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Nondestructive Evaluation of Masonry Materials used in Historic Philippine Structures: Case Study of Structural Performance of Manila Cathedral

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Abstract – *Due to numerous tectonic activities in the Philippines, many old heritage structures are susceptible to damage. These structures are mostly made of adobe, clay, bricks, and the like, which are inhomogeneous and contain cracks of variable sizes. As a step towards preservation, this research aimed to develop correlations between mechanical properties of materials such as Young's modulus of elasticity and uniaxial compressive strength which are usually determined using destructive tests, and nondestructive parameters, such as ultrasonic pulse velocity and wave attenuation. Ultrasonic testing was conducted to determine wave characteristics of different masonry materials used in old Philippine structures. The correlations obtained between these properties and the material properties obtained from destructive testing gave high values of coefficient of determination, resulting in a viable basis for modeling. To demonstrate the usefulness of this method, data from in-situ nondestructive tests were used as parameters in the correlations for the material comprising the Manila Metropolitan Cathedral-Basilica. Using the mechanical properties obtained, a structural model was created through the commercial program SAP2000. Both strength-based and time-history analyses were employed to determine the displacement and stress distribution on the structure when subjected to different load combinations. Results of the analyses confirmed that unreinforced masonry structures may fail due to excessive tensile stresses on certain parts of the structure.*

Keywords—ultrasonic pulse velocity; nondestrucive testing; masonry materials; Young's modulus of elasticity; uniaxial compressive strength; strength based analysis; nonlinear modal time-history analysis

Nomenclature

Symbol	***Symbol Description***	***Units***
UPV	Ultrasonic pulse velocity	m/s
UCS	Uniaxial compressive strength	MPa
YM	Young's modulus of elasticity	MPa
R^2	Coefficient of determination	-

Abbreviations

NDT	Non-destructive testing
MC	Manila Cathedral samples

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I. INTRODUCTION

The Philippines is home to numerous centuries-old Spanish colonial structures such as heritage churches, ancestral homes, and military forts. A large part of these structures are considered national treasures [1] and a number of them are even included in the UNESCO list of World Heritage sites [2]. They can be found in every region of the country, and play an important role in the preservation of its culture and history. That said, most of these structures are made of unreinforced masonry materials like adobe, clay, sea shells, among others; and the age of these structures are probably beyond the design life, making them highly susceptible to natural calamities. This can be seen in the recent 7.2 magnitude earthquake that hit the Visayas region wherein "historic churches dating from the Spanish colonial period suffered the most. Among them is the country's oldest, the 16th-century Basilica of the Holy Child in Cebu, which lost its bell tower." [3] Hence the preservation and possibly, structural retrofitting of these structures should be given importance. This undertaking starts with the structural evaluation of the structures, which cannot be done in a destructive manner since this could degrade the structure and its essence. As an alternative, this study aims to show the applicability of non-destructive testing in determining the structural parameters needed to perform an evaluation of the structures made from different types of masonry materials. These procedures include thermal scanning, sonic and ultrasonic methods, electromagnetic techniques, etc. As stated in [4], "[t]he information obtained by means of the above mentioned non-destructive techniques is necessary to obtain so much the mechanical characteristics, for the analysis of the historical construction and comprehension of its structural behavior to obtain models for the calculation, as well to validate the analysis itself."

As a case study, this research focused on utilizing **Ultrasonic testing (UT)** on materials from the **Manila Metropolitan Cathedral-Basilica**, informally known as the **Manila Cathedral**. Ultrasonic technology is based on the principle that ultrasonic wave through material, which travels at a known velocity, is dependent upon the material properties. A number of studies, such as [5] and [6], have tried to correlate **ultrasonic pulse velocity** obtained by dividing the path length of the wave by the transit time taken to traverse the distance to mechanical properties of different masonry materials. In this research, UT will be done to determine different non-destructive characteristics of the material, which will be used to gage its structural qualities. The results will then be used as a basis for modelling of the structure to determine its performance under different loading conditions.

II. METHODOLOGY

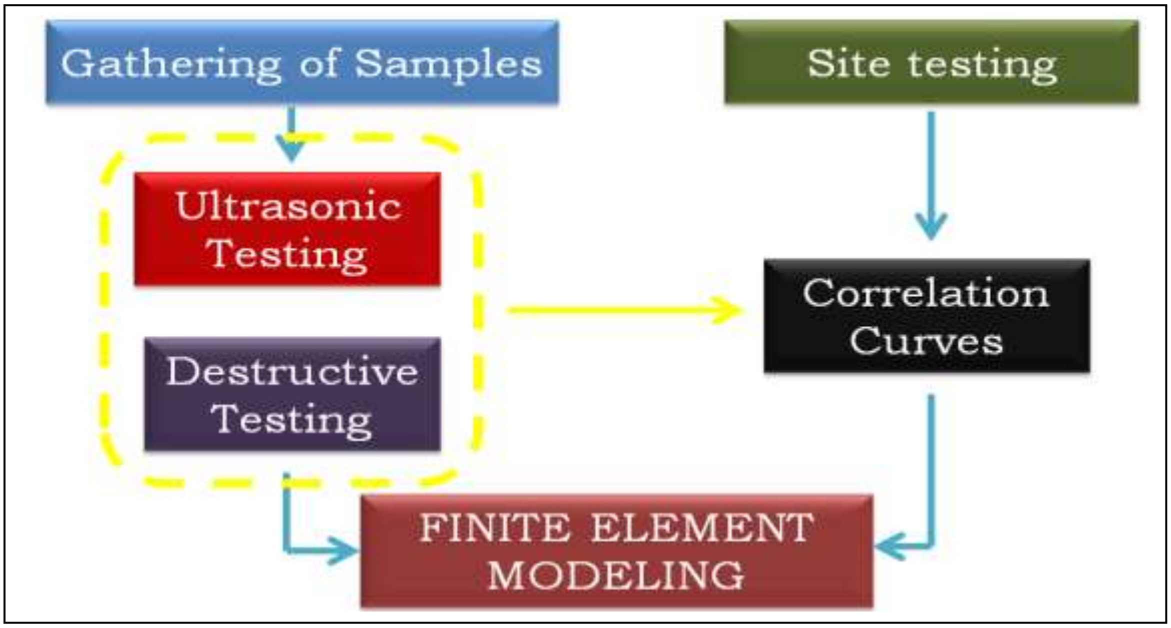

Figure 1. General Methodological Framework

Samples of the material comprising the Manila Cathedral were obtained and brought to the laboratory where ultrasonic testing was conducted to determine the wave characteristics through the material. Ultrasonic pulse velocities were directly obtained from the testing while other ultrasonic parameters such as wave attenuations and frequency distributions were determined through further wave processing. Uniaxial compressive testing was then performed to determine the mechanical properties of the material (i.e. Young's modulus of elasticity and uniaxial compressive strength). These parameters were then correlated with the wave characteristics. Different statistical parameters were used to determine best-fit models for the different sets of parameters.

To determine the actual characteristics of the structure itself, ultrasonic testing was then done on site. The results were used as input parameters to the correlations obtained to determine the mechanical properties. A model of the Cathedral, based largely on the floor model provided by Intramuros Administration, was then constructed in SAP2000 using the obtained material properties and was subjected to different loading conditions to determine the critical sections of the structure.

2.1 Sample Gathering and Preparation

Samples from the Manila Cathedral were gathered and transported to the Construction Materials and Structures Laboratory (CoMSLab) at UP Diliman. After letting them rest at room temperature for 2-3 days, the specimens were then cut to size using the diamond blade cutter at the CoMSLab, The samples were cut to a square cross-section with 100 millimeter sides and a height of 150 millimeters to be able to keep a 1:1.5 width to height ratio while keeping the minimum path length for the ultrasonic testing. As an example, the images before and after cutting of the 6th specimen from Manila Cathedral are shown in Figure 2.

Figure 2. Images before and after cutting of the MC 6 specimen

2.2 Ultrasonic Testing

After letting the specimens dry in room temperature for 24 hours, grids were drawn on the surfaces of samples when possible. These consists 10-20 millimeter boxes, depending on the available surface area. To conduct the ultrasonic tests, the Portable Ultrasonic Non-Destructive Indicating Tester (PUNDIT) Lab of the Building Research Service of UP - Diliman was used. It is an ultrasonic tester made by Proceq© that has an interface, two transducers/receivers, and a USB connector that allows control using an accompanying program called Proceq Punditlink It emits an ultrasonic pulse with a 54 kHz frequency. ASTM E494-10, or the *Standard Practice for Measuring Ultrasonic Velocity in Materials,* states that "for maximum accuracy, the highest possible frequency that will present at least two easily distinguishable back echo reflections, and preferably five, shall be used." But since the equipment only emits a 54 kHz pulse, it was used all throughout the study.

After calibrating the equipment and application of petroleum jelly to ensure good contact between the transducers and the surface of the samples, ultrasonic pulses were sent and received at different points along the material. Figure 3 below shows the interface of the program used in analyzing the ultrasonic wave as it passed through the materials.

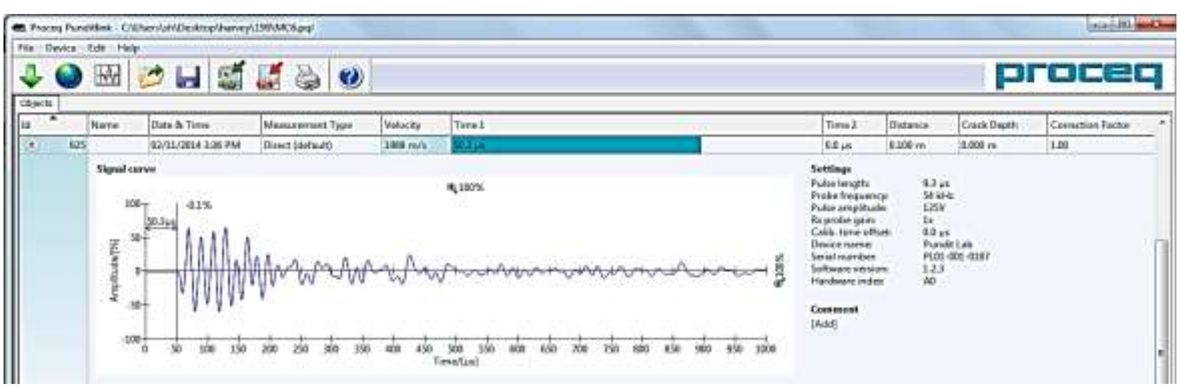

Figure 3. Screenshot of the PunditLink program during ultrasonic testing

2.3 Uniaxial Compressive Testing

After going through ultrasonic testing, the specimens underwent destructive testing. The setup used is shown in Figure 4. The Instron© 5982 floor model 100 kN capacity Universal Testing Machine was used. The equipment comes with a computer interface through the program Bluehill© 3 that allows the user to input the specimen geometry so that it instantaneously obtains the stress based on the load applied. The interface also displays the stress-strain curve as the compressive test goes on. For the test itself, ASTM C1314-12, or the Standard Test Method for Compressive Strength of Masonry Prisms, allows any convenient rate of loading to be used as long as the failure happens between 1-2 minutes. Since the equipment allows for numerous parameters to be taken, the compressive stress at yield and the Young's Modulus of Elasticity were selected as those that will be computed and reported in the output file of each test because these are the parameters to be studied in this research.

Figure 4. Instron 5982 floor model 100 kN capacity Universal Testing Machine with the control panel shown on the upper right.

An image (like the one shown in Figure 5) was taken directly after testing before a piece of the core was weighed and oven dried for 24 hours to be able to obtain the moisture content at testing.

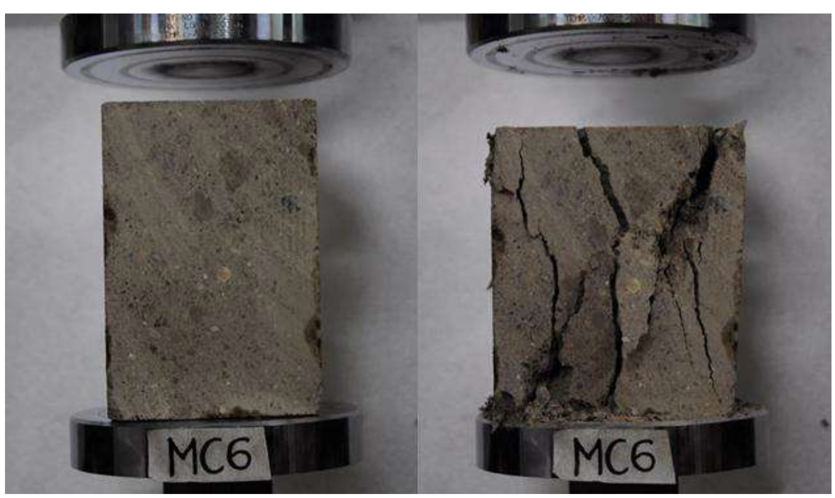

Figure 5. Specimen MC 6 before and after going through destructive testing

2.4 In-situ Testing

Before testing commenced, visual inspection is done to different parts of the structure. This is to determine the critical sections, or where the structure will likely to fail if it was exposed to strong loads like earthquake. This will be characterized primarily by large cracks and discontinuities that could be seen by simple inspection of the church. This is also used for comparison after the results of critical sections were identified from structural simulation. The setup shown in Figure 6 was used to conduct indirect testing. The results from that test were the primary data to be used in this study. All indirect testing setups were spaced out on multiples of 50 mm for uniformity in setup. Indirect transmission method was used in this study because it is impossible to conduct direct tests on these kinds of thick walls.

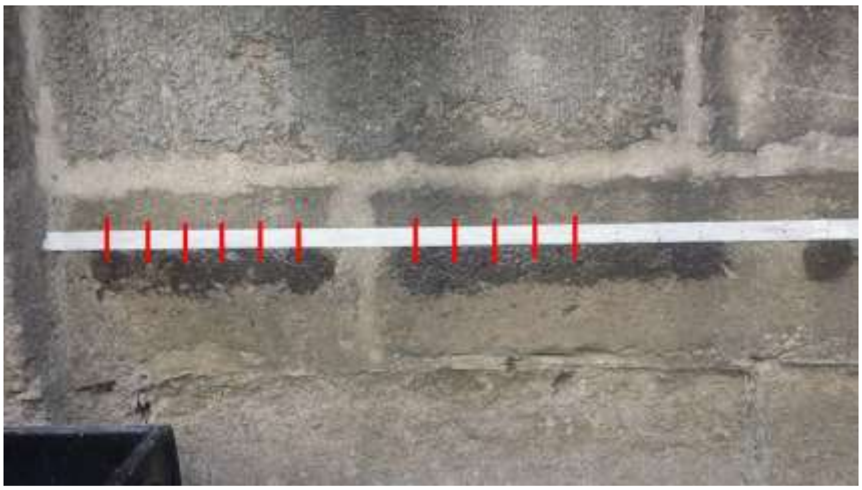

Figure 6. Testing setup for Brick 1 (left) and Brick 2 (right) for indirect transmission method

2.5 Structural Modelling and Analysis

Based from the data of Intramuros Administration and the visual inspection of the Manila Cathedral, it was observed that the structure is generally made of adobe stones with mortar on the interface. However in this study, macro-modelling of the structure was employed for simplicity of the analysis. Therefore, no interface was considered in the model and will be constituted only of one material. Isotropic assumption (i.e., material properties are the same in all direction) was used for the material to further simplify the analysis.

For the purposes of the analysis, material properties of the structure shall be of two cases. One is from the results of *in-situ* testing, in which Young's modulus and compressive strength were acquired. This case only calls for linear static analysis of the structure, i.e. the structure shall be analysed only on the process provided by the provisions of National Structural Code of the Philippines (NSCP) 2010. The second case used the results of laboratory destructive testing of samples, which allows the non-linearity of the material to be utilized in the analysis. Therefore, dynamic analysis of the structure could be obtained from this data by exposing the structure into a certain loading, for example, an earthquake record.

Figure 7 shows the final geometry of the structure generated from SAP2000. It consists of approximately 33000 shell elements with varying thickness, shown in Table 1 below. It is based largely on the floor model of the Manila Cathedral provided by Intramuros Administration. Other data, such as floor and arch thickness are estimated values only. Modelling of the structure utilized center distances; the respective distances between centerlines of structural elements were considered in this study, and therefore deviates slightly to the actual size of the structure. Structural analyses were conducted in the finite-element software SAP2000. Using the parameters acquired from correlation of NDT results, strength-based analysis were conducted, while the results of destructive testing were utilized for the nonlinear modal time-history analysis.

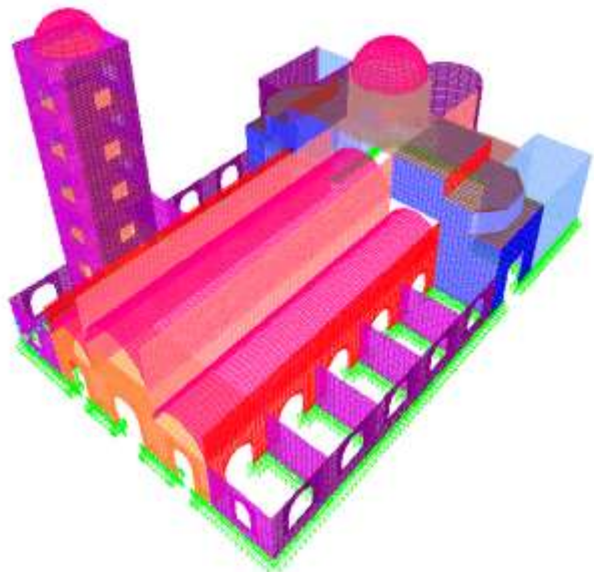

Figure 7. Meshed model of the Manila Cathedral

Table 1.
Thickness Values of Different Structural Elements of the Manila Cathedral

Structural Element	Thickness	Color Legend
External chapel wall	1.3 m	
Collateral nave wall	2.4 m	
Façade	2.4 m	
Choir loft and bell tower floors	1.0 m	
Transept walls	2.3 m	
Dome	1.0 m	
Main altar wall	2.0 m	
Ceiling on the transepts	1.0 m	
Barrel nave ceiling	1.0 m	

Nonlinear dynamic analysis of the structure requires the user to input either simulated loading function for the soil acceleration of the earthquake, or a recorded strong motion acceleration record from an external file. In order to simulate real results, this study utilized the strong motion acceleration (SMA) database of Pacific Earthquake Engineering Research Center (PEER) Next Generation of Ground-Motion Attenuation Models for the Western United States (NGA West) of University of California – Berkeley.

This institution maintains an online accessible database of different earthquake records within the period of 1935 to 2010. After considering the geotechnical data of the location of the Cathedral, its distance from the nearest fault (Marikina fault), and the characteristics of the earthquakes it produces, the 1992 Landers earthquake was chosen to which the model will be subjected to. Figure 8 shows the acceleration record of the said earthquake.

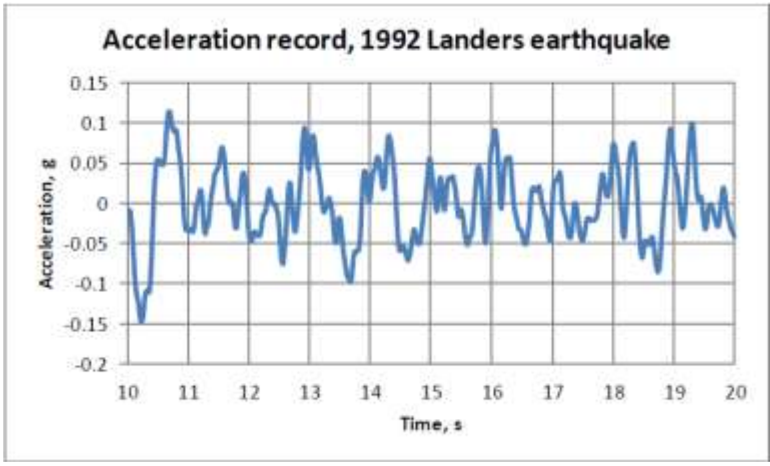

Figure 8. Acceleration record of 1992 Landers earthquake, cut off on the interval t = [10, 20] seconds

III. RESULTS AND DISCUSSION

3.1 Lab Test Results

Originally, a total of six specimens were obtained from the Manila Cathedral, hence the numbering seen and used in documentation. Unfortunately, specimens 2 & 3 were removed because after undergoing destructive testing, the computer accidentally lost power and the data for them were lost. Nevertheless, the four remaining were still used to come up with correlations between the destructive and non-destructive parameters. Figure 9 shows the relationship of the UPV with the UCS and YM of the Manila Cathedral Specimens.

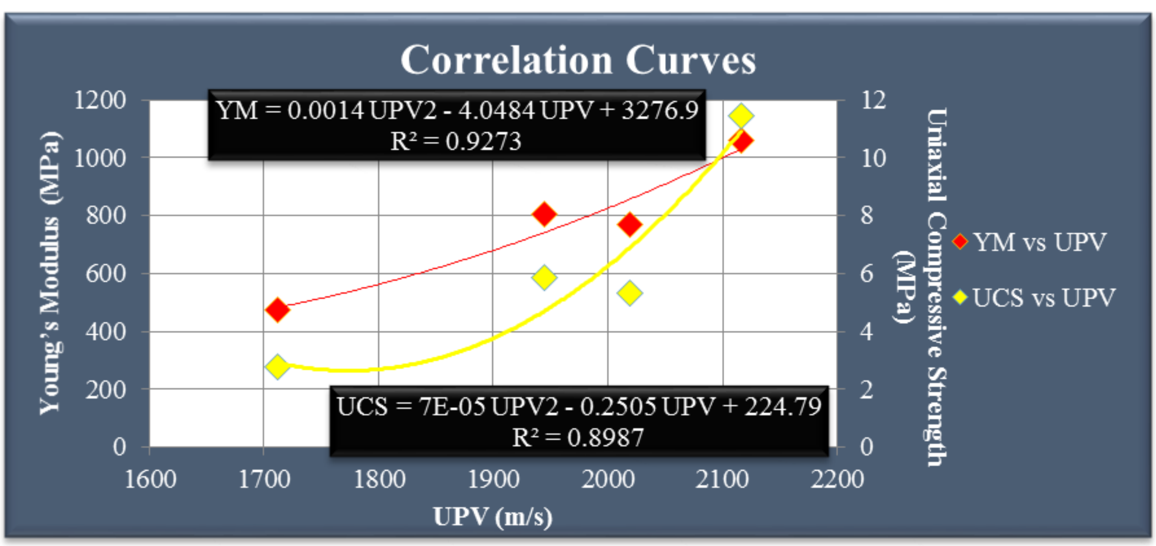

Figure 9. Uniaxial Compressive Strength and Young's Modulus vs. UPV for the Manila Cathedral specimens

Through regression analysis, it was found out that the best fit between UPV and the destructive testing parameters are 2nd degree polynomial relationships. Both cases show very high coefficients of determination (R^2) with values around 0.90. An R^2 value close to unity means that the fit is very good, but caution must be taken because this might be partially due to the limited number of specimens taken. It should also be noted that these equations are obviously empirical and use parameters with respective units (MPa and m/s). These curves, together with the results from the in-situ tests, will be used as basis for the strength based model. As for the non-linear time history analysis, stress-strain diagrams are needed. The results from the laboratory tests of the samples are shown in Figure 10. As observed, sample MC4 provided the highest elastic stress-strain data among the samples, while MC1 has the lowest registered compressive strength. It also shows that the samples tend to consolidate after initial cracking in order to sustain more load.

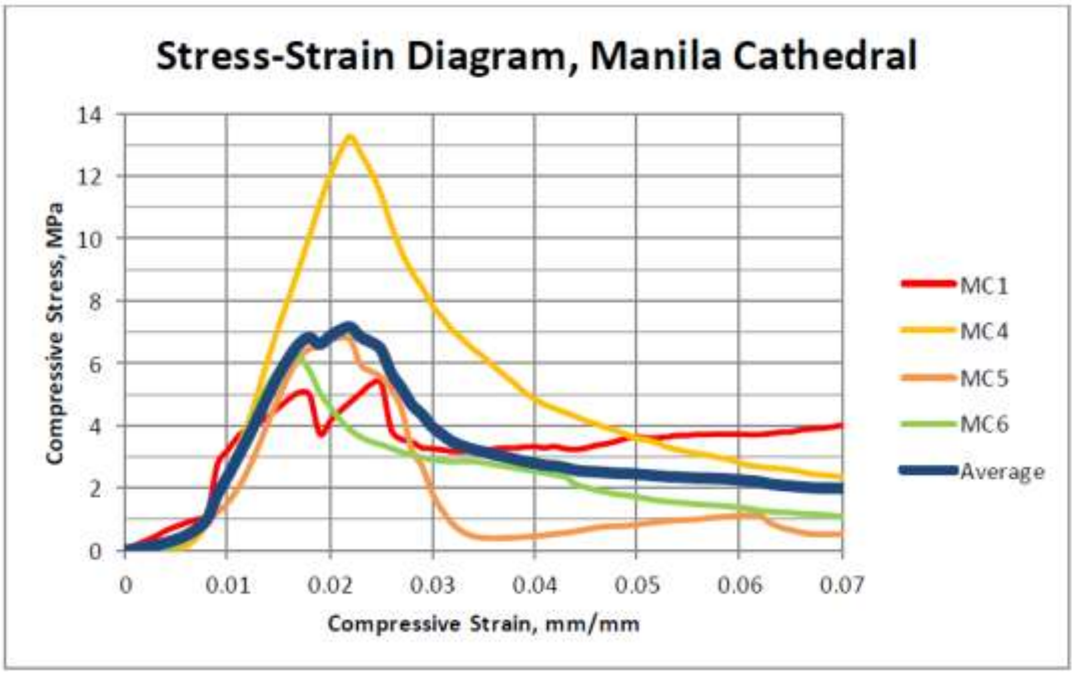

Figure 10. Stress-strain diagram of the Manila Cathedral samples and their average values

To be able to perform the time history analysis, the behavior of the material in tension must also be obtained. Figure 11 shows the modified stress-strain diagram for Manila Cathedral adobe, as stated in [8]. This modification included the tensile behavior of the adobe material. As shown in the figure, the tensile stress of Manila Cathedral adobe is approximately equal to 0.64 MPa (~10 % of its compressive strength), while it reaches tensile failure at approximately 0.05 mm/mm. The blue line was determined from the average values of the different MC samples. This average stress strain diagram was used in modeling the material comprising the structure.

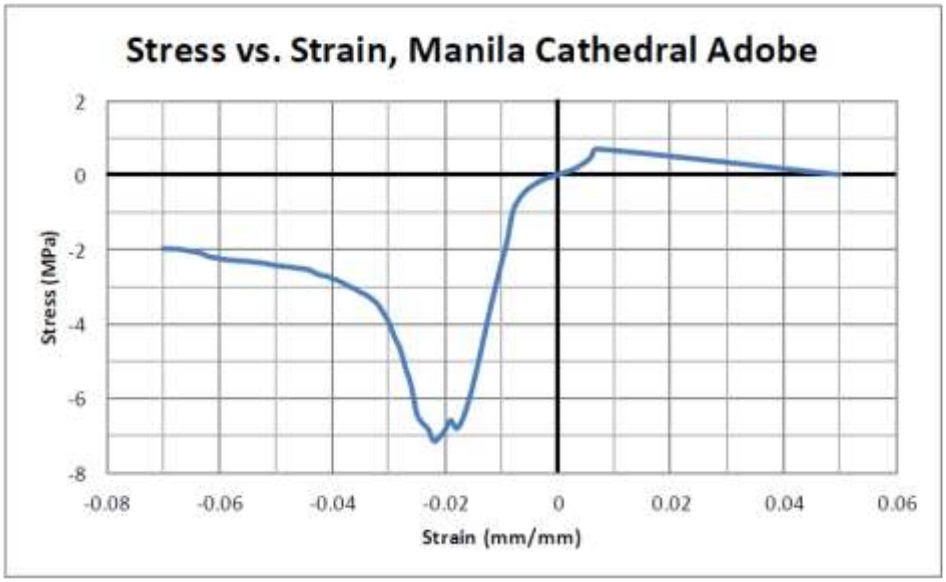

Figure 11. Modified stress-strain diagram of the Manila Cathedral samples

3.2 *In-situ Test Results*

After doing non-destructive *in-situ* testing on the wall of Manila Cathedral, the P-wave velocity transit times, which are already determined by PUNDITLink, were then plotted against the corresponding transducer distances. The slope of the best-fit line corresponds to the ultrasonic pulse velocity (UPV) of that section, assuming that the wall has uniform thickness. Figure 12 shows the measurements taken from bricks 1 and 2 and simultaneously plotted.

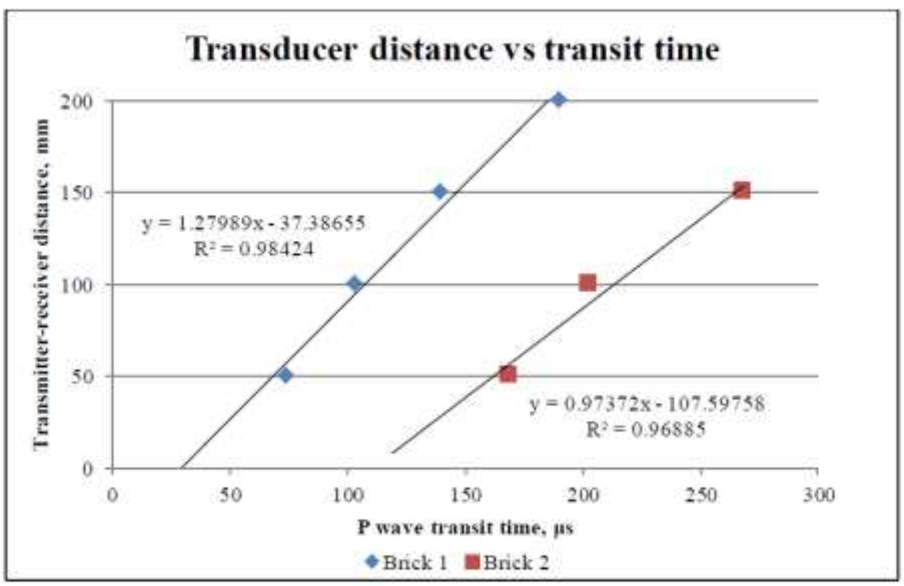

Figure 12. Determination of P-wave transit time (as UPV) in varying transducer distances

3.3 *Elastic Analysis Results*

Since the data available from UPV *in-situ* testing and correlation with laboratory data only involved compressive strength and Young's modulus, this restricted the Manila Cathedral model in

SAP2000 to be simulated using linear static strength-based analysis only. Therefore, the program assumed that it follows linear behavior in both compressive and tensile regions; which means that the behavior of the structure is limited to elastic region only. Among the different earthquake load directions, the combination 1.2 DL + 1.0 Ey (where Ey refers to the earthquake load component along the lateral axis of the structure) resulted in the maximum displacements. This corresponds to earthquake loads along the lateral direction or perpendicular to the longer side of the Cathedral. The maximum resultant displacement of 682 mm occurs at the bell tower of Manila Cathedral. It is also noticeable that aside from the bell tower, the upper parts of the main structure, especially the dome and the central nave barrel ceiling, have larger displacement values compared to the other parts of the structure. These sections can be more critical in assessing the damage in the structure compared to the displacements in the bell tower. Figure 13 shows the displacement contour of the Cathedral under the said loading after elastic analysis.

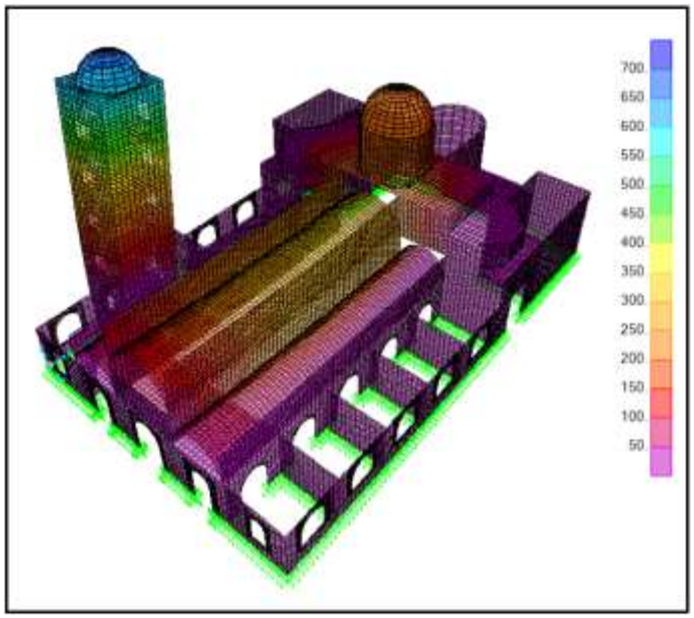

Figure 13. Resultant displacement (in mm) 1.2D + 1.0 Ey (linear elastic analysis)

As for the stresses, Figure 14 shows that most parts of the structure experienced tensile stresses due to earthquake loads. As stated before, the tensile strength of the adobe stones was assumed to be 0.10 times its compressive strength, which could mean that the material enters plastic loading after further increasing the load, until it reaches it ultimate tensile limit. If the average compressive strength of the structure according to UPV results is 33.08 MPa, then the tensile strength of the material at yielding is about 3.31 MPa. Upon inspection of the stress distribution of the whole structure subjected to all load combinations, it can be seen that most parts of the structure always reaches this value, which corresponds to stress contour colors blue-green to blue in Figure 14.

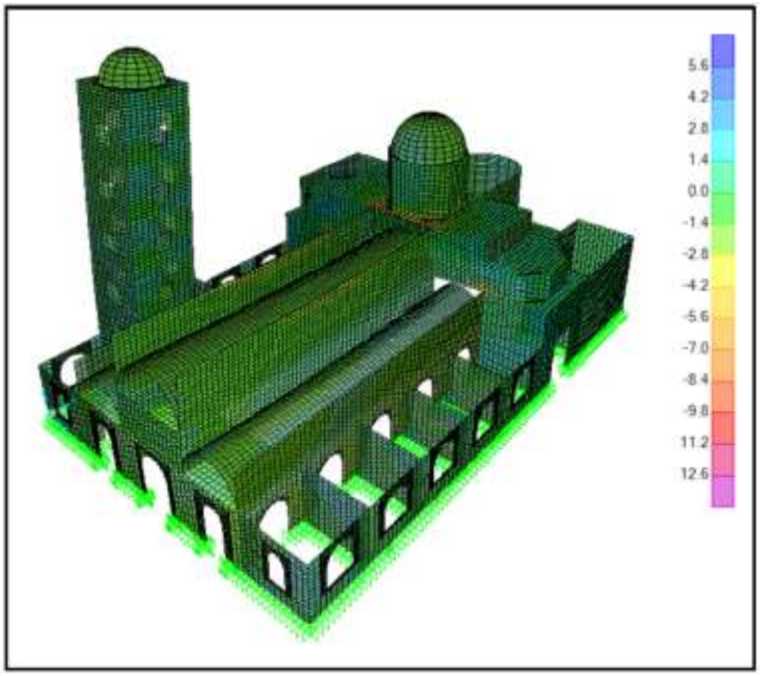

Figure 14. Stress countour (in MPa) 1.2D + 1.0 Ey (linear elastic analysis)

3.4 Time History Analysis Results

Since the data available from UPV *in-situ* testing and correlation curves only allow elastic analysis, the stress strain curves obtained from destructive testing was used to perform the time history analysis. This will allow validation regarding the location of the critical areas along the structure based on their displacement during the selected earthquake. Figure 15 shows the case (earthquake applied along the lateral direction) where the maximum displacement of the bell tower occurs while Figure 15 shows the case (0.7THx + 0.7 Thy) where the maximum overall displacement which happens along the nave.

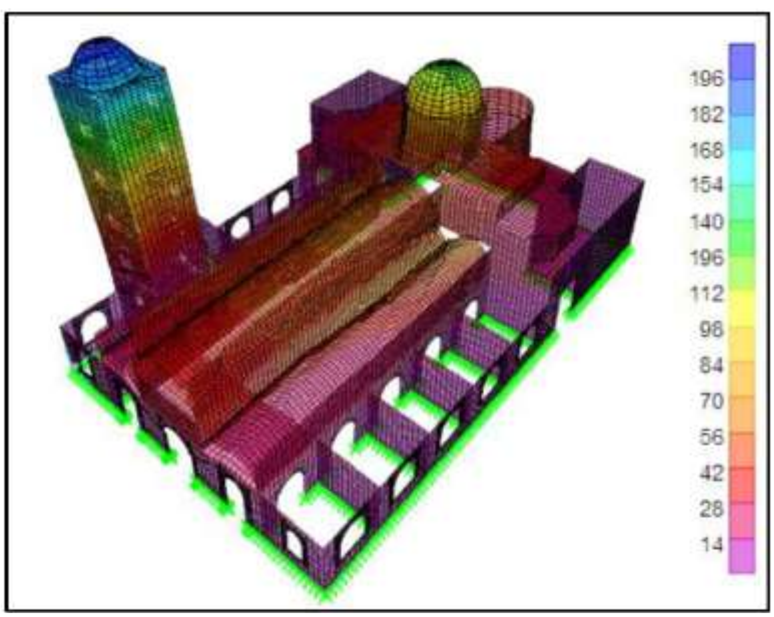

Figure 15. Resultant displacement (in mm) 1.0 THy (time history analysis)

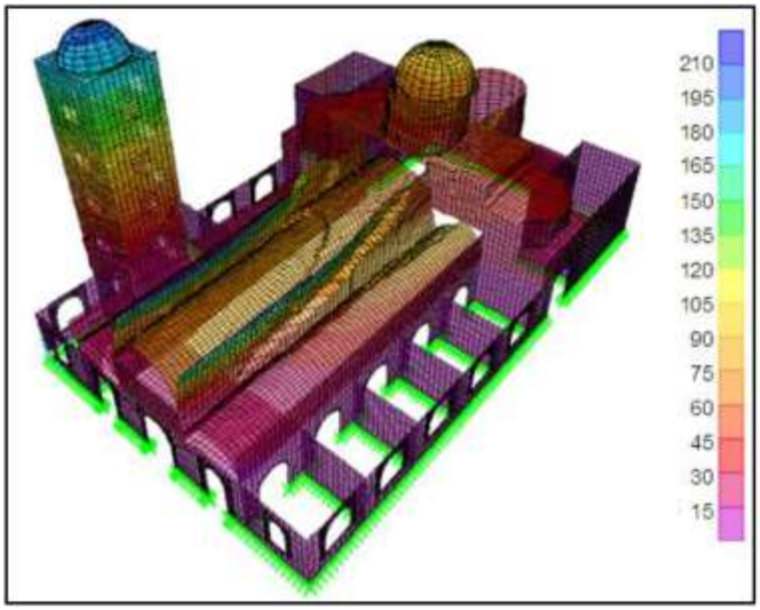

Figure 16. Resultant displacement (in mm) 0.70THx + 0.70THy (time history analysis)

As seen in the displacement envelopes above, all load combinations showed that the areas which experienced the maximum displacements are the same as those with the strength-based analysis: the bell tower, the central dome and the central nave.

IV. CONCLUSION AND RECCOMENDATIONS

In this research, correlations were made to determine the relationships of the non-destructive and destructive test parameters. The regression analyses showed very high coefficient of determination (R^2) values, especially using the UPV parameter. This indicated how effective the ultrasonic pulse velocity, which is the main output of ultrasonic testing, is as a gauge used to determine the mechanical properties of the material. To demonstrate its applicability, a model of the Manila Cathedral was created and tested using mechanical properties directly derived from destructive tests and from correlations with non-destructive parameters. The results show that the behavior of the structure modeled from actual material properties and linear elastic analysis is comparable to the one simulated using time history analysis, in terms of displacement of critical areas of the Manila Cathedral: bell tower, dome and central nave ceiling. Loading along the lateral axis of the structure also produced large displacements on both set of simulations, as shown in Figures 13, 15, and 16. It is recommended that additional samples of the same material be tested and added in the regression to improve its reliability. Additional non-destructive tests may be done to determine the relationship between mechanical properties of materials and other non-destructive parameters, which will further improve the applicability of NDT in heritage structures. As for the structural modeling, it is recommended that further simulation of the structure be made in order to identify the true behavior of the structure (e.g. first major cracks, critical and safe sections, etc.). Lastly, it is suggested that materials from other structures made of different masonry materials found across the country be tested as they will provide a larger scope of understanding and affect the rehabilitation efforts in a much larger sense.

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