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The Influence of Strengthening on the Fundamental Frequency and Stiffness of a Confined Masonry Wall with an Opening for a Door

Emin Z. Mahmud

Abstract**—**This paper presents the observations from a series of shaking-table tests done on a 1:1 scaled confined masonry wall model, with opening for a door – specimens CMDuS (confined masonry wall with opening for a door before strengthening) and CMDS (confined masonry wall with opening for a door after strengthening). Frequency and stiffness changes before and after GFRP (Glass Fiber Reinforced Plastic) wall strengthening are analyzed. Definition of dynamic properties of the models was the first step of the experimental testing, which enabled acquiring important information about the achieved stiffness (natural frequencies) of the model. The natural frequency was defined in the Y direction of the model by applying resonant frequency search tests. It is important to mention that both specimens CMDuS and CMDS are subjected to the same effects. The tests are realized in the laboratory of the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Skopje. The specimens were examined separately on the shaking table, with uniaxial, in-plane excitation. After testing, samples were strengthened with GFRP and re-tested. The initial frequency of the undamaged model CMDuS is 13.55 Hz, while at the end of the testing, the frequency decreased to 6.38 Hz. This emphasizes the reduction of the initial stiffness of the model due to damage, especially in the masonry and tie-beam to tie-column connection. After strengthening of the damaged wall, the natural frequency increases to 10.89 Hz. This highlights the beneficial effect of the strengthening. After completion of dynamic testing at CMDS, the natural frequency is reduced to 6.66 Hz.

Keywords**—**Behavior of masonry structures, Eurocode, fundamental frequency, masonry, shaking table test, strengthening.

I. 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. Due to their importance and value, many of these buildings are classified in the historical and cultural heritage of mankind of the highest category. Given 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. The behaviour of the masonry systems under seismic impacts is substantially influenced by the presence and the location of the openings as well.

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The main purpose of the research is to determine the behavior 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 (UACEG) – Sofia, Republic of Bulgaria and University "Ss. Cyril and Methodius" IZIIS, Skopje, Republic of North Macedonia [1].

In order to fulfil 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 - confined masonry wall without opening), the configuration of the second specimen was with window opening (CMW - confined masonry wall with opening for a window) whereas the third specimen configuration was with door opening (CMD - confined masonry wall with opening for a door). The models were built in scale 1:1, in the laboratory of the IZIIS. 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 behavior 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 plate. The strengthened specimens were tested following the defined testing procedure for the original models, respectively.

The change in frequency and stiffness of the specimens CMFuS and CMF are presented in [2], and for the specimens CMWuS and CMWS are presented in [3].

II. Definition of the Dynamic Characteristics of the Specimens

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, (Tables I and II), 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 5.00 x 5.00 m 5 DOF (Degrees-of-Freedom) MTS seismic shake table at IZIIS Laboratory. Detailed information on the shaking table in IZIIS can be found in [4]. Moreover, for simulating the foreseen real load in the exploitation period of a structure, additional load of 5.20 kN/m^2 (4x400 kg) was placed on the walls. Also, in order in-plane excitation to be provided, special system for lateral support of the models was constructed.

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. The harmonic (sine sweep) motions were performed with in-plane, uniaxial excitation, before testing of the model (initial state), after certain tests and after all performed tests (final state). The assumption that the test structure behaves linearly is essential to attaining accurate FRF measurement.

The experimental determination of the natural frequency of an element/structure is of particular importance in view of their trouble-free serviceability. The fundamental frequency is determined by applying the principles of structural dynamics. All aspects involved in the successful measurement of the frequency response function described in [5], [6] have been observed.

Resonant frequency search tests with the following characteristics were performed: random tests – horizontal, in plane, with frequency range 1÷50 Hz and peak excitation level 0.02g÷0.05g and sine sweep tests – horizontal, in plane, with frequency range 1÷50 Hz, peak excitation level 0.02 g÷0.05 g and sweep rate 2,00 octave/min.

III. Description of the Specimen

Specimen CMDuS is a masonry wall, scale 1:1, confined with reinforced concrete tie-column, reinforced concrete tie-beam and reinforced concrete foundation. The wall has a door opening measuring 94x202 cm. 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 (Fig. 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 [7].

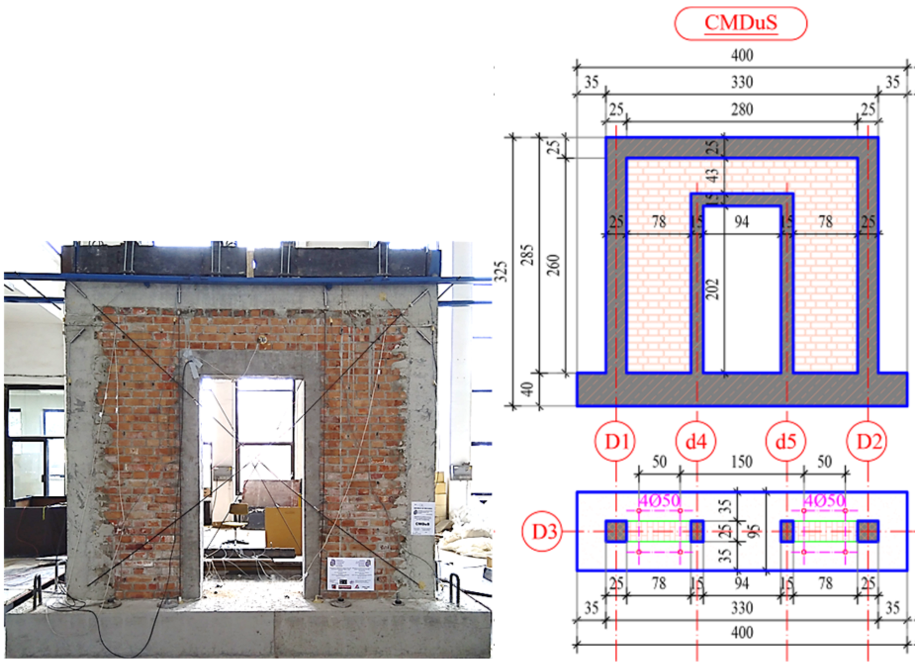

Fig. 1 Geometrical characteristics of specimens CMDuS

The strengthened model (CMDS) presents the same geometry of the unstrengthened one (CMDuS), see Fig. 2. After testing of specimen CMDuS, 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 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 [8] 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 [9]-[12]. In the implementation of CMDuS, 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.

The implementation of the samples complies with the requirements of Eurocode 6 [13] and Eurocode 8 [8]. 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 [8] the longitudinal reinforcement of confining elements may not have a cross sectional area less than 300 mm^2 or 1 % 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 [14].

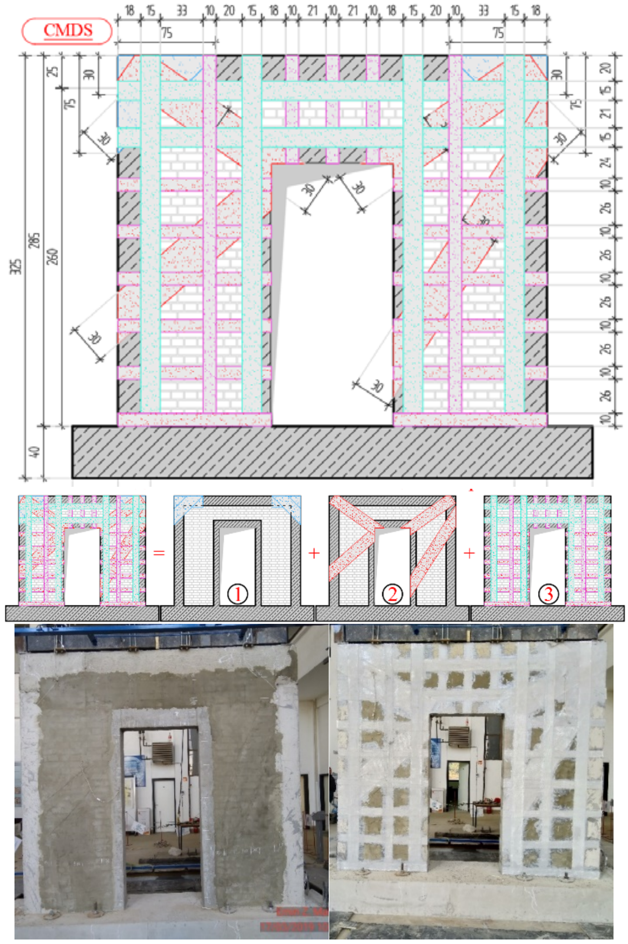

Fig. 2 Specimen CMDS

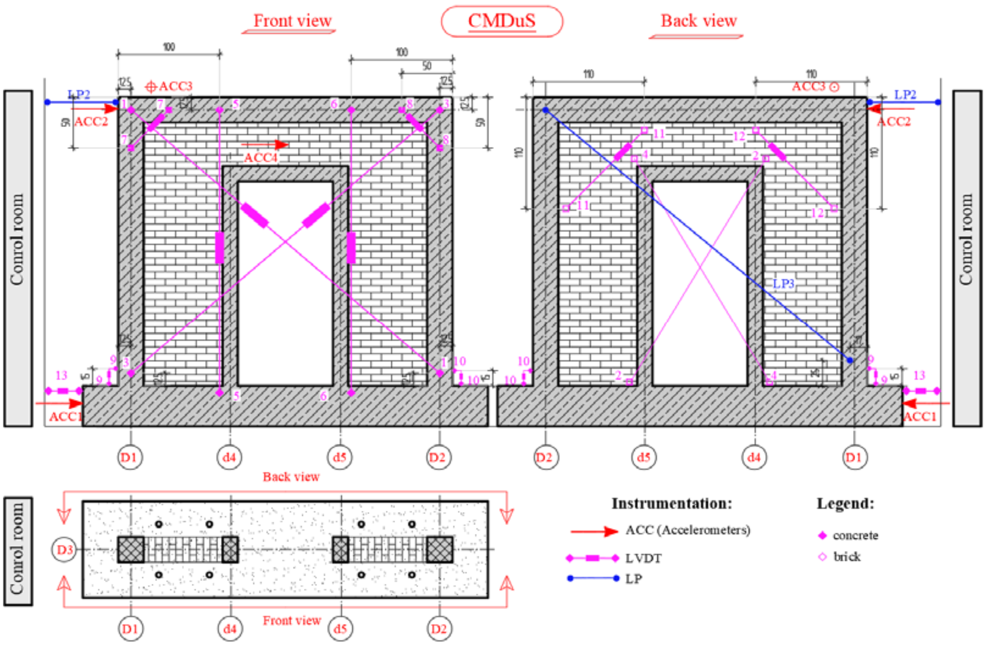

Fig. 3 Instrumentation scheme of specimens CMDuS – technical drawing (front and back view)

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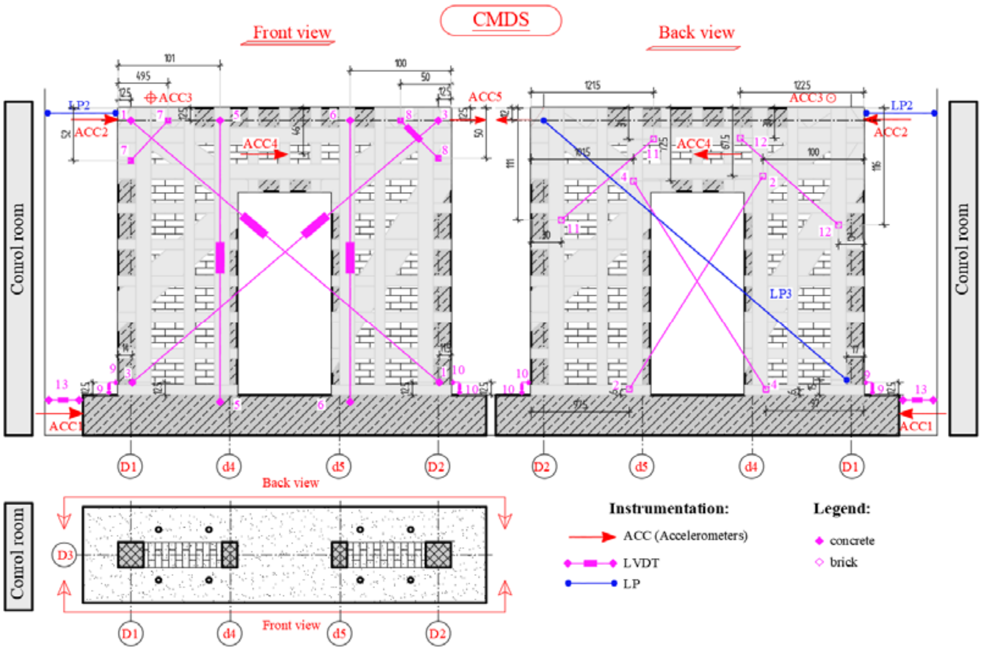

Fig. 4 Instrumentation scheme of specimens CMDS – technical drawing (front and back view)

IV. Instrumentation Set-Up

The model response was monitored by a high-speed data acquisition system consisting of 4 accelerometers (ACC), 13 linear variable differential transformers (LVDT), 2 linear potentiometers (LP) and 12 strain gages (SG), providing information about relative displacements and deformations and strains at selected points and accelerations at different levels and 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 Figs. 3 and 4. Detailed information on the instrumentation can be found in [7].

V. Frequency and Stiffness before and after Strengthening of a Confined Masonry Wall with Opening for Door

A. Specimen CMDuS – before Strengthening

TABLE I
List of Tests for the Specimen CMDuS

№	Tests	Excitation type	Frequency Range [Hz]	Input acc. [g]	Output acc. [g]
1	Random_002	RE	1÷50	0,185.g	0,186.g
2	Sweep_005	SS	1÷50	0,049.g	0,063.g
3	Elcentro_Xz_100	TH	–	0,350.g	0,341.g
4	Elcentro_Xz_400x8	TH	–	1,362.g	0,844.g
5	Elcentro_Xz_800x8	TH	–	2,722.g	1,526.g
6	Sweep_005	SS	1÷50	0,049.g	0,061.g
7	Random_05	RE	6÷15	1,986.g	1,662.g
*8**	Random_09	RE	6÷15	–	–
9	Random_09	RE	6÷15	3,103.g	2,355.g
10	Sweep_005	SS	1÷50	0,029.g	0,041.g

*The duration of the test is about 2 seconds. The test was stopped for technical reasons. No results were obtained from this test.

On March 15, 2019, a specimen CMDuS was tested at IZIIS-Skopje. A total of 10 tests were performed, of which 4 were to determine the fundamental frequency and the remaining + were to investigate seismic behavior on the wall. Table I presents a list of performed tests for specimen CMDuS.

Definition of the dynamic properties of specimen CMDuS was the first step of the experimental testing. The natural frequency is determined in the Y direction (Fig. 5). The frequencies obtained before testing of the model (initial state, Test02), after certain tests and after all performed tests (final state Test10) of the specimen CMDuS are presented in Fig. 6.

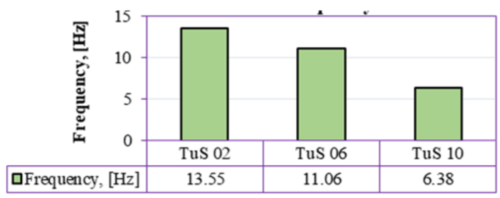

Fig. 5 The first natural frequency: CMDuS

As the damage/cracks in the sample increase with increasing number of tests, the natural frequency begins to gradually decrease. The change in the natural frequency is due to the degradation of the stiffness of the specimen and the damages obtained therein. The first fundamental initial frequency before the start of dynamic testing is 13.55 Hz as determined by Test02. The change in the stiffness of the specimen CMDuS is presented in Fig. 7. Following the completion of the dynamic tests using the El-Centro earthquake acceleration (unscaled and scaled) whereby the PGA reaches 1.526 g, the fundamental frequency drops to

11.06 Hz as determined by Test06. The frequency decreased by 18% compared to the initial frequency. Current stiffness represents 67% of the initial stiffness Ko of specimen CMDuS. After completing a series of three tests using random excitation when the PGA reaches 2.355 g, the frequency drops to 6.38 Hz as determined by Test10. The frequency decreased by 43% by the frequency determined at Test06. After completing all 6-dynamic specimen CMDuS tests, the final frequency is 6.38 Hz. The frequency decreased by 2.33 times compared to the initial frequency. Stiffness is reduced by 67% from the stiffness determined in Test10 and represents 22% of the initial stiffness Ko on specimen CMDuS, see Fig. 7.

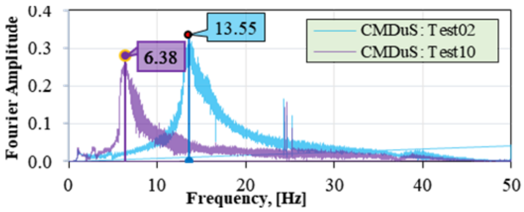

Fig. 6 Fourier amplitude spectrum for Test02 and Test10 of the specimen CMDuS

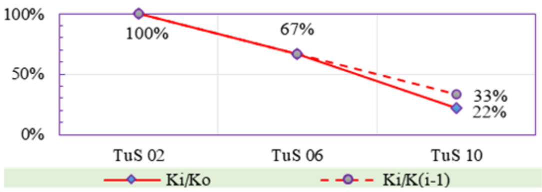

Fig. 7 Stiffness – CMDuS

B. Specimen CMDS – Wall after Strengthening

On March 20, 2019, a specimen CMDS was tested at IZIIS-Skopje. A total of 14 tests were performed, of which 7 were to determine the fundamental frequency and the remaining 7 were to investigate seismic behavior on the wall. Table II presents a list of performed tests for specimen CMDS.

TABLE II
LIST OF TESTS FOR THE SPECIMEN CMDS

№	Tests	Excitation type	Frequency Range [Hz]	Input acc. [g]	Output acc. [g]
1	Random_005	RE	1÷50	0,194.g	0,186.g
2	Sweep_005	SS	1÷50	0,049.g	0,061.g
3	Elcentro_Xz_100	TH	–	0,350.g	0,342.g
4	Elcentro_Xz_400x8	TH	–	1,361.g	0,919.g
5	Elcentro_Xz_800x8	TH	–	2,719.g	1,610.g
6	Sweep_005	SS	1÷50	0,049.g	0,076.g
7	Random_05	RE	4÷12	2,183.g	1,931.g
8	Sweep_005	SS	1÷50	0,049.g	0,061.g
9	Random_09	RE	4÷12	3,060.g	2,385.g
10	Sweep_005	SS	1÷50	0,049.g	0,061.g
11*	Sweep_03	SS	4÷10	–	–
12*	Sweep_005	SS	1÷50	–	–
13*	Sweep_05	RE	4÷10	–	–
14*	Sweep_005	SS	1÷50	–	–

*the results of these tests are of no scientific interest.

As the damage/cracks in the sample increase with increasing number of tests, the natural frequency begins to gradually decrease. The change in the natural frequency is due to the degradation of the stiffness of the specimen and the damages obtained therein. The first fundamental initial frequency before the start of dynamic testing is 10.89 Hz as determined by Test02i Figs. 8 and 9. The change in the stiffness of the specimen CMDS is presented in Fig. 10. The determination of the initial frequency is to obtain information to what extent the stiffness of the unstrengthening specimen CMDS tested after its testing has been restored. Following the completion of the dynamic tests using the El-Centro earthquake acceleration (unscaled and scaled) whereby the PGA reaches 1.610 g, the fundamental frequency drops to 8.09 Hz as determined by Test06. The frequency decreased by 26% compared to the initial frequency. Current stiffness represents 55% of the initial stiffness Ko of specimen CMDS. After completing of another test using random excitation when the PGA reaches 1.931 g, the frequency drops to 6.71 Hz as determined by Test08. For an additional decrease in frequency by 17% compared to the frequency determined at Test06 and 1.62 times compared to the initial frequency. Stiffness is reduced by 31% from the stiffness determined in Test06 and represents 38% of the initial stiffness Ko on specimen CMDS. After completion of another test using random excitation, with a PGA of 2.385g, the frequency drops to 6.66 Hz as determined by Test10. The frequency decreased by 1% by the frequency determined at Test08. After completing all 5-dynamic specimen CMDS tests, the final frequency is 6.66Hz. The frequency decreased by 1.64 times compared to the initial frequency. Stiffness is reduced by 1% from the stiffness determined in Test08 and represents 37% of the initial stiffness Ko on specimen CMDS – see Fig. 10.

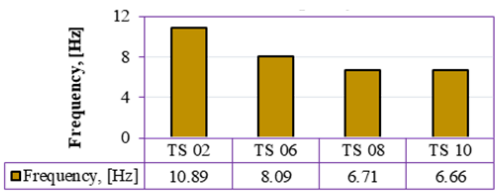

Fig. 8 The first natural frequency: CMDS

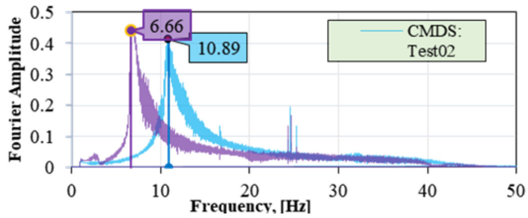

Fig. 9 Fourier amplitude spectrum for Test02 and Test10 of the specimen CMDS

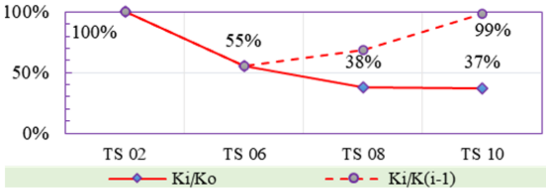

Fig. 10 Stiffness – CMDS

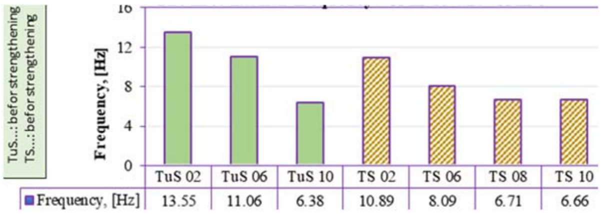

Fig. 11 The first natural frequency: CMDuS and CMDS

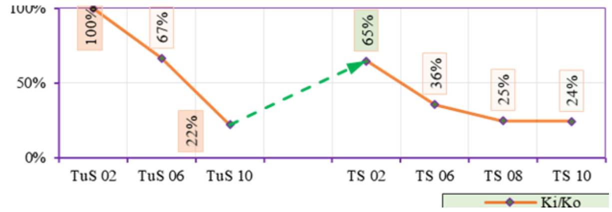

Fig. 12 Change in stiffness from initial stiffness: CMDuS and CMDS

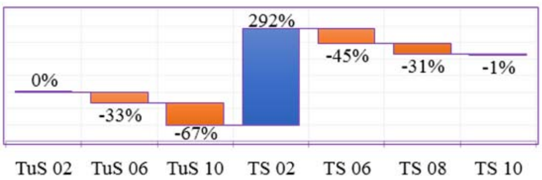

Fig. 13 Percentage change in stiffness from previous test - CMDuS and CMDS

VI. Conclusions

This paper discusses the results of the shaking table tests of a masonry wall with opening for door, before and after strengthening. The methodology used for analyzing the results is first presented, followed by the discussion on the results obtained in the dynamic identification tests. The dynamic identification tests aim at estimating the dynamic properties, namely the frequencies.

The specimens were examined on the shaking table following a defined testing methodology. After testing, 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 plates. The retrofitted specimens were tested following the defined testing procedure for the original models, respectively.

The variation of the first wall frequency is shown graphically in Fig. 11, and Fig. 12 shows the change in stiffness. The following results can be summarized. The initial frequency of the unstrengthening wall is 13.55 Hz and after the realized tests it is reduced to 6.38 Hz, i.e. the degradation is 2.12 times. As a result of the strengthening, the first frequency of the wall increases by 1.70 times and reaches 10.89 Hz. The frequency after completion of the wall CMDS test is 6.66 Hz. Substantial degradation is observed after dynamic tests in the stiffness of the wall. After completion of the tests, the stiffness of the unstrengthened wall is 22% of the initial stiffness. As a result of the strengthening, the stiffness of the wall increases by 2.62 times (Fig. 13), so that the stiffness after strengthened represents 65% of the initial stiffness of the wall CMDuS. Stiffness after completion of the strengthening wall tests represents 37% of the initial stiffness of the wall CMDuS.

The chosen strengthening system allows the wall stiffness to be restored to 65%, which indicates the beneficial effect of strengthening.

The seismic behavior (accelerations, base shear force, displacements, hysteresis curve, damage, etc.) of the specimens CMDuS and CMDS under earthquake will be presented in other publications.

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