AMERICAN UNIVERSITY OF BEIRUT

STRUCTURAL ASSESSMENT OF BUILDINGS AFTER THE BEIRUT PORT EXPLOSION: ANALYSIS OF THE DATA COLLECTED BY THE BEIRUT ORDER OF ENGINEERS AND ARCHITECTS

by
MIRNA AHMAD EL MOGHRABI

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submitted in partial fulfillment of the requirements
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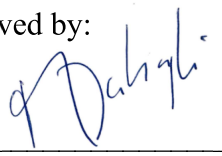

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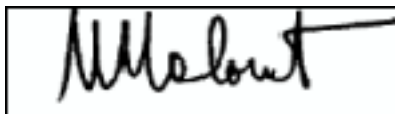

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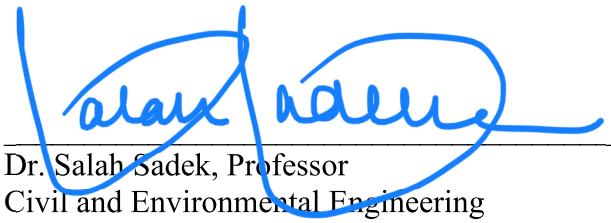

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Moreover, I am extremely grateful to my advisor Dr. Mayssa Dabaghi for her continuous support and guidance throughout my thesis work and for giving me the opportunity in contributing to this work. I would like to thank my committee members, Dr. Mounir Mabsout and Dr. Salah Sadek, for their enlightenment and instructions throughout my thesis.

Last but not least, I would like to express my deepest gratitude and appreciation to my parents, husband, and family for their unwavering support and patience throughout my thesis journey. Their encouragement, understanding, and belief in me have been invaluable in helping me overcome challenges and stay motivated.

ABSTRACT

OF THE THESIS OF

Mirna Ahmad El Moghrabi for Master of Engineering
Major: Structural Engineering

Title: Structural Assessment of Buildings after the Beirut Port Explosion: Analysis of the Data Collected by the Beirut Order of Engineers and Architects

At 18:08 on the 4th of August 2020, a huge explosion occurred in the port of Beirut, Lebanon. The explosion was one of the strongest non-nuclear explosions ever recorded. As per USGS, the size of the blast was equivalent to an earthquake with local magnitude of 3.3. The deadly blast resulted in 220 deaths, and more than 7,000 injuries.

After the blast, multiple efforts contributed to assessing the impacts of the blast on Beirut and to documenting the damage extent on Beirut's buildings. Particularly, the Order of Engineers and Architects in Beirut (OEA) completed in-person structural investigations for five weeks and compiled surveys for about 2,500 Beirut buildings located within 3 km from the blast. The data collected by the OEA included a description of the general state of each building, the damages observed, the possible hazards and threats to public safety, and recommended actions (e.g., isolation of the building) to address potential threats, when needed. However, the OEA surveys did not assign a structural damage class to each building based on the structural damages that occurred.

This work processes and analyzes the data collected by the OEA in order to consistently assign a structural damage class to each surveyed building based on procedures typically applied after an earthquake. The impacts of the explosion on the buildings assessed by the OEA range from full collapse to no structural damage. These spatially variable impacts are documented and analyzed to understand how the damage extent depends on the structural typology and age of the building, its distance from the blast, and whether or not it had a direct line of sight from the blast. The analysis of the data shows that the structures most damaged by the blast are stone masonry structures, older (gravity load designed) reinforced concrete buildings, and buildings located within 1 km from the blast. On the other hand, structures that sustained no to light damage are modern reinforced concrete structures and buildings located at distances greater than 1 km from the blast.

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CHAPTER I

INTRODUCTION

A. Response to Beirut Blast

The devastating Beirut blast, which occurred on August 4, 2020, damaged a large area of Beirut. Transportation, energy, water supply and sanitation, as well as municipal services, all sustained significant damage, resulting in losses of US$390 to $475 million, according to the World Bank (World Bank Group, 2020). More than 300,000 people were forced to leave their homes due to the large destruction. It was later revealed that the explosion was caused by storing, for six years, 2,755 Tons of Ammonium Nitrate, which is used in the manufacture of explosives. However, what ignited the combustible chemical compound remains unknown up till this date (Human Rights Watch, 2021).

After the explosion, several organizations and institutions arranged groups to assess the damage extent. The Disaster Management Sector in the Lebanese Red Cross conducted household surveys reaching 4,194 assessments by August 14th (and eventually 50,000 door-to-door surveys, but a final report covering all surveys was not found). The Red Cross assessment was based on observations and key informant interviews. Based on the assessments conducted until August 14th, it was observed that only 0.34% of the assessed households had complete destruction, 0.49% had a lack of access to basic amenities, and 0.87% had a lack of access to basic services. Most households had one or more types of damages ranging from broken windows, fallen ceilings and/or walls, and collapsed balconies, beams, and/or columns. Finally, 35.33% of the households reported none of the above (LRC, 2020). Additionally, a Beirut-based engineering consultancy firm called ‘The Dar Group’ conducted street-view inspections

of around 7,000 buildings on behalf of the Beirut Municipality, shortly after the Beirut blast. These inspections examined and captured images of buildings at street level, without entering the buildings, with the objective of assessing the extent of structural and façade damage sustained by buildings after the explosion. The goal was to categorize buildings as safe (green), restricted use (yellow), or unsafe (red) for residents based on the degree of structural damage they had incurred (Dar Group, 2020). The inspection also included a determination of the quantity and projected severity of façade damage to the glazing and cladding. Moreover, the Order of Engineers and Architects of Beirut (OEA) conducted building inspection on a larger scale, within a 3 km^2 area closest to and most affected by the Beirut blast, in order to identify if structures are safe or not for occupancy. The OEA issued weekly reports on the inspection progress and updates on the maps that showed the damaged buildings. During these surveys, the OEA also collected images of building exteriors and interiors, as well as data on the number of floors and the year of construction, and pre-existing damages were highlighted when possible. The OEA inspected a total of 2,500 buildings, of which 300 buildings were found in danger of total or partial collapse, 250 buildings were subjected to separation in some parts, and 550 buildings were found to have internal or external cracks that need reparation (OEA, 2020). As illustrated in the GIS map, created by the Beirut Urban Lab at the American University of Beirut (AUB-BUL), and shown in Figure 1, several buildings collapsed, especially structures located within 0.75 km from the blast. The BUL base map was used by several entities, and it showed its importance to track observed damages and casualties. According to the OEA surveys, it was found that the area most severely damaged by the explosion included roughly 360 structures with historical significance that date from the nineteenth century to the 1930s. The

majority of these structures are made from sandstone walls, attic wood frames covered with Marseille roof tiles, brick walls and wooden floors. More than 100 of these buildings were found to be vulnerable to total collapse after the blast. The OEA survey included the following information: building description; type of structural frame; damage description; possible hazards, and technical recommendations related to buildings that need to be evacuated, isolated, and fully or partially reinforced in order to preserve public safety. Other reports published by the Lebanese government, the World Bank, and the United Nations bodies to determine the extent of damage in the affected area adopted the findings of the surveys conducted by the OEA; thus, the OEA reports became the official documents.

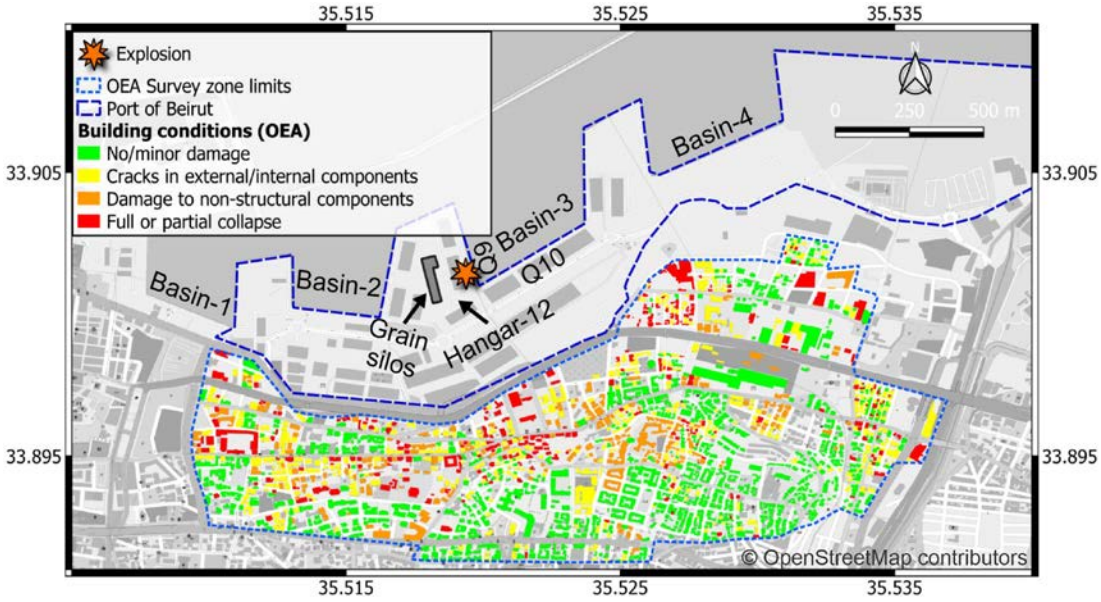


Figure 1. Map of Beirut showing location of explosion, Port of Beirut, and condition of buildings surveyed by the OEA. (Data from OEA 2020; Base map © OpenStreetMap contributors.) “Taken from Sadek et al., 2021”

On the other hand, teams from the department of civil and environmental engineering at the American University of Beirut examined and visually assessed the

structural safety of buildings, provided advice and recommended possible mitigation measures to tenants and owners. The teams photographed structure and facade damages and assessed each structure using survey forms based on the Applied Technology Council ATC-20 (ATC, 1995) and ATC-45 (ATC, 2004). Moreover, with the support of the NSF-sponsored Geotechnical Extreme Events Reconnaissance Association (GEER), a reconnaissance team was created to conduct detailed damage surveys to document the spatially variable impacts on buildings due to Beirut's explosion and focusing on the distribution of structural damage and non-structural damage to impacted buildings. Furthermore, the GEER/AUB-MSFEA team used a GoPro Fusion camera mounted on the roof of a car as an attempt for a street-view high-resolution photograph survey (Sadek et al., 2021). According to Sadek et al. (2021), 172 buildings were inspected in-person by the GEER/AUB-MSFEA team, and an additional 10 heavily damaged buildings were identified based on the street-view photographs. The reconnaissance team thus assigned a damage class ranging from D0 (for no observed damage) to D5 (for complete collapse of floors or the entire structure) to a total of 182 buildings. Additionally, façade damage assessment was conducted using the 360° photos by four investigators who assigned façade damage classes ranging from W0 to W3 and cross-checked their results in weekly meetings (Sadek et al., 2022).

In addition, the municipality of Beirut (MoB) in collaboration with the UN-Habitat Lebanon, coordinated a rapid visual survey at the building level. The surveys covered all building types within a 2 km radius of the blast, to gain an understanding of the extent of damage and particularly structural impacts, immediately identifying buildings or building elements at risk of collapse and in need of evacuation, whilst also providing evidence for formulating early recovery measures. A total of 10,280

assessment surveys were conducted by volunteering engineering and construction companies (among which the Dar Group), with engagement from international non-governmental organizations and academic institutions, all under the coordination of the MoB and UN-habitat. A building damage category was assigned to each structure as follows: 7 buildings were categorized as total collapse, 208 buildings were categorized as unsafe/evacuate, 483 buildings were labeled as restricted use, 6,822 buildings were labeled as safe/minor damage, 524 surveys were vacant plots, and the remaining 2,236 surveys were unclassified (MoB/UN-Habitat,2020).

B. Motivation

In recent decades, natural disasters of all kinds have become more prevalent. Along with causing enormous material losses, earthquakes, floods, hurricanes, and other highly destructive natural and man-made catastrophes also pose a threat to people's lives. In addition to enhancing disaster detection and early warning capabilities beforehand, it is essential to promptly gather catastrophe information once a disaster has already occurred (Contreras, 2021). When a major disaster occurs, it is crucial to detect the areas where damage and casualties are observed in order to quickly direct emergency responders and rescue and relief efforts where they are most needed. Such data can also help advance the knowledge of the effects of disasters on people, buildings, and infrastructure, which ultimately leads to improved procedures for the characterization and mitigation of risk. A manual on-site building-by-building survey at the catastrophe site is the conventional technique of getting real-time assessments to develop a building damage map after a disaster. Detailed inspections are the most reliable and generate invaluable information on the structural performance of the affected building stock, but they are particularly time-consuming (Peña-Mora et

al.,2008). As a result, faster but possibly less accurate (and still somewhat time-consuming) building-by-building street-level surveys are typically performed to expedite the process of collecting data immediately after a disaster.

Recently, tools have been developed to automatically and more rapidly predict the most damaged areas. For example, following major disasters (including the Beirut blast), the Advanced Rapid Imaging and Analysis (ARIA) team at the California Institute of Technology (Caltech) and the NASA—Jet Propulsion Laboratory (JPL) produce Synthetic Aperture Radar (SAR)-based damage proxy maps (DPMs) using pre- and post-disaster satellite data (e.g., Yun et al., 2015). It is however important to validate and calibrate such models. The DPM developed for the Beirut blast is shown in Figure 2.

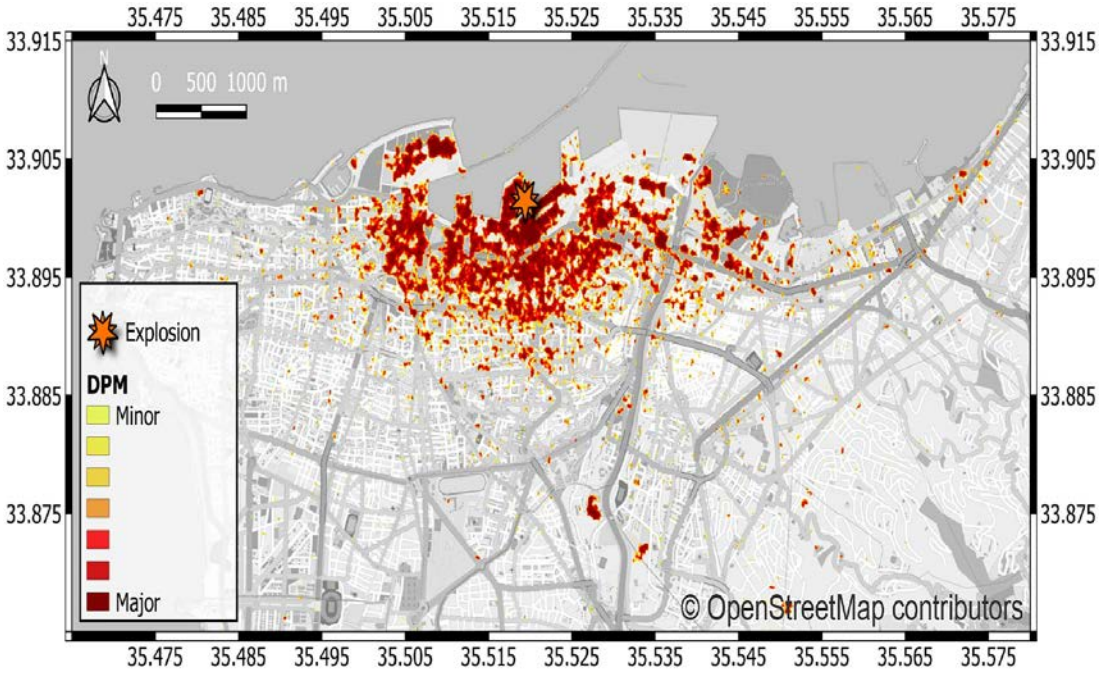


Figure 2. DPM produced following Beirut blast. (Data from NASA-JPL; Base map © OpenStreetMap Contributors.) “Taken from Sadek et al., 2022”

The city of Beirut, which is the capital of Lebanon, has a rich architectural history and contains a stock of 18,340 building structures spanning many construction eras (Krayem, 2021). The structural performance of these buildings when subjected to a

strong earthquake or blast is expected to depend on building age, structural type and height, among other parameters. A building database that includes all this information is therefore crucial to, for example, perform seismic risk and vulnerability assessments, and to have an idea of the buildings and areas that are expected to be most affected if a disaster occurs. After Beirut's port explosion, the various inspection efforts presented in the previous section showed that different structures suffered different levels of damages. Data from field surveys that gather precise damage observations on the extent and scale of damage to structures at a global and component level, and on the mechanism of structural failure, along with records of undamaged structures, can be used to gain a scientific understanding of the physical, socioeconomic, environmental, cultural, and institutional ramifications of how infrastructure and structures operate when subjected to any loading (Contreras, 2021). Therefore, it would be useful to compile a dataset that includes information on a large number of buildings (such as age, type and height) plus the level of structural damage they sustained during the blast (e.g., from field surveys) in order to develop a model of the expected structural performance of buildings in Beirut as a function of their characteristics (for example to predict damage classes in the event of a future strong earthquake). Additionally, it would be useful to compare and validate/calibrate the DPMs produced by the NASA-JPL after the Beirut blast by comparing them with a large dataset of actual damage observations. This was already done by (Sadek et al., 2021), but on a limited dataset of structural damage observations. Their comparison showed that DPMs were able to distinguish among structural damage classes at a high level (no damage, damage, collapse), but do not distinguish among damage levels short of collapse. Moreover, the DPMs were able to distinguish only high façade damage but not low façade damage.

C. Research Objective

The GEER/AUB-MSFEA group consisted of teams led by MSFEA faculty members (some of whom are members of the GEER team), lecturers and lab managers, and assisted by graduate and undergraduate students or alumni. During their inspections, the GEER/AUB-MSFEA group filled the survey form shown in Figure 3, based on the ATC-20 (ATC, 1995) and ATC-45 (ATC, 2004) rapid and detailed evaluation safety assessment forms. Their in-person inspections were limited to 172 buildings but documented specific damages to, and photographs of, structural and non-structural components, in addition to assigning a final posting of green (inspected), yellow (restricted use) or red (unsafe). The survey data was later used in (Sadek et el., 2021) to assign a damage class ranging from D0 to D5 for each structure based on the damages incurred. An additional 10 heavily damaged buildings identified based on the street-view photographs were also assigned a damage class. Nonetheless, the GEER/AUB-MSFEA dataset is too limited to develop predictive models of the expected structural performance, or to perform and meaningful comparison/validation/calibration with the NASA-JPL DPMs.

On the other hand, inspections done by OEA covered 2,500 buildings in the large-scaled affected area. They were rapid assessments, mainly to identify safe and unsafe buildings and buildings that require immediate reparation to avoid collapse, as well as to identify the hazards associated with the damaged buildings, in order to help the residents in Beirut to overcome the catastrophe. The OEA survey form (in Arabic) is shown in Figure 4 and the translation of the survey form to English is shown in Figure 5. The data gathered by OEA included the state of and the damages observed in each building, the possible hazards each building might be subjected to and its threats on

public safety, as well as recommended actions (e.g., isolation) to address potential threats and maintain the safety of people. Photographs of the exterior and interior of buildings were also collected in some cases. Despite the considerable size of the data, it was gathered by a large number of engineering surveyors who were not specifically trained to perform post-disaster structural assessments. Therefore, different surveyors may have had different interpretations of the survey entries, resulting in possibly mislabeled damages and possible hazards. Moreover, the damage entries available in the survey form are not detailed enough to directly assign a structural damage class, and such assignments require making assumptions and interpretations.

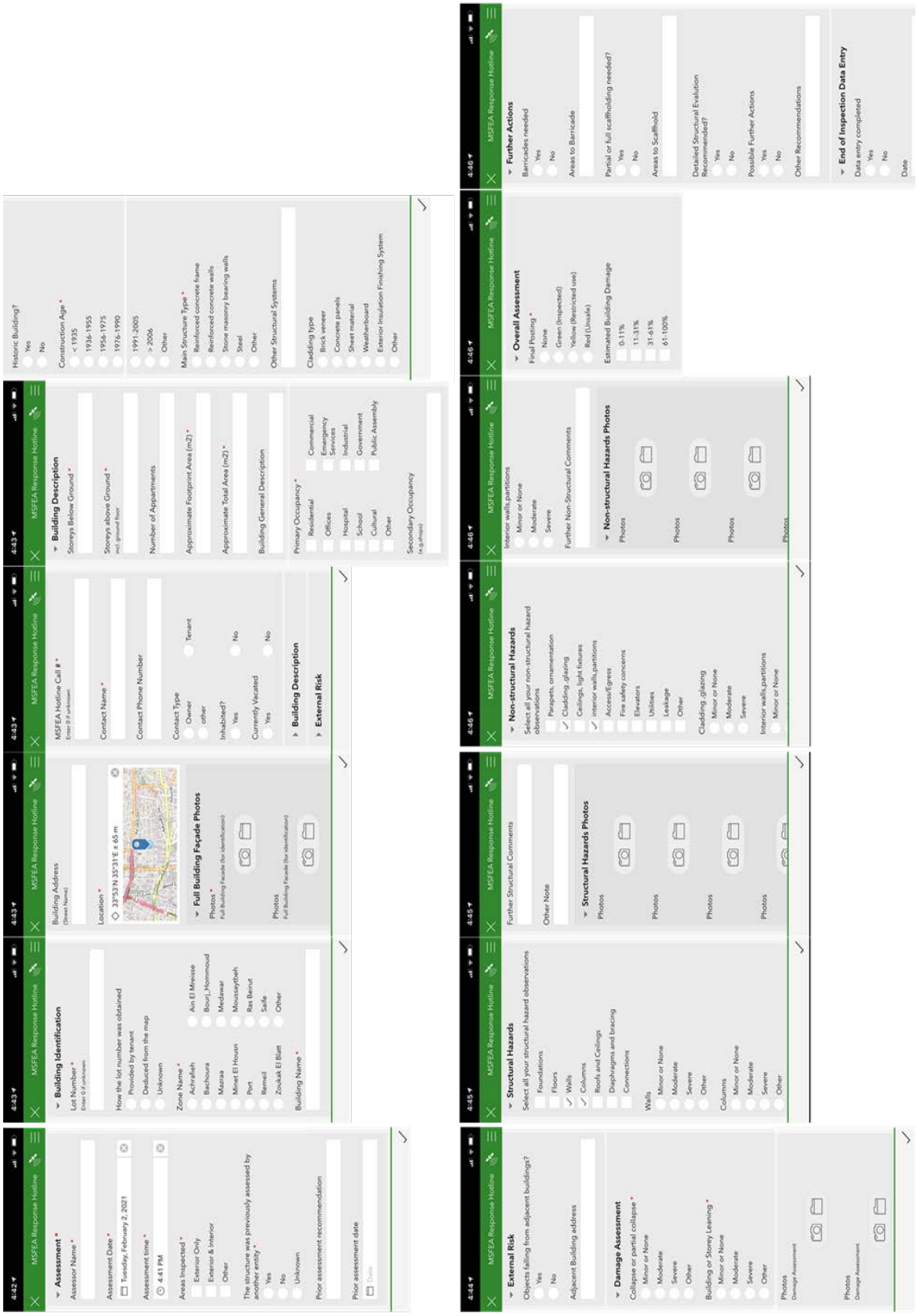


Figure 3. Survey forms filled by MSFEA.

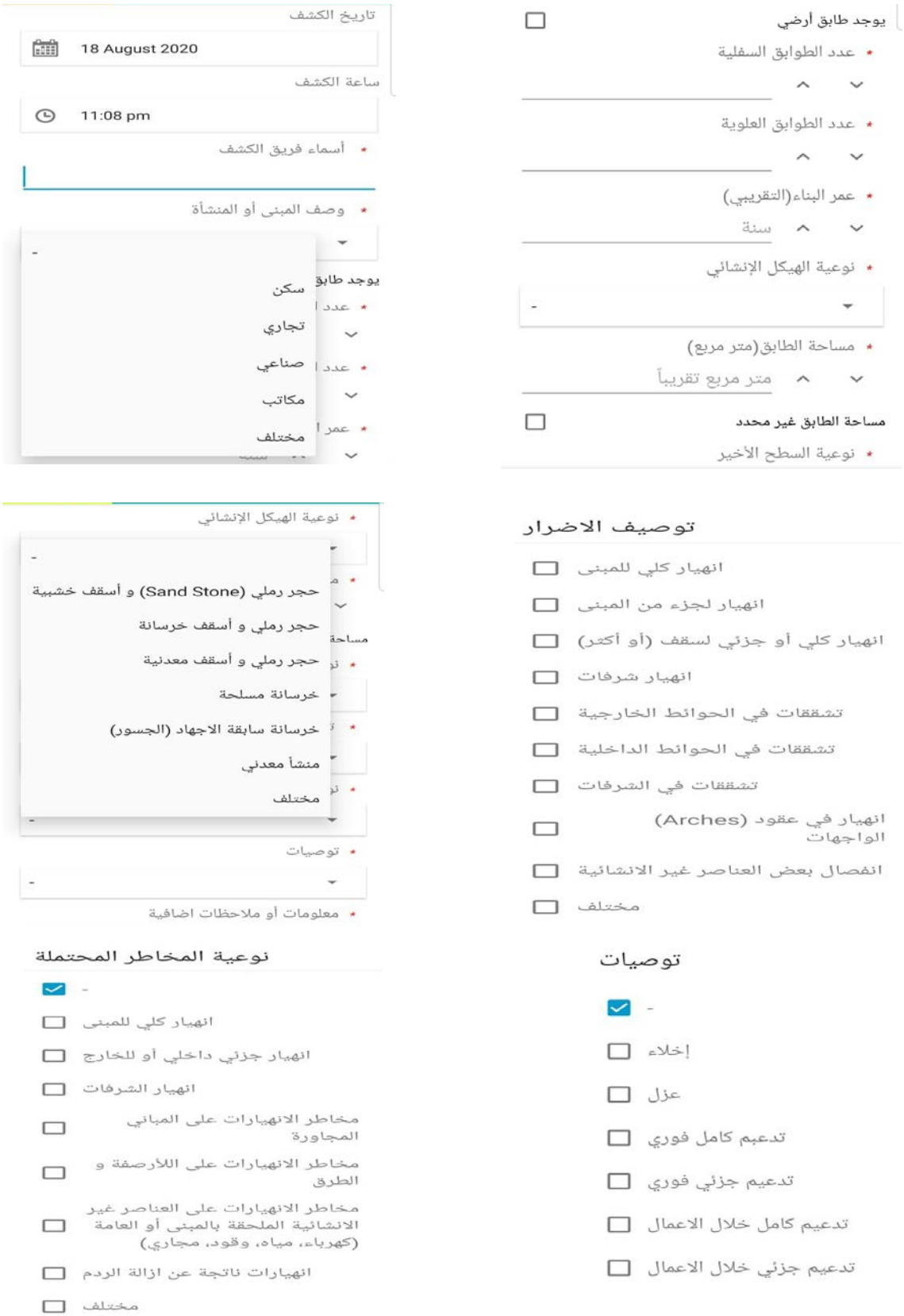


Figure 4. Survey forms (in Arabic) filled by OEA.

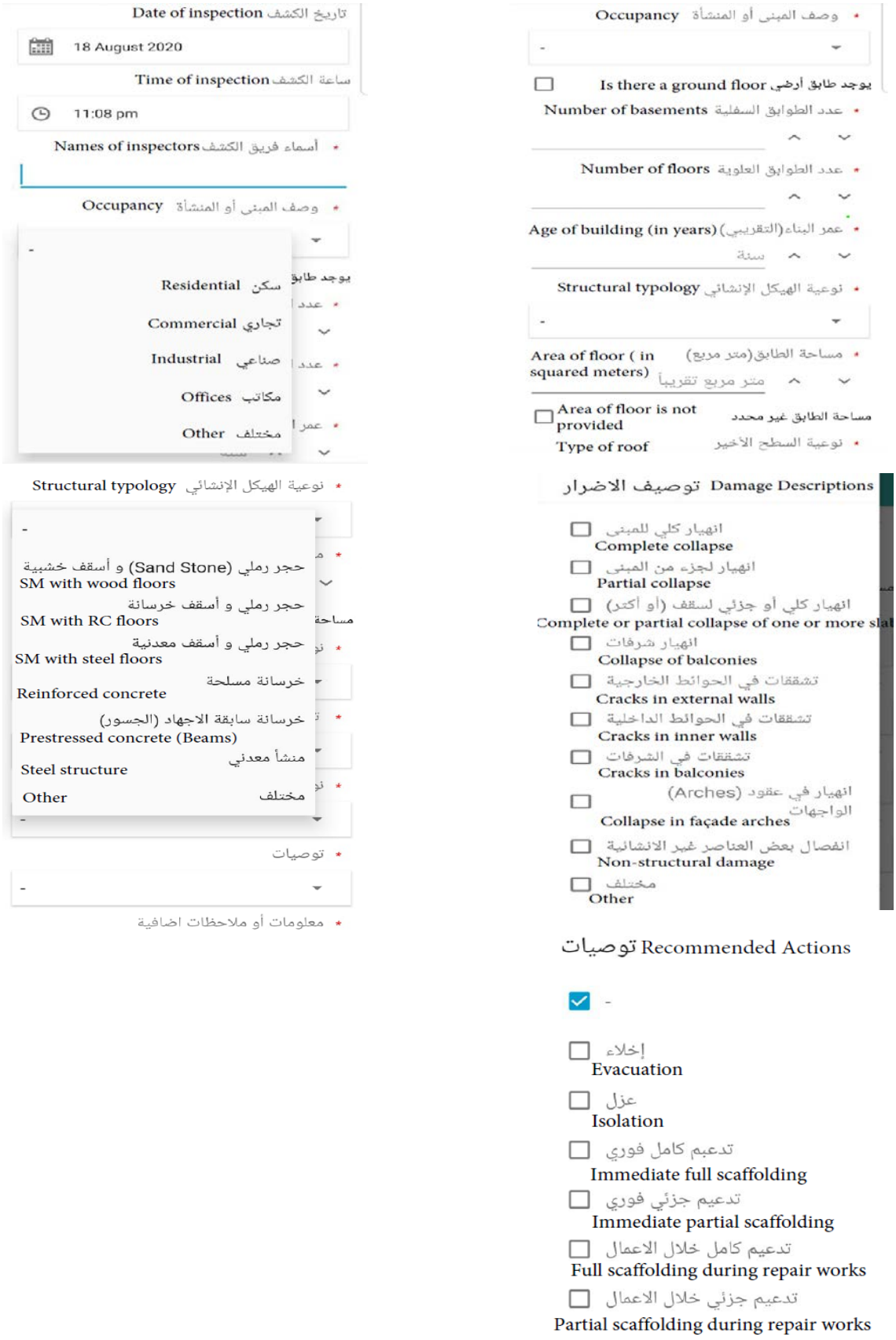


Figure 5. Translation to English of the survey forms filled by OEA.

The objective of this research is to expand the inventory of buildings with an associated structural damage class beyond the 182 buildings inspected by GEER/AUB-MSFEA team. For this reason, the inspection data and imagery from the OEA surveys for 2,500 buildings is used for detailed assessment for buildings in order to expand the dataset, albeit with increased uncertainty. Figure 6 shows the OEA survey zone limits compared to the MSFEA surveyed buildings, where Ground Zero represents the blast location at Beirut Port. In this thesis, the OEA data is processed and analyzed in a detailed manner to assign a structural damage class from D0 to D5. The resulting data will be analyzed to gain insights on the effects of the typology, age and height of the structure, its distance from the blast, and whether or not it has a direct line of sight from the blast. They will also be used to develop a predictive model of structural damage as a function of these parameters. Moreover, this larger dataset of damage observations will be compared with the DPMs produced by the NASA-JPL after the Beirut blast in order to validate and calibrate them.

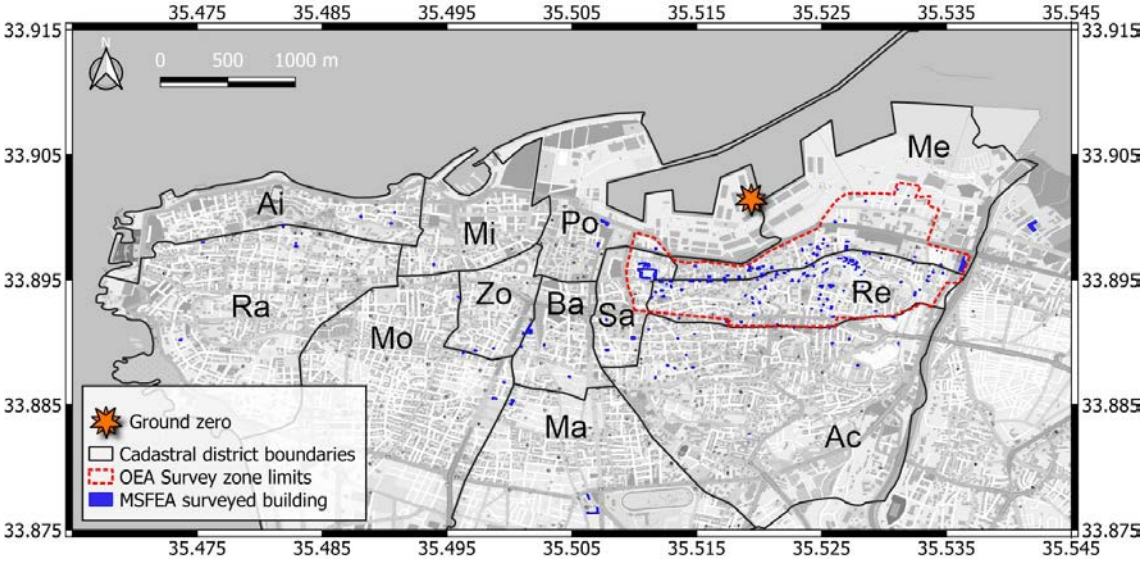


Figure 6. OEA survey zone limits vs. buildings inspected by MSFEA. “Taken from Sadek et al., 2021”

CHAPTER II

LITERATURE REVIEW

A. Worldwide Damage Classifications

Post-disaster damage assessment is required to determine the structure's safety and usability after the disaster. The damage classification depends on a rapid, reliable and computationally easy method of visual assessment in which damage parameters are assigned to each structure. Various methods are implemented worldwide to develop an ideal correlation between the damage parameters and the damage grades. The European Macroseismic Scale (EMS, 1998) divided structures into two types, masonry and reinforced concrete (RC) structures. Each type of structure has a different classification scheme according to the damage parameters. The categorization method of EMS is divided into 5 grades, and it is presented in Table 1. Difference between structural and non-structural damage should be considered carefully.

Table 1. Classification of Damage as per EMS (1998)

Damage Grade	Masonry Structures	RC Structures
Grade 1: Negligible to Slight Damage (No Structural Damage, slight non-structural damage)	1. Hair-line cracks in very few walls. 2. Fall of small pieces of plaster. 3. Fall of loose stones from upper parts of buildings.	1. Fine cracks in plaster over frame members or in walls at the base. 2. Fine cracks in partitions and infills.
Grade 2: Moderate Damage (Slight Structural Damage, moderate non-structural damage)	1. Cracks in many walls. 2. Fall of fairly large pieces of plaster. 3. Partial collapse of chimneys.	1. Cracks in columns and beams of frames and in structural walls. 2. Cracks in partition and infill walls. 3. Fall of brittle cladding and plaster. 4. Falling mortar from the joints of wall panels.
Grade 3: Substantial to Heavy	1. Large and extensive cracks in most walls.	1. Cracks in columns and beam column joints of frames

Damage (Moderate Structural Damage, heavy non-structural damage)	2. Roof tiles detach. 3. Failure of individual non-structural elements (partitions, gable walls).	at the base and at joints of coupled walls. 2. Spalling of concrete cover, buckling of reinforced rods. 3. Large cracks in partition and infill walls, failure of individual infill panels.
Grade 4: Very Heavy Damage (Heavy Structural Damage, Very heavy non-structural damage)	1. Serious failure of walls. 2. Partial structural failure of floors and roofs.	1. Large cracks in structural elements with compression failure of concrete and fracture of rebars. 2. Bond failure of beam reinforced bars. 3. Tilting of columns. 4. Collapse of a few columns or of a single upper floor.
Grade 5: Destruction (Very Heavy Structural Damage)	1. Total or near total collapse.	1. Collapse of ground floor or parts of buildings.

Moreover, Bray and Stewart (2000) adopted a damage scale which ranges from D0 to D5 based on the visual inspection of buildings. The main advantages of using one damage level for each building are to identify the spatially variable damage patterns after the disaster and to evaluate the vulnerability of different building types. The description of the damage categories they used are listed in Table 2.

Table 2. Damage Category adapted from Bray and Stewart (2000)

Damage Level	Description
D0	No damage
D1	Cracking of non-structural elements, such as dry walls, brick or cladding
D2	Major damage to the non-structural elements. Minor damage to load bearing elements.
D3	Significant damage to load-bearing elements, but no collapse
D4	Partial structural collapse
D5	Full collapse

In Sadek et al. (2021), the GEER/AUB-MSFEA team adapted a system from Bray and Stewart (2000) and EMS98 (1998) for assigning to each building a damage class between D0 and D5, but taking into account the typology of the structure (if reinforced concrete or sandstone bearing wall buildings), and the damages incurred to the elements if load-bearing structural or non-structural elements; the system is shown in Table 3.

Table 3. Structural damage classifications used in Sadek et al. (2021). Adapted from Bray & Stewart (2000) & EMS98 (1998)

Structural Elements	Damage Summary	Damage Description by Typology	
		Sandstone Bearing Wall Buildings	RC Buildings
D0	No Damage		
D1	Light Damage		
Load-bearing structural elements	No damage	Hairline cracks in a few walls. Fall of small pieces of plaster only.	Fine cracks in plaster over frame elements or in wall bases
Non-structural elements	Minor damage/cracking		Fine cracks in partition and infill walls
D2	Moderate Damage		
Load-bearing structural elements	Minor damage / cracks	Cracks in many walls. Fall of large pieces of plaster.	Cracks in columns, beams and structural walls.
Non-structural elements	Moderate damage/ cracking.	Moderate damage to façade arches or balconies. Moderate damage to roof or ceilings.	Moderate cracks in partition and infill walls. Fall of brittle cladding and plaster. Moderate to heavy damage of false ceilings.
D3	Heavy Damage		
Load-bearing structural elements	Significant damage, but no collapse	Large and extensive cracks in most walls. Tilting or separation of bearing walls.	Cracks in columns and beam joints of frames at the base and at joints of coupled walls. Spalling of concrete cover. Buckling of steel rebars.

Non-structural elements	Heavy damage/ cracking.	Failure of individual non-structural elements. Heavy damage or failure of façade arches or balconies. Heavy damage to roof or ceilings.	Large cracks in partition and infill walls. Failure of individual infill panels. Heavy damage of false ceilings.
D4	Partial Structural Collapse		
Load-bearing structural elements	Collapse of an individual floor or portion of building.	Serious failure of walls. Partial structural failure of roofs and floors.	Large cracks in structural elements. Compression failure of concrete. Fracture of rebars; Bond failure of beam rebars. Tilting of columns. Collapse of a few columns or a single upper floor.
Non-structural elements	Very heavy damage/ cracking		
D5	Full Structural Collapse		

Furthermore, different guidelines outlining the steps for post-disaster building assessment have been developed by the Applied Technology Council (ATC). It is recommended to use these manuals in the event of earthquakes, hurricanes, snowstorms, windstorms, fires, floods, tsunamis, explosions, collisions, and terrorist acts (Peña-Mora et al.,2008). ATC offers a number of field manuals that offer guidance on assessing structural, geotechnical, and non-structural risks as well as estimating the impact on the safety of various building damage types. The manuals focus on assessing buildings rather than other engineering facilities like bridges or pipelines. Due to its implementation following the 9/11 attacks, the ATC-20 methods were widely embraced in the US and they are now the de facto norm for quick structural assessment of buildings. The ATC defines three levels of evaluation: Rapid evaluation; Detailed

evaluation; and engineering evaluations, which are established for different types of personnel. The goal of each evaluation is presented in Table 4.

Table 4. Building Evaluation Technique from ATC-20 (ATC, 1995)

Technique	Goal
Rapid Evaluation	Rapid assessment of safety. Used to quickly post obviously unsafe and apparently safe structures, and to identify buildings requiring detailed evaluation.
Detailed Evaluation	Careful visual evaluation of damaged buildings and questionable situations. Used to identify buildings requiring an engineering evaluation.
Engineering Evaluation	Detailed engineering investigation of damaged buildings, involving use of construction drawings, damage data and new structural calculations.

The ATC methods include a standard approach to identify buildings through three tiers of color-coded placards in order to clearly define the extent of a building's damage. The three-colored placards with their classification are listed in Table 5.

Table 5. Building Safety Evaluation Classification by ATC-20 (ATC, 1995)

Green	No apparent hazard found, although repairs may be required. Original lateral load capacity not significantly decreased. No restriction on use or occupancy
Yellow	Dangerous condition believed to exist. Entry by owner permitted only for emergency purposes and only at own risk. No usage on a continuous basis. Entry by public not permitted. Possible major aftershock hazard
Red	Extreme hazard, structure may collapse. Imminent danger of collapse from an aftershock. Unsafe for occupancy or entry, except by authorities (entry controlled by jurisdiction)

B. Worldwide Damage Assessment Responses

In recent years various research groups and organizations have focused on structural response after a shock. Similar to what happened after the Beirut blast, response, assessment, and engineering reconnaissance activities are generally mobilized after natural disasters and catastrophic shocks worldwide in order to gather perishable data. It must be noted that these inspections are held under emergency conditions, mainly to

save human life and to protect properties from additional damage (e.g., due to earthquake aftershocks). In these conditions, it must be well understood that the engineer who is inspecting will have neither the time nor the tools to come up with a solution to achieve safety standards. However, the engineer must build his assessment on the observed damage and his experience following the rules that depend on the structural typology.

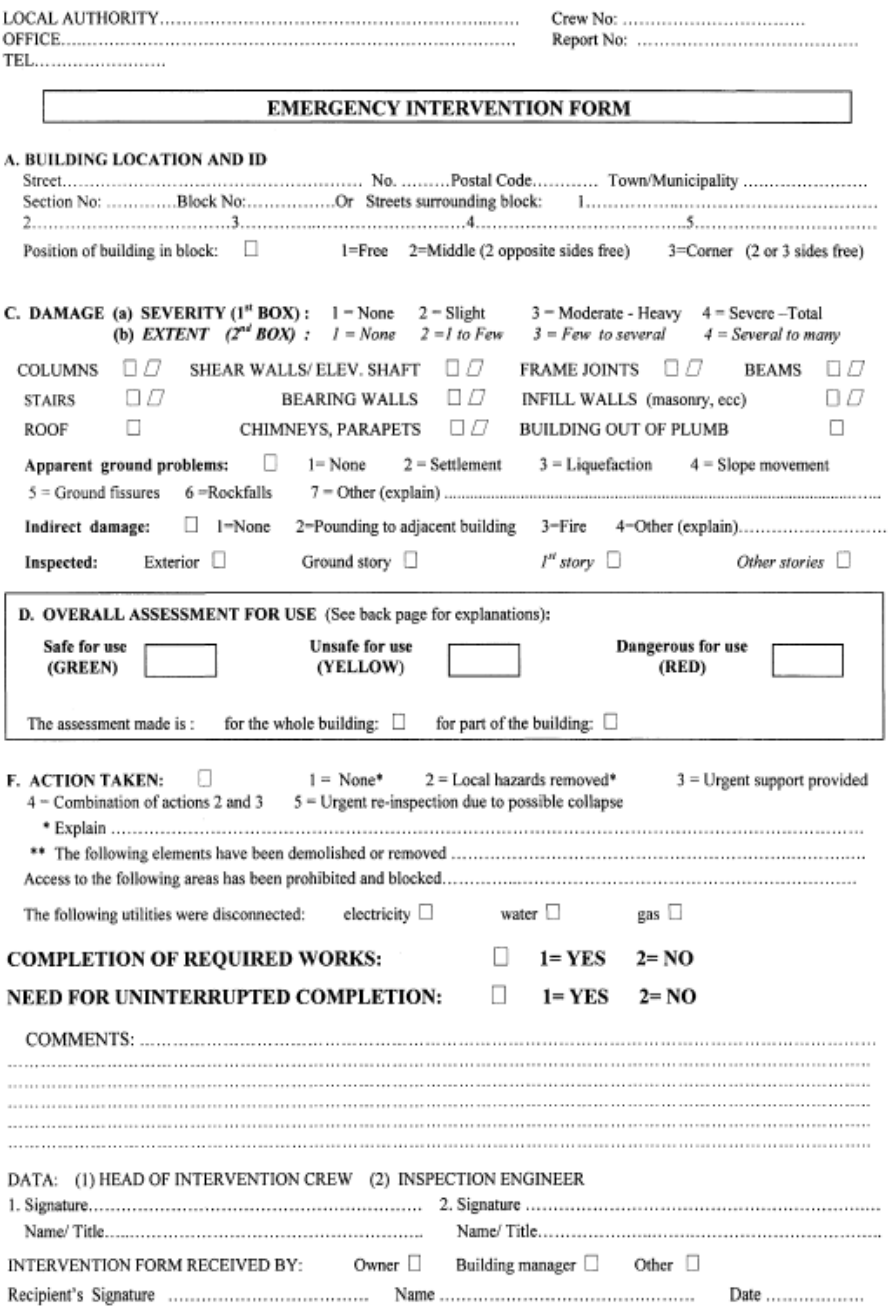
In 2016, an earthquake with magnitude of 6.0 hit the central part of Italy. Two weeks after the mainshock, the US-based GEER team in collaboration with Italian researchers and institutions organized field reconnaissance activities to gather data and record perishable information to gain insight on the types of structures most vulnerable to earthquake shaking and to identify the types of retrofit most successful in limiting structural damage (Lanzo et al., 2016). The reconnaissance approach involved aerial image analysis (orthophotos), 3D texture models from drones, detailed ground surveys, and general qualitative ground surveys. The damage classification adopted was based on visual inspection of buildings. The scheme was provided by the Department of Civil Protection (DPC) in Italy for post-earthquake reconnaissance purposes and its damage scale was adapted from Bray and Stewart (2000) which ranges from D0 (no observed damage) to D5 (complete collapse of floor or entire structure). The DPC approach is comprised of four sections: description of the building, type of construction, structure damage, and soils and foundations. GEER and its associates performed detailed structure-by-structure assessment of damage levels and structural typologies. The one-by-one buildings surveys conducted in the Italian suburbs enabled to detect variable levels of building performance including minor damages. It was found that the structural damage levels deduced from the satellite images were not always accurate.

For example, one of the structures was classified as moderately damaged by the satellite images, however it was fully collapsed. The main issue was that the satellite image recognized the RC roof which was intact while the building under it was fully collapsed.

A similar response was conducted in Turkey, 1999 after the Kocaeli Earthquake. The mapping procedure was a detailed structure-by-structure survey and the damage assessment was performed according to Coburn and Spence (1992), which is similar to that of Bray and Stewart (2000). The investigation provided the means to produce damage patterns with widespread ground failure in Turkey, which gave exceptional field performance data on critical seismic geotechnical phenomena (Bray et al, 2000).

Additionally, Greece is considered one of the most seismically active regions in Europe and it is prone to a great deal of seismic activities (Tsapanos, 2008). An overall earthquake emergency response plan has been adapted in Greece for inspecting buildings after damaging or catastrophic earthquakes, with the use of a computer program to support the planning and execution of building inspection operations (Anagnostopoulos et al, 2004). The emergency inspection after a serious earthquake consists of two types of damage assessment: Rapid assessment and detailed assessment. The rapid assessment quickly identifies buildings as safe for use (Green), dangerous for use (Red), and unsafe for use (Yellow). The detailed assessment is performed only on buildings characterized as yellow or red from the rapid assessment and it finalizes the characterization of the building. The overall assessment of the buildings considers both the severity and extent of damage of the various structural elements. It must be noted that the Greece post-earthquake damage assessment differentiate between different structural systems (RC, masonry, steel, wood) from which the criticality of each load

carrying element can be assessed. Moreover, guidelines for filling the emergency intervention forms are listed to be used as an aid for making the assessment of damages as objectively as possible. The emergency intervention form used in Greece after earthquake for assessing buildings is shown in Figure 7.



LOCAL AUTHORITY..... Crew No: .....
OFFICE..... Report No: .....
TEL.....

EMERGENCY INTERVENTION FORM

A. BUILDING LOCATION AND ID

Street..... No. .....Postal Code..... Town/Municipality .....
Section No: .....Block No:.....Or Streets surrounding block: 1.....
2.....3.....4.....5.....
Position of building in block: ☐ 1=Free 2=Middle (2 opposite sides free) 3=Corner (2 or 3 sides free)

C. DAMAGE (a) SEVERITY (1st BOX) : 1 = None 2 = Slight 3 = Moderate - Heavy 4 = Severe –Total
(b) *EXTENT (2nd BOX) :* *1 = None 2 =1 to Few 3 = Few to several 4 = Several to many*

COLUMNS	☐☐	SHEAR WALLS/ ELEV. SHAFT	☐☐	FRAME JOINTS	☐☐	BEAMS	☐☐
STAIRS	☐☐	BEARING WALLS	☐☐	INFILL WALLS (masonry, ecc)			☐☐
ROOF	☐	CHIMNEYS, PARAPETS	☐☐	BUILDING OUT OF PLUMB			☐

Apparent ground problems: ☐ 1= None 2 = Settlement 3 = Liquefaction 4 = Slope movement
5 = Ground fissures 6 =Rockfalls 7 = Other (explain) .....

Indirect damage: ☐ 1=None 2=Pounding to adjacent building 3=Fire 4=Other (explain).....

Inspected: Exterior ☐ Ground story ☐ *1st story* ☐ *Other stories* ☐

D. OVERALL ASSESSMENT FOR USE (See back page for explanations):

Safe for use (GREEN) ☐ **Unsafe for use (YELLOW)** ☐ **Dangerous for use (RED)** ☐

The assessment made is : for the whole building: ☐ for part of the building: ☐

F. ACTION TAKEN: ☐ 1 = None* 2 = Local hazards removed* 3 = Urgent support provided
4 = Combination of actions 2 and 3 5 = Urgent re-inspection due to possible collapse
* Explain .....
** The following elements have been demolished or removed .....
Access to the following areas has been prohibited and blocked.....

The following utilities were disconnected: electricity ☐ water ☐ gas ☐

COMPLETION OF REQUIRED WORKS: ☐ **1= YES 2= NO**

NEED FOR UNINTERRUPTED COMPLETION: ☐ **1= YES 2= NO**

COMMENTS: .....
.....
.....
.....
.....
.....

DATA: (1) HEAD OF INTERVENTION CREW (2) INSPECTION ENGINEER
1. Signature..... 2. Signature .....
Name/ Title..... Name/ Title.....

INTERVENTION FORM RECEIVED BY: Owner ☐ Building manager ☐ Other ☐
Recipient's Signature ..... Name ..... Date .....

Figure 7. Greece Emergency Intervention Form. “Taken from Anagnostopoulos et al, 2004”

CHAPTER III

DATA PREPARATION

In order to reach the mentioned objectives, several steps should first be performed in terms of data preparation. These steps include translation of the OEA data from Arabic to English, processing the collected data and dividing them into categories, and pinpointing and correcting or discarding any irrelevant or incorrect data. Finally, we will make sure that our data includes all information that will help us to assign a damage class for the different structures with minimal uncertainties.

A. OEA Data Description

In this thesis, our main focus is on the data provided by the surveys conducted by the OEA groups after the Beirut blast. Each group from OEA filled the survey form shown in Figure 3 for each investigated building (2,354 buildings in total). The survey form is in Arabic form and has tick options as well as spaces to enter written information. The survey includes several entries that provide information about the surveyed structure that are important for our analysis, and other entries that are irrelevant to our analysis (such as number of elevators, water tanks, electrical motors etc.). For this reason, only the important data are presented in what follows and divided into sets for simplicity. The first set of entries gathered for each building provides a description of the building. It contains the following information: the building's location, occupancy, number of floors, age, and type of structure. The second set of entries contains the damages incurred by each building. This set is a tick option, and the OEA groups selected one or more of the following "Damage Descriptions" for each building: Complete collapse; Partial collapse; Complete or partial collapse of one or

more slabs; Collapse of balconies; Cracks in external walls; Cracks in inner walls; Cracks in balconies; Collapse in façade arches; and Non-structural damages. To be more specific, OEA groups added written damage descriptions to some of the buildings, which are used and processed in this thesis, as described later on. The third set of entries contains the “Possible Hazards”, which is also a tick option, and OEA groups selected one or more of the following possible hazards: Possibility of building collapse; Possibility of partial interior or exterior collapse; Collapse of balconies; Danger of falling hazard onto neighboring buildings; Danger of falling hazard onto roads/sidewalks; Danger of falling hazard onto non-structural or public infrastructure (electric, mechanical, water or sewer systems); and Collapse due to debris removal. To be more specific, OEA groups added written descriptions of possible hazards to some of the buildings, which are used and processed in this thesis, as described later on. The fourth set of entries contains the “Recommended Actions”, which is also a tick option, and the OEA groups selected one or more of the following: Evacuation; Isolation; Immediate full scaffolding; Full scaffolding during repair works; Immediate partial scaffolding; and Partial scaffolding during repair works. Furthermore, a section containing a written note is provided by the OEA groups for some of the buildings and may contain important information for our analysis and assignment of a structural damage class.

Additionally, for each building inspected, a parcel ID or PID is included. The PID consists of two letters that refer to the cadastral zone, followed by a number that refers to the lot number of the parcel. For instance, the PID (Ac_107) refers to the parcel with lot number 107 in the Achrafieh zone. Also, OEA surveyors provided coordinates for each building inspected. It should be noted that for some buildings, the coordinates

provided do not present the exact location of the building, and mark instead the location from where the survey form of the building was first created. In most cases, the provided coordinates were close to the actual building location (e.g., next to the building, or on the street facing the building), but in a few cases they were inconsistent with the actual building locations (e.g., the coordinates of the OEA offices). Moreover, photos for most of the buildings surveyed are provided, which are also used to assign the final damage classes. The information gathered by the OEA from field surveys is collected into one dataset and processed for further analysis.

B. OEA Data Processing

The information mentioned in the previous section are processed for further analysis to facilitate the damage classification. Each set of entries is divided into categories based on the available information provided by OEA surveyors.

1. Type of Structure

To begin with, the "Type of structure" is divided into categories, since the vulnerability of each structure depends on its type. The type of structure is either selected by the OEA from the different available options, or it is specifically written. However, for some buildings, the type of structure is not selected nor written, so we checked the available notes and photos and deduced its type, whenever possible. It must be noted here that 18 buildings do not have any classification for their type nor an available photo, so these buildings are labeled as "No Information" for their type. The categories for the "Type of structure" are the following:

- Stone Masonry (SM): refers to structures with sandstone columns and walls and different type of slabs such as reinforced concrete, steel or wooden slabs.

- Reinforced Concrete (RC): refers to structures with RC columns, beams, slabs, and shear walls for more recent constructions. These structures might also contain pre-stressed elements such as beams.
- No Building: refers to empty parcels, parcels that are excavated in preparation for construction, parking lots, parks, roads, etc. It is worth mentioning that 83 surveys (out of the 2354 surveys) do not have buildings on the inspected parcel. These surveys are excluded from our analysis later on.
- Steel: refers to structures with steel bearing elements.
- RC + Steel: refers to composite structure which is part RC and the other steel.
- RC + SM (Evolved): refers to structures built during the period where RC started being incorporated as a construction material (e.g., these structures include SM bearing walls combined with RC columns and slabs) or to structures that were mainly SM, but new RC structural elements were later added to the structure (to strengthen it and/or add a floor).

2. Structural Damage Characterization

On the other hand, the entries related to “Damage Descriptions”, “Possible Hazards” and “Recommended Actions” are divided into categories based on the options mentioned in the previous section. A “Yes” or “No” entry is assigned to each category, depending on whether the damage description, possible hazard or recommended action is selected or not in the survey by the OEA groups.

To reduce the uncertainties in the damage classification, the written entries related to damage descriptions and possible hazards are processed as well, since they may contain useful information for the damage classification, mainly to differentiate between

the D2 and D3 classes. These written information are many and varied, since each OEA group wrote the information in their own way. However, we compiled the written damage descriptions into the following categories with a Yes/No option:

- No damage, which refers to no observed damages to the building.
- Non-structural damage to glazing, doors, window frames, contents, equipment, cladding and parapets. This category will be used to assign façade damage classes only and not in the structural damage classification.
- Non-structural damage to partitions, roofs, false ceilings, balconies, and façade arches. This category will be used to assign structural damage classes.
- Minor non-structural cracks, which refer to small cracks in partitions, balconies, and/or arches.
- Minor structural cracks, which refer to small cracks in columns, shear and bearing walls, beams, and/or slabs.
- Major non-structural cracks, which refer to large cracks in partitions, balconies and/or arches.
- Major structural cracks, which refer to large cracks in columns, shear and bearing walls, beams, and/or slabs.
- Substantial structural damage which refers to collapse of slabs, beams, columns, and/or walls.

Similarly, we compiled the written entries related to possible hazards into the following categories with a Yes/No option:

- No hazard.
- Possibility of collapse of exterior façade or cladding. This category will be used for façade classification.

- Possibility of collapse of nonstructural elements, which includes partitions, balconies, etc.
- Possibility of collapse of structural elements, which includes columns, walls, beams, or slabs.

Furthermore, a “Pre-existing Damage” category is added which includes entries such as corrosion, deterioration, effects of war, and old building. These entries are added according to notes provided by OEA groups to some of the buildings.

3. Building Location

Most of the OEA buildings have a unique PID, but in some cases the same PID appears in multiple OEA building surveys, which means that either there is more than one building on the parcel or the same building has been inspected more than one time. With the help of the BUL, a map of the buildings in the area inspected by the OEA is kindly shared with us as a GIS layer. The BUL Beirut buildings layer in the study area is shown in Figure 8 using a software called “ArcGIS”. The building map is made up of polygons that were digitized from satellite images of the city and that represent building footprints. Each building from the BUL map has several information (obtained from ground surveys conducted by the BUL in 2018 and 2019) that can be utilized in our work such as PID and number of floors.

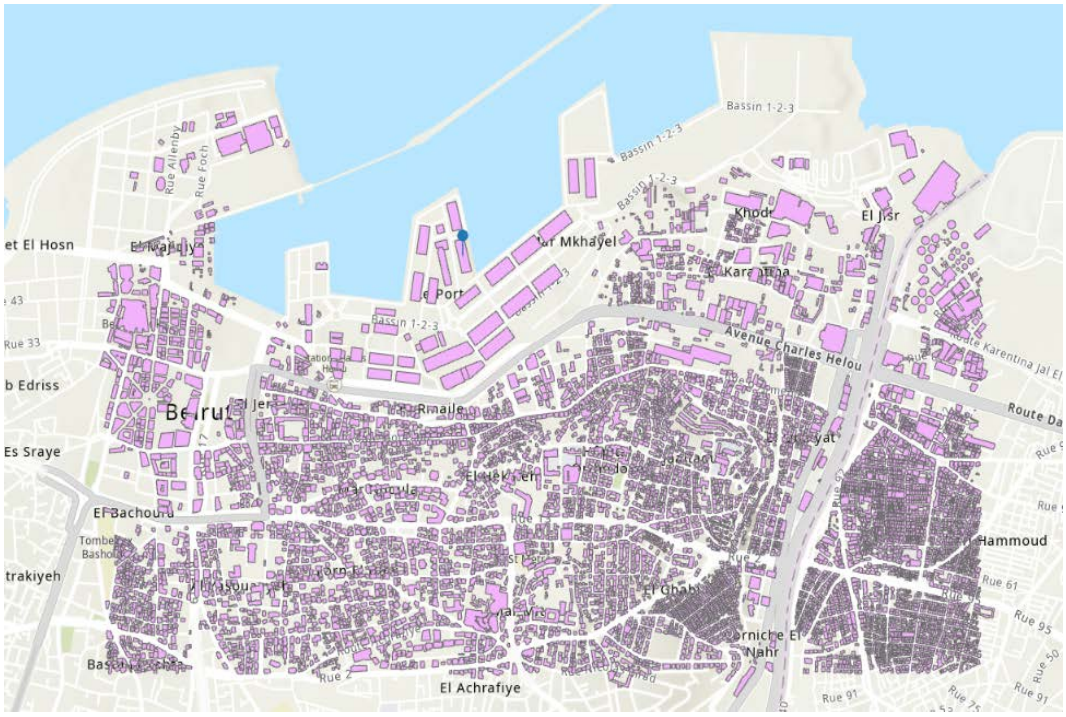


Figure 8. Map of Beirut buildings provided by BUL.

A copy of the BUL buildings map has been created using “ArcGIS” to show the OEA buildings with their exact location, and all the important data obtained from the OEA surveys is linked with each building in this new map (hereafter called the OEA map).

First of all, the buildings inspected by OEA which have a unique PID are directly linked with the buildings having the same unique PID in the BUL map. For example, there is only one building with PID (Me_1006) in both the OEA data and on the BUL map, so this building will be shown on the OEA map with the same shape and location of the building found on the BUL map. Additionally, there are several cases, where there is one building with one unique PID from OEA surveys, but on the BUL building map there are multiple buildings with that same PID. In such cases, only one building is considered and the remaining buildings from the BUL building layer are neglected. For

instance, there is only one building with PID (Ac_108) in the OEA data, while there are two buildings with that PID on the BUL map. The building from the BUL map with the same number of floors or approximately the same (plus or minus one floor) with the OEA data is considered and the other building is neglected.

On the other hand, for some cases, there are multiple buildings with the same PID from OEA. For these buildings, the BUL buildings map is used to highlight the parcels that contain only one building and the parcels that contain more than one building. One reason for having multiple OEA buildings with the same PID but only one building with that PID from the BUL is that OEA surveyors inspected the same building more than once. In such cases, the photos for the inspected buildings (when available) are checked one-by-one to identify whether they are for the same buildings. For example, two buildings with the same PID (Me_1097) are present in the OEA data, while there is only one building with PID (Me_1097) in the BUL building data. After checking the buildings' photos from the OEA data for the two surveys, it was found that it is the same building. This means that the building has been inspected twice by OEA surveyors. A total of 82 buildings are found to be inspected twice by OEA; thus, 41 surveys are removed from our database while keeping the other 41 surveys for further analysis and they are directly linked with their corresponding buildings from the BUL map. It must be mentioned that, for the surveys which have the same building inspected multiple times, the OEA entries are sometimes different from one survey to another, so the survey which has the most consistent entries with the building's photos are taken into consideration for the analysis later on.

After this processing, there remain 69 buildings that have the same PID repeated multiple times in the OEA surveys, while having less buildings with the same PID from

the BUL. For example, three buildings with PID (Me_1046) are inspected by OEA, while there is only one building with that PID on the BUL map. After checking the photos of each building, it was found that they are indeed different buildings. Moreover, the satellite images of that parcel were visually checked and there is reason to believe that the parcel in fact contains three different buildings. This indicates that for some cases, the digitization of satellite images by the BUL captured multiple buildings as one unit (one polygon in the BUL map) instead of several units. Such cases are not removed from our analysis: after checking that the building survey coordinates are consistent with the assigned PID (i.e., that they fall within or close to the corresponding parcel), either the polygon is divided into several units (if the division is obvious from satellite images), or the surveys are represented as data points located based on the coordinates provided by OEA surveys.

Moreover, there are 159 buildings whose PIDs are not available on the BUL building map. The BUL at AUB was informed of such cases in order to update the BUL building map. Some parcel lots have been combined with adjacent parcels to construct a recent high rise building, and this is the reason the PID is not available on the BUL building layer. For other cases, the parcels are available, but a street-inspection is required to locate the exact location of the buildings and update the BUL building map. These missing PIDs are represented as point data on the OEA map and they are located based on the coordinates provided by OEA surveys.

After locating the data points based on their coordinates on the BUL map, it was found that some buildings were located on the OEA headquarter building which gives us an insight that the surveys for these buildings were filled and completed in the OEA headquarter building. These data points were moved to a location near to the provided

PID of each building. Also, some data points were located exactly on what appear to be an un-surveyed buildings on the BUL map, so these data points were checked one by one. It was found that for some data points, the PID provided by OEA surveyors were incorrect. For example, a data point had a PID (Me_1476) and it was located exactly on a building from BUL map. After checking the PID of the building on the BUL map, it was found to be (Re_1476). This shows that the OEA surveyors provided the wrong PID for the building and the PID was corrected to be (Re_1476*) and the OEA building was linked with the BUL building instead of putting it as a data point. Figure 9 shows the BUL building map (pink polygons), with the OEA inspected buildings (green polygons) which are in total 2,103 buildings, and data points not linked to the building layer (in blue), which are in total 108 buildings.

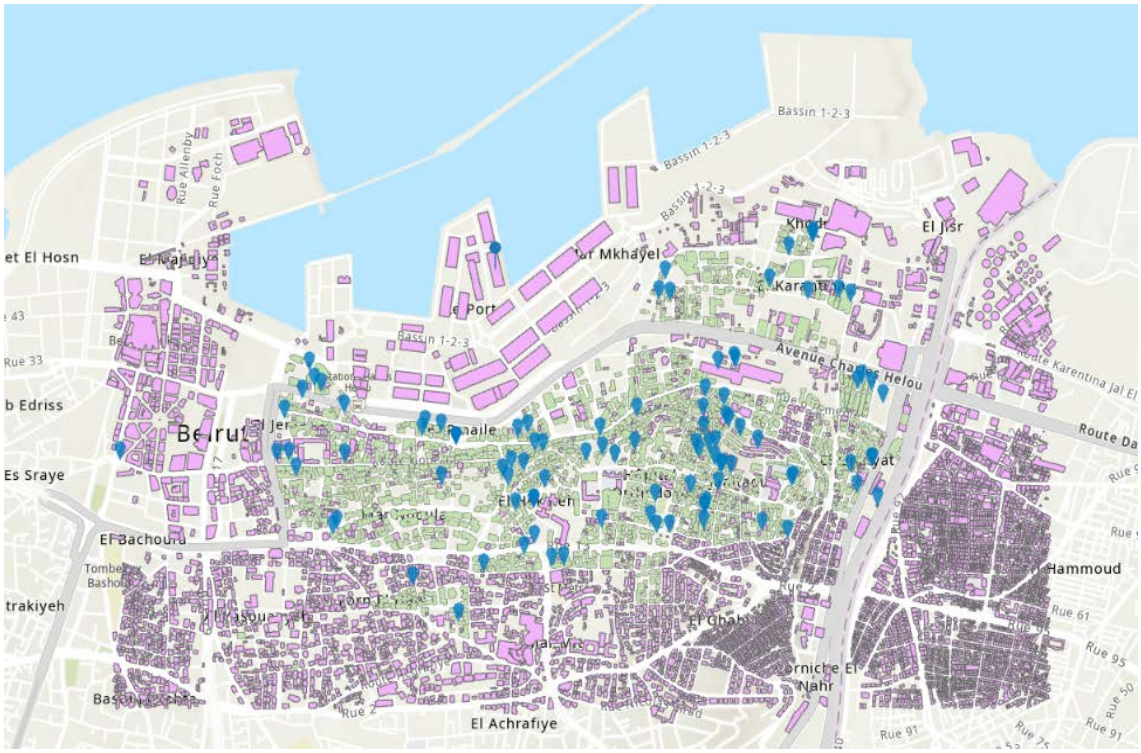


Figure 9. Map showing BUL buildings and OEA inspected buildings.

C. Additional Data

All the data shown and discussed in previous subsections are directly provided from OEA surveys, but the entries are processed to remove any irrelevant data, to correct the provided information when errors are found, and, as described in the following chapter, to consistently assign a structural damage class for each building.

In this subsection, additional data is presented which is compiled by various sources (BUL, MSFEA, etc.) and not provided by OEA surveys. The additional data are important for the analysis and validation of the damage classification results, and for studying and understanding the spatial variability of the obtained damage classes.

The first additional data is the “Distance from Blast” for each building. With the help of BUL, the distance of each building from the blast was calculated based on the PID of each building. However, BUL was not able to provide the distance for some buildings which are not available on the BUL map (the missing PIDs on the BUL map, as discussed earlier). In such cases, the coordinates which are provided from OEA surveys were used to calculate the distance from the blast.

The second additional data is the “Construction Period” for each building. The construction period of most of the buildings was assigned by Prof. Aram Yeretzian and recent graduates from the Architecture department of MSFEA at AUB, by checking the street-view images of each building (in the framework of the Masters thesis of CEE graduate student David Wardan). The ages of the buildings provided in the OEA surveys were not used since they are found to be unreliable. Based on the expert architectural assessment, 1,339 buildings were labeled with a construction period. The remaining buildings were left unlabeled because either no photos were available for these buildings, or the photos were not clear enough to allow labeling, or the photos did

not show the whole building to allow labeling. The following construction periods are used for the buildings: “Pre1935”, “1935-1955”, “1956-1971”, “1972-1990” and “Post1990”. Moreover, as part of a UNESCO-funded BUL project on Identifying Cultural Heritage Attributes in Beirut Blast Damaged Areas (Beirut Urban Lab, 2022) , a data set of buildings in Beirut was developed with their corresponding construction period classified into Late Ottoman Heritage (1850-1919), Colonial Eclectic Heritage (1920-1935), Early Modernist (1936-1955), and High Modernist (1956-1971). This data was kindly shared with us, and it includes the PID of the buildings with their construction period. Based on the UNESCO data, 482 additional buildings were labeled with a construction period. A total of 391 buildings were left unlabeled in our dataset.

The third additional data is the “Direct Line of Sight” of each building from the blast. The damage distribution of buildings is likely affected by whether or not there is a direct line of sight from the blast. The shielding of some of the portions of the city from tall intervening structures is a topic of interest. A 3D model is developed for the city of Beirut, and the direct line of sight is analyzed using the “ArcGIS” software in order to assign a line of sight indicator for each building. This feature is provided for the OEA buildings which are present on the BUL map (green polygons shown in Figure 9), and not provided for the buildings presented as data points (blue points shown in Figure 9). The process for developing a 3D model for Beirut is as follows: The topography layer and building layer of Beirut was kindly shared with us by the BUL at AUB. The topography layer of Beirut includes the ground elevation from sea level for the Beirut area. As discussed earlier, the building layer of Beirut contains the footprint of buildings with a polygon shape, along with the number of floors and height of most of the buildings. In order to develop the 3D model, the building layer must first be

converted into a “Digital Elevation Model” or “DEM” using the height of each building. Using the ArcGIS tool, a DEM layer of building’s height was created while keeping all areas outside the buildings at zero elevation. After that, the topography layer and the building’s height layer were combined in order to add the elevation of both layers to each point on the map. Once the two elevations were added, the 3D model was developed. ArcGIS supports visibility analysis and has several tools to calculate whether a target location is visible from an observer location or not. The “Viewshed” tool is used in this thesis. The viewshed analysis determines locations visible to an observer in all directions, so it shows all visible and non-visible points in all of the surrounding areas based on elevations and obstruction data. An observer point is placed on the map and a raster output indicating visibility is developed. In this thesis, the blast location is marked as the observer point and the viewshed tool is used for the combined layer of elevations. As shown in Figure 10, the viewshed tool created a raster layer for locations visible to the blast. Each building highlighted in orange is visible to the blast and a “1” indicator is provided for these buildings, while buildings which are not highlighted in orange are assigned a “0” indicator.

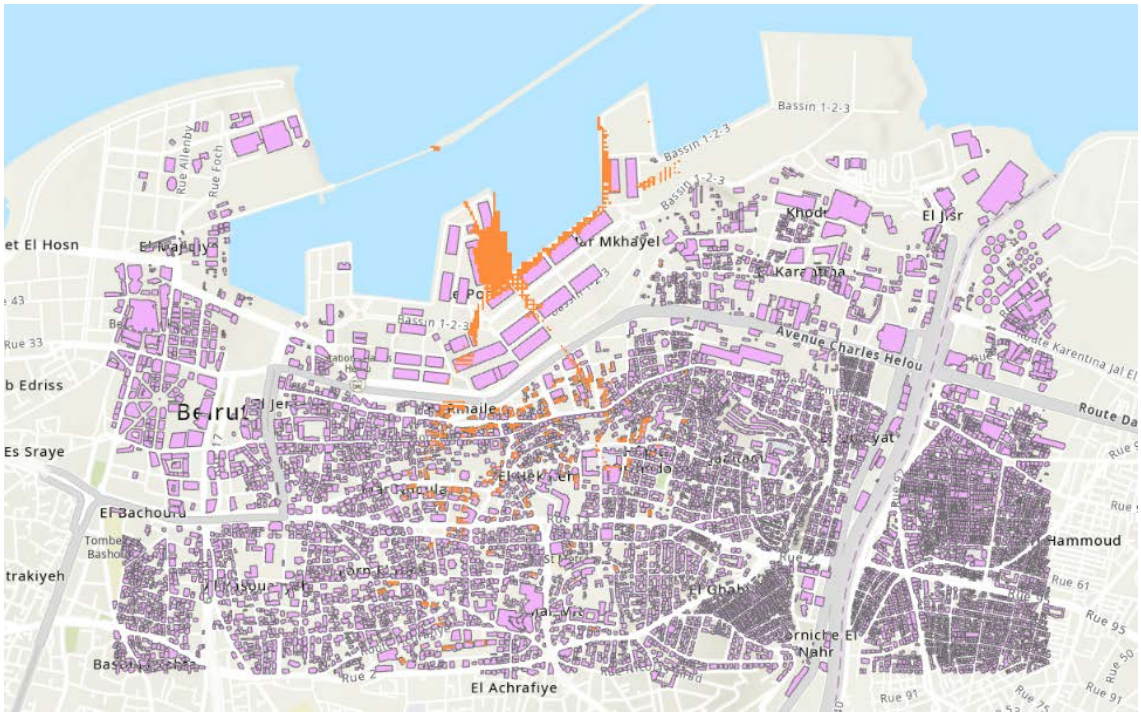


Figure 10. Viewshed map showing in orange the points with a direct line of site from the blast.

CHAPTER IV

DAMAGE CLASS MAPPING

The objective of this thesis is to assign damage classes to the buildings inspected by OEA and analyze their spatial variability to understand how the damage extent depends on the typology, age and height of the structure, its distance from the blast, and whether or not it has a direct line of sight from the blast. To achieve this objective, the processed data is used to assign a damage class to each building. The same structural damage classification used in GEER/AUB-MSFEA surveys is adopted in this thesis (see Table 3). As discussed in the literature review, the classification used is a system adapted from Bray and Stewart (2000) and the European Macroscale 1998. Damage classes ranged from D0 for no observed damages to D5 for complete collapse.

A. Damage Class Based on Damage Description

The mapping of OEA entries to damage classes is divided into three sets of classifications. The first set of classifications is based on the “Damage Description” entries. Table 6 shows the damage class assigned to each damage description entry in accordance with Table 3. Some of the entries, such as cracks in external walls, cracks in inner walls, and cracks in balconies, cannot be accurately mapped onto a single damage class, and thus result in a range of damage classes. A more accurate assignment would require knowledge of the size of cracks and the type of wall that exhibited the crack (e.g., whether it is a bearing wall or a partition wall). For some of the buildings, the OEA groups provided more specific information in the written entries (e.g., specification of the size of cracks and of the type of wall), thus helping us in assigning one damage class instead of a range.

As a result, based on the OEA damage description entries, each building might be labeled with several damage classes. The maximum damage class or range among them is considered as the damage classification based on damage descriptions. Buildings for which the OEA did not provide any damage description entries (neither ticks nor written) are labeled as “Unclassified” instead of classifying them as “D0”, because these buildings may have sustained some damages that were not be visible to the OEA groups, or because the OEA groups may have left the survey form of that building incomplete.

Moreover, for the cases where the damage description set results in a lower damage classification than the classifications based on the possible hazards and recommended action sets (presented next), then the photos of these buildings are checked (if available). For these buildings, a new damage description entry based on the photos is added in accordance with Table 3, and their damage classification based on damage descriptions is updated to account for the new photo entry.

Table 6. Damage Classes Assigned based on Damage Description Entries.

	Damage Description Entry	Damage Class
Ticked Entries	Complete Collapse	D5
	Partial Collapse	D4
	Complete or Partial Collapse of One or More Slabs	D4
	Collapse of Balconies	D3
	Cracks in External Walls	D1/D2/D3
	Cracks in Inner Walls	D1/D2/D3
	Cracks in Balconies	D1/D2
	Collapse in Façade Arches	D3
	Non-structural Damage	D1/D2
Written Entries	No Damage	D0
	Non-structural Damage to Partitions, Roofs, False Ceilings, Balconies and Arches	D1/D2/D3
	Minor Non-structural Cracks	D1
	Minor Structural Cracks	D2
	Major Non-structural Cracks	D2
	Major Structural Cracks	D3
	Substantial Structural Damage	D3/D4
Photo	Classification based on photo (when necessary)	

B. Damage Class Based on Possible Hazards

The second set of classifications is based on the entries of the "Possible Hazards" the building is exposed to. Table 7 shows the damage class assigned to each possible hazard entry in accordance with Table 3. Some entries were not mapped into a damage class since they do not explicitly reflect what the damages are to the building itself; thus, they are not used in the damage classification (e.g, Danger of falling hazard onto neighboring buildings; Danger of falling hazard onto roads/sidewalks; Danger of falling hazard onto non-structural or public infrastructure (electric, mechanical, water or sewer systems); and Collapse due to debris removal). For some buildings, the OEA groups provided more specific information in the written entries (e.g., specification of the possibility of collapse of structural or non-structural elements). The possibility of collapse of non-structural elements is assigned a damage class (D2), while the

possibility of collapse of structural elements is assigned a damage class (D3) since it reflects a more severe damage to the building. On the other hand, the “No hazards” written entry cannot be mapped with certainty into the (D0) damage class and it is mapped instead into the (D0/D1) damage class range since some damages might have been induced to the building with no hazards shown.

Again, based on the OEA possible hazards entries, each building might be labeled with several damage classes. The maximum damage class or range among them is considered as the damage classification based on possible hazards. Moreover, for the same reasons mentioned for the damage description entries, buildings for which the OEA did not provide any possible hazards entries (neither ticks nor written) are labeled as “Unclassified” instead of classifying them as “D0”.

Table 7. Damage Classes Assigned based on Possible Hazards Entries.

	Possible Hazards Entry	Damage Class
Ticked Entries	Possibility of Building Collapse	D4
	Possibility of Partial Interior or Exterior Collapse	D3
	Collapse of Balconies	D2
Written Entries	No Hazards	D0/D1
	Possibility of Collapse of Non-structural Elements	D2
	Possibility of Collapse of Structural Elements	D3

C. Damage Class Based on Recommended Actions

The third set of classifications is based on the “Recommended Actions” entries. Table 8 shows the damage class assigned to each recommended action entry in accordance with Table 3. A single damage class is assigned to each entry, even though the recommended action entries do not accurately reflect the true state of damages

sustained by the building, which increases the uncertainty in the classification based on this set of entries. For example, the recommended action entries: Evacuation, immediate full scaffolding and immediate partial full scaffolding are mapped into the (D3) damage class, while the full scaffolding during repair works and the partial scaffolding during repair works entries are mapped into the (D2) damage class.

Here too, based on the OEA recommended actions entries, each building might be labeled with several damage classes. The maximum damage class or range among them is considered as the damage classification based on recommended actions. And again here, buildings for which the OEA did not provide any recommended actions entries (neither ticks nor written) are labeled as “Unclassified” instead of classifying them as “D0”. In fact, OEA surveyors filled the damage description entries for most of the buildings, but most of the possible hazards and recommended action entries were kept unfilled; thus, the damage description classification is based on the entries, while the building is “Unclassified” based on the possible hazards and recommended action classifications.

Table 8. Damage Classes Assigned based on Recommended Actions Entries.

Recommended Actions Entry	Damage Class
Evacuation	D3
Immediate Full Scaffolding	D3
Full Scaffolding During Repair Works	D2
Immediate Partial Scaffolding	D3
Partial Scaffolding During Repair Works	D2

D. Final Damage Classification

The final classification, which is used for further analysis, is assigned for each building based on three above-mentioned damage classifications.

In order to obtain the most accurate classification, the strategy described next is adopted for the final damage classification of each building. This classification depends mainly on the damage description entries because it is believed to be the most informative and most reliable classification between the three sets.

If the building has available a classification based on damage description entries, it is used as the final classification. However, if the damage description classification is the wide range (D1/D2/D3), then the classifications based on the possible hazards and recommended action sets are used as well to reduce the final classification range to either (D1/D2) or (D2/D3).

If the building is classified as (D1/D2/D3) based on the damage description entries, the lower range (D1/D2) is used as the final classification in the following cases: (1) the building is unclassified based on both the possible hazards and recommended action entries; (2) the building is unclassified based on one of the possible hazards entries or the recommended action entries, and classified as (D2) or lower based on the other; and (3) the building is classified as (D0/D1) based on the possible hazards entries and classified as (D2) based on the recommended action entries.

If the building is classified as (D1/D2/D3) based on the damage description entries, the upper range (D2/D3) is used as the final classification in the following cases: (1) the building is classified as (D2) based on both the possible hazards and recommended action entries; and (2) the building is classified as (D3) or (D4) on one of the possible hazards entries or the recommended action entries, regardless of what the classification of the other is.

On another hand, if the building is unclassified based on the damage description entries, then the final classification depends on the possible hazards and recommended

action classifications. If one of the latter two is labeled as unclassified, then the other is used as the final classification (except if the possible hazards classification is (D0/D1) and the recommended action classification is unclassified, then the final classification is D0). If both sets have a damage class, then the average damage class between them is used as the final classification.

Finally, if the building is unclassified based on the three sets (damage description, possible hazards, and recommended actions), then the final classification is D0 (Unclassified) to distinguish it from buildings confidently classified as D0 based on survey entries. Note that the photos of buildings with a final classification of D0 (Unclassified) were checked, but they did not provide additional information allowing to assign a different or more precise damage class.

CHAPTER V

DAMAGE CLASSIFICATION RESULTS

A. Preliminary Classification Results

As mentioned in the previous section, the buildings are assigned three distinct damage classes, according to the maximum classification of each of the three sets of entries: damage description, possible hazards, and recommended actions. For the preliminary classification presented in this section, 2,212 buildings (out of 2,354 surveys) are assigned three distinct damage classes based on each of the three sets, ranging from D0 to D5 or unclassified. 101 surveys are not used because there is no structure or there is no data for the structure surveyed, and 41 surveys are not used because the buildings were inspected twice.

The damage classifications of all buildings based on each set are shown in Figure 11. As shown in Figure 11, the classification based on the damage description entries shows that most buildings are classified into a damage class ranging from D0 to D5, while based on the possible hazards and recommended action entries most of the buildings are unclassified. This could be because some of the OEA groups might have filled in only the damage description entries, leaving the possible hazards entries and the recommended action entries unfilled. Moreover, according to the damage description classification, the number of buildings with damage classes D1, D2 and D3 are limited. This is because the information provided for the size of cracks and the type of the walls experiencing the cracks were not clearly indicated in the written damage description entries. For this reason, to account for such uncertainties and the inability to assign a specific damage class, a range of damage classes (e.g., D1/D2 and D1/D2/D3) was assigned for most of the classified buildings. Additionally, damage description

entries explicitly point out the non-damaged buildings “D0”, because many OEA surveys specified buildings that are undamaged by writing it in the written damage description entries. On the other hand, the totally destroyed buildings (D5) are indicated by ticking the “Complete Collapse” entry among the damage description entries. Moreover, it can be noticed that a large number of buildings are classified as partially collapsed (D4) based on the damage description set. This is accurate for some cases, but for several buildings, the OEA groups may have overestimated this input (using it to indicate cases of heavy structural or non-structural damage).

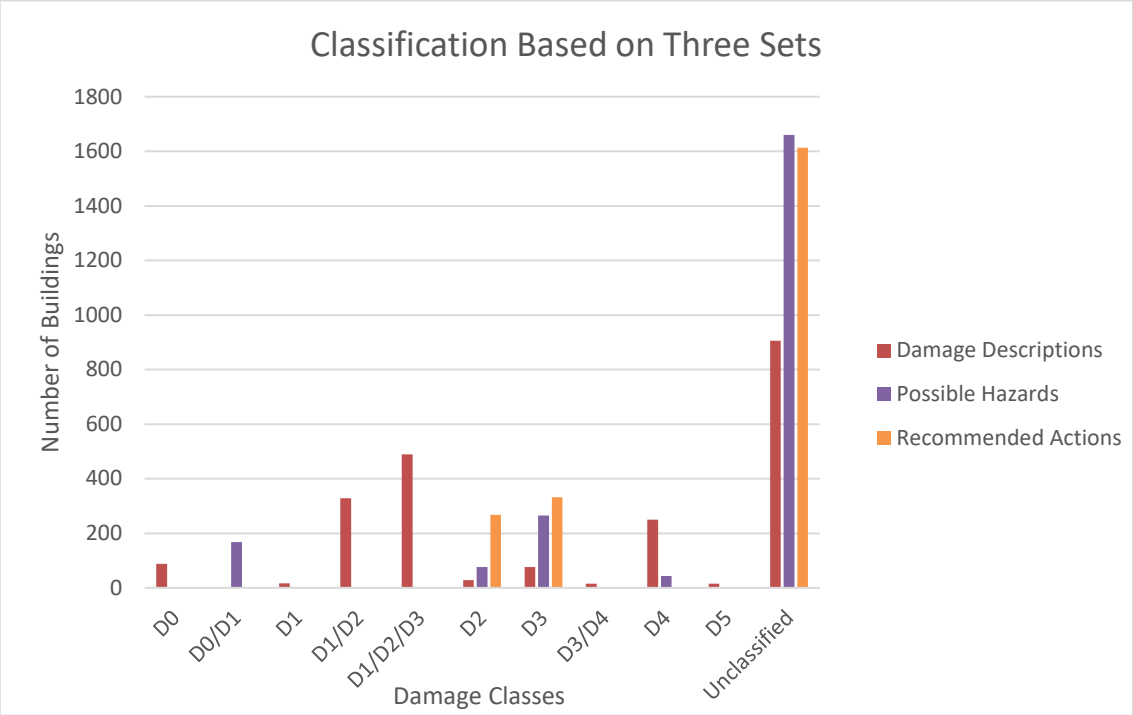


Figure 11. Structural damage classification based on (a) damage descriptions; (b) possible hazards; and (c) recommended actions.

In order to check the consistency of the damage class assigned for each building based on the three sets, the damage class based on the possible hazards entries versus the damage class based on the damage description entries is plotted in Figure 12;

similarly, the damage class based on the recommended action entries versus the damage class based on the damage descriptions entries is plotted in Figure 13; likewise, the damage class based on the recommended action entries versus the damage class based on the possible hazards entries is plotted in Figure 14. In these figures, each point represents the number of inspected buildings (shown next to each point) at the intersection of the classifications based on each of the two considered sets. The solid line indicates classifications that are equal in both sets, and the dashed lines indicate classifications that differ by plus or minus one damage class.

Figure 12 and Figure 13 show that a large number of buildings which are unclassified based on the possible hazards entries and recommended action entries did sustain damages and were classified based on the damage description entries. As mentioned earlier, this gives us an insight that the OEA groups filled the damage description entries, while often keeping the possible hazards and recommended action entries unfilled. Moreover, it is clearly shown that when classifications based on the possible hazards or the recommended actions are available, most of them fall within a range of plus or minus one damage class from the damage classification based on the damage descriptions. However, when the difference is larger, the damage class based on the damage descriptions is usually higher. For this reason, in order to have a conservative (but also more confident) classification, the final classification depends mainly on the damage description entries, as described in the previous chapter.

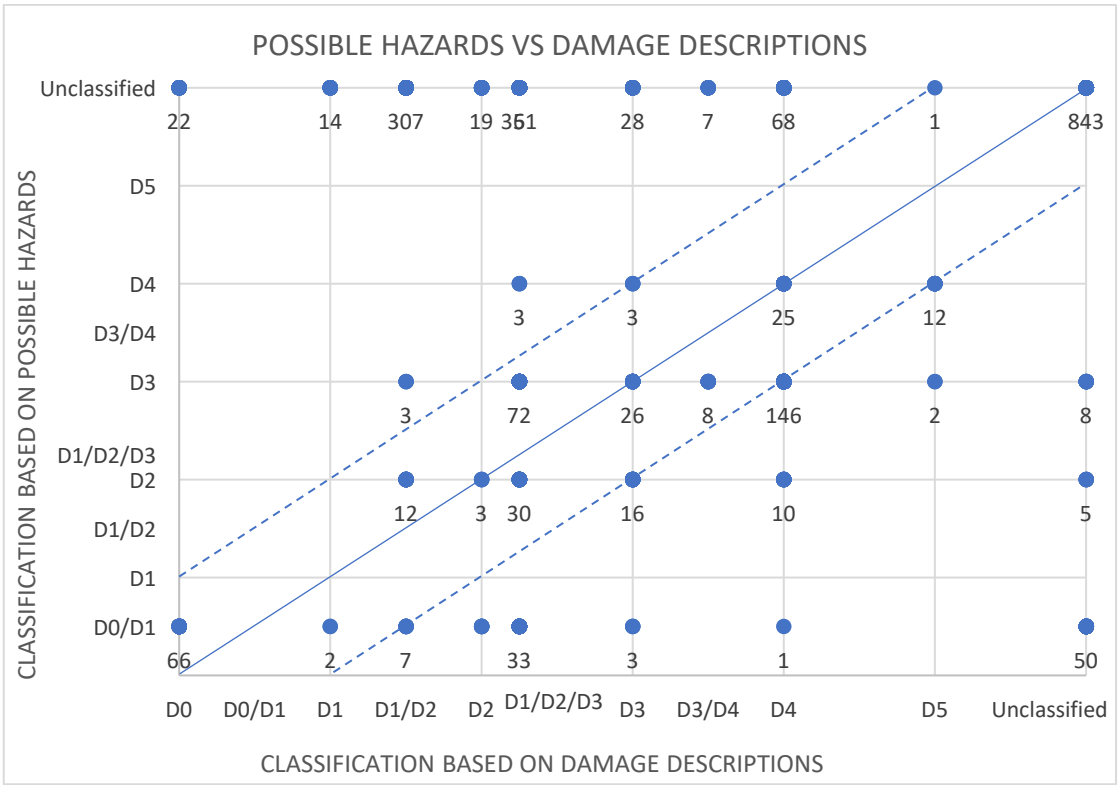


Figure 12. Damage class classification based on possible hazards vs damage descriptions.

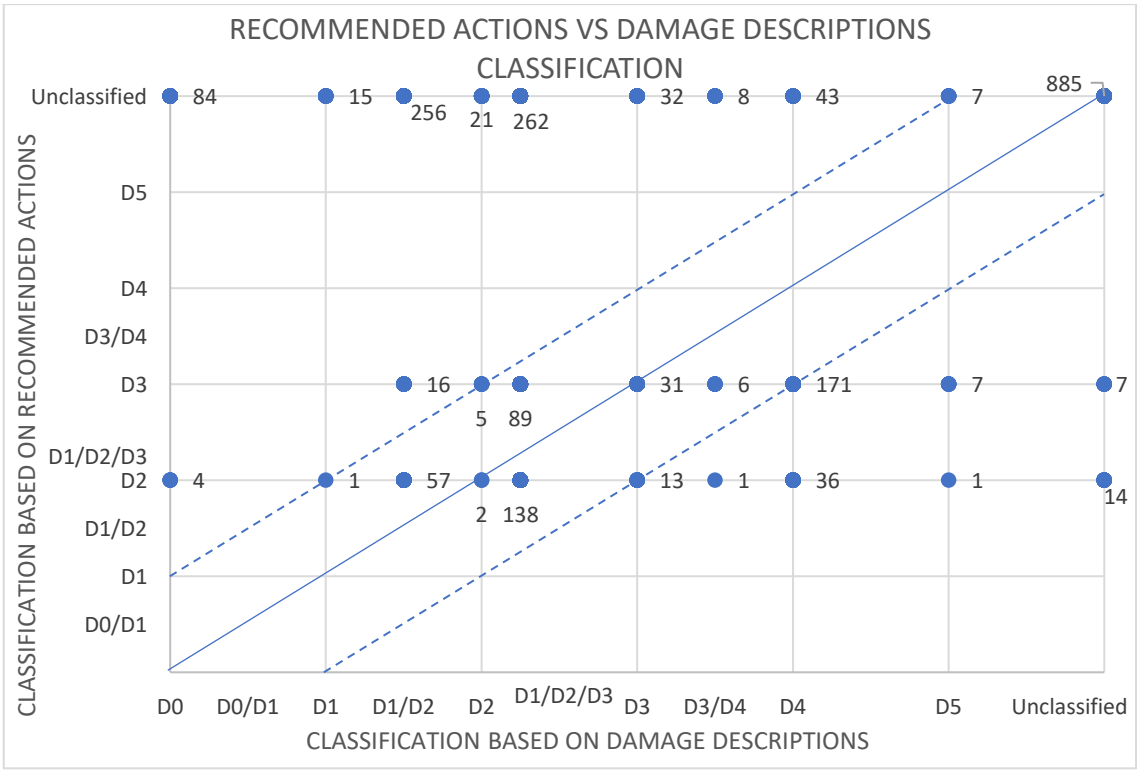


Figure 13. Damage class classification based on recommended actions vs damage descriptions.

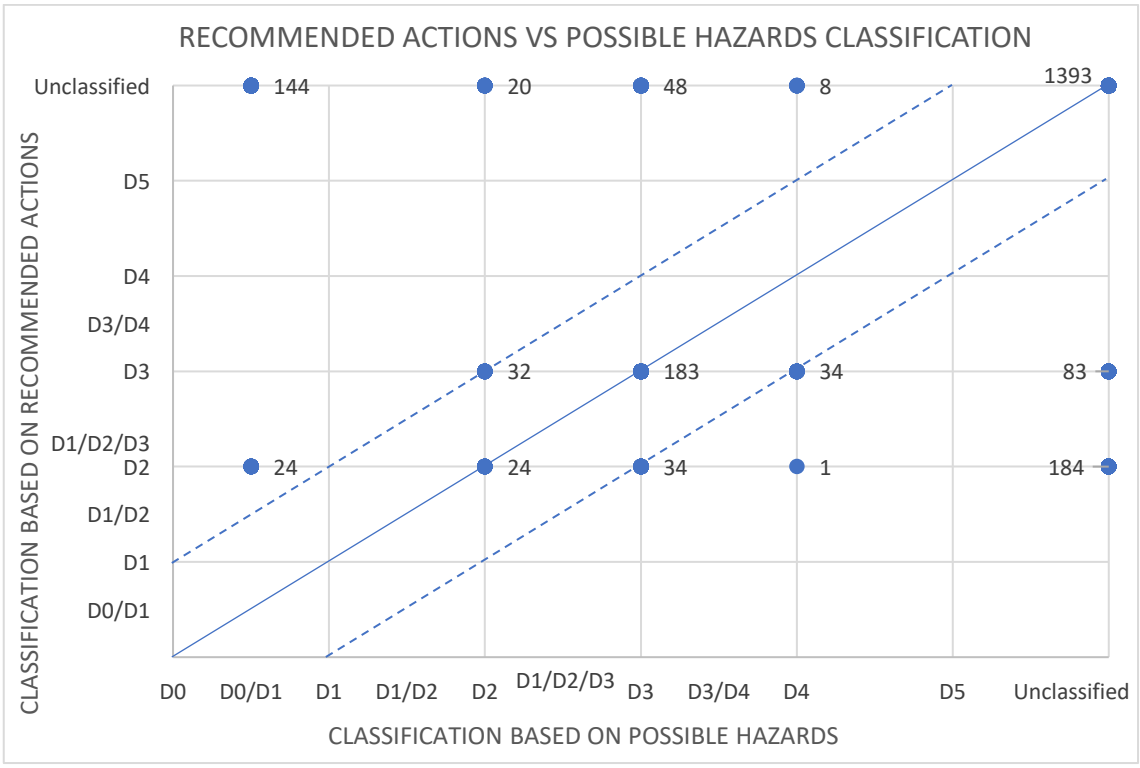


Figure 14. Damage class classification based on recommended actions vs possible hazards.

As mentioned in the previous chapter, a new damage description entry based on photos (when available) is added when the classification based on the damage description set is lower than the classifications based on the possible hazards and recommended action sets. In such cases, the damage classification based on damage descriptions is updated to account for the new photo entry. For example, as shown in Figure 15, the photos clearly show that the steel roof structure is partially collapsed (D4). However, according to the OEA entries shown in Table 9, OEA surveyors ticked only “Non-structural damage” which is mapped to (D1/D2) in the damage description entries, while based on the possible hazards entries and recommended actions entries, their input resulted in a classification of (D3). This example illustrates the value of

adding the new entry “Classification based on photo” to the damage description entries in similar cases.

Figure 15. Partially collapsed (D4) steel structure.

Table 9. Partially collapsed (D4) steel structure entries and damage class mapping.

_45	OEA Survey Entries	Damage Class	Tick	Classification	Final Classification
Damage Description Entry					D4
Ticked Entries	Complete Collapse	D5		D4	
	Partial Collapse	D4			
	Complete or Partial Collapse of One or More Slabs	D4			
	Collapse of Balconies	D3			
	Cracks in External Walls	D1/D2/D3			
	Cracks in Inner Walls	D1/D2/D3			
	Cracks in Balconies	D1/D2			
	Collapse in Façade Arches	D3			
	Non-structural Damage	D1/D2	✓		
Written Entries	No Damage	D0			
	Non-structural Damage to Partitions, Roofs, False Ceilings, Balconies and Arches	D1/D2/D3			
	Minor Non-structural Cracks	D1			
	Minor Structural Cracks	D2			
	Major Non-structural Cracks	D2			
	Major Structural Cracks	D3			
	Substantial Structural Damage	D3/D4			
Photo	Classification based on photo	D4	✓		
Possible Hazards Entry					
Ticked Entries	Possibility of building collapse	D4		D3	
	Possibility of partial Interior or exterior Collapse	D3	✓		
	Collapse of Balconies	D2			
Written Entries	No Hazards	D0/D1			
	Possibility of Collapse of Non-structural Elements	D2			
	Possibility of Collapse of Structural Elements	D3	✓		
Recommended Actions Entry					
Ticked Entries	Evacuation	D3	✓	D3	
	Immediate Full Scaffolding	D3			
	Full Scaffolding During Repair Works	D2			
	Immediate Partial Scaffolding	D3	✓		
	Partial Scaffolding During Repair Works	D2			

Another example of a damage description classification that was updated based on photos is shown in Figure 16. Based on the OEA entries for this structure and the damage class mapping shown in Table 10, the damage description entries has a lower classification (D1/D2) than the possible hazards classification and recommended actions classification (D3). After checking the photos of the building, it is clearly shown that there is heavy non-structural damage (large cracks in infill walls) which should be mapped into a (D3) damage class. Thus, a new entry “Classification based on photo” is added to the damage description entries and it is mapped based on the photo into (D3).

Figure 16. Heavily damaged (D3) RC building

Table 10. Heavily damaged (D3) RC building entries and damage class mapping.

Po_1243	OEA Survey Entries	Damage Class	Tick	Classification	Final Classification
Damage Description Entry					D3
Ticked Entries	Complete Collapse	D5		D3	
	Partial Collapse	D4			
	Complete or Partial Collapse of One or More Slabs	D4			
	Collapse of Balconies	D3			
	Cracks in External Walls	D1/D2/D3			
	Cracks in Inner Walls	D1/D2/D3			
	Cracks in Balconies	D1/D2			
	Collapse in Façade Arches	D3			
	Non-structural Damage	D1/D2	✓		
Written Entries	No Damage	D0			
	Non-structural Damage to Partitions, Roofs, False Ceilings, Balconies and Arches	D1/D2/D3			
	Minor Non-structural Cracks	D1			
	Minor Structural Cracks	D2			
	Major Non-structural Cracks	D2			
	Major Structural Cracks	D3			
	Substantial Structural Damage	D3/D4			
Photo	Classification based on photo	D3	✓		
Possible Hazards Entry					
Ticked Entries	Possibility of building collapse	D4		D3	
	Possibility of partial Interior or exterior Collapse	D3	✓		
	Collapse of Balconies	D2			
Written Entries	No Hazards	D0/D1			
	Possibility of Collapse of Non-structural Elements	D2			
	Possibility of Collapse of Structural Elements	D3			
Recommended Actions Entry					
Ticked Entries	Evacuation	D3		D3	
	Immediate Full Scaffolding	D3			
	Full Scaffolding During Repair Works	D2			
	Immediate Partial Scaffolding	D3	✓		
	Partial Scaffolding During Repair Works	D2	✓		

B. Final Classification Results

Figure 17 shows the number of buildings with their damage class based on the final classification discussed previously.

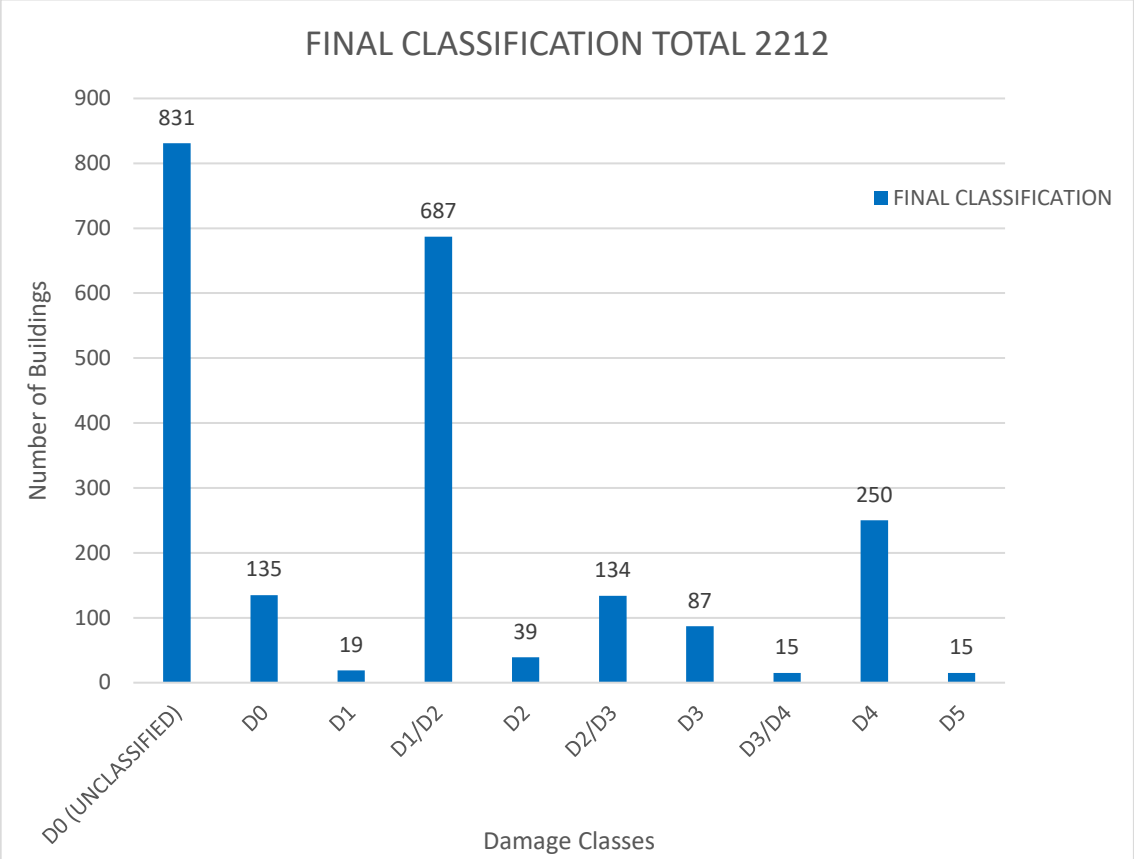


Figure 17. Damage class based on the final classification.

With the aim of validating the final classification, buildings that were inspected by both the OEA and MSFEA are compared (in total 97 buildings). Figure 18 shows the final classification of buildings inspected by the OEA versus the MSFEA classification. Each point represents the number of buildings (which is shown next to each point) at the intersection of the final classifications based on each of the two datasets. The solid

line indicates classifications that are equal in both datasets, and the dashed lines indicate classifications that differ by plus or minus one damage class.

As shown in Figure 18, most of the OEA classifications are within a one damage class from their corresponding MSFEA classification. Cases that differ by more than a single damage class can generally be split into two categories. For some cases, the OEA surveyors probably ticked entries conservatively indicating a higher damage class than the actual level of damage induced to the building (in particular by indicating Partial Collapse (D4) instead of heavy damage (D2 or D3). For other cases, buildings are classified as (D0) based on the OEA classification, while they are classified as (D1/D2) or (D2) based on the MSFEA classification possibly because, contrary to the MSFEA surveyors, the OEA surveyors did not enter most of the buildings, and thus did not observe and document some of the interior damages.

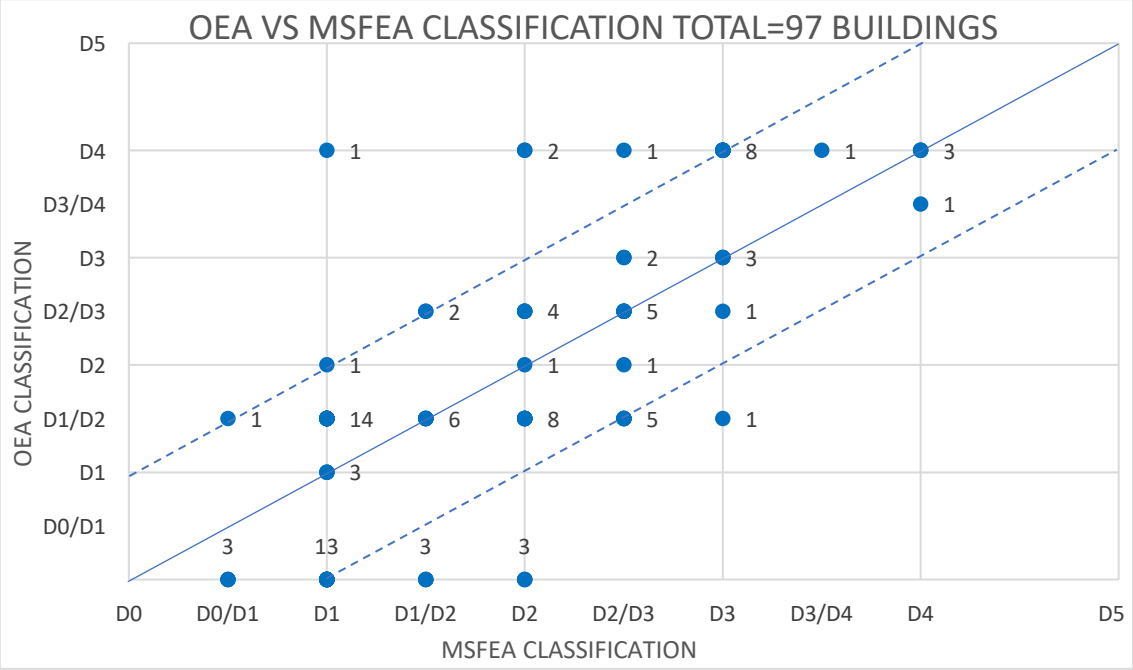


Figure 18. OEA classification versus MSFEA classification

As shown in Figure 18, there is one building which is classified as D4 based on OEA classification, while it is classified D1 based on the MSFEA classification. This shows that for some cases, the OEA groups overestimated the partially collapse (D4) entry. For example, the building shown in Figure 19 has been inspected by OEA and MSFEA. According to the entries shown in Table 11, the OEA surveyors ticked partial collapse for the building which is mapped into the (D4) damage class. However, according to the MSFEA, this buildings is classified (D3). The pictures in Figure 19 show some heavy damages, but none of them supports a partial collapse (D4) of the building. This supports the hypothesis that the OEA surveyors likely overestimated the (D4) damage class for some of the buildings.

Figure 19. RC building classified (D4) and (D3) based on OEA and MSFEA classifications, respectively.

Table 11. RC building inspected by OEA and MSFEA: OEA entries and damage class mapping.

Re_955	OEA Survey Entries	Damage Class	Tick	Classification	Final Classification
Damage Description Entry					
Ticked Entries	Complete Collapse	D5		D4	D4
	Partial Collapse	D4	✓		
	Complete or Partial Collapse of One or More Slabs	D4			
	Collapse of Balconies	D3			
	Cracks in External Walls	D1/D2/D3	✓		
	Cracks in Inner Walls	D1/D2/D3	✓		
	Cracks in Balconies	D1/D2			
	Collapse in Façade Arches	D3			
	Non-structural Damage	D1/D2	✓		
Written Entries	No Damage	D0			
	Non-structural Damage to Partitions, Roofs, False Ceilings, Balconies and Arches	D1/D2/D3			
	Minor Non-structural Cracks	D1			
	Minor Structural Cracks	D2			
	Major Non-structural Cracks	D2			
	Major Structural Cracks	D3			
	Structural Damage	D3/D4			
Possible Hazards Entry					
Ticked Entries	Possibility of building collapse	D4		D3	
	Possibility of partial Interior or exterior Collapse	D3	✓		
	Collapse of Balconies	D2			
Written Entries	No Hazards	D0/D1			
	Possibility of Collapse of Non-structural Elements	D2			
	Possibility of Collapse of Structural Elements	D3			
Recommended Actions Entry					
Ticked Entries	Evacuation	D3		D3	
	Immediate Full Scaffolding	D3	✓		
	Full Scaffolding During Repair Works	D2			
	Immediate Partial Scaffolding	D3			
	Partial Scaffolding During Repair Works	D2			

On another hand, sometimes the photos taken by OEA surveyors do not show the whole and true state of the building. For example, the building shown in Figure 20 and Figure 21 has a consistent damage class (D3) based on OEA and MSFEA. No damages are shown in the photo taken by OEA surveyors (Figure 20), while the photos taken by MSFEA (Figure 21), show the actual damages induced in the building.

Figure 20. Photo taken by OEA of a (D3) classified building according to OEA.

Figure 21. Photos taken by MSFEA of the same building also classified as (D3) by MSFEA.

C. Classification Examples of Damaged Buildings

This section presents a few illustrative examples of buildings with the OEA assessment entries, their corresponding photos, and our processing, damage mapping and final classification. Additional examples are shown in Appendix A. This section helps us to check if the final damage classification and the photos are consistent or not. The interpretation of spatial patterns of the data is presented in the upcoming chapter.

Figure 22 shows a steel structure with a (D5) final damage classification (which is based on the OEA damage description entries and classification), and its entries and damage class mapping are shown in Table 12. As shown in Table 12, according to the damage description classification, the structure is completely collapsed which is mapped into (D5), while based on the possible hazards and recommended action classifications, the building has (D4) and (D3) damage class, respectively. This shows that the damage description classification reflects the true damage state of the structure, while the possible hazards and recommended actions in this case gave a lower damage class than the actual damage shown in the photos.

Figure 23 shows a SM structure with a (D4) damage class, and its entries and damage class mapping are shown in Table 13. The SM building sustained heavy structural damage, namely significant collapse of portion of the building and structural failure of roofs and floors.

Figure 22. Complete collapsed (D5) steel structure.

Figure 23. Partially collapsed (D4) SM building.

Table 12. Complete collapsed (D5) steel structure entries and damage class mapping.

Me_159	OEA Survey Entries	Damage Class	Tick	Classification	Final Classification
Damage Description Entry					D5
Ticked Entries	Complete Collapse	D5	✓	D5	
	Partial Collapse	D4			
	Complete or Partial Collapse of One or More Slabs	D4			
	Collapse of Balconies	D3			
	Cracks in External Walls	D1/D2/D3			
	Cracks in Inner Walls	D1/D2/D3			
	Cracks in Balconies	D1/D2			
	Collapse in Façade Arches	D3			
	Non-structural Damage	D1/D2			
Written Entries	No Damage	D0			
	Non-structural Damage to Partitions, Roofs, False Ceilings, Balconies and Arches	D1/D2/D3			
	Minor Non-structural Cracks	D1			
	Minor Structural Cracks	D2			
	Major Non-structural Cracks	D2			
	Major Structural Cracks	D3			
	Structural Damage	D3/D4			
Possible Hazards Entry					
Ticked Entries	Possibility of building collapse	D4	✓	D4	
	Possibility of partial Interior or exterior Collapse	D3			
	Collapse of Balconies	D2			
Written Entries	No Hazards	D0/D1			
	Possibility of Collapse of Non-structural Elements	D2			
	Possibility of Collapse of Structural Elements	D3			
Recommended Actions Entry					
Ticked Entries	Evacuation	D3	✓	D3	
	Immediate Full Scaffolding	D3			
	Full Scaffolding During Repair Works	D2			
	Immediate Partial Scaffolding	D3			
	Partial Scaffolding During Repair Works	D2			

Table 13. Partially collapsed (D4) SM structure entries and damage class mapping.

Me_142	OEA Survey Entries	Damage Class	Tick	Classification	Final Classification
Damage Description Entry					D4
Ticked Entries	Complete Collapse	D5		D4	
	Partial Collapse	D4	✓		
	Complete or Partial Collapse of One or More Slabs	D4			
	Collapse of Balconies	D3			
	Cracks in External Walls	D1/D2/D3	✓		
	Cracks in Inner Walls	D1/D2/D3	✓		
	Cracks in Balconies	D1/D2			
	Collapse in Façade Arches	D3			
	Non-structural Damage	D1/D2	✓		
Written Entries	No Damage	D0			
	Non-structural Damage to Partitions, Roofs, False Ceilings, Balconies and Arches	D1/D2/D3			
	Minor Non-structural Cracks	D1			
	Minor Structural Cracks	D2			
	Major Non-structural Cracks	D2			
	Major Structural Cracks	D3			
	Structural Damage	D3/D4			
Possible Hazards Entry					
Ticked Entries	Possibility of building collapse	D4	✓	D4	
	Possibility of partial Interior or exterior Collapse	D3			
	Collapse of Balconies	D2			
Written Entries	No Hazards	D0/D1			
	Possibility of Collapse of Non-structural Elements	D2			
	Possibility of Collapse of Structural Elements	D3			
Recommended Actions Entry					
Ticked Entries	Evacuation	D3	✓	D3	
	Immediate Full Scaffolding	D3	✓		
	Full Scaffolding During Repair Works	D2	✓		
	Immediate Partial Scaffolding	D3			
	Partial Scaffolding During Repair Works	D2			

Moreover, the building shown in Figure 24 has a (D2/D3) damage class based on OEA classification, while it is classified (D3) based on MSFEA. The OEA entries and mapping are shown in Table 14. The upper bound (D2/D3) of the damage description classification, which is (D1/D2/D3), is considered as the final classification since both the possible hazards and recommended action classifications assign a (D3) damage class. As seen in Figure 24, the building sustained moderate damage mainly cracking to its exterior walls.

Also, Figure 25 shows a modern high-rise RC structure with a (D1/D2) damage classification based on OEA classification and (D2) damage classification based on MSFEA. The OEA entries and damage class mapping of the building are shown in Table 15. This building sustained moderate damage to non-structural components (e.g., cladding and false ceilings), but no apparent structural damage.

The examined examples show that the final classification is overall acceptable, possibly conservative in some cases (as mentioned before). The damage description classification, which is mostly the basis for the final classification, generally gives better insights about the damages induced in each building compared to the possible hazards and recommended actions classifications. Meanwhile, the photos taken by OEA surveyors do not always illustrate or support the damage entries marked in the surveys; they usually only show the whole building rather than focusing on illustrating the damages.

Figure 24. (D2/D3) RC building.

Figure 25. Modern RC (D1/D2) building.

Table 14. (D2/D3) building entries and damage class mapping.

Me_53	OEA Survey Entries	Damage Class	Tick	Classification	Final Classification
Damage Description Entry					D2/D3
Ticked Entries	Complete Collapse	D5		D1/D2/D3	
	Partial Collapse	D4			
	Complete or Partial Collapse of One or More Slabs	D4			
	Collapse of Balconies	D3			
	Cracks in External Walls	D1/D2/D3	✓		
	Cracks in Inner Walls	D1/D2/D3	✓		
	Cracks in Balconies	D1/D2	✓		
	Collapse in Façade Arches	D3			
	Non-structural Damage	D1/D2			
Written Entries	No Damage	D0			
	Non-structural Damage to Partitions, Roofs, False Ceilings, Balconies and Arches	D1/D2/D3			
	Minor Non-structural Cracks	D1			
	Minor Structural Cracks	D2			
	Major Non-structural Cracks	D2			
	Major Structural Cracks	D3			
	Structural Damage	D3/D4			
Possible Hazards Entry					
Ticked Entries	Possibility of building collapse	D4		D3	
	Possibility of partial Interior or exterior Collapse	D3	✓		
	Collapse of Balconies	D2			
Written Entries	No Hazards	D0/D1			
	Possibility of Collapse of Non-structural Elements	D2			
	Possibility of Collapse of Structural Elements	D3			
Recommended Actions Entry					
Ticked Entries	Evacuation	D3	✓	D3	
	Immediate Full Scaffolding	D3			
	Full Scaffolding During Repair Works	D2			
	Immediate Partial Scaffolding	D3			
	Partial Scaffolding During Repair Works	D2	✓		

Table 15. Modern high-rise RC (D1/D2) building entries and damage class mapping.

Me_77	OEA Survey Entries	Damage Class	Tick	Classification	Final Classification
Damage Description Entry					D1/D2
Ticked Entries	Complete Collapse	D5		D1/D2	
	Partial Collapse	D4			
	Complete or Partial Collapse of One or More Slabs	D4			
	Collapse of Balconies	D3			
	Cracks in External Walls	D1/D2/D3			
	Cracks in Inner Walls	D1/D2/D3			
	Cracks in Balconies	D1/D2			
	Collapse in Façade Arches	D3			
	Non-structural Damage	D1/D2	✓		
Written Entries	No Damage	D0			
	Non-structural Damage to Partitions, Roofs, False Ceilings, Balconies and Arches	D1/D2/D3			
	Minor Non-structural Cracks	D1			
	Minor Structural Cracks	D2			
	Major Non-structural Cracks	D2			
	Major Structural Cracks	D3			
	Structural Damage	D3/D4			
Possible Hazards Entry					
Ticked Entries	Possibility of building collapse	D4		Unclassified	
	Possibility of partial Interior or exterior Collapse	D3			
	Collapse of Balconies	D2			
Written Entries	No Hazards	D0/D1			
	Possibility of Collapse of Non-structural Elements	D2			
	Possibility of Collapse of Structural Elements	D3			
Recommended Actions Entry					
Ticked Entries	Evacuation	D3		Unclassified	
	Immediate Full Scaffolding	D3			
	Full Scaffolding During Repair Works	D2			
	Immediate Partial Scaffolding	D3			
	Partial Scaffolding During Repair Works	D2			

CHAPTER VI

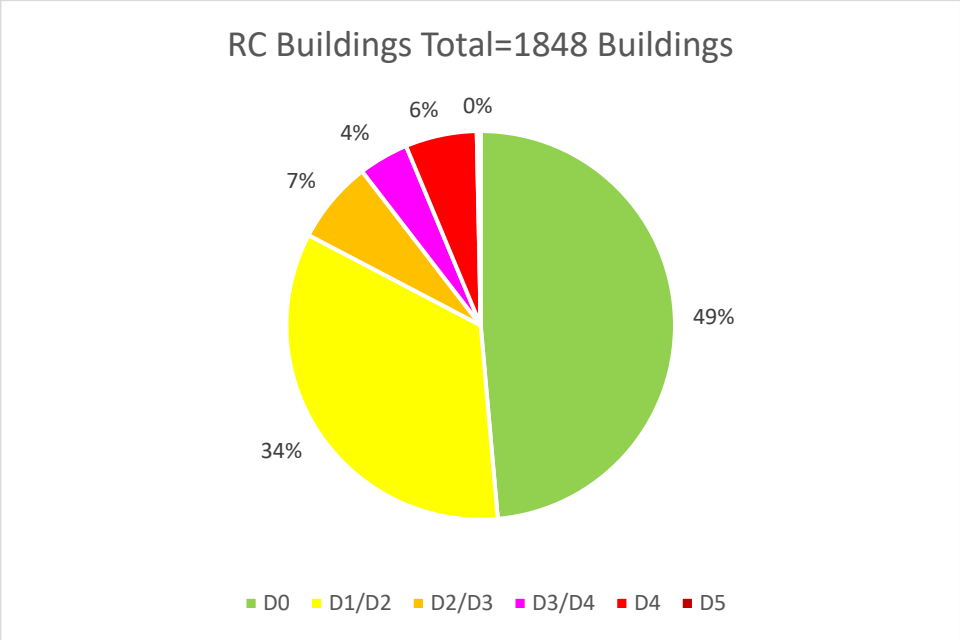
ANALYSIS AND INTERPRETATION

The structural damage in a structure likely depends on the typology of the structure, its construction period, and its location and distance relative to the blast. Therefore, we examine and discuss in this chapter the trends observed between the damage classification and each of structural typology, construction period and distance. We also compare the damage classification of structures with and without a direct line of sight from the blast because we suspect that this parameter might affect damages. This chapter also discusses the damage classification comparison to DPMs. It should be noted that for all the upcoming figures, the damage classes are combined as follows: “D0” includes damage classes D0 and D0(Unclassified), “D1/D2” includes D1 and D1/D2, “D2/D3” includes D2 and D2/D3, “D3/D4” includes D3 and D3/D4, while the “D4” and “D5” damage classes are not combined.

A. Damage Classification V.S Structural Typology

The major two types of structures in Beirut are stone masonry (SM) buildings and reinforced concrete (RC) buildings. Based on the OEA assessments, a total of 1,814 RC buildings, 332 SM buildings, 23 RC+SM buildings, 11 RC+steel, and 32 steel buildings were inspected. The number of steel buildings is limited and they are thus removed from the analysis of this chapter. As for RC+SM and RC+steel buildings, they are combined with RC buildings for the purposes of this analysis. Figure 26 and Figure 27 illustrate the distribution of damage classes D0 to D5 within RC structures and SM structures, respectively. It is clearly shown from Figure 26 and Figure 27 that SM buildings generally suffered more damage than RC buildings. SM buildings sustained

full collapse (D5) damage class while RC buildings merely suffered full collapse. More than 35% of SM buildings are classified (D4) which reflects a partial collapse, while only 6% of RC buildings are classified (D4). Moreover, around 50% of RC buildings sustained no damage (D0), yet only 20% of SM buildings sustained no damage (D0). It can be concluded that SM buildings sustained higher levels of damages, which is likely



a consequence of their structural design and material quality.

Figure 26. Damage class distribution for RC buildings.

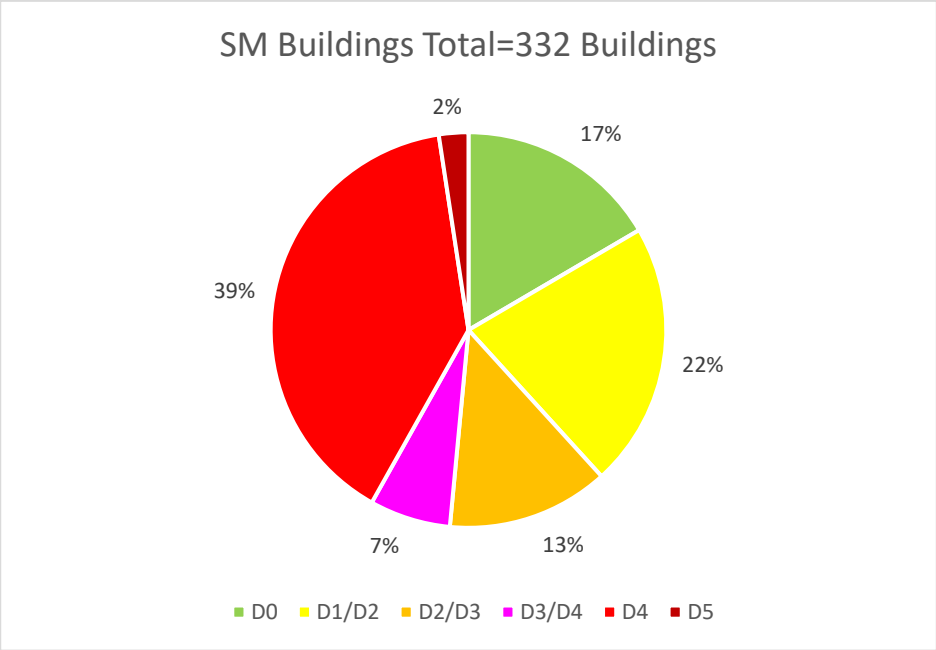


Figure 27. Damage class distribution for SM buildings.

B. Damage Classification V.S Construction Period

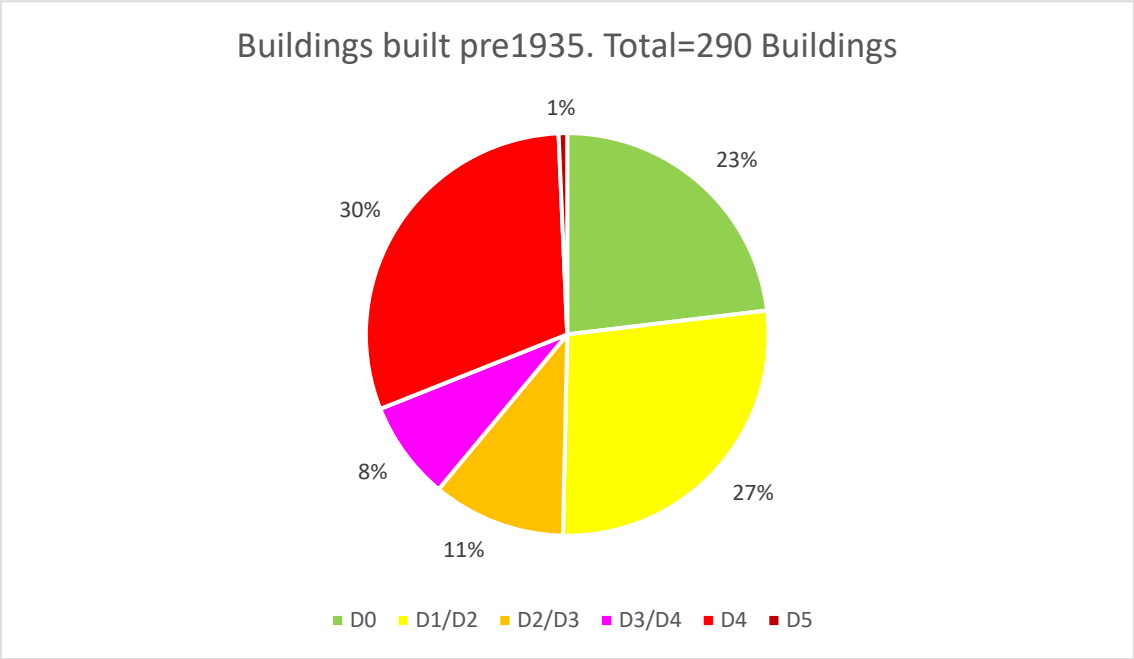
Beirut has a rich architectural heritage with structures from several construction eras. Structures constructed prior to 1930s were typically low-rise stone masonry bearing wall buildings. In the 1930s, reinforced concrete started being introduced, and then mid-rise reinforced concrete frame structures started to emerge. During the civil war (1975-1990), several buildings in Lebanon may have suffered from lack of quality control on their design, materials and construction. Moreover, despite Lebanon's known seismic activity, most buildings in Beirut were designed to withstand gravity loads exclusively, with little or no regard for lateral resistance. Seismic codes were eventually developed in the 1990s, but were not strictly enforced until 2013 (Sadek et al., 2022).

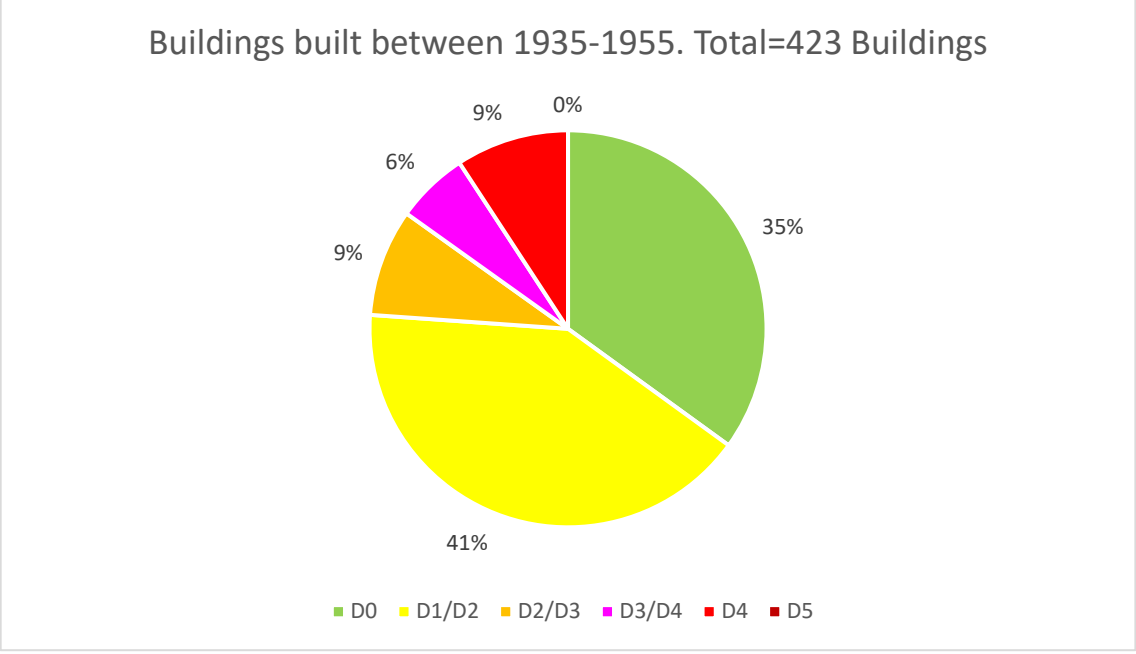
As mentioned in Chapter 3, a total of 1,883 buildings were labeled with one of the following construction periods: Pre1935; 1935-1955; 1956-1971; 1972-1990 and post1990. They construction periods were either assigned by Prof. Aram Yeretzian and

recent graduates from the Architecture department of MSFEA at AUB, by checking the building street-view photos provided by OEA surveyors (in the framework of the Masters thesis of CEE graduate student David Wardan), or obtained from the dataset of a UNESCO-funded BUL project on Identifying Cultural Heritage Attributes in Beirut Blast Damaged Areas.

Since the age of the building directly influences the structural integrity and efficiency, the damage class versus the construction period must be analyzed. Figure 26 shows the damage class distribution versus the construction period of each building for: (a) buildings built pre1935; (b) buildings built between 1935-1955; (c) buildings built between 1956-1971; (d) buildings built between 1972-1990; and (e) buildings built post1990. As it can be deduced from Figure 28, buildings built pre1935 sustained high levels of damage, often reaching partially collapsed (D4) and fully collapsed (D5) classes. The reason is that during this era, all buildings were SM, and RC buildings were not introduced yet.

As also observed from Figure 28, more than 50% of buildings built between 1972-1990 and post 1990 had no damage (D0), and more than 25% of these buildings sustained only low damage classes (D1/D2). These buildings rarely sustained high levels of structural damages, since most of these buildings are RC buildings. Moreover, structures built post 1990 are generally seismically designed, so more resistant to lateral loads (including blasts). When damages were observed in these buildings, they were mostly non-structural.


Buildings built pre1935. Total=290 Buildings
1%
23%
30%
8%
27%
11%
D0
D1/D2
D2/D3
D3/D4
D4
D5


Buildings built between 1935-1955. Total=423 Buildings
9%
0%
6%
35%
9%
41%
D0
D1/D2
D2/D3
D3/D4
D4
D5

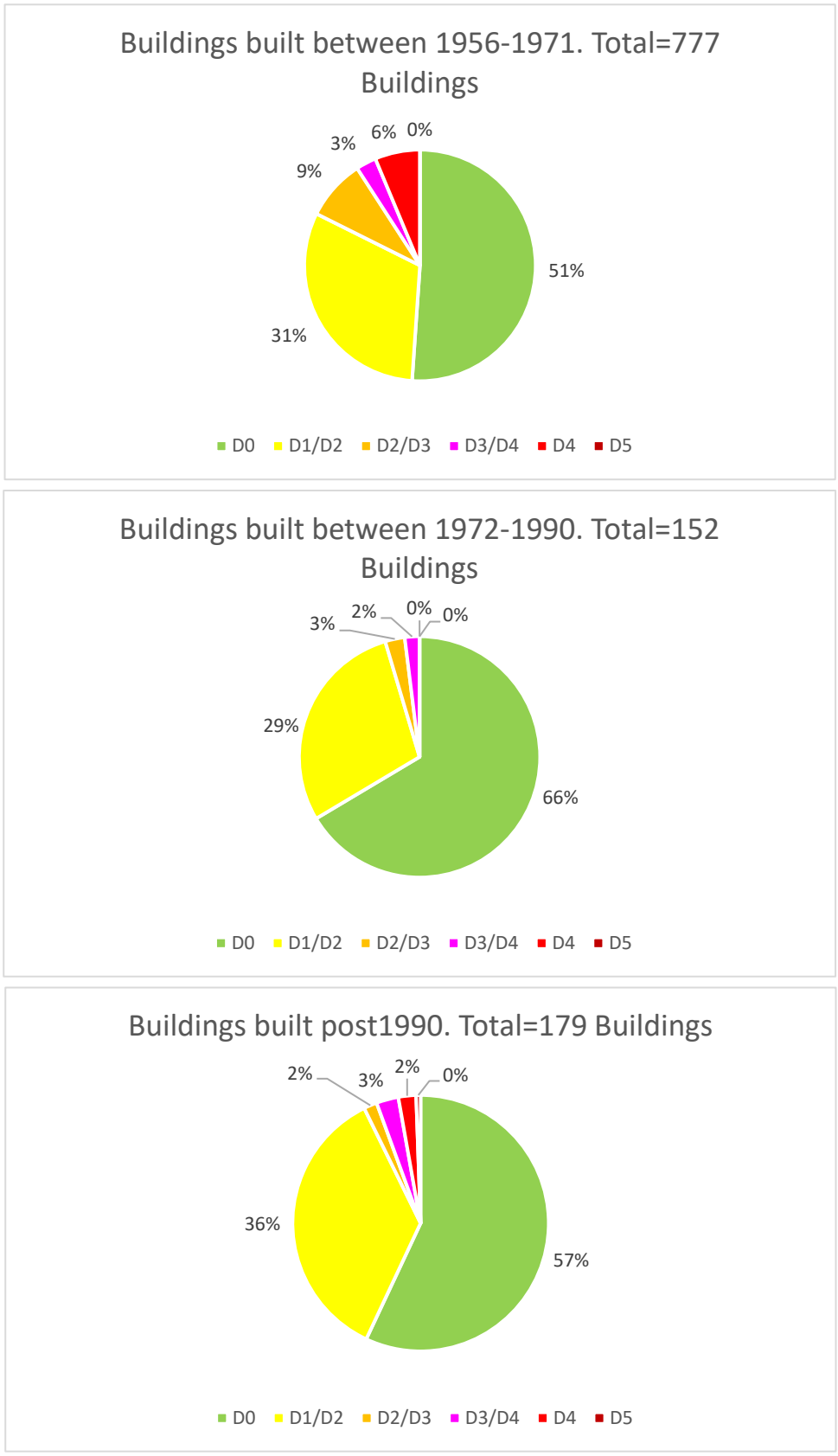


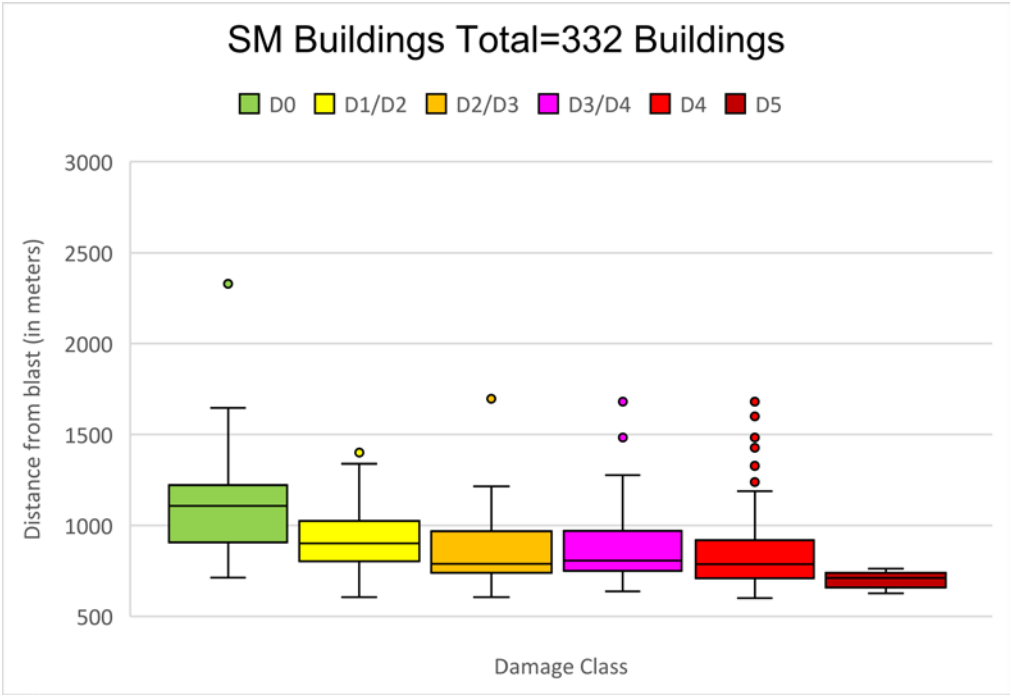
Figure 28. Damage class distribution for buildings built in (a) pre1935; (b) 1935-1955; (c) 1956-1971; (d) 1972-1990 and (e) post1990.

C. Damage Classification V.S Distance from Blast

Figure 29 shows the distribution of damage classes D0 to D5 with distance from the blast for the two types of structures, RC and SM buildings (represented by box and whisker plots). For the box and whisker plots, the two ends of the boxes represent the upper and lower quartiles, which shows that 25% of the data are greater than the upper quartile value and 25% of the data are smaller than the lower quartile value. The horizontal line inside the box represents the median value, and the two whiskers represent the minimum and maximum values within each damage class, excluding the outliers. The outliers are the points located outside the whiskers. They are data points having extreme values that differ from most other data points in a dataset. They can have a big impact on the statistical analyses if they are considered within the data of the whisker.

All buildings assessed by OEA were mostly within 2km from the blast. As shown in Figure 29, for both types of structures, SM and RC, buildings that suffered full collapse (D5) were located within 700m from the blast. This also applies to steel structures. For example, the steel structure with a (D5) damage class shown in Figure 22 is located at ~ 500 m from the explosion.

In general, the most severe damage classes (D5) and (D4) occurred at closer distances from the blast, with less severe damage classes (D0), (D1/D2) and (D2/D3) occurring at greater distances. In general, SM buildings suffered more damage than RC buildings at a similar distance from the blast. However, there could also be a few complicating factors such as shielding, i.e., whether there is a direct line of sight with the blast or not, that could have hampered the natural attenuation of damage class with distance. This factor is explored next.



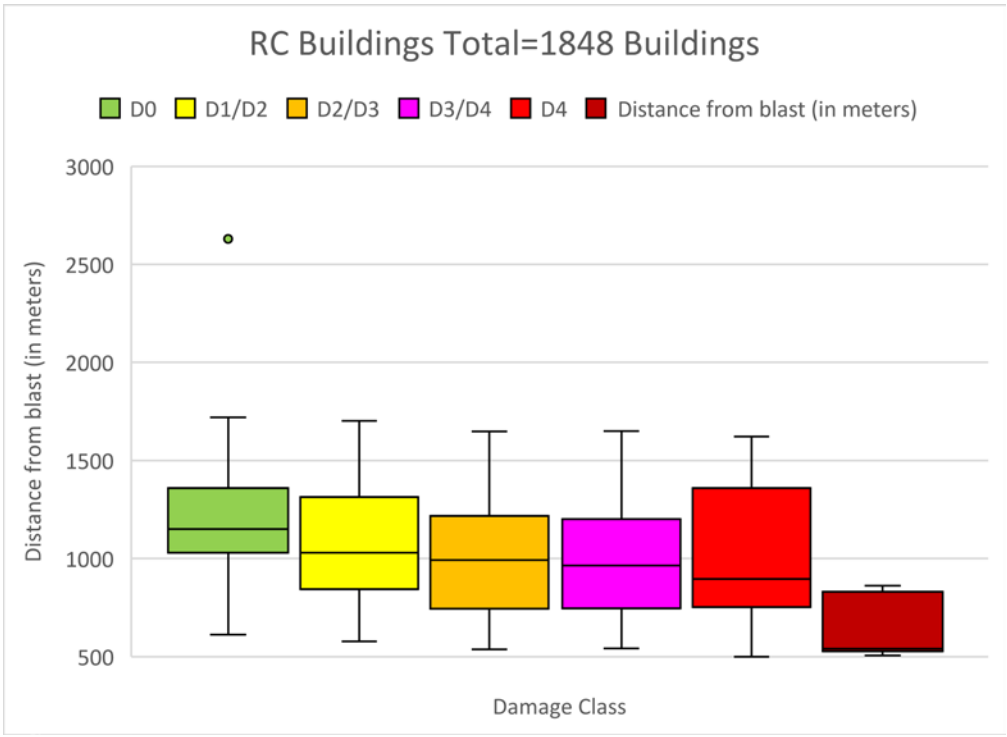


Figure 29. Damage class distribution versus distance from blast for (a) SM buildings and (b) RC buildings.

D. Damage Classification V.S Presence or Absence of Direct Line of Sight

Figure 30 shows the distribution of damage classes D0 to D5 for buildings with and without a direct line of sight from the blast. As it can be deduced from Figure 30, only 174 buildings are visible to the blast, and they generally sustained higher levels of damage compared to blocked buildings. Buildings that had a fully collapsed (D5) class were visible to the blast. As also observed, around 45% of buildings being blocked to the blast had no damage (D0), and 31% of these buildings sustained low damage classes (D1/D2), while for visible buildings, only 29% of them sustained no damage (D0) and a greater proportion of 47% sustained low damage classes (D1/D2). The reason for this difference could be the shielding of tall intervening structures that could have hampered the propagation of the blast pulse throughout the city, resulting in lower damages for blocked buildings. We also note that the presence or absence of a direct line of sight is also strongly correlated with distance from the blast, which could be another factor affecting the observed differences.

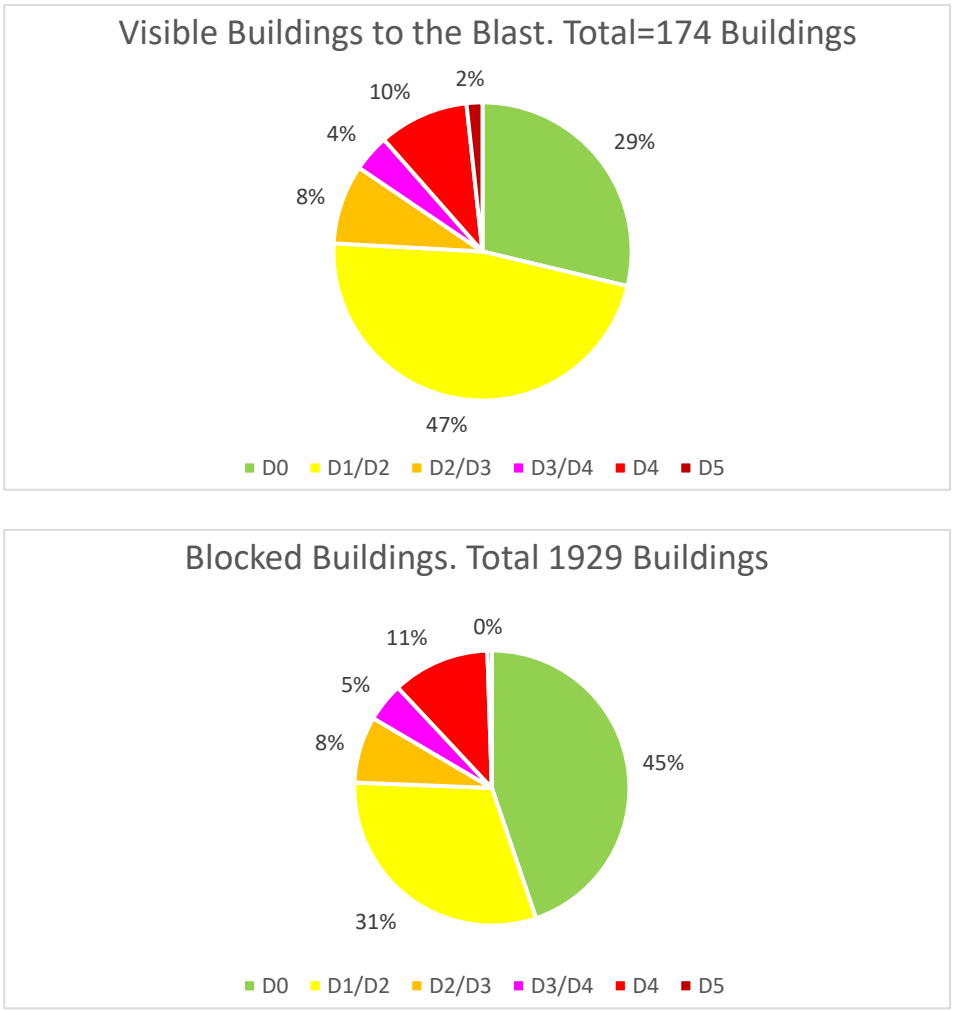


Figure 30. Damage class distribution versus (a) Presence of direct line of sight from the blast and (b) Absence of line of sight from the blast.

E. Damage Classification V.S DPMs

Damage proxy maps (DPMs) are generated following disasters worldwide to show the predicted impact these disasters could have on buildings. DPMs are generated by comparing pre- and post-disaster radar data using a process based on changes in phase statistics of microwaves returning to a satellite (e.g., Fielding et al., 2005; Yun et al., 2011,2015). Following the Beirut blast on August 4, 2020, a DPM was produced for Beirut using SAR data from the Copernicus Sentinel-1 satellites acquired from four different tracks both pre- and post-explosion (Sadek et al., 2021). This DPM was already shown in Figure 2. In that figure, colored pixels represent zones where there was significant change in radar wave scattering at the reflectors, which may indicate damage from the explosion.

Figure 31 is a box and whisker plot highlighting how DPM correlates with structural damage. The DPM has been converted to a numerical index between 0 and 1. DPM index values in the range of 0.75-1 correspond to different colored shadings on the DPM map shown in Figure 2, while the index range of 0-0.75 produces no map shading (Sadek et al., 2021). For this figure, the results of the dual classifications (D1/D2), (D2/D3) and (D3/D4) are combined with the lower classifications (D1), (D2) and (D3), respectively. The undamaged buildings (D0) coincide with a median DPM index value~ 0.8. The damaged buildings coincide with median DPM index values greater than 0.85, and increasing slightly with increasing damage class, reaching 0.9 for fully collapsed structures (D5). The minimum DPM index also tends to increase with increasing damage class. This shows that the DPM index is somehow effective in distinguishing no damaged (D0), damaged (D1, D2, D3 or D4) and fully collapsed (D5) buildings.

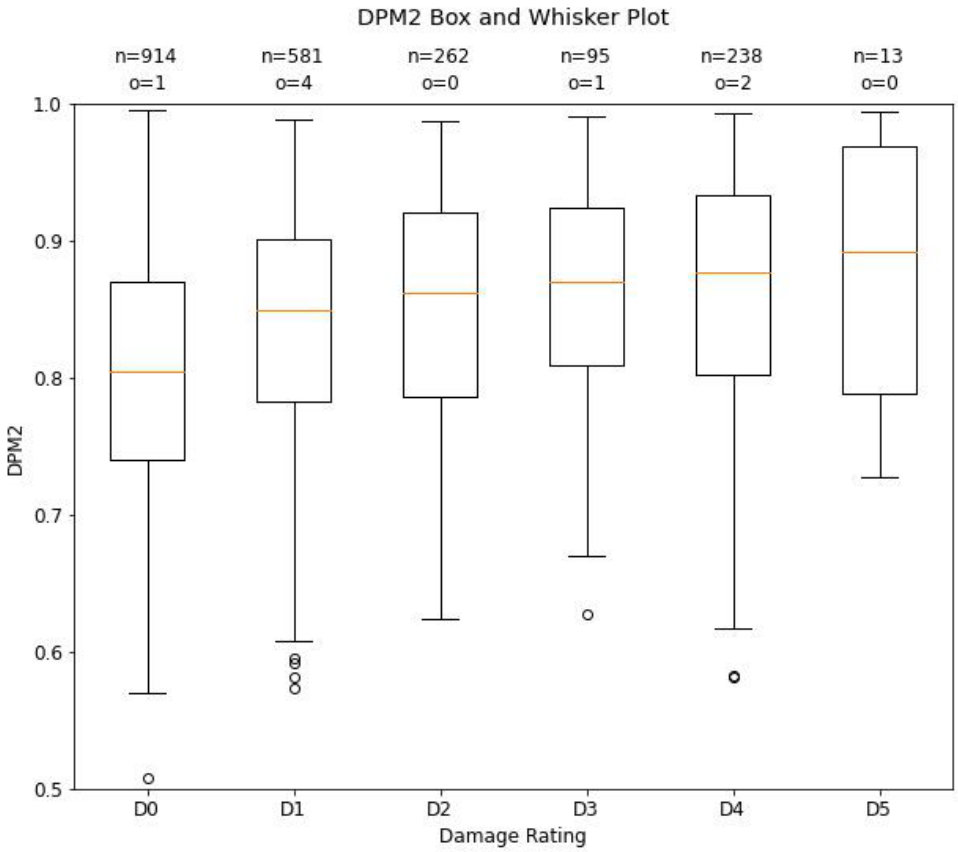


Figure 31. Relationship between numerical index of DPM (0-1) and structural damage classes. Prepared by Timothy M. O'Donnell.

F. Overall Trends in Damage Classification

In the previous subsections, each parameter (Distance from blast, construction period, structural typology, and direct line of sight) is analyzed by itself, and a trend is concluded, while not focusing on other parameters. However, this subsection analyzes the effect of the combination of all parameters at the same time for each building. This can help us to classify buildings post-disasters based on their location, structural typology, age and presence or absence of direct line of sight. For this reason, Table 16 and Table 17 are developed to easily identify the damage class of each building based on its parameters. Table 16 shows the total number of buildings for each case (n), the median of the assigned damage class (Med), the average of the assigned damage class (Avg), and the maximum of the assigned damage class (Max). For example, for a SM building which is built pre1935 and is located at a distance 500-800 m from the blast with absence of direct line of sight with the blast (DLS=0), then the damage class assigned for such building has a median of 4 which reflects a D4 damage class. However, if the building is RC, but all other parameters are the same (Built pre1935, distance from blast 500-800 m, and absence of direct line of sight), then the damage class assigned for such building has a median of 2.5 which reflects a D2/D3 damage class. This shows that for the same distance, SM buildings sustained higher damage classes than RC buildings.

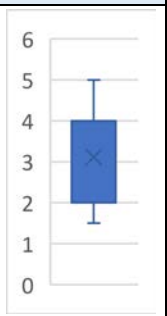
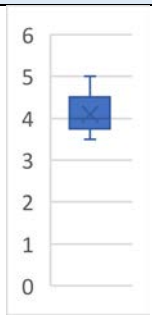
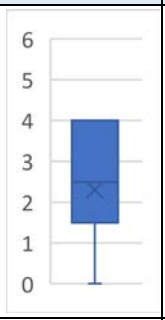
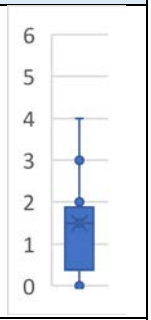
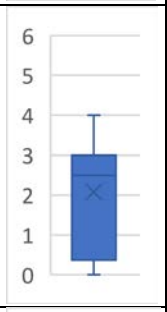
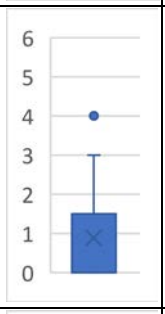
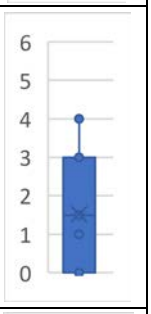
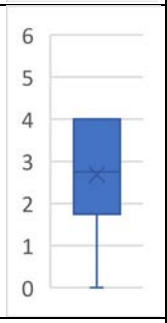
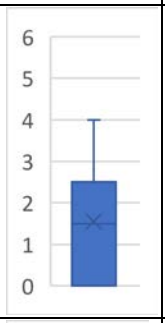
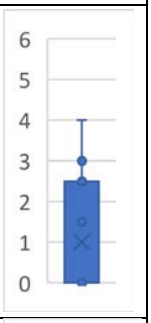
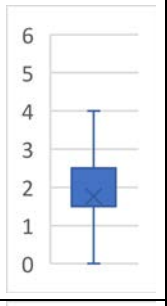
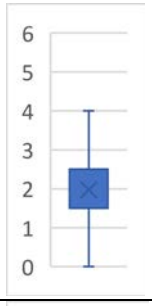
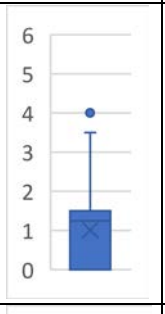
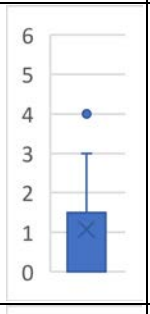
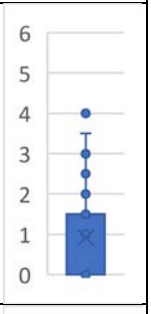
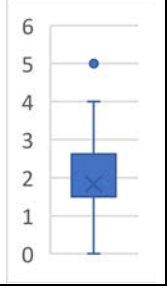
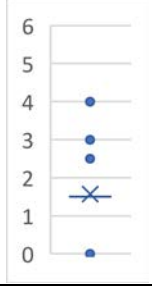
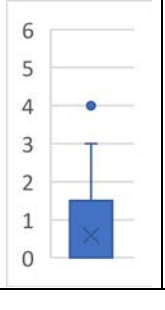
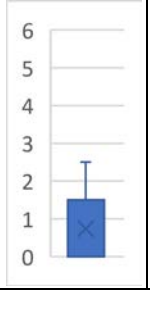
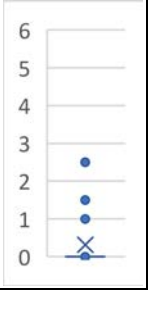
Furthermore, for the same building, if it is SM building built between 1935-1971 and located between 800-1200 m away from the blast, the assigned damage class differs if there is a direct line of sight with the blast or not. If there is absence of direct line of sight (DLS=0), then the median of damage class is 1.5 which reflects damage class D1/D2, but if there is presence of direct line of sight (DLS=1), then the median of damage class increases to 2.75 which reflects a damage class in the range D2/D3. This also shows that the presence or absence of direct line of sight effects the classification of each building.

Moreover, Table 17 shows a box and whisker plot for each case analyzed. It clearly shows the median and maximum of each case. In general, for the same type of building, with same distance and age, the damage class increases if there is a direct line of sight with blast or not. Also, the age of structure plays a major role in the damage classification of each structure. If all parameters are fixed, as the building age increases, the damage class increases as well. Moreover, the damage class increases if the structure is SM rather than RC while keeping all other parameters fixed.

Table 16. Total, median, average and maximum of overall trends in damage classification.

	Distance	500-800 m		800-1200 m		1200+ m
Construction Period	Type	DLS=0	DLS=1	DLS=0	DLS=1	DLS=0
Pre 1935	SM	n=73 Med=4 Avg=3.1 Max=5	n=5 Med=4 Avg=4.1 Max=5	n=101 Med=2.5 Avg=2.29 Max=4	n=2 Med=2.7 Avg=2.7 Max=4	n=12 Med=1.5 Avg=1.5 Max=4
	RC	n=12 Med=2.5 Avg=2.08 Max=4	n=4 Med=2 Avg=2 Max=2.5	n=56 Med=0 Avg=0.88 Max=4	n=0	n=25 Med=1.5 Avg=1.52 Max=4
1935-1971	SM	n=24 Med=2.75 Avg=2.68 Max=4	n=4 Med=2 Avg=2 Max=4	n=27 Med=1.5 Avg=1.55 Max=4	n=2 Med=2.7 Avg=2.7 Max=4	n=11 Med=0 Avg=1 Max=4
	RC	n=118 Med=1.5 Avg=1.75 Max=4	n=38 Med=1.5 Avg=1.97 Max=4	n=526 Med=1.25 Avg=1 Max=4	n=32 Med=1.5 Avg=1.0 Max=4	n=418 Med=0 Avg=0.9 Max=4
Post 1972	RC	n=26 Med=1.5 Avg=1.82 Max=5	n=23 Med=1.5 Avg=1.56 Max=4	n=113 Med=0 Avg=0.58 Max=4	n=42 Med=0 Avg=0.7 Max=2.5	n=125 Med=0 Avg=0.31 Max=2.5

Table 17. Boxplots for overall trends in damage classifications.

	Distance	500-800 m		800-1200 m		1200+ m
Construction Period	Type	DLS=0	DLS=1	DLS=0	DLS=1	DLS=0
Pre 1935	SM					
	RC					
1935-1971	SM					
	RC					
Post 1972	RC					

CHAPTER VII

CONCLUDING REMARKS

A. Summary and Conclusion

In this thesis, the effects of the disastrous 4 August 2020 explosion on the structural integrity of the Beirut building stock were studied. For this purpose, the survey data collected by the OEA was processed, and irrelevant or incorrect entries were corrected or discarded. The processed data was then used to map each assessed building onto a structural damage class between D0 (no damage) and D5 (complete collapse). To this end, the OEA surveys were analyzed, and three of their sets of entries were focused on: Damage description; Possible Hazards; and Recommended Actions. Each set has several entries, and each entry was mapped into a single damage class or a range of damage classes.

As a preliminary classification, each building was classified three times, based on the maximum damage class from each set. The three classifications were then compared for all buildings. The damage description classification was found to be the most reliable between the three classifications, and was thus used as the final classification. However, for a few cases, the classifications from the three sets were combined to obtain the final classification. For example, when the damage description classification was (D1/D2/D3), the final classification also depended on the possible hazards and recommended actions classifications. The preliminary and final classifications were illustrated for several buildings of different types and having different levels of damage.

The analysis of the final classification data showed that the blast produced varying levels of effects on buildings at blast distances under 2 km in the City of Beirut:

from full collapse to non-structural damages to no damages. The variability of the structural damage is mainly linked with the structural typology, age of building and the distance from the blast. The structures most damaged by the blast (D4 and D5) were sandstone bearing-wall structures and older or deteriorated RC structures. Modern RC structures mostly had no to light damage to their structural elements, but several suffered damages to their non-structural elements (D1, D2 and D3). As expected, the more recent seismically designed RC buildings had better structural performance than older gravity load designed RC buildings at similar distances from the blast. Moreover, buildings that sustained heavy damage or suffered partial or full collapse (D3, D4 and D5) were generally located at distances closer to the blast, while buildings located at distances far from the blast sustained light to moderate damage (D1 and D2). Furthermore, buildings that sustained full collapse (D5) were generally visible to the blast, while most of the buildings which were blocked from the blast had a greater proportion of undamaged buildings (D0) compared to buildings visible to the blast. Finally, a clear trend was observed when comparing damage classes with DPMs, whereby the minimum and median DPM values were found to increase with increasing damage class.

Compared to previous work on the impacts of the Beirut blast on structures in Beirut, this thesis has the advantage of including a much larger dataset (2,212 buildings in this thesis versus 182 buildings considered in Sadek et al., 2022). This larger dataset could be utilized for different purposes by future researchers and academics from different disciplines, opening the door to more effort and research on the impacts of the blast and the factors affecting damage distributions in Beirut.

B. Limitations and Future Work

Even though this work results in an increased database size, one of its limitations is the uncertainty and potential errors in some of the entries. In fact, many of the OEA engineers generally lacked experience collecting damage survey data and were not familiar with international damage classifications. Moreover, the OEA did not provide a common training to all its volunteers about how to fill the surveys forms before sending them to the field. This likely resulted in some differences between surveyors in their interpretations of the various survey entries and their selection of the extent of damages based on their visual assessment. Moreover, in several cases, the ticked and written entries were not accurate enough in showing the actual damage extent to each building, such that a single damage class could not be deduced, and a range was assigned instead. Moreover, in many cases, OEA surveyors did not provide photos of the actual damages induced in each building, and instead provided a photo of the whole building without focusing on the damages.

The OEA data collected and processed to assign a structural damage class for each building can be used in future research. A predictive model can be developed to further study the patterns of the damage class with the structural typology and age of the building, its distance from the blast, and whether or not it had a direct line of sight from the blast. Such a model can also be used to predict structural damages from future blasts of similar magnitude and occurring in cities with similar types of construction, given information about the affected structures and their distance and visibility from the blast source. Moreover, the dataset can be used in a more detailed analysis to study the DPM effectiveness in detecting damages from a blast. On the other hand, the analysis and lessons learned from the collected OEA data can be used to create a tool to assess

structures after disasters to collect data accurately and gain perishable information for post-disasters analysis.

APPENDIX A

Me_84	OEA Survey Entries	Damage Class	Tick	Classification	Final Classification
Damage Description Entry					D5
Ticked Entries	Complete Collapse	D5	✓	D5	
	Partial Collapse	D4			
	Complete or Partial Collapse of One or More Slabs	D4			
	Collapse of Balconies	D3			
	Cracks in External Walls	D1/D2/D3			
	Cracks in Inner Walls	D1/D2/D3			
	Cracks in Balconies	D1/D2			
	Collapse in Façade Arches	D3			
	Non-structural Damage	D1/D2			
Written Entries	No Damage	D0			
	Non-structural Damage to Partitions, Roofs, False Ceilings, Balconies and Arches	D1/D2/D3			
	Minor Non-structural Cracks	D1			
	Minor Structural Cracks	D2			
	Major Non-structural Cracks	D2			
	Major Structural Cracks	D3			
	Substantial Structural Damage	D3/D4			
Possible Hazards Entry					
Ticked Entries	Possibility of building collapse	D4	✓	D4	
	Possibility of partial Interior or exterior Collapse	D3			
	Collapse of Balconies	D2			
Written Entries	No Hazards	D0/D1			
	Possibility of Collapse of Non-structural Elements	D2			
	Possibility of Collapse of Structural Elements	D3			
Recommended Actions Entry					
Ticked Entries	Evacuation	D3	✓	D3	
	Immediate Full Scaffolding	D3			
	Full Scaffolding During Repair Works	D2			
	Immediate Partial Scaffolding	D3			
	Partial Scaffolding During Repair Works	D2			

MSFEA classification: D4

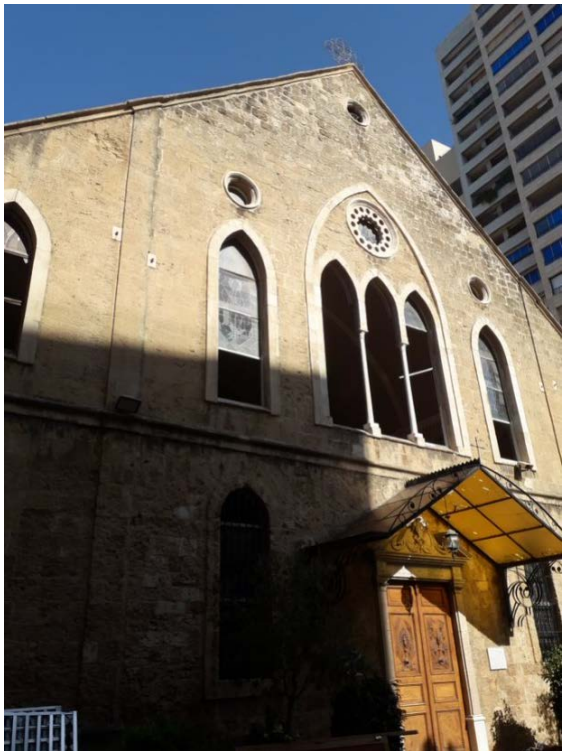
Re_1158	OEA Survey Entries	Damage Class	Tick	Classification	Final Classification
Damage Description Entry					D3/D4
Ticked Entries	Complete Collapse	D5		D3/D4	
	Partial Collapse	D4			
	Complete or Partial Collapse of One or More Slabs	D4			
	Collapse of Balconies	D3			
	Cracks in External Walls	D1/D2/D3			
	Cracks in Inner Walls	D1/D2/D3	✓		
	Cracks in Balconies	D1/D2			
	Collapse in Façade Arches	D3			
	Non-structural Damage	D1/D2			
Written Entries	No Damage	D0			
	Non-structural Damage to Partitions, Roofs, False Ceilings, Balconies and Arches	D1/D2/D3			
	Minor Non-structural Cracks	D1			
	Minor Structural Cracks	D2			
	Major Non-structural Cracks	D2			
	Major Structural Cracks	D3			
	Substantial Structural Damage	D3/D4	✓		
Possible Hazards Entry					
Ticked Entries	Possibility of building collapse	D4		D3	
	Possibility of partial Interior or exterior Collapse	D3	✓		
	Collapse of Balconies	D2			
Written Entries	No Hazards	D0/D1			
	Possibility of Collapse of Non-structural Elements	D2			
	Possibility of Collapse of Structural Elements	D3			
Recommended Actions Entry					
Ticked Entries	Evacuation	D3		Unclassified	
	Immediate Full Scaffolding	D3			
	Full Scaffolding During Repair Works	D2			
	Immediate Partial Scaffolding	D3			
	Partial Scaffolding During Repair Works	D2			

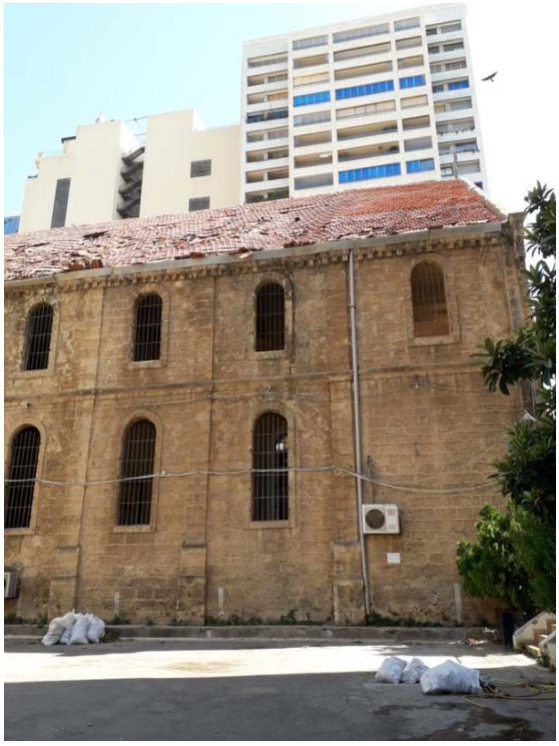
Photos provided by OEA surveyors.

Photos provided by MSFEA.

MSFEA classification: D2/D3

Sa_211	OEA Survey Entries	Damage Class	Tick	Classification	Final Classification
Damage Description Entry					D2
Ticked Entries	Complete Collapse	D5		D2	
	Partial Collapse	D4			
	Complete or Partial Collapse of One or More Slabs	D4			
	Collapse of Balconies	D3			
	Cracks in External Walls	D1/D2/D3			
	Cracks in Inner Walls	D1/D2/D3			
	Cracks in Balconies	D1/D2			
	Collapse in Façade Arches	D3			
	Non-structural Damage	D1/D2			
Written Entries	No Damage	D0			
	Non-structural Damage to Partitions, Roofs, False Ceilings, Balconies and Arches	D1/D2/D3			
	Minor Non-structural Cracks	D1			
	Minor Structural Cracks	D2			
	Major Non-structural Cracks	D2	✓		
	Major Structural Cracks	D3			
	Substantial Structural Damage	D3/D4			
Possible Hazards Entry					
Ticked Entries	Possibility of building collapse	D4		Unclassified	
	Possibility of partial Interior or exterior Collapse	D3			
	Collapse of Balconies	D2			
Written Entries	No Hazards	D0/D1			
	Possibility of Collapse of Non-structural Elements	D2			
	Possibility of Collapse of Structural Elements	D3			
Recommended Actions Entry					
Ticked Entries	Evacuation	D3		Unclassified	
	Immediate Full Scaffolding	D3			
	Full Scaffolding During Repair Works	D2			
	Immediate Partial Scaffolding	D3			
	Partial Scaffolding During Repair Works	D2			

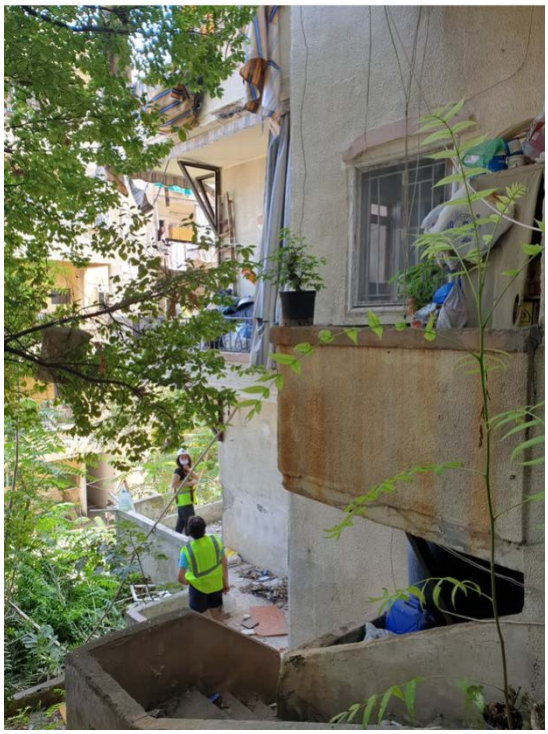




MSFEA classification: D2

Re_1811	OEA Survey Entries	Damage Class	Tick	Classification	Final Classification
Damage Description Entry					D1/D2
Ticked Entries	Complete Collapse	D5		D1/D2/D3	
	Partial Collapse	D4			
	Complete or Partial Collapse of One or More Slabs	D4			
	Collapse of Balconies	D3			
	Cracks in External Walls	D1/D2/D3	✓		
	Cracks in Inner Walls	D1/D2/D3			
	Cracks in Balconies	D1/D2			
	Collapse in Façade Arches	D3			
	Non-structural Damage	D1/D2			
Written Entries	No Damage	D0			
	Non-structural Damage to Partitions, Roofs, False Ceilings, Balconies and Arches	D1/D2/D3			
	Minor Non-structural Cracks	D1			
	Minor Structural Cracks	D2			
	Major Non-structural Cracks	D2			
	Major Structural Cracks	D3			
	Substantial Structural Damage	D3/D4			
Possible Hazards Entry					
Ticked Entries	Possibility of building collapse	D4		Unclassified	
	Possibility of partial Interior or exterior Collapse	D3			
	Collapse of Balconies	D2			
Written Entries	No Hazards	D0/D1			
	Possibility of Collapse of Non-structural Elements	D2			
	Possibility of Collapse of Structural Elements	D3			
Recommended Actions Entry					
Ticked Entries	Evacuation	D3		Unclassified	
	Immediate Full Scaffolding	D3			
	Full Scaffolding During Repair Works	D2			
	Immediate Partial Scaffolding	D3			
	Partial Scaffolding During Repair Works	D2			

1811



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