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STRUCTURAL EVALUATION OF FAÇADE PROJECTIONS AND THEIR SUPPORTING CAMBERED CORBELS AT HISTORICAL MASONRY BUILDINGS IN CAIRO FROM MEDIEVAL PERIODS WITH A PROPOSAL FOR STRENGTHENING AND RETROFITTING

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ABSTRACT

External and internal façade walls at historical buildings in Cairo usually comprise projections that are carried on corbels. The corbels are usually built of stone, timber or composite (i.e. timber and stone). These masonry façade projections are usually vulnerable to structural damages and failures due to several causes, which can lead to successive failure and collapse of the timber roofs that support on them, so that the whole building maybe abandoned, in addition to possible injuries and death of passing-by during façade's falling-down and routes' blocking from its ruins. The present work studies the masonry façade projections of the historical medieval buildings in Cairo and their supporting stone corbels to determine their structural behaviour and failure mechanism. It reveals the significances of distinctive cambering of the corbels to the stability of the projections. Besides, a proposal for strengthening of the projection walls and corbels is provided.

KEYWORDS: Façade projection, Corbel, Camber, Stonemasonry, Timber, Deflection, Strengthening.

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1. INTRODUCTION

Historical and heritage buildings in Egypt contain respectable resources of valuable information and mysteries about structural design and construction technology of un-reinforced masonry (URM) and timber buildings that still have not been completely revealed yet. The structural survey, study and evaluation of either their visual parts or hidden ones that are uncovered during restoration works; enables to understand the structural behaviour and deficiency mechanisms of their various structural elements, which are essential to establish proper conservation, restoration and retrofitting works. Besides, the results can significantly enrich and modify the current engineering practices for designing and constructing contemporary masonry and timber structures.

External and internal façade walls at historical masonry buildings in Cairo usually comprise projections at floors above ground level that may extend along the whole façade or can be limited to a closed balcony that is called "*Mashrabiyya*"; an ornamenting woodwork made of small pieces of turned wood (Ibrahim and Lami, 1990). The first type was utilized to expand the upper floors' area (starting generally from the first floor), to provide a shaded path below and to overcome the narrow lanes and roads where its building is located. The second type was a traditional system in Cairo during the medieval periods till the beginning of 19th Century, which allowed inhabitants, especially women; to see outdoor in privacy and to enjoy indirect day-light and air (Yeomans, 2006). These projections in façades are always carried on corbels, which type and design were established based on the architectural design and function of the projection. These corbels are usually built of stone, timber or composite (i.e. a timber corbel carried on a stone one). The façades' projections are usually vulnerable to structural damages and failures owing to several causes; such as: excessive deflection and/or failure in their main supporting elements (e.g. floor's timber joists or their supporting corbels); besides seismic loads. The collapse of the projections with their façade masonry walls is usually followed by successive failure and collapse of timber roofs that rest on them, so that the whole building maybe abandoned. Besides, the possible injuries and death of pedestrians during façade's falling-down, as well routes' blocking from its ruins.

Although the great importance and vital role of these URM façades' projections; most of the previous researches studied the structural failures in plain façades only (i.e. free from any projections); such as Lagomarsino (1998), D´Ayala and Speranza (2002), D´Ayala and Speranza (2003) and D´Ayala (2006). Dogan et al. (2007) studied the vulnerability and failures of façades' projections under seismic loads either in masonry and reinforced concrete buildings; and recommended to limit their projection length and loads. Moreover, few researches concerning architecture of the 'Historic Cairo' have covered some aspects of the stone corbels. Waziri (2000) and Ibrahim et al. (1990) provided a number of drawings of the corbel that is named "*Kab-bas*". Maury et al. (1983) demonstrated important old photos of several corbel types at the historical medieval Cairo that reveal their construction technology and building materials. Ormos (2013) provided a drawing of a carved stone corbel in a façade of a historical building behind "*Sultan al-Ghawri*" complex. Bashandy et al. (2017) conducted an experimental program to investigate the feasibility of using different valid materials and techniques to repair and strengthen timber cantilever beams in historic and new buildings. They concluded that their repairing and strengthening using steel plates or glass fibre (GFRP) wraps or carbon fibre (CFRP) laminates can increase the value of failure load of the cantilever beam and decrease its deflection.

The present work highlights the notable structure and construction technology of façade projections of historical medieval buildings in Cairo, which have not been studied enough before. The medieval architects had introduced a distinctive design for the façade projections to overcome their general vulnerability, which make them to last for centuries. They considerably cambered the corbels that carry the projection upward to a respect-able angle (10° with the horizontal), which is considered excessive by contemporary construction engineering practices. Besides, they made the façade walls to lean very slightly inward to the building side. This system was not generally found in other neighbouring countries at Middle-East and Europe (see e.g. Elyamani, 2018).

The contemporary building codes apply cambering practice to counterbalance the expected deflection; by rising-up the main beam's framework at its mid-span while construction; thus in the future as the beam attains deflection it is turned almost flat instead of sagging. Accordingly; it is also not recommended to camber the cantilever beams (Dogan et al., 2007) for the associated problems related to rain-water drainage, etc.

The significances of the present work lie in introducing the various aspects of the historical cambered façade projections (i.e. architecture, structural, materials, etc.) and their structural analysis and assessment. Besides, it determines and reveals the main reasons for the over-cambering, which are not only confined to minimize their deflection and stresses. This is proved by the present work through comparison between flat and cambered conditions of the main supporting corbels of the projections.

The paper studies the external and internal masonry façade projections and their various supporting corbel systems. It also utilizes numerical modelling to structurally analyze their behaviour and stability to establish the possible major structural deficiencies of the projections and outline a proposal of their strengthening methodology.

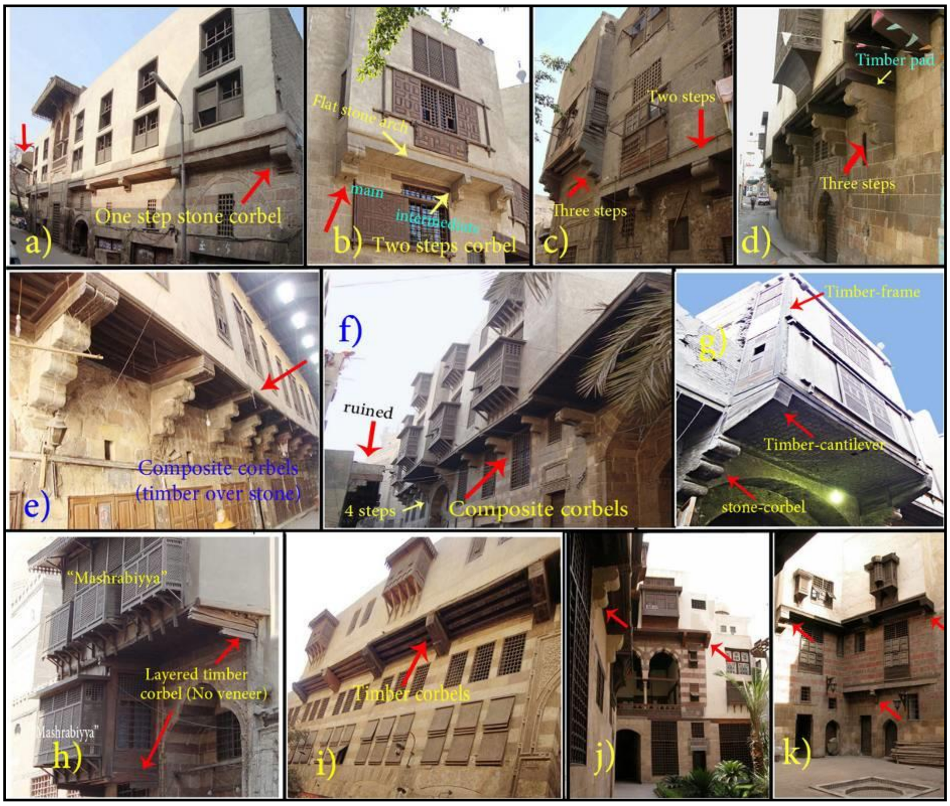


***Figure 1:** Examples of façade projections at historical medieval buildings in Cairo. At external façades: a) "Rab'a Qazlaar" 13th Century A.D.; b) House of "Ibrahim Agha Mustahfazan" 1641 A.D. (1051 A.H.); c) "Sabil" of "Ibrahim Agha Mustahfazan"; d) House of "Jamal al-Din al-Dhahabi" 1637 A.D. (1047 A.H.); e) "Qasabet Radwan Bay" 1650 A.D. (1060 A.H.); f) "Wekalet Bazar'aa" 17th Century A.D.; g) "Waqf Radwan Bay" entrance; h) "madrasa of Taghri-Bardi" 1440 A.D. (844 A.H.); i) "Wekalet Qayetbey" 1477 A.D. (822 A.H.) and at internal façades: j) House of "al-Suhaymî" 1648 A.D. (1058 A.H.); k) House of "Jamal al-Din al-Dhahabi" 1637 A.D. (1047 A.H.).*

2. RESEARCH AIM

The present research aims to structurally study the façade projections and their supporting cambered corbels at historical medieval masonry buildings in Cairo, since their cambering is evident and excessive than analogous contemporary constructions; and their failures are usually catastrophic; besides previous studies scarcely covers their architectural or structural aspects. This study reports the general dimensions, building materials, construction technology of these historical masonry façade projections and their supporting corbels and assesses their main structural behaviour and deficiencies. The structural significances of the over-cambering are established; besides a proposal for strengthening and retrofitting the projection and its corbels is suggested.

3. MASONRY FAÇADE PROJECTIONS AND THEIR SUPPORTING CORBELS AT HISTORICAL BUILDINGS IN CAIRO

The historical medieval buildings in Cairo include dwellings, palaces, service buildings such as "Wakala" and "Khan", etc.; are usually include projections in external and/or internal façades at floors above ground level. The most popular cases that represent these masonry projections are shown in Fig.1. These projections are usually built of red-brick "Ajur" walls in timber-framing (i.e. timber-posts are placed at corners of the walls and timber-ties extend horizontally through them). Their floors are built of either stone flat arch (Fig.1-b) or traditional timber roofs (Fig.1-e), which is prevailing. They support on stone corbels (Fig.1-a), timber corbels (Fig.1-h), or composite corbels (Fig.1-f), which all are always cambered upward to an average angle of 10° with the horizontal direction. The projections' masonry walls always include wide window-openings with wooden sliding shutters (Fig.1-b), timber grills (Fig.1-c), "Mashrabiyya" (Fig.1-h) or some of them together (Fig.1-f). These are aimed to lighten the dead loads on the supporting corbels; thus reducing their resulting deflection and stresses. The present research proposes a general classification of the masonry façade projections at medieval Cairo based on their supporting corbels as follows:

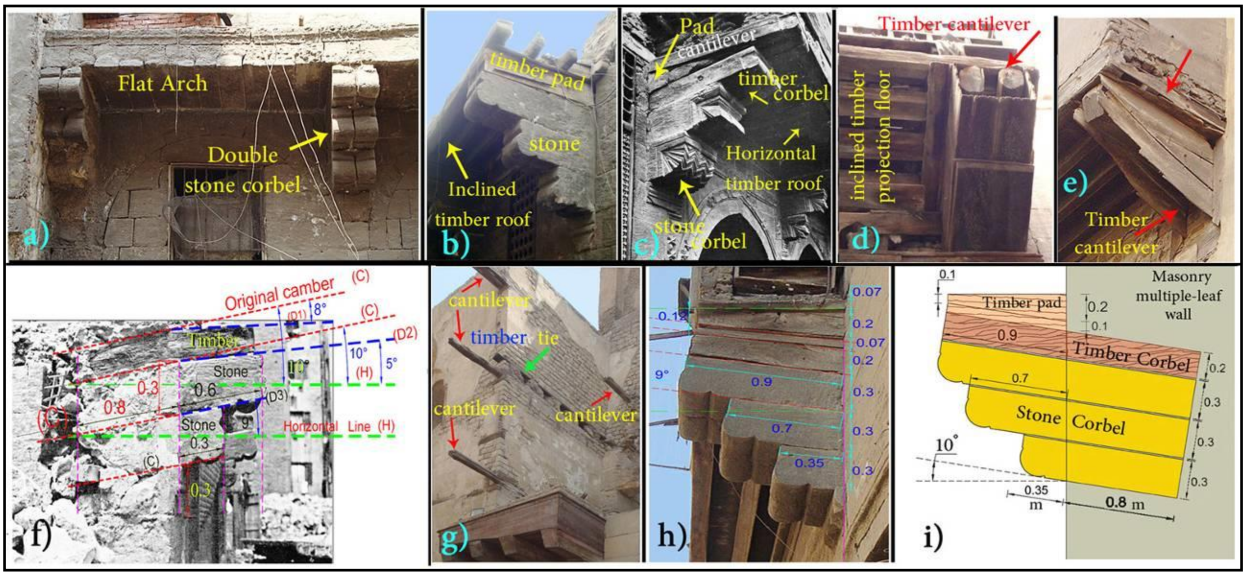


Figure 2: Analysis of various building materials and construction technology of historical corbels in medieval Cairo: a) stone projection and corbels "Sabil of Ibrahim Agha Mustahfazan"; b) inclined floor projection "Waqf Radwan Bay"; c) horizontal floor projection at house of "Ali Katkhuda" (after: Ormos, 2013); d) built-up timber cantilever at mosque of "al-Qammari"; e) timber cantilever at "Rab'a Qazlaar"; f) geometric analysis by the research of typical historical corbel (ruins of "al-Sitt Wasīla" dwelling; old photo after: Maury et al. 1983); g) timber-ties reinforcement of masonry walls above corbels "Qasr Alin Aq"; h) and i) photo dimensions of the generalized cambered stone corbel at Historic Cairo to be considered in all the numerical models.

3.1. Projections on Stone corbels

Stone corbels were most likely utilized with heavy masonry façade projections, which walls' height is 4 m or more (Fig.1-a: Fig.1-f). The floor of these projections is built of either stone; as a flat arch (Fig.2-a); or timber that may be inclined (Fig.2-b) or horizontal (Fig.2-c). The corbel always has a short-span length (ranges between 0.35 to 1.1 m), which equals to its total depth. The depth and breadth of the corbel were determined according to load, span-length and type of the façade projection. The following characteristics are generally found:

- The corbel's depth is composed of one, two or three steps (layers); and infrequently of four steps (Fig.1f). Length of the lower step is usually in range of 0.3 ~ 0.4 m. The length of each step generally extends outside the step below it with a course height (~0.3 m); see Fig.2-h; Fig.2-i.
- The corbel is commonly shaped in a simple console with a rounded bottom edge. It is usually surmounted by a timber pad whenever the projection has a timber floor. The pad may follow the inclination of stone corbels and consequently the projection floor will be inclined (Fig.2-b); or it can be wedge shaped whenever the projection floor is horizontal (Fig.2-c).
- The stone steps are similar in thickness (i.e. ranges between 0.29 to 0.35 m) and morphology (i.e. colour, texture, etc.) to ashlars stone units of the adjoined façade wall.
- In-case the floor of projection is built of stone flat arch; the corbel supports the arch ends without using timber pads. Both corbel and arch stone units are all cambered similarly (Fig.2-a).
- The average breadth of the corbel's unit is 0.15m. The main corbel is generally composed of two adjoined units, although in some cases (e.g. lighter loads) it is built of only one unit.
- An intermediate corbel with one stone unit is built in-between the main corbels (Fig.1-i) following door or window opening of the lower floor. Its obvious function is to minimize the mid-span sagging of the timber joists of the projection floor.
- Main corbels are uniformly distributed along façade projection with uniform spacing ranges between 3 ~ 5m.

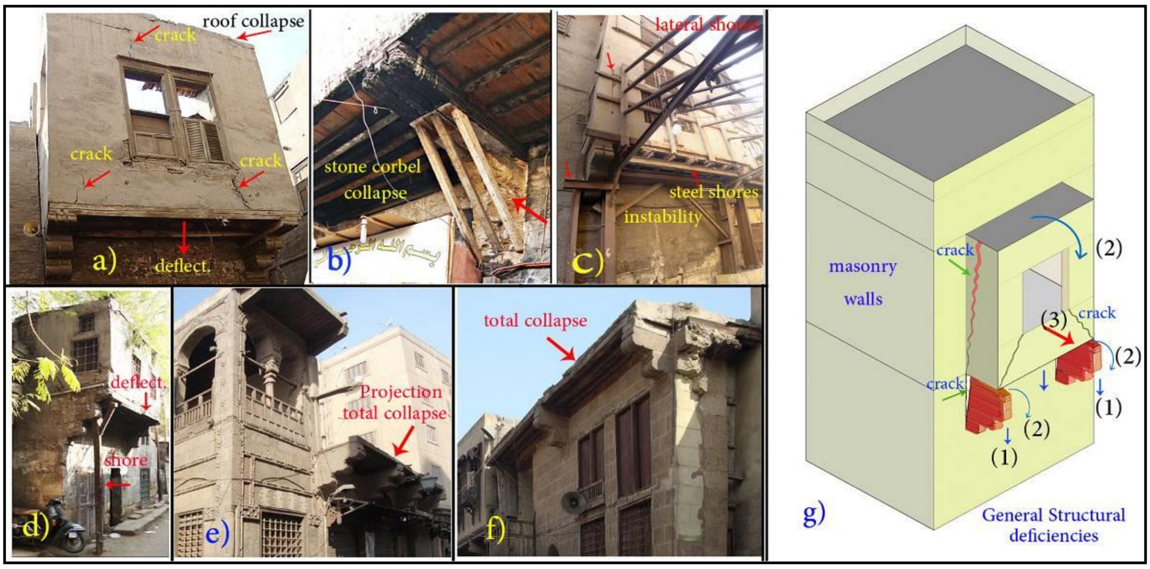
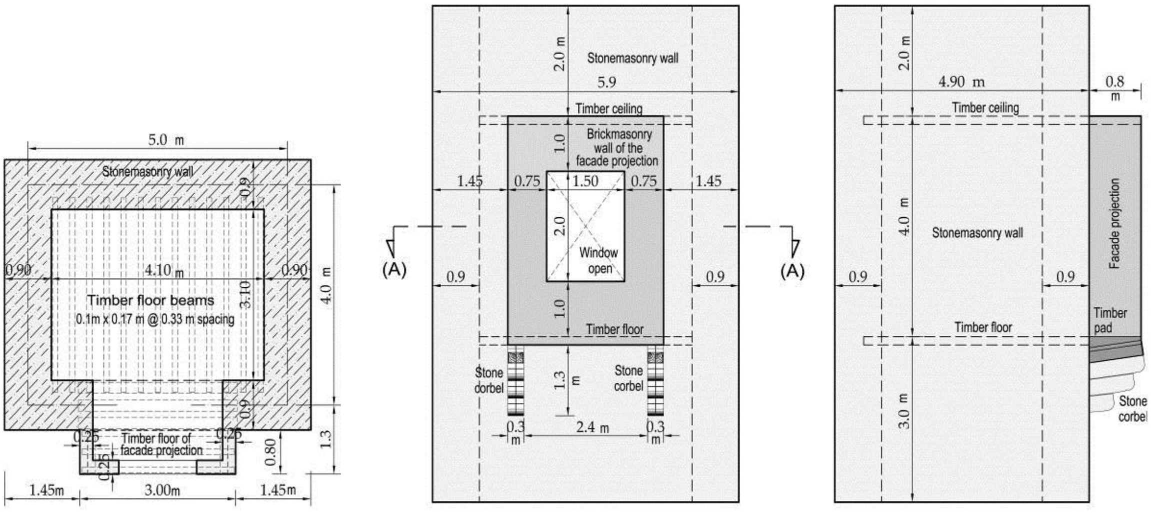


Figure 3: Main structural deficiencies and failures of façade masonry projections at historical medieval Cairo: a); b) "waqf Radwan Bay" 1650A.D.; c) "wekalet Oddah Pasha" 1673A.D.; d) "qubet Ali-Najm" 17th Century A.D.; e) "sabil-kuttab Qi-tass" 1630A.D.; f) "Kahla" workshop complex; g) AutoCAD drawing (by the researcher) to summarize the deficiencies.

3.2. Projections on timber corbels

Timber was utilized to support masonry projections (Fig.1-h;-i and Fig.2-d;-e). It is generally made either a corbel or a cantilever extending form a timber ceiling girder in the historical building. The timber corbel provides longer spans than stone one (≤ 1.8m); while it has less load carrying-capacity thus projection walls above it were made lighter (e.g. wide window-openings, walls of one-floor high, etc.).

It is generally built of robust timber species with big cross-section that is formed by either a built-up section (Fig.1-h; Fig.2-d) or a massive solid part (Fig.2-e). It is usually covered by thin wood veneers that make it looks appealing. The masonry walls at the projection sides are always reinforced with few timber-ties that are extended from the internal building walls, which are in-plane with the main (end) corbels (Fig.2-g).



a) Sectional plan (A-A)

b) Main elevation

c) Side-view

Figure 4: The AutoCAD architectural drawings of the generalized prototype URM building proposed by the researcher to study the historical medieval façade projection and its supporting stone corbels (in meter).

3.3. Projections on composite corbels

A composite corbel is built of a stone corbel surmounted by a timber corbel (Fig.1-e: Fig.1-g) or cantilever that extends from an embedded timber beam inside one of building's masonry walls or ceilings. It was utilized to acquire a longer span than the first two types (ranged between 1.5 to 2.5m) and it had the combination of features of both stone and timber types. The stone corbel is found the widespread type in the historical medieval buildings in Cairo. Its full geometric analysis is provided in Fig.2-f, Fig.2-h and Fig.2-i. The embedded length for all corbel layers inside its supporting masonry wall usually equals to the maximum required span of the corbel, which is demonstrated in the historical ruins in Fig.2-f (i.e. the original cambering C-lines, the past excessive deflections lines: D1, D2 and D3 with their inclination to horizontal and the full dimensions). The corbel in Fig.2-h is chosen as a prototype that well-represents the historical stone type. Hence; it is adopted in all the structural analysis works of the following sections of this paper. Its geometry is analyzed by AutoCAD drawing in Fig.2-i.

4. STRUCTURAL DEFICIENCIES OF MASONRY FAÇADE PROJECTIONS AT HISTORICAL MEDIEVAL BUILDINGS IN CAIRO

The general deficiencies and failures that are found at masonry façade projections of historical medieval buildings in Cairo and their apparent causes are briefly reported as follows (Fig. 3):

a) Deterioration of the main building materials (i.e. stone and timber) and creep of corbels and floor girders of the façade projections due to normal loads; can cause unsafe deflection and associated cracks (Fig.3-g).
b) Excessive deflection and unsafe stresses in the corbels may cause them to rotate (Fig.3-g: #1; #2), which can finally cause collapse of the corbel (Fig.3-b) or instability of the whole projection (Fig.3-c;-d).
c) Collapse of the main corbels causes the projection above them to fall down (Fig.2-g).
d) Seismic action can also cause lateral deformation in façade wall (Fig.3-g #3), vertical separation cracks and rotation (#2), which may result in instability and collapse of the façade projection (Fig.2-a; Fig.3-e;-f).

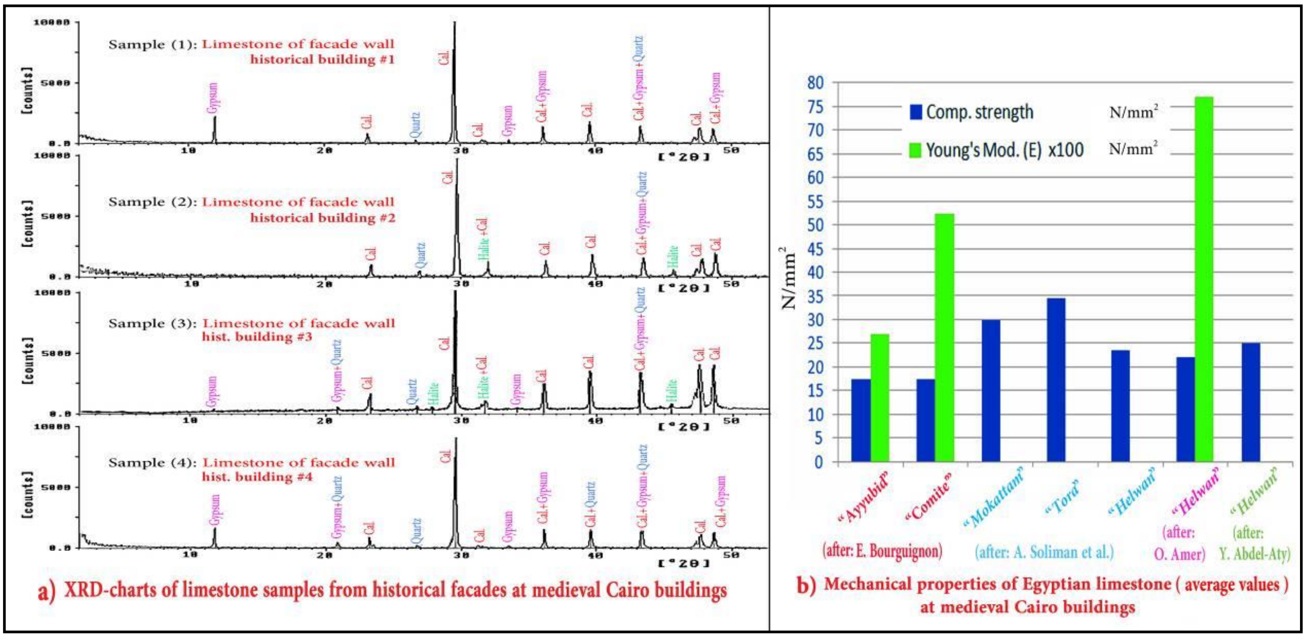
5. METHODOLOGY AND MATERIALS OF THE PRESENT RESEARCH

The following parts investigate analytically the structural behaviour, stability and a strengthening proposal for the masonry façade projections that are supported by cambered stone-corbels at historical medieval buildings in Cairo; as they are the common type. A number of numerical models using the codes of finite element method (F.E.M.) of the utilized software are conducted. A simple one-story rectangular URM building with timber ceilings and one façade projection that rests on two cambered stone-corbels is proposed by the researcher to represent the studied historical medieval prototype. The plan, elevation and side-view with full dimensions (in meters) of this model building are shown in Fig.4; besides the isometric view is alike to Fig.3-g. These dimensions and design are made to focus merely on the façade projection's structural behaviour, stability and its corbels' over-cambering effect; besides being well-representative to the analogues at Historic Cairo.

The first 2D-models compare the general structural behaviour of the flat and cambered corbels under static loads only (i.e. D.L+L.L), while the main 3D-model studies the proposed URM building under static and dynamic (i.e. eigenvalue and linear response-spectrum) load cases, to reveal and demonstrate the advantages of the over-cambering of the corbels to the structural stability of their façade projections, along with establishing a strengthening proposal for it.

The research extracted four stone samples from the main façade ashlars' stones in four different historical buildings at Historic Cairo to identify its stone type using X-ray Diffraction (XRD) analysis. The XRD charts in Fig.5-a shows all samples are composed mainly of Calcite ($CaCO3$); designated by 'Cal.', which is the major constituent of limestone, besides traces of Gypsum ($CaSO4{\cdot}2H2O$), Halite ($NaCl$) and Quartz ($SiO2$) that are either ingredients, salts or impurities (less than 5%). This formation results agree with the previous researches of Soliman et al. (1972), Bourguignon (2000), Abdel-Aty (2012) and Amer (2018). Consequently; the major properties of similar historical Egyptian limestone from these previous works are adopted with all the following numerical models, which their mean values of both axial compressive strength and Young's modulus (E) are demonstrated in Fig.5-b.

The timber elements used in the construction of wooden ceilings; besides inserting them in masonry walls and corbels at the medieval historical buildings in Cairo follow wood species; most probably; of 'Pinus rigida' that is commercially known as 'Pitch pine', referring to the previous researches of Abdel-Aty (2018), Mahir et al.(2015), Hadidi (2002) and Hamed (2009). Accordingly, the average properties of the main building materials, which would be considered in the structural analysis and evaluation works; comply with the references: Bourguignon (2000), Soliman et al.(1972), Amer (2018), Abdel-Aty (2012; 2004), Mourad et al. (1994; 1994), ECP 204-2005, Bell et al.(2002) and Anzani et al. (2004) for limestone and lime-mortar, besides EN 1995-1-1 2005, Wood Handbook (2010), Grippa et al. (2009), UNI-11119 (2004) for wood. They are demonstrated in Table 1.



a) XRD-charts of limestone samples from historical facades at medieval Cairo buildings

b) Mechanical properties of Egyptian limestone (average values) at medieval Cairo buildings

Figure 5: Major properties of Egyptian limestone used at historical medieval buildings in Cairo: a) X-Ray Diffraction (by the researcher) charts of four stone samples of the studied corbel and its surrounding façade wall; b) average values of the major mechanical properties of Egyptian

6. STRUCTURAL ANALYSIS AND EVALUATION OF THE HISTORICAL MASONRY FAÇADE PROJECTIONS

6.1. *Structural evaluation of the cambered stone corbels*

This section starts by determining the structural behaviour and the over-cambering advantages of the stone-corbels below the façade projection of the proposed URM building model; by comparing the analysis' results of their conducted 2D-numerical models. The models (Fig.6) utilize the frame and shell finite elements and codes of SAP2000 v.16 software (CSi 2013) through linear elastic analysis. The prototype model of the stone corbel (Fig.2:-h;-i) includes almost all the features of its type; as it is composed of three stone layers forming inverted steps that are bonded together by lime-mortar at bed-joints of 1 cm thickness. The layers' protrusions are 0.35, 0.7 and 0.9 m respectively from the façade. The average embedded length of every stone layer is 0.8m and the cambering angle is 10°. The breadth (0.3m) is composed of two adjoined corbel units. The corbel is toped by a timber pad of two layers; the lower follows the upper stone layer (in length and inclination), while the upper is made to level horizontally the corbel's top. The façade projection is a closed one-story balcony, which walls are constructed of brick-masonry of 0.25m thickness, its main façade includes a wide window-opening and its floor is composed of three timber girders that are simply supported on the two corbels at their ends. The façade wall that carries the corbel is 0.9m thickness and 3m high. All models are strictly discretized following the mentioned geometry and dimensions. The frame-element models (Fig.6-a) study the homogenized state, which is composed of one layer of stonemasonry. This helps to analyze the overall structural behaviour within the elastic stage. The shell-element models (Fig.6-b) study the composite state of the corbels, which determine stresses at each layer. The structural analysis is achieved under static load case only according to the code of ECP-201 (2008) for the following loads: **i)** dead loads (D.L.) of self-weight and flooring load =1.5kN/m^2; **ii)** live load (L.L.) = 3kN/m^2. The materials' densities and properties in Table 1 are respected with all the models.

Hence, the distributed vertical load from the masonry wall above the corbel = 17.65kN/m and the reaction forces of the timber girders of the projection floor (i.e. concentrate loads) are shown in Fig.6-a. The variable depths are assigned to relevant frame-elements F1; F2; F3 (Fig.6-a). The full span of the corbel = 1.3m (i.e. the clear span + half of wall thickness).

Table 1: Average values of the main building materials (major properties, strength and allowable 'working' stresses) that are respected with all the structural analysis and evaluation works of corbel and façade projection models.

Main building material	Bulk density ρ (kN/m³)	Elasticity modulus E (N/mm²)	Comp. strength f_{cu} (N/mm²)	Comp. all. Stress f_{cw} (N/mm²)	Tensile strength f_{tu} (N/mm²)	Tensile all. Stress f_{tw} (N/mm²)	Flex. tensile strength $f_{b\,u}$ (N/mm²)	Flex. tensile all. Stress $f_{b\,w}$ (N/mm²)	Shear all. Stress q_w (N/mm²)	Poisson's ratio ν
Limestone	21	5500	22	5.5	2	--	3.1	0.20	*	0.22
Lime-mortar	17	10	2.0	0.4	0.15	--	0.5	*	*	0.30
Stone-masonry	20	3500	5.0	1.2	*	--	*	0.07	0.5	0.25
Brick-masonry	16	1500	3.0	0.5	*	--	*	0.01	0.2	0.26
Timber	5	9000	47	7	73	6	68	8	0.6	0.29
(all.): allowable. (*): Unspecified. (--): Direct tension is not allowed. Red values are after (UNI 11119: 2004)										

Comparing the structural analysis' results of flat and cambered cases, one can find that both models provide almost the same results. Only the cambered model has axial compressive force that maximum value at fixation = -6.75kN. The axial component of resultant vertical force has slight effect (<2%) on the final normal stresses at fixed-end section of the corbels due to the over-cambering. Besides, all results of the two cases (i.e. deflection and stresses) are safe according to Table-1. To have detailed overlook at stresses of each layer of the corbel (i.e. stone, mortar and timber) shell-element models are conducted. The yellow coloured shell-elements in Fig.6-b model the homogenised stonemasonry supporting wall, the red ones models stone layers, the green ones models mortar and the blue elements model timber-pad. The meshing of the models is refined to accurately simulate all parts. The same loads of the frame-models are assigned to the shell-models. As in frame-element models; both flat and case-I of cambered corbels provide nearly the same analysis results (i.e. identical stress-contours; while deflection decreased by 12% in flat case). The deflection and stresses are respectably reduced in case-II; as timber pad thickness increased (i.e. 40% reduction in deflection from flat case). Besides, principal tensile stresses in flat, case-I of cambered type are unsafe in all stone layers' top-side; while they are almost safe in case-II of cambering.

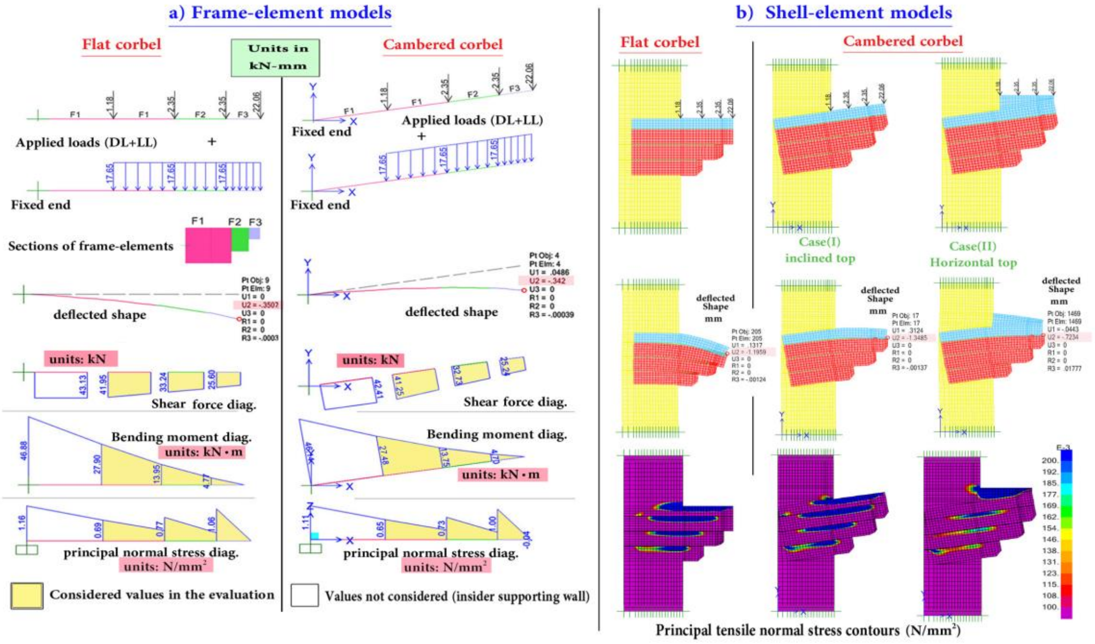


Figure 6: First 2D-models to compare structural behaviour of flat and over-cambered stone corbels at medieval Cairo: a) frame element models (overall behaviour); b) shell element models for composite (layered) behaviour.

The final conclusions of this section are: i) no advantages of over-cambering the stone corbel to its deflection or its structural safety from flat one; consequently the old architect utilized over-cambering for other structural goals of the stability of façade projections; ii) over-cambering the corbel with increasing its timber pad thickness (case-II in Fig.6-b) can reduce its deflection and stresses towards safe levels; iii) the corbel should be structurally analyzed as a composite section (i.e. layered) to attain more accurate results; iv) the full bond between the corbel layers (i.e. studied by frame-models) cause the corbel's stresses to be safe, while the deterioration of the mortar in its joints cause the layered behaviour (i.e. studied by shell-models) to prevail that stresses are unsafe.

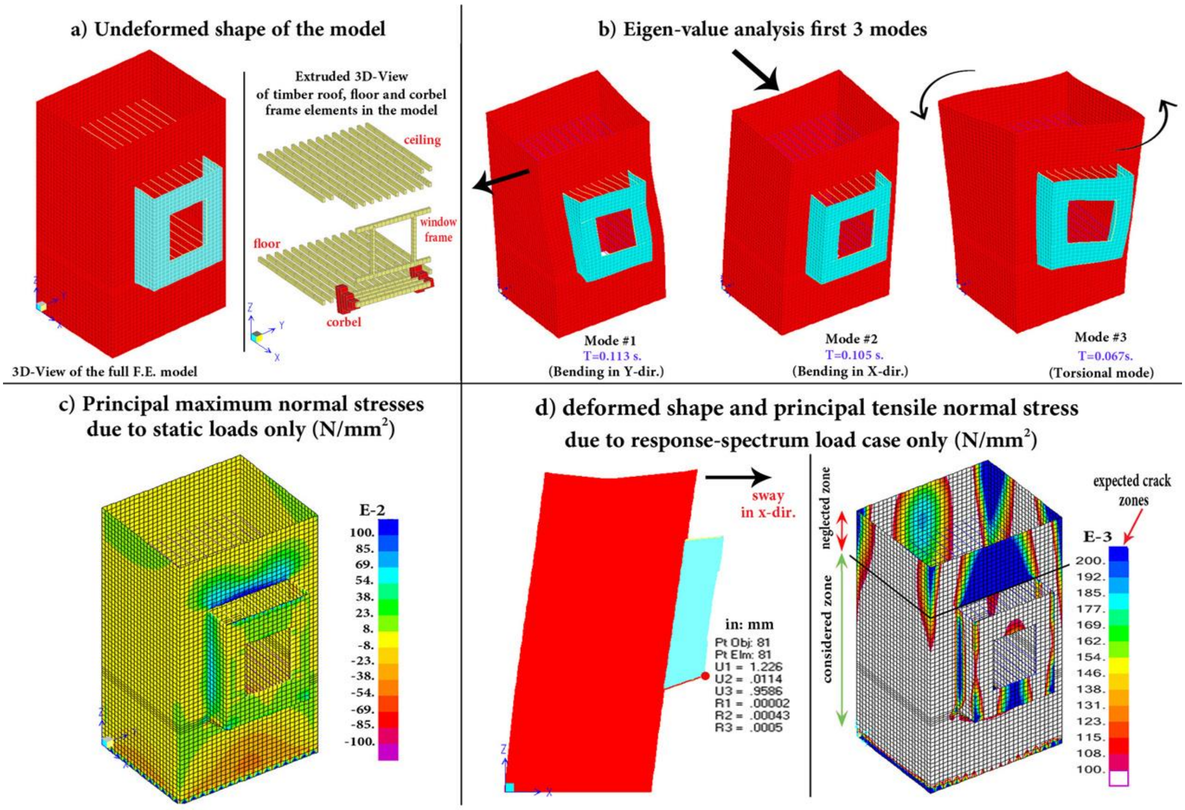


Figure 7: Main results of structural analysis of the 3D F.E. model of the proposed prototype URM building under static and dynamic load cases: a) the model; b) the first three modal shapes of eigen-value analysis; c) principal normal stresses under static load-case; d) response-spectrum analysis: deformed shape and principal tensile stress contours

6.2. *Structural evaluation of the façade projection of the proposed building model*

This section evaluates the structural stability, failure and strengthening of the façade projection of the proposed prototype model that represents the historical analogues in medieval Cairo. It also aims to establish the main reason for the corbels' over-cambering. The proposed building was accurately 3D modelled in the same software (CSi 2013) following the full dimensions and design in Fig.4; by using refined mesh of shell and frame elements and utilizing Table-1. The projection corbels, timber beams and permanent loads are considered similar to section (6.1). The static analysis shows safe stresses and deformations according to allowable values in Table1 (Fig.7-c). The results of the dynamic linear analysis show the major (first) three modes of eigen-value analysis in Fig.7-b (i.e. bending in y and x directions; and torsion modes); besides the response spectrum analysis referring to Abdel-Aty (2018); ECP-201 (2008) and applying its acceleration in the projection direction (x-axis) that demonstrates the deformed shape and principal tensile stress contours in Fig.7-d. The focus of the analysis and evaluation is on the façade projection and its surrounding walls of the model; while the upper part above the timber ceiling is neglected. The blue contours allocate the zones of unsafe tensile stresses; where cracks are expected. Their agreement with the reported cracks and deformation in Fig.3-g validates the proposed URM building and its numerical model.

6.3. *Discussion of the results*

The analysis and evaluation of all the conducted F.E. models' results; besides the previous sections of the paper; help to derive the following conclusive remarks:

i. The over-cambering of the corbels does not reduce the deflection or the stresses under normal loads compared with the flat case; although the timber topped cantilever and pad can effectively decrease them.

ii. The calculated stresses and instantaneous deflections of the corbels for all studied cases are safe according to the code of ECP-204 (2005). The risk arises by deterioration of the corbel's main building materials, by creep effect or by incompatible use of the projection that increases its applied loads and causes its corbels to excessively deflect, crack and finally collapse causing subsequent damages to the projection.

iii. The failure of the supporting corbels can cause: detachment of the projection side-walls from the façade by vertical crack, cracks in the walls and finally overturning and collapse of the projection.

iv. The main goal for the over-cambering of the corbels in the historical façade projection is summarized in Fig.8; where a comparison between flat and cambered cases is schematically illustrated. For each one-meter of corbel's length; its free-end is raised ≈16cm for average cambering angle 9°, while its above walls are leaned inwards for about 2°~5° (Fig.8-a). Under long-term deflection (assumed 5 cm); the C.G. of the projection in the flat-case (Fig.8-b-i) lies between its middle and its free-side, which causes overturning moment (M1) outwards. This finally can cause the shown separation crack and the collapse of the walls. Whilst under the same deflection; the C.G. of the historical cambered-case (Fig.8-b-ii) lies in the inner-side. This causes a stabilizing moment (M2) that maintains the projection above its corbels even after it cracks by seismic actions.

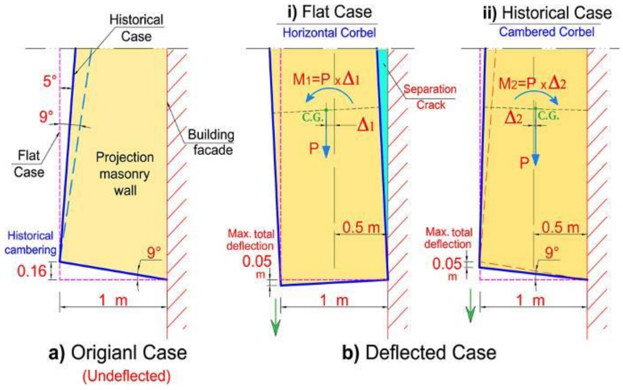


Figure 8: Schematic illustration of the structural stability of flat and over-cambering cases of façade projections under long-term deflection.

7. A PROPOSAL FOR STRENGTHENING THE HISTORICAL FAÇADE PROJECTIONS

To enhance the structural stability of the façade projections at historical medieval buildings in Cairo; the following methodology is proposed to reduce their deflection and to strengthen and rehabilitate their spaces:

i. The work must begin with properly erecting vertical shoring to support the timber beams of the projection floor and their supporting corbels. Besides; all loads on the floor; including the flooring tiles and layers; are removed.

ii. New timber-ties of robust wood-species will be inserted through the surface of the two sides of the masonry side-walls of the projection (above the main corbels) similar to original ones in Fig.2-g. The new ties should be distributed @ 1m along walls' height or in-between the original ties. Consequently, façade ashlars' stones at locations of these insertions should be properly dismantled and grooves through walls for similar length to corbel's span or wall's thickness (whichever less) are made at these locations. This would reinforce the masonry walls at sides of the façade projections (at their conjunctions) against the possible separating vertical crack (i.e. resist the tensile stresses).

iii. Strong grout should be properly injected into these grooves after the insertion of the timber-ties to efficiently bond them inside the main façade walls. The grout's composition should follow the recommendations of fine-restoration experts.

iv. The inserted timber-ties are concealed under the surface plaster of the walls or by stone thin tile-plates.

v. The joints between stone-layers of the corbel should be thoroughly cleaned from their original mortar. A new robust mortar should be injected inside these joints instead; following the fine-restoration plan. This would ensure the full bond between different layers of the corbel (i.e. stone and timber); thus it structurally behaves as stone-masonry work rather than composite (layered) action.

vi. The flexure stiffness and strength of the corbel can be respectably increased by stabilizing the timber-pad through confining it with two-steel channels from its sides. The veneers over surfaces of the timber-pad are removed. Two steel channels would be inserted and fixed inside the façade wall;

around and along the timber-pad; using efficient cementing mortar. This would decrease the future deflection of the corbel and help to rehabilitate the projection and its attached space at the historical building.

vii. The timber veneers will be re-erected over the timber-pad surfaces to conceal the steel channels.

viii. Considering the full loads are carried by the steel-channels only in their design and ignoring the load-portion carried on the original corbel; increases the provided structural safety of the historical corbel retrofitting.

8. CONCLUSIONS AND RECOMMENDATIONS

The present research has studied the masonry façade projections and their supporting cambered corbels at historical URM buildings in Cairo from medieval periods. It reports their main architectural features and their common structural deficiencies and failures. Besides, it analyzes and evaluates their structural behaviour under possible loads. The main advantages of over-cambering the corbels and façade failure mechanisms are established. Besides, a proposal methodology for their strengthening and retrofitting is provided. The following conclusions and recommendations are derived:

- The projections at internal and/or external façades of these buildings always rest on corbels, which are built of stone, timber or composite (stone and timber). All corbel types are cambered with average angle of 10° to the horizontal, which is considered over-cambering according to the contemporary constructions.
- The projection flooring is generally built of timber, where its girders rest on the stone-corbels by either timber pads that horizontally level the corbels' top or timber cantilever that extends from the ceiling. Sometimes, the flooring is built of stone flat-arch that rest directly on the back of the stone-corbels and follow its cambering inclination.
- The stone corbels are always built of two adjoined stone units and infrequently of only one unit. Each unit is shaped as a console with a rounded bottom edge. Its breadth is 0.15m and depth is built up of one to four of façade's course height (~0.3m). The corbel span equals to its total depth (~1m).
- The façade projections are generally vulnerable to damages and failures by structural deficiencies of their supporting corbels (e.g. excessive deflection, unsafe stresses, cracks, etc.) and/or seismic loads.
- Both flat and over-cambered corbels have almost the same structural behaviour under normal loads (i.e. deflection and internal stresses).
- The over-cambering of the corbels and the floor of façade projections at historical medieval Cairo was mainly devoted to prevent the outward overturning of the projection in case it detaches from the main façade and keep it on the corbels without falling-down.
- For strengthening and retrofitting of the studied façade projection and its stone corbels; it is proposed to increase the number of timber-ties' reinforcement through the side walls of the projection and to replace the mortar at joints between stone-layers of the corbel with new and robust injection to have full-bond between its layers and cause them to structurally behave as one-material. Also, installation of steel angles around timber-pad above the corbel can increase its structural carrying capacity and reduce its future deflection; thus help their rehabilitation.

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