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A QUALITATIVE APPROACH TO IDENTIFYING STRUCTURAL DEFICIENCIES AND DAMAGES IN TIMBER REINFORCED MASONRY BUILDINGS AT HISTORIC JEDDAH AND THEIR CAUSES

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ABSTRACT
There are many serious structural deficiencies and problems facing the heritage buildings in historic Jeddah today, which could threaten their sustainability and survival. An exact identification of a building deficiency necessitates knowledge and familiarity with the original structural design and construction technique of a building combined with an indulgent of methods of scientific exploration. This paper presents a brief description of structural deficiencies patterns and damages found in Jeddah's heritage buildings and their construction details. The followed qualitative approach**,** based on the intensive survey and direct observation through a close up visual inspection of slightly or severely damaged buildings, besides the ruined ones revealed that the common construction system at Jeddah's heritage buildings is multiple-leaf stone masonry loadbearing walls. There are numerous structural deficiencies patterns in these walls that led to their structural instability, in addition to the degradation of the structural condition of their shallow foundations and flat timber ceilings. Since the accurate cause of a building deficiency and the form of its appearance must be understood prior to a sensible remedy can be applied. This paper will discuss on the important causes that led to the deficiencies and damages in Jeddah's heritage buildings. Accordingly, appropriate conservation plans will be developed.

KEYWORDS: Historic Jeddah, Heritage Buildings, Stone masonry walls, Structural deficiencies, Direct observation, Conservation.

1. INTRODUCTION

In the past, Jeddah's heritage buildings conservation technology was vastly underrated and ignored by owners, managers, and professionals, combined with the informal transformations made by their occupants; as many of these buildings are living houses and tenants still use them as residences. Accordingly, these historic buildings have been turned into neglected places for many centuries and exposed to all types of deterioration and encroachments or trespasses, as well as they have been encircled by high new buildings; because some of the historic buildings were demolished by owners and substituted by new modern buildings. Therefore, most of the historic buildings in Jeddah today suffer from many serious structural deficiencies and deterioration aspects that led to high levels of deterioration of these buildings, and they are also experiencing rapid deterioration of building materials mainly caused by lack of conservation, fragility of the materials used in them, harsh marine weather conditions, ageing of materials (natural wear and tear), use of incorrect or incompatible materials for repair, and the defects and errors of the original construction techniques and structural design.

Unfortunately, very few previous studies and researches were conducted that concern these buildings, which mostly covers architectural and urban studies. Consequently, the author has conducted an intensive survey and experimental campaign to study all structural aspects of these heritage stone masonry buildings reinforced with timber ties at Historic Jeddah. The present research presented part of this campaign and research study, which focuses on the identification of the structural deficiencies and damages in these Heritage buildings, their possible causes and preservation recommendations. In order to identify the appropriate preservation of heritage buildings in historic Jeddah, it is important to identify the form and detailing of architectural materials and construction details, structural deficiencies, deterioration aspects and their possible causes that are important in design the conservation plans of the buildings that are to be conserved, preserved and rehabilitated in the right way.

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The adopted qualitative approach in this research is based on a direct observation of the structural deficiencies, damages and construction material decay as well as historical research, where direct observation of the building is an essential phase of the structural study phases of buildings to be preserved beside the quantitative approach, it usually carried out by a qualified team to provide an initial understanding of the building structure and to give an appropriate direction to the subsequent investigations and analysis [1]. The main objective of this phase is identifying deficiencies, damages, and their possible causes. Since, the assessment of the remaining strength of the building structure includes the identification of damages as it will reveal the weaknesses of the structure and define the level and type of intervention. Normally in-situ as well as laboratory testing (non-destructive or semi destructive) is necessary. The most common method for the diagnosis of damages is the visual inspection, which is very quick and cost effective. Visual inspection is mainly used to detect surface problems such as cracks. Data collected during visual inspection is related to the geometry (dimensions such as width, height and length), width of cracks, size of deformations, etc. [2].

On-site examination of historic buildings and extensive photographic documentation of the buildings condition were carried out. The intensive site survey was achieved, where the data was obtained from the close up visual inspection of deficiencies and defects at its exact location or based on building structural elements. Measurements construction details, foundation survey, identification of major alterations and documentation of the condition of the building structural elements were detailed step-by-step with digital photographs.

2. HISTORICAL BACKGROUND TO JEDDAH HERITAGE BUILDINGS

Jeddah City, the port of the two holy cities, the gateway to the city of Makkah and main seaport of contemporary Saudi Arabia [3], is located at 21°29' north and 39°12' east on the Tihama coastal plain of the Red Sea in the western region of Saudi Arabia (Fig. 1a) [4]. Historic or old Jidda City, which is now a neighbourhood within the City Jidda, is a square kilometer area with properties built during different time periods. The Historic Jeddah, which was established in 646 AD, is the forefront of the Saudi Arabia heritage sites that UNESCO recently registered in the World Heritage List in 2014. The old Jeddah sites have a long history that extends from the pre-Islamic eras and through all the following Centuries until the present. The Historic District of Jeddah that named as "Al-Balad" possesses hundreds (over 500) of timber reinforced stonemasonry buildings that are recognized as historic [3] (Fig. 1b, c).

The heritage houses in historic Jeddah are of four to seven storeys, but the historic houses which are affected by the Ottoman architectural style, are of 2 to 3 storeys' houses (Fig. 1d), it seems fairly certain that the tall coral houses of Jeddah of four, five, six and even seven storeys (Fig. 1e) emerged in the late nineteenth century and spread in the early twentieth. Travellers' accounts from the seventeenth century and later confirm the fact that the houses of the old town of Jeddah were only of two to three storeys) [4]. Those tower houses that are the characteristic feature of the old city were built during the Ottoman period and represent the last major surviving example of Red Sea Architecture. These traditional houses were built with three main considerations i.e. privacy, the segregation between men and women and response to the hot humid climate. These factors have a great influence on the design of the houses people live in. Depending on the socio-economic status of inhabitants there are three types of traditional residential buildings of Jeddah. There are Simple Houses which are small and for small family. Then there are Large Houses which are tall structures meant for rich people, generally merchants. These were examples of outstanding Jeddah traditional domestic architecture. Their plan forms and their stylistic character were subjected to wide variations from one type to another. Finally, there are Multiple Units which are like palace for the very rich people. It is like more than one house combined together [5].

Architectural shapes with vertical patterns and openings like roshans and moucharabiehs that decorate facades characterize the buildings in historic Jeddah. Typical of Jeddah's traditional houses was the vertical distribution of rooms around a stairwell or airshaft. At the ground level, there were usually two entrances to the house, one for the male visitors, the other for the family. Some manner of connection between the two entrances was provided, and this formed a kind of central circulation axis (4). Islamic traditions are presented as leaf and floral patterns engraved on wooden doorways that lead to dahlis or entrance hallways leading to ground floor rooms, and at the back there are utility rooms. Various floors are accessed by the main staircase that leads to the suffah or transitional sitting room and majlis or main sitting room. At the back of the building there are makhazin or storage rooms, baitalma's or bathrooms, and mirakkab or kitchens (Fig 1e). During hot summers, roof terraces or kharjah or

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adjacent rooms are used for sleeping. High walls surround terraces to a height of around two meters, but wooden screens help the cooling winds from the sea to lower temperatures (6 and 7).

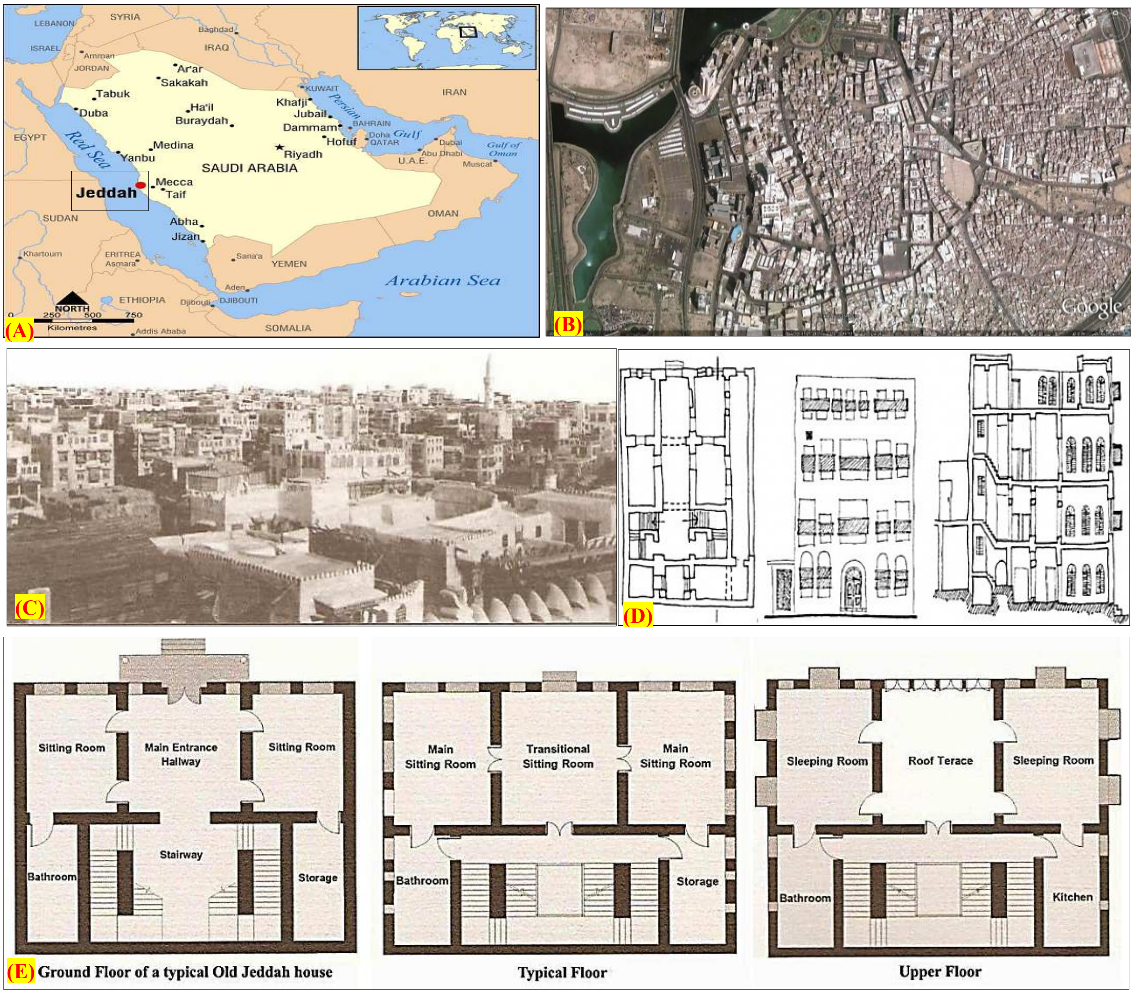

Figure. 1: *(A) Map of Saudi Arabia showing the location of Jeddah (Source: www.mapsof.net/ map/jeddahsaudi-arabia); (B) Settlement Pattern and Layout of Al Balad region of old Jeddah (Source: maps.google.com); (C) A photo of the old city of Jeddah in 1928 AD. (Source: Alaidarous, 2011); (D) Ground Floor Plan, Elevation, and Section respectively, of a typical historic house in historic Jeddah (Source: Kamal, 2014); (E) Site plans showing an architecture design character of Jeddah heritage house. (Source: Alaidarous, 2011)*

3. STRUCTURAL SYSTEM AND CONSTRUCTION DETAILS OF JEDDAH HERITAGE BUILDINGS

In order to identify the appropriate preservation of heritage buildings in historic Jeddah, it is important to identify the construction technique, structural system and type of building materials of those buildings that are important in determining the optimal conservation plan of the buildings that are to be retained and preserved [8]. The degree of deterioration of these buildings does offer valuable insights into the techniques of their original construction. Based on the achieved intensive survey and close visual inspection of the heritage buildings in Historic Jeddah, whether slightly or severely damaged, besides the ruined ones we revealed that:

Most of the heritage buildings in historic Jeddah were constructed with multiple-leaf stone masonry loadbearing walls, which consist of two sides (outer leaves) with an infill in between (inner core leaf), the thickness of these walls, were greater at the base and then the thickness reduced at each floor level (Fig. 4a). There are various typologies of these walls, which have a slender or small thickness (0.45-0.55 m), moderate thickness (0.6-0.8 m)

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and wide thickness (> 1 m) (Fig. 2). The external leaves of these walls are built of stone blocks in the form of dressed-stone (ashlar) or rubble stone (undressed or irregular shaped stones) that stuck with each other by mud-lime mortar and laid in coursing or randomly. The texture of the external leaves is divided in three major categories (Fig. 3) based on the stones shape and their laying manner (continuity of courses): i) ashlar facing stone masonry, in this masonry carefully and finely dressed stones are laid in level courses (horizontal rows), these courses are of uniform height (stones having the same height within each course, but in few instances each course varying in height), all the joints are regular, thin and have uniform thickness, ii) uncoursed random rubble stone masonry, the most basic form of this masonry is composed of both large and small irregular stones used indiscriminately either as delivered from the quarry or broken down by the hammer to make them fit with one another, these stones which are of different sizes and shapes, are laid without any particular order (without forming courses). Vertical joints are not plumbed, joints are filled and recessed. Large stones are used at corners and at jambs to increase their strength. Through stones are used at certain intervals in the face area for joining faces and backing, iii) coursed rubble stone masonry, in this masonry roughly cut or undressed stones are laid in layers or in somewhat level courses. Headers of one coursed height are placed at certain intervals. While the inner core of these walls is generally built of rubble stones in abundance of mud-lime mortar (This core or infill was produced where the original masons filled the cavity with loose rubble stones at the same time as the outer leaves were constructed. A semi-liquid mud-lime mortar was then poured over the loose stones of the infill to form a solid core). These walls were reinforced with timber tie-beams (called Gandal or taglilat) at an approximate height of 1.2 m (every 5 or 6 stone courses) that were laid horizontally and transversally, and this to distribute the load on the light coral stone, to improve the tensile performance of the walls, to provide additional strength, resilience and prevent cracking that result from differential settlement because of these tie-beams attract most of the tensile forces developed in walls under imposed loads, and since they lock with the beams in neighbouring walls they probably have a reinforcing effect laterally, and also to tie the interior and exterior sections of multiple-leaf walls together. The horizontal tie-beams were usually visible on the wall's surface and not concealed inside it which means the plaster rendering did not cover the horizontal timbers (Fig. 4b) [9 and 4]. These walls were also covered or plastered with two different wall plaster layers (external and internal lime plaster), the internal layer is a thick coat and made of lime and sand, the external layer is a thin coat and made of lime wash, this layer has different colors (white, ochre and blue) according to the type of materials added to lime. This lime plaster or render was applied to protect these fragile stone walls from the combined effects of humidity, heat, salts, seasonal rains, sand storms (Fig. 4c).

About the type of the building materials used in Jeddah heritage buildings and their sources, the stones were used in the construction of the multiple-leaf masonry walls are local limestones of marine-origin (e.g. fossiliferous limestone and coral stone). Fossiliferous limestone, that is vernacularly named as "Mangabi", has been widely used in these walls, it was brought by a contractor either from quarries north of Jeddah and along the sea shore or was dug from al-Manqabah lagoon located north-west of the town [10], and then cut at the construction site into cubes which vary in dimensions from building to another but the predominant dimension is roughly 25 x 25 x 40 cm. These local stones are characterized by shell-formation inside, low density, very high porosity and low mechanical strength. Nevertheless, these stones have high resistance to humidity, heat isolation and are abundantly available, thus they were found in all historic buildings. A dark brown marine mud obtained from the bottom of the lagoon served as a cementing material to bind the stone blocks, in addition to local and imported timber beams for reinforcement [4]. Mud-lime mortars readily adhere to marine origin limestone were used as plaster layers, mortars of this plaster were comprised either of a slaked lime and local sand, with the mortar being left out to mature for five days before being used, or of a local sand, a slaked lime and a clay or silt from the bottom of the al-Manqabah lagoon. The lime was traditionally produced from coral that was burnt locally. Whitewashed lime stucco was used as a protective coating, the lime used in this layer was produced either by burning small pieces of white coral rubble, or by burning seashells which produced a very hard 'marble like' plaster [11].

For the floors and roofs over the loadbearing walls, the most common form of floor structure was timber planks with about 3cm thickness laid on timber beams fitted into half the thickness of the walls, about 15-20cm in diameter. This supporting structure was usually covered with straw or palm leaves mats, followed by terrace layer made of a mixture of pulverized pebbles and coral limestone fragments bonded with lime mortar, and finally floor mortar "finishing layer" (Fig. 4d) or tiles in some instances in more recent heritage houses. Roofs were similarly constructed, but with an addition of water-resistant lime plaster on top of the roof to protect from rainwater. The

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final screed over the floors was normally around 200 mm in thickness, but roof floors were thicker, so that rainwater would drain away from the building through timber water spouts quickly [4, 11].

As for the foundation of the walls, the stone masonry loadbearing walls of heritage Buildings at Historic Jeddah are founded on shallow foundations (continuous stone masonry strip footings) with depth ranges between 0.5 m to 2.5 m, which considered an extension of these walls under the ground surface up to the foundation level, they were usually the same thickness as the walls, which were built above them (Fig. 4b), except in a few cases, these foundations were thicker than the walls. It is well recognized that the foundations support the wall weight and provide an interface between the underlying soil and the building structure [12].

With regard to the distribution and transferring the loads in the load-resisting system of Jeddah heritage buildings, the loadbearing walls at both sides of the building support the roof load through timber joists which are span horizontally across the short width of the building, then these walls transfer the applied loads to them in addition to their own-weight to continuous stone masonry foundations under them, and then these shallow foundations transfer the entire load to the underlying bearing soil [13].

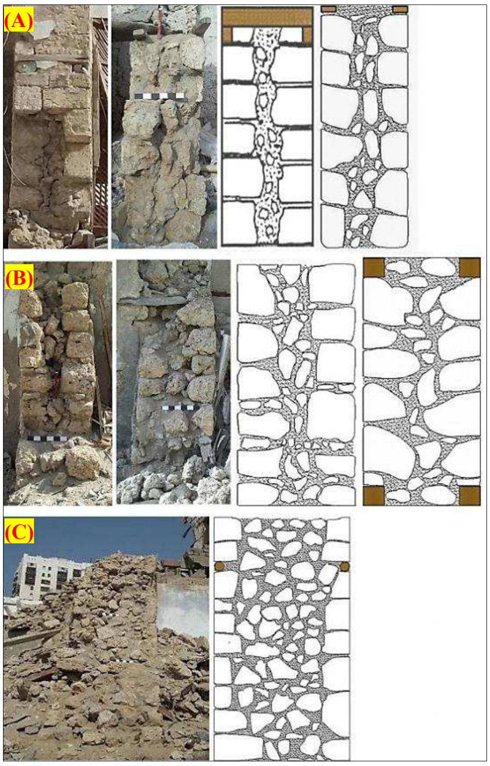

Figure. 2: *Examples of the major types of the multiple-leaf stone masonry walls of the heritage buildings at Historic Jeddah; (A) small thickness (0.45-0.55 m); (B) medium thickness (0.6-0.8 m); (C) large thickness (> 1 m).*

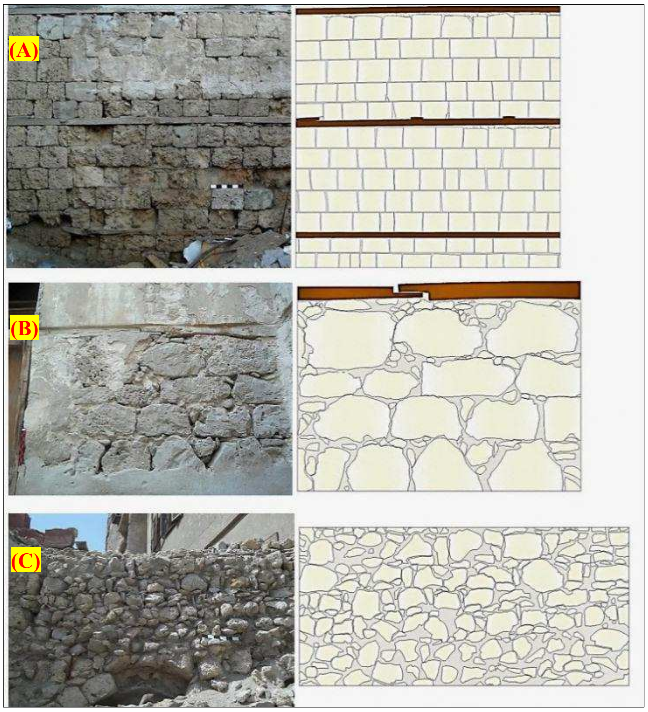

Figure. 3: *External face for various textures of stone masonry walls of the heritage buildings at Historic Jeddah; (A) ashlar facing stone masonry; (B) coursed rubble stone masonry; (C) uncoursed random rubble stone masonry.*

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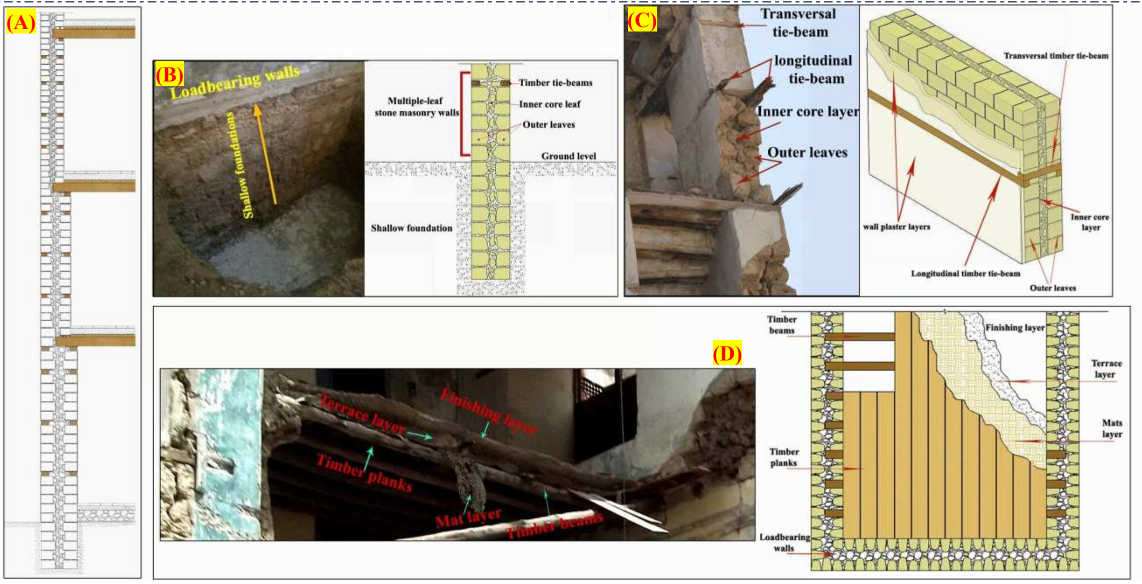

Figure. 4: Construction details of Jeddah heritage buildings; (A) Sketch drawing of the external wall cross-sectional view shows that the wall thickness reduced at each floor level, (B) Photo and cross-sectional view of the wall foundation, (C) Photo and 3D-model of stone masonry loadbearing walls and their components, (D) Photo and plan view of the predominant traditional roof.

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4. IDENTIFICATION OF DAMAGE/DEFICIENCY CAUSES AND THE ACTUAL STRUCTURAL CONDITION OF JEDDAH HERITAGE BUILDINGS

The identification of the accurate causes of damages, deficiencies and the form of their appearance in heritage buildings at historic Jeddah and the technical condition of those buildings is very important prior to identifying and undertaking appropriate conservation measures. Most of the heritage buildings at historic Jeddah have born too much stamp of wear and tear because of the dearth of serious maintenance for centuries. Some buildings are completely falling beyond economic repair. The dilapidation or ruins survey and close examination of existing deficient buildings revealed that these buildings suffer from many structural deficiencies and degradation aspects as follows:

4.1 Degradation of the structural condition of the buildings' foundations

The shallow foundations of the heritage buildings at historic Jeddah suffer from many structural deficiencies and deterioration patterns (e.g. differential settlement, structural cracks, sliding, twisting, rotation, crushing and erosion of their calcareous components (Fig. 6). The possible causes responsible for these problems are:

- Location of buildings; where these Buildings are located near the red sea shore and have common building defects in coastal areas. This is because the water coming from the ground caused dampness penetration and structural instability. In addition, salts (e.g. halite and gypsum) which came from the sea caused erosion and damage to their building materials (coralline lime stones blocks and mud-lime mortars) as shown in (Fig. 6a, b) [14].
- Poor properties of the foundation soil; which included fill materials composed mainly of clay, sand and gravels, where a surface layer to a depth of about 3.5 m almost of fill materials composed of silty sand soil medium dense to very dense with some gravel dry light-colour. The subsurface layer extends from a depth of 3.5 m to 9 m which composed of limestone, very weak, perforated, fossiliferous, with marl intercalations, as shown in (Fig. 5a). As well as contaminated and saline underground water table rising (the groundwater was found at depths of 1.1– 1.2 m), as shown in (Fig. 5b and 6c). In addition to inadequate design for these foundations, which in most cases have been built without specific account for geotechnical problems. Most of the time, the foundations damage arises as a consequence of soil settlings, that is of displacements which may occur across the whole lifetime of the building.
- Insufficient depth of foundation bed; which prevents soil portions lying aside to stabilize the foundation itself.
- Excess of acting load or excessive vertical loads; which is the result of construction of additional stories or new architectural elements, or due to the modification of structural layout, or misuse of these buildings. The increase

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in vertical loads (live and dead), which are usually non-uniformly distributed, limits the ability of these weak foundations to carry the imposed loads.
- Variation of subsurface water level; which can produce soil consolidation and, hence, increase of displacement independently of applied load.
- Excavation aside the existing foundation during the construction of adjacent high new building, or demolition of an adjoining construction and loss of lateral support and confinement.
- The impact of ground vibrations due to heavy traffic and vehicles, adjacent developments or demolitions, any extensions to the original structure, or even the excavation of a nearby foundation. In addition to seismic actions that can involve a strong increase of the horizontal load acting on foundation, depending on the building configuration [15].

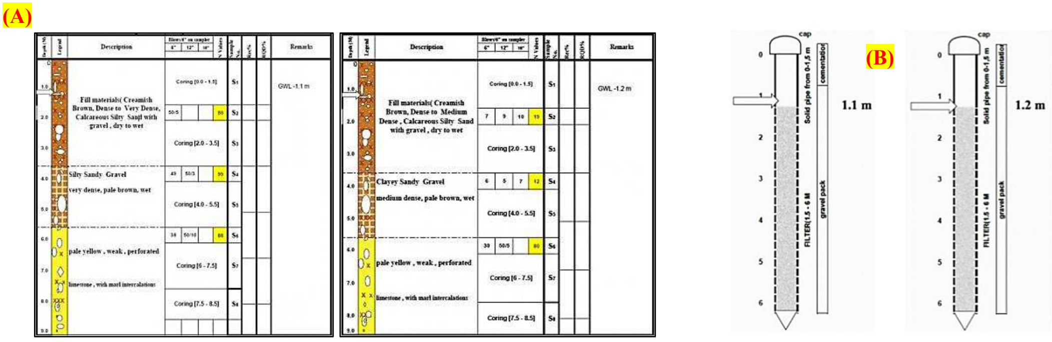

Figure. 5: *(A) The logs of boreholes that were drilled in one of the heritage buildings in Historic Jeddah (Xenel house), show detailed information and data about the soil stratification; (B) Result of monitoring the underground water table during drilling, shows a high level of groundwater, inferred level of groundwater which was (1.1m to 1.2 m).*

Figure. 6: *(A, B) Illustrate the vulnerability of the structural state of the shallow foundations of heritage buildings in historic Jeddah; (C) shows the ground water rise and its leakage to the foundation.*

4.2 Structural deficiencies and damages of the multiple-leaf stonemasonry loadbearing walls

Based on our intensive survey and close up visual inspection, we observed that most of the stone masonry walls of heritage buildings at historic Jeddah suffer from many structural deficiencies and degradation aspects, which can be summarized as follows:

4.2.1 Propagation of significant vertical structural cracks within the masonry walls

It has been observed the spread of the deep and penetrative vertical structural cracks in stone masonry walls at many heritage buildings, which extend along most of the entire wall height (continuous vertical cracks) or at a lower height (discontinuous vertical cracks), that also different in depth and breadth from building to another (Fig. 7). The possible causes responsible for these cracks are:
- Differential settlement of the underlying bearing soil and shallow foundations.
- Non-extension or disconnection of timber tie-beams which supporting the walls, their improper position, dryness, compressional, weakness and damage of these tie-beams, as well as their separation from masonry walls.
- Lack of sufficient structural connections at corners and intersections.

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- Occurrence of modifications, or addition of parts (e.g. additional storeys or newly architectural elements), or change in use, or misuse, or improper structural restoration of these heritage buildings. These things usually lead to increase the dead and live vertical loads, which are usually non-uniformly distributed, thus an excessive increase in stresses due to these excess loads, which their value exceeds the ability of the loadbearing walls to resist them, this causes cracks in these walls, In addition to a change in their construction and structural system (this is because some heritage buildings were built to only hold certain loads and sometimes may not withstand additional loads).
- In some cases, vertical loads act eccentrically; this is resulting from lack of the verticality or straightening of the loadbearing walls (out-of-plumb walls).
- Creep; which occurs over time, under the influence of high dead loads.
- Decomposition, erosion and disintegration of structural mortar in the mortar joints between the stone units as well as erosion of the stone units themselves, due to natural wear of construction materials and deterioration of these materials where physiochemical factors often play a prominent role in the occurrence of this damage, resulting in imbalance in the distribution of loads within these walls, which eventually lead to take place cracks, which gradually expand and cause a deficiency of the entire building.
- Horizontal movement resulting from vibrations with no good horizontal connection between walls.

Figure. 7: ***Large vertical structural cracks run through the entire height of the masonry walls of some heritage buildings at historic Jeddah.***

4.2.2 The presence of diagonal structural cracks within the masonry walls

It has been noticed the propagation of deep diagonal structural cracks (in-plane shear cracks) along the entire height of the portions of masonry walls between the bottom of the upper openings and the top of the lower openings, and they can be observed in piers between openings. These cracks whether be stepped through mortar joints only or straight through both stone units and joints in the masonry loadbearing walls at heritage buildings in historic Jeddah (Fig. 8) may occur due to the following causes:
- The impact of lateral loads caused by differential settlement of foundations and bearing soil, or by the vibrations, earthquakes and wind forces.
- The impact of an increase in vertical loads which are usually non-uniformly distributed.

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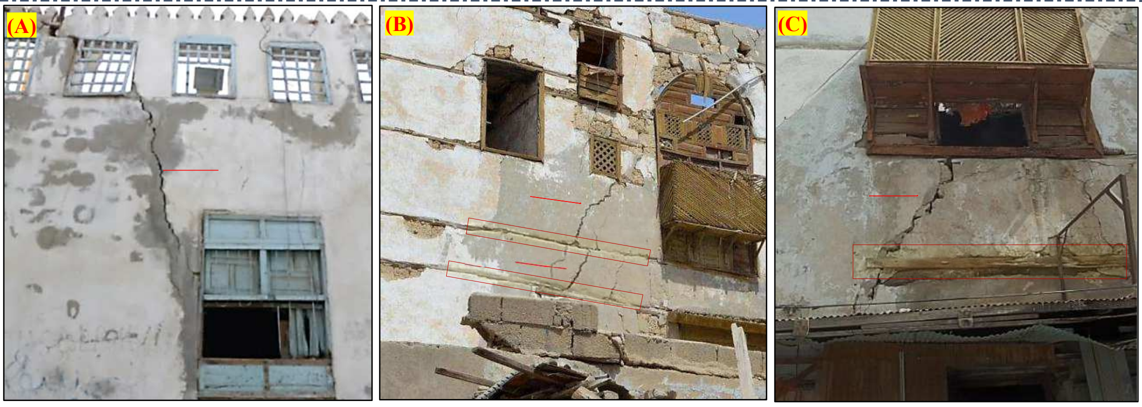

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Figure. 8: Diagonal Structural cracks in masonry loadbearing walls of some heritage buildings at historic Jeddah.

4.2.3 The presence of vertical separation cracks between perpendicular and intersecting walls

It has been observed a separation or disconnection at the corners of orthogonal and intersecting walls in some heritage buildings at historic Jeddah (Fig. 9), where the vertical cracks between these walls occur in intersection areas due to the stress concentrations that occur at the intersection of perpendicular walls. Instability of corner sections often occurs because two sides of the corner are unrestrained. Therefore, the corner section is free to collapse outward from the building due to their inadequate connection and flexible floor diaphragms or to weakness of the structural connections between these walls because of decomposition of the building materials, In addition to the impact of vibrations caused by earthquakes, excavation work, and movement of vehicular traffic, or to the differential settlement of foundations and bearing soil, or to increase imposed vertical loads.

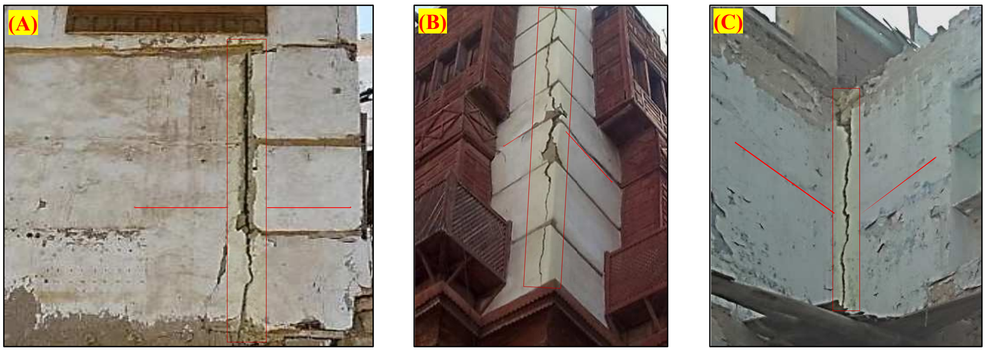

Figure. 9: Vertical separation cracks at corners; (A, B) Vertical cracking in perpendicular walls, external; (C) vertical cracking at intersecting walls, internal.

4.2.4 Deterioration and deficiency of inner core leaf in the multiple-leaf masonry walls

It has been observed that the inner core (rubble infill leaf) in the multiple-leaf masonry loadbearing walls suffers from deterioration, cracking and propagation of voids and cavities within it, as well as lack of adhesion between it and external layers or detachment of these layers (Fig. 10A), such is due to either increasing in vertical loads or washing out and damage of its constituent materials. As the fine materials are removed from the infill due to leakage and penetration or percolation of rainwater into these walls through the damaged parts of the roofs, defective water gutters and degraded parts of the walls themselves, in addition to the penetration of sea spray and high humidity that lead to washing out and removing fine materials of binding mortar in rubble infill leaf, thus the occurrence of cracking and damage to this layer, in addition to weakness or loss of bond strength between rubble stones in the rubble infill leaf and loss of adhesion between the inner core leaf and the outer leaves.

Since rainwater has been allowed to penetrate the inner material, the water inevitably percolates downwards, removing fine material and leading to consolidation at lower levels, that makes the upper parts of walls that

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constantly exposed to the rainwater be less dense and stiffness than the lower parts. In severe cases, loss of fill material from its original upper position in upper levels within a wall can create large voids, reducing the inner and outer leaves to independent structures.

It is worth mentioning that the voids and cavities that have been found in the inner core leaf of the multiple-leaf walls may be attributed either to deterioration of its binding mortar or to defects in its original construction technique. Damage and cracking of this inner core leaf led to generate a lateral internal pressure exerted on the outer leaves, which resulting in bulging or horizontal crack at the level of one of the horizontal joints (Fig. 10B), or partial collapse of these layers in some cases.

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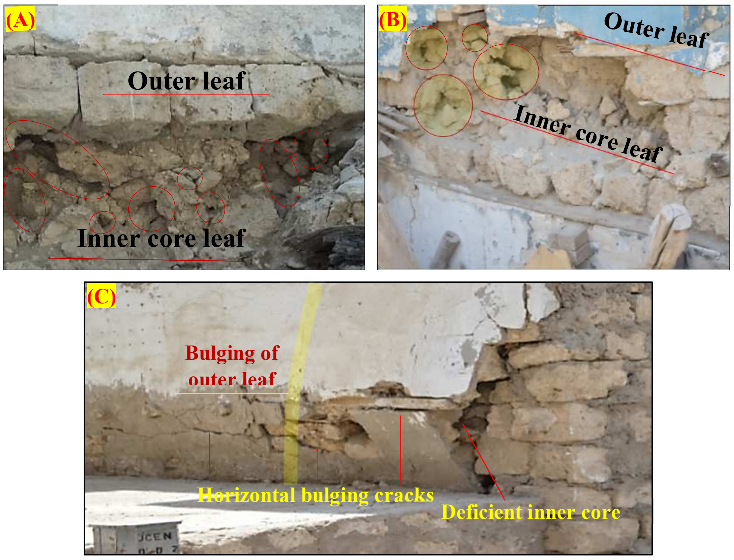

***Figure. 10:** (A and B) Damaged rubble infill exposed (C) Shows horizontal cracks as a result of bulging of the outer layer due to deterioration of the inner core.*

4.2.5 Vulnerability and deterioration of embedded timber ties in masonry walls

The main problem of timber reinforced masonry walls of heritage buildings at historic Jeddah is the degradation of timber over time, in addition to the original construction techniques defects. It has been observed that the embedded timber tie-beams within stonemasonry loadbearing walls were severely decayed, deteriorated and in some cases separated as a result of the following causes:

- The impact of high temperatures: High temperatures results in a loss of the internal water content and cellulose content of the timber of ties, thus leads to dryness, fragility, weakness of the timber surface and changes in the original dimensions of these beams, and therefore development of fissures and cracks that differ in length, depth and breadth. In addition to, the damage and thermal decomposition over time, which reduces the moisture absorption rate of the timber beams, and thus lead to their dryness, compressional, which eventually lead to deformation of these beams and separation them from the masonry walls, along with the sliding of stone units from over these beams as a result of overloading (Fig. 11a, b) [16].
- The effect of high humidity: High humidity results in a hydrolysis of the timber ties; because the timber is a hygroscopic material affected by water and has a great ability to absorb moisture, due to the hydroxyl groups (OH) of cellulose [17, 18]. Therefore, the physical and chemical properties of the timber ties weaken and lose their mechanical properties, in addition to the inevitability that it be infected with microorganisms. As the humidity over 20% and significant humidity changes result in biological attack that may lead to complete decomposition and disintegration of timber tie-beams and of the entire tie system [19]. As a result, masonry walls are weakened and deficient (Fig. 11c).
- The effect of the original construction technique defects and errors: some construction defects were observed in the masonry walls, which increased the vulnerability of these walls. These defects can be summarized as follows:

a- In many cases, timber tie-beams do not continue along most of the entire wall length and do not continue in the corner zone of masonry. Thus, their tying role is not activated, so the cracking occurred (Fig. 11d).

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b- In some cases transversal timber tie-beams are simply resting on the longitudinal ones (inadequate connection between longitudinal and transversal timber ties), thus connection of the two external leaves of masonry not be sufficient, resulted in the separation of these layers (Fig. 11e).
c- In some cases there is poor splicing of timber ties. Thus, their tying action is lost (Fig. 11f).
d- In many cases lack of connection between longitudinal timber tie-beams (the two longitudinal timber ties are not spliced). As a result, these tie-beams did not prevent cracks to propagate (Fig. 11g).
e- In some cases there is a common mistake is location of poor quality connection among longitudinal timber-ties in the same location vertically, that led to the vulnerability of the masonry loadbearing wall and allowed cracks to propagate through this location (Fig. 11h).
f- In some cases, one or more timber tie-beams are not posed in the same level in the perimeter and internal loadbearing walls, so these beams do not function as a tie, but as simple reinforcement to the masonry walls, as well as the lack of connection between intersecting walls led to out-of-plane collapse of them.

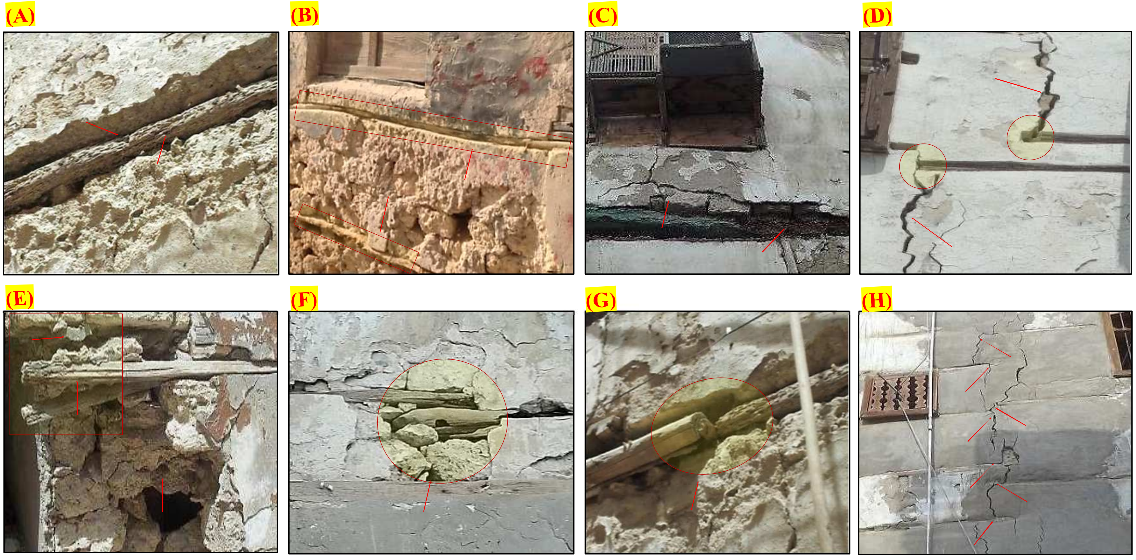

Figure. 11: *Shows deterioration aspects of timber tie-beams; (A, B) The effect of high temperatures; (C) The effect of high humidity; (D) Non-extension or disconnection of timber ties; (E) inadequate connection between longitudinal and transversal timber ties; (F) the poor splicing of longitudinal timber ties; (G) lack of connection between longitudinal timber tie-beams; (H) location of poor quality connection among longitudinal timber-ties in the same location vertically.*

4.2.6 The occurrence of severe deformation of stone masonry walls

The stone masonry loadbearing walls of some heritage buildings suffer from tilting, either at the entire wall length (Fig. 12a, b), or at a shorter length in the form of bulging in limited parts (bowing of a certain area of the wall surface) (Fig. 12c). Such these deformations attribute to the following reasons:
- Differential settlement in foundations due to erosion of their components, or increased loads imposed.
- Increased vertical loads that are usually non-uniformly distributed, which consider the important cause of deformations, due to the compressive load on the wall will be higher than its load capacity.
- Lateral and shear forces and their effects lead to twisting, warping, rotation and tilting of walls, where the worst defect of these masonry walls is that they are not monolithic in the lateral direction, and this can happen for instance when the wall is made by small pebbles or by two external layers even well-ordered but not mutually connected and containing a rubble infill. This makes the wall more brittle, particularly when external forces act in the horizontal direction. The same problem can happen under vertical loads if they act eccentrically.
- Construction of high new buildings adjacent to the heritage buildings (excavation works and resulting vibrations - soil pressure and settlement) leading to severe tilting or twisting of the loadbearing walls at these heritage buildings.
- The occurrence of damage and cracking to inner core layer leads to generate a lateral internal pressure, which exerts on the outer leaves, resulting in bulging of these layers and their partial collapse.

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- Deterioration of the bond between the external leaves and rubble inner core or its loss over time; due to crushing of the construction materials due to the vertical and horizontal in-and out-of plane actions, the wall does not behave as a whole. The slenderness of the external leaves (that resist the major part of any imposed action) is increased and the probability of severe deformation or even collapse is enhanced.
- Expansion, shrinkage and erosion of stone units and their binding mortar. Decomposition and erosion of embedded timber tie-beams in the loadbearing walls.

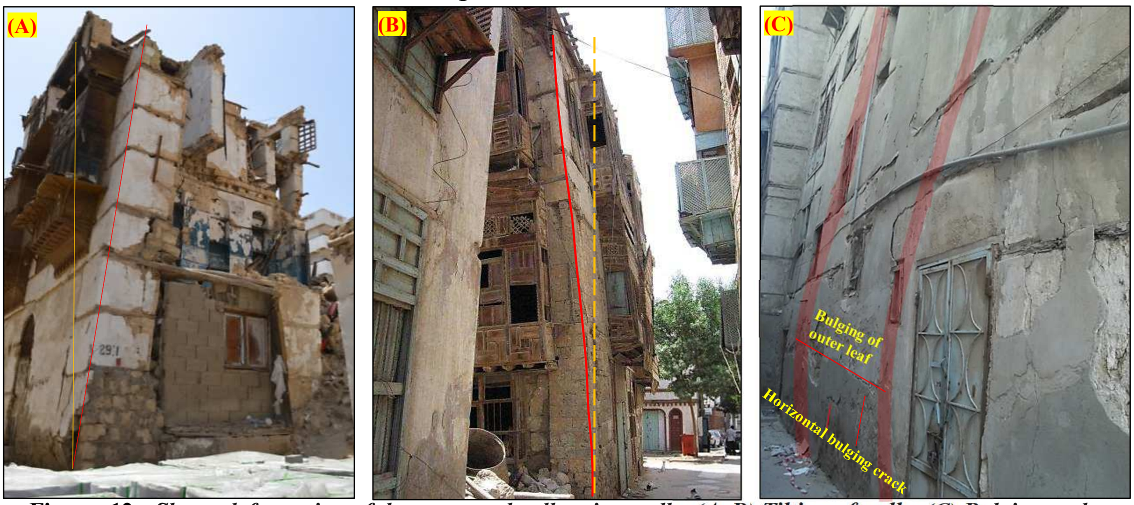

Figure. 12: ***Shows deformation of the masonry loadbearing walls; (A, B) Tilting of walls; (C) Bulging at the lower part of the wall.***

4.2.7 Deterioration and deficiency of the stone arches in the stone masonry loadbearing walls

The stone arches at some heritage building walls suffer from structural deficiencies and severe deterioration, due to the occurrence of a severe deterioration to their stone units "voussoirs" and pulled them apart as a result of damage and missing of mortar joints, as well as the erosion and deformation of the stone pillars that support these arches. In addition to the differential settlement of the bearing soil and foundations under these pillars (Fig. 13).

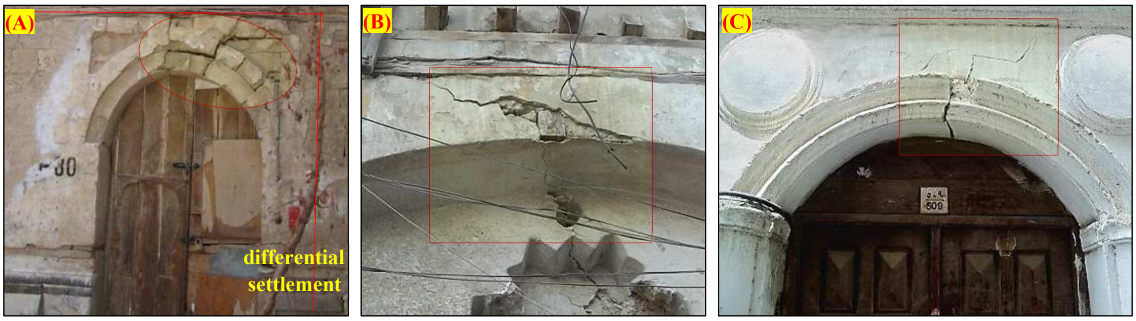

Figure. 13: Shows the deterioration and deficiency of the stone arches.

4.2.8 Fragility and deterioration of the external leaves components of the multiple-leaf masonry walls

Many heritage buildings at historic Jeddah are experiencing rapid deterioration of masonry material mainly caused by lack of conservation, severe marine climatic conditions, ageing of materials, use of improper or incompatible materials for repair, and the defects and errors of the original construction techniques and the original structural design.

There is severe deterioration and dismantling of the stone units used in the outer leaves, as the coralline limestone units were found in very poor state, severely deteriorated, are mostly friable and suffer from many forms of deterioration and degradation such as granular disintegration, powdering, pitting, sanding, alveolization, fissuring, flaking or exfoliations, spalling, crushing and salts crystallization. In addition, partial failures to stones at certain

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locations were noted (Fig. 14a). There are also damage and loss of the structural mortar in these external leaves, as well as erosion and fallen down on their external plaster layers which protect them (Fig. 14b). This is due to the combined effects of high humidity, extreme air temperature, sea spray, acid rainwater, salts efflorescence on the surface of these walls, microorganisms effect and contaminated ground water table rising, in addition to the effect of severe heat resulting from fire and the wet extinguishing process which results in the deformation and erosion of stone units, jointing mortar and the outer coating layer (Fig. 14c), as also the impact of the use of black cement mortar in repointing the joints and coating the walls (Fig. 14d).

It is worth mentioning that the soluble salts which came from the sea and together with the presence of polluted atmosphere caused the deterioration of the exterior surfaces of the external façades at heritage buildings in historic Jeddah, where the stone walls and their porous calcareous components absorb the salt solutions, when the soluble salts come into contact with air they crystallize (often to a larger size than the pores) and can cause spalling or flaking and disintegration.

In fact, the deterioration of the joints mortar usually resulting from the soft and friable mud-lime mortar that was used in the construction of masonry walls at Jeddah's heritage buildings. Because of little binding agent in this mortar, a high number of pores and shrinkage cracks prevails, so the deteriorated of mortar joints resulting from its softness and weakness [20].

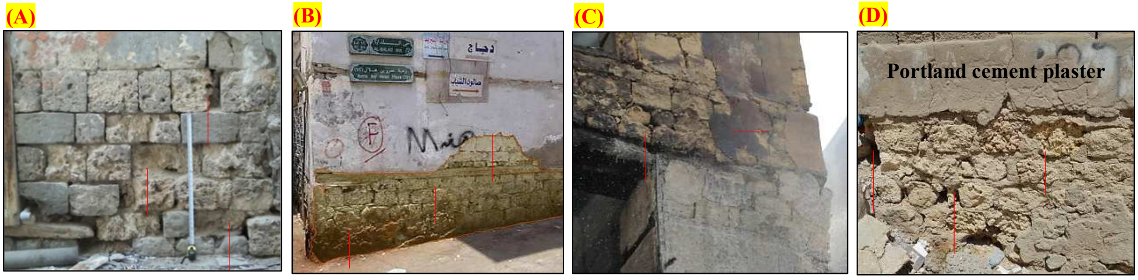

Figure. 14: ***Photos illustrate the weakness and deterioration of the external leaves constituent materials.***

4.3 Partial and total collapse of some heritage buildings in historic Jeddah

Some heritage buildings in historic Jeddah have been collapsed, these collapses (Fig. 15a, b) are the result of severe neglect of those buildings and left them neglected and abandoned without use and without repair or maintenance for a long period of time along with their exposure to all factors and forces of damage, which led to the degradation of their structural condition, and then to their collapse. These collapses also result from fires either as deliberate or unintentional human action as a result of neglect and the random extinguishing of these fires with a wet way (Fig. 15c). In addition to the demolition and removal works resulting from the urban growth and development of the old city of Jeddah, and lack of awareness about the historical, heritage, structural, architectural and aesthetic value of these heritage buildings which led to demolition some of these buildings by their owners, in order to construct modern residential buildings in their place and exploitation of the entire land area, and to save restoration cost of the heritage buildings and thus achieving financial gains.

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Figure. 15: ***Failure and collapse of some heritage buildings; (A) Partial collapse; (B): Total collapse; (C) Partial collapse caused by fires.***

4.4 Degradation of many heritage buildings' condition due to the use of incompatible building materials

In the efforts to restore some heritage buildings at historic Jeddah, incompatible materials (e.g. red bricks, cement sand or sand crete blocks and black cement mortar) were used (Fig. 16). The black cement mortar (Portland cement), which is chemically, physically and aesthetically incompatible with the calcareous components of the stone-masonry walls, was used extensively in previous restoration attempts, especially in repointing and plastering of these walls, where it seems clear in the most of the heritage buildings in Jeddah, except those that have been restored in an appropriate method. The cement mortar was used for the coating of the friable fossiliferous and coral limestone, which were the basic building materials for those buildings, such is done by persons engaged in maintenance and restoration work to strengthen them, improve their appearance and to stop the decay of the stone units in the walls from their point of view, ignoring the negative effects of this mortar, which can be summarized as follows:

- It causes moisture retention inside the wall's components (stone units and joints mortar), preventing their ventilation due to the lack of its pores, which leads to the decomposition and disintegration of them, where the Portland cement is composed of aluminum silicates, calcium sulfate and alkaline salts. These chemicals penetrate into the stones creating discoloration, efflorescence and salt crystallization stresses, in addition to the coating of cement plaster with plastic paint in some cases, this problem increases the severity of the problem of moisture retention, whose negative effects begin to appear only after a few months, causing removal the plastic paint and gradual decay of the porous calcareous stone and lime mortar.
- It is impermeable and has low porosity, so it traps vapour as well as water and prevents evaporation. Consequently, it is no good for curing damp walls. In fact, the reverse is true, for if used it only drives moisture upwards. When used as mortar its impermeability accelerates frost damage and increases internal condensation.
- It shrinks on setting, leaving cracks for water to enter, and because it is impermeable such water has difficulty in getting out. Therefore, it increases defects caused by moisture.
- Its use is not reversible. To remove it damages all historic building materials.
- It is too strong in compression, adhesion and tension, so that it is not compatible with the weak materials of historic buildings. It is a paradox that such weak materials have the greatest durability.
- Because of its high strength, it lacks elasticity and plasticity when compared with lime mortar, thus throwing greater mechanical stresses on adjacent traditional materials and hastening their decay, because the use of cement mortar can create a bond that is stronger than the stones themselves, causing the stone to crack first in case of stresses. It also can modify the stiffness and the overall behaviour of the original structure in a negative way.
- The cement mortar and stone units can react differently to heat and moisture creating imbalanced expansion or contraction, as well as the cement grout has high thermal conductivity and may create cold bridges when used for injections the walls.
- It causes concealment of the heritage value of the historic buildings and destroys the original look of them, due to the fact that their colour is 'cold' grey and rather dark. The texture is too often smooth and 'steely'. These characteristics are generally judged aesthetically incompatible with traditional materials [21 and 22].

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Figure. 16: *Shows the effects of the use of incompatible building materials; (A, B) black cement plaster (Portland cement); (C, D) red bricks and sand crete blocks.*

4.5 The presence of structural problems with the roofs and floors of heritage buildings

The timber roofs of some heritage buildings were found damaged, deficient and sometimes collapsed, this is either as a result of the absence of a proper rainwater drainage system, the absence of insulation and protective layers of the surfaces or damage of these layers due to improper installation, which resulted in leakage of water to the roofs (Fig. 17a), and then the infiltrated water damaged their timber elements and created structural problems such as severe sagging in their middle span, twisting of timber beams and planks which carrying the roof layers and occurrence of longitudinal cracks in these timber elements or breaking them (Fig. 17b), and thus a partial or total collapse of these roofs.

Some timber floors were also found damaged and collapsed (Fig. 17c) as a result of deterioration of the structural state of the structural timber elements which were used for roofing due to the various damage factors (e.g. physico-chemical and biological factors), increased imposed loads, and the use of bearing joists or beams with small sections that do not fit the span between the support walls, in addition to the lack of adequate connection of the floors to the masonry walls. Also were noticing that the excessive deflection of timber roof is the main problem, it could be due to overloading or creep along with material weakening, perhaps due to moisture. As well as in some cases were noticed that rotting occurred especially at the end of timber beams which rest on masonry walls affected by moisture.

It is known that the structural damage of the timber floors and roofs makes the upper parts of the masonry walls that were laid on them vulnerable to damage and collapse. It has been observed that the timber roofs of heritage buildings with timber joists spanning two walls in a room, instead of spanning the full length of the building. As a result, the floor in each room acts as an independent system, and has a tendency to pull apart from the other floors during the strong ground shaking. This will cause a partial or total collapse of them [23].

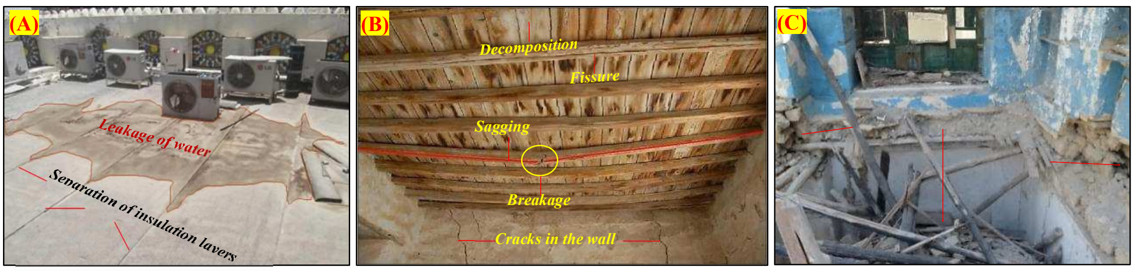

Figure. 17: Shows damage to roofs and floors; (A) Water leakage and separation of insulation layers; (B) Sagging, breakage, fissure and decomposition; (C) Total collapse.

5. CONCLUSION

Based on our extensive survey on deficient, dilapidated, ruined and collapsed heritage buildings at historic Jeddah, we revealed that the structural system of these buildings is loadbearing walls system that follows multiple-leaf stone masonry walls technique, these walls have small thickness (0.45-0.55 m), moderate thickness (0.6-0.8 m) and wide thickness (> 1 m), the texture of their external leaves has been classified into three types, namely ashlar facing stone masonry, coursed rubble stone masonry and uncoursed random rubble stone masonry. These high loadbearing walls were reinforced with horizontal and transversal timber tie-beams with a square, circular or

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semicircular section, the horizontal tie-beams were usually visible on the surface of the external leaves, and they were rendered with two different layers of traditional lime plaster. Most of the loadbearing walls of Jeddah heritage buildings are based on shallow foundations with a depth of 0.5m to 2.5m, and are covered with timber flat ceilings.

The close visual inspection of the deficient and damaged masonry walls at Jeddah heritage buildings revealed that the most important structural deficiencies patterns and deterioration aspects of these walls which led to their structural instability were the propagation of significant vertical, diagonal and horizontal structural cracks within the walls, the presence of very severe deformation (e.g. tilting, twisting, wrapping, bulging), partial and total collapse of those walls or one of their outer layers, cracking and deterioration of inner core layer, weakness and disintegration of its stone units, damage and loss of the structural mortar in mortar joints between the stone units and loss of the external lime plaster layer. As well as, the occurrence of surface damage, dryness, compressional, weakness and separation of the timber ties which were used for the reinforcement of those walls. The most important structural deficiencies patterns that have been observed in their shallow foundations were differential settlement, cracks, sliding, twisting, rotation and crushing, and also the erosion of their calcareous components and loss of mortar between their stone units. Likewise, the structural condition of their timber ceilings was found poor, where these ceilings deteriorated and collapsed in some cases.

There are many causes that led to the structural deficiencies and damages of the heritage buildings in historic Jeddah and affected their structural condition, the most important distinctive causes are mainly the action of excessive loads (overloading), the effect of differential settlement of bearing soil and shallow foundations, low-quality and fragility of building materials, modification in the use of a building, the effect of fires and their random extinguishing, the effect of a harsh marine climate, human negligence and the effect of incompatible materials which were used extensively in the previous restoration attempts. Each of these causes led to different types of structural problems however the synergistic effect resulted to the acceleration of damages.

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