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COMPARATIVE STRUCTURAL STUDY OF INNOVATIVE STRENGTHENING PROPOSALS OF TIMBER BEAMS IN HISTORICAL BUILDINGS IN CAIRO USING TWO-LAYERED COMPOSITE SYSTEM

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ABSTRACT

Traditional restoration and rehabilitation work of flat timber ceilings at historical Islamic buildings in Cairo generally require the dismantling of most of their timber parts (i.e. timber planks, secondary beams, etc.) to expose the timber main beams and conduct the work. Hence, these parts are liable to damage and lose during the dismantling that requires time, money and effort to achieve. Hence, the author conducted this study to overcome the dismantling work and propose effective strengthening techniques for the timber beams utilizing two-layered composite system. This paper reported the limited application of the layered system in the construction of the historical timber beams in Cairo. It studied a number of innovative strengthening proposals of the timber beams from their upper-side merely while leaving the exposed bottom surface intact, apart from its indispensable shoring. Hence, a small experimental and a wide comparative analytical investigation of the strengthening proposals utilizing two-layered composite system are conducted. Several 2D Finite Element numerical models using well-known software were conducted. The modelling techniques of various interfacial conditions of the two-layered beams are established and evaluation of the strengthening proposals is conducted. Finally, conclusions and recommendations are derived.

KEYWORDS

Timber, Layered, Composite, Ceiling, Strengthening.

الملخص

إن أعمال الترميم والتأهيل التقليدية، للأسقف الخشبية بالمباني الأثرية الإسلامية في مدينة القاهرة؛ غالباً ما تعتمد على فك معظم أجزائها الخشبية (مثل ألواح التطبيق، والعوارض، إلخ) بغرض الكشف عن البراطيم الخشبية، والتي تعد العناصر الإنشائية الرئيسة في الأسقف؛ لتنفيذ أعمال التدعيم والصيانة بها، مما يجعل الأجزاء المفكوكة عرضة للتلف والضياع، وخاصة في حالة الأسقف الملونة والمذهبة وذات الزخارف والتركيبات ..الخ، إلي جانب ما تأخذه عملية الفك من وقت وجهد وتكاليف، مما دفع الباحث للتفكير في طرق مبتكرة تتغلب على عملية الفك. ويقوم هذا البحث بتوثيق استخدام المعمار المسلم، على مدي محدود لأسلوب البناء للأسقف باستخدام كمرات مركبة من عدة طبقات، وهو ما استوحي منه الباحث مقترح التقنيات الابتكارية للتدعيم الإنشائي لبراطيم الأسقف الأثرية من أعلي ألواح الطبق المثبتة فوقها فقط، ودون المساس بسطحها السفلي إلا من خلال أعمال الصلب والسند الضرورية. وقد قام الباحث بدراسة تجريبية محدودة لتحديد الخواص الميكانيكية الأساسية للأخشاب الأثرية في حالتها المتداعية، ثم قام بعمل دراسة تحليلية وتقييمه مقارنة على نطاق واسع، للكمرات المركبة من طبقتين، والتي تمثل السفلي منها الكمرة الأثرية، والعليا منها كمرة التدعيم المقترحة، وباستخدام طرق النمذجة الرقمية ثنائية الأبعاد بالعناصر المحددة (**Finite Element**) لأحد برامج الحاسب الآلي المشهورة. وقد توصل الباحث لعدد من الطرق لنمذجة الوصلة بين الطبقتين باستخدام هذا البرنامج، والتي تحقق حالة وصلة بالارتكاز فقط مع السماح بالانزلاق، وحالة الربط بين الطبقتين بأربطة قص من مسامير الصلب. وقد قارن بين الطرق المقترحة للترميم وتوصل إلى نجاح وضع كمرة تدعيم فوق ألواح الطبق، على أن تعلوا الكمرة الأثرية مباشرة، بحيث يربط بينهما بصف من مسامير الصلب، والأفضلية لأن تكون كمرة التدعيم من قطاعات الصلب، وتشغل هذه الكمرة 6 سم من طبقة الرمل، لطبقات الأرضيات فوق سطح السقف، وختم الباحث بالخلاصة والتوصيات المقترحة.

الكلمات الدالة

أخشاب، الكمرات المركبة من طبقتين، الأسقف، التقوية.

INTRODUCTION

A structural element that is built of one or more layers, with similar or different cross-section, using the same building material (e.g. steel, timber, etc.) is generally called 'layered' or 'built-up'. While the layers are built of different materials, they are widely known as 'composite'[1]. The layers are generally bonded together at their interface, either chemically (by adhesives and resins) or mechanically (by shear connectors), although in few cases (or with time) the layers lose their bond. The structural behaviour of any layered beam in flexure and shear is primarily dependent on the bonding efficiency that affects the interfacial slip condition and the material and geometric properties of each layer[2].

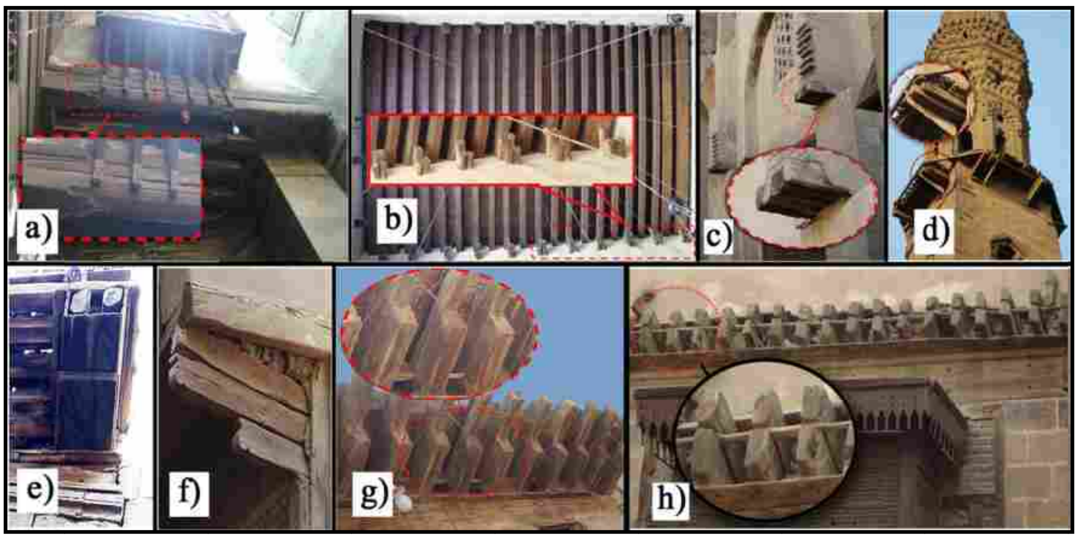

Figure 1: **A number of historical Islamic evidences of the application of layered construction system for timber beams: a) madrasa of "*al-Salihyya*" (641 A.H./ 1243 A.D.); b) and c) madrasa of "*al-Nasir Mohamed ibn-Qalawan*" (695 A.H./ 1295 A.H.); d) minaret of "*Sonqur al-Sa'adi*" (716 A.D./ 1315 A.H.); e) dome of "*al-Qammari*" (730 A.H./ 1329 A.D.); f) madrasa of "*Taghri-Bardi*" (844 A.H./ 1440 A.D.); g) house of "*Ibrahim Agha Mustahfazan*" (1051 A.H./ 1641 A.D.); h) "*Qasabet Radwan Bay*" (1060 A.H./ 1650 A.D.)**.

This paper reported through intensive field survey and previous researches[3,4] that the builders in Egypt during Islamic eras had occasionally employed the layered system in constructing timber beams at various buildings to attain bigger cross-section that is required for supporting heavy loads and wide-span girders and cantilevers (Fig. 1). The layered system satisfies the required structural safety by raising the flexure stiffness and reducing deflection of the beam (or cantilever). Besides, it overcomes the slenderness of the available timber elements and the moderate wooden quality[5]. The major applications of the layered system are: i) in the main girders of the flat wooden ceilings (Fig. 1a); ii) in bundles of grouped timber joists (Fig. 1b); iii)

[1] Monetto and Campi, "Numerical analysis of two-layer beams".
[2] Wen et al., "Analytical model for flexural response".
[3] Abdel-Aty, "Proposals for seismic retrofitting of timber roofs".
[4] Abdel-Aty, "Roles of timber tie-rods".
[5] Abdel-Aty, "Proposals for Seismic Retrofitting of Timber Roofs".

laterally aligned beams beside one another (Fig. 1c-1e) or vertically mounted above each other. They build up lintels, corbels (Fig. 1f-1g) and girders (Fig. 1h). The lateral bundle was usually utilized as lintels to cover the whole thickness of masonry walls, while the other types were used for heavy loads and/or wide-span girders and cantilevers. The built-up section was usually covered from out-side by wooden veneer panels (Fig. 1e) for aesthetic purpose forming a closed box, besides its surfaces were ornamented, coloured and gilded.

Numerous researches have structurally studied the layered and composite timber beams and their applications in timber restoration. Sousa and Silva [6] studied analytically the behaviour of the general case of multi-layered composite beams with interlayer slip, under 'Euler-Bernoulli' and 'Timoshenko' beam's theories. They presented new mathematical formulations of the linear case with interlayer slips for statically determinate beams. O'Loinsigh et al.[7] studied experimentally novel full-scale multi-layered timber beams with composite action achieved by welded-through wood dowels as shear connecting elements. The results proved great enhancement in the flexure stiffness and efficiency of the composite action of the beams with the increase in dowel number and using more than one row. Gubana[8] presented a state-of-the-art report that covers the new techniques developed and tested to achieve in-plane and out-of-plane stiffness upgrading of ancient timber ceilings using less invasive and reversible interventions, focusing on wood-based element techniques. Monetto et al.[9] simulated analytically the progressive nonlinear interface failure of two-layered beams with partial shear connection and interlayer slip, and provided the fundamental analytical solution in vector form. Wen et al.[10] developed an exact analytical model based on a Higher-order Beam Theory (HBT) for an accurate prediction of the flexural response of two layered composite beams with partial shear interactions that are caused by the longitudinal separation or shear slip between the two layers at their interface due to the deformability of shear connectors. Daňková et al.[11] demonstrated results of an experimental study concerning the structural behaviour of a timber-concrete composite floor structure with a novel non-metallic connection using plywood glued board. Shear test were conducted for twelve samples and results of secant slip modulus were determined. Analysis of results and conclusions were derived confirming the enhancement in structural resistance of composite system rather than non-composite one. Chiara and Massimo[12] verified numerically the results data of past experimental research that investigated the timber-to-timber joints and composite beams with inclined self-tapping screws (STSs). Hence, they achieved 3D solid Finite Element (F.E.) models using ABAQUS software. The results proved the validation of the models and their numerical analysis work. Giongo et al.[13] presented a novel technique to pre-stress and camber composite beams that are built of various materials, although the paper applied to Timber-to-Timber Composite beams (TTC). The technique utilizes screw fasteners that to be distributed and inserted diagonally to the axes of the beams. Analytical formulations and F.E. modelling that calculate the required camber and the internal forces generated by the technique were conducted.

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[6] Sousa and Silva, "Analytical and numerical analysis of multilayered beams".
[7] O'Loinsigh et al., "Experimental study of timber-to-timber composite beam".
[8] Gubana, "State-of-the-art report on high reversible timber".
[9] Monetto et al., "Numerical analysis of two-layer beams".
[10] Wen et al., "Analytical model for flexural response".
[11] Daňková et al., "Experimental investigation and performance of timber-concrete".
[12] Chiara and Massimo, "Numerical analysis of timber-to-timber joints".
[13] Giongo et al., "Innovative pre-stressing and cambering".

The results were finally validated experimentally using two full-scale TTC-beam specimens. Although the Worldwide interest and researches of the field of this paper, very few of them studied the historical buildings, while most of researches focus on the contemporary timber structures.

In the last decades, restoration and strengthening of timber flat ceilings in historical Islamic buildings in Egypt generally follow the conventional techniques, such as the replacement of decayed part(s) or the full joist with compatible new timber and using suitable connections. Generally, this entails the dismantling of all flooring layers above the ceiling, its timber planks and all ornamental and false-ceiling hanging on it. Hence, the dismantled elements can be liable to damage and lose. Besides, this work consumes more time, money and effort to achieve. This paper proposes innovative strengthening techniques in Egypt that were not utilized in any restoration projects before, which are fully reversible, less-invasive and preserving the bottom surface of the timber ceilings (intact), as they are all applied merely from their upper-side. These techniques are inserted within the sand-layer of the flooring and above the timber planks of the ceiling after dismantling the flooring layers till exposing the planks. Each technique would occupy 6 cm depth of the sand-layer, which thickness normally ranges: 10 - 15 cm. Besides, the comparative structural evaluation provided and the utilization of rigid foam boards that would fill in-between the strengthening beams, are not studied in previous researches before.

RESEARCH AIM

This paper aims to cover the following objectives:

- The research reports the major applications of the layered and composite structural systems in constructing the timber beams of the flat ceilings at historical Islamic buildings in Cairo.
- It achieves a limited experimental work to determine the bending strength (f_b) and the elasticity modulus (E) of the historical timber beams at their existing condition. This helps to establish the reduction in structural efficiency and stiffness by various deterioration phenomena, which necessitate strengthening.
- It establishes the different modelling techniques of two-layered composite beams using the codes of the utilized Finite Element (F.E.) software.
- The paper conducts a wide comparative analytical investigation of the original historical beams and a number of strengthening proposals utilizing layered and composite systems. The works will be applied from the upper surface of the ceiling leaving the bottom (visible) side intact.

METHODOLOGY AND MATERIALS OF THE PRESENT RESEARCH

Generally, flat timber ceilings at historical Islamic buildings in Cairo are composed of parallel rows of simply supported timber beams that usually have rectangular cross-section. They are either built of one layer or more (i.e. bundle). The timber planks are fixed on the upper-surface of the joists of the ceiling that form together a solid plane. In some cases, the planks are fixed on secondary timber beams that are distributed above the main beams and perpendicularly to their direction. More details about these

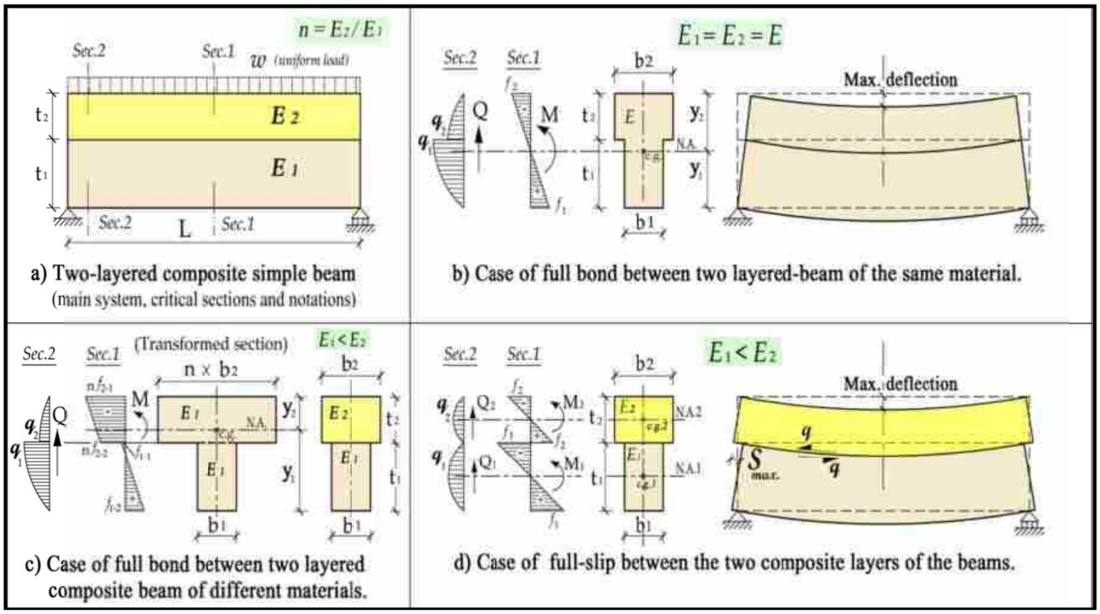
historical ceilings are found in Abdel-Aty[14]. The results of this research together with other researches[15, 16, 17, 18] helped to derive the prevailing dimensions and wood species of the common timber beams of regular rooms' ceilings in the historical Islamic buildings in Cairo, which are applied to the generalized F.E. models that represent the historical timber beam and its various strengthening proposals. The ranges of prevailing dimensions are: the span (L) = 3 to 5 m, the cross-section breadth (b) = 0.07 to 0.14 m and the depth (d) = 0.10 to 0.20 m. Hence, the considered average dimensions in all structural analysis works are: (L) = 4.0 m, (b) = 0.1 m and (d) = 0.15 m. Also, the common wood species of these beams are '*Pinus Rigida*' and '*Abies-Alba Mill.*'. More details about the wood species of the historical ceilings in Cairo are found in a previous research of the author[19].
The following sections of this paper study the drop in mechanical properties, structural strength and safety level of these historical timber beams by deteriorating actions, which necessitate there strengthening to enhance their safety. The known structural behaviour of the layered and composite beams in the previous researches will be verified by the conducted F.E. models of this paper to validate the various modelling techniques of the applied software. These models will be used in the comparative study of the various strengthening proposals of this research.

The structural behaviour of a two-layered composite beam: Numerous researches and references (e.g.[20, 21, 22]), besides the previously mentioned in the introduction; experimentally and analytically studied the structural elastic behaviour of layered composite simple-beams under vertical static (main) loads (Fig. 2a). One of the following three cases would occur according to the bonding condition between the two-layers[23]:

i) The layers act as one solid layer, when they are fully bonded without slip at the interface.
ii) The layers independently behave, as they are not bonded together causing the upper layer to only rest by bearing with full interfacial-slip on the lower one.
iii) The layers are partially bonded together with shear connectors that cannot fully restrain the interfacial-slip.

Figure 2 summarizes the results of the first two conditions by providing the major elements of this behaviour, which are: the deformed shape, the stress distribution of both bending (*f*) along section 'sec.1' where the maximum bending moment (M), and shear (*q*) along 'sec.2' where maximum shear force (Q).

[14] Abdel-Aty, "Proposals for seismic retrofitting of timber roofs".
[15] Ramadan, "Timber ceilings during Ottoman era".
[16] Gindy, "Archaeological and artistic study".
[17] Hamed, "Study of changes in dissection composition".
[18] Abdel-Samad, "Study on the effect of iron".
[19] Abdel-Aty, "Roles of timber tie-rods".
[20] Sousa and Silva, "Analytical and numerical analysis of multilayered beams".
[21] Hajianmaleki and Qatu, "Mechanics of composite beams".
[22] Johnson, "Composite Structure".
[23] Wen et al., "Analytical model for flexural response".



a) Two-layered composite simple beam (main system, critical sections and notations)

b) Case of full bond between two layered-beam of the same material.

c) Case of full bond between two layered composite beam of different materials.

d) Case of full-slip between the two composite layers of the beams.

Figure 2: **Graphical illustrations of the established structural behaviour of various cases of the two-layered composite simple-beams.**

The lower layer with elasticity modulus (E_1) represents the original timber beam, while the upper layer with modulus (E_2) represents the strengthening beam. Fig. 2b demonstrates the case (i) where the two layers are fully bonded by perfect adhesive and they are made of the same material (e.g. timber species) with different cross-sectional dimensions. Hence, the two sections are considered as a homogenous one that neutral axis (N.A.) passes by the 'centroidal' point (c.g.) of this section. The details of calculating the location of centroid (y_1 and y_2), the flexure (f) and shear (q) stresses are well-known in all structural analysis' references[24], which are (Fig. 2b):
[$f_1 = M\cdot y_1 / I$]; [$f_2 = - M\cdot y_2 / I$]; [$q_1 = Q\cdot S_x / (I\cdot b_2)$] and [$q_2 = Q\cdot S_x / (I\cdot b_1)$]; where: (I) is the moment of inertia of the total cross-section and the first moment of area $S_x = b_2\cdot t_2\cdot t_2/2$.
As the materials of the two layers in case (i) are different (Fig. 2c), the layers' sections are analytically calculated by transforming the upper section (E_2) into an equivalent one of the lower layer material (E_1), by multiplying its breadth (b_2) with (n) ratio that equals (E_2/E_1). Hence, the properties of the transformed section are calculated. The stress values of the upper layer must be multiplied by (n) ratio[25]. Consequently, the stresses (Fig. 2c) are:
[$f_{1\text{-}1} = M\cdot(y_1-t_1) / I$]; [$f_{1\text{-}2} = M\cdot y_1 / I$]; [$f_{2\text{-}1} = - n\cdot M\cdot y_2 / I$]; [$f_{2\text{-}2} = - n\cdot M\cdot(t_2-y_2) / I$]; [$q_1 = Q\cdot S_x / (I\cdot n\cdot b_2)$] and [$q_2 = Q\cdot S_x / (I\cdot b_1)$]; where (I) is the moment of inertia of the full transformed section and (S_x) is the first moment of area of its upper layer only.
For case (ii), the two-layers have different materials and they are not bonded together. The upper layer will rest on the back-side of the lower one by bearing with full interfacial-slip (Fig. 2d) that its maximum value (at beam's end) is 'S_{max}'. The total bending moment at any section of the beam (M) will be divided between the lower layer (M_1) and the upper one (M_2), thus: $M = M_1+M_2$. The two layers should

[24] Hibbeler, "Structural Analysis".
[25] Hajianmaleki and Qatu, "Mechanics of composite beams".

identically deflect, as the upper layer bears on the back of the lower one without separation. Hence, by equating the maximum deflection (Δ) of the two layers, we deduce that the total applied load (w) is also divided between the two layers as (w_1) and (w_2) following their flexure stiffness (EI); as:

$w_1 / w_2 = (E_1 I_1) / (E_2 I_2)$ ……………………………………………………….. (1)

Where: (I_1) and (I_2) are the moment of inertia of the layers.

Knowing the load portion on each layer, the shearing force, bending moment and their resulting stress distributions of each layer can be calculated as followings (Fig. 2d): [$f_1 = \pm 6M_1 / (b_1 \cdot t_1^2)$]; [$f_2 = \pm 6M_2 / (b_2 \cdot t_2^2)$]; [$q_1 = 1.5Q_1 / (b_1 \cdot t_1)$] and [$q_2 = 1.5Q_2 / (b_2 \cdot t_2)$].

The interfacial shear stress distribution between layers (q) follows the simple beam shear[26] (i.e. maximum at supports and null at mid-point). The full-bond provides the least deflection and stress values of the layered beam (i.e. the lower-limit), while the full-slippage provides the highest values of both[27] (i.e. the upper-limit). In-case the two layers are connected by semi-rigid shear connectors, the expected behaviour lies between the previous two limits. These values will be numerically verified in the next section of this paper by F.E. modelling work.

Experimental investigation of historical timber properties: The author tested three timber samples under flexure standard test, for determining the main mechanical properties of the prevailing wood species of the historical ceilings in Cairo at its existing conditions. They were cut from an old timber joist, which were extracted from debris of a ceiling of a collapsed old masonry building (built in 1930s) in 'Historic Cairo'.

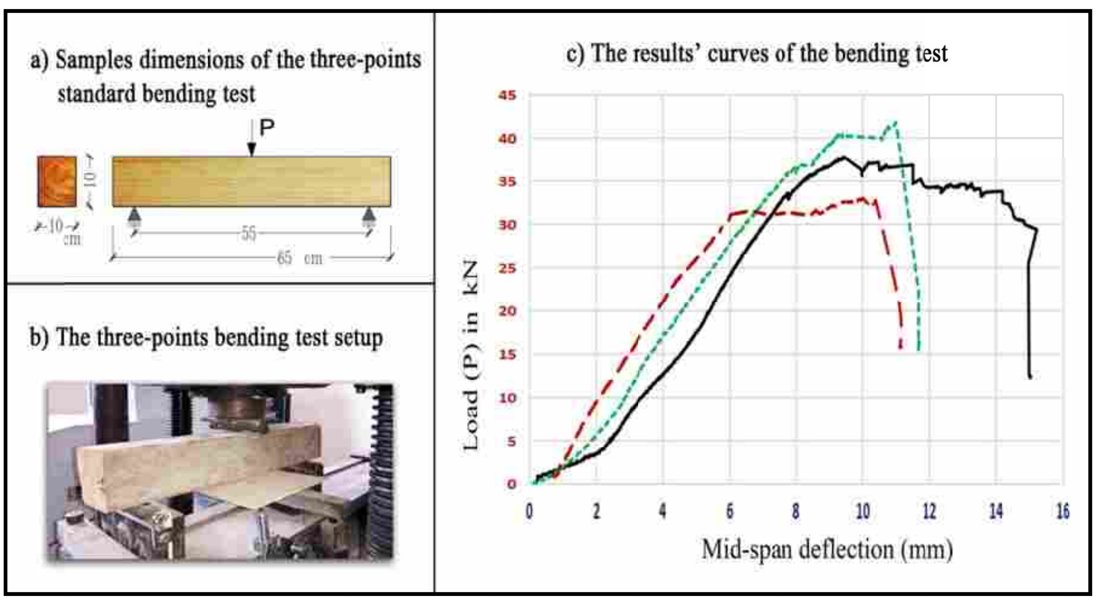


Figure 3: **Experimental investigation of the mechanical properties of historical timber.**

26 Sousa and Silva, "Analytical and numerical analysis of multilayered beams".
27 Monetto et al., "Numerical analysis of two-layer beams".

The wood species and structural and construction conditions of such beams usually resemble that of the studied historical ceilings. Besides, they are always utilized in the substitution works of the deficient historical beams, whether partially or completely. The samples' were saw-cut dividing it to dimensions of 65 cm length and square cross-section of 10 cm side-length. The span between supports of the testing samples is 55 cm (Fig. 3a). The preliminary identification of the wood showed it follows the '*Pinus Rigida*' species that is commercially known as 'Pitch Pine'. The testing machine type is 'Instron-R5500' that automatically records the deformation with measuring accuracy of 0.001 mm, see test setup in Fig. 3b. The limited experimental work is due to the lack of ruined heritage timber beams and the main goals of the present work that are based on analytical study. Hence, the experimental campaign is devoted for testing the bending behaviour and strength, besides the Young's modulus of the wood samples.

Tests' results are shown in the curves of Fig. 3c. Accordingly, the calculated elasticity modulus (E) ranges between 1307 and 1665 N/mm^2, with average value 1519 N/mm^2. The bending strength (f_b) ranges between 26.9 and 34.5 N/mm^2, with average value 31 N/mm^2. Comparing these results with the corresponding properties' of new pitch-pine wood[28], which are: E = 8300-9000 N/mm^2 and f_b = 47-74 N/mm^2, we find drop in (E) by 82% and in (f_b) by 49%. This is attributed to the deterioration and moisture levels of the heritage timber in its existing status. The reduction in the main mechanical properties causes considerable increase in the beam's deflection beyond the allowable limits and decrease in flexure strength, which make the beam structurally unsafe and vulnerable to damage.

THE COMPARATIVE STUDY OF STRENGTHENING PROPOSALS USING TWO-LAYERED COMPOSITE SYSTEM

This section studies the structural behaviour of the general timber beams that compose the historical flat ceilings in Cairo through their current (deteriorated) condition and with a number of strengthening proposals that utilizes the two-layered composite system. Hence, a number of 2D numerical models are conducted using the codes of F.E. of the SAP2000[29] (ver.19.1.1) software. The models utilize the F.E. frame-elements and the four nodes shell-elements of the software, with highly refined meshing to efficiently simulate the layers, the interface conditions and the screw connectors.

To generalize this study, the author assigned the average dimensions of the historical timber flat ceiling, which were provided in the methodology section, to the studied timber beam in this section. The proposed ceiling is built of parallel rows of timber beams, uniformly spaced by 0.33 m (i.e. three joists in each one meter of room length). The beams assumed dimensions are: (b) = 100 mm, (d) = 150 mm and (L) = 4000 mm. The Timber planks' layer that surmounts the beams has a thickness = 15 mm, and it is simulated in all models by an interfacial void between the layers, owing to its insignificant connection with the beams. The average properties of the tested

[28] FPL, "Wood Handbook".
[29] CSI, "Analysis Reference Manual for SAP2000".

wood samples are assigned to the original timber beam (i.e. density = 5 kN/m^3, E = 1500 N/mm^2 and f_b = 31 N/mm^2). The calculated static loads on the studied beam include: dead load (D.L.) and live load (L.L.). The 'D.L.' is composed of the self-weight (of the beam and planks) and the flooring cover load = 1.50 kN/m^2. The self-weight of the ceiling timber elements for every 1 m^2 area is as follows: i) the timber planks = (0.015) ×5 = 0.075 kN/m^2; ii) timber beams = 3× (0.1×0.15) ×5 = 0.225 kN/m^2. The total D.L. = 0.075+0.225+1.50 = 1.8 kN/m^2. The considered L.L. is 3 kN/m^2 (according to ECP 201-2008[30], clause: 4-1). Consequently, the total load (D.L.+L.L.) on the beam is a uniform distributed load = 0.33× (1.8+3) = 1.584 ≈ 1.6 kN/m.

The comparative study is held between the original historical timber beam in its existing (i.e. weak and deficient) condition and the various innovative strengthening techniques. The techniques follow either one of the two methodologies for the strengthening beam that would be mounted above the original historical beam (Fig. 4a): the beam will only be mounted by bearing (i.e. without any bond), or it will be connected to the original beam by a row of steel screws that are uniformly distributed along its length by 5 cm spacing.

For all strengthening proposals, the spaces between them are filled with rigid foam boards of 6 cm thickness (Fig. 4b). This foam is characterized[31] by light weight and significant normal and flexure stiffness (i.e. density = 0.15-0.38 kN/m^3, compressive-strength = 70-270 kPa and flexure-strength = 170-410 kPa).

The proposed type of strengthening beam is one of the following three types:

i) A robust new timber (Fig. 4c/i) of a rectangular cross-section (b= 150 mm and d= 60 mm).
ii) A steel channel section 'UPN 140' (Fig. 4c/ii) following the European standards in dimensions (DIN 1026-1: 2000, NF A 45-202, 1983). It has a flange width = 60 mm with thickness = 10 mm and a web height = 140 mm with thickness = 7 mm (the total cross-sectional area = 2040 mm^2).
iii) A steel box (Fig. 4c/iii) section (b= 150, d= 60 mm and thickness = 5 mm).

The new timber is 'pitch-pine' with the following required properties[32]: density (ρ) = 5 kN/m^3, elasticity modulus (E) = 7000 N/mm^2 and bending strength (f_b) = 50 N/mm^2. The steel sections are made of mild steel 'St-37' (ρ= 78.5 kN/m^3, E= 21000 N/mm^2, yield stress (f_y) =240 N/mm^2 and ultimate strength (f_u) = 360 N/mm^2).

Finally, each of the three cases, will be evaluated twice, both un-bonded and shear anchored by steel screws (Fig. 4c).

[30] MHUUC, "Egyptian code of practice for calculating loads".
[31] FSC, "IRC wall bracing".
[32] FPL, "Wood Handbook".

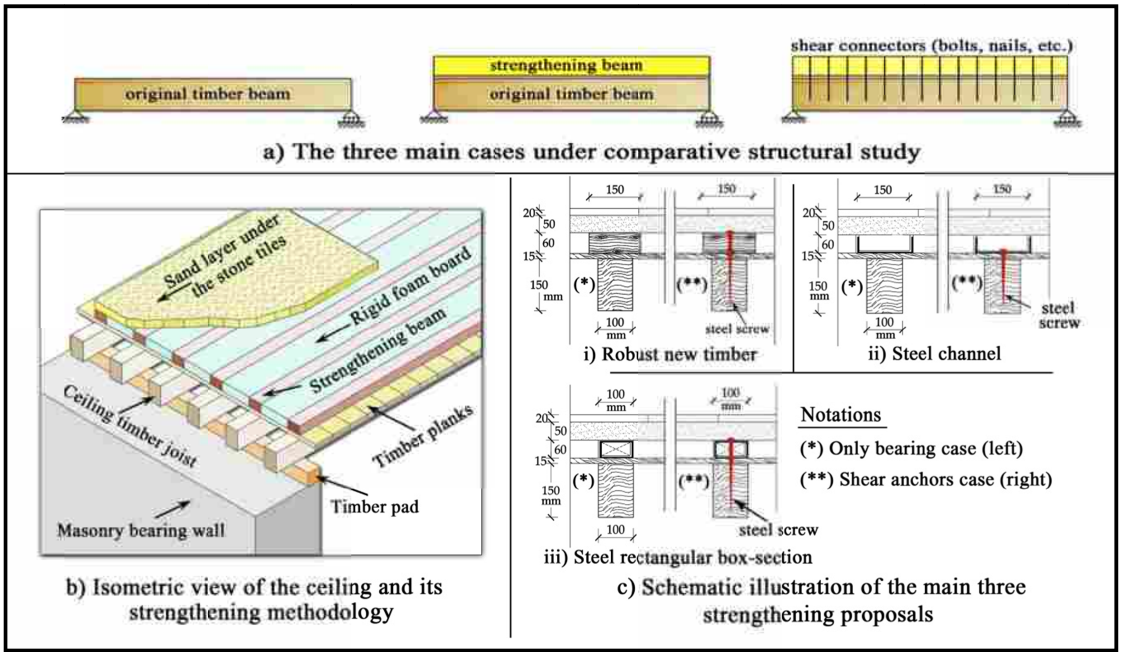


Figure 4: **'2D' and '3D' ACAD-drawings showing the different structural analysis cases of the original and strengthening proposals.**

Allowable values for deflection and stresses: The working stress method will be implemented in the evaluation of the beam and its strengthening, following the allowable values for deflection in the Egyptian code[33] (clause: 3-3-2-4) and for stresses of timber in the Italian code[34] (clause: UNI 11035-2, 2003). The allowed deflection under total loads (D.L.+L.L.) is (L / 250) for ceilings and (L / 600 <7 mm) for lintels and beams supporting brittle materials (e.g. gypsum). Hence its value is (400 / 250) = 1.6 cm. The permissible working-stresses of timber in bending (f_{bw}) is 8.0 N/mm^2 and in shear (q_w) is 0.6 N/mm^2. It is worth mentioning that the enhancement of structural safety of the historical structures by being as close as possible to the requirements of the contemporary building codes is always feasible and better than the full satisfaction of these requirements with excessive structural interventions[35].

Analysis' results of the historical beam in its existing condition: The comparative structural study starts with the proposed generalized timber simple-beam that simulates the original (historical) beam in its deteriorated condition. As one-layered simple-beam, it is directly calculated as in Fig. 2b, which analysis' results are: i) the maximum deflection at mid-span (Δ) = 12.42 cm; ii) the maximum flexure stress (f_b) = ±8.49 N/mm^2 (as no normal force); iii) and the maximum shear stress (q) = 0.32 N/mm^2. The deflection is highly unsafe (its value is 776% of the allowed), flexure-stress is unsafe by 6% (nearly safe), while shear stress is safe. Hence, strengthening the ceiling's beams is indispensable.

[33] MHUUC, "Egyptian code of masonry buildings".
[34] UNI, "UNI 11119:2004".
[35] Abdel-Aty, "Proposals for seismic retrofitting of timber roofs".

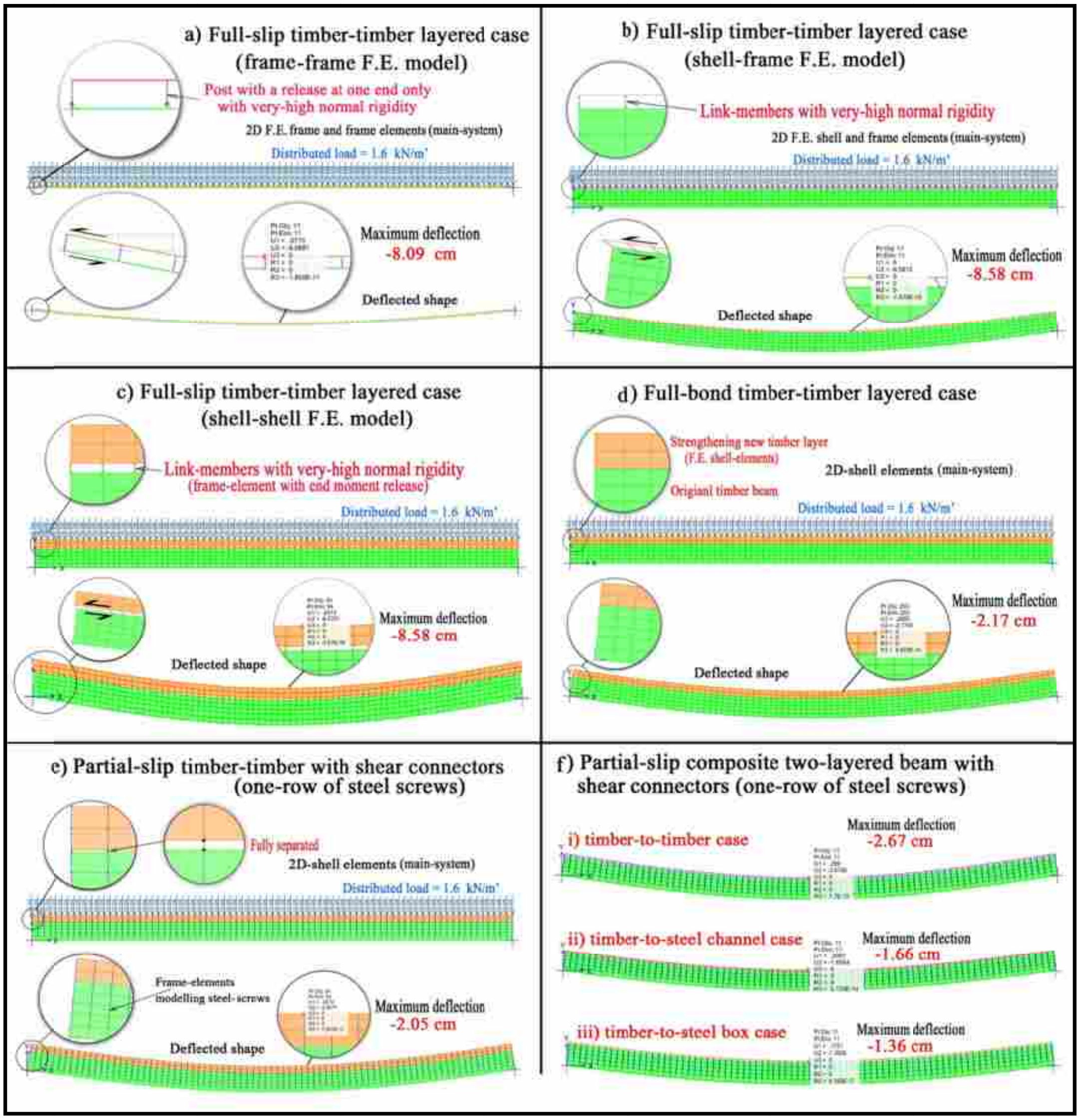


Figure 5: Comparison between various F.E. modelling techniques of a composite two-layered beam and the interfacial studied conditions (full-slip, full-bond and shear anchors).

Comparative evaluation of the various strengthening proposals: The author conducted an intensive investigation to establish various modelling techniques that accurately simulate the different interfacial conditions (i.e. the full-slip, the full-bond and the shear connectors with steel screws) between the lower layer (of the original beam) and the upper layer (of its strengthening), thus establishing their structural behaviour. Hence, the F.E. frame-element of the software[36] was utilized to cover all the interfacial conditions (Fig. 5), utilizing the moment-releasing option that nullifies the moment at frame's end (i.e. it inserts hinge at this end). Moreover, the meshing spacing in both (X-Y) directions ranges between 15 to 50 mm. The validation and success of the modelling method for each case is conducted accordingly to the analytical results, which were provided in the previous section (Fig. 2).

[36] CSI, "Analysis Reference Manual for SAP2000".

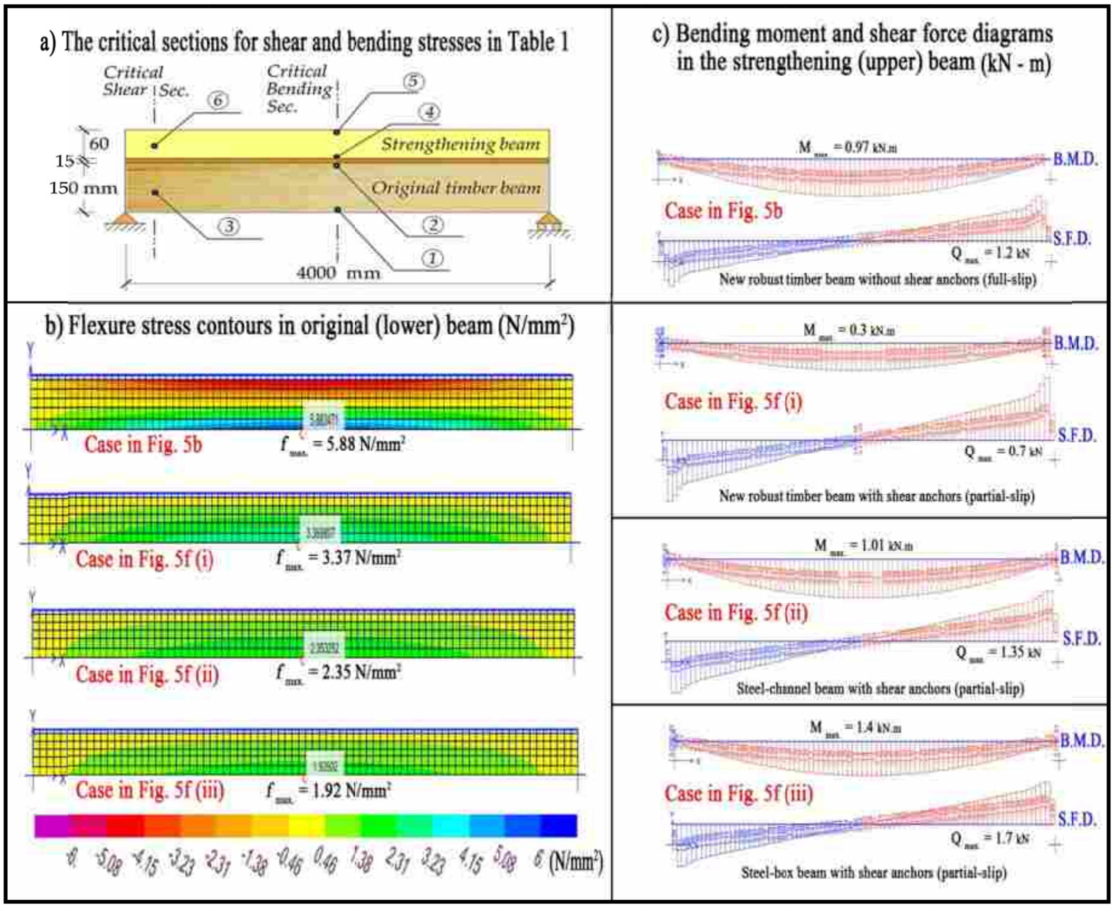


Figure 6: Locations of critical sections of Table-1 and analysis' results of the main strengthening proposals.

The full-slip case: The simulation of the bearing of the upper layer (the strengthening beam) on the lower one (the original beam) with full-slip, is achieved by connecting the two layers at interface at all nodes by short posts (Fig. 5a) of enormous normal rigidity (i.e. frame-elements with $E = 10^8$ N/mm^2 and a squared cross-section of 100 mm length). The following three established modelling methods are:

i) The two layers can be simulated by frame-elements and the linking posts must be moment-released at only one of its ends (Fig. 5a).

ii) The bottom layer is simulated by shell-elements while the top one is modelled by frame-elements (Fig. 5b). The linking posts must be moment-released at both ends (i.e. link-members).

iii) The two layers are simulated by shell-elements (Fig. 5c). The linking posts must also be moment-released at both ends.

The interfacial slippage provided in Fig. 2-d is fully attained in the second and third methods, while it is achieved by posts' rotation in the first method. The maximum values of the deflection are identical for the last two methods and 94% of the first one (i.e. results of the three methods are nearly the same). Similarly, the results of internal forces and stresses (shear and bending) are almost equal. Finally, all results satisfied the analytical equations in the methodology section. It is worth mentioning that the following colours are applied to all models in Fig. 5: 'green' for historical timber beam, 'orange' for new-timber strengthening beam, 'blue' for steel screws and 'pink' for steel top layer.

The full-bond case: The model is achieved directly by utilizing shell-elements of the software for the two layers that are directly connected without separation (Fig. 5d).

The partial slip case: The second and third modelling methods of the 'full-slip case' are only utilized (i.e. shell-shell model in Fig. 5e and shell-frame models in Fig. 5f). Frame-elements of circular cross-section of 10 mm diameter simulate the mild-steel screws. The interfacial void between the layers (Fig. 5e) was reduced to 3 mm, for comparing its results with the full-bond case (Fig. 5d). The timber-to-timber composite section model, with shear connectors of steel-screws, resulted in nearly similar deflection value of the full-bond case. This satisfies the results of the previous researches, such as[37]. The replacement of timber strengthening beam by a steel section of either channel or box section, reduces the resulting deflection by 38% and 49% respectively.

The full results of the maximum deflection at mid-span and the internal bending (*f*) and shear (*q*) stresses at both layers are demonstrated in Table 1, which locations are in Fig. 6a. Besides, Fig. 6b and 6c demonstrate the analysis' results of the main strengthening techniques in Fig. 5, which are: i) the installation of a robust timber beam by bearing (without shear anchors) and with shear anchors; ii) the installation of steel beam of either channel or box section and with shear anchors as it provides behaviour nearly similar to full-bond case. These results are also concluded in the Table 1 and Fig. 7.

Table 1: Results of the maximum deflection, besides bending and shear stresses at the critical sections (Fig. 6a) of the original beam and its strengthening one.

Case No.	Case type	Maximum Deflection in (cm)	Original beam			Strengthening beam		
			f_1 N/mm^2	f_2 N/mm^2	q_3 N/mm^2	f_4 N/mm^2	f_5 N/mm^2	q_6 N/mm^2
Case 1	Original timber beam only	12.42	8.49	-8.49	0.32	--	--	--
Case 2	Timb.-timb. with interfacial **full-slip**	8.58	5.88	-5.88	0.22	10.80	-10.80	0.183
Case 3	Timb.-timb. with interfacial **full-bond**	2.17	3.00	0.18	0.055	0.18	-5.30	0.162
Case 4	Timb.-timb. bonded by **shear connectors**	2.67	3.37	-0.25	0.067	0.2	-5.14	0.117
Case 5	Timber-steel Ch. with interfacial full-slip	2.77	1.87	-1.87	0.068	101.3	-101.3	3.025
Case 6	Timber-steel Ch. bonded by **shear connectors**	1.655	2.35	0.15	0.055	60.55	-60.55	2.148
Case 7	Timber-steel box-sec. with **full-slip**	2.45	1.675	-1.675	0.062	87.3	-87.3	6.5
Case 8	Timber-steel box-sec. with **shear connectors**	1.361	1.925	0.1	0.0344	49.77	-49.77	4.25

DISCUSSION OF THE RESULTS

Evaluating the results, we can establish the followings:

- The drop in the modulus of elasticity value of the historical timber due to deteriorating actions, leads to excessive deflection in the ceilings' beams that is highly unsafe and to reduce the material strength and stiffness. In time and without strengthening and conservation the beams can damage and break, which generally occur nowadays.

[37] Chiara and Massimo, "Numerical analysis of timber-to-timber joints".

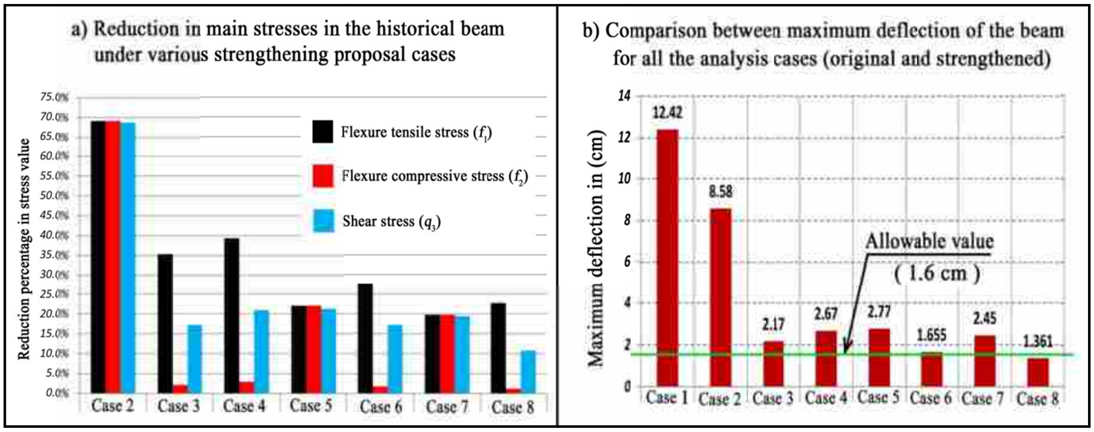


Figure 7: Enhancement of structural behaviour of the historical beam under various strengthening proposal cases in Table-1.

- The best modelling technique for the composite two-layered beam with full-slip interfacial condition is the one in Fig. 5b. Its deformation and stresses fulfill the analytical results (Fig. 2) and the frame-element of the top-layer can efficiently acquire any cross-sections (e.g. channel, box, etc.). Besides, the shear anchors are modelled similar to the model in Fig. 5e with nearly equal results. Hence, the final focus (Fig. 5f, 6b and 6c) was on its models.
- The installation of a new timber beam without shear anchors would slightly enhance the structural behaviour of the historical beam, while maintaining unsafe deflection and high flexure stresses in the original beam (Fig. 5b, 6b and 6c).
- If the new robust timber beam is shear-anchored into the historical one by steel screws, the deflection is greatly reduced although it is still unsafe (it is 167% of the safe value), while the maximum flexure stress is 56% of the allowed value. It also provides similar analysis' values to the full-bond case. Though, the full-bond (Fig. 5d) is practically difficult to achieve owing to the timber plank layer that hampers the full adhesion between the two layers, its study is only used for comparison.
- The strengthening proposal (case 4 in Table-1 and Fig. 7) using new timber beam that is anchored in the original beam with efficient steel-screw of 10 mm (diameter) provides a fully conservative and reversible solution. Although it is not the optimum from structural evaluation and safety point-of-view. It merely satisfies the concept of enhancing the structural safety (see the end of the allowable value section).
- The use of steel beams of standard rolled sections (i.e. channel or box) for strengthening provides the best structural strengthening of the historical beams, whether with or without shear anchors (cases 5 to 8 in Table1 and Fig. 7). The both sections provide nearly equal results, although box-section is safer. Their un-bonded condition (of cases 5 and 7) provides similar results to the bonded timber strengthening beam. While, the anchored condition (of cases 6 and 8) provides the safest strengthening.
- All the strengthening proposals (i.e. the new beams and the rigid-foam boards that fill the voids in-between) will occupy the first 6 cm of the sand layer that usually constitutes the majority of flooring layer above the timber planks (about 10-15

cm). Instead, only 4 cm sand-layer will be installed, under the mortar-layer that bonds the stone-tiles. The rigid-foam boards will reduce the dead-load of the flooring as its density is highly less than sand. Besides, they laterally confine the strengthening beams and create with them a diaphragm action with respectable in-plane stiffness, which would enhance the seismic resistance of the historical masonry building[38].

- The increase in dead load due to the strengthening beams is about 3% for timber beams and 7% for steel beams, which are both of negligible effect on the structural behaviour.

CONCLUSIONS AND RECOMMENDATIONS

- The demonstrated techniques of this paper help in the structural restoration and/or rehabilitation with the adaptive reuse of the timber ceilings in the historical masonry buildings in Egypt. The dimensions of the strengthening beam should be determined based on the structural design of the work. Hence, the proposed dimensions in this paper are liable to increase, while the total depth of the beams is maintained = 6 cm. Although, this depth may be increased according to floor levels, door openings of the building and in-case of the final (inaccessible) roofs.
- The historical timber ceiling under strengthening must be properly shored before the work starts.
- The strengthening should be applied to all the beams of the ceiling, and not confined to the damaged and deficient ones.
- The strengthening beams' locations must completely coincide above the original main-beams of the ceiling. They should also be inserted into the bearing masonry wall similarly to the original beams and not less than one-third of wall's thickness.
- It is highly recommended to apply the strengthening technique of the historical ceiling's beams using either the timber beam with screw shear anchors (case 4) or anyone of the steel beams (cases: 5-8) to the structurally deficient and unsafe historical timber ceiling's beams.
- The steel beams should be properly isolated against corrosion and rust by anti-rust paint before using in the strengthening. Besides, the bonding screws must be of stainless steel.
- Future expansion of this research is planned to experimentally verify the results established in this paper by the analytical F.E. numerical modelling works.
- The success of the proposed techniques demonstrated in this paper and the future experimental expansion of this research would help of their large practical implementation for the structural restoration of any timber ceiling without dismantling it.

[38] Abdel-Aty, "Proposals for seismic retrofitting of timber roofs".

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