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Original article

Proposals for seismic retrofitting of timber roofs to enhance their in-plane stiffness and diaphragm action at historical masonry buildings in Cairo

Yaser Yehya Amin Abdel-Aty

Cairo University, Faculty of Archaeology, Conservation Department, 12613 Al-Orman, Giza, Egypt

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ABSTRACT

The in-plane stiffness of flat roofs plays crucial role in the structural stability and safety of historical load bearing masonry buildings under lateral hazardous loads. For decades, many restorers of historical buildings used to provide the original timber roofs with rigid diaphragms action using modern engineering systems; such as building reinforced concrete (R.C.) thin slabs. The present research studies analytically the installation of simple and robust timber bracing system above timber boards and under flooring layers of timber flat roofs; to improve the seismic behavior and stability of their historical load bearing masonry buildings in Cairo. The study will evaluate among various alternatives of bracing systems using numerical modelling techniques of computer software that applies Finite Element (F.E.) method. The research applies the numerical investigation to one of archaeological buildings in Cairo from Ottoman era, which is the "*Sabil*" of "*Khusraw Pasha*" (1535 A.D./942 A.H.). The timber x-bracing system provides remarkable results relative to rigid diaphragm and steel bracing for seismic retrofitting of historical timber roofs.

1. Introduction

Historical load bearing masonry buildings in Cairo with horizontal timber ceilings are generally vulnerable to horizontal loads, especially seismic and severe wind actions. Accordingly, these buildings are usually prone to various degrees of structural deficiencies, damages and destructions after moderate to severe earthquakes. These deficiencies were surveyed and reported during the last decades and especially after the Egypt's October 1992 earthquake; by many studies such as: [1–4,5]. Many of the structural damages can be attributed to the disability of the timber roofs to have sufficient in-plane stiffness that enable them to play the role of rigid diaphragm action. Also, these historical masonry buildings always lack to direct and clear bracing systems that can safely transfer lateral loads to buildings' foundation. Consequently, the whole building would not respond as one unit under lateral forces, instead its constituting load bearing walls would respond almost independently. This can raise the resulting loads, stresses and the produced damages and deficiencies in each wall rather than being connected to a rigid diaphragm at each floor level [6].

Horizontal timber roofs at most of historical masonry buildings in Cairo are usually composed of parallel and uniformly spaced rows of timber girders with rectangular cross-section, which extend along the shorter direction of their rooms; see Fig. 1. The girders' end connections with their bearing walls always satisfy simple beam system; since lateral slippage of girder's ends can occur [7]. Moreover, most of the historical masonry buildings in Egypt were empirically designed and constructed to carry vertical loads merely, while special provisions were simply provided to overcome and minimize the damaging effects of lateral loads. These provisions are such as: embedding of timber-ties and use of timber-frames through masonry walls in seismic prone cities. In fact, such provisions were conducted following accumulative construction experience with time, while they definitely do not satisfy the current safety levels and requirements of the present national masonry building code [8].

The in-plane stiffness of timber roofs at all floors of historical load bearing masonry buildings in Cairo plays the major role to create together with their bearing masonry walls simple paths for seismic loads and bracing systems (to certain extent). Besides, lateral stiffness of these roofs that is achieved by robust connection between roofs' timber girders and their bearing walls, is also of great importance for buckling stability of masonry walls of the historical building as it provides lateral support for the walls, so that they would not be free standing over their full height; thus behaving like tall cantilevers. Also, it is essential to avoid early collapse of masonry walls under large out-of-plane bending moments,

E-mail addresses: yaser_yehya@yahoo.com, yaseryehya@gmail.com

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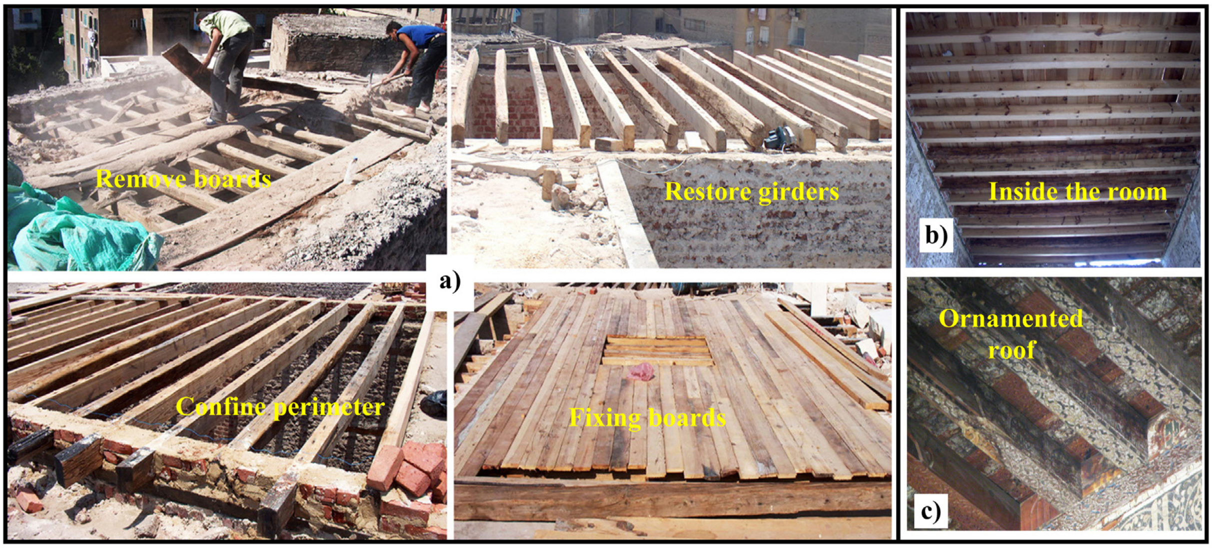

Fig. 1. Main parts of traditional timber flat roofs at archaeological medieval buildings in Cairo. a) photos shot by the researcher during the restoration work of "*Khawand Barakah*" school (1369 A.D./770 A.H.) in the year 2006; b) views from inside the room after reconstruction of the roof; and c) an example of ornamented roof in "*al-Tunbugha al-Maridani*" mosque (1340 A.D./740 A.H.).

which arise when the walls are not effectively restrained to floors [7]. Therefore, the in-plane stiffness of timber roofs at historical masonry buildings in Cairo should be improved, since it cannot generally fulfil the rigid diaphragm action and the other mentioned lateral restraining criteria. Moreover, Egypt, as many countries; has its seismic zoning and masonry building code been recently developed and updated during the last decades. Accordingly, the structural stability and safety of old masonry buildings in Cairo that were built with fewer or even without seismic provisions should be evaluated against seismic risks in order to comply with safety requirements of the recent building code. Consequently, any historical building that is undergoing major rehabilitation, renovation or change of its use for either the whole building or a significant portion of it should be checked for earthquake loading following the same calculations applied in the design of modern masonry buildings [9]. Either one of the following two categorization concepts that are commonly used in earthquake engineering can be implemented with the interventions of any historical building to reduce its seismic vulnerability:

- seismic strengthening or upgrading; which leads the structure to withstand a design earthquake of exceptional level like a new building;
- seismic improvement, which is a milder, less invasive, more local intervention intended to eliminate possible criticalities and without implementing a general upgrading of the structural capacity to the same level as in the new building designs.

The approach of seismic improvement is more suitable and applicable for historical buildings in Cairo. Through the last decades, many researchers besides the implemented restoration projects abroad have provided a number of alternatives that help to create rigid diaphragm action at roofs of historical buildings; thus raising their in-plane stiffness. A number of researches that study the structural behavior of timber roofs and provide various solutions to either strengthen or enhance their diaphragm in-plane stiffness are: [6,9–15]. The traditional strengthening technique always applies rigid solutions such as installing reinforced concrete (R.C.) thin slabs above timber roofs. It is characterized by low reversibility, incompatibility and contradicting with conservation principles of heritage buildings. Observation of damages caused by recent earthquakes in un-reinforced masonry buildings (URM) at many heritage centres in Europe has revealed that the substitution or strengthening of original timber roofs with stiff R.C. diaphragms often does not lead to significant improvement of the seismic performance of their heritage buildings, instead it can be one of the main causes of local or global failures of its buildings as it increases roofs' mass, thus raises the resulting seismic loads, besides other structural problems [9].

The present research highlights the importance of utilizing the new advances of computer numerical modelling and software to study non-traditional retrofitting and structural improving works of historical masonry buildings in Cairo that satisfy the requirements of conservation principles. Thus, the research investigates the installation of simple timber bracing truss-system above the timber roofs at each floor of the historical masonry buildings using numerical Finite Element (F.E.) modelling technique. It studies and evaluates the improvement of seismic stability and resistance of these buildings through the enhancement of in-plane stiffness and rigid diaphragm action of their roofs. Also, the installation of such bracing system at each roof helps to limit out-of-plane displacements of different masonry walls of the building and to distribute horizontal earthquake forces between them. Since girders of every timber roof at archaeological medieval buildings in Cairo always extend between only two facing masonry walls for every room of the building (i.e. simple beams) and never extend to cover the neighboring room; the selected case-study was chosen as a simple archaeological masonry building from Ottoman period in Cairo; of only one-room with two stories. This would ensure that the results reached and conclusions provided for the case study is generalized and applied to numerous heritage buildings in Cairo.

2. Research aim

The present research aims to propose conservative solutions for structural retrofitting of timber flat roofs at historical load bearing masonry buildings in Cairo, to enhance their in-plane stiffness and rigid diaphragm action that would help to improve seismic stability and resistance of their buildings. The alternatives provided would overcome the various structural problems of traditional restoration work concerning substitution or strengthening of historical timber roofs with stiff diaphragms using reinforced concrete slabs. The