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# The August 4, 2020 Beirut (Lebanon) explosion: a technological disaster within crises

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# About

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Of the National and Kapodistrian University of Athens, Faculty of Geology and Geoenvironment, Department of Dynamic Tectonic Applied Geology

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## THE AUGUST 4, 2020, BEIRUT (LEBANON) AMMONIUM NITRATE EXPLOSION

On the afternoon of August 4, 2020, a fire broke up in the waterside Warehouse 12 at the Port of Beirut city. The warehouse contained a huge amount of ammonium nitrate (2750 tons) and it was located next to a grain silo and close to other port facilities.

As the fire ranges on, a first explosion caused a smoke cloud over several meters height, which was followed by a long series of white light flashes at the base of the smoke column accompanied by popping sounds. Few seconds later, a massive explosion struck Beirut. It released a high toxic red-orange smoke cloud of nitrogen dioxide resulted from the explosion of the stored ammonium nitrate and surrounded by a white condensation cloud.

The second explosion vanished the warehouse, devastated the port and the adjacent facilities and greatly affected the city's densely populated residential neighborhoods and downtown shopping districts. It resulted in considerable damage to buildings and vehicles. It was felt in northern Israel and in Cyprus located at a distance of 240 kilometers westwards.

As regards the impact on the local population in Beirut, the blast was felt up to two miles radius, an area where more than 750000 people live. This massive explosion resulted 178 fatalities, more than 6000 injured and about 300000 homeless people (data on August 14, 2020).

The ammonium nitrate explosion in Beirut port generated both blast shockwaves and ground shocks. The blast shockwave was the dominant factor to account for the building damages surrounding the explosion site.

Based on records of the United States Geological Survey and the Geological Survey of Israel, the explosion in Beirut port was equivalent to an ML=3.3-4.5 earthquake.

Based on historical and recent data, the Beirut blast is the biggest non-nuclear explosion in the history. Similar events of ammonium nitrate detonation and subsequent explosion took place in 1947 in Texas City (U.S.A.) and in 2015 in Tianjin (China).

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## EXPLOSION SEQUENCE IN BEIRUT PORT

The ammonium nitrate explosion disaster comprised the following four stages


A fire broke up in the Warehouse 12


The stored ammonium nitrate was detonated


The ammonium nitrate exploded resulted in a red-orange smoke cloud of nitrogen dioxide ...


... and a white condensation cloud

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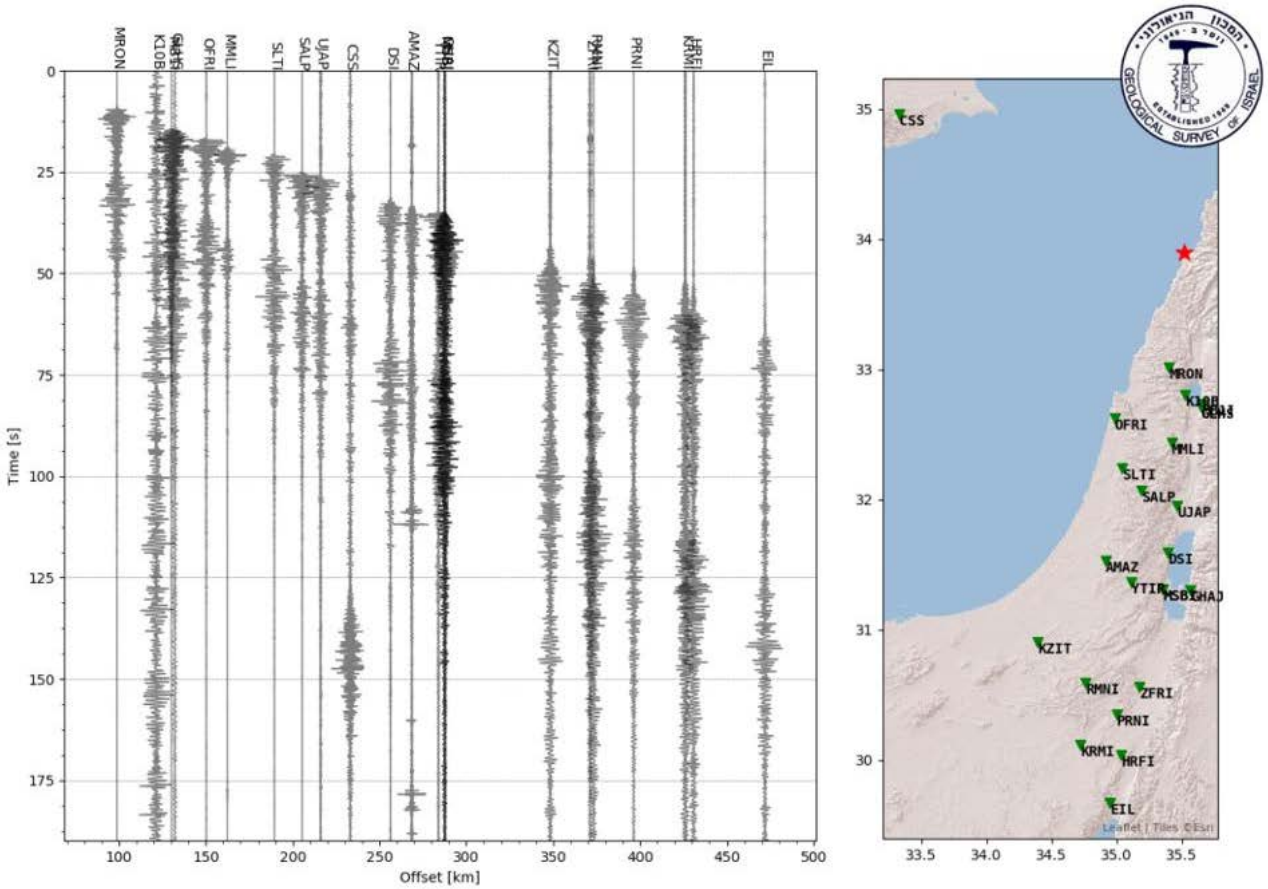
# THE EXPLOSION IN BEIRUT PORT AND THE RECORDED SEISMIC WAVES




The seismic waves produced by the Beirut explosion were recorded by the seismographic network of the United States Geological Survey (USGS) and the Geological Survey of Israel. According to the recordings of the Geological Survey of Israel, the blast was equivalent to an earthquake of ML=4.5 earthquake and comparable to the energy released by the detonation of 1.000 to 3.000 tons of TNT. According to the recordings of USGS, a lower equivalent earthquake magnitude 3.3 is reported.

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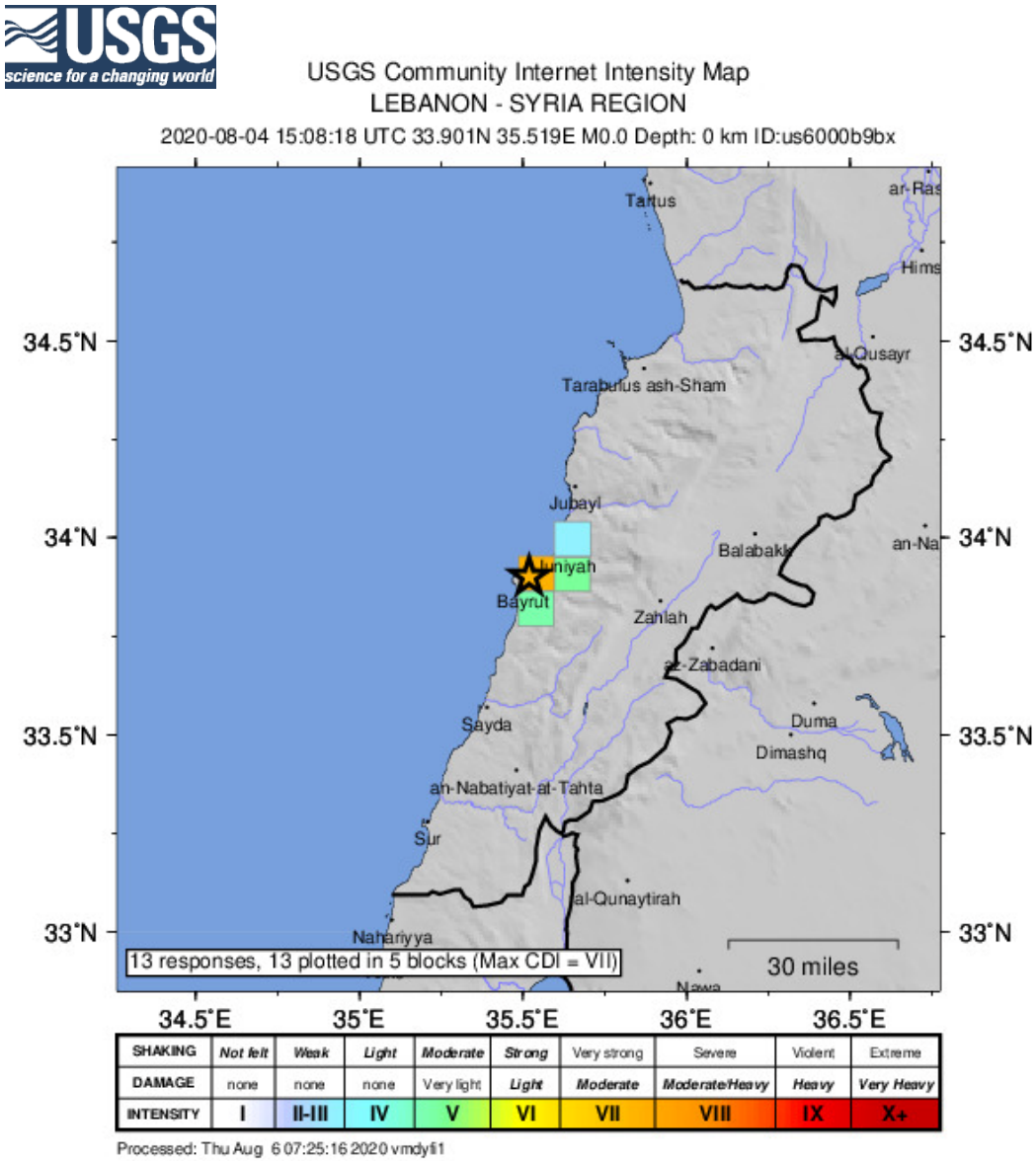
# THE EXPLOSION IN BEIRUT PORT AND THE RECORDED SEISMIC WAVES




This explosion was processed by USGS with the same basic methods that are applied for regional earthquakes. Standard methods were used for the calculation of the magnitude. Based on this analysis conducted, the explosion was equivalent to an earthquake of local magnitude ML=3.3 and of maximum intensity MM=VII.

The magnitudes reported by the aforementioned earthquakes differ. The differentiation of the reported magnitudes are attributed either to the different methodologies used for the calculation of magnitudes or to the fact that the explosion took place on the ground surface, where seismic waves are not as efficiently generated.

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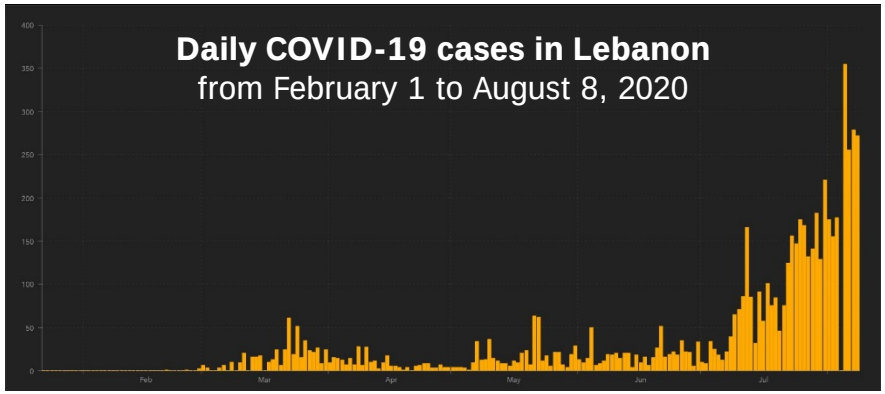
# A DISASTER WITHIN CRISES

## COVID-19 PANDEMIC AND HEALTH CARE SYSTEM CRISIS IN LEBANON

The ammonium nitrate explosion and its undesirable sequences on the local population and the built environment of Beirut City came at one of the worst times for Lebanon.

The COVID-19 pandemic in Lebanon is part of the ongoing worldwide pandemic of coronavirus disease 2019 (COVID-19) caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The virus was confirmed to have reached Lebanon in February 2020. As of August 9, 2020, some of the hardest-hit cities and towns in the country include Beirut and its metropolitan area, Bcharre in the north of the country and Majdel Anjar in the Beqaa Governorate. The public health reports referred 6223 confirmed Corona virus cases, 2043 totally recovered cases and 78 deaths. This pandemic along with the already existing and ongoing socio-economic crisis already resulted in a strained health system in the capital of the country, Beirut, which will be further aggravated not only by the thousands of blast-induced injuries but also by the partial or complete destruction of important health facilities in the city of Beirut.

In order to slow the spread of coronavirus, the government imposed a strict lockdown from the middle of March comprising restrictions of movement and transition and an overnight curfew. In May, the lockdowns were renewed again amid a surge in cases. Today Lebanon is still under some strict restrictions, with some shops only trading on Tuesday and Wednesday this week. These measures for limiting the spread of the virus unfortunately deepened the economic crisis, which the government of Lebanon has already been called upon to face.




COVID-19 Dashboard by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU)
https://coronavirus.jhu.edu/map.html

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## A DISASTER WITHIN CRISES
### SOCIAL AND ECONOMIC CRISES

Lebanon is in the midst of the worst economic crisis in its history comprising currency, debt, fiscal and banking problems that had led to mass business failures and job losses even before coronavirus struck. Nearly a third of the population was living near or below the poverty line. The Lebanese pound has lost about 80% of its value over the past 10 months, while businesses had lost access to foreign exchange and imports, households faced limitations in accessing their bank accounts and people's savings are locked up in inaccessible bank accounts due to unofficial capital controls.

Based on the updated poverty numbers in Lebanon published by the World Bank in March 2020, it was estimated that by the end of 2020, unemployment would rise from 12 to 30% (by January, about 220,000 jobs were lost compared to October 2019) (World Bank, 2020) However, according to more recent estimates presented by the World Bank that take into account the impact of the COVID-19 pandemic to the economy, poverty would rise from 30% in 2019 to an expected 45% or more by the end of 2020, while extreme poverty would more than double to 22% (*World Bank, 2020*).

Last March, Lebanon government announced a gross public debt reaching around 170% of GDP. This meant that Lebanon was close to be the world's most heavily indebted state. Consequently, Lebanon declared bankruptcy for the first time in its history. Talks with international donors have stalled due to reforms required before disbursing aid. So, the country of Lebanon began negotiations with the IMF. However, the IMF and western donors have also conditioned the disbursement of aid after the implementation of wide-ranging reforms in the public sector. These reforms have once again been an obstacle to the continuation of the negotiations and the reaching of a financial agreement.

As a result, people were and are very angry and frustrated about the inability of the Lebanese government to provide the basic services, conditions and activities for the poor in order to form foundations of a fair and equal society. Among other difficulties and problems, they have to deal with fuel shortages, daily power blackouts, soaring prices of basic necessities, lack of potable water, food insecurity and hunger. All these negative aspects of the economic crisis forced residents to take to the streets and protest for their rights.

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# A DISASTER WITHIN CRISES

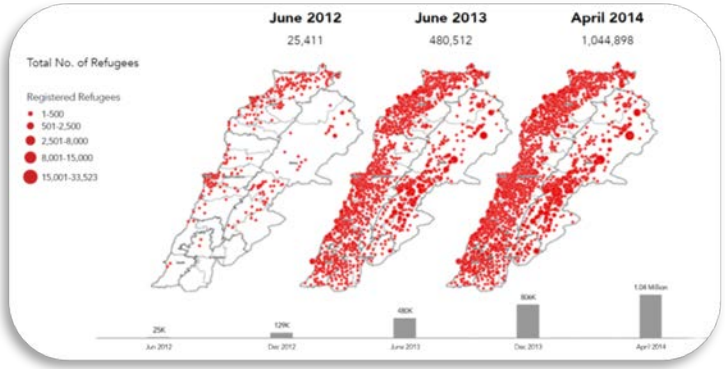
## REFUGEE CRISIS

Since 2011, Lebanon has received a massive influx of Syrian refugees. Lebanon has taken in 1.5 million refugees since war erupted in neighboring Syria in 2011 (*WHO, 2016*; *European Commission 2020*) comprising more than 892,000 Syrians, 27,000 Palestinians from Syria, 270,000 Palestinians and more than 19,900 other nationalities registered refugees.

Syrian refugees spread throughout the country, and there is no single village in Lebanon that does not contain Syrian refugees (*WHO, 2016*). This represents a 30% increase in the population of Lebanon. This is the highest per capita concentration of refugees in the world (*WHO, 2010*). This percentage is the equivalent of 20 million refugees heading to France. Taking into account that the distribution of 100000 refugees across 28 European countries constitutes a crisis, one can imagine the heavy refugee crisis in Lebanon and its effects in various sectors including the economy and the health system among others.

Refugees have been permitted to settle throughout the country and are found across 1500 localities. 50% of refugees live in informal tented settlements in some of the poorest areas of the country, and a significant proportion are classified as extremely vulnerable (26.5% are women of childbearing age, 18.8% are aged under 5 years, 53.3% are children, aged 0–17 years, 2.8% are aged above 60).

Poverty levels in Lebanon have been rising as a result of the Syrian crisis (*WHO, 2016*). In 2008, background poverty rates in Lebanon were assessed at 28.5% (based on a poverty line of US$ 4 per capita per day). Since the crisis began, a further 170 000 Lebanese have been pushed into poverty, according to World Bank estimates.




Time-series for Syrian refugees registered in Lebanon (*UNHCR, 2014*)

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## A DISASTER WITHIN CRISES
### POLITICAL CRISIS

As is increasingly the case, the deep economic crisis in Lebanon has been attributed to long term corruption and financial mismanagement. It paused activities in various productive sectors, desolated business and shopping centers, increased crime and levels of societal violence among other negative aspects of the daily life.

The mission of the government became very difficult to impossible resulting in its fall. The successive governmental scheme failed to intercept the bad course and gain the trust of the people. The main characteristic of this difficult situation has been the resignation of many state officials revealing that Lebanon is plunged into political chaos.

The accumulated social, economic, political crises along with the ongoing pandemic forced people to participate in anti-government protests, which paralyzed not only the capital city of Beirut, but the country in its entirety. They first erupted on 17 October 2019 due to planned taxes. They rapidly expanded into a country – wide condemnation of the stagnant economy, the corruption in the public sector and the failures of the government to provide basic services such as electricity, water and sanitation. They still continue even after the devastating explosion in Beirut port. While this issue was being prepared, the government of Lebanon resigned amid anti-government protests and growing anger over the deadly blast in Beirut that killed nearly 200 people.

All these reveal an ongoing humanitarian crisis.

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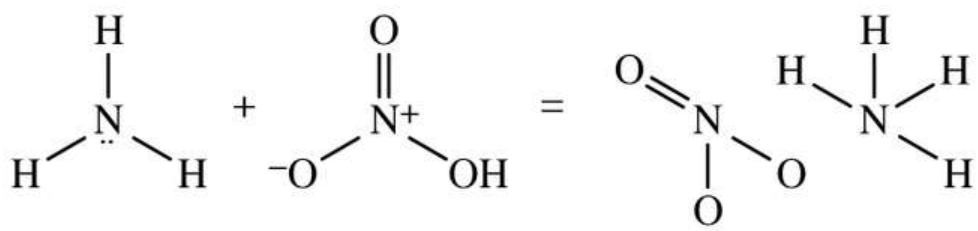
# AMMONIUM NITRATE

Ammonium nitrate is the nitrate salt of the ammonium cation ($NH_4NO_3$, sometimes written as $N_2H_4O_3$) that is a white crystal solid and is highly soluble in water.

All ammonium nitrate plants produce an aqueous ammonium nitrate ($NH_4NO_3$) solution through the reaction of ammonia ($NH_3$) and nitric acid ($HNO_3$) in a neutralizer according to the following equation:



ammonia ($NH_3$) + nitric acid ($HNO_3$) = ammonium nitrate ($NH_4NO_3$)

| CHARACTERISTICS OF AMMONIUM NITRATE | |
|---|---|
| **Melting point** | 169.6 °C |
| **Boiling point** | 210 °C |
| **Molecular weight** | 80.06 gr/mol |
| **Density** | 1.725 at 25 °C |
| **Solubility in water** | 118 gr/100 cc $H_2O$ at 0 °C |
| **pH** | 5.43 |

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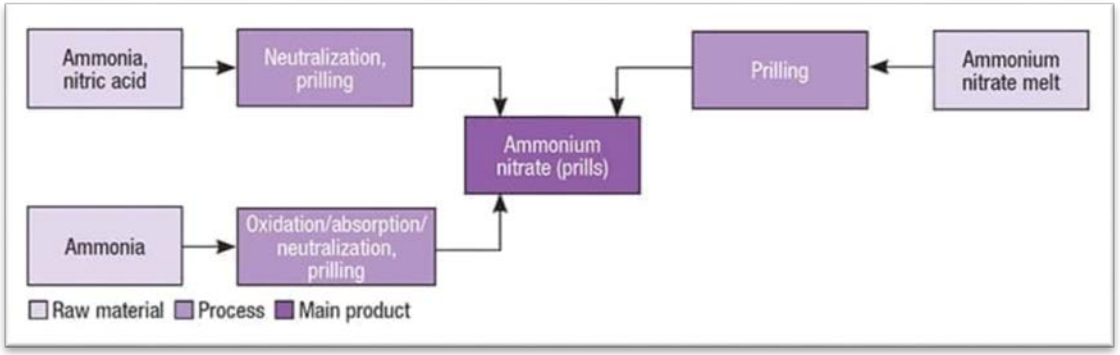
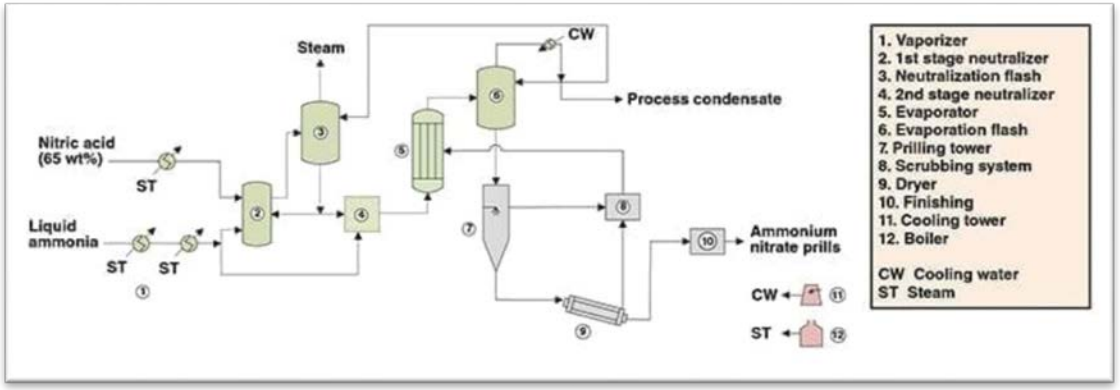
# PRODUCTION OF AMMONIUM NITRATE




Raw materials and processes for the production of ammonium nitrate prills (*Intratec Solutions, 2020*)




A typical vacuum-neutralization process with two major sections for the production of ammonium nitrate porous prills, which are neutralization and finishing (*Intratec Solutions, 2020*).

Ammonium nitrate is an ammonium compound of great importance in production volume and usage. This significance is attributed to the fact that the salt incorporates nitrogen and it is used by plants and crops in two forms comprising nitrate ion and ammonia. The ammonium nitrate is mainly used as fertilizer and as an explosive in the mining, military and civil engineering industries. It is mainly commercialized as aqueous solution, prills (pellets) and granules.

The production process for ammonium nitrate porous prills presented here is a typical vacuum-neutralization process including two major sections, neutralization and finishing.

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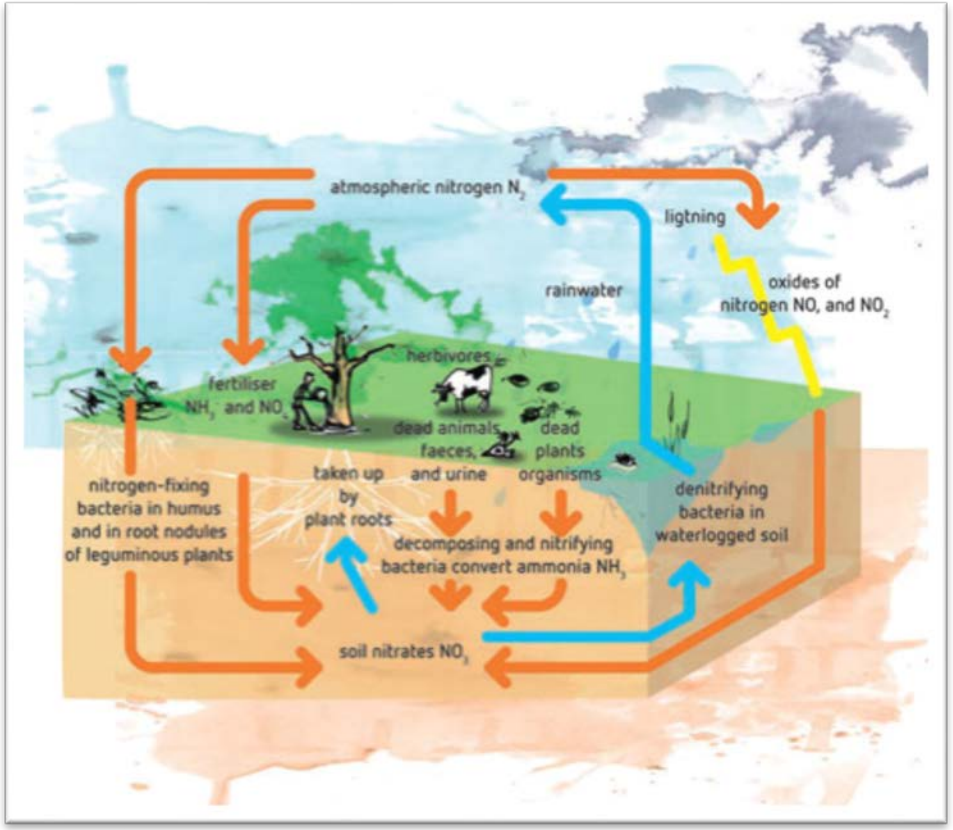
# AGRICULTURE USE OF AMMONIUM NITRATE




The Nitrogen cycle. Nitrogen applied by fertilizers is absorbed by plants and turned into proteins in plant tissue. Ultimately, the nitrogen is returned to the soil. When organisms die, it is converted back to inorganic forms by decomposers.

Ammonium nitrate is predominantly used in agriculture as a popular high-nitrogen fertilizer. It is produced by oxidizing ammonia to nitric acid and then neutralizing the nitric acid with additional ammonia. Usually the neutralization gives a solution of about 80 to 90% concentration. For production of prills, the solution is evaporated to an essentially anhydrous melt prior to solidification. To produce liquids, the solution is used as made, but it is diluted in the process.

Production of ammonium nitrate prills requires about 8 million BTU/ton N in addition to the energy required to produce the ammonia (total of 50 million BTU/ton N). For the ammonium nitrate solution, about 4 million BTU are consumed, not including ammonia preparation (total of 46 million BTU/ton N).

The nitrate form moves readily with soil water to the roots, where it is immediately available for plant uptake. The ammonium fraction is taken up by roots or gradually converted to nitrate by soil microorganisms.

From *Davis and Blouin (1977)*

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## APPLICATION OF AMMONIUM NITRATE IN EXPLOSIVES

Ammonium nitrate in crystalline form, porous prills/granules or as saturated aqueous solution is mainly used for the production of industrial explosives.

Ammonium nitrate in crystalline form, porous prills/granules or as saturated aqueous solution is mainly used for the production of industrial explosives (*Negovanović et al., 2015*). Along with various components comprising Trotil, nitroglycerine, fuel oil, water, thickeners, emulsifiers and emulsion matrix, ammonium nitrate can produce ammonium nitrate powder explosives, dynamite, ammonium nitrate fuel oil (ANFO), water gel/slurry explosive, emulsion explosives and heavy ANFO.

| Main Oxidizing Salt | Component | | Explosive | |
|---|---|---|---|---|
| **Ammonium nitrate** | + | Trotil | = | Ammonium nitrate powder explosives |
| | + | Nitroglycerine | = | Dynamite |
| | + | Fuel oil | = | ANFO |
| | + | Water, fuel oil, thickener | = | Water gel / slurry explosives |
| | + | Water, fuel oil, emulsifier | = | Emulsion explosives |
| | + | Emulsion matrix | = | Heavy ANFO |

From *Negovanović et al. (2015)*

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## STORAGE OF AMMONIUM NITRATE

From https://allaboutammoniumnitrate.weebly.com/

The proper storage of ammonium nitrate is extremely important because of its potential hazards: (a) fire hazard, (b) decomposition hazard and (c) explosion hazard.

During the storage of ammonium nitrate in solution form, the gas state of ammonia should be frequently added in small amounts in order to sustain the ideal pH and account for any ammonia lost while in storage. In addition, the confinement of ammonium nitrate should be limited greatly. Proper ventilation, maintenance, and contamination control must be addressed, as inappropriate confinement can increase the risk of explosions. Ammonium nitrate is hygroscopic, meaning it can easily collect water molecules from its surrounding environment. Because of this, it cannot be exposed to excessive humidity, as any water absorbed by the compound can influence its explosive function. The careful storage of this chemical compound is a necessity and must be taken seriously.

In addition, particular attention needs to be paid to the storage of ammonia nitrate in order to protect the stockpile from bounce, overturn and shock that may be produced in case of a natural disaster and in particular an earthquake.

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## HAZARDS ASSOCIATED WITH AMMONIUM NITRATE

The main hazards associated with ammonium nitrate are the following:

### (a) Fire Hazard

Based on experience from previous similar events, the fires of the ammonium nitrate start in combustible materials inappropriately stored near the fertilizer or in associated equipment. Other sources of ignition include electrical faults and hot welding or grinding works.

### (b) Decomposition Hazard

Ammonium nitrate decomposes by way of a number of exothermic and endothermic reactions when heated to well above its melting point. The synergy of these reactions resulted in a self-limiting thermal effect up to a certain temperature and free escape of gases. If the gases are not able to freely escape, the endothermic effect can be suppressed and lead to a rapid exothermic effect and subsequent explosive behavior. Gases formed in the decomposition process are toxic and comprise ammonia ($NH_3$) and nitrogen oxides ($NO/NO_2$).

### (c) Explosion Hazard

The events relevant to the explosive hazard of the solid ammonium nitrate are the rapid thermal decomposition and the detonation. Rapid Thermal decomposition causing release of gases and pressure build up in a container leading to its rupture. As regards detonation, the reaction rates are extremely fast, the front of the resulted blast shockwave travels with supersonic speed and is very destructive.

From *European Fertilizer Manufacturers' Association, (2000)* and *Negovanović et al. (2015)*

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# CLASSIFICATION AND LABELLING OF AMMONIUM NITRATE

## HAZARD PICTOGRAMS

1

2

3


4


5

Although pure ammonium nitrate is stable at ambient temperature and pressure under many conditions, the chemical itself does not burn. Ammonium nitrate is a strong oxidizing agent and it supports and accelerates the combustion of organic (and some inorganic) material, increasing the fire hazard and complicating the fire fighting challenges. Ammonium nitrate may explode when exposed to strong shock or when subjected to high temperatures in confinement.

1. Oxidizing: It gives off heat when exposed to other substances.
2. Health hazard / Hazardous to the ozone layer: Harmful skin irritation, serious eye irritation
3. Explosive
4. Oxidizing Agent (Class 5.1): A material that may, generally by yielding oxygen, cause or enhance the combustion of other materials
5. UN 1942 Class 5.1: Ammonium nitrate, with not more than 0.2% of combustible substances, including any organic substance calculated as carbon, to the exclusion of any other added substance

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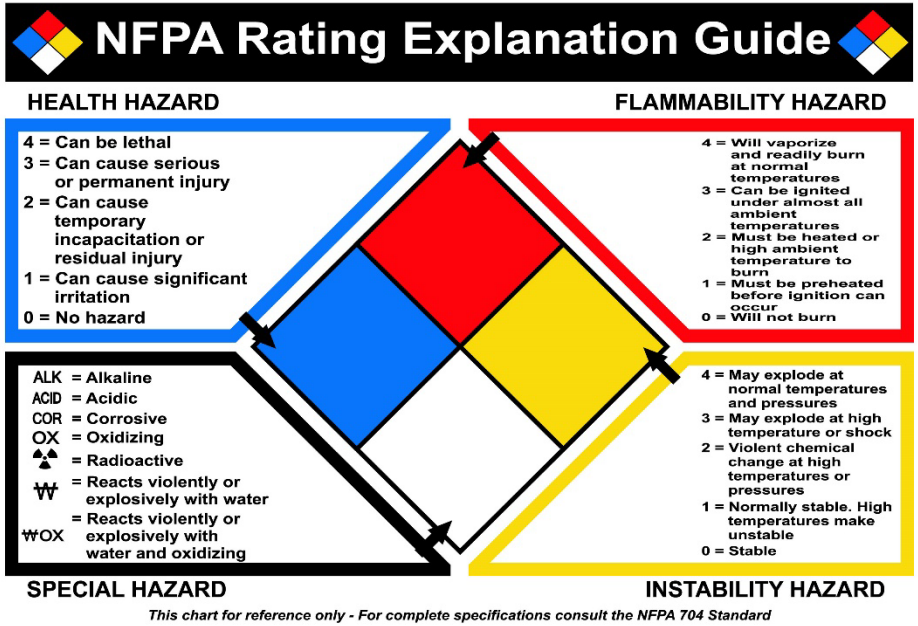
# HEALTH, FLAMMABILITY, INSTABILITY AND SPECIAL HAZARDS OF AMMONIUM NITRATE





The **National Fire Protection Association** assigns flammability, instability, health and special hazard ratings in a range of 0-4 to ammonium nitrate in order to highlight its potentially hazardous properties:

**Flammability Hazard**

The ammonium nitrate will not burn (flammability rating 0 in a range of 0-4)

**Instability Hazard**

The ammonium nitrate may explode at high temperature or shock (instability rating 3 in a range of 0-4)

**Health Hazard**

The ammonium nitrate can cause significant irritation to eyes, skin and respiratory track (health hazard rating 1 in a range of 0-4)

**Special Hazard**

The ammonium nitrate can be oxidizing (OX) and capable of igniting combustible materials

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## REDUCTION OF THE AMMONIUM NITRATE EXPLOSION HAZARD

### STORAGE / PROCESS CONDITIONS TO AVOID

Persons engaged in the handling, management or emergency planning for ammonium nitrate must be aware of the hazards of ammonium nitrate and ensure that the conditions that may lead to an explosion are not present.

- Avoid heating ammonium nitrate in a confined space.
- Ensure that ammonium nitrate is not exposed to strong shock waves from explosives.
- Avoid contamination of ammonium nitrate with combustible materials or organic substances such as packing materials, dust, seed, oils, and waxes.
- Avoid contamination of AN with inorganic materials that may contribute to its sensitivity to explosion, including chlorides and some metals, such as aluminum powder, chromium, copper, cobalt, and nickel.
- Maintain the pH of AN solutions within the safe operating range of the process. In particular, avoid low pH (acidic) conditions.
- Keep molten or solid AN out of confined spaces, especially sewers or drains where it can react with organic materials there.

From *The Environmental Protection Agency (EPA), the Occupational Safety and Health Administration (OSHA), and the Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) (2013)*; https://rib.msb.se/Filer/pdf%5C27206.pdf

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## REDUCTION OF THE AMMONIUM NITRATE EXPLOSION HAZARD
### REQUIRED AND RECOMMENDED BUILDING DESIGN AND SAFETY

- Store only in one-story buildings and buildings with no basements, unless the basement is open on one side.
- Use fire and explosion resistant walls within 50 feet of combustible building or materials.
- Flooring in storage and handling areas should be constructed of noncombustible material or protected from impregnation by ammonium nitrate.
- Avoid installing, or remove or close off any open drains, traps, tunnels, pits or pockets into which molten ammonium nitrate can flow and be confined in the event of fire.
- Buildings should be kept dry and free of water seepage through roofs, walls and floors.
- Have adequate ventilation or be constructed to self-ventilate in the event of a fire to avoid pressurization.
- Do not place AN into storage when the temperature of the product exceeds 130°F (54.4°C).

From *The Environmental Protection Agency (EPA), the Occupational Safety and Health Administration (OSHA), and the Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) (2013)*; https://rib.msb.se/Filer/pdf%5C27206.pdf

As regards the protection of natural disasters:

- the stockpile must be protected by shock, bounce and overturn in case of generation of a natural disaster, in particular in case of an earthquake and especially when the floor of the storage area is flexible and vulnerable to the vertical component of the earthquake ground motion.

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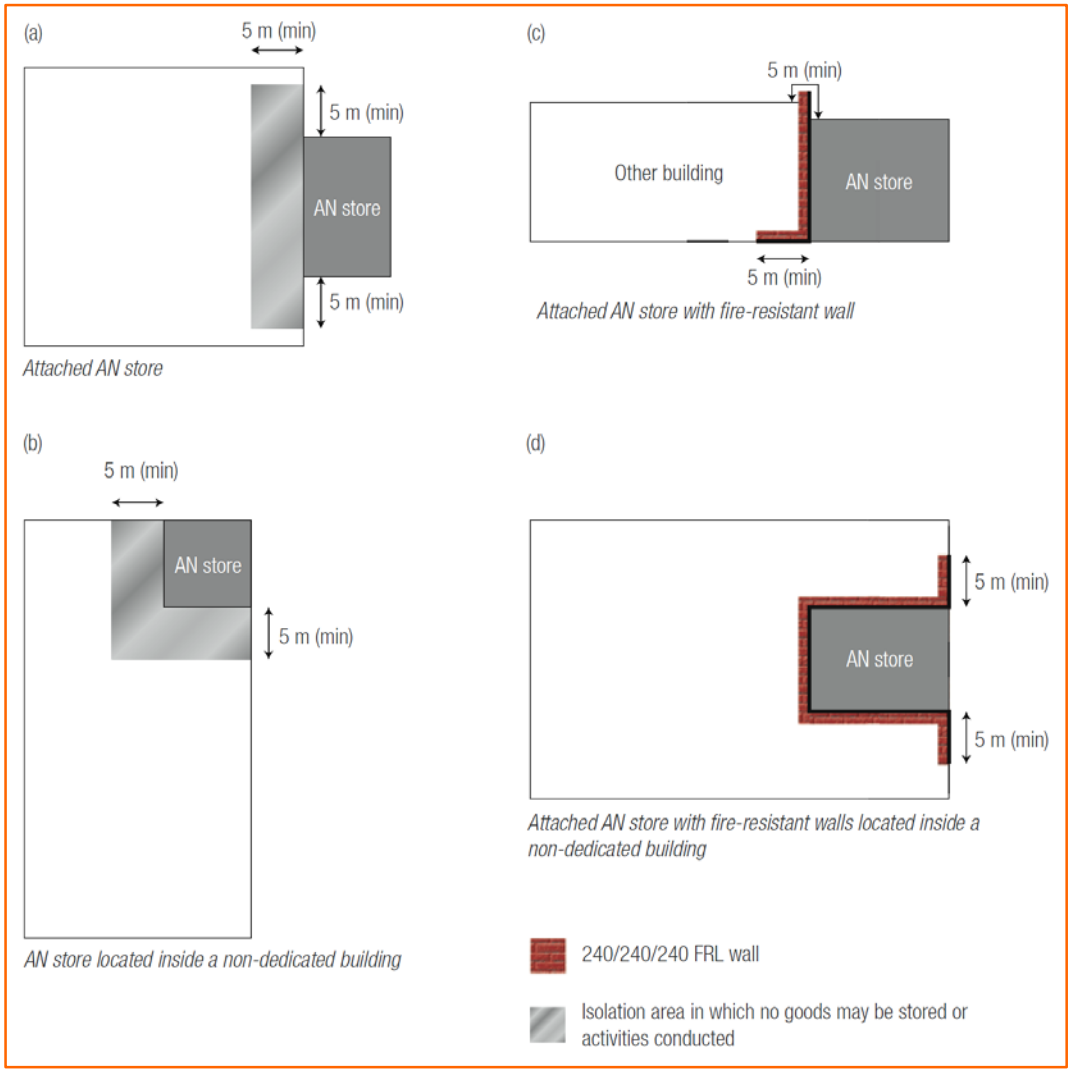
## REDUCTION OF THE AMMONIUM NITRATE EXPLOSION HAZARD
### REQUIRED AND RECOMMENDED BUILDING DESIGN AND SAFETY




Examples illustrating the required isolation of ammonium nitrate stores of 10 tons or less

From *Department of Mines and Petroleum (2013)*

https://www.dmp.wa.gov.au/Documents/Dangerous-Goods/DGS_COP_StorageSolidAmmoniumNitrate.pdf

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## HAZARD REDUCTION
## REQUIRED AND RECOMMENDED SAFE STORAGE

### Storage in bags, drums or other containers

- Piles of bags, drums and other containers should be no closer than 36 inches below the roof or supporting beams.
- Bags should be stored no less than 30 inches from walls or partitions.
- Piles of bags, drums, and other containers should not exceed a height of 20 feet, width of 20 feet, and length of 50 feet, unless the building is of non-combustible construction or protected by automatic sprinklers.
- Maintain aisles of at least 3 feet width between piles.

### Storage in bulk

- Bins for storing bulk ammonium nitrate should be kept clean and free of materials.
- Piles or bins must be adequately sized, arranged and moved periodically to minimize caking.
- Do NOT use dynamite, explosives or blasting agents to break up or loosen caked ammonium nitrate.
- Protect piles of ammonium nitrate from absorbing moisture from humid air by covering them with water impermeable sheeting or using air conditioning.
- Do not store AN with organic chemicals, acids, or other corrosive materials, materials that may require blasting during processing or handling, compressed flammable gases, flammable and combustible materials or other contaminating substances.

https://rib.msb.se/Filer/pdf%5C27206.pdf

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## HAZARD REDUCTION
### REQUIRED AND RECOMMENDED SAFE STORAGE

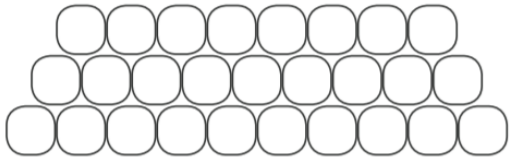
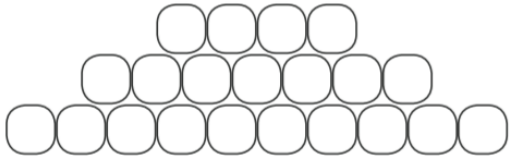
| Type of storage | Stacking configuration | Separation between stacks (metres) |
|---|---|---|
| IBCs | Normal configuration where each successive layer is set back half an IBC diameter from the layer below  | 16 (low density)<br>9 (medium density)<br>1 (high density) |
| IBCs | Pyramidal configuration where each successive layer is set back one and a half IBC diameters from the layer below  | 9 (low density)<br>7 (medium density)<br>1 (high density) |

Table showing the recommended minimum distances to be maintained between stacks of intermediate bulk containers of ammonium nitrate in order to minimize the likelihood of a detonation event in one stack from propagating to an adjacent stack. Separation distances were derived from small-scale gap tests performed between ammonium nitrate fuel oil and ammonium nitrate to determine the critical initiation pressure to produce sympathetic detonation, followed by simulations. Special attention must be paid in the undesirable movements of the stockpile in case of a natural disaster. For example, special care and measures must be taken in order to avoid shock, bounce and overturn in case of a strong earthquake, in seismically active areas.

https://www.dmp.wa.gov.au/Documents/Dangerous-Goods/DGS_COP_StorageSolidAmmoniumNitrate.pdf

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## HAZARD REDUCTION
### FIRE PROTECTION OF THE AMMONIUM NITRATE STORAGE AREAS

- Ammonium nitrate storage areas should be equipped with an automatic sprinkler system, or have an automatic fire detection and alarm system if the areas are not continuously occupied.
- Facilities should NOT store more than 2500 tons of bagged ammonium nitrate without an automatic sprinkler system.
- Suitable fire control devices such as hoses and appropriate portable fire extinguishers shall be provided throughout the warehouse and loading areas. Water supplies and fire hydrants should be available.
- Store ammonium nitrate fertilizer in separate buildings or separated by approved fire walls from organic, combustible or reactive materials.
- Ammonium nitrate fertilizer should NOT be stored in the same building with explosives or blasting agents.
- Prohibit smoking or heat sealing working in ammonium nitrate storage areas.

From *The Environmental Protection Agency (EPA), the Occupational Safety and Health Administration (OSHA), and the Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF) (2013)*; https://rib.msb.se/Filer/pdf%5C27206.pdf

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## WAVES AND SHOCKS PRODUCED BY EXPLOSIONS AND INTERACTION WITH BUILDINGS

An explosion is the large-scale, rapid and sudden release of stored energy. This release causes increase in temperature and pressure so that the materials are converted into hot compressed gases. Since these gases are at high temperature and pressure, they expand rapidly creating a pressure wave, which is known as shock waves. The shock waves resulted from the combination of air blast and ground shock.

The air blast is the main mechanism for producing damage in the built environment surrounding the explosion site. The air blast has either incident pressure or dynamic pressure. The first effect results from the propagation of the air blast. The wave front (or shock front) travels with supersonic velocity and causes compression of air molecules in its propagation path.

Fast movement of the wave overshoots ambient pressure. This results in the creation of a vacuum behind the blast wave, which is widely known as negative phase or under-pressure. During this negative phase, partial vacuum is formed and air is sucked in. Moreover, this is accompanied by high suction winds, which have the potential to carry debris over long distances away from the explosion site.

As the shock wave reaches an object (e.g. rigid and massive walls of a building), it is reflected, resulting in amplification of the over-pressure by some significant factor ranging from 2 up to 13. The air blast enters the building through shattered doors and broken windows and affects not only the non-structural elements of the building, but also its structural elements comprising slabs and columns. The shockwave undergo several diffractions attributed to the interaction with various surfaces resulting in increase or decrease of the pressure.

The pressure decay exponentially in time and with radial distance from the explosion site. The greater the standoff distance of the building from the site, the smaller the damage to the buildings.

When an explosion takes place on the ground surface, a portion of the energy is also imparted to the ground resulting in the creation of a crater and the generation of a ground shock that produces motions similar to those produced by a short-duration earthquake with high intensity.

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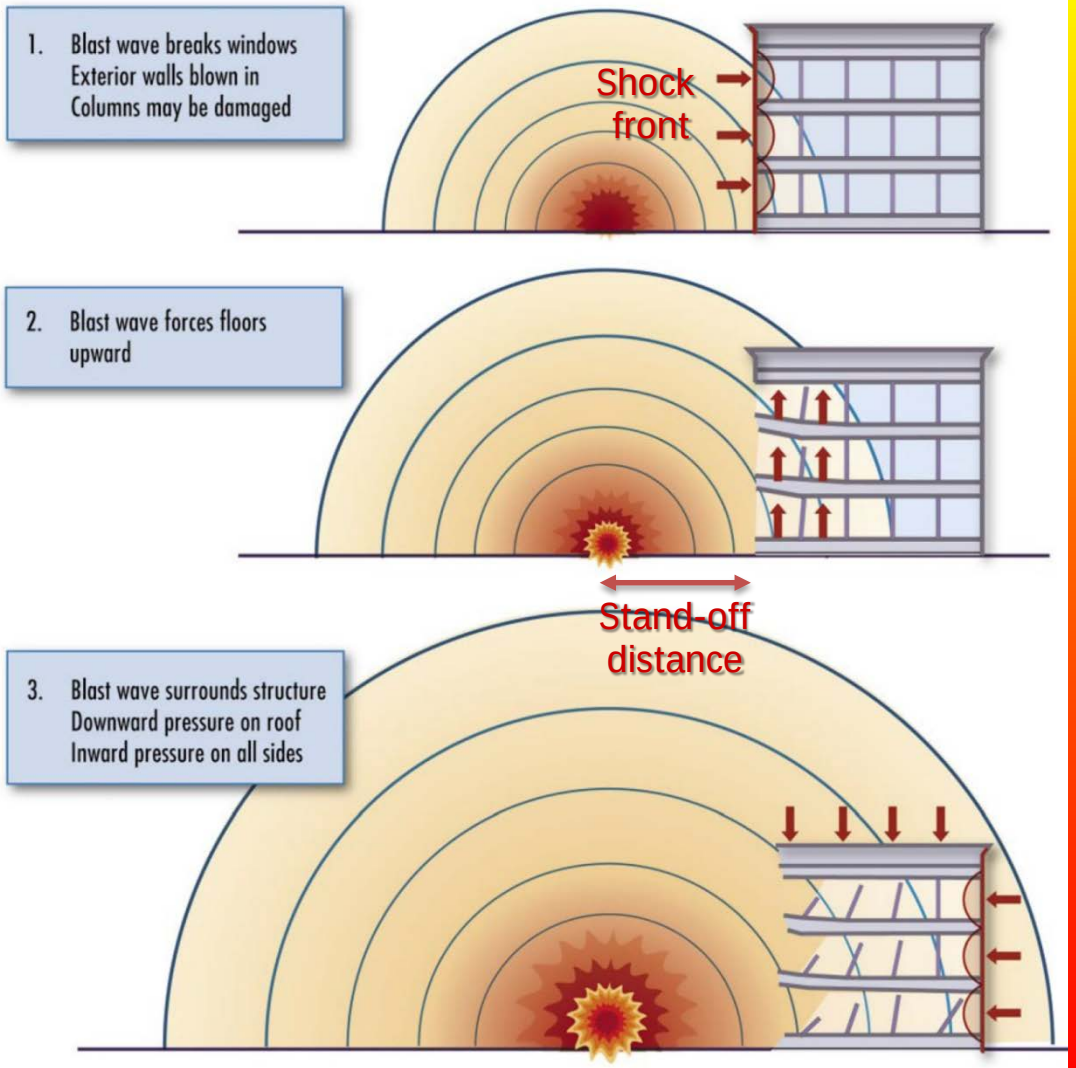
## BLAST SHOCKWAVE AND PRESSURE EFFECTS ON A STRUCTURE
### FOR A BUILDING WITH SMALL STANDOFF DISTANCE




From *Naval Facilities Engineering Service Center (1998)*

**1st stage**
The initial blast shockwave breaks windows and affect the building façade comprising architectural features, mechanical and electrical components and systems, fire protection systems, plumbing systems and components. It also exerts pressure on the roof and walls that are not directly facing the blast resulting in damage.

**2nd stage**
The blast shockwave enters the building and exerts pressure on the structure. This effect may extremely affect the structural elements comprising slabs and columns, due to the fact that it acts contrary to the design used to withstand gravity loads.

**3rd stage**
The building frame is loaded totally as the blast shockwave surrounds the building. Downward pressure on roof and inward pressure on all sides take place and the structure responds as it would to a short-duration earthquake with high intensity.

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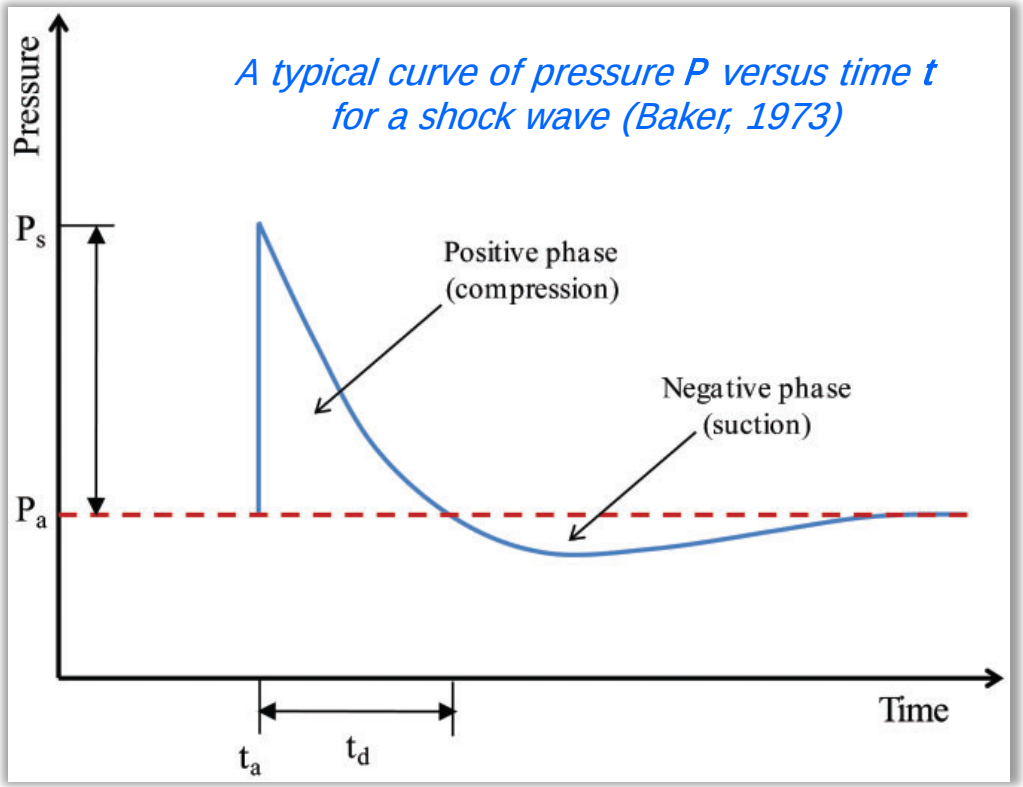
## CURVE OF PRESSURE P VERSUS T FOR A SHOCK WAVE




Pressure increases very rapidly at the arrival time ($t_a$) of the shock wave. The peak air pressure above ambient air pressure (Pa) is referred to as the peak overpressure and is shown as Ps. After the peak overpressure is almost instantaneously reached, the pressure generated by the shock wave decreases in a much slower fashion until it reaches ambient air pressure at time (ta+td). The pressure then starts dropping below ambient air pressure after time (ta+td). The duration where pressure is greater than ambient air pressure is referred to as the positive phase. The duration where pressure is lower than ambient air pressure is referred to as the negative phase.

From *Tarefder et al. (2014)*

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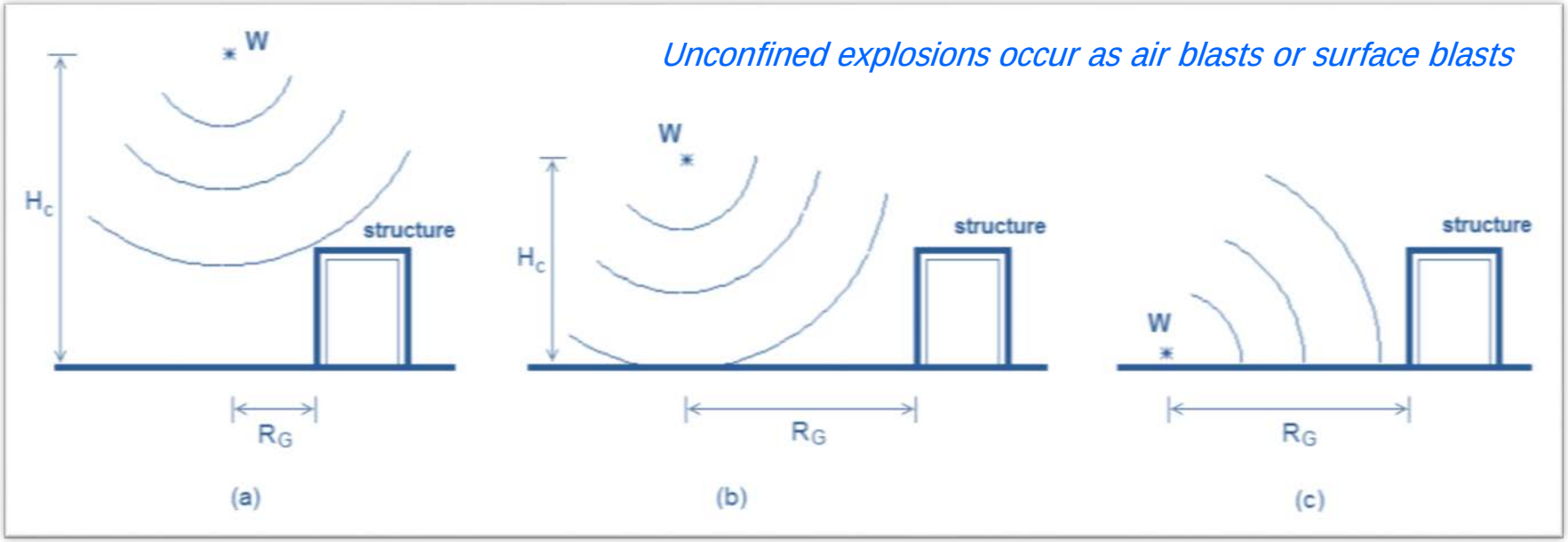
## TYPES OF UNCONFINED EXPLOSIONS




(a) **Free-air burst**
The explosive charge is detonated in the air, the blast waves propagate spherically outwards and impinge directly onto the structure without prior interaction with other obstacles or the ground.

(b) **Air burst**
The explosive charge is detonated in the air, the blast waves propagate spherically outwards and impinge onto the structure after having interacted first with the ground; a Mach wave front is created.

(c) **Surface burst**
The explosive charge is detonated almost at ground surface, the blast waves immediately interact locally with the ground and they next propagate hemispherically outwards and impinge onto the structure.

From *Karlos and Solomos (2013)*

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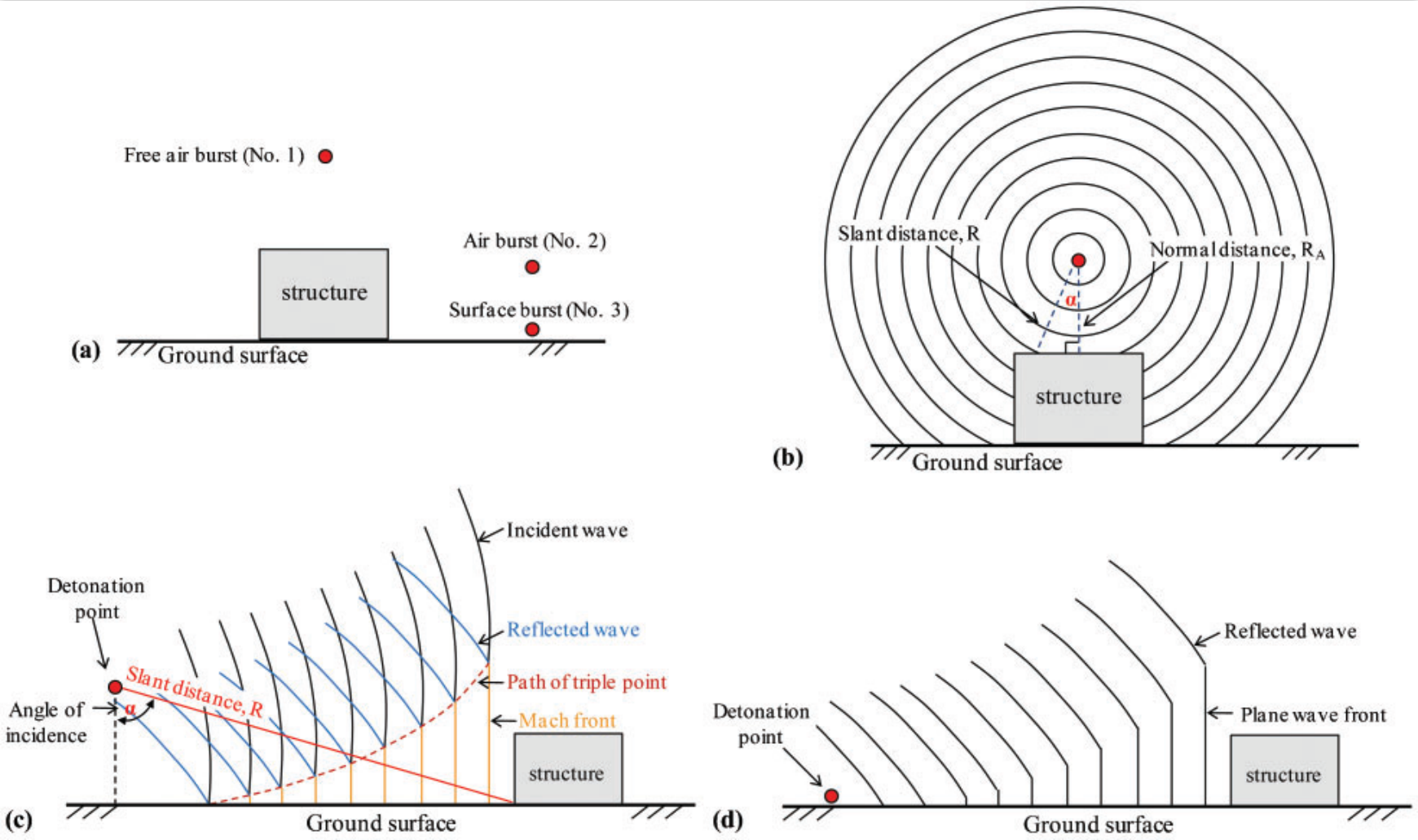
## TYPES OF UNCONFINED EXPLOSIONS




Types of unconfined explosions: (**a**) locations of free air burst, air burst, and surface burst relative to a structure, (**b**) free air burst, (**c**) air burst, (**d**) surface burst

From *US Army (1990)*

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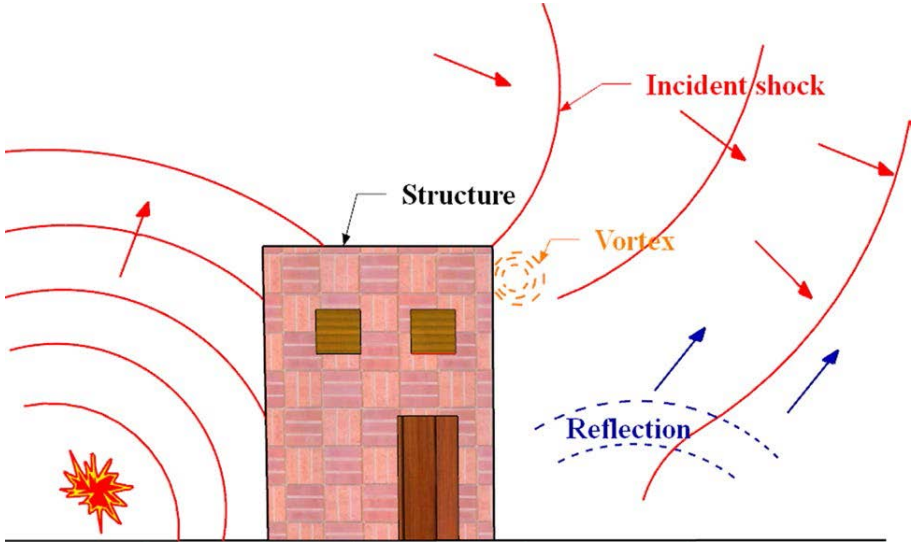
## REFLECTION, REFACTION AND DIFFRACTION




From *Shirbhate and Goel (2020)*

When the incident blast wave strikes the object, reflection, rarefaction and diffraction occur. Reflection of blast wave amplifies the incident waves due to coalescent effect of incident and reflected wave. However, in some cases, incident waves pass over and diffract around the object, resulting in reduction of intensity of blast overpressure behind the object. Height of the barrier influences diffraction effect on structure.

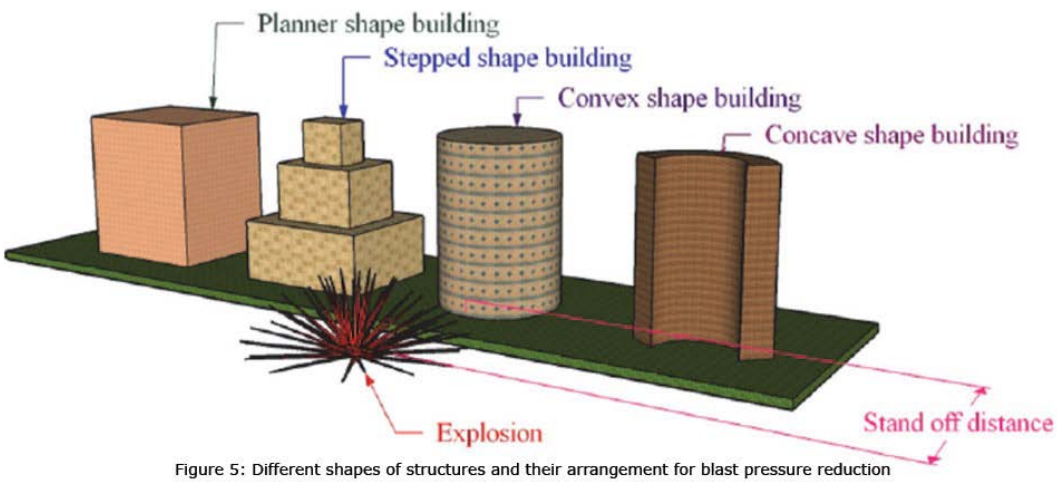



Figure 5: Different shapes of structures and their arrangement for blast pressure reduction

From *Goel and Matsagar (2014)*

The geometry of the structure and its components also have important role in intensity of blast pressure. Curve shaped structures reflect the blast wave. Re-entrant corners of the building are more susceptible to diffraction effect and hence, increases the duration of air blast.

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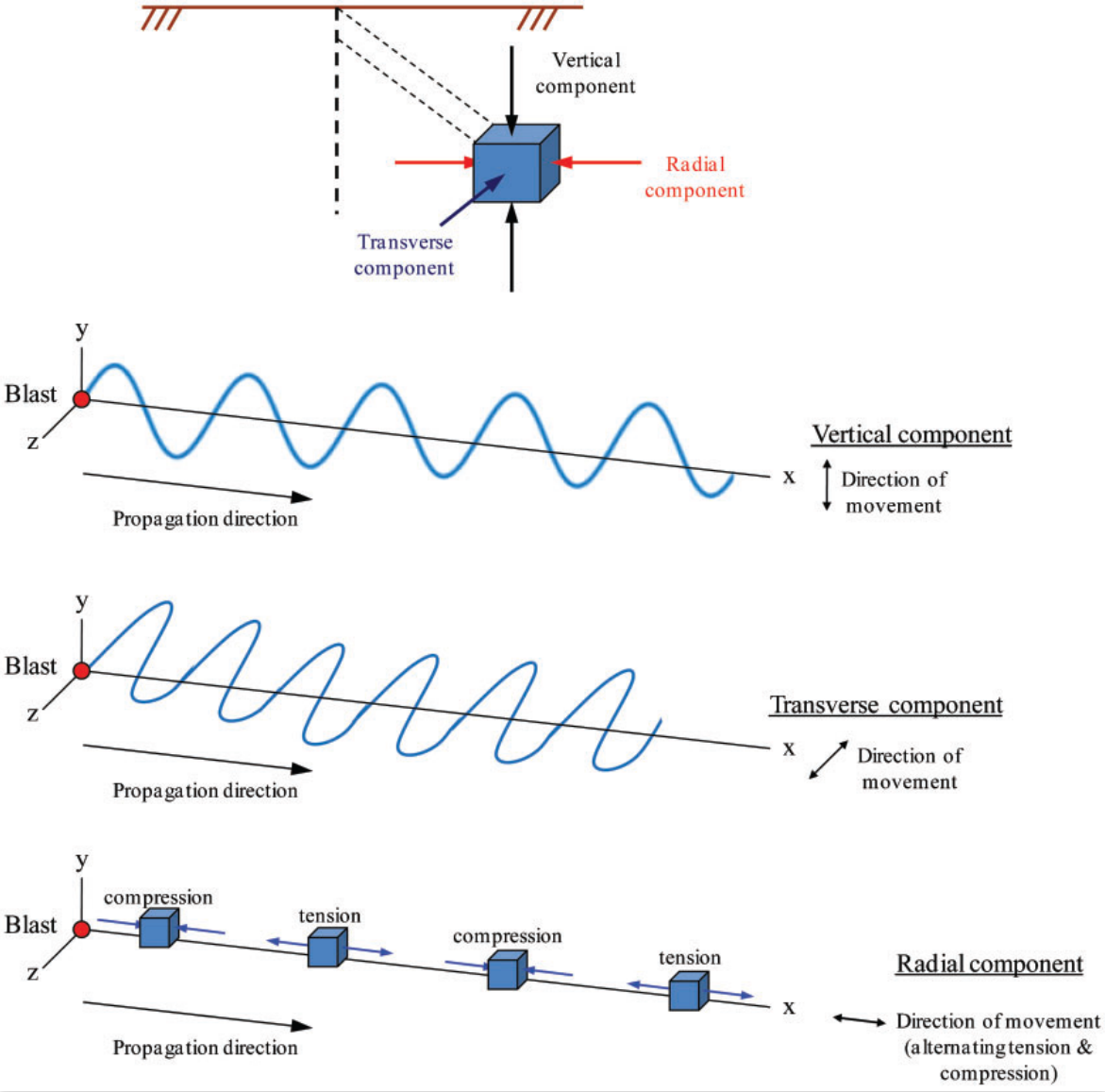
# COMPONENTS OF THE BLAST-INDUCED GROUND MOTION




**Vertical Component**
It represents vertical motion that is perpendicular to the horizontal ground surface.

**Transverse Component**
It represents motion perpendicular to the radial component. The transverse component describes a shearing motion.

**Radial Component**
It represents motion perpendicular to the blast source. Motion in the radial component takes the form of alternating compressive and tensile waves.

From *Tarefder et al. (2014)*

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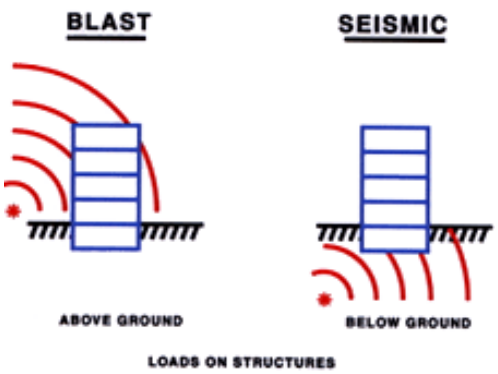
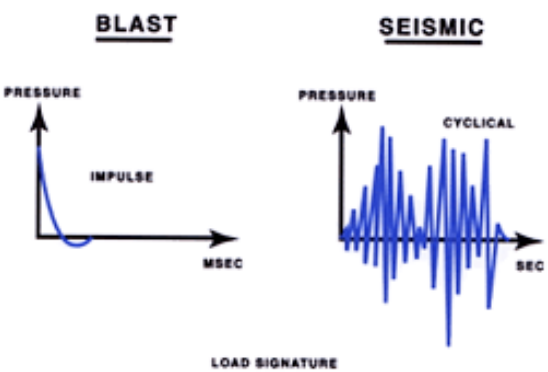
# EXPLOSIONS AND EARTHQUAKES

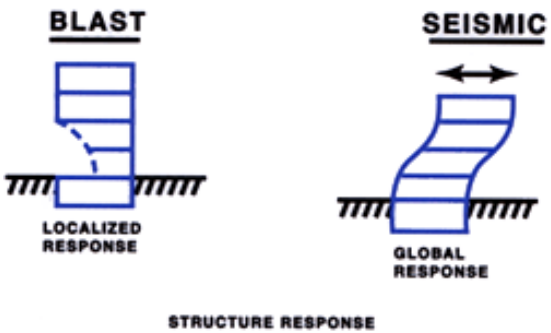
## BUILDINGS AND THEIR BEHAVIOR IN EXPLOSIONS AND EARTHQUAKES




**1. Seismic vs blast loading type**




**2. Seismic vs blast loading time histories**




**3. Seismic vs blast response**

From *Hinman (2017)*

Earthquake resistant buildings are unlikely to meet the direct effects of an air-blast loading acting on the exterior skin of a building.

**1.** Explosion loads act directly on the exterior envelope whereas earthquakes load buildings at the base of the building. Consequently the focus is on out of plane response for explosions and in plane response for seismic loads.

**2.** Explosion loads are characterized by a single high pressure impulsive pulse acting over milliseconds rather than the vibrational loading of earthquakes which is acting over seconds.

**3.** Explosion loads generally cause localized damage whereas seismic loads cause global response.

Mass helps resist explosion loads, whereas mass worsens earthquake response

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## BLAST INDUCED BUILDING DAMAGE SEVERITIES AND DAMAGE SCALES

| DAMAGE SCALES OF WOOD LIGHT-FRAME BUILDINGS | | |
|---|---|---|
| **DAMAGE SCALE** | **DAMAGE DESCRIPTION** | **$P_s$ [kPa (psi)]** |
| **DS1 Minor damage** | Typical window glass breakage<br>Large and small windows shattered<br>Occasional damage to window frames<br>Minor damage to house surfaces | 1.03 - 6.90 (0.15 - 1.0) |
| **DS2 Repairable moderate damage** | Moderate damage to roof (small deflections, large size, or amount of shingle torn-offs)<br>Moderate damage to brick façade (small areas of collapse and cracks) and wall panels (small holes on wood panel, metal panel failure, and buckling) | 6.90 - 13.79 (1.0 - 2.0) |
| **DS3 Hazardous failure** | Severe roof surface damage (holes and large deflections)<br>Severe wall surface damage (large area of façade collapse and large holes on wood panels)<br>Some structural member damage | 13.79 - 20.68 (2.0 - 3.0) |
| **DS4 Destructive failure** | Collapse of roofs and walls<br>Failures of structural members | Over 20.68 (3.0) |
| | | 1 psi = 6.90 kPa |

From *Huang et al. (2015)*, based on data related to the 2013 Fertilizer Plant Explosion at West, Texas

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## BLAST INDUCED BUILDING DAMAGE SEVERITIES AND DAMAGE SCALES

| DAMAGE SCALES OF ENGINEERING BUILDINGS | | |
|---|---|---|
| **DAMAGE SCALE** | **DAMAGE DESCRIPTION** | **$P_s$ [kPa (psi)]** |
| **DS1 Minor damage** | Typical window glass breakage<br>Shattering of large and small windows<br>Occasional damage to window frames<br>Minor damage to the building structures | 1.03 - 6.90<br>(0.15 - 1.0) |
| **DS2 Repairable moderate damage** | Major damage to the building surfaces (metal siding anchorage failure, metal sheeting torn off, corrugated metal panels failed and buckled, and external cladding walls pushed in)<br>Some structural and/or nonstructural elements damages (the internal wall damages, steel frames of building slightly distorted, and partial or complete collapse of masonry bearing walls and their supported roofs) | 6.90 - 13.79<br>(1.0 - 2.0) |
| **DS3 Hazardous failure** | Building still standing; cladding and internal walls destroyed; non-reinforced concrete or cinder block walls shattered; steel frame systems severely distorted and/or pulled away from foundation; concrete frames partially or completely collapsed | 13.79 - 20.68<br>(2.0 - 3.0) |
| **DS4 Destructive failure** | Building completely destroyed [masonry bearing wall buildings completely destroyed at 20.68 kPa (3.0 psi), steel frame and concrete frame buildings completely destroyed at 34.47 kPa (5.0 psi)] | Over 20.68<br>(3.0) |
| | | 1 psi = 6.90 kPa |

From *Huang et al. (2015)*, based on data related to the 2013 Fertilizer Plant Explosion at West, Texas

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## GROUND SHOCK INDUCED BUILDING DAMAGE SEVERITIES AND DAMAGE SCALES

| DAMAGE SCALES OF WOOD LIGHT-FRAME BUILDINGS | | |
|---|---|---|
| **DAMAGE SCALE** | **DAMAGE DESCRIPTION** | **PPV (mm=s)** |
| **DS1 Minor damage** | Large or small area of façade wall collapse with diagonal boundary lines | 62-121 |
| **DS2 Repairable moderate damage** | Severe vertical cracks on façade walls | 121-247 |
| **DS3 Hazardous failure** | Air blast incident overpressure dominant | 247-345 |
| **DS4 Destructive failure** | Air blast incident overpressure dominant | Over 345 |

From *Dai et al. (2015)*, based on data related to the 2013 Fertilizer Plant Explosion at West, Texas

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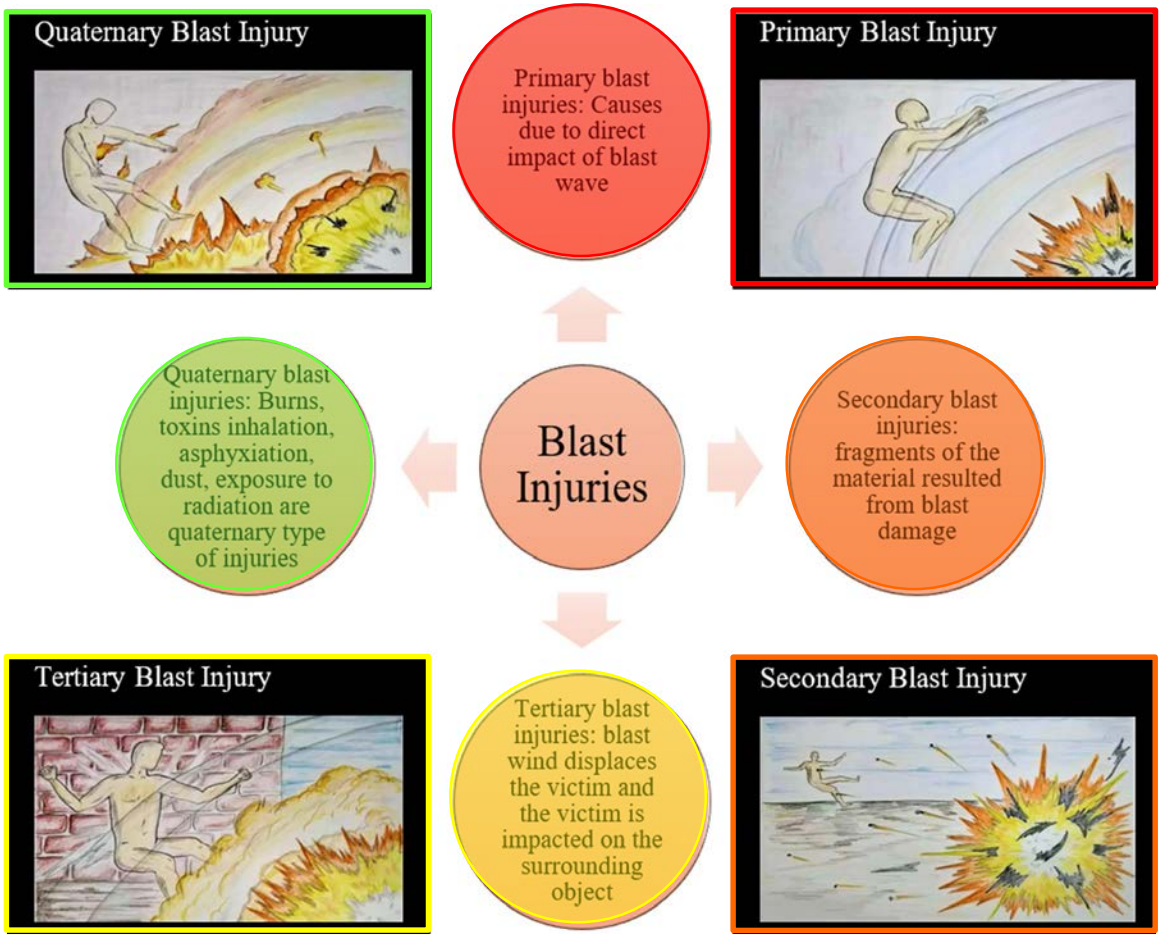
## CLASSIFICATION OF BLAST-INDUCED INJURIES




From *Shirbhate and Goel (2020)*

The effect of blast pressure on human body has been evaluated in several research works. The pressure ranges corresponding to injuries are briefly presented in this section. The intensity of blast pressure and duration has a significant influence on human. During the explosion, the propagation of the blast shockwave causes injuries and fatalities. The injuries are classified into the following categories: primary, secondary, tertiary and quaternary.

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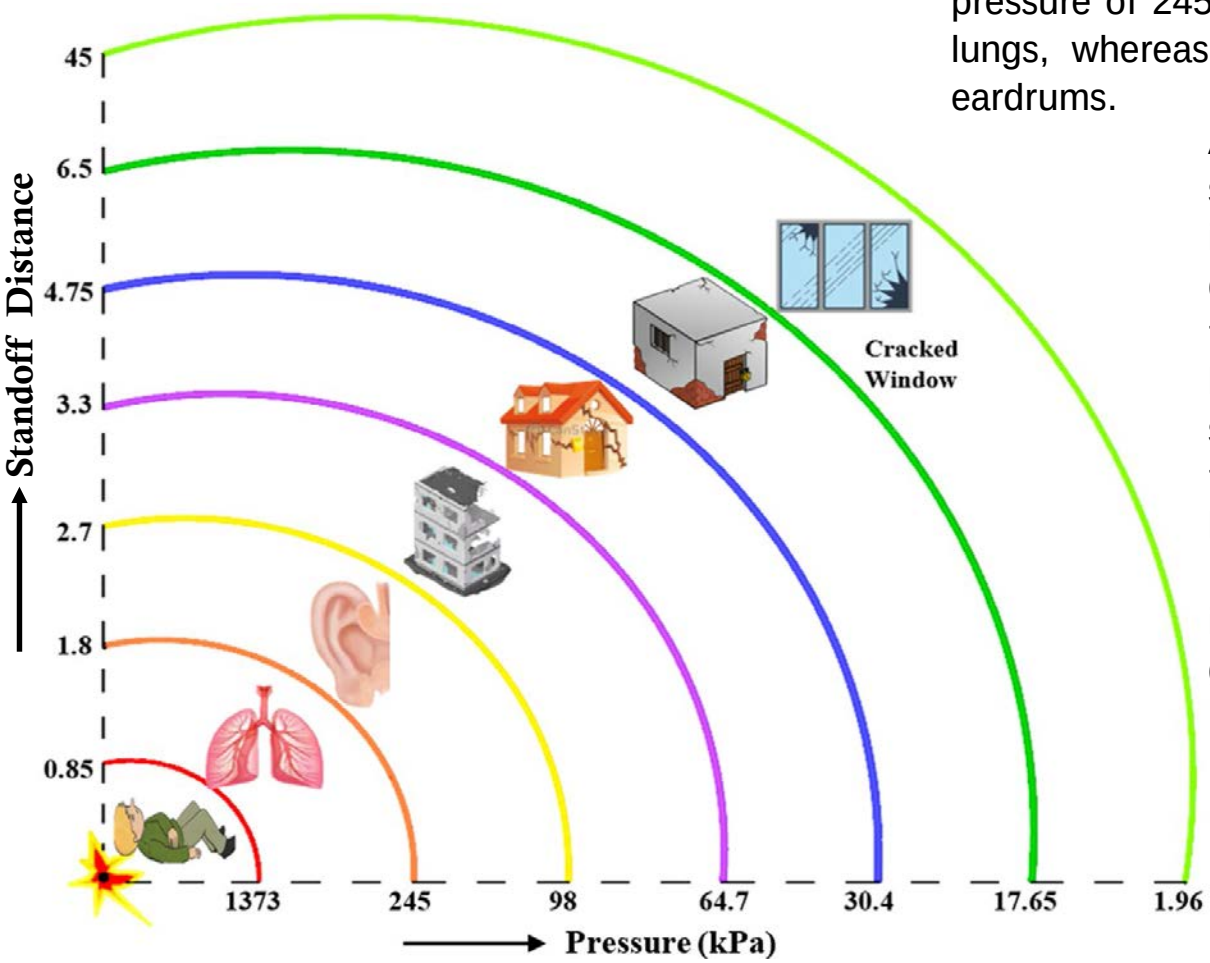
## BLAST INJURIES CORRESPONDING TO OVERPRESSURE RANGES AND RESPECTIVE STANDOFF DISTANCES

In close proximity to the explosion, where the pressure is approximately 1373 kPa, the blast shockwave can inflict fatal injuries to human resulting in loss of life. A pressure of 245 kPa and more can result in collapse of lungs, whereas 98 kPa of pressure can damage the eardrums.




As regards the structures, when the standoff distance is small, the damage is heavy comprising cracks and deformation of structural elements of the buildings including columns, slabs, beams and walls. The greater the standoff distance of the building from the site, the smaller the damage to the buildings. As mentioned before, major role in the severity of the damage induced by the explosion plays the geometry of the building.

From *Shirbhate and Goel (2020)*

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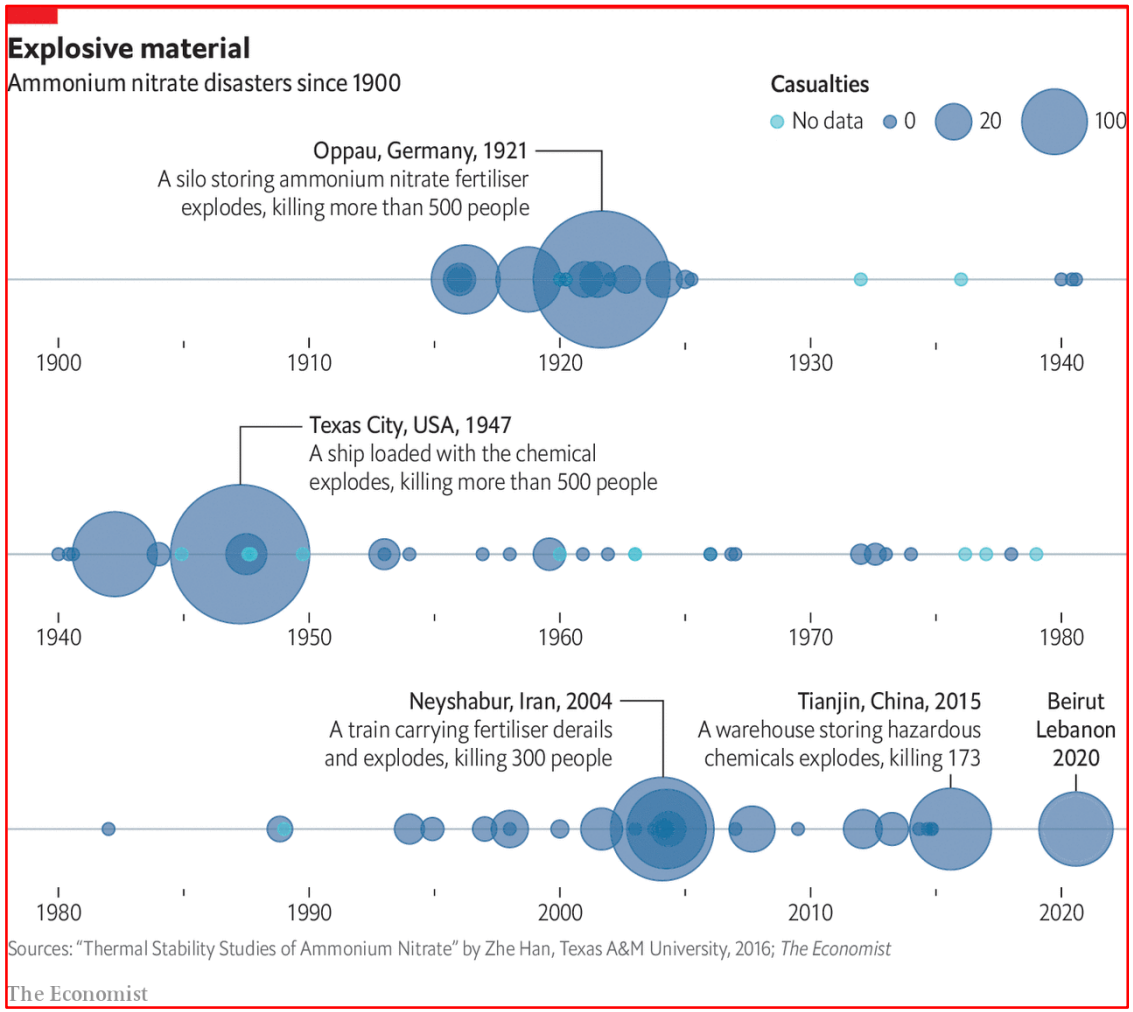
# GLOBAL HISTORY OF AMMONIUM NITRATE DISASTERS
## FROM 1900 TO PRESENT




There have been a number of disasters due to ammonium nitrate explosions. For example, Texas City disaster of 1947 is reputed to be the deadliest industrial accident in the U.S. history killing at least 581 people and injuring nearly 8000.

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## AMMONIUM NITRATE DISASTERS

| Country | Location | Date | Fatalities | Ammonium Nitrate (tonnes) |
|---|---|---|---|---|
| United States | Gibbstown, New Jersey | January 14, 1916 | 1 | 1.81 |
| United Kingdom | Faversham, Kent | April 2, 1916 | 115 | 700 |
| United States | Oakdale, Pennsylvania | September 15, 1916 | 6 | 1.36 |
| Germany | Kriewald | July 26, 1921 | 19 | 30 |
| Germany | Oppau, Ludwigshafen | September 21, 1921 | 561 | 450 |
| United States | Nixon, New Jersey | March 1, 1924 | 20 | 2 |
| United States | Muscle Shoals, Alabama | May 3, 1925 | 0 | |
| France | Miramas | August 5, 1940 | 0 | 240 |
| Belgium | Tessenderlo | April 29, 1942 | 189 | 150 |
| Canada | St. Stephen, New Brunswick | 1947 | 0 | 360 |
| United States | Texas City | April 16, 1947 | 581 | 2086 + |
| France | Brest | July 28, 1947 | 29 | 1700-3309 |
| United States | Presque Isle, Maine | August 26, 1947 | 0 | 217 |
| United States | Roseburg, Oregon | August 7, 1959 | 14 | 4.1 |
| United States | Traskwood, Arkansas | December 17, 1960 | 0 | 140-180 |
| Australia | Taroom, Queensland | August 30, 1972 | 3 | 12 |
| United States | Kansas City, Missouri | November 29, 1988 | 6 | 23 (ANFO) |
| Papua New Guinea | Porgera Gold Mine | August 2, 1994 | 11 | 80 (ANE) |
| United States | Port Neal, Iowa | December 13, 1994 | 4 | |
| China | Xingping, Shaanxi | January 6, 1998 | 22 | 27.6 |
| France | Toulouse | September 21, 2001 | 31 | 200-300 |
| Spain | Cartagena, Murcia | January 2003 | 0 | |
| France | Saint-Romain-en-Jarez | October 2, 2003 | 0 | 3-5 |
| Spain | Barracas | March 9, 2004 | 2 | 25 |
| North Korea | Ryongchŏn | April 22, 2004 | 162 | |
| Romania | Mihăileşti, Buzău | May 24, 2004 | 18 | 20 |
| Spain | Estaca de Bares | 2007 | 0 | 400 |
| Mexico | Monclova, Coahuila | September 9, 2007 | 28 | 22 (ANFO) |
| United States | Bryan, Texas | July 30, 2009 | 0 | |
| United States | West, Texas | April 17, 2013 | 15 | 240 |
| Australia | Wyandra, Queensland | September 5, 2014 | 0 | 56 |
| China | Port of Tianjin | August 12, 2015 | 173 | 800 |
| Lebanon | Beirut | August 4, 2020 | 220+ | 2750 |

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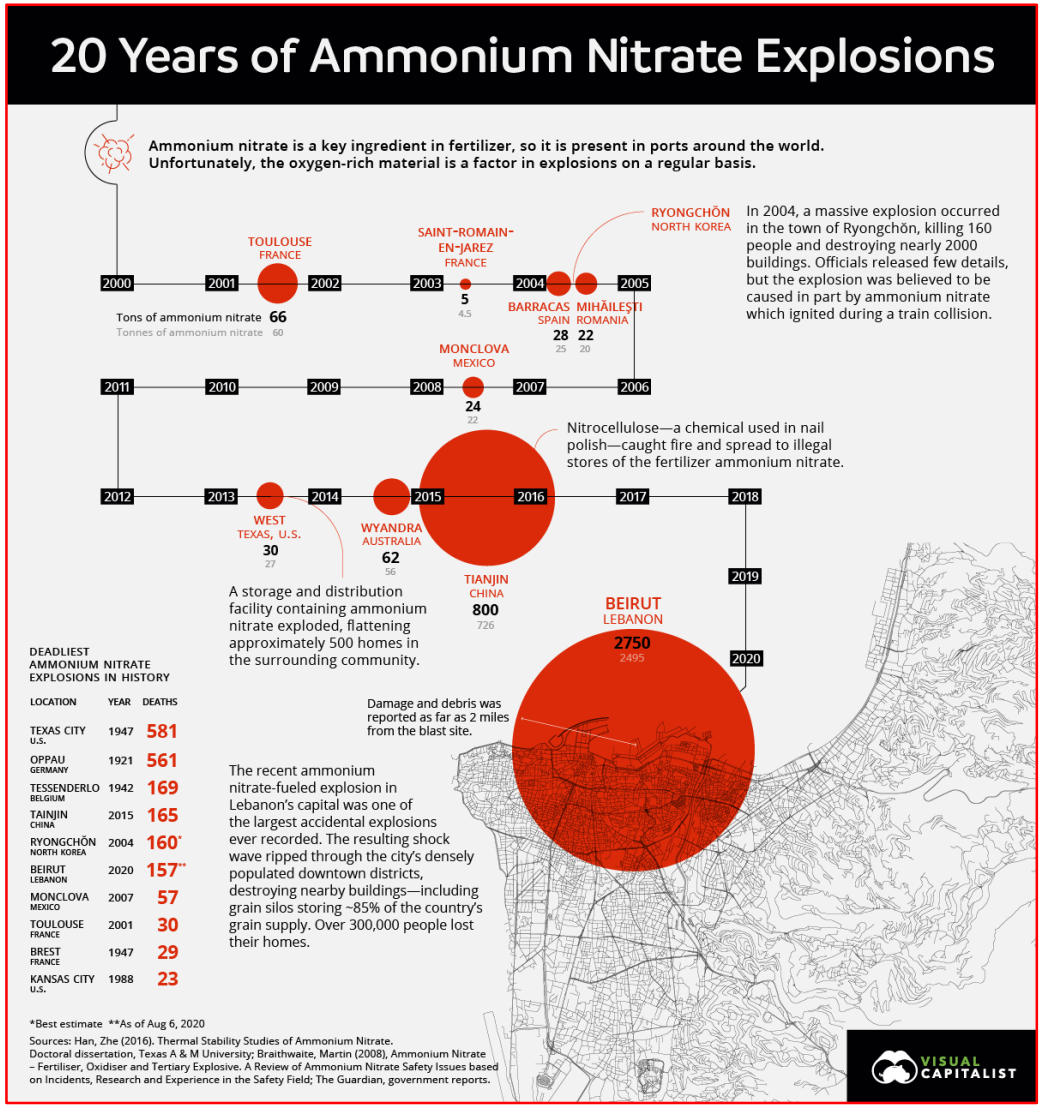
# GLOBAL HISTORY OF AMMONIUM NITRATE DISASTERS
## FROM 2000 TO PRESENT




**DEADLIEST AMMONIUM NITRATE EXPLOSIONS IN HISTORY**

| LOCATION | YEAR | DEATHS |
|---|---|---|
| TEXAS CITY U.S. | 1947 | 581 |
| OPPAU GERMANY | 1921 | 561 |
| TESSENDERLO BELGIUM | 1942 | 169 |
| TAINJIN CHINA | 2015 | 165 |
| RYONGCHŎN NORTH KOREA | 2004 | 160* |
| BEIRUT LEBANON | 2020 | 157** |
| MONCLOVA MEXICO | 2007 | 57 |
| TOULOUSE FRANCE | 2001 | 30 |
| BREST FRANCE | 1947 | 29 |
| KANSAS CITY U.S. | 1988 | 23 |

as of August 6, 2020

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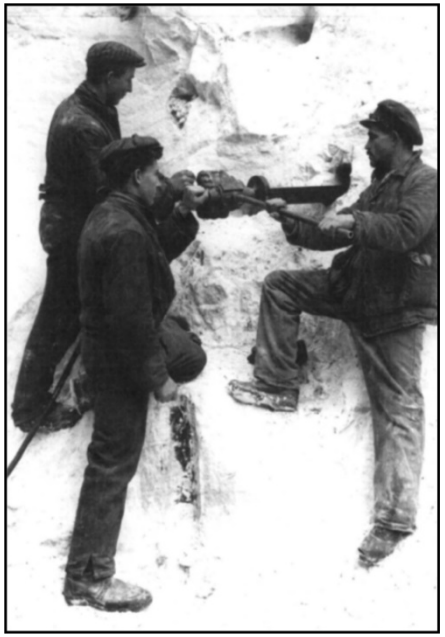
## THE 1921 OPPAU (GERMANY) DISASTER



Preparation of blasting operation in order to loosen stored ammonium sulfate nitrate (*Hörcher, 2016*)

On September 21, 1921, the Oppau area was affected by an ammonium nitrate accident. There were two successive explosions attributed to routine blasts, carried out to loosen ammonium sulfate nitrate fertilizer stored in a silo. The first one was weak, while the second was massive and devastating. It created a crater with depth of 20 m that corresponded to explosion of 400 tons of ammonium nitrate sulfate. The plant was completely destroyed. The explosion had destructive impact on the surrounding area, which suffered severe damage.

The explosions were recorded by seismographs operated in Stuttgart located 150 km from the Oppau plant and the second massive explosion was heard in Munich located 275 km from the explosion. The 80 % of buildings in Oppau were destroyed. As regards the impact on population, 561 fatalities, 1952 injured and 7500 homeless were officially reported. The economic loss was about 1700000 US$.

To avoid repetition of such an event in the future, the breaking down of ammonium nitrate stockpiles by blasting were prohibited. These masses were then broken by use of mechanical means.

From *French Ministry of Environment (2008)*, *Negovanović et al. (2015)* and *Hörcher (2016)*

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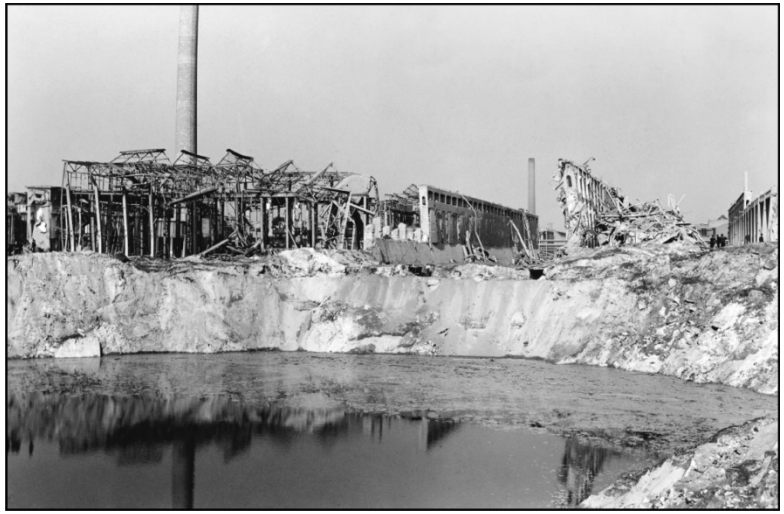
## THE 1921 OPPAU (GERMANY) DISASTER






The massive explosion in Oppau destroyed the plant. It created a 20 m deep crater.
From *French Ministry of Environment (2008)*, *Negovanović et al. (2015)* and *Hörcher (2016)*

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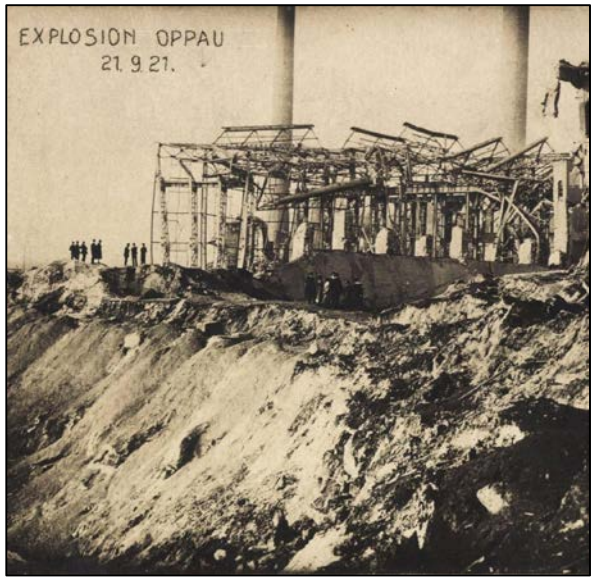
## THE 1921 OPPAU (GERMANY) DISASTER




The area within 1.5 km around the explosion site, numerous buildings were heavily affected. Damage ranged from slight damage in non-structural elements of the buildings to partial or total collapse of the buildings. In Oppau, over a thousand buildings were affected.

https://thecanadian.news/2020/08/05/fertilizer-explosion-in-1921-the-catastrophe-at-basf-world/

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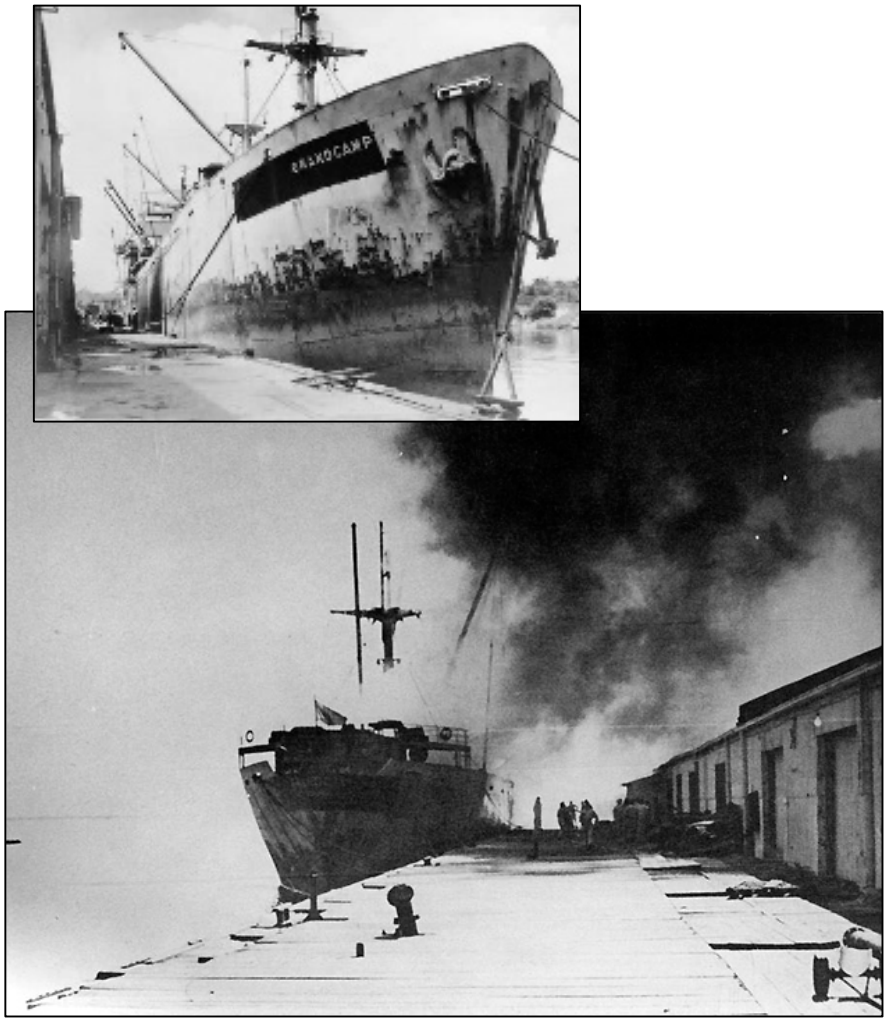
## THE 1947 TEXAS CITY (USA) DISASTER




The S.S. Grandcamp moored at dockside and on fire before the explosion (http://www.texascity-library.org/page/history.1947.fire)

The 1947 Texas City disaster is the deadliest industrial accident and the largest non-nuclear explosion in the U.S.A. history resulting in at least 581 fatalities and injuring nearly 8000 people. One third of all buildings were demolished and 2500 people were homeless. No window in Texas City remained unbroken. It is the biggest ammonium nitrate explosion that has taken place in the U.S.A.

The cargo ship *Grandcamp* with nearly 2300 tones of ammonium nitrate on board was in Texas City harbor when a fire was detected in the hold. The captain closed the hold and pumped in pressurized steam. One hour later, the ship exploded, claiming the lives of several hundred people and setting fire to an adjacent vessel, the *High Flyer*, which was moored 250 m away. This ship contained 1050 tones of sulfur and 860 tones of ammonium nitrate. The S.S. *Grandcamp* explosion created a shockwave and knocked two small planes flying at 460 m (1500 ft) out of the sky. The *High Flyer* exploded the next day, after having burned for many hours. The explosions started a chain reaction of fires and explosions in the adjacent refinery and oil tanks resulted in total destruction.

From *Wheaton (1948); Stephens (1993); Vallero and Letcher (2013)*

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## BEFORE THE 1947 TEXAS CITY DISASTER

Aerial view of the port area and its facilities before the 1947 Texas City Disaster
From *The Portal to Texas History*, https://texashistory.unt.edu

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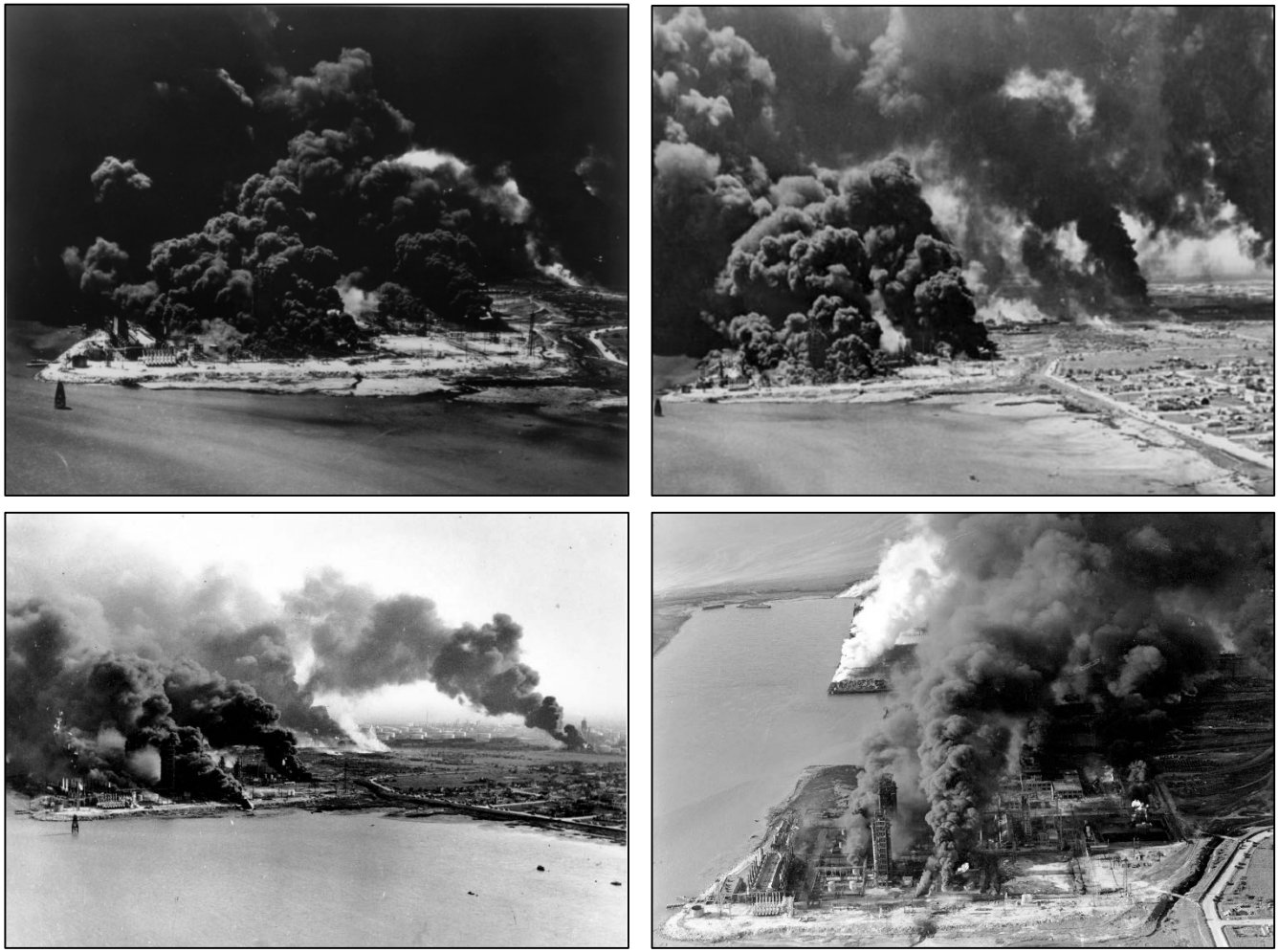
## DURING THE 1947 TEXAS CITY DISASTER



The explosion of the S.S. *Grandcamp* completely destroyed the Monsanto Chemical Company plant and resulted in ignitions, fires and explosions in nearby refinery, oil and chemical tanks. Massive smoke clouds covered the entire area for days.

From *AP*

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## DAMAGE INDUCED BY THE 1947 TEXAS CITY DISASTER
### VEHICLES






Vehicles damaged by the blasts in the port area of Texas in 1947. They presented twisted and crushed parts, heavy compression damage, crushing and missile damage and blown-out or broken windows. Many of them were covered with black soot and/or oil (From *The Portal to Texas History*, https://texashistory.unt.edu)

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## DAMAGE INDUCED BY THE 1947 TEXAS CITY DISASTER

### SHIPS




Ships close to the explosions were either very heavily damaged or washed ashore by the blasts in the port area of Texas in 1947
(From *The Portal to Texas History*, https://texashistory.unt.edu)

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## DAMAGE INDUCED BY THE 1947 TEXAS CITY DISASTER
### STORAGE TANKS AND REFINERY STRUCTURES

Tanks damaged by the blasts in the port area of Texas in 1947. Some of them exploded and were completely destroyed. Others presented significant crushing damage especially visible along the top and sides as well denting in various parts (From *The Portal to Texas History*, https://texashistory.unt.edu)

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## DAMAGE INDUCED BY THE 1947 TEXAS CITY DISASTER
### RESIDENTIAL BUILDINGS

Characteristic views of residential buildings with damage induced by the 1947 Texas City disaster. Many structures suffered very heavy structural damage and collapsed. Most of the affected buildings suffered major non-structural damage comprising roof and wall damage. Their windows and doors were blown out. Boards and beams have fallen down. Others were very badly damaged and leant noticeably. In several cases, some parts of the building structure were completely missing. Metal and wooden debris was widely scattered around the buildings.

From *The Portal to Texas History*, https://texashistory.unt.edu

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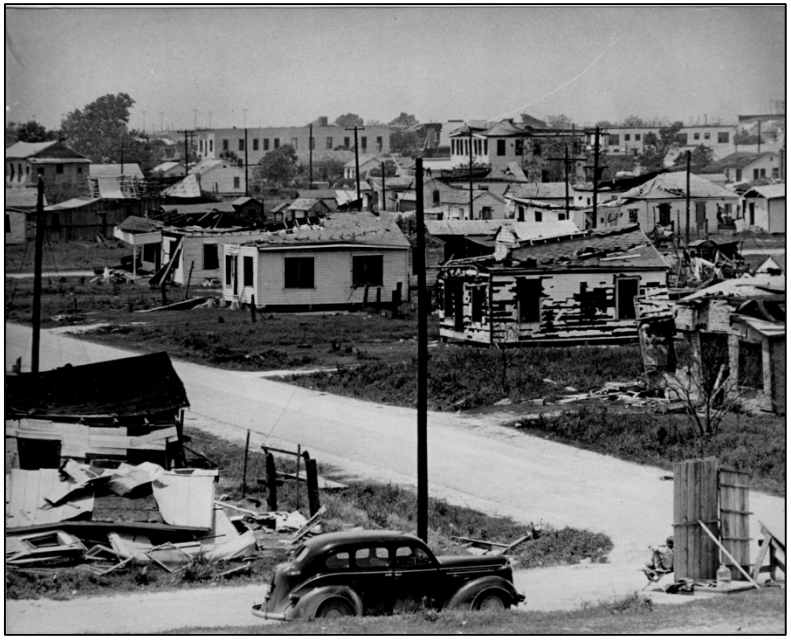
## DAMAGE INDUCED BY THE 1947 TEXAS CITY DISASTER
### RESIDENTIAL BUILDINGS



From *The Portal to Texas History*, https://texashistory.unt.edu

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## DAMAGE INDUCED BY THE 1947 TEXAS CITY DISASTER

### DEBRIS

Debris was widely scattered after the explosions. Large pieces of metal and wood were bent, broken and twisted.

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## DAMAGE INDUCED BY THE 1947 TEXAS CITY DISASTER
### WAREHOUSES





Warehouses at the port were razed to the ground by the explosions. The metal structures were twisted and warped. The concrete structures were less affected, but their windows and doors were blown out. Warehouses in larger distance were slightly affected.

From *The Portal to Texas History*, https://texashistory.unt.edu

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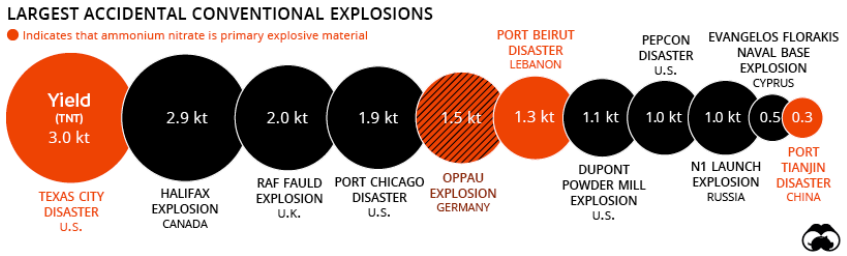
# THE 2015 TIANJIN (CHINA) DISASTER

On 12 August 2015, a series of massive explosions struck the port in the Binhai New Area of Tianjin, China after a fire started in a container placed at a container storage station of a logistics company handling hazardous chemicals. The first two explosions within 30 seconds of each other took place in an industrial area of the Tianjin port city. The second explosion was attributed to the detonation of about 800 tonnes of ammonium nitrate. These explosions started a chain reaction of fires and explosions in the industrial area resulting in 10 explosions in total.

Based on the official report on the impact of the explosions on population, 165 fatalities (24 active public security firefighters involved in rescue and disposal, 75 Tianjin Port firefighters, 11 public security police, 55 employees of the accident company, surrounding enterprises and surrounding residents), 8 missing and 798 injured people were reported. It is significant to mention that 104 of the 173 fatalities were firefighters who first responded and went to address the fire without knowing that dangerous and hazardous chemicals were stored on the site. The water they used did not work as an extinguishing agent, but as an accelerator for the propagation of the fire and the explosions.

As regards the impact on the built environment, buildings surrounding the explosion site suffered severe damage. Many container stacks were toppled and thrown by the blast. Thousands of new cars parked in a nearby lots were totally burned. Based on the official report of the disaster, 304 buildings, 12428 commercial vehicles and 7533 containers were damaged. As of December 2015, the approved direct economic loss has been 6.866 billion yuan.

The accident rescue and on-site disposal and clean-up tasks were completed on September 2015. More specifically, 1176 tons of hazardous chemicals, 7641 vehicles, 13834 containers and 14000 tons of cargo were cleared and transported.



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## SCENE OF THE 2015 TIANJIN DISASTER


The New York Times; photograph by Yue Yuewei/AP

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## DAMAGE INDUCED BY THE 2015 TIANJIN DISASTER
### ADJACENT BUILDINGS

*From Xu et al. (2016)*


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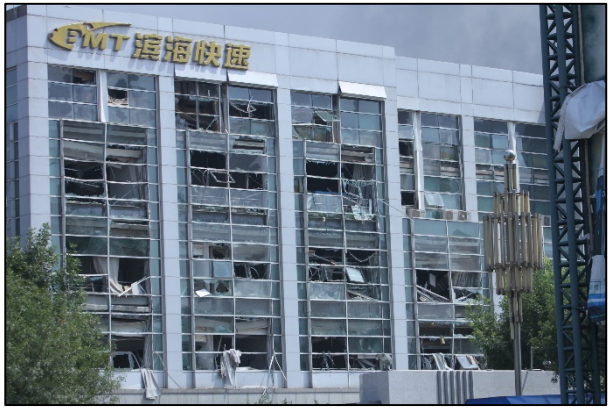
# DAMAGE INDUCED BY THE 2015 TIANJIN DISASTER
## DISTANT BUILDINGS

*From Xu et al. (2016)*

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## DAMAGE INDUCED BY THE 2015 TIANJIN DISASTER
### VEHICLES

*From various sources (The Atlantic magazine, The Independent, abc NEWS)*

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## DAMAGE INDUCED BY THE 2015 TIANJIN DISASTER
### CONTAINERS

*From various sources*
*(The Independent, Quartz, The Atlantic magazine)*

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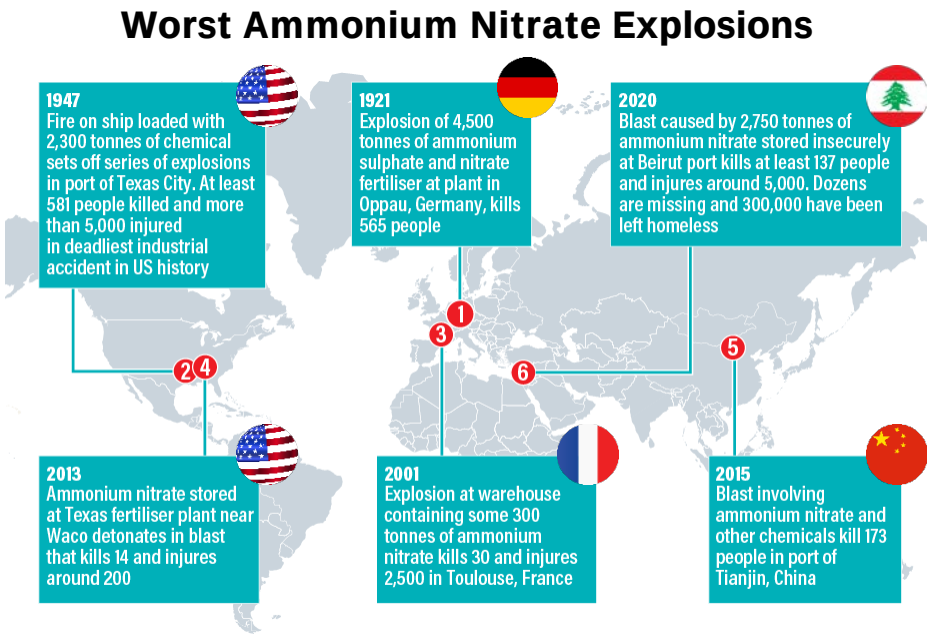
## LESSON LEARNT FROM PREVIOUS AMMONIUM NITRATE ACCIDENT AND DISASTERS

Several lessons have been learnt as a result of previous ammonium nitrate accidents and disasters and from studies related on its potentially hazardous properties. The conditions of storage and the materials co-located with ammonium nitrate while in storage are crucial to the safety and stability of the ammonium nitrate.




From https://www.thenational.ae/, modified

- Ammonium nitrate will self-compress/self-confine under some conditions, becoming much more likely to explode. Adding heat, such as a booster charge intended to break up clumps, can initiate a general detonation of the ammonium nitrate.
- Ammonium Nitrate is at risk for explosion when stored near other material that can add fuel to the ammonium nitrate – such as sugar, grain dust, seed husks, sawdust, other organic contaminants, even in fairly low percentages, and most especially petroleum fuels such as diesel.
- Ammonium nitrate is a powerful oxidizer and a rich source of nitrate, which provides energy to an explosion. Thus, the presence of fuel and/or heat (and especially both) near ammonium nitrate is a very high hazard situation.
- Special attention must be paid in the protection of the ammonium nitrate stockpile from natural disasters that can produce shock, overturn and bouncing of the ammonium nitrate storage

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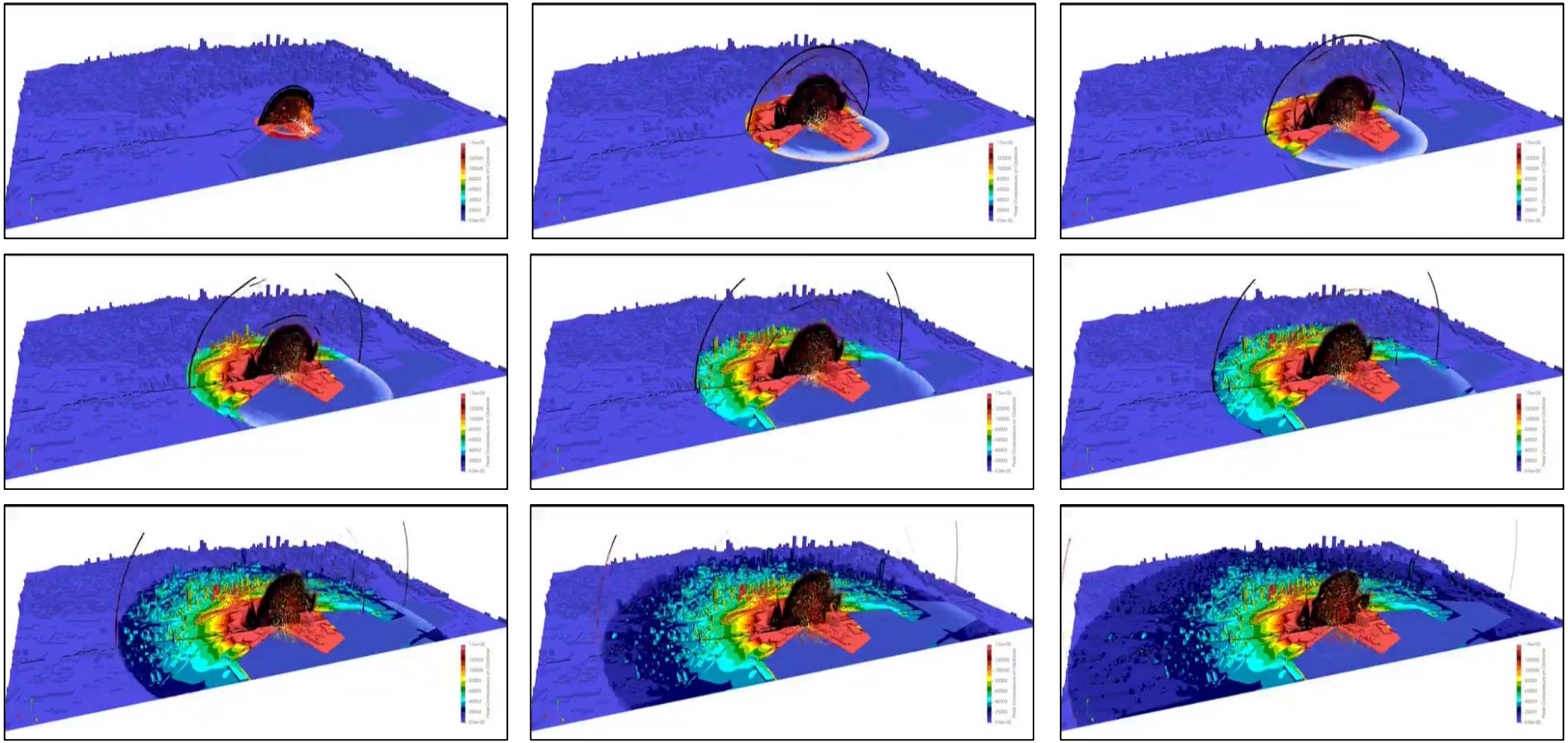
## PROPAGATION OF THE SHOCKWAVE INDUCED BY THE EXPLOSION IN BEIRUT PORT



Computational Fluid Dynamics (CFD) blast analysis for the 3D reconstruction of the dynamics of the wave. Different colors correspond to different values of peak overpressure on obstacle. It is concluded that the shockwave was propagated in an asymmetric way. The asymmetry of the blast is due to the grain silo which acted as an obstacle for the propagation of the wave and as a protective shield for the area behind the silo.

https://twitter.com/garshouni/status/1291566840376852481

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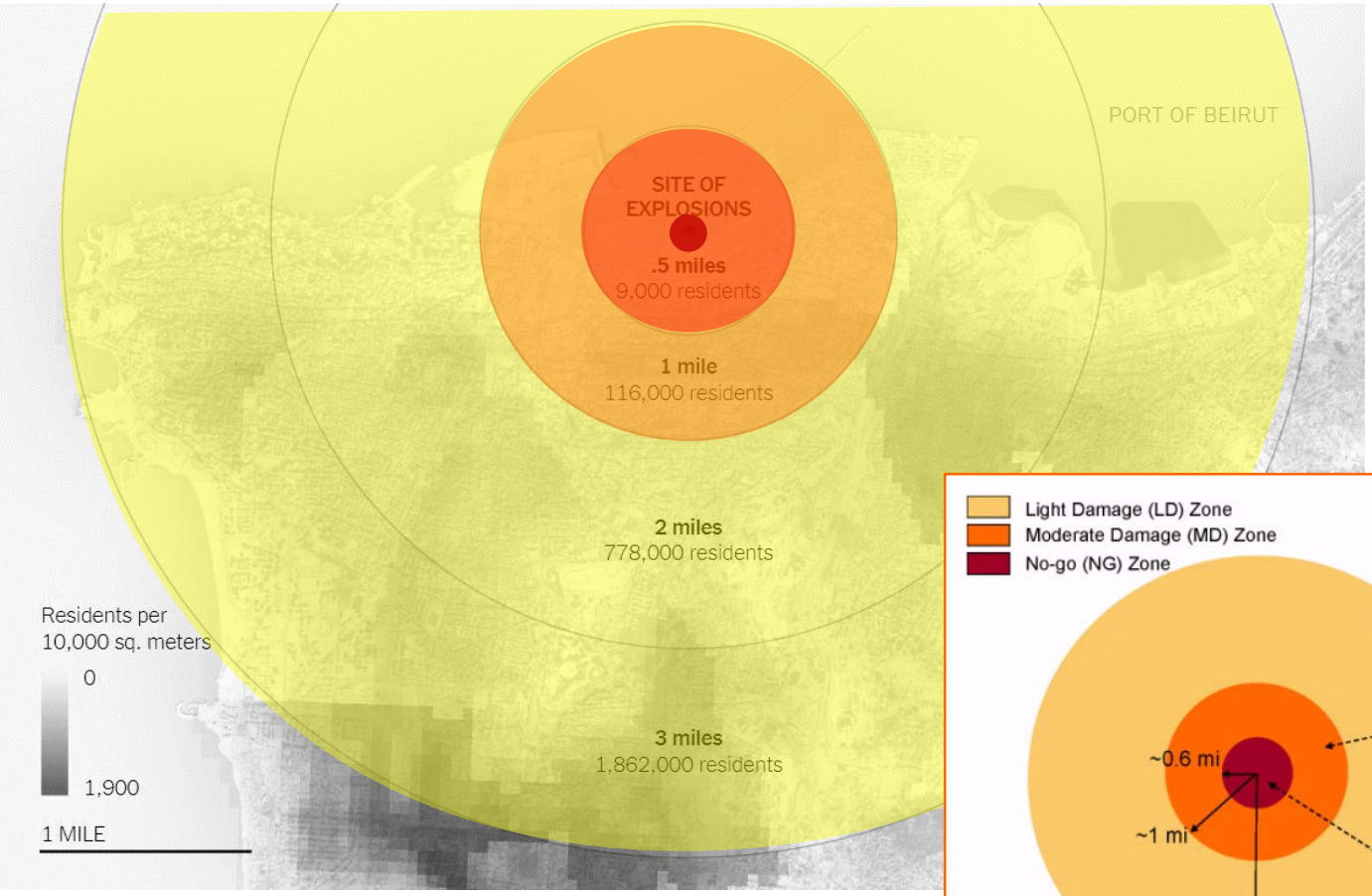
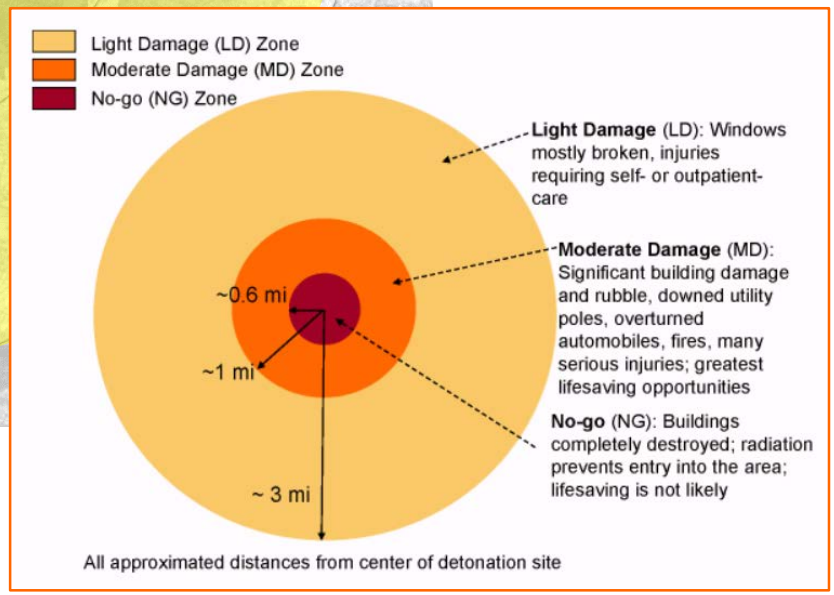
# DAMAGE ZONES INDUCED BY THE EXPLOSION IN BEIRUT PORT
## AND COMPARISON WITH DAMAGE ZONES INDUCED BY NUCLEAR EXPLOSION




**Damage zones in Beirut**

| |
|---|
| Total devastation |
| Severe damage |
| Moderate damage |
| Light damage |
| Negligible damage |

9000 residents live within the red zone
116000 residents live within the orange zone
2640000 residents live within the yellow zone




Representative damage zones for 10 kt nuclear explosion

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## DAMAGE ZONES INDUCED BY THE EXPLOSION IN BEIRUT PORT

In the **epicenter of the explosion**, the devastation is total. The warehouse was vanished and the explosion created a crater. Around the epicenter, within the black zone of total devastation, warehouses either pulverized or sustained very heavy structural damage, anchored ships were totally destroyed, capsized or washed ashore. Vehicles were blown away by the explosion and suffered heavy crushing damage. There were larger lifesaving opportunities in comparison with the explosion epicenter.

Within the **red zone** of severe damage (epicenter to 0.5 miles), old masonry buildings suffered heavy structural damage including partial collapse due to failure of their load-bearing walls. The recently constructed reinforced buildings sustained lighter damage to their non-structural elements including detachment of their brick infill walls from the surrounding reinforced concrete frame. Glazing breakage and detachment of cladding from building facade were observed throughout the entire zone. Many people suffered mild, moderate and severe injuries from the blast shockwave and by falling debris from the building façade.

Within the **orange zone** of moderate damage (0.6 to 1 mile), the old masonry buildings suffered significant damage, while the reinforced concrete buildings sustained only glazing breakage and detachment of the glazing from the building facade. The later damage was observed in a large scale but not throughout the entire zone. People also suffered injuries by falling debris.

Within the **yellow zone** of light damage (1.1 to 3 miles), glazing breakage was observed in many buildings.

With the **grey zone** of negligible damage (> 3 miles), the explosion was widely felt without causing serious damage. Glazing breakage was observed in several buildings.

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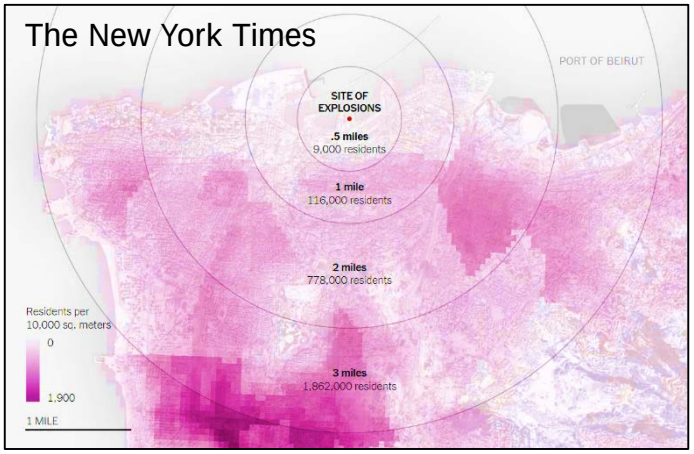
# DISTRIBUTION OF DAMAGE INDUCED BY THE EXPLOSION IN BEIRUT PORT


The explosion destroyed the port and affected the central part of Beirut comprising important facilities, buildings and infrastructures including hospitals (Karantina, St. George, Wardieh and Bahman hospitals), monumental and religious structures (Mohammad Al amin Mosque), governmental buildings (the government headquarters in Grand Serail), cultural sites (the National Museum of Beirut, the Sursock Museum, the Archaeological Museum of the American University of Beirut, cultural spaces and galleries), companies (electric power supply company), hotels as well as commercial and residential buildings. Damage was mainly observed in the area southwest and east of the explosion site.

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## ZONES OF DAMAGE DISTRIBUTION AND RELATED POPULATION


https://reliefweb.int/sites/reliefweb.int/files/resources/Lebanon_Beirut%20Blast_Rapid%20Needs%20Assessment%20Report_August%202020_final.pdf

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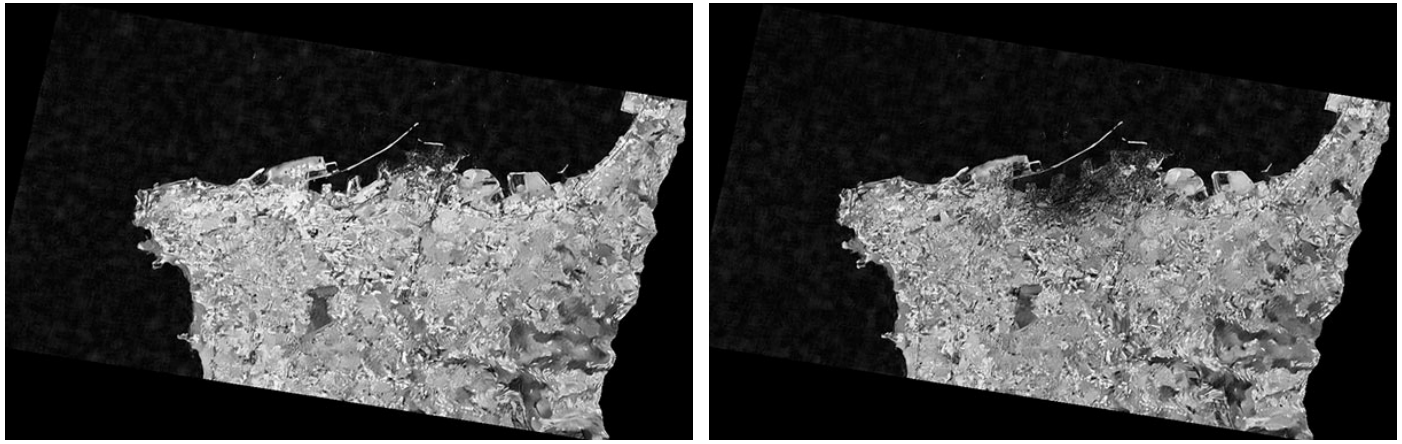
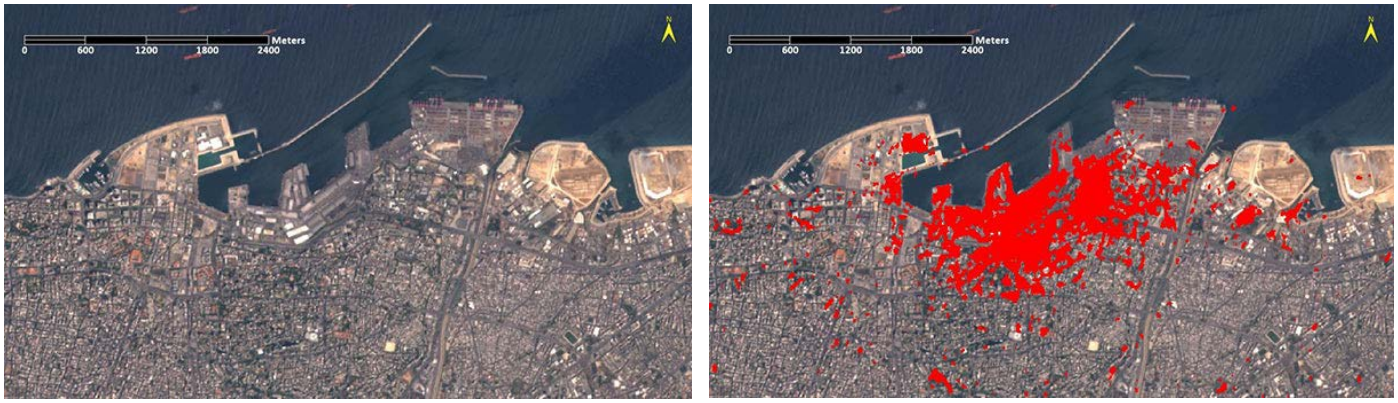
## MAPPING OF DAMAGE INDUCED BY THE EXPLOSION IN BEIRUT PORT WITH THE USE OF SYNTHETIC APERTURE RADAR DATA



The above image shows a coherence map created from the Sentinel-1 both before the explosion in Beirut (on the left) and soon after (on the right). Dark areas show stark dissimilarity between the collects.




The Sentinel-2 RGB image (on the left) was collected on July 24, 2020. The image on the right shows the damage superimposed onto the image. Damage could include anything altered by the explosion.
https://www.harrisgeospatial.com/Learn/Case-Studies/Case-Studies-Detail/ArtMID/10204/ArticleID/23935/SAR-Data-Used-to-Extract-Damage-From-Beirut-Explosion

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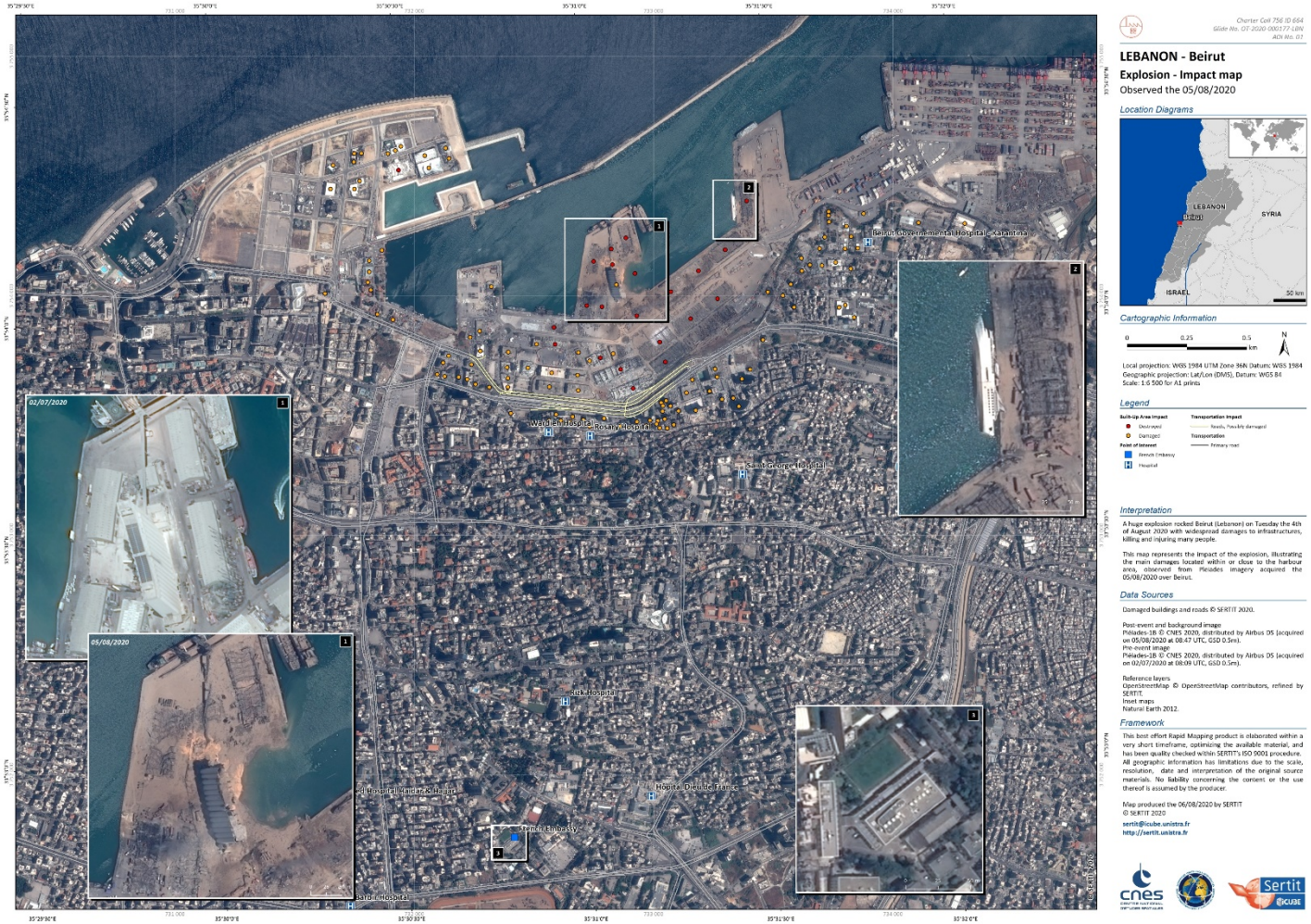
## SATELLITE IMAGERY AND RAPID IMPACT MAPPING




This map represents the impact of the explosion, illustrating the main damages located within or close to the harbor area, observed from Pleiades imagery acquired the 05/08/2020 over Beirut.
https://disasterscharter.org/image/journal/article.jpg?img_id=6697640&t=1596730788892

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## SATELLITE IMAGERY AND RAPID IMPACT MAPPING


**Built up area impact**
**Red circles** correspond to destroyed port facilities and buildings.
**Yellow circles** correspond to damaged port facilities and buildings.

**Post-event and background image**
Pleiades-1B (c) CNES 2020, distributed by Airbus DS (acquired on 05/08/2020 at 08:47 UTC, GSD 0.5 m)

**Pre-event image**
Pleiades-1B (c) CNES 2020, distributed by Airbus DS (acquired on 02/07/2020 at 08:09 UTC, GSD 0.5 m)

**Link**
https://disasterscharter.org/image/journal/article.jpg?img_id=6697640&t=1596730788892

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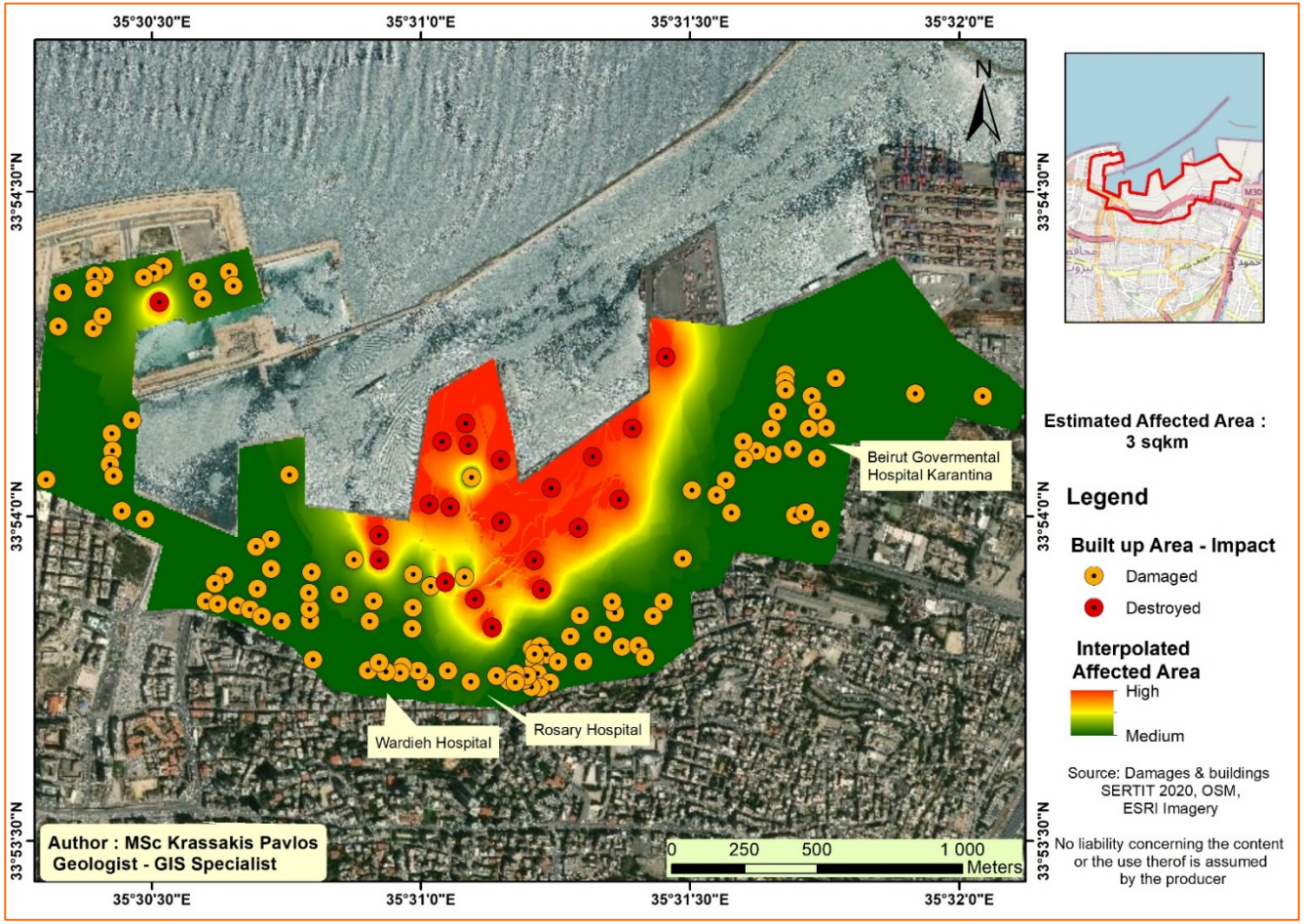
## BLAST-INDUCED DAMAGE INTERPOLATION




Map of the area affected by the Beirut explosion. Red circles correspond to destroyed port facilities and buildings. Yellow circles correspond to damaged port facilities and buildings. In the western part of the affected area, damage is less than the eastern part and this is attributed to the occurrence of the silo, which acted as a barrier to blast shockwave propagation to the west and as a protective shield for buildings, structures and residents (Contribution: *Pavlos Krassakis, MSc Geologist, GIS Specialist*)

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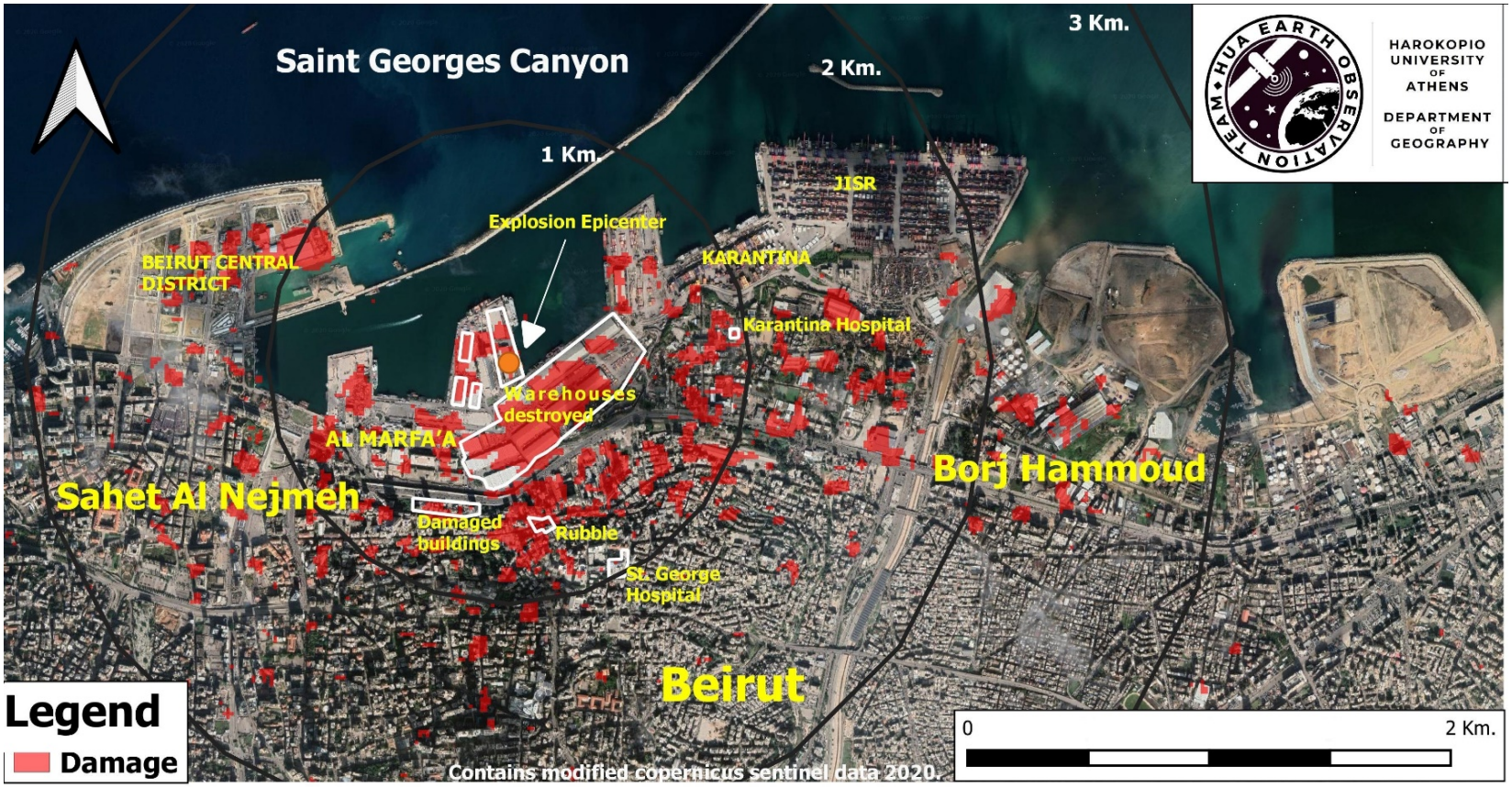
## DETECTION OF BLAST-INDUCED DAMAGE WITH COHERENCE DIFFERENCE ANALYSIS




The Earth Observation Team of the Department of Geography in Harokopeio University (Athens, Greece) has detected the damage caused by the explosion with the method of coherence difference analysis. Three Sentinel-1 images were used in order to produce two coherence images, one before and one after the accident (pre-pair: 13/07/2020-25/07/2020 post-pair: 25/07/2020-06/08/2020). It is clear from the produced damage map that the impact of the explosion reaches up to 3-4 kilometers inside the city from the port, where the ammonium nitrate were stored. The eastern and the southern mainly parts are affected. Many of the buildings hit by the shockwave are places of population concentration (Contribution: *Prof. Isaak Parcharidis and the Earth Observation Team*).

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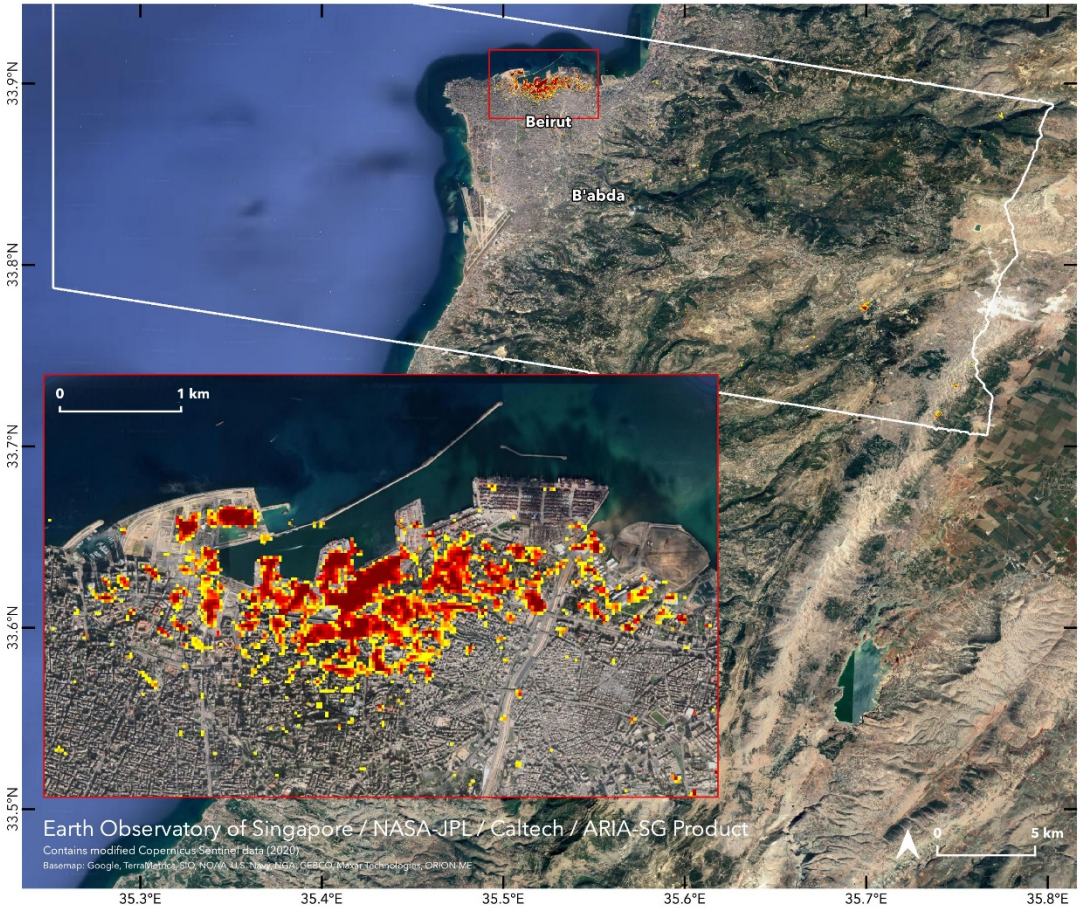
# ADVANCED RAPID IMAGING AND ANALYSIS (ARIA) OF BLAST-INDUCED DAMAGE IN BEIRUT




The map contains modified Copernicus Sentinel data processed by ESA (European Space Agency) and analyzed by ARIA team scientists at NASA's Jet Propulsion Laboratory, Caltech, and Earth Observatory of Singapore. Based in Pasadena, California, Caltech manages JPL for NASA.

https://www.jpl.nasa.gov/spaceimages/details.php?id=PIA23692

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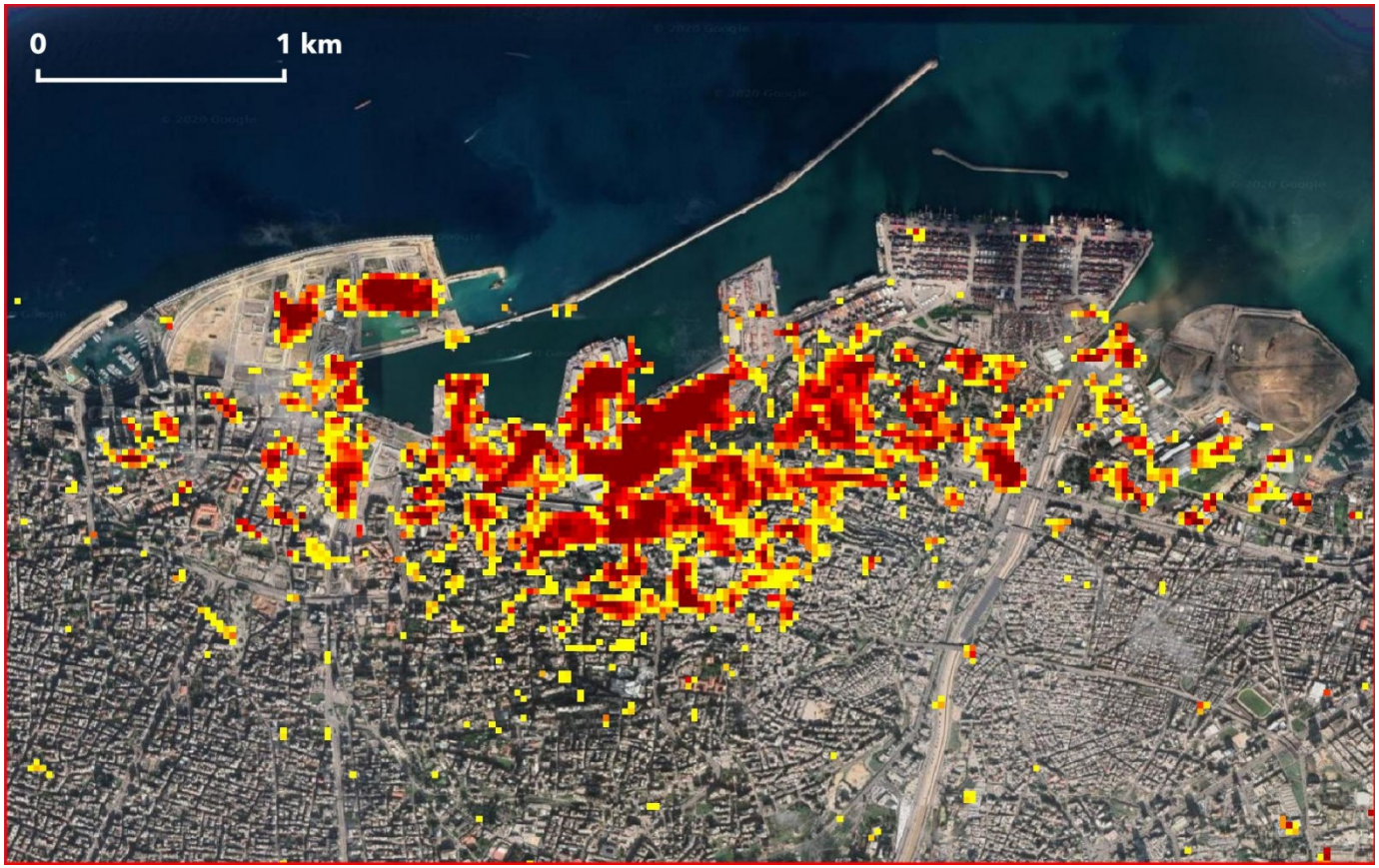
## DETECTION OF BLAST-INDUCED DAMAGE




NASA's ARIA team, in collaboration with the Earth Observatory of Singapore, used satellite data to map the extent of likely damage following the massive explosion in Beirut. Dark red pixels represent the most severe damage. Areas in orange are moderately damaged, and areas in yellow are likely to have sustained somewhat less damage. Each colored pixel represents an area of 30 meters.

https://www.jpl.nasa.gov/spaceimages/details.php?id=PIA23692

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## BEFORE/AFTER VIEWS OF BEIRUT PORT SHOWING BLAST-INDUCED DAMAGE


Pléiades satellites, lofted by Soyuz from the Spaceport, provided before/after views of Beirut's port showing damage from the Aug. 4 blast.
From *CNES / AirbusSpace*

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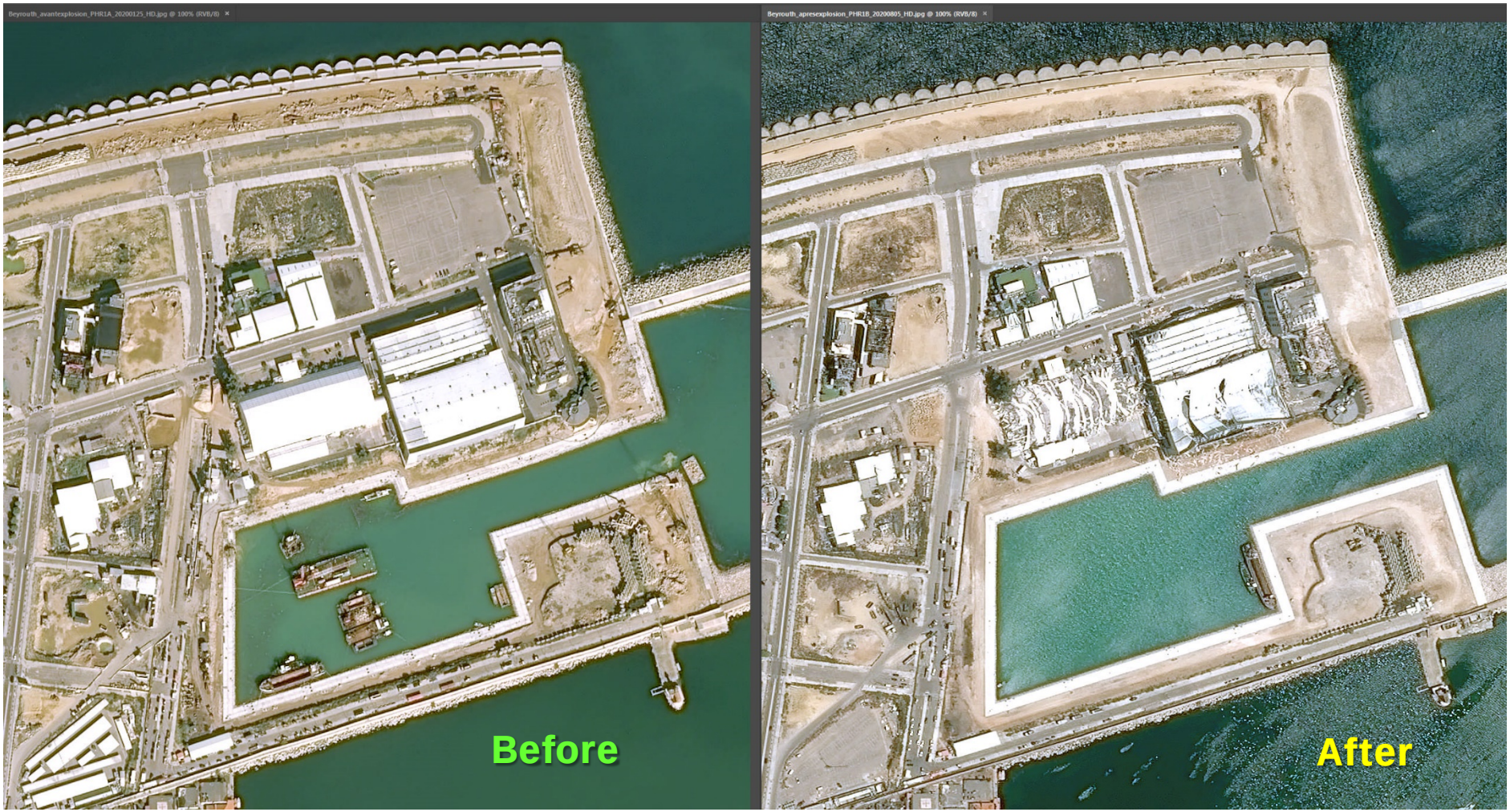
## BEFORE/AFTER VIEWS OF BEIRUT PORT SHOWING BLAST-INDUCED DAMAGE




Pléiades satellites, lofted by Soyuz from the Spaceport, provided before/after views of Beirut's port showing damage from the Aug. 4 blast.
From *CNES / AirbusSpace*

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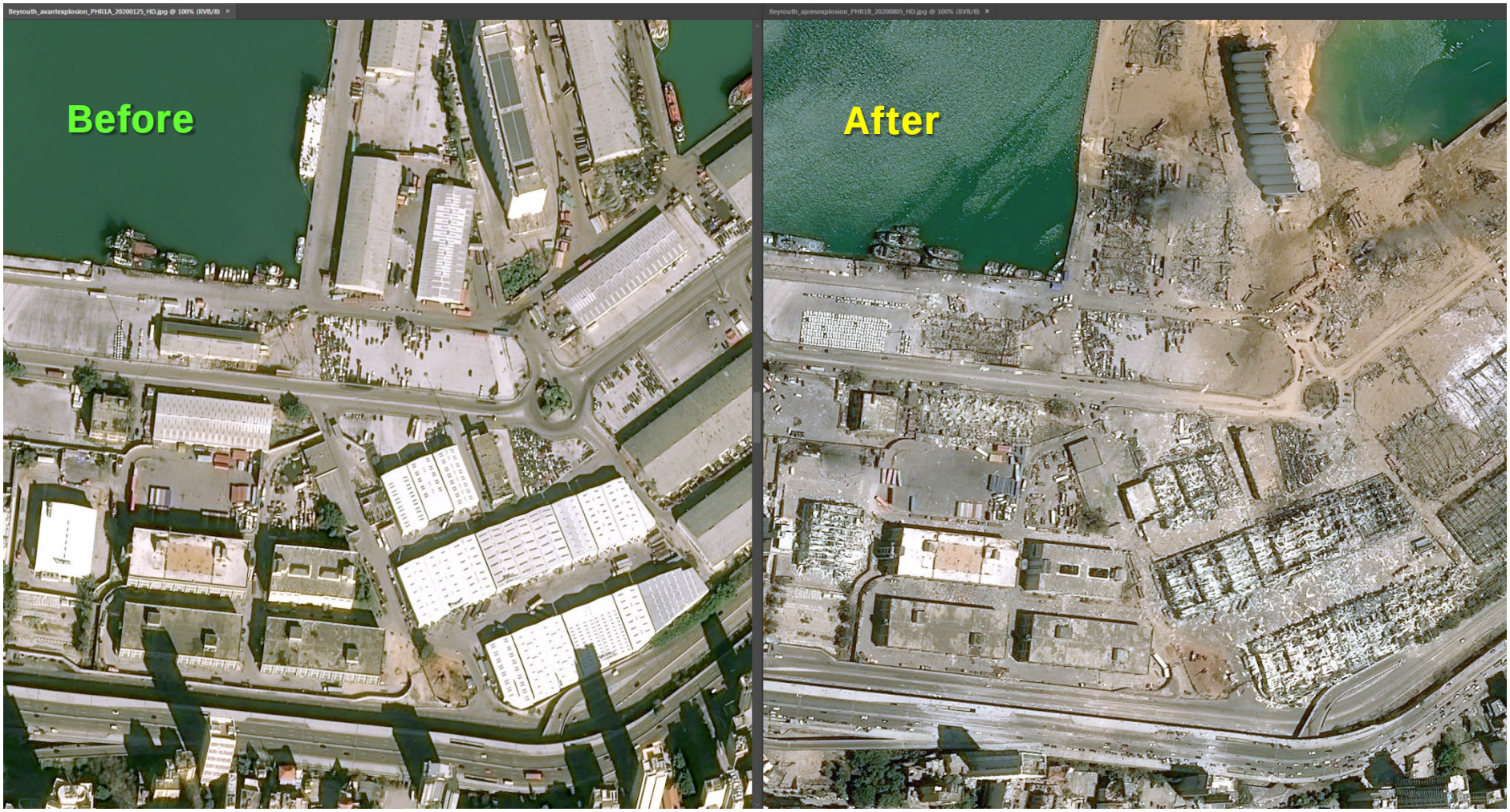


Pléiades satellites, lofted by Soyuz from the Spaceport, provided before/after views of Beirut's port showing damage from the Aug. 4 blast.
From *CNES / AirbusSpace*

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From *CNES / AirbusSpace*

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## BEFORE/AFTER IMAGERY OF BEIRUT PORT SHOWING BLAST-INDUCED DAMAGE


on May 31, 2020

SkySat imagery shows
the impact of the explosion in Beirut.


on August 5, 2020

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## BEFORE/AFTER IMAGERY OF BEIRUT PORT SHOWING BLAST-INDUCED DAMAGE

Very High Resolution satellite images captured with WorldView-2 by European Space Imaging highlight the scope of the damage to the surrounding blast site. Almost 20 buildings have been completely destroyed, whilst hundreds have been significantly damaged. A cruise ship has been overturned and four tankers have been damaged.

https://www.euspaceimaging.com/beirut-lebanon-satellite-images-show-explosion-damage/



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## BEFORE/AFTER IMAGERY OF BEIRUT PORT SHOWING BLAST-INDUCED DAMAGE


https://www.euspaceimaging.com/beirut-lebanon-satellite-images-show-explosion-damage/

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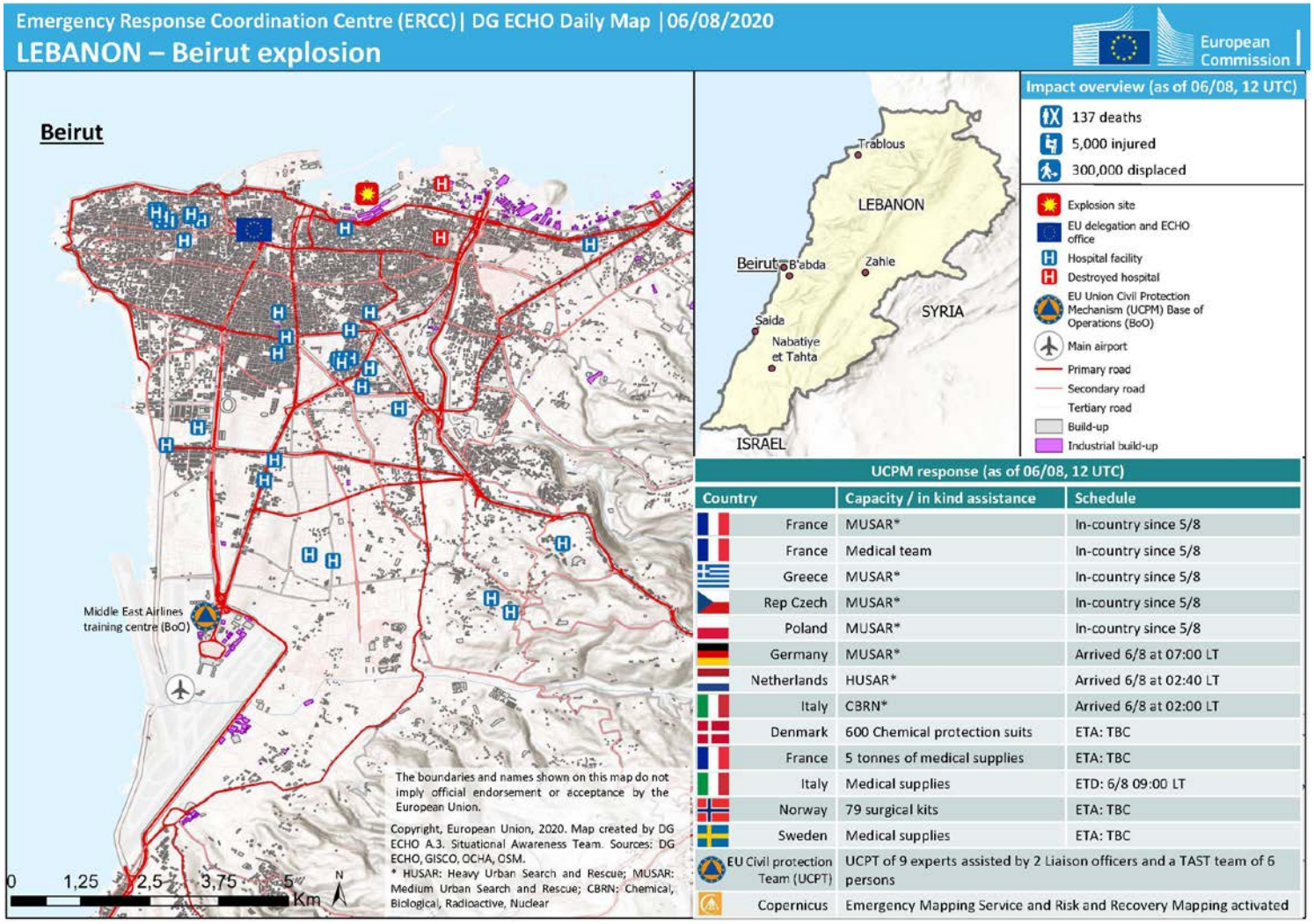
# EMERGENCY RESPONSE COORDINATION CENTER -DG ECHO DAILY MAP ON AUGUST 6, 2020




https://erccportal.jrc.ec.europa.eu/getdailymap/docId/3415

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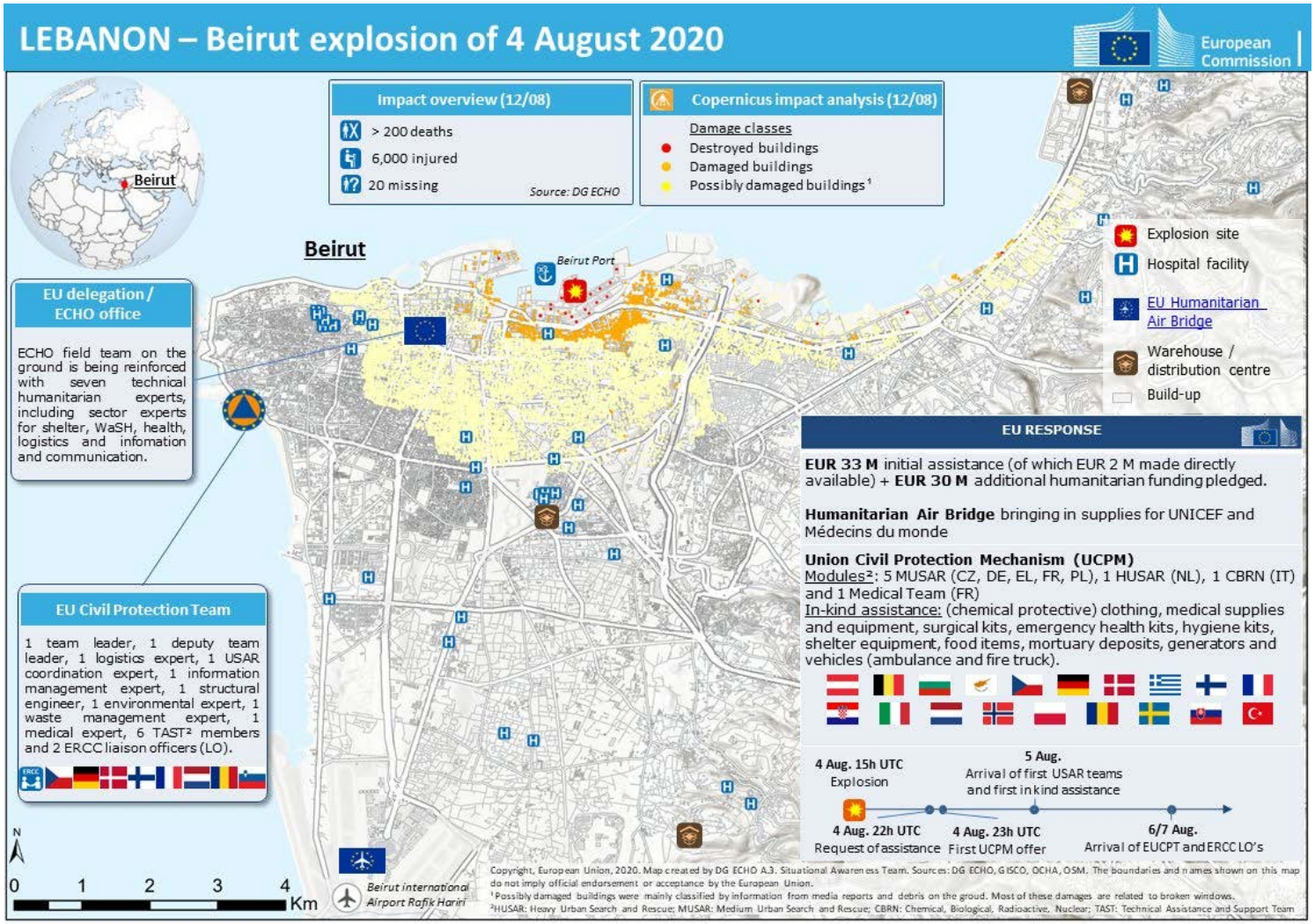
# EUROPEAN UNION RESPONSE
## EUROPEAN UNION CIVIL PROTECTION



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## CHARACTERISTICS AND EVOLUTION OF THE BUILDING STOCK IN BEIRUT

As the explosion in the port of Beirut city largely affected buildings and infrastructures, it is important to dedicate a chapter to the building stock of Beirut with emphasis on its evolution from the beginning of the 20th century to present and on the dominant building types constructed generally in Lebanon and particularly in Beirut.

The building stock in Beirut is relatively recent. More specifically, younger than one century old as Beirut has been subjected to an intense urban expansion over the last decades. As a result, the city expanded from the Mediterranean coast to the foot of the Lebanon Mt. Exception to the rule were some monumental structures constructed during the Ottoman Empire period. During the French mandate succeeded the Ottoman period from 1921 to 1940, development and growth in the construction of buildings and infrastructures were reported. The construction of buildings with sandstone as the main construction material gave way to extensive use of reinforced concrete. A delay in further development and growth of the Beirut City was attributed to the Lebanese Civil War lasted from 1975 to 1991, when there was any control of construction activities, if and where these activities existed. After the end of the civil war, the construction practice has been improved with the implementation of standardized quality control. The seismic building code was first issued in 2005 and is applied on buildings above 3 floors. One of the main disadvantages of the code is the lack of control in the permit process and practice prior, during and after the construction. As a result, the seismic vulnerability and the seismic risk are higher attributed to the resulted heterogeneity in buildings' type and quality.

It is significant to note that Lebanon is a country of moderate to high seismic hazard attributed to the development of the 1200-km-long Levant Fault System and its fault branches, which have generated strong and destructive earthquakes with considerable impact to urban areas including the city of Beirut.

(Based on *Harajli et al., 2002; Salameh et al., 2014, 2016*)

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## QUALITY OF CONSTRUCTION MATERIAL AND BUILDING PRACTICE THROUGHOUT THE URBAN EVOLUTION OF BEIRUT CITY

| Construction period | Construction material | | | | | Height | |
|---|---|---|---|---|---|---|---|
| | Type construction material | Assumed quality of cement | Assumed quality of sand | Assumed quality of steel | Water/ cement dosage | Height limitation | Average height per floor |
| Prior 1950, French mandate (Ruppert 1969) | Sandstone or mixed: sandstone/reif. concrete | Good | Good | | Manual | 26 m | Approx. 5 m for ground floor, 4 m per floor |
| 1950–1970, after WWII (Ruppert 1969) | Reinforced concrete | Good | Good | | Manual | 1954: suppression in certain cases of height limitation. beginning of column floor | Approx. 3m25 |
| 1970–1975 | Reinforced concrete | Good | Good | | Automatic | 1970: exemption of limitation for "big group structures" | Approx. 3m25 |
| 1975–1980 | Reinforced concrete | Probably bad | Probably bad | | Automatic | | Approx. 3m25 |
| 1980–1990 | Reinforced concrete | Probably bad | Probably bad | Often bad, problems at import | Automatic | 1990–1997: possibility of increasing one floor ("Floor el-Murr") | Approx. 3m25 |
| 1990–2005 | Reinforced concrete | Good | Medium | Good | Automatic | | Approx. 3m25 |
| Post 2005 | Reinforced concrete | Good | Medium | Good | Automatic | Lebanese seismic code application | Approx. 3m25 |

From *Salameh et al. (2016)*

Prior 1950, in particular during the French mandate (1921-1940), sandstone and sandstone with reinforced concrete prevailed as construction materials in buildings. Their quality of sand and cement is assumed to be good. From 1950 to 1970, the construction with sandstone gave way to the extensive use of reinforced concrete. During the Lebanese civil war (1975-1990), problems and no control were observed in various processes of a building construction, while the quality of the constructions material workmanship was probably poor. The first seismic code was issued in 2005, but lack of controls resulted in to heterogeneity in buildings' type and quality.

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# DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN SPECIAL STRUCTURES

## GRAIN SILOS



The grain silos located nearby the exploded warehouse stored around 85 percent of the country's grain. The grain inside the silos was compacted under the enormous blast pressure, but also absorbed and deflected some of the blast. Moreover, the structure act as a barrier to the propagation of the blast shockwave resulting in asymmetric distribution of the induced damage and lighter damage to the area behind the silos.

It is significant to note that the grain silos are characterized by particularly increased strength against horizontal movements. This strength is attributed to its static function and its increased mass.

Moreover, its geometry results in decrease of the pressure from the waves, a phenomenon which is eliminated due to the connection and creation of recesses between them. If the same silos were at a distance from each other, it is very likely that they would not have suffered such great damage.

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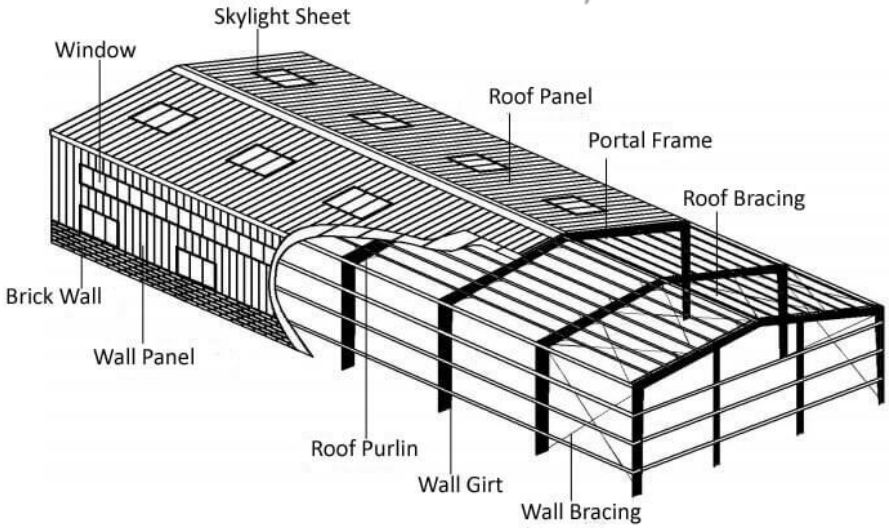
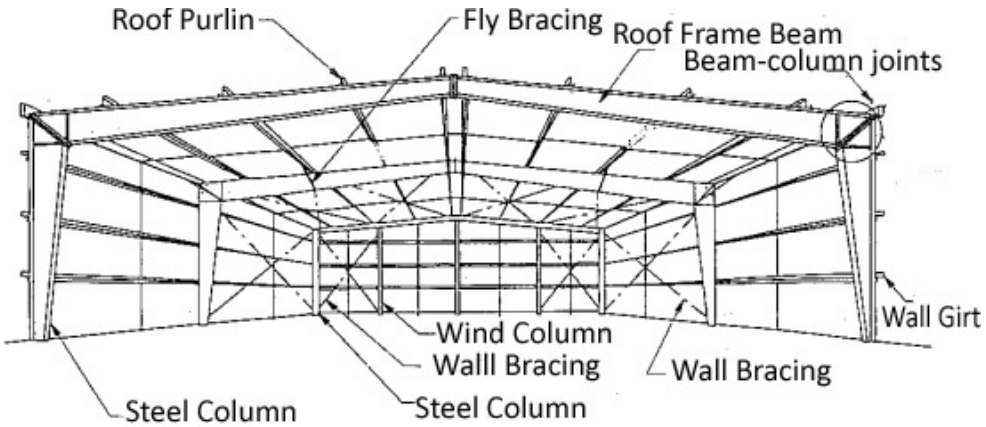
# DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN STEEL AND METAL FRAME BUILDINGS

## WAREHOUSES, COMMERCIAL AND RESIDENTIAL BUILDINGS




Main structures of steel and metal frame warehouses

Steel frame buildings in the area affected by the explosion in the port of Beirut are classified into two categories: (a) warehouses in the port area and (b) residential and commercial buildings in the city.

The port warehouses suffered very heavy structural damage comprising: (a) absolute extinction in the explosion epicenter, (b) total destruction of the adjacent warehouses and (c) severe deformation of the primary and secondary framing, the envelope structure and the auxiliary structures for the most distant warehouses (transverse, load-bearing, longitudinal frame, roof, wall and bracing structures).

The residential and commercial steel frame buildings undergo lighter damage than the port warehouses. Non-structural elements comprising glazing were mostly affected. The glass in the windows of residential buildings and the store fronts in the commercial buildings were shattered by the blast.

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## DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN STEEL AND METAL FRAME BUILDINGS

### WAREHOUSES IN THE EPICENTER OF THE EXPLOSION


The port warehouses suffered: (a) absolute extinction in the explosion epicenter, (b) total destruction of the adjacent warehouses and (c) severe deformation of the primary and secondary framing, the envelope structure and the auxiliary structures for the most distant warehouses.

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## DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN STEEL AND METAL FRAME BUILDINGS

### WAREHOUSES ADJACENT TO THE EXPLOSION EPICENTER

Photos:
*E. Lekkas*

The metal frame of the warehouses adjacent to the explosion epicenter has been completely destroyed due to the blast shockwave and the high temperatures. The external cladding of the warehouses including roof panels, wall panels, perimeter brick walls, windows and skylight sheets have been totally pulverized.

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## DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN STEEL AND METAL FRAME BUILDINGS

### WAREHOUSES DISTANT FROM THE EXPLOSION EPICENTER

Photos:
*E. Lekkas*

The metal frame of the distant warehouses, comprising columns, beams and bracing, was slighter deformed by the blast shockwave. However, the exterior cladding has been severely affected. The wall panels were swept away and the roof panels were ripped off leaving the metal frame uncovered and the stock exposed.

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# DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN STEEL AND METAL FRAME BUILDINGS

## DAMAGE TO THE EXTERIOR CLADDING OF WAREHOUSES

Photos:
*E. Lekkas*

The exterior cladding of the affected warehouses comprised roof and wall panels and the perimeter brick walls. They proved to be highly vulnerable to the propagation of the blast shockwave. The intensity of the deformation of the exterior cladding is strongly related to the standoff distance of the warehouse. The greater the standoff distance of the warehouse, the smaller the damage to its elements.

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# DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN MASONRY BUILDINGS

## MODERATE STRUCTURAL DAMAGE

Buildings with masonry load-bearing walls made of bricks suffered partial collapse of their walls. This structural damage is attributed not only to the blast shockwave, but also to the produced ground shock. Glazing in windows and doors is shattered in the majority of the observed masonry buildings in the severely affected area, while doors and windows were broken.

Photos: *E. Lekkas*

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# DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN MASONRY BUILDINGS

## HEAVY STRUCTURAL DAMAGE

Masonry building partially collapsed not only by the blast shockwave but also by the produced ground shock. The walls made of sandstone bricks were partially collapsed and the roof is on the verge of collapse. Doors, windows and glazing are completely absent.

Photos: *E. Lekkas*

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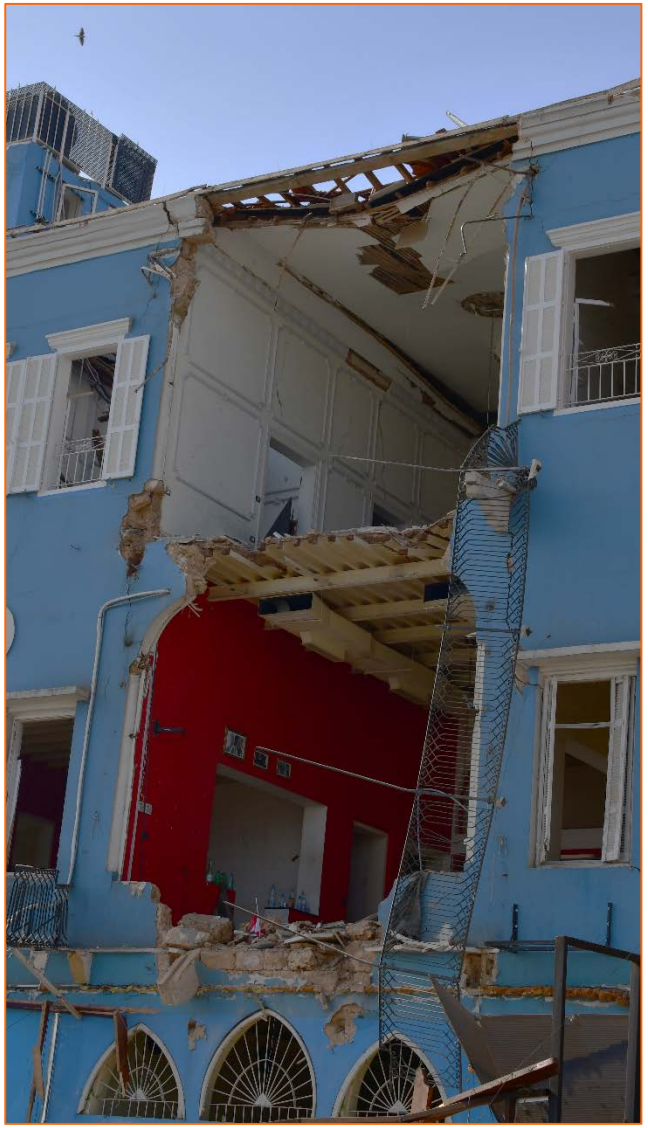
# DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN MASONRY BUILDINGS

## HEAVY STRUCTURAL DAMAGE



Buildings with masonry load-bearing walls made of sandstone were partially collapsed not only by the blast shockwave but also by the produced ground shock. Herein, a building of this type suffered partial collapse of the masonry walls and partial damage of the floor. The roof is on the verge of collapse. Non-structural elements comprising glazing, railings and balconies were heavily damaged. Glass in the windows were shattered, railings were deformed and balconies collapsed.

Photos: *E. Lekkas*

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# DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN MASONRY BUILDINGS

## VERY HEAVY STRUCTURAL DAMAGE

Buildings with masonry load-bearing walls made of sandstone were not only partially but also totally collapsed by the blast shockwave.

Photos: *The Atlantic Magazine*

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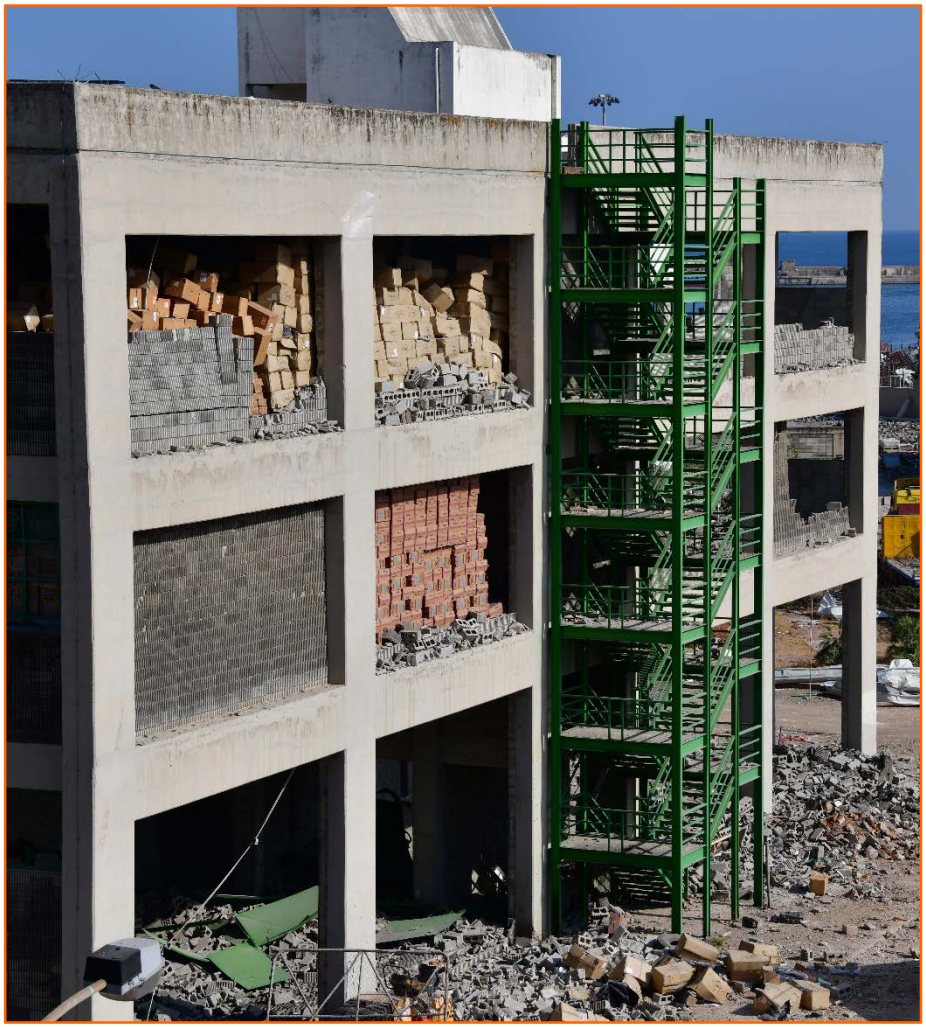
# DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN REINFORCED CONCRETE BUILDINGS

## NON-STRUCTURAL DAMAGE



Buildings with reinforced concrete frame and infill brick walls suffered only non-structural damage including partial or total collapse of the infill walls.

Photos: *E. Lekkas*

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## DAMAGE INDUCED BY THE BEIRUT EXPLOSION
### DAMAGE TO BUILDING' S FAÇADE

Air-conditioning units mounted on the external walls of the buildings were detached from their hanging support and either hang without destruction or are completely destroyed after crash on the road.

Photos: *E. Lekkas*

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# DAMAGE INDUCED BY THE BEIRUT EXPLOSION

## DAMAGE TO EXTERIOR CLADDING OF BUILDINGS


Examples of exterior wall cladding material

Cladding is a construction technique that comprised elements attached to the primary building in order to form distinctive external surfaces.

There are different types of exterior wall cladding design materials including stone, brick, UPVC, wood, timber, metal, ceramic, concrete, weatherboard and glass. Moreover, it may be composite comprising multiple and different materials. It is mainly used for protection of the building from harsh external weather conditions and from the undesirable impact of wind, rain and sun. Moreover, it is used for insulation and noise control as well as for aesthetic purposes, as it adds aesthetic value to the building.

Usually, the frames (doors - windows) and the Air-conditioning units are based on the cladding system. Many times, after heavy rain, stormy winds, earthquakes, or even with no particular reason, fall of parts or entire claddings takes place. Workmanship, in addition to the construction material, plays an important role in their stability and longevity.

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## DAMAGE INDUCED BY THE BEIRUT EXPLOSION

### DAMAGE TO EXTERIOR CLADDING OF BUILDINGS

Photos:
*E. Lekkas*

The explosion in the port of Beirut affected the exterior wall cladding of buildings. It was partially or totally ripped off the walls resulting in large amount of debris on the roads surrounding the affected buildings. Moreover, the falling cladding constituted a great danger for pedestrians passing by these affected buildings resulting in injuries, even several days after the disaster.

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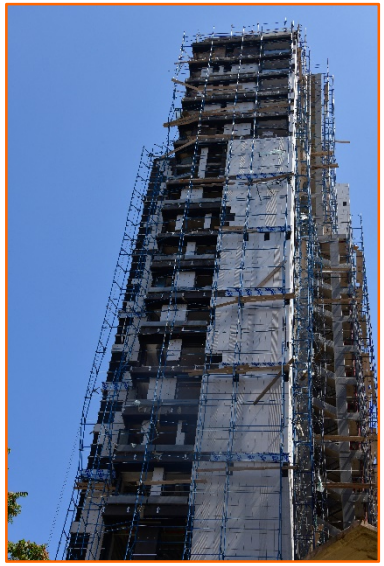
## DAMAGE INDUCED BY THE BEIRUT EXPLOSION

### DAMAGE TO EXTERIOR CLADDING OF BUILDINGS



The exterior wall cladding composed of different materials has been ripped off by the blast shockwave generated by the explosion

Photos: *E. Lekkas*

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## DAMAGE INDUCED BY THE BEIRUT EXPLOSION

### DAMAGE TO EXTERIOR CLADDING OF BUILDINGS

Cladding of different materials has been ripped off by the blast shockwave generated by the explosion

Photos: *E. Lekkas*

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## GLASS BREAKAGE AND FRAGMENTS

From *The Atlantic magazine, Associated Press*




Glass is often the weakest part of a building, breaking at low pressures compared to other components such as the floors, walls, or columns. Glass breakage due to massive explosions may extend for miles. Glass fragments have been shown to be a major contributor to injuries. For incidents within downtown city areas, falling glass poses a major hazard to passengers on the sidewalks below and prolongs post-incident rescue and cleanup efforts by leaving tons of glass debris on the street (From *FEMA, 2013*)

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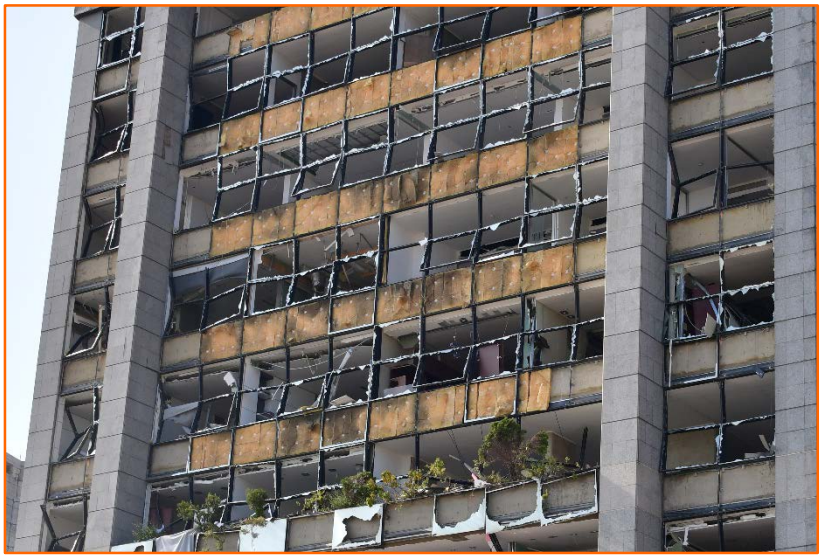
# DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN BUILDINGS

## GLASS BREAKAGE

Glass is often the weakest part of a building, breaking at low pressures compared to other components such as the floors, walls, or columns. Glass breakage due to the massive explosion in the port of Beirut extended for miles. Glass fragments were a major contributor to injuries.

Photos: *E. Lekkas*

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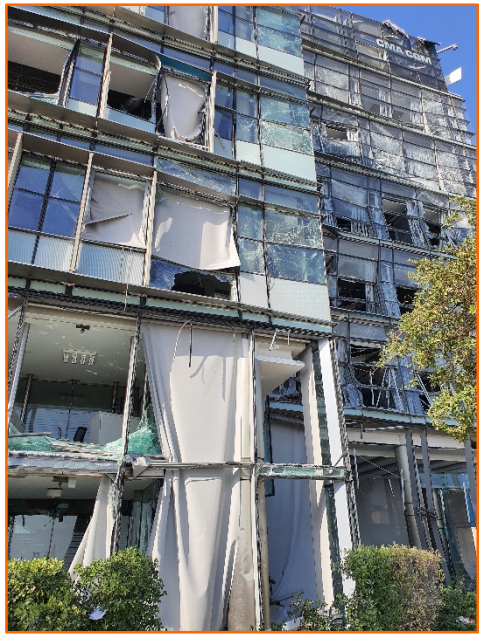
# DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN BUILDINGS

## GLASS BREAKAGE





Photos: *E. Lekkas*

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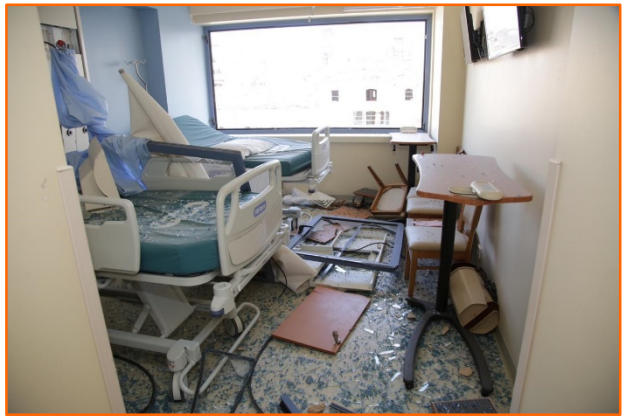
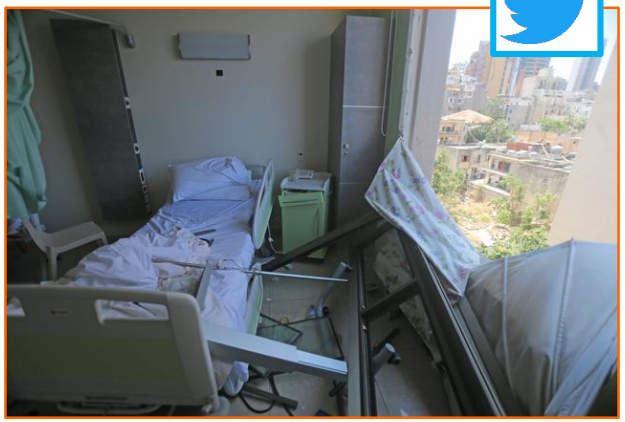
# DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN HEALTH CARE FACILITIES

## DAMAGE TO HOSPITALS





At least three hospitals have been heavily damaged in Beirut massive explosion and they remained unfunctional. They could not admit victims of the blast. Two other hospitals also suffered damage but remained operational (*WHO, 2020*). As a result, the personnel of the destroyed hospitals evacuated and transferred patients to other facilities and a loss of 500 hospital bed capacity was reported (*WHO, 2020*). A preliminary rapid assessment within a 15 kilometer radius of the explosion revealed that out of 55 medical facilities, only half are fully operational and around 40% have suffered moderate to serious damage and need rehabilitation (*UNICEF, 2020*). Most of the health facilities managed to resume critical activities within 2 days. Moreover, a warehouse with vaccine supply for all the country was also affected. Based on this data, the health care system of Beirut has been severely hit by the explosion during a period of an ongoing pandemic and public health crisis.

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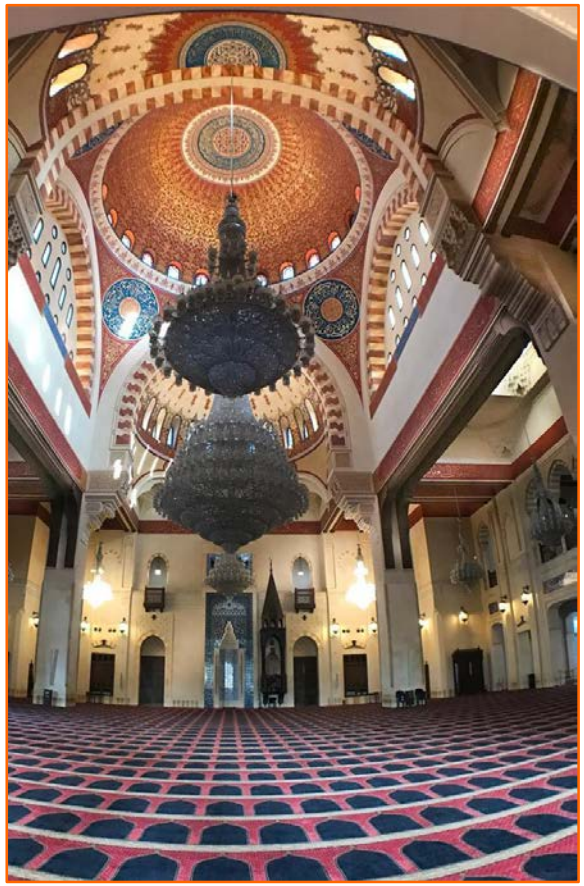
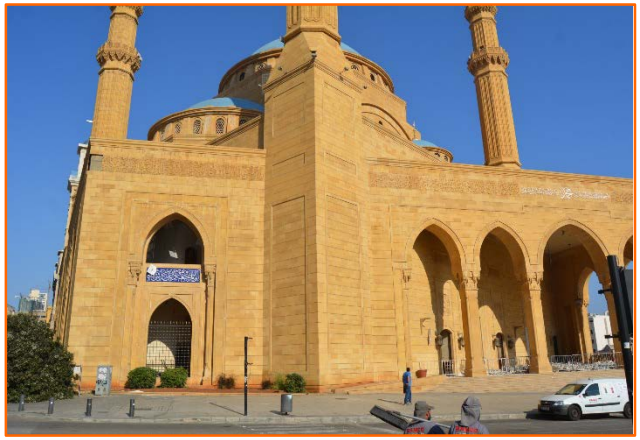
# DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN MONUMENTAL AND RELIGIOUS BUILDINGS

## DAMAGE TO THE MOHAMMED AL AMIN MOSQUE





The mosque is located 2 km from the explosion epicenter. Its glazing was shattered by the blast shockwave. The glass fragments covered the floor of the mosque. Moreover, it suffered partial collapse of some of its walls.

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## DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN CULTURAL SITES

### DAMAGE TO THE SURSOCK MUSEUM

The museum suffered damage not only to its façade, but also to its interior. Several artworks at the museum have been either destroyed or damaged.

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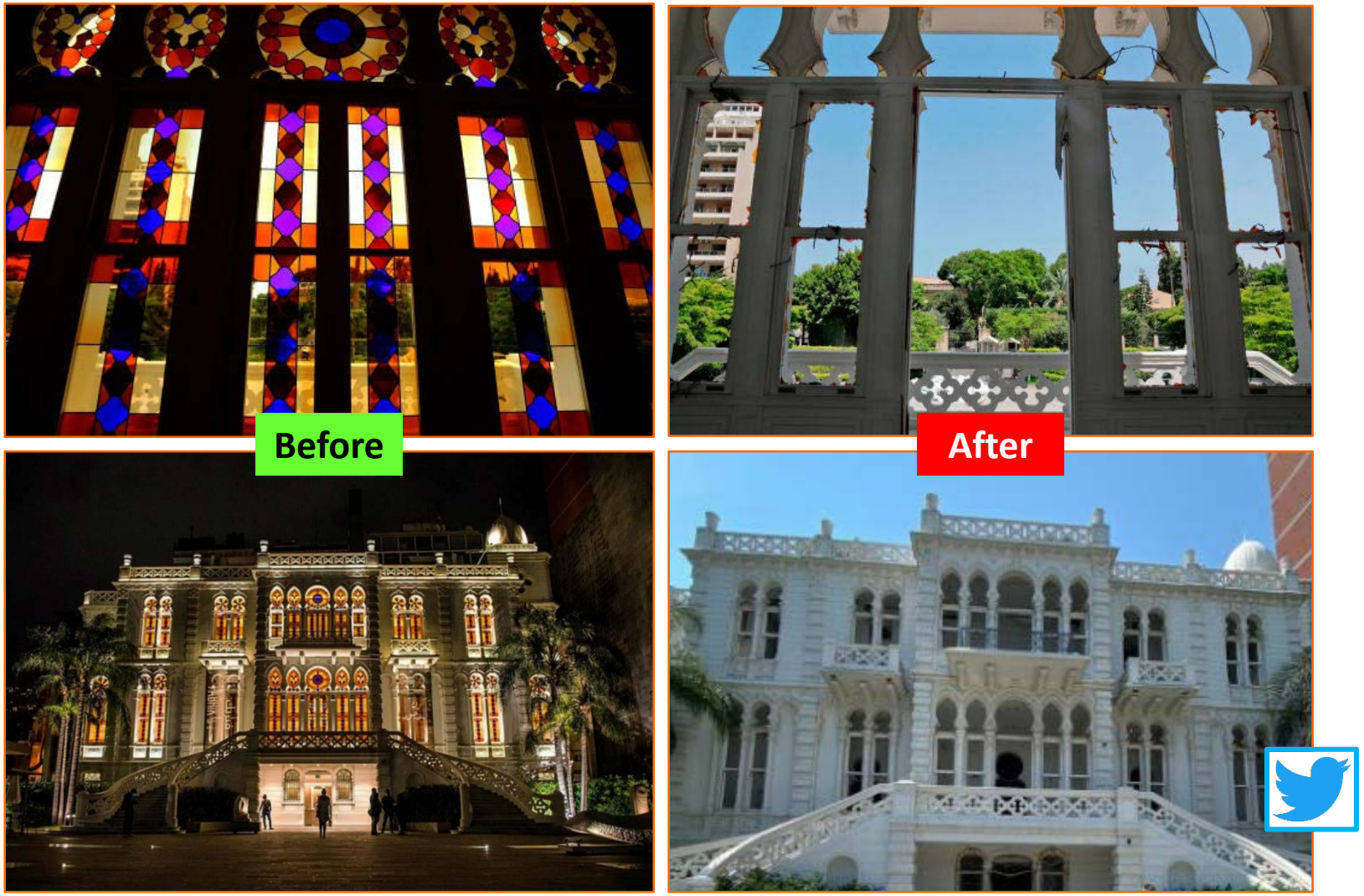
## DAMAGE INDUCED BY THE BEIRUT EXPLOSION IN CULTURAL SITES

### DAMAGE TO THE SURSOCK MUSEUM




Courtesy of Sursock Museum

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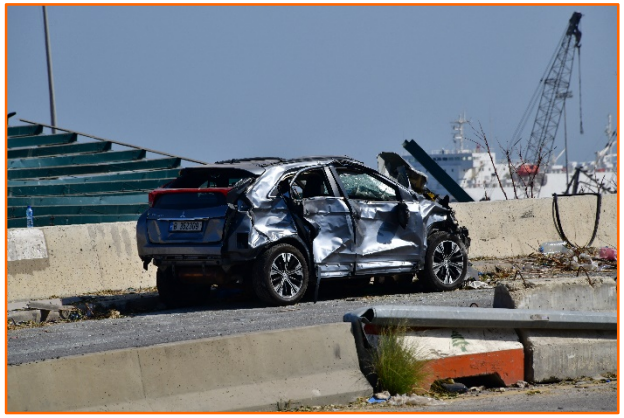
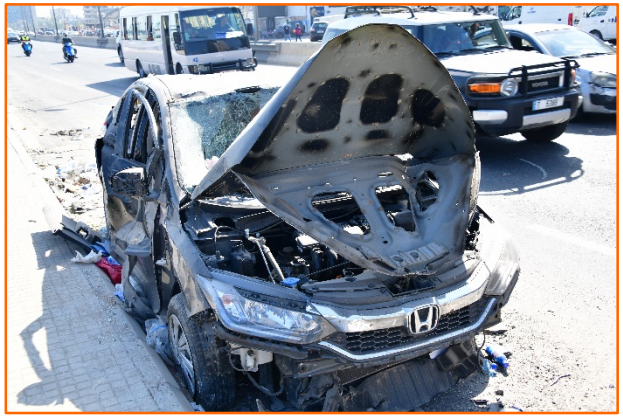
## DAMAGE INDUCED BY THE BEIRUT EXPLOSION

### VEHICLES AFFECTED BY THE BLAST





Cars were also affected by the explosion in the port of Beirut. The majority of them presented twisted and crushed parts, heavy compression damage, crushing and missile damage, especially visible along the top and sides as well in various parts and blown-out or broken windows. The observed damage was both direct-primary and indirect-secondary, attributed to the propagation of the blast shockwave, to crushing with explosion debris and with falling parts from the facade of buildings. Many of them were covered with dust from the surrounding environment.

Photos: *E. Lekkas*

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## DAMAGE INDUCED BY THE BEIRUT EXPLOSION

### VEHICLES AFFECTED BY EXPLOSION DEBRIS AND FALLING PARTS FROM FACADE OF BUILDINGS





Cars parked mainly in front of partially or totally collapsed buildings suffered crushing damage attributed to blocks falling during the collapse. This fact was observed in front of masonry buildings that suffered very heavy structural damage not only from the blast shockwave, but also by the ground shock produced by the blast.

Photos: *E. Lekkas*

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# DAMAGE INDUCED BY THE BEIRUT EXPLOSION

## SHIPS

The explosion in the port of Beirut affected anchored ships in several ways comprising burning, washing ashore, capsizing and sinking. The distance of the ships from the epicenter of the explosion ranged from few meters ("Abou Karim I" and "Abou Karim III") to about 450 meters ("Orient Queen").

"Abou Karim I" and "Abou Karim III" located few meters from the explosion epicenter were heavily damaged or destroyed in the explosions. Abou Karim I, was unstable and had leaned towards the other ship, Abou Karim III, until it finally capsized.

"Amadeo II" also located few meters from the explosion epicenter was washed ashore on the port by the blast and was completely destroyed by fire.

The "Orient Queen" was docked in the port. The blast seriously damaged the ship and water entered. An effort was made to quickly and effectively repair the blast induced damage, but without success. The ship sank overnight.

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## DAMAGE INDUCED BY THE BEIRUT EXPLOSION
### SHIPS

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## DAMAGE INDUCED BY THE BEIRUT EXPLOSION

### INFRASTRUCTURE

Photos:
*E. Lekkas*

Tangled power lines and messy electric wiring in the streets of Beirut city after the propagation of the blast shockwave. This damage will exacerbate the existing problems with electricity supply, which is characterized by daily power blackouts for many years now.

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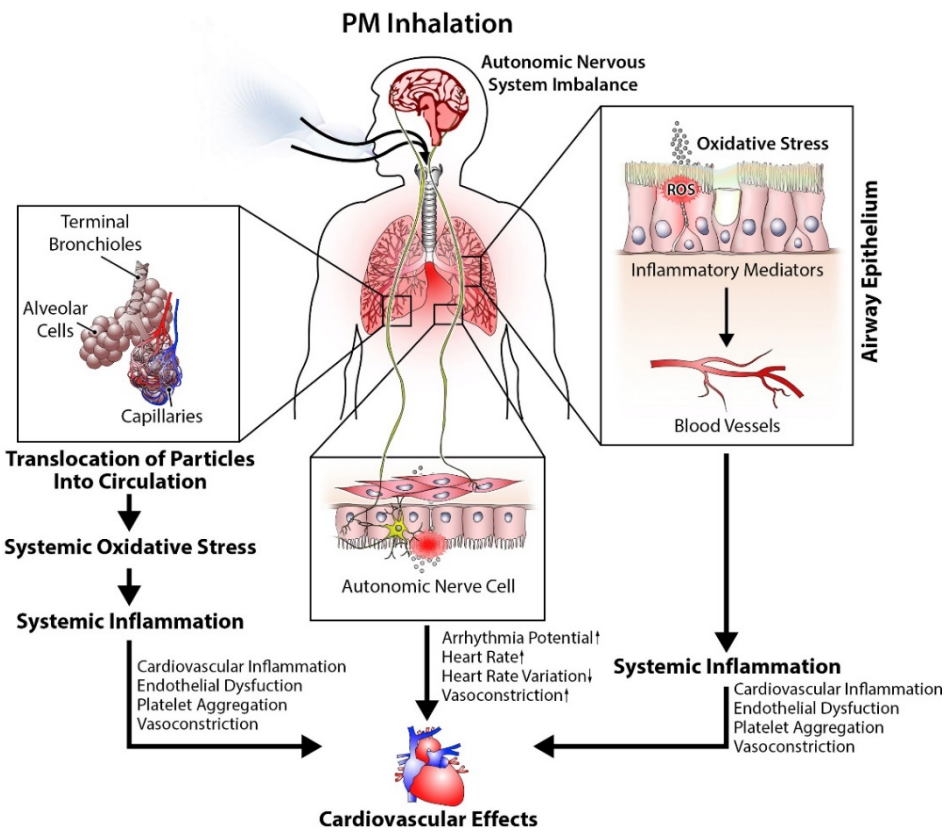
# EXPLOSION IN THE PORT OF BEIRUT AND IMPACT ON HEALTH




The inhalation of particulate matter and effects on human health

From *Wu et al. (2018)*

The explosion of ammonium nitrate in the port of Beirut, the resulted smoke cloud of nitrogen dioxide and the combustion products released large quantities of very toxic chemicals in the air, hazardous for human health. These chemicals include polycyclic aromatic hydrocarbons.

Moreover, particulate matter produced by the explosion and the subsequent fire in the port may cause problems in the normal function of the respiratory system and in particular in the lung function. Patients with asthma may experience acute exacerbations of symptoms and a loss of disease control.

As regards the air pollution monitoring in the city of Beirut, there is no consistent and continuous monitoring of the air quality. However, a sharp increase of the particulate matter has been observed by a monitoring system operating under the supervision of the American University of Beirut.

From *Devi (2020)*

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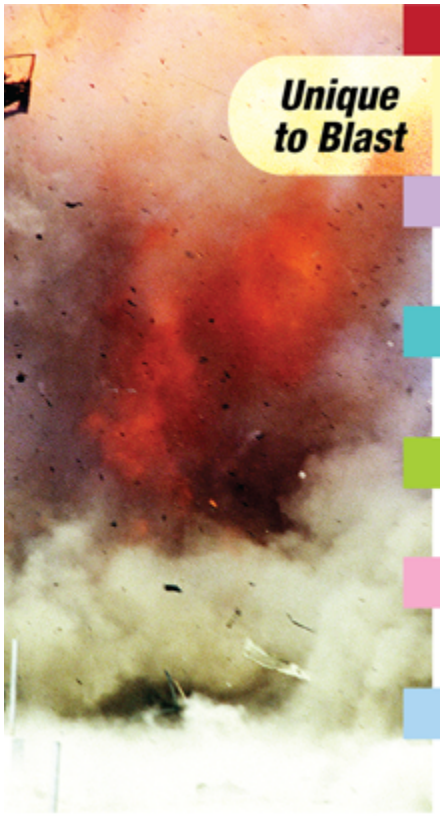
## EXPLOSION IN THE PORT OF BEIRUT AND IMPACT ON HEALTH
## FATAL AND NON-FATAL INJURIES



**Unique to Blast**

### PRIMARY
- Blast lung
- Eardrum rupture and middle ear
- Abdominal hemorrhage and perforation
- Eye rupture
- Non-impact, blast-induced mTBI?

### SECONDARY
- Penetrating ballistic (fragmentation) or blunt injuries
- Eye penetration

### TERTIARY
- Fracture and traumatic amputation
- Closed and open brain injury
- Blunt injuries
- Crush injuries

### QUATERNARY
- Burns
- Injury or incapacitation from inhaled toxic fire gases

### QUINARY
- Illnesses, injuries, or diseases caused by chemical, biological, or radiological substances (e.g., "dirty bombs")

### *PSYCHOLOGICAL TRAUMA (including PTSD)
* Added based on latest research suggesting a high risk of developing PTSD following a concussion

From *Brooks et al. (2011)*

The blast of ammonium nitrate in the port of Beirut resulted in fatalities and injuries. This impact on the human body and the public health can be classified into the categories of primary, secondary, tertiary, quaternary and quinary blast injuries. As regards the mental health of people exposed to the undesirable effects of the massive explosion, there is a high risk of developing post-traumatic stress disorder (PTSD).

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## CONCLUSIONS

The August 4, 2020, massive explosion in Beirut is a technological disaster with great impact on the port of the city and considerable effects on the local population and the built environment of the Beirut city. Taking into account the already existing social, economic, political and refugee crises and the ongoing COVID-19 pandemic and health care system crisis, it could be characterized as a disaster within crises and a crisis within an ongoing humanitarian challenge. In order to address the undesirable effects of the aforementioned phenomena, the need for a multiparametric and interdisciplinary approach is considered imperative.

The ammonium nitrate explosion in Beirut port generated both blast shockwave and ground shocks. It vanished the warehouse with the stored ammonium nitrate resulting in a crater, devastated the adjacent port facilities and relevant equipment including warehouses, cranes, ships, containers and vehicles. Moreover, it greatly affected the city's densely populated residential neighborhoods and downtown shopping districts. It caused damage to residential and commercial buildings, vehicles, vessels and infrastructures.

As regards the evolution of structures in Beirut, the building stock of the city is relatively recent. The dominant building types comprised historical structures with masonry load-bearing walls, timber floors and roofs as well as recent structures with reinforced concrete frame and infill walls. Some residential and commercial buildings with steel frame are also observed in the city. The port comprised warehouses with metal framing and roof and wall panels as well as reinforced concrete warehouses with infill walls.

Due to the fact that Lebanon and Beirut city have suffered wars and conflicts and their undesirable effects in various sectors, including building construction among others, for many years (the World War II, the 1975-1990 Lebanese Civil War and the 2006 Israel-Hezbollah War), there is a large heterogeneity in buildings' type and quality. This fact is responsible for high vulnerability not only to physical processes, like earthquakes, but also to man-made processes, like explosions.

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## CONCLUSIONS

As regards the observed building damage:

- The masonry buildings suffered the most by the explosion. Structural damage in this building type included partial or total collapse of load-bearing masonry walls, floors and roofs.

- The reinforced concrete buildings with brick infill walls undergone non-structural damage including detachment of the infill walls from the surrounding reinforced concrete frame. Damage to the structural elements of this type was not observed or reported.

- The steel and metal structures undergo structural and non-structural damage depending on the standoff distance of the structure from the explosion epicenter. Warehouses in the explosion epicenter were vanished, adjacent structures were pulverized, distant warehouses were intensively deformed. Residential and commercial steel frame structures within the city suffered only non-structural damage in their perimeter elements.

- The blast shockwave had considerable effect on glazing and cladding of buildings. The majority of glasses in windows, doors, roofs and cladding were shattered. This damage has been observed for long distances from the explosion epicenter.

- Unfortunately, the explosion had caused damage to health care facilities, monumental and religious buildings, governmental buildings and cultural places and sites.

- With emphasis on the health care facilities, three hospitals were heavily damaged and remained unfunctional after the explosion, while two more were heavily damaged but still operational.

- The aforementioned damage is attributed to the propagation of the blast shockwave and the ground motion resulted from the massive explosion. Based on previous similar accidents and taking into account the performance of building in the Beirut event, it is concluded that the blast shockwave is the dominant factor to account for the building damage surrounding the explosion site.

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## CONCLUSIONS

- The phenomenon of "shadow" during the transmission of shockwaves was also observed in this case.

- The phenomenon is more impact-type than dynamic-oscillating and its results depend on the projected resistance of the buildings during the propagation of shockwaves.

- It is interesting to mention that the motion – displacement of structures due to a horizontal ground shock is towards the epicenter, while the respective motion – displacement in the case of a propagating blast shockwave is towards the opposite direction. Therefore:
    - if the debris of a collapsed part of a wall is on the side of the epicenter, the cause should be attributed to the ground shock.
    - If the debris are found at the opposite side, the cause is due to the blast shockwaves.
    - If the debris are found within the vertical plane with that of the damaged wall, the cause should be attributed to the vertical component of the ground shockwaves.
- In most of the cases, we may observe a coincidence of all those three cases to occur, in structures located rather close to the epicenter, but as already mentioned the damage due to the blast shockwaves is dominating.

The explosion had the potential to affect public health. It resulted in more than 170 fatalities, more than 6000 injuries, more than 300000 homeless. The blast induced injuries comprised primary, secondary, tertiary, quaternary and quinary injuries related to the distance from the blast, while it will probably affect the mental health of the local population with is a high risk of PTSD in people greatly affected and largely involved in the disaster management.

Moreover, the generated fires and explosions released very toxic materials and particulate matter in the air of the affected area. These materials have the potential to adversely affect human health. In order to avoid undesirable consequences, accurate, precise systems for continuous monitoring of the air pollution must be installed.

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## CONCLUSIONS

Similar events have taken place in several countries and facilities worldwide. About 30 events of explosion of ammonium nitrate have been reported and recorded world wide with effects on the local population, the natural environment and the built environment of the surrounding affected area.

Three of the most characteristic examples are herein presented:
(a) the 1921 Oppau (Germany) disaster,
(b) the 1947 Texas City (USA) disaster and
(c) the 2015 Tianjin (China) disaster.

Taking into account these accidents and the subsequent disasters, guidelines for the reduction of the potential fire, decomposition and explosion hazards of the ammonium nitrate have been published. These guidelines include storage conditions to avoid, required and recommended building design and safety, required and recommended safe storage and fire protection of the ammonium nitrate storage areas. Moreover, the stored ammonium nitrate must be clearly, properly and distinctly marked with the appropriate pictograms and the personnel of the storage areas as well as the fire fighting personnel must be properly trained to deal with such phenomena and to reduce or eliminate their negative consequences.

Unfortunately, these guidelines are not always followed and key safety details are ignored resulting in accidents that shock the world.

*This work is dedicated to the memory of all who have unjustly lost their lives in Beirut explosions. Moreover, to anyone involved in the management of dangerous goods, in order to realize the magnitude of damage that can be resulted from non-compliance with the relevant safety measures.*

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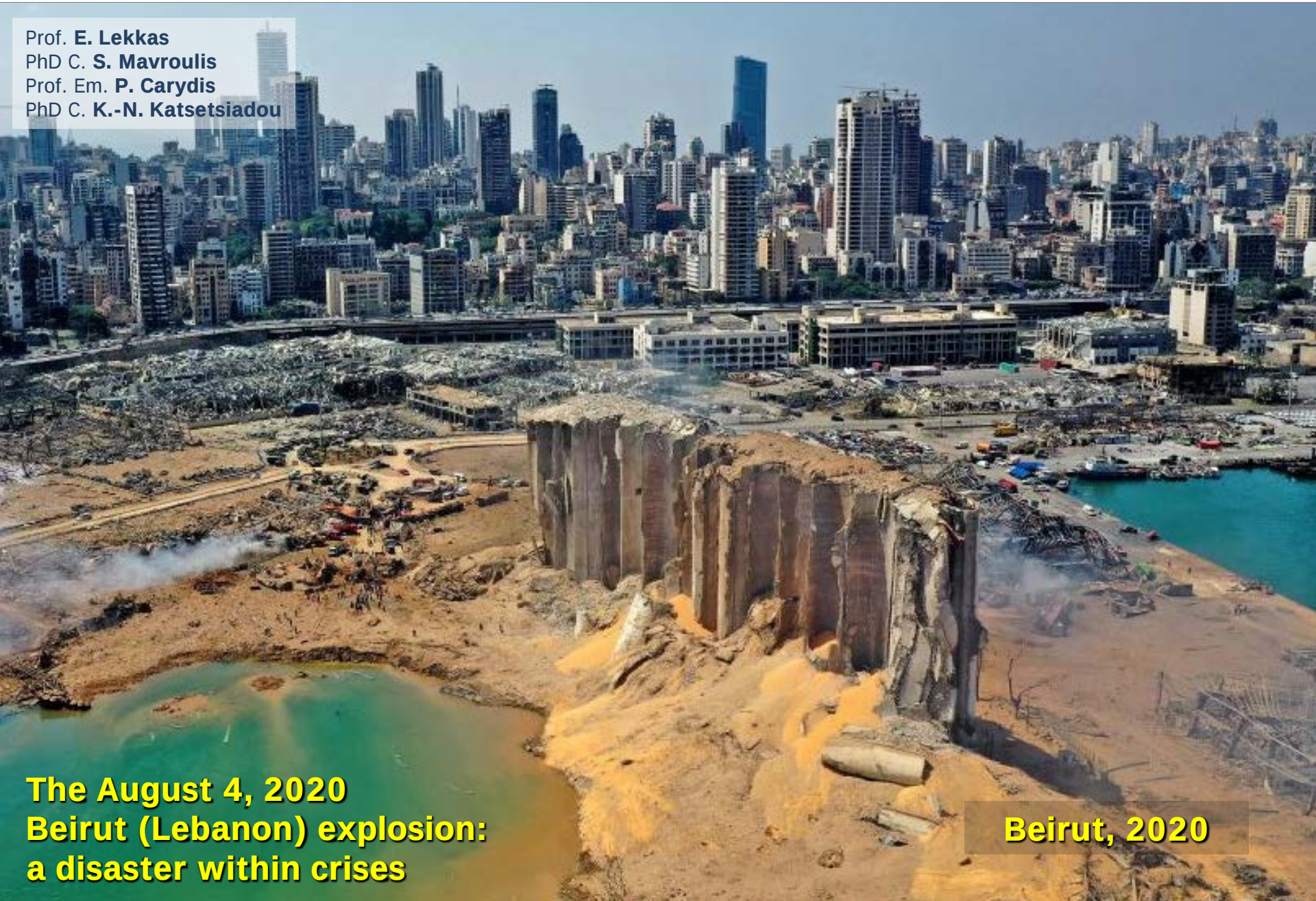
# The August 4, 2020 Beirut (Lebanon) explosion: a disaster within crises



Beirut, 2020