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ARTICLE

Assessment and Rehabilitation of Damaged Buildings in Historic Benghazi City

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ABSTRACT

The primary focus of the study is to assess and classify the damage in the old Benghazi City. Specifically, it aims to evaluate buildings within a designated area, which is bordered by Umar Ibn Al-Aas Street to the south, Omar Al-Mukhtar Street to the north, Ben Issa Street to the east, and the extension of Gamal Abdel Nasser Street to the west. The main objective is to gather valuable insights and data that can support effective rehabilitation or reconstruction efforts. By comprehending the extent of the damage and categorizing it accordingly, the study seeks to provide essential information for decision-making processes and determine the most appropriate approach for restoration. The ultimate aim is to ensure the safe return of residents to the affected area. In addition to this, the restoration process aims to preserve and revitalize the city's religious, historical, and distinctive features. This includes safeguarding religious structures, landmarks, and elements that contribute to the city's unique identity. To achieve this, the study proposes separate rehabilitation schemes tailored for ordinary buildings and historic buildings.

Keywords: 3D Panels; Buildings; Rehabilitation; Historical buildings; Benghazi City

1. Introduction

The main goal of this study is to evaluate and categorize the damage in the old Benghazi City, which has suffered extensive destruction and is considered the most affected area within Benghazi. Specifically, the study focuses on assessing the region bounded

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by Umar Ibn Al-Aas Street to the south, Omar Al-Mukhtar Street to the north, Ben Issa Street to the east, and the extension of Gamal Abdel Nasser Street to the west (**Figure 1**). The damage is classified into four distinct scenarios based on severity: minimum damage, medium damage (which is deemed rehabilitee), medium to high damage (requiring further study), and buildings that are completely demolished or set to be demolished. The evaluation aims to provide valuable insights and data that will support the effective rehabilitation or reconstruction of the targeted area. By comprehending the scope of the damage and categorizing it accordingly, the study seeks to guide decision-making processes and determine the most suitable course of action for restoration efforts. The ultimate objective is to ensure the safe return of residents to the damaged area. In addition to prioritizing the safety and well-being of the residents, the restoration process aims to preserve and revive the city's religious, historical, and unique features [1]. This entails reconstructing and repairing religious structures, historical landmarks, and other significant elements that contribute to the city's distinct identity. To achieve these objectives, the study proposes two rehabilitation approaches. For ordinary reinforced concrete (RC) buildings, the use of 3D panels is recommended [2,3]. This technique can facilitate the rehabilitation and reconstruction process. For historic buildings, a combination of textile reinforcements and special mortar is suggested. This approach ensures that the restoration maintains the original architectural style and materials, preserving the historical significance of these structures [4-7].

2. Criteria for classification of damage levels in the study

Table 1 provides an overview of the four damage level criteria employed to classify buildings within the study area. Additional information regarding these classifications can be found in sections 2.1 to 2.4.

2.1 Minimum damage or nill (L1)

In this section, the structure has either sustained no damage or only minor damage. It is generally considered to be in good condition and does not require any significant repairs or rehabilitation. Routine maintenance and regular inspections are typically sufficient to ensure its continued functionality and safety. Buildings that exhibit minimal damage are classified as having negligible damage. This includes micro-cracks with a width of less than 0.30 mm and a differential settlement of less than 3 cm. Additionally, the angular rotation of buildings in this category is less than 1/300. Negligible damage typically does not require extensive repairs or structural interventions.

Figure 1. Location of old Benghazi City on the general map.

Table 1. Criteria for classification of damage levels.

Damage level	Classification	Crack width (mm)	Angular rotation
L1	Minimum damage or nill	< 0.30	< 1/300
L2	Medium damage and can be rehabilitated	< 3	1/240 to 1/175
L3	Medium to high damage and needs thorough study	5-10	1/175 to 1/120
L4	Completely demolished or to be demolished	>10	1/120 to 1/70

2.2 Medium damage and can be rehabilitated (L2)

In this section, the structure has experienced moderate damage, which may affect its functionality or structural integrity to some extent. However, it is still deemed feasible to rehabilitate the structure through repairs and improvements. This usually involves assessing the extent of the damage, identifying the necessary remedial actions, and implementing appropriate repair strategies to restore the structure's performance and safety. Buildings categorized as having medium damage are those that still show signs of damage, even after the collapse of 1 or 2 structural elements, however, the damage is localized and still in the elastic range and can be recovered [8,9]. These buildings typically have cracks with a maximum width of 3 mm, experience a differential settlement ranging from 4-5 cm, and exhibit an angular rotation between 1/240 to 1/175. To address this damage, it is crucial to repair and seal both external and internal cracks using appropriate treatment materials and techniques. After the repairs, refinishing work is carried out in the damaged areas. Additionally, there may be a need to reinstall architectural elements, such as walls, doors and windows, once the necessary repairs have been completed.

2.3 Medium to high damage and the structure needs thorough study to decide on rehabilitation or demolition (L3)

In this section, the structure has suffered significant damage, ranging from moderate to high levels. The extent of the damage is substantial enough to warrant a comprehensive evaluation and study of the structure's condition [10]. Structural engineers and experts need to conduct detailed assessments, including structural analysis, material testing, and non-destructive inspections, to determine whether the structure can be effectively rehabilitated or if demolition is the more viable option. Based on the findings, a decision can be made on whether to proceed with rehabilitation efforts or to demolish the structure and rebuild it. Medium to high damage is observed after the collapse of one or more structural elements. It is characterized by cracks ranging from 5-10 mm in width or multiple cracks wider than 3 mm. The differential settlement typically ranges from 5-8 cm, and the angular rotation falls between 1/175 to 1/120. In this category, addressing the damage may involve opening, expanding, and cleaning the cracks before treating them with appropriate repair materials. If the building has brick walls, it may be necessary to replace some bricks and ensure proper refinishing of the walls. Windows and doors may be impacted, service pipes might break, and the effectiveness of insulation could be compromised.

2.4 Structure either completely demolished or to be demolished (L4)

In this section, the structure has either already been completely demolished, or it is determined that demolition is the only feasible course of action due to severe damage, safety concerns, or other factors. This decision is often made when the damage is extensive, compromising the structural integrity to such an extent that rehabilitation is no longer practical or cost-effective. Demolition involves the controlled dismantling or destruction of the structure, making way for potential reconstruction or repurposing of the site. In this case, the collapse of multiple structural elements. It is evident through the presence of large cracks > 10 mm in width. The walls may exhibit significant curvature or even collapse entirely, while the floors could show noticeable slopes or complete failure. Additionally, door and window frames may be visibly distorted. Low-stiffness beams may also be observed in severe damage scenarios. The differential settlement in such cases ranges from 8-13 cm, and the angular rotation falls between 1/120 to 1/70.

3. Results of visual inspection and classification: Assessing damage levels

A rigorous on-site examination was conducted on a substantial number of buildings in the region. These buildings were subsequently classified and evaluated based on the expertise and familiarity of the research participants with the area. A comprehensive inspection was conducted on a total of 300 buildings, which consisted of 80 structures dating back to the Italian colonial era and 220 units constructed in subsequent periods. The findings of the evaluation are presented in **Table 2**.

Table 2. Classification of building damage extent.

Damage level	No. of buildings	% of total
L1	168	56%
L2	83	27%
L3	13	4%
L4	36	13%
Total	300	100%

3.1 Buildings without significant damage

Among the buildings inspected, a subset of 168 structures (56% of the total) fall into this category. The observed damage in these buildings is non or limited to specific architectural elements while maintaining the integrity of their structural components. Examples of these buildings are shown in **Figure 2**.

Figure 2. Examples illustrating buildings without significant damage.

3.2 Buildings with medium damage: Feasibility of rehabilitation

Within the set of examined structures, a subset of 83 buildings, accounting for 27% of the total, have been identified as having medium damage. These buildings display a level of damage that is deemed feasible for rehabilitation to their structural integrity. This rehabilitation process will involve the implementation of appropriate repair techniques, the use of suitable materials, and the application of structural reinforcements where necessary. Illustrative examples are the buildings shown in **Figure 3**.

Figure 3. Examples illustrating buildings with medium damage.

3.3 Damaged buildings requiring further investigation

Within the examined structures, a subset of 13 buildings (4%) necessitates additional studies that involve testing the structural elements and conducting a comprehensive structural analysis. These investigations are crucial for making informed decisions regarding whether to rehabilitate or proceed with demolition and subsequent reconstruction. Illustrative examples are the buildings shown in **Figure 4**.

3.4 Completely demolished or severely damaged buildings

Out of the inspected buildings, a total of 36 structures (13%) were found to be either completely collapsed or severely damaged. These buildings are determined to be beyond repair and necessitate demolition, followed by the reconstruction process. Illustrative examples are the buildings shown in **Figure 5**.

Figure 4. Examples illustrating buildings require further investigation.

Figure 5. Examples illustrating buildings of completely demolished or severely damaged.

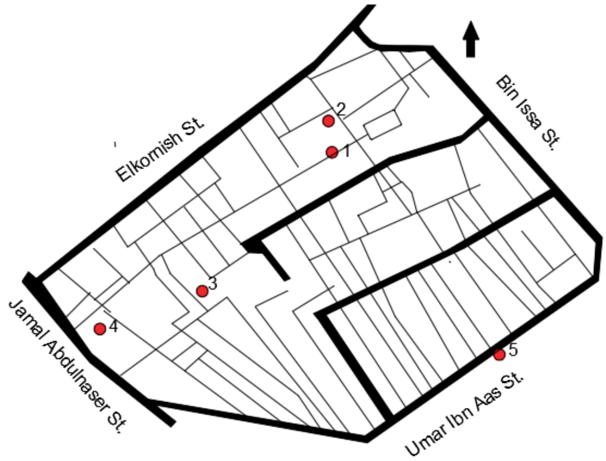
4. Historical buildings in old Benghazi City

A significant proportion of the buildings in this area hold historical importance, primarily dating back to the Italian colonial era. These buildings, with their rich heritage and architectural fabric, are recommended for rehabilitation to ensure the preservation of their historical status. To maintain the cultural value of these historical buildings, it is advised to undertake their rehabilitation using the same architectural style and materials that were originally employed in their construction. This approach not only safeguards their historical integrity but also contributes to the preservation of the overall architectural fabric of the area. Illustrative examples are the buildings shown in **Figure 6**.

Figure 6. Examples illustrating old structure buildings.

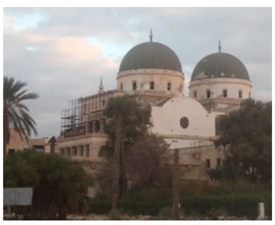
These buildings hold significant historical value within the study area, they are located as shown in **Figure 7**. Photos of the buildings are shown in **Figure 8**. Each building represents a distinct aspect of the region's heritage and cultural identity. Preserving these special buildings is crucial to maintaining the historical fabric and upholding the architectural legacy of the area. These buildings are:

1) Old Mosque
2) Osman Mosque
3) The Cathedral Church
4) Qasr Al-Manar (University of Libya)
5) The Italian Consulate



1. Old Mosque

2. Osman Mosque



3. The Cathedral Church

4. Qasr Al-Manar

5. The Italian Consul

Figure 8. Photos of prominent historical buildings.

5. Rehabilitation materials and techniques

5.1 Rehabilitation of reinforced concrete frame buildings with 3D panels

3D panels, also known as three-dimensional panels or sandwich panels, are prefabricated building components that consist of a lightweight core material (such as foam, polystyrene or honeycomb) sandwiched between two layers of structural material (such as concrete or mortar). These panels are designed to provide strength, rigidity, and insulation to structures. In the context of rehabilitating reinforced concrete frame buildings, 3D panels can offer several advantages:

1) **Strengthening and structural integrity**: By installing 3D panels on the existing concrete frame, the panels can provide additional strength and enhance the structural integrity of the building. This is particularly useful in cases where the original concrete elements have deteriorated or become weak over time.

2) **Seismic resistance**: Reinforced concrete frame buildings are often vulnerable to seismic forces. The use of 3D panels can improve the seismic resistance of the structure by adding stiffness and reducing the chances of structural failure during an earthquake.

3) **Thermal insulation**: 3D panels typically have good insulation properties, which can help improve the energy efficiency of the rehabilitated building. By reducing heat transfer through the walls, the panels can contribute to maintaining a comfortable indoor environment and potentially reducing heating and cooling costs.

4) **Acoustic insulation**: Depending on the composition of the 3D panels, they can also provide soundproofing benefits. This can be advantageous in urban areas or buildings located near noisy environments, as it helps to minimize the transmission of external noise into the interior spaces.

5) **Speed of construction**: Prefabricated 3D panels are manufactured off-site, allowing for faster construction compared to traditional on-site methods. This can significantly reduce the overall project duration and minimize disruption to building occupants during the rehabilitation process. It's important to note that the use of 3D panels for rehabilitating reinforced concrete frame buildings should be done in consultation with structural engineers and professionals experienced in retrofitting techniques. Each building is unique, and proper analysis and design are necessary to ensure that the panels are appropriately integrated and meet the specific requirements and safety standards. The use of 3D panels can be a viable option for rehabilitating reinforced concrete frame buildings, offering benefits such as enhanced structural strength, improved seismic resistance, thermal and acoustic insulation, and faster construction. **Figures 9 and 10** show the details and materials used in this system.

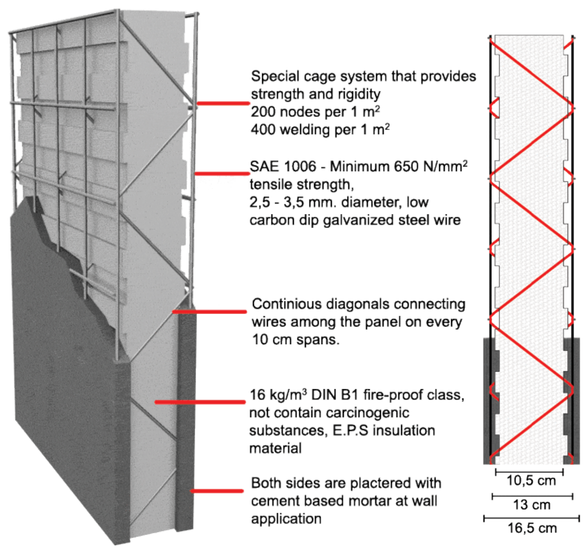


Figure 9. 3D view and cross-section details of the 3D panel.

5.2 Restoring historical buildings: Utilizing textile reinforcements and special mortars

The repair and rehabilitation of old historic structures is a complex task that requires careful consideration of the interaction between existing and new elements. Unfortunately, there is often a lack of global technical guidelines for such projects, which can make the process challenging. However, there are certain techniques and materials that are commonly employed in the restoration of historic structures, particularly in places like old Benghazi city. One approach involves the use of textile reinforcements and lime-based mortars. Textile reinforcements, such as fibers or fabrics, are incorporated into the mortar to improve its mechanical properties and increase its resistance to cracking and deformation. Lime-based mortars, on the other hand, are preferred over cement-based mortars due to their breathable and flexible properties, which are well-suited for historical structures that are susceptible to decay and deterioration. In the restoration of historic structures, lime-based mortars are often modified by incorporating various additives to enhance their performance [4,5]. Some commonly used additives include white cement, gypsum, lignin sulfonate, and silica fume. These additives can impart specific properties to the mortar, making it more suitable for restoration work. For example, the addition of silica fume to lime-based mortars has been shown to improve their mechanical strength. Silica fume is a byproduct of the silicon and ferrosilicon alloy production process and is composed of very fine particles. When added to lime mortar, it enhances the mortar's compressive, tensile, and shear strengths, making it more robust and durable. On the other hand, the inclusion of lignin sulfonate in lime-based mortars can improve their performance during wetting and drying cycles. Lignin sulfonate is a byproduct of the pulp and paper industry and acts as a water-reducing and plasticizing agent. It enhances the workability and cohesion of the mortar and reduces the detrimental effects of moisture variations on its durability. This is particularly important for historic structures that may be exposed to fluctuating moisture levels. In terms of structural behavior and bonding, lime-based mortars with lignin sulfonate have been found to exhibit improved load capacity. This means that they are better able to withstand external forces and maintain their structural integrity. These mortars can be used to reinforce model walls, providing strength and stability to the structure. **Figure 11** illustrates restoration work carried out on a historic structure, demonstrating how the application of these materials can help preserve and protect the building while maintaining its historical character. The utilization of lime-based mortars with additives, such as silica fume and lignin sulfonate, is gaining popularity in the restoration of heritage buildings. These mortars offer favorable mechanical properties, durability during wetting and drying cycles, and improved load capacity for structural behavior and bonding. Their breathable and flexible nature makes them well-suited for historic structures prone to decay and deterioration, ensuring their long-term preservation.

Figure 10. Use 3D panels as infill walls with good connections with the peripheral frames.

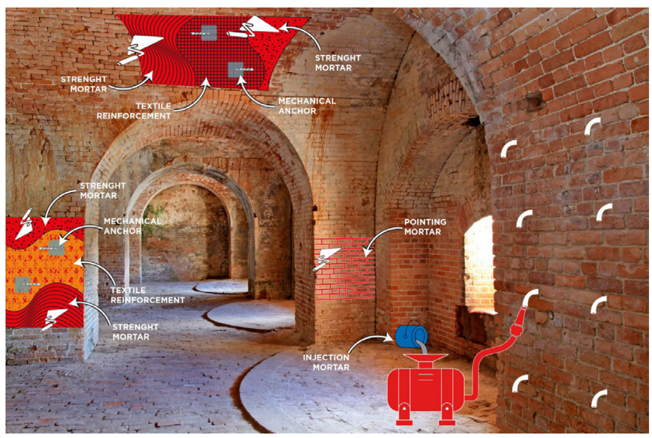


Figure 11. Rehabilitation with textile reinforcements and special mortars.

6. Conclusions

In this study, the authors conducted an assessment specifically focused on evaluating and categorizing the damage in the old area of Benghazi City. The aim was to gain a better understanding of the condition of buildings within a designated region and provide insights for rehabilitation and reconstruction efforts. The researchers performed visual inspections of over 300 building units. These inspections involved carefully examining the structures to identify and document any visible damage or deterioration. In addition, more than 100 photographs were captured to supplement the visual inspection process and provide a visual record of the damage observed. The main objective of the study was to classify the damage into four levels based on its severity so that decision-makers can prioritize and plan for appropriate restoration and rehabilitation strategies. The study also proposed specific methods for restoring the damaged buildings. One approach suggested the use of 3D panels for reinforced concrete frame buildings. These panels can provide structural reinforcement and contribute to the overall stability and safety of the buildings. Additionally, the researchers recommended employing textile reinforcements with special mortars for historical structures. This approach can help preserve the unique architectural characteristics of the historic buildings while ensuring their structural integrity.

Author Contributions

The three authors equally, contributed to this research.

Conflict of Interest

There is no conflict of interest.

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