Assessment and Repair of Damaged Concrete Structures due to War Case study (The Republic of Yemen)

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***Abstract*— Lately, many wars occurred in many Arab countries, including Republic of Yemen. Thus, those wars caused a lot of damage to infrastructure in general and to the concrete structures in particular; after an explosion, it is common that people are in doubt to determine which buildings should be demolished, which ones must be repaired, and which ones must be strengthened and how to do it. This study has been prepared to answer the previous questions and explain what can be done easily, practically, simple, and relatively with a low cost. Moreover, an integrated methodology was prepared to assess the various structural and non-structural damages caused by wars on concrete structures, in order to suggest appropriate restoration methods according to the results of the assessment, through the application on six case studies of concrete structures that were damaged as a result of the war in Yemen erupting from the year 2015. In addition, it will produce solutions to assist the participating companies in carrying out the required remediation of the affected reinforced concrete elements.**

Keywords*— *Infrastructure; Reinforced concrete; Structures; Explosion; Restoration methods; Assessment.

I. INTRODUCTION

Existing engineering structures in general and reinforced concrete structures in particular are exposed to many types of damages and deterioration due to different causes and exposure conditions during their life cycle, which reduce the resistance of the structural members by affecting building materials and structural systems. These causes may be natural or manmade, such as wars, which result in explosions that cause damages on concrete structures that varies in type, severity, and extent from one building to another building and from one element to another. In Yemen, as a result of the ongoing war since 2015, many reinforced concrete structures in several cities have exposed to various damages, most of which were caused by explosions caused by rocket-propelled grenades.

One of the objectives of this paper is to identify and describe the various damages caused by wars on reinforced concrete structures, develop a methodology for evaluating and rehabilitating concrete buildings that have been damaged by wars in general and in Yemen in particular and suggest solutions to assist in carrying out the required repair of damaged reinforced concrete elements.

II. RESEARCH SIGNIFICANCE

Yemen is still suffering from the devastation of the war, which has caused a huge negative impact on concrete structures, but it certainly will not continue, and the war will stop and then start thinking about reconstruction. This requires a comprehensive study of the various damages caused by wars and then conducting an assessment of these damages to determine the type, extent and its severity to the structure as a whole or to one of its structural elements. Therefore, it is very important to contribute the finding and developing methods that help to assess and restore buildings damaged as a result of the war in Yemen to rehabilitate them again.

III. METHODOLOGY

This paper dealt with the damage caused to concrete structures in Yemen and the various evaluation methods. Then the application of the assessment method to a group of damaged concrete structures by describing and assessment the deterioration for six damaged concrete structures. Thus several field visits to these structures were highlighted and the assessment methodology which proposed in this investigation was applied, then solutions were chosen to process of renovating and rehabilitating these structures.

i. The methodology used in this paper was as follows:
ii. Develop assessment methodology
iii. Selection of six damaged concrete structures in Yemen.
iv. Conducting field visits to damaged concrete buildings.
v. Inspection of damaged concrete buildings.
vi. Assessment of all components of the damaged buildings.
vii. Take the appropriate decision for repair.

IV. FORMS OF EXPLOSIONS ON THE BUILDINGS

Unconfined explosions can occur as an air-burst or a surface burst. In an air burst explosion, the detonation of the high explosive occurs above the ground level and intermediate amplification of the wave caused by ground reflections occurs prior to the arrival of the initial blast wave at a building as the shock wave [1]. The pressures of air-blast shockwave exerts on a structure's surfaces may be orders of magnitude greater than the stresses that structure has been designed to sustain. The shock wave may also act in directions that the building has not been designed to resist. Fig. 1 shows the effects of an air-blast shockwave on a structure. The pressures associated with explosive detonations decay very rapidly as distance from the source increases. As a result, direct primary air-blast damages tend to be more localized and may be, for example, significantly more severe on the side of a structure facing an explosion than the opposite side [2]. However, a surface burst explosion occurs when the detonation occurs close to or on the ground surface. The initial shock wave is reflected and amplified by the ground surface to produce a reflected wave.

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Unlike the air burst, the reflected wave merges with the incident wave at the point of detonation and forms a single wave. In the majority of cases, terrorist activity occurred in built-up areas of cities, where devices are placed on or very near the ground surface. When an explosion occurs within a building, the pressures associated with the initial shock front will be high and therefore will be amplified by their reflections within the building. This type of explosion is called a confined explosion. In addition, and depending on the degree of confinement, the effects of the high temperatures and accumulation of gaseous products produced by the chemical reaction involved in the explosion will cause additional pressures and increase the load duration within the structure. Depending on the extent of venting, various types of confined explosions are possible. If detonating explosive is in contact with a structural component, e.g., a column, the arrival of the detonation wave at the surface of the explosive will generate intense stress waves in the material and resulting crushing of the material. Except that an explosive in contact with a structure produces similar effects to those of unconfined or confined explosions. There are many forms of high explosive available and as each explosive has its own detonation characteristics, the properties of each blast wave will be different. TNT is being used as the standard benchmark, where all explosions can be expressed in terms of an equivalent charge mass of TNT. The most common method of equalization is based on the ratio of an explosive's specific energy to that of TNT [1].

V. WAR DAMAGE ON CONCRETE STRUCTURAL (EXPLOSION DAMAGE)

Wars cause many explosions with severe loading condition which might cause general collapse of a properly designed reinforced concrete member. Blast damage of reinforced concrete frame structures occurs due to the excessive overpressure from the explosion or forces from fragments of missiles impacting the structure. The degree of damage depends on the intensity of the blast and the strength of the loaded structural element. Columns or beams may be damaged along their entire length or may suffer localized damage from high intensity loads over a small area. Fragments of missiles impacting reinforced concrete frame members can cause spalling of concrete and loss of material. Damage to masonry walls during blasting is primarily from overpressures normal to the wall, but lateral distortions of the structural frame in the plane of the walls can cause diagonal shear cracking similar to earthquake damage. Masonry walls damaged from lateral blast loads can remain in place with crack patterns determined by the nature of the loads and boundary conditions.

There are three primary factors that affect the extent of damage created by explosion (TM 5-855-1 1986) [1] .

1. Explosion Loading; the force that impacts the structure, as a function of the type, weight, and location of the explosive relative to the structure.

2. Structural Characteristics; the type of structural system used, particularly the external walls and roof.

3. Construction Materials; the type of materials, design details, and quality of construction.

In addition, there are other factors affect the extent of damage created by explosion as:

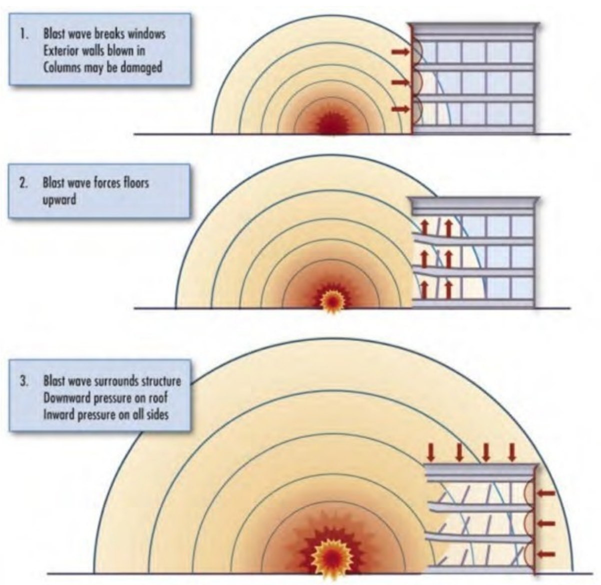

Fig. 1. The *effects of an air-blast shockwave on a structure*

4.Structural system of building and members measurements.

5. Distance between explosion location and building and location of explosion; Air or ground explosion.

6. Explosion source and type; Shell, fragment, an explosive charge.

7. Detonation general location; presence of dampers or nearby structures that help mitigate the shock.

VI. DAMAGES CAUSED BY THE WAR ON THE CONCRETE STRUCTURES IN YEMEN

Yemen has not witnessed any previous wars for a long time, and as a result, designers who are not concerned with design considerations in the event of explosions near or inside the structure. The war started in Yemen since 2015 and caused great damage in all structures in general and in the concrete structures in particular. Some structures were subjected to air bombardment by airplanes, and this bombing is either direct bombing that directly targets the building or targets part of it, which leads to complete or partial destruction. Indirect bombardment is at a certain distance from the structure, and this type of bombing causes damage to the structure as a result of the projectiles flying from the missile or slight damage that leads to the breaking of non-structural elements such as walls, windows and doors, one of the cities that subject from this type of bombing is Sana'a. Some of the structures were subjected to the same previous damage, but not as a result of the air bombardment , but rather as a result of the internal bombing that occurs as a result of fighting between two parties inside the city, which leads to various damages in structural and non-structural elements, but does not reach the degree of risk, such as the damage that results from air bombardment, because the aerial bombardment is very strong, One of the cities that subject from this type of bombing are Aden and the Taiz.

Type of damages varies from structure to another and from one element to another, in addition; the structure or its elements may be subject to one type of damage or to several different types.

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a. Plastic deformation

Structural elements subjected to plastic deformation as a result of explosion pressure, thus the resulting deformation is a displacement that occurs to the element (slab, beam, column, concrete wall), usually this displacement takes horizontal direction and, in some cases, could be vertical, considering that the members deform during the positive phase of shock wave, and in many cases the member cracks but still in service without any loss in cross section, Fig. 2.

b. Scaling or crushing of concrete

Loss or crushing of the surface concrete mortar, as a result of vibration that causes the force of the explosion wave when the structural member is tough enough so that does not collapse under missile strike, depending on several factors, as the intensity of the shock that results from the force of the explosion, as well as the distance between the element and the site of the explosion and the hardness and quality of the concrete element material, Fig. 3.

c. Spalling or disintegration (loss in cross section)

The spalling is more severe than the Scaling, where spalling usually in the shape of a flake, as a result of vibration that causes the force of the explosion wave when the structural member is tough enough so that does not collapse under explosion strike but losses part of the cross section while stays in service but in critical condition, Fig. 4.

Fig. 2. *Plastic* deformation *with cracks in concrete slab.*

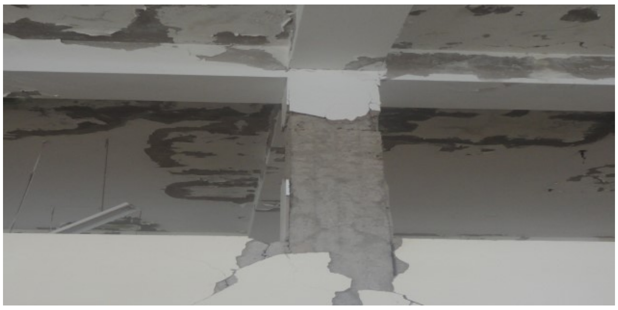

Fig. 3. *Scaling in concrete column.*

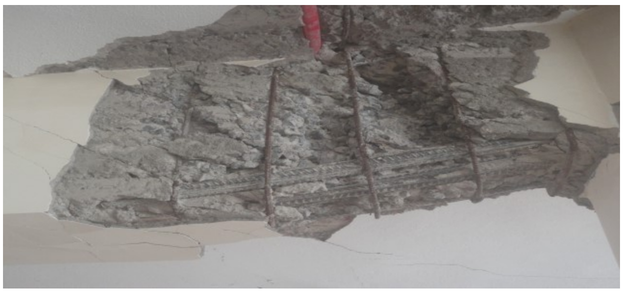

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Fig. 4. *Spalling in concrete beam*

d. Separation in linear elements

As a result of the intensity of the force of the explosion wave and the fragments flying from the explosion or from other damaged elements, linear elements such as beams and columns are subjected to shear forces greater than the resistance of these elements, which causes fracture, in addition to steel yielding and permanent deflection with large cracks, Fig. 5.

e. Hole in flat concrete elements

Hole occurs in the flat elements such as concrete slabs and walls as a result of two main reasons:

1. The flat element was subjected to a direct missile strike, which leads to a hole that may be large or small without collapsing of the flat concrete element.

2. When the building is subjected to direct strong impact, some of structural members parts form fragments in addition to explosion fragments. These fragments cause holes in the flat concrete elements and also cause serious damage for other structural members in the building and lives, Fig. 6.

f. Partial collapse

Partial collapse of building subjected to explosion loading takes place when part of the building is located in a very strong shock wave circle or when a very destructive missile strikes part of the building Without affecting the other part, causing several concrete members to be out of service in this part, Fig.7

g. Total collapse

Total collapse of building subjected to explosion loading takes place when the building is located in a very strong shock wave circle or when a very destructive missile strikes the building causing several structural members to be out of service leading the structural system to failure, Fig. 8.

Fig. 5. *Separation* in *concrete column*

Fig. 6. *Hole in concrete slab*

Fig. 7. *Partial collapse* in *R.C structure*

Fig. 8. *Total collapse in R.C structure*

VII. METHODOLOGY OF ASSESSMENT OF EXPLOSIONS DAMAGES IN R.C STRUCTURES

Util now, there is no national standard in Yemen concerned with assessing existing concrete structures with regard to their structural strength, safety, and serviceability. Also since Yemen has recently been affected by war damage, the issue of developing a national approach to assessing war damage to existing structures is still lacking, but due to the great similarity between explosion damage and earthquake damage, some standards and steps used to assess earth-quake damage can be used when assessing explosion damage.

In this study, a methodology was developed to conduct a comprehensive assessment of the damage to concrete structures resulting from the effect of wars (explosions) in Yemen, where this methodology was applied in assessing six damaged concrete structures (case studied). The evaluation methodology relied on assessing the severity and extent of the damage and then assessing the usability of the damaged structure and the safety level of the structure as a whole, then for each element individually, to arrive at appropriate solutions for rehabilitation and restoration, according to Post Earthquake Damage And Usability Assessment Of Buildings (EPPO) [3],guideline for Post-earthquake Damage Evaluation and Rehabilitation[4] and with the aid of the assessment steps in American Concrete Institute (ACI) [5,6,7]. Fig. 9.

The main assessment steps are:
Step 1: Quick assessment.
Step 2: Preliminary assessment.
Step 3: Detailed assessment.
Step 4: Final Report.

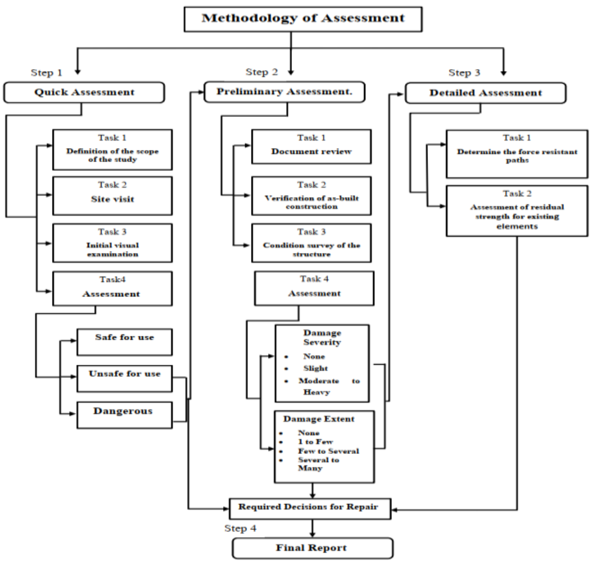

Fig. 9. *Methodology of assessment*

Step 1: Quick assessment

A quick assessment is done takes place within during the short period after occurrence of the explosion and is restricted to assessment of the exterior of the building. The quick assessment is done by an assessment team with experience in the explosions damage assessment and the most experienced member of the team is named team leader, and his opinion prevails in the case of disagreement between the members of the assessment team.

The tasks of quick assessment:

Task1: Definition of the scope of the study

Objective: Determine an owner's needs (person, company, government agency, etc.), listening to his complaint, and understanding his objectives.

Task2: Visit the damaged site

Objective: To let expert's eyes, identify the case and take an initial impression regarding the condition of the structure.
Tools: camera, a tape, a Notebook, a pen, a hammer, etc.

Task 3: Initial visual examination

Objective: a. Determine the general case and take an initial impression regarding the condition of the damaged structure. b.Visual inspection of the damaged structure the building from the outside. c. Searching for damage to all visible structural elements, especially columns, shear walls, core elements, beams and stairways. Take photos documenting the damages.

Task 4: Assessment

After completing the first tasks of the quick assessment step a quick assessment is done.

Objective: a. Assessment of the general condition of the damaged structure according to safety of people as follows [32]

1. Safe for use: An initial visual examination has shown that the original capacity of the building has not decreased and that no major hazard is present and no observable permanent deformations of the structural. Non observable or slight structural damage. Minor nonstructural damage. Fracture in non-structural components of the structure, such as windows and doors. Use and occupancy allowed, except in areas marked AREA UNSAFE indicating the presence of some local hazard, photos (1 and 2) in Fig. 10.
2. Unsafe for use: are characterized the buildings with reduced capacity, though not to the extent of being in danger of sudden collapse. Medium cracking with observable minor permanent deformations and low spalling. The load carrying capacity and stiffness of the structural element may be reduced and any subsequent overloading may cause widespread damage or collapse. They have to be repaired before they could be occupied on a continuous basis. Although some of them may also need emergency support, the risk when entering them for short periods of time, e.g. for removing valuables, securing contents of apartments etc., is deemed to be low (but not negligible). It should be noted that buildings in this category present the greatest uncertainty in the classification; if the inspector has doubts about his evaluation, he should be conservative, photo (3) in Fig. 10.
3. Unsafe for use (dangerous for use): Extensive cracking or loss of material with gross permanent local or overall

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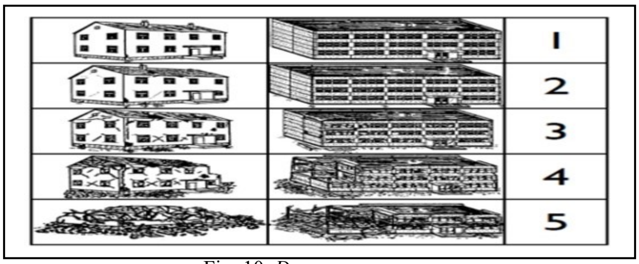

Fig. 10. *Damage sequence*

deformations. The strength and stiffness of the element or structure are reduced to dangerously low levels, and failure under dead loads is possible due to general instability of the system and thus are prone to sudden collapsing. Entry is prohibited and the need for emergency support as well as protection of the surroundings must be considered, photos (4 and 5) in Figure in Fig. 10.

b. Definition of the needed efforts for preliminary assessment (If that is required) according to the structure condition as judged in assessment of the general condition of the damaged structure.

c. Identify buildings in need of urgent demolition, local hazards that have to be removed for safety purposes.

Step 2: Preliminary assessment

The Preliminary assessment follows the quick assessment and finalizes the characterization of all the damaged structure elements. It is performed only in buildings characterized as unsafe for use or dangerous for use (but the building can still be rehabilitated) from the quick assessment or when the owner can justify a reinspection in case of safe for use.

The tasks of preliminary assessment:

Task 1: Document review

Objective: a. obtaining of design information. b. Materials information. c. Construction information. d. Service history of the structure. e. Design and construction personnel.

Task 2: Verification of as-built construction

Objective: a. Verification of geometry and structural materials. b. Verification of Loadings and environment (Dead, Imposed. Wind, snow, and seismic loads).

Task 2: Verification of as-built construction

Objective: a. Thorough Visual examination. b. Measure and record crack width, depth, length, location, and type. c. Surface defects such as spalling or scaling (shape, area, and depth). e. Corrosion of reinforcement, including the extent and amount of reduced cross section. f. Visible deviations and deformations.

Task 3: Condition survey of the structure

Objective: a. Thorough Visual examination (Use of photographs, notes, and sketches to document this examination. Abnormalities should be recorded as to type, magnitude, location, and severity). b. Measure and record crack width, depth, length, location, and type .c. Surface defects such as spalling or scaling (shape, area, and depth) .d. Corrosion of reinforcement, including the extent and amount of reduced cross section. e. Visible deviations and deformations.

Task 4: Assessment

Objective: a. Assessment of severity and extent of damage for the individual elements: the assessment of severity and extent of damage Includes a study of information, measurements and the field survey that was carried out in the step of field investigations, a one to four numerical scale has been adopted and is described verbally as follows [3]:

First: Classification of the severity of the damage:

1. None 2. Slight 3. Moderate to Heavy 4. Severe to Total

TABLE I. TYPICAL DAMAGE SEVERITY

Damage severity	Description
None	- No signs of any distress - Very light non-structural damage - Fine cracks in the mortar. - Light spalling of concrete
Slight	- Small cracks ($d \leq 3.0$ mm) in partition walls. - Falling down of slab tiles or mortar. - Inclination of building barely visible - Some spalling of concrete - Cracks in some structural elements Beams: $d_{diag} \leq\sim 0.5$ mm, $d_{vert} \leq \sim 2.0$ mm Columns: $d_{diag} \leq\sim 0.5$ mm, $d_{horiz} \leq \sim 2.0$ mm Shear Walls: $d_{diag} \leq\sim 0.5$mm, $d_{horiz} \leq \sim 1.0$ mm Stairs: $d \leq \sim 3.0$ mm Slabs: $d \leq \sim 1.0$ mm
Moderate to Heavy	- Extended large diagonal or other cracking in partition ($d > 3.0$) - Sliding and failure of slab tiles. - Visible inclination of building. Slight dislocation of structural - Minor ground movement but no signs of foundation failure - Spalling-partial disintegration of concrete. - Larger cracks in several structural elements Beams: $d_{diag} \leq\sim 2.0$ mm, $d_{vert} \leq \sim 4.0$ mm Columns: $d_{diag} \leq\sim 2.0$ mm, $d_{horiz} \leq \sim 5.0$ mm Shear Walls: $d_{diag} \leq\sim 1.0$ mm, $d_{horiz} \leq \sim 3.0$ mm Stairs: $d \leq \sim 10.0$ mm Slabs: $d \leq \sim 2.0$ mm Joints: $d \leq\sim 2.0$ mm
Severe to Total	- Partial or total collapse. - Widespread failure of partition or severe cracking visible from - Considerable dislocation of structural elements, residual drift - Substantial ground movement, uplift of footings or fracture of - Large number of crushed structural elements and connections, - Very large cracks in several structural elements. Beams: $d_{diag} > 2.0$ mm, $d_{vert} \geq 4.0$ mm Columns: $d_{diag} > 2.0$ mm, $d_{horiz} \geq 5.0$ mm Shear Walls: $d_{diag} > 1.0$ mm, $d_{horiz} \geq 3.0$ mm Stairs: $d > 10.0$ mm Slabs: $d > 2.0$ mm Joints: $d > 2.0$ mm

Second: Classification of the extent of the damage:

Extent of damage refers to the number of elements with the particular damage severity marked:

1. None 2. 1 to Few 3. Few to Several 4. Several to Many

b. Assessment the damaged for individual elements in use [3]

the preliminary damage assessment (safe, unsafe and dangerous) for the individual elements can be decided according to the criteria given in Table II. The structural elements in Tables (1) and (2) are grouped into the following categories: A: Bearing Elements (RC columns, shear walls, beams, frame joints). B1: Stairs. B2: Partitions (Infill masonry walls). B3: slabs.

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TABLE II. CRITERIA FOR ASSESSMENT OF DAMAGED

Damage Severity	Extent of damage	A: Bearing Elements
1, 2	1, 2	Safe
2	3, 4	Unsafe
3	2	
3	3, 4	Dangerous
4	2, 3, 4	
		B.1: Stairs
1, 2	1, 2	Safe
2	3, 4	Unsafe
3	2	
3	3, 4	Dangerous
4	2, 3, 4	
		B.2: Partitions
1, 2	1, 2, 3, 4	Safe
3	2	
3	3, 4	Unsafe
4	2	
4	3, 4	Dangerous
		B.3: Slabs
1, 2	1, 2	Safe
2	3, 4	Unsafe
3	2	Dangerous

c. Preliminary assessment of damage for the building [3]

The Preliminary assessment for use of the building (safe, unsafe, or Dangerous) takes into account the partial Preliminary damage assessment classifications for each structural element according to Table-III.

d. Decide if a detailed assessment is needed or not

The team has to decide this according to the results of the previous tasks. In cases where it is found that the structure as a whole or some of its parts are still in doubt regarding their structural capacity.

TABLE III. CRITERIA FOR PRELIMINARY ASSESSMENT OF DAMAGED BUILDING

Damage Assessment of the various element categories (A to B3)	Preliminary assessment of the building
A, or B1, or B2: Dangerous	Dangerous
A, or B1, or B2 : Unsafe and B3 : Safe	Unsafe
A and B : Safe and C or D: Unsafe or Dangerous	Unsafe or Dangerous
A and B : Unsafe and C or D: Unsafe or Dangerous	Dangerous
A and B1 and Safe and B3 : Unsafe or Dangerous and (C, D) : Safe	Safe For part of the building Need for intervention
A and B1 and B2 and B3 : Safe	Safe

Step 3: Detailed assessment

After determining the severity and extent of the damage in the preliminary assessment step, in some cases, a procedure may be required thorough detailed investigation is performed to evaluate the existing strength and stiffness of the damaged structure, to determine the force resistant paths, to explain why certain members sustained damage while other members were essentially undamaged, and to develop alternate repair schemes or to recommend demolition and rebuilding in case the damage is too severe for any repair scheme to be feasible.

The tasks of Detailed assessment:

Task 1: Determine the force resistant paths

Determine the force resistant paths, explain why certain members sustained damage while other members were essentially undamaged, and know the safety of the building, adopted computer modeling by applying a complete simulation of the building after the occurrence of damage, and applying the loads on it during the occurrence of damage. This method gives a clear idea of the complete spatial behavior of all the elements of the structure, which helps to predict the locations of potential stresses that appear urgently as a result of the redistribution of loads in the elements based on the conditions of the new structure. Practical experience is one of the important issues in knowing whether the element has gone out of its function of use or not. The element that has the severity of damage (Severe or Total) can be considered an element outside its function and it is not modeled in computer programs when analyzing to determine the path of forces and their distribution to other elements.

Task 2: Assessment of residual strength for existing elements

The assessment of the present conditions of the construction materials and the evaluation of the remaining strength of damaged members can be accomplished by in-situ non-destructive methods such as the rebound "Schmidt" hammer test, the ultrasonic pulse-velocity method. The assessment of the residual strength of the elements affected by the explosion is somewhat similar to the assessment of the residual strength after an earthquake, so the residual seismic capacity index (R) will be used to assess the residual strength after the explosion. A residual capacity ratio index R, which corresponds to building damage, is defined as the ratio of capacity of post-damaged to that of pre-damaged condition (i.e., the ratio of the residual capacity to the original) [4]:

$$R = \frac{{}_{D}Is}{Is} \times 100 \quad (\%)$$

where, Is : seismic capacity index of structure before earthquake damage
${}_{D}Is$: seismic capacity index of structure considering deteriorated member capacity

The severity of the damage is determined for each element through the index (R) is calculated from the equation in Table IV

TABLE IV. RESIDUAL CAPACITY RATIO INDEX (R) ACCORDING TO DAMAGE SEVERITY.

Residual capacity ratio index (R)	Damage severity
95 (%) ≤ R	None
80 (%) ≤ R < 95 (%)	Slight
60 (%) ≤ R < 80 (%)	Moderate
R < 60 (%)	Heavy
R = 0 due to overall/partial collapse	Severe to Total

Step 4: Final Report

The final step of the assessment process is the assessment report. It has to reflect the efforts exerted by the assessment team, describe the condition of the structure in a professional and technical way and present documented information regarding the case. The entire investigation should be summarized in a comprehensive report describing the assessment method as a whole with sufficient description of all the findings including:

1. Purpose and scope of investigation.
2. Existing construction and documentation.
3. Field observations and condition survey.
4. Sampling and material testing.
5. Assessment.
6. Findings and recommendations.

The contents of the final report depend on the assessment method used, when only the quick assessment is satisfied, the contents of the report are reduced, unlike the preliminary assessment and the detailed assessment report, where the detailed assessment report is comprehensive for both the quick and preliminary assessment report. The recommended rehabilitation actions have to be fully described in the report with adequate details concerning the repair technique, needed materials, locations, construction details and drawings, etc. Sometimes some protective measures to prevent or eliminate the occurrence of further damages or deteriorations should be addressed in the assessment report.

VIII. CASES STUDIED AND ASSESSMENT

The damage assessment for six concrete structures as cases studied in Sana'a was conducted using a methodology of assessment. The three assessment steps were used to assess the damage resulting from the war.

1. Case Study (1)

A. General Description

The building is an educational institute located at Sanhan area in Sana'a city. The damaged building was identified during the site visit and it was composed of four stories. The building was subjected to an air bombardment with two missiles at the beginning of the war, as the bombing was indirect at a distance of 12 meters from the northeastern corner of the building, Fig. 11.

B. Application *of Assessment Methodology*

Step 1: Quick assessment

Through the site visit and the initial visual examination, and a description of the external and internal damages It turns out that the original capacity of the building has not decreased and that no major hazard is present and no observable permanent deformations of the structural, minor structural damage, slight nonstructural damage and fracture in non-structural components of the structure, such as windows and doors, as a result the building can be described as “Safe for use".

Since the building is safe for use and as a result of this damage is confined to a very simple area of the building, and the building was exposed to indirect bombardment, therefore, the structure does not require a preliminary assessment.

Fig. 11. *General view of damaged building and Location of the explosion.*

2. Case Study (2)

A. General Description

The building is a residential located at Jahana area in Sana'a city. The damaged building was identified during the site visit and it was consisted of two stories, it subjected to a direct air bombardment with three missiles, Fig. 12.

B. Application *of Assessment Methodology*

Step 1: Quick assessment

Through the site visit and the initial visual examination, and a description of the external and internal damage. It turns out that the building exposure extensive damages such as total collapse, extensive cracking with observable permanent deformations and large spalling for the most structural elements (about 80%). The strength and stiffness of the element or structure were reduced to dangerously low levels, and the building maybe prone to sudden collapse. As a result, the building can be described as “Un safe for use (dangerous for use)" and It is not possible to conduct a preliminary assessment because entering the building poses a danger because the structure is almost collapsed.

3. Case Study (3)

A. General Description

The building (South mass) is an educational located at Hamdan area in Sana'a city. The damaged building was identified during the site visit and it was found that it is a three stories. The building subjected undirect bombardment with four missiles, Fig. 13.

B. Application *of* Assessment *Methodology*

Step 1: Quick assessment

Through the site visit and the initial visual examination, and a description of the external and internal damage. It turns out that the building exposure some damage to the structural elements on the first story. The bearing capacity of the building may be low, especially on the first story, In addition to minor damage to some non-structural elements, as a result, the building can be described as “Un safe for use" and the building requires a preliminary assessment.

Step 2: Preliminary assessment

a. Preliminary assessment of damage for the building:

Through the preliminary assessment of all the damaged individual elements of the building and according to criteria for preliminary assessment of damaged building, the building is "Dangerous for use (unsafe)" Table V.

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Fig. 12. *General view of damaged building in Jahana*

Fig. 13. *General view of damaged building in Hamdan (South mass)*

TABLE V. PRELIMINARY ASSESSMENT OF THE INDIVIDUAL ELEMENTS

Elements	Preliminary assessment
A-RC columns	Dangerous for use (Unsafe)
A-RC beams	Safe for use
B2- Partitions	Dangerous for use (Unsafe)
B3- Slabs	Safe for use

b. Decide whether or not a detailed assessment is needed

Through assessment the damage to all the individual elements, it was found that there are only two columns that were severely damaged, while some other structural elements were slightly damaged, and this indicates that the resistance of these elements is great as they were able to absorb the explosion wave. Therefore, a detailed assessment is not required.

4. Case Study (4)

A. General Description

The building is an educational located at Juhana area in Sana'a city. The damaged building was identified during the site visit and it was found that it is a two stories. The building subjected direct bombardment with two missiles, Fig. 14.

Fig. 14. *General view of damaged building in Juhana*

B. Application of Assessment Methodology

Step 1: Quick assessment

Through the site visit and the initial visual examination, and a description of the external and internal damage. It turns out that the building exposure extensive damages such as total collapse, some cracking with observable permanent deformations and large spalling for some structural elements. The strength and stiffness of the element or structure maybe reduced to low levels, and the building maybe prone to sudden collapsing, as a result, the building can be described as "Un safe for use" and the building requires a preliminary assessment.

Step 2: Preliminary assessment

a. Through the preliminary assessment of all the damaged individual elements of the building and according to criteria for Preliminary assessment of damaged element building, the building is "Dangerous for use (Unsafe)", Table-VI.

b. Decide whether or not a detailed assessment is needed

Through assessment the damage to all the individual elements, it was found that the severity of the damage to some elements is a total collapse due to direct explosion, and as for the rest of the elements, the severity of the damage was either Slight or none a, and this indicates that the resistance of these elements is great as they were able to absorb the explosion wave. However, the strong blast wave that directly hit the building may reduce the resistance and quality of the elements that were not damaged or that were exposed to his slight damage. Therefore, the resistance and quality of these elements must be ensured after the damage occurred through in-place tests.

TABLE VI. PRELIMINARY ASSESSMENT OF THE INDIVIDUAL ELEMENTS

Elements	Preliminary assessment
A-RC columns	Dangerous for use (Unsafe)
A-RC beams	Dangerous for use (Unsafe)
B2- Partitions	Dangerous for use (Unsafe)
B3- Slabs	Dangerous for use (Unsafe)

Step 3: Detailed assessment

Assessment of residual strength for existing elements by in-place tests. Non-destructive tests were conducted for samples of structural elements whose severity was evaluated (Slight and None) and some of the elements whose severity was (Moderate to Heavy). Non-destructive tests (Schmidt hammer and ultrasound test) were used to ensure the quality and resistance of concrete elements after damage Table VII.

Through the results of the non-destructive tests in table-VII, it turns out that the quality and resistance of the meet the design requirements after being damaged, except one beam except for the beam B27-2 Fig. 15.

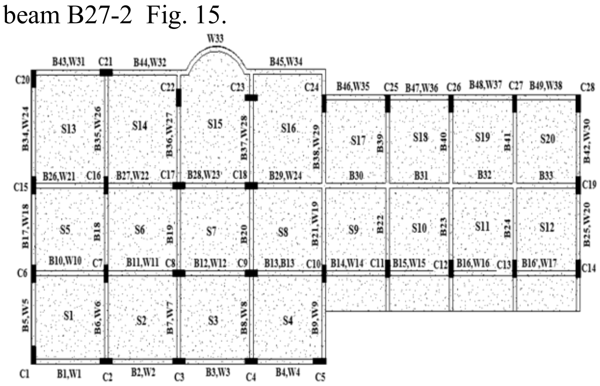

Fig. 15. *Plan of damaged building*

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TABLE VII. RESULTS OF NON-DESTRUCTIVE TESTS

Elements	Schmidt hammer test		
C_{6-1}	34	100 < R	No damage
C_{7-2}	35	100 < R	No damage
B_{9-1}	26	100 < R	No damage
C_{27-2}	18	60 < R<80	Moderate
S_{13-1}	28	100 < R	No damage
	Ultrasonic test		
	Velocity	Quality of concrete[8]	
C_{6-1}	4.7	Very Good	
C_{7-2}	4.19	Very Good	
B_{9-1}	4.3	Very Good	
C_{27-2}	3.4	Satisfactory but loss of integrity is suspected	
S_{13-1}	3.6	Good	

5. Case Study (5)

A. General Description

The building (Middle Mass) is an educational located at Hamdan area in Sana'a city. The damaged building was identified during the site visit and it was found that it is a three stories. The building subjected undirect bombardment with four missiles, Fig. 16.

B. Application *of* Assessment *Methodology*

Step 1: Quick assessment

Through the site visit and the initial visual examination, and a description of the external and internal damage. It turns out that the west part of building on the first and second stories exposure extensive damages such as total collapse, extensive cracking with observable permanent deformations, large spalling and fractures of some elements. The strength and stiffness of the element or structure were reduced to dangerously low levels, and the building maybe prone to sudden collapsing as a result, the building can be described as Dangerous for use (unsafe)" and the building requires a preliminary assessment.

Step 2: Preliminary assessment

a. Through the preliminary assessment of all the damaged individual elements of the building and according to criteria for Preliminary assessment of damaged element building, the building (Middle Mass) is "(Dangerous for use (Unsafe)", Table.VIII.

b. Decide whether or not a detailed assessment is needed

It is noticed through the preliminary assessment of the individual elements that some elements have been damaged as a result of the damage of other elements, and this indicates a change in the path of the loads. Also, the elements which were not damaged require confirmation of their internal resistance. So, the building requires detailed assessment.

Step 3: Detailed assessment

a. Determine the force resistant paths

Adopted computer modeling (Robot) by applying a complete simulation of the building after the occurrence of damage, and applying the loads on it during the occurrence of damage. The

Fig. 16. *General view of damaged building in Juhana*

TABLE VIII. TAPRELIMINARY ASSESSMENT OF THE INDIVIDUAL ELEMENTS

Elements	Preliminary assessment
A-RC columns	Dangerous for use (Unsafe)
A-RC beams	Dangerous for use (Unsafe)
B1- stairs	Unsafe for use
B2- Partitions	Dangerous for use (Unsafe)
B3- Slabs	Dangerous for use (Unsafe)

building has been modeled according to structural drawings after documents review and verification of as-built construction .Removing the columns that were severely damaged (from severe to total) and applying the loads present during the explosion Fig. 17.

It turns out that the path of the loads has changed as a result of exposure of some elements to total collapse. The non-damaged elements and have not been subjected to total collapse may have decreased their resistance as a result of the redistribution of loads and moments, as a result: 1) The elements that have been exposed "damage severity" (Severe to Total) Should be removed and rebuilt using appropriate scientific methods. 2) The elements that have been exposed "damage severity" (Moderate to Heavy) can be restored using appropriate scientific methods but after assessment of residual strength. 3) The elements that have been exposed "damage severity" (slight) can be restored using the simple ways but after assessment of residual strength. 4) The elements that have been exposed "damage severity" (none) Should assess of residual strength.

b. Assessment of residual strength for existing elements

Non-destructive tests were conducted for samples of structural elements whose severity was evaluated (Slight and None) and some of the elements whose severity was (Moderate to Heavy) Table IX..

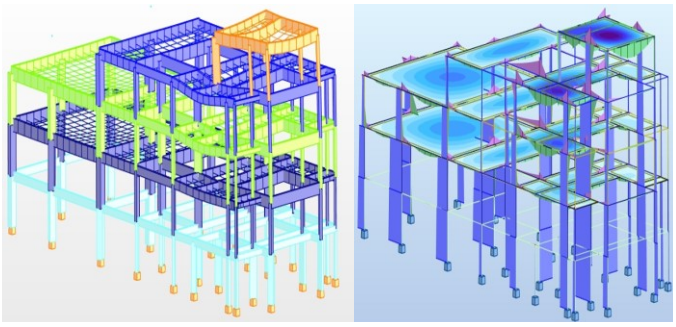

Fig. 17. *Views of behavior and deformation.*

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TABLE IX. RESULTS OF NON-DESTRUCTIVE TESTS

Elements	Schmidt hammer test		
$C_{13\text{-}2}$	29	100 < R	No damage
$C_{6\text{-}4}$	32	100 < R	No damage
$B_{12\text{-}6}$	16	60 < R<80	No damage
$C_{16\text{-}2}$	28	100 < R	Moderate
$S.T_{2\text{-}2}$	25	100 < R	No damage
	Ultrasonic test		
	Velocity	Quality of concrete [8]	
$C_{13\text{-}2}$	3.9	Good	
$C_{6\text{-}4}$	4.5	Very Good	
$B_{12\text{-}6}$	3.4	Satisfactory but loss of integrity is suspected	
$C_{16\text{-}2}$	3.8	Good	
$S.T_{2\text{-}2}$	3.7	Good	

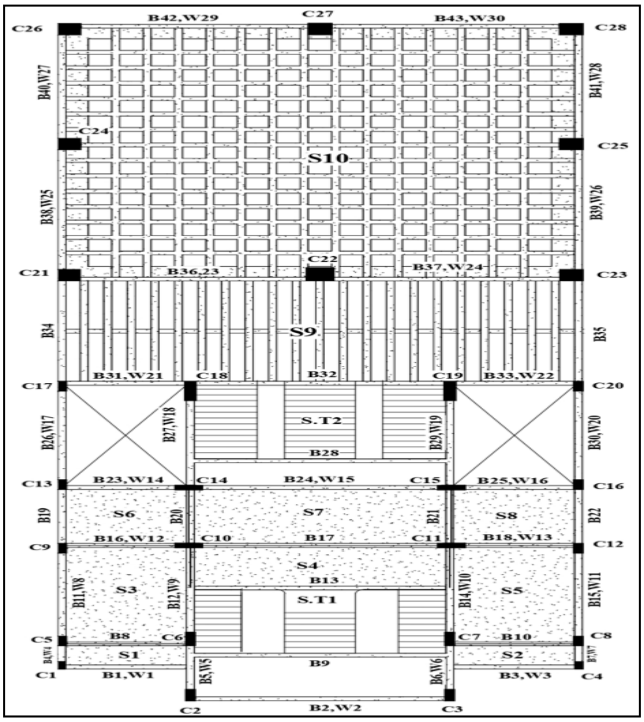

Fig. 18. *Plan of damaged building*

Through the results of the non-destructive tests in table-10, it turns out that the quality and resistance of the elements meet the design requirements after being damaged, except for the beam B12-6 Fig. 18.

6. Case Study (6)

A. General Description

The building (North mass) is an educational located at Hamdan area in Sana'a city. The damaged building was identified during the site visit and it was found that it is three stories. The building subjected direct bombardment with four missiles, Fig -19.

B. Application *of* Assessment *Methodology*

Step 1: Quick assessment

Fig. 19. *General view of damaged building in Hamdan*

Through the site visit and the initial visual examination, and a description of the external and internal damage. It turns out that the west part of building exposure extensive damages such as total collapse, extensive cracking with observable permanent deformations and large spalling for the most structural elements. The strength and stiffness of the element or structure were reduced to dangerously low levels, and the building maybe prone to sudden collapsing, in addition to destroying most non-structural elements as a result, the building can be described as Dangerous for use (unsafe)" and the building requires a preliminary assessment.

Step 2: Preliminary assessment

a. Through the preliminary assessment of all the damaged individual elements of the building and according to criteria for Preliminary assessment of damaged element building, the building (Middle Mass) is "(Dangerous for use (Unsafe)", Table.X.

b. Decide whether or not a detailed assessment is needed

It is noticed through the preliminary assessment of the individual elements that some elements have been damaged as a result of the damage of other elements, and this indicates a change in the path of the loads. Also, the elements which were not damaged require confirmation of their internal resistance. So, the building requires detailed assessment.

TABLE X. PRELIMINARY ASSESSMENT OF THE INDIVIDUAL ELEMENTS

Elements	Preliminary assessment
A-RC columns	Dangerous for use (Unsafe)
A-RC beams	Dangerous for use (Unsafe)
B2- Partitions	Dangerous for use (Unsafe)
B3- Slabs	Dangerous for use (Unsafe)

Step 3: Detailed assessment

a. Determine the force resistant paths

Adopted computer modeling (Robot) by applying a complete simulation of the building after the occurrence of damage, and applying the loads on it during the occurrence of damage. The building has been modeled according to structural drawings after documents review and verification of as-built construction. Removing the columns that were severely damaged (from severe to total) and applying the loads present during the explosion Fig. 20..

It turns out that the path of the loads has changed as a result of exposure of some elements to total collapse. The non-damaged elements and have not been subjected to total collapse may have decreased their resistance as a result of the redistribution of loads and moments, as a result:1) The elements that have

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Fig. 20. *General view of damaged building*

been exposed "damage severity" (Severe to Total) Should be removed and rebuilt using appropriate scientific methods. 2) The elements that have been exposed "damage severity" (severe to total) can be restored using appropriate scientific methods but after assessment of residual strength .3) The elements that have been exposed "damage severity" (slight) can be restored using the simple ways but after assessment of residual strength . 4) The elements that have been exposed "damage severity" (none) Should assess of residual strength.

b. Assessment of residual strength for existing elements

Non-destructive tests were conducted for samples of structural elements whose severity was evaluated (Slight and None) and some of the elements whose severity was (Moderate to Heavy) Table XI..

TABLE XI. :RESULTS OF NON-DESTRUCTIVE TESTS

Elements	Schmidt hammer test		
C_{19-3}	30.1	100 < R	No damage
C_{7-1}	42.55	100 < R	No damage
B_{32-2}	26	100 < R	No damage
B_{4-1}	17	60 < R<80	Moderate
S_{11-2}	26.5	100 < R	No damage
	Ultrasonic test		
	Velocity	Quality of concrete [8]	
C_{19-3}	6.89	Very Good	
C_{7-1}	3.97	Good	
B_{32-2}	4.38	Very Good	
B_{4-1}	2.9	Poor and loss of integrity exist	
S_{11-2}	4	Good	

Through the results of the non-destructive tests in table-12, it turns out that the quality and resistance of the elements meet the design requirements after being damaged, except for the beam B4-1. Fig. 21.

IX. REPAIR OF DAMAGED ELEMENTS

Through the results of the assessment of damage caused by explosions, it is clear that the actions that can be applied to rehabilitate the components of damaged concrete structures are divided into two types, according to the type of the structure components:

A. Structural Repair

The purpose is to carry out structural repair to load bearing

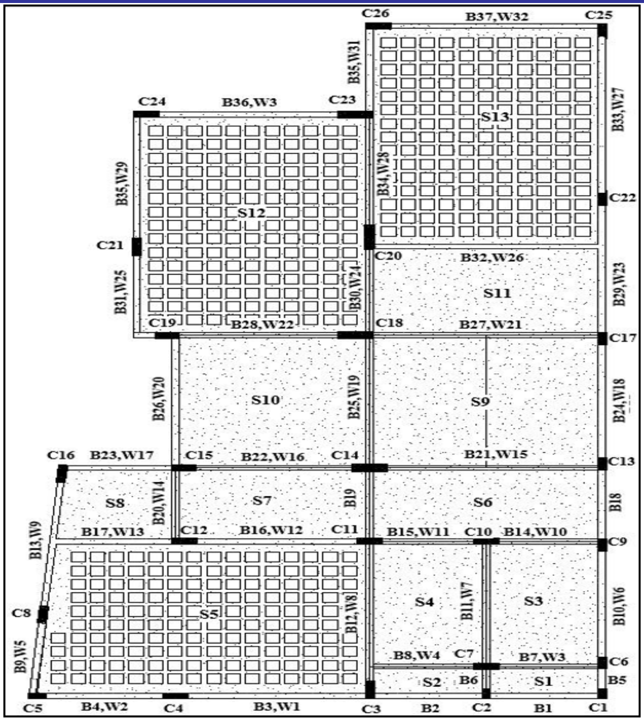

Fig. 21. *Plan of damaged building*

elements to restore its original strength as beams, columns, slabs.

B. Non-structural Repai

Aimed to restore the architectural shape of the building so that all services start working and the function of building is resumed as doors, windows, partitions…, etc

1. Required Decisions for Repair the cases Studied

According to the results of the assessment for each case, it is possible to determine whether the structure as a whole is capable for rehabilitation, and in this case, rehabilitation measures are determined or it is recommended to demolish and rebuild again.

a. Case Studied (1)

According to the results of the assessment, this structure can be rehabilitated, as most of the damage was non-structural and confined to a small part of the structure, the repairs required for rehabilitation are simple non-structural Repairs. In addition to very minor structural repairs to damaged structural elements.

b. Case Studied (2)

According to the results of the assessment, the structure was subjected to almost complete collapse and that the components which did not completely collapse were severely damaged, reducing their resistance and no longer meeting the instability requirements. Therefore, this structure cannot be restored and it is more appropriate to remove the building and rebuild it again.

c. Case Studied (3)

This building requires removing the collapsed elements whose severity has been assessed (Severe to Total) and reconstructing them again. After that, structural repairs are carried out for the elements whose severity has been assessed (Slight & None), and then non-structural Repairs are made for the non-structural elements.

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d. Case Studied (4)

This building requires removing the collapsed elements whose severity has been assessed (Severe to Total) and reconstructing them again. After that, structural repairs are carried out for the elements whose severity has been assessed (Slight & None), and then non-structural repairs are made for the non-structural elements. It is not appropriate to completely remove the structure because the area that requires removal does not exceed (32%) from the total area,Fig -22 and also the structure consists of only two stories, so there is no problem in terms of poor stability or resistance of the structure after its restoration with time as a result of explosion damage. The removal is carried out from top to bottom using appropriate removal methods without affecting the undamaged elements

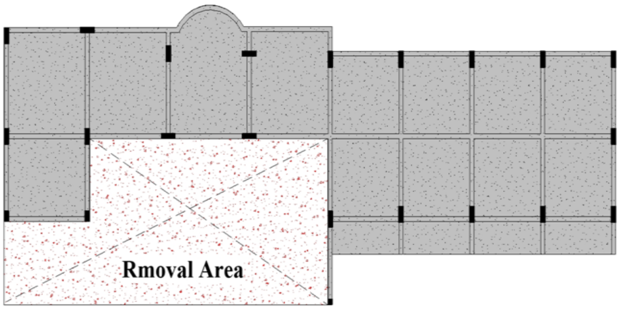

Fig. 22. *Removal area in Case Study (4)*

e. Case Studied (5)

This building requires removing the collapsed elements whose severity has been assessed (Severe to Total) and reconstructing them again. After that, structural repairs are carried out for the elements whose severity has been assessed (Moderate to Heavy) and (Slight & None), and then non-structural Repairs are made for the non-structural elements. The removal is carried out from top to bottom using appropriate removal methods without affecting the undamaged elements.

f. Case Studied (6)

This building requires removing the collapsed elements whose severity has been assessed (Severe to Total) and reconstructing them again. After that, structural repairs are carried out for the elements whose severity has been assessed (Slight & None), and then non-structural repairs are made for the non-structural elements. It is not appropriate to completely remove the structure because the removal area is located in the first and second story Fig -23, and also the non-affected part of the building is still useable and there is no decrease in resisting its elements according to the results of non-destructive tests, so there is no problem in terms of poor stability or resistance of the structure after its restoration with time as a result of explosion damage. The removal is carried out from top to bottom using appropriate removal methods without affecting the undamaged elements.

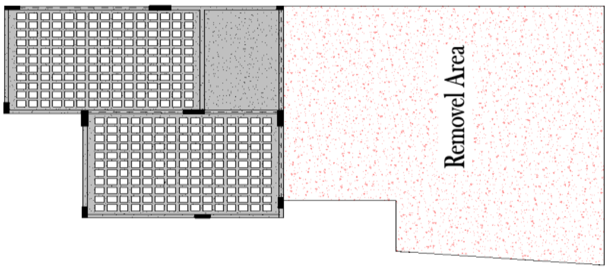

Fig. 23. *Removal area in Case Study (6)*

2. Required Decisions' for Repair the Cases Studied Elements.

The choice of the type of structural repair for damaged elements was based on analysis of the investigation data and results of the damage classification. The purpose of any repair procedure is to restore the load carrying capacity and stiffness of a structural element. However, the presence of very fine cracks in a concrete element make it impossible to perfectly restore the stiffness of the element. Calculations for each alternative scheme must be performed to assess the effects of the strengthening measures on the structural system and the load resisting paths. Items to be considered in the comparison of the alternative schemes include the feasibility of the construction, availability of materials and experienced workmen, economic considerations, aesthetics, and sociological considerations

A. Structural Repair

The type of structural repair method and appropriate materials were determined based on the type and severity of the damage to each element. These methods can be describe as follows:

a. Removing and replacing the defective and spalled concrete

Removing the concrete cover area that has been subjected to spalling, re-casting using repair material which should introduce a protective and durable environment around the reinforcement. A monolithic behavior has to be achieved between the repair material and the old concrete to get satisfactory behavior of the repaired structural element. Repair materials should be dimensionally stable, shrinkage-free, and compatible with the old concrete. The coefficient of thermal expansion and the modulus of elasticity of the repair material have to be similar to those of the concrete being repaired. it is recommended to use higher strength concrete with low water/cement ratio and superplasticizers or to use expansive cements. When cast-in-place concrete or shotcrete is to be used, the existing concrete surface should be prepared to insure sound bond between old concrete and new concrete. First, all unsound, damaged, or deteriorated concrete should be chipped away by mechanical means. The second step is to rinse the surface, clean it and roughen it by sandblasting, and then rinse it again. The third step is to saturate the surface and then allow it to approach dryness just before placing the new concrete. In some cases, the concrete surface is prepared with epoxy or mortar to improve bond of the new concrete with the existing surface [9,10]. Any exposed reinforcement should be cleaned of corrosion, oil, and dirt by sandblasting or wire brushing.

b. Repair of cracks which its damage severity was slight

Non-shrink grouts are used to repair cracks, to fill voids, or to close the space between adjacent concrete portions. Epoxy grouts are recommended for conditions when high shear forces or positive bonding is necessary across a void. Low viscosity resins are used for small width crack injection while higher viscosity resins can be used to fill larger cracks or voids. Dry packing is the hand placement of a very dry mortar and the subsequent tamping or ramming of the mortar into place, producing an intimate contact between the mortar and the existing concrete surface. The low water/cement ratio of the material reduces the shrinkage potential.

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c. Repair pf partial disintegration of concrete without curvature or inclination in the element

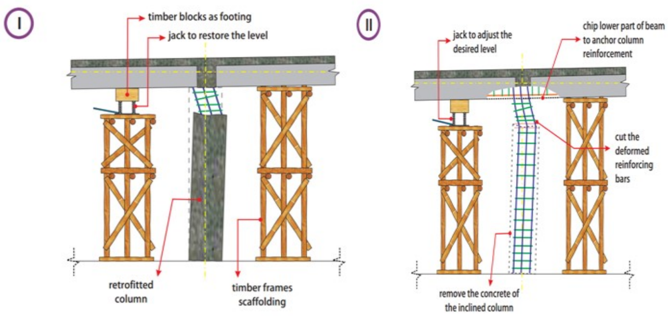
Define the area needs to be repair, provide temporary shoring to take the load of the damaged column until repair is complete, remove loose and deteriorated concrete, making the surface rough after cleaning, use suitable bonding agent, re-casting using higher strength shotcrete concrete and use appropriate curing practices

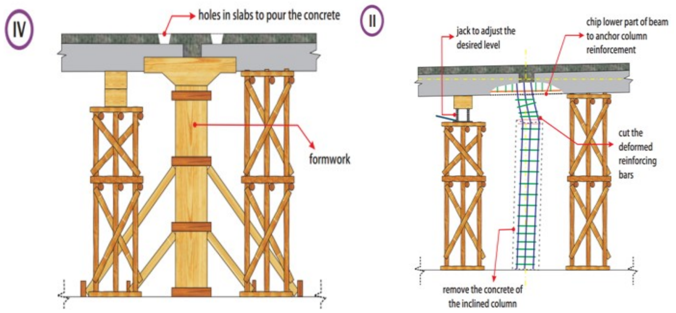
d. A heavily damaged structural element classified under "Severe to Total" damage

Should be removed and replaced with new material to restore strength and stiffness. Severe to total damage is indicated by total collapse, extensive disintegration of concrete, buckling of reinforcement, large cracks, visible inclination (residual drift), rotation and separation in connection. If only repair is required and the original cross-section is to be maintained, then damaged concrete should be removed, buckled reinforcement cut, new longitudinal reinforcement and new ties inserted, and non-shrink concrete should be placed. Example of removing one of the damaged columns and replaced with new material to restore strength and stiffness, Fig -24.

I. Support the beams around the column to be retrofitted during construction.
II. The slanted beam must be supported and jacked-up to restore the Level, fig -I. Note: If Jacking Is Difficult, The Deformed The Deformed Column Reinforcement can be cut First.
III. Remove the concrete of the inclined column.
IV. Cut the deformed reinforcing bars, fig -II.
V. Remove the concrete of the lower part of the beam and for improving the joint reinforcement detail, fig -II.
VI. Install the new column reinforcement and splice with the existing one. the length of splice between the existing and the new reinforcement is minimum 40d, fig -III.
VII. Construct the formwork of 9 mm thick plywood. the formwork must be shaped like a cone, fig – iv [11].

Fig. 24. *Column (C12) in story two incase studied (3)*





B. Non-Structural Repair

The actions will include the following:

- Patching up of defects such as cracks, and fall of plaster
- Stitching of walls across cracks by using steel reinforcement on wall faces and covered by cement mortar, or grouting of cracks using cement or epoxy like adhesive materials which are stronger than mortar and have tensile capacity.
- Repairing doors, windows, and replacement of glass panels.
- Checking and repairing or replacement of electric wires.
- Checking and repairing of water pipes & plumbing services.
- Rebuilding non-structural walls, boundary walls, ... etc.
- Re-Plastering of walls as required.
- Rearranging disturbed roofing tiles.
- Addition of reinforcing mesh on both faces of the cracked wall, holding it to the wall through spikes or bolts & then covering it suitably.
- Removal of portions of cracked masonry walls & piers and rebuilding them in richer mortar. use of non-shrinking mortar will be preferable.

X. CONCLUSIONS

This study resulted in a detailed description of the various types of damages to concrete structures due to explosions and rockets that resulted from the wars in Yemen. After that, a comprehensive assessment of these damages was conducted, and appropriate methods for the rehabilitation process were suggested, through the study of six cases, and the following conclusions can be drawn in:

I. According to this investigation, the damage caused by wars, whether as a result of explosions or missile shells, on concrete structures or its individual elements, can be summarized as follows; total collapse, partial collapse, exposure and buckling of reinforcement, horizontal cracks, diagonal cracks, deflection, disintegration of concrete, rotation, separation in connection, spalling of concrete cover, out of plumb.
II. By describing the damages in the six-case studied, it was found that the damages are similar in terms of the type of damage, but they differ in terms of severity and this depends on the type of explosion or missile shelling [direct or indirect], in the case of indirect depends on its location from the structure. In addition, the quality of materials, overestimated dimensions and reinforcement of concrete elements help to absorb the blast wave and reduce its effects. Also, the presence of the structural spacer helps not to affect the surrounding mass of the target block because its elements do not come into contact with each other.
III. According to this investigation, the damages caused by wars are assessed in three phases (Quick, Preliminary and Detailed

assessment). Then a report is prepared for each phase, provided that a final report is finalize if two or three phases are considered.

IV. The phases required in the assessment depends on the assessment results of the previous phase, where the assessment process begins with the quick assessment, and through the assessment results for this phase, it is determined whether the damaged structure requires initial assessment and may requires the detailed assessment according to its initial assessment results.

V. According to this study, a damage assessment was done for six cases studied on concrete structures. It was found that the first and second cases required quick assessment only, thus the third case required quick and initial assessment, and the fourth and fifth cases required quick, preliminary and partial detailed assessment, and the sixth case required a comprehensive assessment.

VI. As a result of the assessment procedure, the required repairs were divided into structural repairs applied to concrete elements only, and nonstructural repairs applied to other components.

XI. ACKNOWLEDGEMENTS

I am in great depth for all those who have participated to complete this work in the present form.

I would like to grate fully thank my supervisor, **Dr. Ali Hussein Mohamed Ali** for his kind and close supervision.

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