Memo: Investigating the Mariupol Drama Theater Bombing[1]
Dr. F. Dalnoki-Veress
James Martin Center of Nonproliferation Studies (CNS)
Middlebury Institute of International Studies
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On March 16th Russia dropped at least one bomb on the Drama Theater in Mariupol (Драмтеатр, Donetsk Academic Regional Drama Theatre formally) where hundreds of people were sheltering. The area is still an active war zone and access to the area for detailed investigation is not possible. Further, confounding estimating the effect of the bomb is the attacks that occurred after the event, the fire that occurred and the collapse of a large part of the building afterwards. Rather than depend on subsequent videos and photographs this analysis is based on the Maxar satellite image taken immediately after the building depicted in Figure 1 with the third-floor architectural drawing superimposed. One exception are screen captures from a drone video taken later after subsequent bombing and collapse of the building which will only be used to substantiate the satellite image and other images to establish the structure of the building.

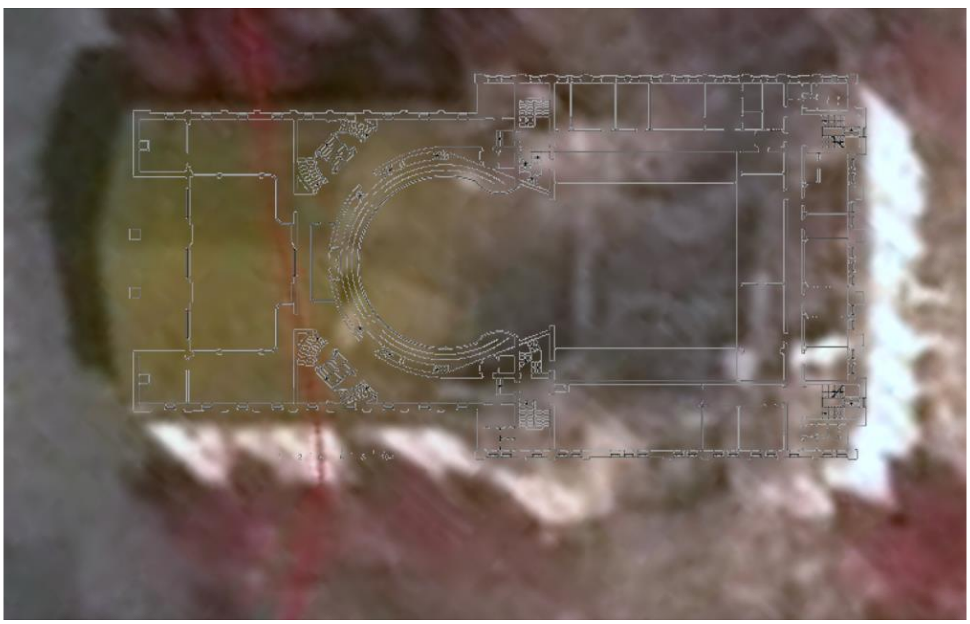

Figure 1: We use almost exclusively the satellite photo taken soon after the initial explosion. There have been many photographs since but since we are interested in the initial explosion this is primarily the photograph we analyze. We have also superposed the Third-Floor architectural drawing to give a sense of where we expect the walls to be. [Source: satellite image and architectural images provided by Mr. Brian Castner (Senior Crisis Advisor – Weapons & Military Operations, Amnesty International).]

[1] The views, judgments, and conclusions in this report are the sole representations of the author and do not necessarily represent either the official position or policy or bear the endorsement CNS or the Middlebury Institute of International Studies at Monterey.

Figure 2: We analyze in this report the damage to the various walls to determine the size of the explosion that is consistent with the damage observed from the satellite image. However, we also use some of the screen capture from the subsequent drone videos but only to substantiate what we see not to estimate the damage since we don't know if the damage in the insets are due to subsequent explosion, fire etc.[Source: https://twitter.com/Militarylandnet/status/1509438591952424962?s=20&t=mmNFdiM4gpJV-LLotC8CrQ]

<u>From the images we make the following observations:</u>

1) The entire top roof of the building was destroyed in the initial blast. The bomb likely penetrated the roof and detonated in flight as it fell to the ground. Note there are no pictures of the bomb itself and would have likely been removed from the scene by the Russian troops that control the area. There are images of pieces of the red roof nearby among the other debris. Part of the roof on the side opposite of the building was intact immediately after the explosion. This allows us to compare the integrity of the side of the building that sustained the bomb (right side in Figure 2 above) to the left side that at the time had a part of the roof that did not collapse. We notice that about 2/3rd of the building suffered damage due to the initial bomb consistent with an area of about 1500 m^2.

2) **Location of bomb detonation:** Note I don't have high confidence in this point but not knowing the location does not change the estimate of the yield. It appears that the bomb detonated on the side towards W2' rather than W2. That is because it appears that the damage on the side towards W2' was more severe. This is based on the satellite image since the shadow in the satellite picture was not as pronounced for W1' and W2' meaning that at the time what was left of the wall was likely lower. In later images we note that the beam likely supporting the 3rd floor was left but the wall was mostly gone.

Figure 3: Top: Image from the side of the building looking towards wall W1. In the distance is the Nielsen electronics market, the street which according to Yandex is translated as *"Prospect of the World"* away from the theater. Notice the red roofing and the trees that have broken as if a wind shear passed through. See 4) for further discussion about this. Bottom: view of expanded scene from further vantage point extracted from video. [Source: https://twitter.com/ESSA_A1I/status/1508457903442870276?s=20&t=6ubAAZvLP_NyhOSTsbyJgA]

3) **The minimum yield of the explosion ranges from about 400-800 kg TNT equivalent consistent with the damage:** Since we know the distance between the walls W1/W1' and W2/W2' we can make a simplistic estimate of the yield of the bomb using *Jarret Curve* analysis which is often done as an initial estimate of the bomb size. [2] [3] We can relate the damage observed and the distance from the explosion at which it is observed and the mass of explosives TNT equivalent according to the formula:

$$\mathrm{ACR} = \frac{\mathrm{R_b k_{ACR} Q^{\frac{1}{3}}}}{[1 + (\frac{\mathrm{Q_{ACR}}}{\mathrm{Q}})^2]^{\frac{1}{6}}}$$

Where k_{ACR} = 7.1 m/kg1/3 and Q_{ACR} = 3,175 kg and Q is in kg. ACR is the Average Circle Radius at which the effect Rb is experienced. [4] If a particular damage consistent with Rb is observed at a certain distance ACR away, then this formula can be inverted to obtain Q. The worst damage which is consistent with a collapse of the walls ("A") can be expressed as:

[2] Jarrett, D. E. "Derivation of the British explosives safety distances." Annals of the New York Academy of Sciences 152, no. 1 (1968): 18-35.
[3] Gilbert, S. M., F. P. Lees, and N. F. Scilly. A model for hazard assessment of the explosion of an explosives vehicle in a built-up area. LOUGHBOROUGH UNIV OF TECHNOLOGY (UNITED KINGDOM) DEPT OF CHEMICAL ENGINEERING, 1994.
[4] van der Voort, M. M., R. M. M. van Wees, S. D. Brouwer, M. J. van der Jagt-Deutekom, and J. Verreault. "A structured approach to forensic study of explosions: The TNO Inverse Explosion Analysis tool." In 5th DAPS conference, pp. 19-21. 2015.

$$Q_A[\mathrm{kg}] = \left(\frac{D[\mathrm{m}]}{0.3309}\right)^{1.5078}$$

Where Q_A [kg] represents the charge mass in TNT equivalent for a pressure consistent with “almost complete demolition” of buildings based on an analysis done of World War II destruction of buildings, and D [m] is the standoff distance of the bomb that would produce those effects. [5] We note that while the destruction is different on both sides, both walls W1/W1’ and W2/W2’ suffered damage consistent with requiring “complete demolition”, no repair is possible. Therefore, if we assume a distance x from the wall W1 is where the bomb exploded then the distance to W1’ is L1-x where L1=33.9 m. The distance L1$\pm$0.5 m was determined from the architectural drawings which are assumed to be drawn to scale, but I will assume has a distance error of at least 0.5 m. Similarly, L2 is estimated to be 21.1$\pm$0.5 m. We can say that the distance for W1/W1’ is bounded by 0 (explosion very close to wall which is very unlikely) to L1 which is equally unlikely. Likely the explosion between walls W2 and W2’, ie $6.4<x<27.5$. If D=8 m (from wall W1) then the distance of the explosion to W1’ is D=25.9 m. If this is the case, then we have two estimates for the minimum and maximum charges Q that would damage the walls, one for a distance at 8 m from the wall (D_{min}) and another at a distance of 25.9 m from the wall (D_{max}).

However, since both of the walls suffered non-repairable damage and it is only possible that there was one charge that caused both walls to be damaged then it is reasonable to assume that the maximum charge produced the damage is consistent with the largest of both values of D, namely $Q=\max(Q(D_{min}),Q(D_{max}))= Q(Dmax)$. This is because the smaller charge estimate attributable to Dmin may not be able to cause the observed damage in the wall (L1-x) away since we are measuring a threshold. See comparison of two cases in Figure 4.

[5] We assume that this criterion is a measure of the strength of the blast and that the pressure that the walls/beams experienced were consistent with “A” level damage or 47 kPa or 6.817 psi.

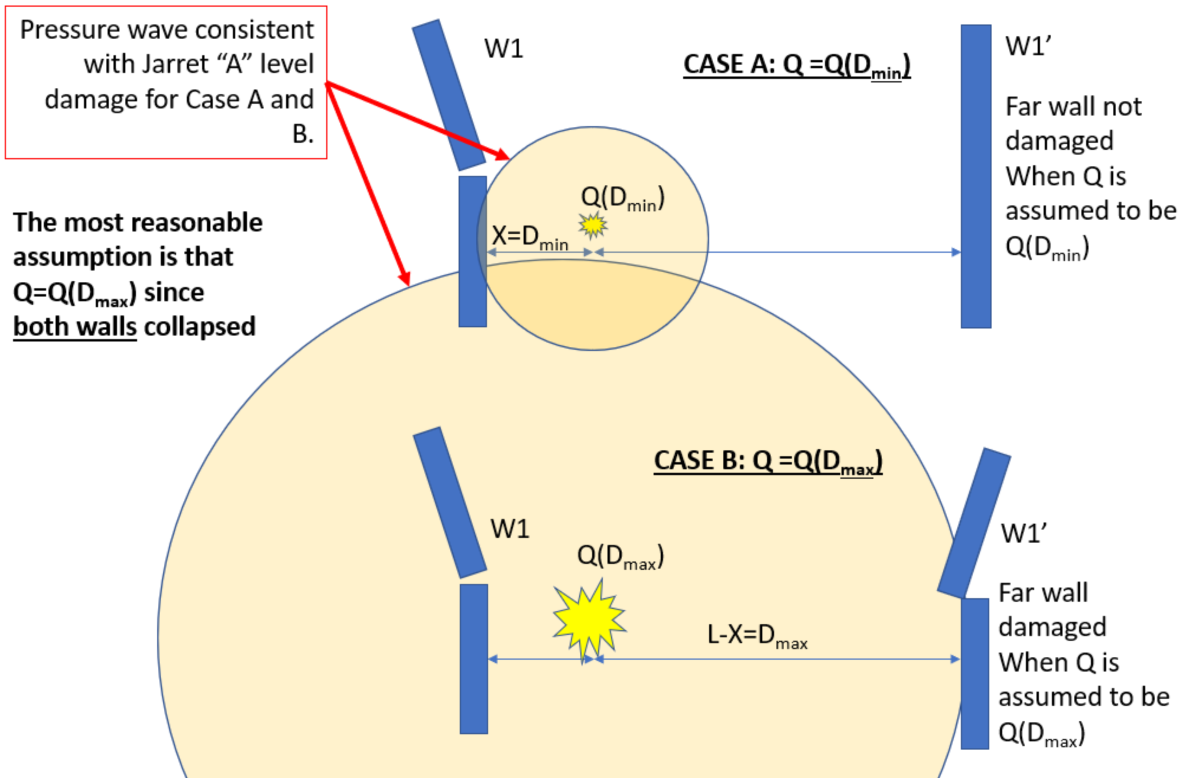

Figure 4: Comparing two cases demonstrating why when both walls are damaged (Case B) it is reasonable to assume that the damage to the walls is due to the larger of the distances implying a higher yield estimate based on $D_{ma}x$ rather than D_{min}.

If the bomb happened to fall in the center between the two walls then the distance from both walls W1/W1' is D≈17 m implying a charge of Q= $Q(D_{min})$= $Q(D_{max})$=380 kg TNT equivalent. So, we can assume that the charge range consistent with what is observed is the distance D=L1/2≈17 m and D=L1-W2/2≈27.5 (or equivalently 10.5+10.5+6.4). This fixes the minimum range in the explosive charge of Q(Dmin)=380±20 kg TNT equivalent to Q(Dmax)=780±20 kg TNT equivalent.[6] The part of the building facing the direction of the playground was left mostly intact after the bomb and likely since the building from the façade to the wall W4 was able to absorb the energy of the initial blast which is a distance 11 m. Note that in this analysis I have not taken into account the slant distance from the wall to the explosion which further increases the bomb size. Note it is likely that the yield range of about 400-800 kg TNT equivalent is very conservative since Ukraine is prone to earthquakes so that building is likely fitted to withstand earthquakes. The "A" level of damage as Jarret calculates is that of collapsed buildings is based on WWII damage.

4) **The pressure immediately outside the building exceeded 2.6 psi.** Note that research on trees found that there is a threshold windspeed at which all trees break which is 90 mi/hour or 42

[6] The uncertainty is purely measurement error. The method itself has uncertainties that I don't quantify.

m/s. This occurs when the pressure is consistent with 2.6 psi overpressure.[7] [8] This is lower than the 6.8 psi of "A" level damage but demonstrates that the pressure outside exceeded 2.6 psi.

[7] Virot, Emmanuel, Alexandre Ponomarenko, É. Dehandschoewercker, David Quéré, and Christophe Clanet. "Critical wind speed at which trees break." Physical Review E 93, no. 2 (2016): 023001.

[8] I fit the curves for maximum wind speed vs overpressure to get: V[mi/hr] = -0.4144 P[psi]^2 + 33.074 P[psi] + 6.0509. Solving for the pressure we get: P[psi]=$\frac{(82685 \pm \sqrt{6899496549-10360000\, V[\frac{mi}{hr}]}}{2072}$ so that for V[mi/hr]=90 miles/hour P[psi]=2.62 psi. See: https://www.wolframalpha.com/input?i=solve+y+%3D+-0.4144x%5E2+%2B+33.074x+%2B+6.0509+for+y%3D90. Dynamic overpressure data is found in Glasstone, Samuel, and Philip J. Dolan, eds. The effects of nuclear weapons. Vol. 50, no. 3. US Department of Defense, 1977.