abstract
On August 4th 2020, tremendous explosion occurred in Beirut, Lebanon’s capital, specifically in its port. The resulting damage was humongous, impacting the city along a radius of about 600m. Series of grains silos adjacent to the center of the explosion, at 85m proximity, had been importantly damaged. The cause was anticipated to explosion of Ammonium Nitrate that had been stored in the port, of “said” quantity equal to 2750t, whereby different opinions have emerged regarding the amount of the explosive materials and the magnitude of the explosion. The aim of this research work is to define the magnitude of the explosion, using structural engineering approach throughout non-linear finite element modeling of the silos. The magnitude of the explosion is defined as the numerical model magnitude that generated the silos damages. The study is based on silos detailed drawings, data collected from site visits, and the use of the Conventional Weapons Effects Blast Loading (CONWEP) method. In addition, damage assessment for the “standing” silos has been conducted and final recommendations are included. This paper shows that the magnitude of the explosion is significantly smaller than the equivalent TNT of the original declared quantity of stored Ammonium Nitrate.

Keywords: Beirut explosion, Grain silos, Nonlinear analysis, Ammonium Nitrate, TNT equivalent, Dynamic analysis

1. Introduction

In recent times, explosions incidents have increased in different parts of the world, causing harms to lives and serious damages to infrastructure. This attracted the attention of many researchers in the field of structural engineering to study the effects of these explosions on various structural elements. Beirut port explosion killed more than 200 people and wounded more than 6000 people. This explosion had also incurred extensive damages in the city of Beirut areas surrounding the port. An important feature of this explosion, as reported by many media outlets, is the grain silos in Beirut Port, which was said to have protected part of the city and its people from the blast. This had drawn our attention to study the Silos structure and assess the corresponding level of damage inflicted by the explosion; consequently, allowing to determine the magnitude of the explosion.

This research project aims to determine the magnitude of Beirut explosion by structurally analyzing the grain silos facing the explosion, using non-linear finite element numerical analysis of the exact dimensions of the silos, which had been accurately determined from existing execution drawings, data collected from several sources, and from site visits; and whose material properties, of both concrete and steel reinforcement, were determined by samples extracted from the silos and tested in material labs.

2. Methodology

Beirut grain silos (Figure 1) were built in the port of Beirut in the late 1960s and were inaugurated in 1970. The silos structure consists of 42 cylinders, with an internal diameter of 8.5 meters (each cylinder), walls thicknesses 17cm, and a height of 48 meters. Over the years, expansion and rehabilitation works had been executed. In the late 1990s, six new silos were added to the main 42 silos. In 2002, due to concrete...
carbonization, silos had undergone restoration works.

2.1. Geometry and Reinforcement

2.1.1. Original design

The silos construction process was performed in three stages as illustrated in Figures 2 and 3.
2.1.2. Internal layout of silos

Figure 4: Internal division of silos (cm)

Figure 5: L.S dimensions below and above Slab 1 level (cm)

2.1.3. Silos reinforcement

Figure 6: Walls and L.S reinforcement (mm)

Figure 7: T.S reinforcement (mm)
2.1.4. Rehabilitation of Silos

From 2000 to 2002, the silos underwent rehabilitation works due to concrete deterioration in the two external silos long rows.

Figure 8: Silos walls’ reinforcement after rehabilitation (mm)

Figure 9: Section 1-1 for the silo’s wall (mm)

2.2. Material properties

2.2.1. Concrete coring and testing

Concrete properties of silos were determined based on experimental procedure. Site visit was conducted to extract concrete cores for material testing as shown in Figure 10.

Figure 10: Concrete coring

Figure 11: Core testing
2.2.2. Steel rebar testing

2.3. Damage assessment

The research team, in cooperation with the Directorate of Engineering in the Lebanese Army, conducted field visits to assess the damages of the silos. In addition, the Lebanese Air Force provided the research team with aerial high-resolution photos for the silos, as shown in Figure 20.
Two silos from the second and third row were destroyed

Figure 16: Aerial photo by the Lebanese air force

Figure 17: Side view for the damaged silos

Figure 18: Front view for the damaged silos

Figure 19: Sketch showing damaged silos after the explosion
A three-dimensional scanning for the silos was performed by a Switzerland company showing the deformed shape of the remaining part (14 silos in the third row) as illustrated in Figure 20.

2.4. Numerical modeling

2.4.1. Finite element model

After collecting all the information related to the silos, a non-linear numerical analysis was conducted using ABAQUS software, to determine the magnitude of the explosion based on the silo’s damages. Four-node thin shell elements were used to model the silos elements, all reinforcements are defined as rebar layers assigned to the shell elements. The grains are modeled with 8-node linear brick elements, and placed inside the silos.

2.4.2. Material definition

The concrete material is defined as written script considering the dynamic effect on material properties. The behavior of concrete in uniaxial tension and compression (including cycles of loading - unloading) integrated in this model is shown in Figure 23:
The general stress Equation can be written as:

$$\sigma - \sigma_{ft} = E_0(1 - D)(\varepsilon - \varepsilon_{ft})$$  \hspace{1cm} (1)

The damage parameter $D_c$ only evolves during compressive

$$\sigma - \sigma_{ft} = E_0(1 - D_c)(\varepsilon - \varepsilon_{ft})$$  \hspace{1cm} (2)

The damage parameter $D_{\text{t-comp}}$ can be evaluated indirectly from the damage of Mazars in compression from $(\varepsilon - \varepsilon_{ft0})$ (Figure 24) as follows:

$$\sigma - \sigma_{ft0} = E_0(1 - D_{\text{t-comp}})(\varepsilon - \varepsilon_{ft0})$$  \hspace{1cm} (3)

Regarding the tensile damage $D_{\text{t-tens}}$ due to a tensile loading, it suffices to consider the $D_{\text{t-tens}}$ damage of Mazars evaluated at strain $(\varepsilon - \varepsilon_{ft0})$.

$$P(t) = P_i(t)[1 + \cos \theta - 2 \cos^2 \theta] + P_r(t) \cos^2 \theta$$  \hspace{1cm} (4)

for $\cos \theta > 0$

$$P(t) = P_i(t), \text{ for } \cos \theta < 0$$  \hspace{1cm} (5)

Where $P(t)$ is the total surface pressure at time $t$, $P_i$ is the incident pressure, and $P_r$ is the reflected pressure.

### 2.4.3. Blast load definition & work plan

ABAQUS built-in CONWEP model is used to model the blast load in this study. It simulates the loading effects due to an explosion in air for both spherical waves (air blast) and hemispherical incident waves (surface blast) in terms of both incident and reflected pressure. The typical pressure history for a blast wave is shown in Figure 26. Based on this method, the total pressure applied on the front surface is defined as:

$$P(t) = P_i(t)[1 + \cos \theta - 2 \cos^2 \theta] + P_r(t) \cos^2 \theta$$  \hspace{1cm} (4)

for $\cos \theta > 0$

$$P(t) = P_i(t), \text{ for } \cos \theta < 0$$  \hspace{1cm} (5)

Where $P(t)$ is the total surface pressure at time $t$, $P_i$ is the incident pressure, and $P_r$ is the reflected pressure.
In order to specify the detonation center point of the explosion, the aerial photos captured by the Lebanese Army Air Force are used to preliminary define the detonation center point as shown in Figures 27 and 28. Figure 27 shows ward number 12 that contained the explosive materials and the silos.

Since the explosive material in ward number 12 is Ammonium Nitrate (AN), a scaling factor is used to transform the AN mass to equivalent TNT mass, to enable using it in the numerical study as input. The following Equation is adopted for this purpose:

\[
W_d = \frac{H_d^{\text{exp}}}{H_d^{\text{TNT}}} W_{\text{exp}}
\]  

According to Equation 6, the scaling factor \(\frac{H_d^{\text{exp}}}{H_d^{\text{TNT}}}\) ranges between 0.35 - 0.39 for AN to TNT transformation. Referring to the data provided by the Lebanese army (based on their investigations), a scaling factor of 0.39 is recommended to transfer the explosive mass from AN to TNT. This implies that the total original mass of AN of 2750t, is equivalent to 1100t of TNT.

The analytical program is divided into 8 cases, as illustrated in Table 2. Two parameters are considered to calibrate the model, the degree of damage as shown in Figure 19, and the top lateral sway for the remaining third row of silos shown in Figure 20.

<table>
<thead>
<tr>
<th>Case</th>
<th>Equivalent TNT mass (t)</th>
<th>Standoff distance (m)</th>
<th>Centroid shift (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>1100</td>
<td>75</td>
<td>0</td>
</tr>
<tr>
<td>Case 2</td>
<td>500</td>
<td>75</td>
<td>0</td>
</tr>
<tr>
<td>Case 3</td>
<td>400</td>
<td>75</td>
<td>0</td>
</tr>
<tr>
<td>Case 4</td>
<td>300</td>
<td>75</td>
<td>0</td>
</tr>
<tr>
<td>Case 5</td>
<td>200</td>
<td>75</td>
<td>0</td>
</tr>
<tr>
<td>Case 6</td>
<td>100</td>
<td>75</td>
<td>0</td>
</tr>
<tr>
<td>Case 7</td>
<td>50</td>
<td>75</td>
<td>0</td>
</tr>
<tr>
<td>Case 8</td>
<td>200</td>
<td>85</td>
<td>10</td>
</tr>
</tbody>
</table>
3. Results and discussion

3.1. First round of calibration

Results for all study cases are summarized in Table 2. Figure 29 shows the damage pattern for all load cases. It is noted that for equivalent TNT mass of 1100t, 500t, 400t, and 300t respectively, all silos will be totally destroyed. Reducing the mass of explosion to 50t results in destruction of just one row of silos as shown in Figure 29.

Table 2: Summarized results for all study cases

<table>
<thead>
<tr>
<th>Case</th>
<th>TNT (t)</th>
<th>ds (m)</th>
<th>Zb (m/kg^{1/3})</th>
<th>Damage level</th>
<th>δmax (cm)</th>
<th>P_s (MPa)</th>
<th>F_{base-max} (kN)</th>
<th>M_{base-max} (kN.m)</th>
<th>δb (s^{-1})</th>
<th>Wt (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>1100</td>
<td>75</td>
<td>0.727</td>
<td>3 rows</td>
<td>202</td>
<td>17.2</td>
<td>1846180</td>
<td>1818540</td>
<td>4</td>
<td>6.28 x 10^9</td>
</tr>
<tr>
<td>Case 2</td>
<td>500</td>
<td>75</td>
<td>0.945</td>
<td>3 rows</td>
<td>82</td>
<td>9.1</td>
<td>1121450</td>
<td>1113400</td>
<td>1.41</td>
<td>1.68 x 10^9</td>
</tr>
<tr>
<td>Case 3</td>
<td>400</td>
<td>75</td>
<td>1.018</td>
<td>3 rows</td>
<td>62</td>
<td>7.5</td>
<td>956968</td>
<td>940165</td>
<td>1.25</td>
<td>1.15 x 10^9</td>
</tr>
<tr>
<td>Case 4</td>
<td>300</td>
<td>75</td>
<td>1.120</td>
<td>3 rows</td>
<td>44</td>
<td>5.35</td>
<td>796972</td>
<td>744287</td>
<td>1.24</td>
<td>7.04 x 10^8</td>
</tr>
<tr>
<td>Case 5</td>
<td>200</td>
<td>75</td>
<td>1.282</td>
<td>2 rows</td>
<td>31</td>
<td>3.82</td>
<td>615301</td>
<td>523658</td>
<td>0.68</td>
<td>3.56 x 10^8</td>
</tr>
<tr>
<td>Case 6</td>
<td>100</td>
<td>75</td>
<td>1.615</td>
<td>2 rows</td>
<td>18</td>
<td>1.9</td>
<td>462448</td>
<td>288411</td>
<td>0.47</td>
<td>1.12 x 10^8</td>
</tr>
<tr>
<td>Case 7</td>
<td>50</td>
<td>75</td>
<td>2.036</td>
<td>1 row</td>
<td>10</td>
<td>0.95</td>
<td>380292</td>
<td>158076</td>
<td>0.24</td>
<td>3.6 x 10^7</td>
</tr>
<tr>
<td>Case 8i</td>
<td>200</td>
<td>85</td>
<td>1.453</td>
<td>2 rows</td>
<td>26</td>
<td>2.63</td>
<td>575718</td>
<td>451001</td>
<td>0.68</td>
<td>2.58 x 10^8</td>
</tr>
</tbody>
</table>

(a) (b)
3.2. Second round of calibration

In this phase, the blast centroid is shifted by 10m towards the zone where the last two silos were totally destroyed, to provide results matching the damage level as the actual case. Figure 30 shows the damages.
Figure 30: Damage pattern for case


Figure 31: Maximum displacements for each silo (cm)
The blast pressure history for case 8 is shown in Figure 32.

**Figure 32: Blast pressure history (MPa)**

**Figure 33: Peak blast pressure for remaining silos (MPa)**

### 3.3. Additional Analysis Findings

#### 3.3.1. Scaled Distance Ratio

The scaled distance ratio:

\[
Z = \frac{d}{m_{TNT}^{1/3}} \quad (7)
\]

The scaled distance value for case 1 (1100t of TNT) is 0.727. As for case 8, which is corresponding to the actual the scaled distance is 1.453

#### 3.3.2. Strain Rate

The strain rate:

\[
\dot{\varepsilon} = 0.45 + 141.275e^{-5.063Z} \quad (8)
\]

The applied work varies from 6.28x109J for case 1 (1100t of TNT) to 2.58x108J for case (case 8),

#### 3.3.3. Total Work

The Authors derived the work Equation:

\[
W = 1.24 \times 10^8 + 6.11 \times 10^{14}e^{-6.3Z} \quad (9)
\]

According to the UFC code [40], the total energy released by the explosion of 200t of TNT equivalent is 8.36 x 1012J. This means that the silos dissipated around 0.003% of the total energy released by the explosion (Total work/released energy = 2.58x108 / 8.36 x 1012). Based on the above finding, the silos role was to diffract the blast wave and not to absorb it.

### 3.3.4. Refinement of Detonation Magnitude and Location

In order to refine the determined magnitude of the explosion, five additional cases are studied considering small variation of both detonation centroid location and detonation mass.

The analysis results led to 209t TNT, as a final magnitude of the explosion corresponding to 535t of AN. This implies that the percentage of AN mass exploded is 19% of the 2750t, the original stored quantity, declared.

### 4. Conclusion

The results of this study lead to the several important conclusions, most importantly:

1- Based on the results of this study, it is concluded that the explosive amount of Ammonium Nitrate is much less than the total original amount. The analysis results prove that an amount equivalent to 209t of TNT or 535t of AN is adequate to generate damages similar to those resulting from the explosion. This amount represents 19% of the original stored amount (2750 t).

Table 5 below shows the results of this research compared to results generated by other research works.
Table 3: Comparison between Temsah et al findings to other research findings

<table>
<thead>
<tr>
<th>Study</th>
<th>Yield energy (J)</th>
<th>TNT mass (t)</th>
<th>AN mass (t)</th>
<th>Calculation Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jorge [19]</td>
<td>4.19 x10^{12}</td>
<td>1000</td>
<td>2560</td>
<td>Fireball Analysis</td>
</tr>
<tr>
<td>Rigby [20]</td>
<td>----</td>
<td>500 - 1100</td>
<td>1280 - 2816</td>
<td>Blast Empirical Formulas</td>
</tr>
<tr>
<td>Lu [21]</td>
<td>2.65 x 10^{12}</td>
<td>662</td>
<td>2070</td>
<td>Wilson Cloud</td>
</tr>
<tr>
<td>Al-Housseiny [22]</td>
<td>----</td>
<td>2200 - 4400</td>
<td>5630 - 11265</td>
<td>Wilson Cloud</td>
</tr>
<tr>
<td>Aouad [23]</td>
<td>1.289 x10^{12}</td>
<td>308</td>
<td>810</td>
<td>Fireball Analysis</td>
</tr>
<tr>
<td>Temsah</td>
<td>8.36 x 10^{12}</td>
<td>209</td>
<td>535</td>
<td>Numerical Structural Analysis</td>
</tr>
</tbody>
</table>

It is concluded that Aouad’s and Temsah findings are relatively close, whereas the findings of all others are significantly larger.

2- Regarding the position of explosive centroid, it is found from the crater’s dimensions that the standoff distance of the explosive ranges from 75m to 85m, and the centroid lies with 10m to 20m shift towards the direction where the last two silos, of each row, were totally destroyed.

3- The total work dissipated by the silos is 2.58x10^9J. This value is used to determine the energy absorbed by the silos, which is around 0.003% of the total released energy by 200t of TNT equivalent mass. This refutes the claims that the silos protected Beirut city from total destruction, yet they helped in diffracting the wave away from the buildings lying behind.