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Engineering Investigation, Analyses and Retrofit Procedures for Earthquake Damaged Heritage URM Churches in Bohol Island, Philippines

Emilio M. Morales CE, MSCE, F. ASCE

Principal

EM²A Partners & Co., Quezon City, Philippines

Contact: emmorales07@gmail.com

Abstract

This paper is based on the Structural Engineering studies conducted as part of the engagement with the ***National Museum of the Philippines*** as well as independent studies made by the authors. The studies were focused on heavily damaged Heritage URM churches in the Island of Bohol. The causative mechanisms were analyzed together with the contributory factors and include considerations that structure Geometry and layout played in the damage sustained and includes an understanding of the Period Construction Methods used. The studies were checked against Finite Element Analyses FEM models of the structures and their responses to Earthquake lateral loads. The FEM runs validated the observed results in the field. The results of this study enabled us to formulate Engineering intervention and remediation strategies and recommendations that addressed the cause/s rather that the outright reconstruction without regard to what have caused the distress.

Keywords: Unreinforced Masonry, Buttress, Nave, Transept, Agramasa, Lime mortar, Masonry anchors.

1 Introduction

The investigation of 9 URM churches was done by the author as part of an engagement with the National Museum of the Philippines, in order to document, investigate and assess what could be done by way of engineering intervention to restore or remediate the damaged churches and watch towers.

3D laser scanning were performed to document the existing geometry and condition of the various structures and also to serve as inputs and guide to our overall engineering assessment and studies. Drone flybys were also conducted by an associate company in order to obtain a more comprehensive survey of the existing condition for each specific site, something not attainable by any other means. 3D Laser scanning was also performed in order to determine the actual condition of the damaged churches including the distribution and severity of cracks. Subsurface soil Exploration was also done per site to determine the underlying soil conditions. These information gathered in the field served as valuable inputs to our studies.

Engineering studies were also performed using *finite element plate* models to depict the *cruciform* layout of the churches. These were then subjected to loads in order to simulate earthquake lateral loads in two orthogonal directions. The

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