Seismic behaviour before and after strengthening of solid confined masonry walls with glass fiber reinforced polymers - analysis of hysteresis curves, obtained by shaking table tests

E Abdulahad and E Mahmud*
Department Reinforced Concrete Structures, Faculty of Structural Engineering, University of Architecture, Civil Engineering and Geodesy (UACEG), 1 Hristo Smirnenski Blvd., Sofia 1046, Bulgaria

* E-mail: dipl.ing.eminmahmud@gmail.com

Abstract. Masonry is one of the oldest building construction methods used by man thousands of years ago, and one of those used today. The masonry buildings look stable and give a sense of security and comfort, leaving a lasting impression of strength. Shaking table tests are planned in order to deepen the understanding of the behaviour of confined masonry structures. This paper presents the observations from a series of shaking table tests done on a 1:1 scale confined masonry wall model without openings. The specimen was tested under constant gravity load and incrementally increasing in-plane loading seismic up to the occurrence of damage. The horizontal load applied is in-plane of the specimen. Then, the seismically damaged specimen was strengthened, using glass fiber reinforced polymers (GFRPs), and tested again. The specimen was strengthened on the surface of two sides. Hysteresis curves before and after with GFRPs wall strengthening are analysed. The tests results indicate that the GFRP system restores and increases the lateral load capacity of strengthened walls. Moreover, GFRP helps to increase the area of hysteresis curves, leading to increased seismic energy dissipation.

1. Introduction
Masonry systems have a wide variety of forms and have been used as structural material for thousands of years. Some very old stone and brick masonry buildings still exist, proving that masonry successfully resists loads and impacts of environment. For their importance and value, many of those building have been classified into mankind’s historical and cultural heritage of highest category. Considering that many of these buildings were built in the past, most of them do not meet the requirements of the Eurocode 8 recommendations and should be properly reinforced. Furthermore, from past earthquakes, it has been observed that the behaviour of the masonry systems under seismic impacts is substantially influenced by the presence and the location of the openings as well.

The main purpose of the research is to determine the behaviour of the masonry walls with different types of openings under seismic/dynamic action and to evaluate innovative retrofitting technique for strengthening existing structures with vulnerable confined masonry structural systems in order to increase their seismic resistance. The experimental program was fully realized in March 2019, within the scientific cooperation between University of Architecture, Civil Engineering and Geodesy
In order to fulfill the purposes of the project three confined masonry walls with the same geometrical and material characteristics but with different configuration of the openings were tested. All specimens were designed and detailed by UACEG, Sofia. The first specimen was designed without opening (CMF), the configuration of the second specimen was with window opening (CMW) whereas the third specimen configuration was with door opening (CMD). The models were built in scale 1:1, in the laboratory of the Institute of Earthquake Engineering and Engineering Seismology. Moreover, the scheme of instrumentation for the models was conceived in a way to get as many as significant and valid experimental results, defining the types of measurement instruments, optimal location and number of measuring points, according to the available capacity of instruments and systems acquisition in the laboratory of IZIIS. The specimens were examined separately on the shaking table, with uniaxial, in-plane excitation following a defined testing methodology consisting of 2 phases - definition of the dynamic characteristics of the specimens and definition of the dynamic behaviour of the specimens under earthquake/dynamic excitation. After the testing, the entire surface of the damaged walls was coated with three-component thixotropic epoxy mortar, whereas the larger cracks were further strengthened with externally glued GFRP (Glass Fiber Reinforced Plastic) plate. The strengthened specimens were tested following the defined testing procedure for the original models, respectively.

This paper presents the observations from a series of shaking table tests done on a 1:1 scale confined masonry wall model without openings. The resulting hysteresis curves from the specimen tests before and after strengthening will be analysed. The remaining results are in the scope of future publications.

2. Description of the specimens and instrumentation set-up

2.1. Description of the specimens
Specimen CMFuS is a masonry wall, scale 1:1, confined with reinforced concrete tie-column, reinforced concrete tie-beam and reinforced concrete foundation. The wall was designed without an opening. The masonry wall is 2.60 m height, with length of 2.80 m and thickness of 25 cm, whereas the dimensions of the confined wall are 2.85 m, 3.30 m and 25 cm, respectively. Geometrical characteristics of specimens CMFuS and CMFS are presented in figure 1. The size of reinforced concrete tie-column and tie-beam are 25x25 cm and the foundation is 400x95x40 cm. The foundation provides 8 holes with a diameter of 50 mm for fixing the specimens to the shake table. The wall was built with materials typical of the Republic of Bulgaria and the region. Detailed information on the specimens can be found in [2]. The strengthened specimen (CMFS) presents the same geometry of the unstrengthened one (CMFuS) – see figure 2. After testing of specimen CMFuS, the entire surface of the damaged walls was coated with a three-component thixotropic epoxy mortar, whereas the larger cracks were further strengthened with the externally glued GFRP (Glass Fiber Reinforced Plastic) plates. The retrofitted specimens were tested following the defined testing procedure for the original models, respectively.

The sequence followed while building the wall was: building the foundation first, then the masonry, and finally the reinforced concrete tie-column and tie-beam. Eurocode 1998 [3] requires that in order to obtain an effective connection between the tie-elements and the masonry, the concrete in the tie-elements must be poured after the masonry has been built. Good bonding between RC tie-columns and a masonry wall can be achieved and by toothing or horizontal reinforcement anchored into tie-columns [4]-[7]. In the implementation of CMWaS, the connection between the RC tie-elements and the masonry is by toothing, and the concrete in the restraining elements is poured after the masonry has been built.
Figure 1. Geometrical characteristics of specimens CMFuS (wall before strengthening).

Figure 2. Geometrical characteristics of specimens CMFS (wall after strengthening).
The implementation of the samples complies with the requirements of Eurocode 6 [8] and Eurocode 8 [3]. The vertical joints are completely filled with mortar. The horizontal and perpendicular joints made of general-purpose masonry mortar are between 6 mm and 15 mm thick.

According to Eurocode 8 [3] the longitudinal reinforcement of confining elements may not have a cross sectional area less than 300 mm$^2$ or 1,00 % of the cross-sectional area of the confining element. The longitudinal reinforcement in the confining element is 4Ø14. Lap splice is 60 bar diameters in length. Stirrups are 8 mm in diameter spaced in 100 and 150 mm are provided around the longitudinal reinforcement. Reinforcing steel is of Class B in accordance with [9].

2.2. Instrumentation Set-up

The specimens’ response was monitored by a high-speed data acquisition system consisting of accelerometers (ACC), linear variable differential transformers (LVDT), linear potentiometers (LP) and strain gages (SG), providing information about accelerations at different levels and points, relative displacements and deformations and strains at selected points. Also, input parameters are obtained from the fixed instruments under the shaking table. The position and the general information for the instruments are given in figure 3 and figure 4. For specimens CMFuS and CMFS, detailed information on the instrumentations can be found in [2].

Figure 3. Instrumentation scheme of specimens CMFuS – (front and back view).

Figure 4. Instrumentation scheme of specimens CMFS – (front and back view).
3. General methodology for testing of the specimens – phases, ground motion and instrumentation

The testing procedure consisted of two main phases. Phase 1: Tests for definition of the dynamic characteristics of the models, in order to check the stiffness degradation of the model produced by the micro or macro cracks developed during the tests – resonant frequency search tests. Phase 2: Seismic testing by a selected earthquake record until heavy damage. The tests were performed in several steps, by increasing the input intensity of the earthquake, (table 1 and table 2), in order to obtain the response in the linear range, as well as to define the initial crack state, the development of the failure mechanism and the possible collapse of the model – seismic response tests. In such a way, the complete seismic performance of the structures starting from the linear range, the appearance of the first cracks in the walls up to the development of the failure mechanisms was captured. The testing has been performed on 5,00x5,00m 5 DOF (Degrees-of-Freedom) MTS seismic shake table at IZIIS Laboratory – figure 5. Detailed information on the shaking table in IZIIS can be found in [9]. Moreover, for simulating the foreseen real load in the exploitation period of a structure, additional load of 5,20 kN/m2 (4x400kg) was placed on the walls (figure 6). Also, in order in-plane excitation to be provided, special system for lateral support of the models was constructed. Detailed information on the specimens can be found in [2].

Figure 5. The shaking table (a) and the relevant hydraulic system (b) at the Dynamic Testing Laboratory at IZIIS, Skopje [10].

Figure 6. Additional load for the walls (technical drawing) and system for lateral support.

3.1. Definition of the dynamic characteristics of the specimens

Determination of dynamic characteristic of the specimens, in-plane, was done using harmonic sine sweep excitation and random excitation, generated by the seismic shaking table. Peak excitation level is around 0,05g. The change in frequency and stiffness of the specimens CMFuS and CMFS are presented in [11]. The values of the measured natural frequencies are given in Table 1 and Table 3.

3.2. Definition of the seismic behaviour of the specimens under earthquake/dynamic excitation

To determine the seismic response of the specimens under earthquake excitation, in-plane, uniaxial tests were performed. As representative real earthquake excitation, El-Centro (Imperial Valley, California, 18 May, 1940) time history record was used. Since the El-Centro time history record has different dominant frequencies compared with the natural frequency of the specimens, it had been frequently scaled with factor 8.0. The tests were conducted by gradually increasing the intensity of the excitation. Because the specimens could not be significantly damaged with the representative earthquake, both with the original and the scaled one, the models were further excited with random and sine sweep excitation in a previously specified frequency range in a correspondence with the natural frequencies for each
model separately. Firstly, random vibrations in defined frequency range were performed, with increase in the intensity of the excitation. Afterwards, sine sweep excitation was carried out with frequency range changed almost in every test, following the decrease in the natural frequency. The intensity of the sine sweep excitations was also progressively raised. Following are the time history records for the representative earthquakes and artificial excitation as well as the Fourier amplitude spectrums of the excitations (figure 7).

![Time history record and Fourier amplitude spectrum](image)

Figure 7. Time history record and Fourier amplitude spectrum.

4. Shaking table tests for seismic behaviour of the specimens
The real nonlinear behaviour of the wall under seismic influences could be established from the experimentally determined hysteresis curves. Under alternating load, the wall gradually reduces its stiffness as cracks form in the masonry (and the tie-columns) depending on the direction of the load. Upon reaching a certain limit deformation in the wall, a significant degradation of the stiffness is observed, which is reflected in a subsequent significant deformation and a decrease in the total bearing capacity of the wall. In order to clarify the nonlinear behaviour of the wall under alternating impact, such as an earthquake, based on the conducted experimental studies and the results obtained for shear force at the base and relative displacement at the top of the wall, the hysteresis curves are drawn.

4.1. Specimen CMFuS – confined masonry wall before strengthening
The specimen was subjected to a sequence of incremental dynamic tests. A series of table motions of increasing intensity were applied with the objective of assessing the ultimate capacity and failure modes of the specimen. On March 6, 2019, a specimen CMFuS was tested at IZIIS-Skopje. A total of 20 tests were performed, of which 7 were to determine the fundamental frequency and the remaining 13 were to investigate seismic behaviour on the wall. Table 1 presents a list of performed tests for specimen CMFuS.
Figure 8 shows the hysteretic base shear-top displacement response of the specimen CMFuS. The base shear has been obtained by summing the product of each accelerometer installed on the specimen time the related mass portion. The proportion between the two axes of all the plots is the same. In this way the eventual progressive specimen stiffness degradation and the consequent fundamental period elongation may be appreciable.

Table 1. List of performed tests for specimen CMFuS.

| Test Number | Name of the test      | Excitation type | Input Frequency range (Hz) | Acceleration | Measured fundamental frequency (Hz) |
|-------------|-----------------------|----------------|---------------------------|--------------|-------------------------------------|
| TuS 01      | Test01_Random_002     | Random         | 1÷50                      | 0.066.g      | /                                   |
| TuS 02      | Test02_Sweep_002      | Sine sweep     | 1÷50                      | 0.030.g      | 24,63                               |
| TuS 03      | Test03_Elcentro_50    | Time history   | /                         | 0.147.g      | /                                   |
| TuS 04      | Test04_Elcentr_100    | Time history   | /                         | 0.340.g      | /                                   |
| TuS 05      | Test05_Elcentro_50_X8| Time history   | /                         | 0.142.g      | /                                   |
| TuS 06      | Test06_Elcentro_200_X8| Time history  | /                         | 0.568.g      | /                                   |
| TuS 07      | Test07_Elcentro_400_X8| Time history | /                         | 1.088.g      | /                                   |
| TuS 08      | Test08_Elcentro_800_X8| Time history  | /                         | 1.739.g      | /                                   |
| TuS 09      | Test09_Random_005     | Random         | 1÷50                      | 0.169.g      | 21,18                               |
| TuS 10      | Test10_Random_015     | Random         | 8÷28                      | 0.537.g      | /                                   |
| TuS 11      | Test11_Random_05      | Random         | 8÷28                      | 1.464.g      | /                                   |
| TuS 12      | Test12_Random_09      | Random         | 8÷28                      | 2.274.g      | /                                   |
| TuS 13      | Test13_Sweep_005      | Sine sweep     | 1÷50                      | 0.062.g      | 18,89                               |
| TuS 14      | Test14_Sweep_03       | Sine sweep     | 15÷22                     | 0.331.g      | /                                   |
| TuS 15      | Test15_Sweep_100      | Sine sweep     | 14÷20                     | 1.089.g      | /                                   |
| TuS 16      | Test16_Sweep_005      | Sine sweep     | 1÷50                      | 0.062.g      | 12,99                               |
| TuS 17      | Test17_Sweep_100_8-16| Sine sweep     | 8÷16                      | 1.247.g      | /                                   |
| TuS 18      | Test18_Sweep_005      | Sine sweep     | 1÷50                      | 0.061.g      | 11,65                               |
| TuS 19      | Test19_Sweep_03_5-12  | Sine sweep     | 5÷12                      | 0.388.g      | /                                   |
| TuS 20      | Test20_Sweep_005      | Sine sweep     | 1÷50                      | 0.062.g      | 10,60                               |

The hysteretic base shear-top displacement response of the specimen CMFuS immediately before and after the formation of significant damage is presented in figure 9. It very well illustrates the significant degradation of stiffness, which is reflected in the subsequent significant displacement as a result of damage to the specimen. The hysteresis curve before the damage is marked in red and in purple after the damage. Both hysteresis curves are from Test17 with an acceleration of 1,247g (table 2). The maximum shear force before damage is 185.81kN (point A) and -178.35kN (point B) with the corresponding top-displacements -1.92mm and 1.70mm. The maximum shear force after damage is reduced to 102.91kN (point E) and -139.59kN (point F), and top-displacements are increased to -1.86mm and 2.15mm, respectively. The ratio between the maximum shear force at the base before and after damage is from 1.28 (at negative values) to 1.81 (at positive values). The maximum horizontal top-displacement before damage is -2.96mm (point C) and 2.85 mm (point D) with corresponding forces of 80.02kN and -77.06kN. The maximum horizontal top-displacement after damage increases to -4.23mm (point G) and -4.14mm (point H), and the forces decrease to 30.78kN and -13.77kN, respectively. The maximum horizontal top-displacement after the damage compared to before the damage increases between 1.43 times (at negative values) and 1.45 times (at positive values).
Figure 8. Hysteretic curve – specimen CMFuS (confined masonry wall before strengthening).

Table 2. Characteristic points in the hysteresis curve – CMFuS: Test17.

| Point | Base shear force, [kN] | Top displacement, [mm] |
|-------|------------------------|------------------------|
| A     | 185.91                 | -1.92                  |
| B     | -178.35                | 1.70                   |
| C     | 80.02                  | -2.96                  |
| D     | -77.06                 | 2.85                   |
| E     | 102.91                 | -1.86                  |
| F     | -139.59                | 2.15                   |
| G     | 30.78                  | -4.23                  |
| H     | -13.77                 | 4.14                   |

Figure 9. Hysteretic curve – CMFuS: Test17.
4.2. Specimen CMFS – confined masonry wall after strengthening

The specimen was subjected to a sequence of incremental dynamic tests. A series of table motions of increasing intensity were applied with the objective of assessing the effect of strengthening, the ultimate capacity and failure modes of the specimen. On March 26, 2019, a specimen CMFS was tested at IZIIS-Skopje. A total of 12 tests were performed, of which 7 were to determine the fundamental frequency and the remaining 5 were to investigate seismic behaviour on the wall. Table 3 presents a list of performed tests for specimen CMFS.

| Test Number | Name of the test                  | Excitation type | Input Frequency range (Hz) | Acceleration | Measured fundamental frequency (Hz) |
|-------------|-----------------------------------|-----------------|-----------------------------|--------------|------------------------------------|
| TS 01       | Test01_Random_005                 | Random          | 1÷50                        | 0,191 g      | 19.78                              |
| TS 02       | Test02_Sweep_005                  | Sine sweep      | 1÷50                        | 0.063 g      | /                                  |
| TS 03       | Test03_Random_005                 | Random          | 1÷50                        | 0.175 g      | /                                  |
| TS 04       | Test04_Random_005                 | Random          | 1÷50                        | 0.117 g      | /                                  |
| TS 05       | Test05_Elcentro_100               | Time history    | /                           | 0.333 g      | /                                  |
| TS 06       | Test06_Elcentro_400_X8            | Time history    | /                           | 1.007 g      | /                                  |
| TS 07       | Test07_Elcentro_800_X8            | Time history    | /                           | 1.733 g      | /                                  |
| TS 08       | Test08_Random_005                 | Random          | 1÷50                        | 0.142 g      | 18.44                              |
| TS 09       | Test09_Random_09                  | Random          | 12÷22                       | 2.058 g      | /                                  |
| TS 10       | Test10_Sweep_005                  | Sine sweep      | 1÷50                        | 0.063 g      | 13.91                              |
| TS 11       | Test11_Sweep_1g                   | Sine sweep      | 10÷16                       | 1.179 g      | /                                  |
| TS 12       | Test12_Sweep_005                  | Sine sweep      | 1÷50                        | 0.063 g      | 12.48                              |

Figure 10 shows the hysteretic base shear-top displacement response of the specimen CMFS. The base shear has been obtained by summing the product of each accelerometer installed on the specimen time the related mass portion. The proportion between the two axes of all the plots is the same. In this way the eventual progressive specimen stiffness degradation and the consequent fundamental period elongation may be appreciable.

Figure 10. Hysteretic curve – specimen CMFS (confined masonry wall after strengthening).
Figure 11 shows the hysteretic base shear-top displacement response of the specimens CMFuS and CMFS. The proportion between the two axes of all the plots is the same. The hysteresis curve before strengthening is marked in red and in green after the strengthening.

![Hysteretic curve - specimen CMFuS and specimen CMFS](image)

5. Conclusions

The dependence between base shear force and horizontal top-displacement was obtained experimentally. The hysteresis curves are obtained, and their area is a measure of the energy dissipated by the structure. The hysteresis curves were obtained before and after strengthening of the specimen with glass fiber reinforced polymers (GFRPs). According to the understandings in [3] of two constructions, the one that dissipates more energy is better protected from earthquakes. Figure 11 shows a comparison of the hysteresis curves obtained before and after strengthening of the specimen. The tests results indicate that the GFRP system restores and increases the lateral load capacity of strengthened walls. Moreover, GFRP helps to increase the area of hysteresis curves, leading to increased seismic
energy dissipation. In the specimen CMFS, which was tested after strengthening, the dissipated energy is about 1.80 times higher than in the specimen CMFuS before strengthening. This is obvious with increasing dimensions of the curves. Dissipated energy is due to the development of inelastic deformations. The use of externally bonded GFRPs materials exhibit considerable potential as an alternative solution to traditional strengthening techniques.

The strengthening also contributes to increased energy dissipation in specimens with an opening (CMWuS, CMWS, CMDuS and CMDS). Further on, the investigations of walls with openings are ongoing and will be presented in other future publications.

Acknowledgments
This research project under contract D-111/2018 was supported financially by the Centre for Research and Design at the University of Architecture, Civil Engineering and Geodesy (UACEG) (www.uacg.bg). The authors would like to express their deepest appreciation to the staff of the Centre for Research and Design.

The authors would like to express their deep gratitude and appreciation to the team of the following companies for their support for the successful implementation of the experiments: A&K Engineering Ltd. (www.akengeneering.org), Isomat International Ltd. (www.isomat.bg), Baumit Bulgaria Ltd. (www.baumit.bg), Shpici stroi Ltd. (www.shpici-stroi.com), Arcon Construction Ltd. (www.arcon.com.mk), and Emil Kroumov & Co. Ltd. (www.kroumov.com).

The authors would also like to thank all participants who contributed to the realization of the experimental tests and to the staff of the Dynamic Testing Laboratory at IZIIS, Skopje (www.iziis.uzim.edu.mk).

The authors express their heartfelt gratitude to all participants who contributed to the implementation of the experimental research.

References
[1] Krstevska L and Poposka A 2019 Shake table test of masonry wall specimens in scale 1:1 - IZIIS – REPORT 2019-34 IZIIS - Dynlab, Skopje.
[2] Abdulahad E and Mahmud E 2019 Implementation of Samples and Preparatory Activities before Dynamic Tests Annual of the University of Architecture, Civil Engineering and Geodesy, vol. 52, no. 3, pp. 891–900, Sofia, Bulgaria.
[3] Eurocode 8: Design of structures for earthquake resistance, European Committee for Standardization, 2005.
[4] Brzev S and Meli R 2012 International Guideline for Seismic Design of Low-Rise Confined Masonry Buildings in Regions of High Seismic Risk The 15th World Conference on Earthquake Engineering (15WCEE), Lisbon, Portugal.
[5] Jain S, Brzev S, Bhargava L, Basu D, Ghosh I, Rai D and Ghaisas K 2015 Confined Masonry for Residential Buildings. Gandhinagar: Indian Institute of Technology.
[6] Singhal V and Rai D 2014 Seismic Behavior of Confined Masonry Walls When Subjected to In-Plane and Out-of-Plane Loading Tenth U.S. National Conference on Earthquake Engineering. Anchorage, Alaska.
[7] Singhal V and Rai D 2014 Role of Toothing on In-Plane and Out-of-Plane Behavior of Confined Masonry Walls Journal of Structural Engineering.
[8] Eurocode 6: Design of masonry structures, European Committee for Standardization, 2005.
[9] Eurocode 2: Design of concrete structures, European Committee for Standardization, 2005.
[10] Corbi I and Rakicevic Z 2013 Shaking Table Testing for Structural Analysis International Journal of Mechanics, vol. 7, no. 4, pp. 459–466.
[11] Mahmud E and Abdulahad E 2020 Shaking table tests for investigation of the change of fundamental frequency and stiffness before and after strengthening of a confined masonry Annual of the University of Architecture, Civil Engineering and Geodesy, vol. 53, no. 3, Sofia, Bulgaria.