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Behavior of RC frame structures with added floors made of different materials subjected to seismic loadings

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Abstract

With the increase of the population in densely populated areas, the lack of living space leads to an increase of need for upgrades to existing buildings. The problem related to upgrades is of greater importance in seismically active areas, especially in older buildings designed according to old codes. Depending on the type of upgrade, it may affect the existing structure differently, but on the other hand, the existing structure affects the upgrade as well. In the paper first a short review of achievements in the world regarding this problem has been discussed and then the activities conducted in IZIIS related to the investigation of the influence of different material upgrade systems on the integral structural behaviour have been briefly described. This comparative investigation has been performed by conducting a total of 177 dynamic tests on the 5x5 m shaking-table at the IZIIS Laboratory, using harmonics, synthetic and real earthquake records as input in one horizontal direction. Elastic tests with low level of excitation without occurrence of damages and plastic deformations have been conducted first and then capacity tests have been performed up to the failure of the models. The various upgrade systems were constructed of steel frame, light- frame timber, cross-laminated wooden panels and composite systems of wood and glass. The first two floors represented the existing reinforced concrete, and the third floor was the upgrade system which was changed during all the tests. The main purpose of the investigation was to investigate the behavior of this kind of upgrades systems subjected to seismic loadings and their applicability in seismic prone areas. Important output regarding the National annex parameters needed for Eurocode design has been also expected from this investigation. This investigation will be realized within the frame of a part of the doctoral thesis that is to be proposed.

Key words: Added floors, cross-laminated timber, light timber frame, shaking-table tests, FEM analysis

1 Introduction

Adding new floors involves additional loads on the old structure and the soil, but of course more important is the problem of increasing mass which also causes an increase in seismic force. Therefore, the problem with floor upgrades is greater in seismically active areas, especially in older buildings that are designed according to old regulations. On the other hand, depending on the type of upgrade, it may affect the existing structure differently, but on the other hand it should not be forgotten that the existing structure affects the upgrade. In our current regulation, superstructures are regulated only by Article 115a of the Rulebook on construction of buildings in seismically active areas (PIOVS 81 with amendments): However, apart from the fact that this single article does not solve the problem of designing upgrades, it is also quite ambiguous and confusing, which often causes misinterpretation and application.

2 Brief overview of research in the world for solving the problem with upgrades

Larger cities in the world lack space, as available space can be quite expensive. Thus, adding levels to existing structures is one of the most appropriate ways to increase the functional space of residential and administrative buildings. Thus, with the increase in population in densely populated areas, the lack of living space leads to an increase in upgrades to existing buildings. From an architectural point of view, this may mean adding a unique and modern space above the existing building or, preserving the continuity in the construction and adding the existing floors to the additional levels [1].

Very often, the calculation of the additional soil load and the additional seismic force that results from the increase in mass leads to the conclusion that the only solution is an easy upgrade. One such solution is already proposed in the world with a prefabricated steel frame-panel system SUNDAY TM which includes prefabricated wall panels, roof grilles and more. [2]. From an engineering point of view, this system is advantageous because it allows the use of various lightweight building materials and techniques for new levels, including timber systems, such as cross-laminated timber (XLAM or CLT), laminated timber (Glulam) or lightweight timber frames (LFT), then using steel frames with composite plate, as well as reinforced concrete and prestressed structures. Thus, the idea of lightweight upgrades is already gaining popularity around the world in order that building owners and investors to add value to existing buildings.

In this area there are many innovative solutions that differ depending on the height of existing buildings, as well as the capacity of the structure and the materials available for use in the construction of new levels. However, there are several principles that are consistent with all and should be taken into account when evaluating an existing new load structure [3]. These principles include: 1. Defining the life of the structure; 2. Assessment of the condition of the construction, i.e., the stability of the skeleton, and at the same time, the simpler the existing construction, the easier it is to add more load and any additional reinforcement of the structural elements; 3. For multi-storey garages or office buildings it is necessary that there is no interruption in the vertical elements; 4. For new floors it is important to evaluate what materials are available for use.

Regarding the fourth principle in the reference [3], it is estimated that if a wooden structure is used for the new floors, they would weigh approximately 20% of the weight of the concrete structure with about one third during operation, together with the payload. However, for every location in the world there are restrictions in terms of the possibility of what material can be used, then in terms of construction legislation, fire protection regulations, which change based on the location of the building, height and local regulations, etc. The vertical upgrade can be grouped into three categories [4]:

- Category I: This type of upgrade was previously planned during the calculation of the existing construction. The original documentation is readily available and the foundations and structural elements are designed to withstand a certain amount of additional floors. Minimal constructive analysis and verification is required to proceed with the upgrade.
- Category II: In this case, the original structure is not designed with a view to future upgrades. Original formwork, cross-sections and details or drawings are available. It is necessary to check the existing structural elements, and it is also necessary to check the accuracy of the drawings in relation to the real performance and condition of the construction. In general, analysis is needed to assess the impact of the upgrade, as well as to dimension the upgrade itself.
- Category III: In this case, the structure was not originally designed with a view to future upgrades. There is no technical documentation available for the construction - project graphic bases, sections and details. This case requires detailed on-site diagnostic investigations to determine the geometry, physical and mechanical properties of the materials in order to assess the condition of the existing structure. In addition, numerical modelling and analysis of the existing building is required in order to assess the condition and capacity of the existing system, as well as analysis of the integrated system: existing building + upgrade.

3 Test models

A total of 177 dynamic tests were performed on the shaking table in the IZIIS laboratory. The research consisted of harmonics, synthetic and real earthquakes, as an input in a horizontal direction. From the point of view of the intensity of input excitations, two groups of tests were performed: 1. Elastic tests with low excitation level and without the occurrence of damage and plastic deformations; and 2. Tests to determine the capacity of models or to evaluate their nonlinear behavior in order to investigate the failure mechanisms of the various upgrade systems under consideration. Steel frame (STL), light wood (LFT), cross-laminated wood panel (XLAM) and wood and glass composite

(GLS) systems are considered. The research is planned to be analytical and experimental. The FELISA / 3M software package will be used in the analytical research.

In the experimental research, the tested construction, including all combinations with the upgrades, is treated as a life-size model. The existing RC frame system (hereinafter referred to as sample RCF1) is a two-storey single-span structure with dimensions of 340cm x 240 cm (Figure 1), consisting of 20/20 cm RC columns, 20/20 cm RC beams and RC slabs with a thickness of 7 cm. Each of the columns is dimensioned with 4 longitudinal reinforcement bars F16 mm and stirrups F8 mm / 10 (20) cm. The reinforcement in the beams is placed symmetrically in the upper and lower zone, with a total of 4 longitudinal reinforcement bars F14 and stirrups F8 mm / 10 (20) cm. The foundation beams are dimensioned with a height of 20 cm and are fastened to the vibrating platform using special screws. The foundation beams are reinforced symmetrically with longitudinal reinforcement of 4 bars F14 with stirrups F8 mm / 10 (20) cm.

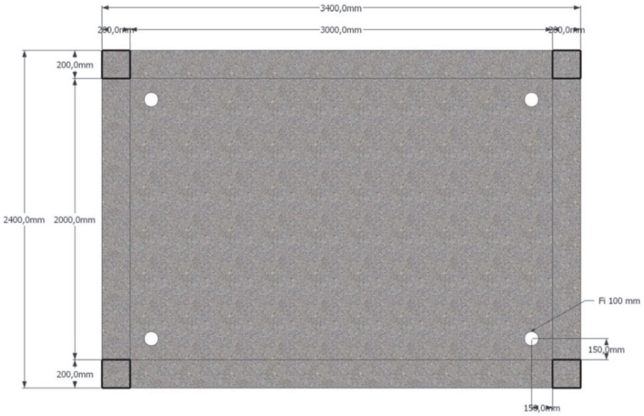

Figure 1. Plan view of the model placed on the shaking table

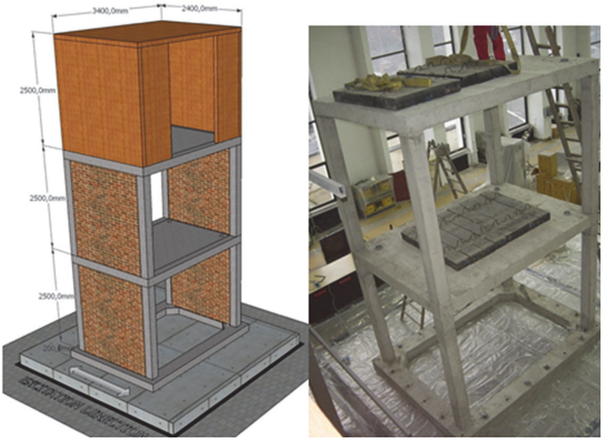

Figure 2. a) Storey hights on the model with added floor of CLAM; b) The model with added loads in order to simulate live load

4. Results from the research in IZIIS-Skopje

Some of the comparative results from the performed dynamic tests on the vibrating platform are shown in Figs. 3 and 4. Figure 3 refers to the response of the basic model with two floors (RCF1), while Figure 4 shows the response of the three-storey model with light steel upgrade (designated RCF1 + STL): It can be noticed that the amplitudes of the movements on the third floor of the upgraded model RCF1 + STL are less than those on the second floor. This leads to the conclusion that higher mode shapes become more significant in the dynamic response when material such as steel is used to upgrade the RC structure. This phenomenon was also observed visually during the test. Figure 5 refers to the response of the three-story model with cross-laminated wood upgrade (RCF1 + XLAM2): Unlike the previous case with the steel upgrade, it can be seen that, in the case of cross-laminated upgrade, the usual amplitudes of displacements and accelerations (by gradually increasing their values from the first to the third floor) show that as a result of uniform stiffness throughout height of the structure, the first mode shape becomes dominant in the dynamic response of the integral system. Lightweight LFT light frame integral systems (Fig. 6) and GLS glass module superstructure (Fig. 7) show similar behaviour. The blue line graphs show the results for the first floor, the red line for the second floor, and the green line for the third floor. The upper graphs show the displacements, and the lower graphs show the accelerations.

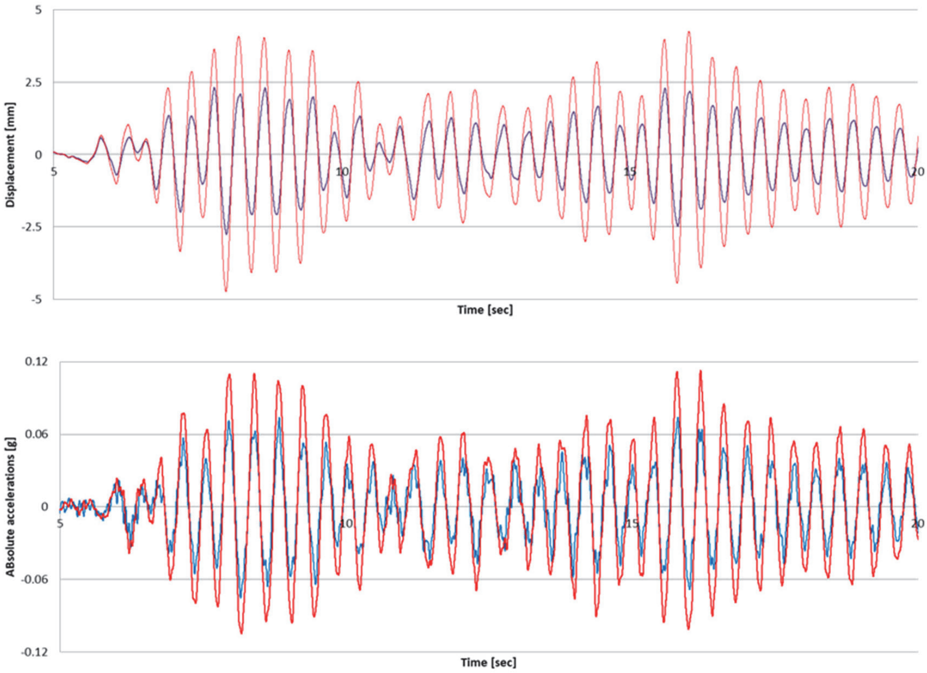

Figure 3. Experimentally obtained time histories of relative displacements and accelerations for RCF1 (test 03, EQ Petrovac)

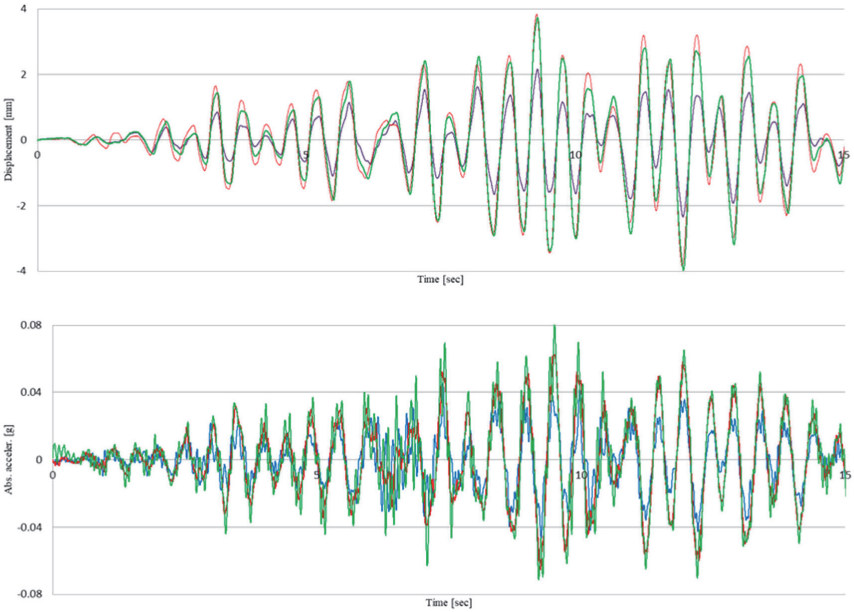

Figure 4. Experimentally obtained time histories of relative displacements and accelerations for RCF1 + STL (test 08, EQ: Landers)

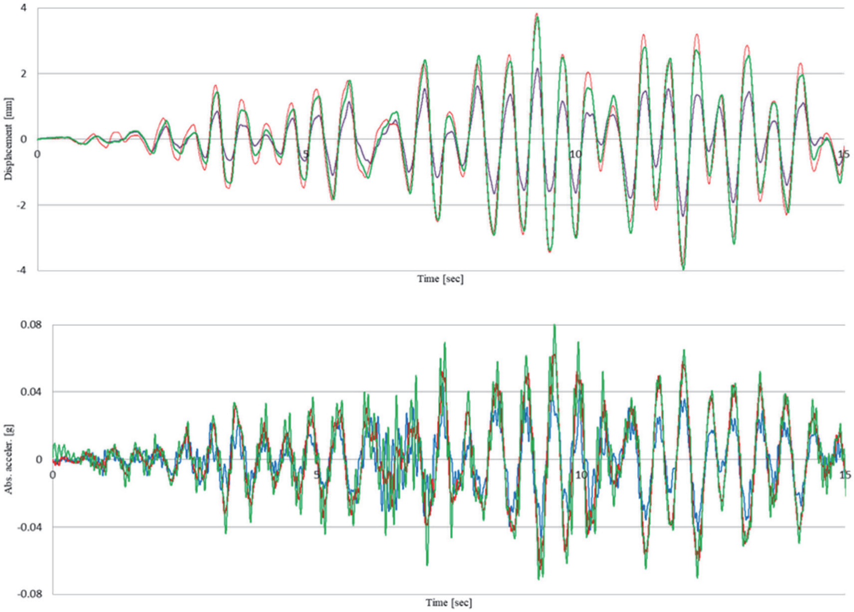

Figure 5. Experimentally obtained relative displacement and acceleration time histories for the RCF1 + XLAM2 model (test 17, EQ Landers)

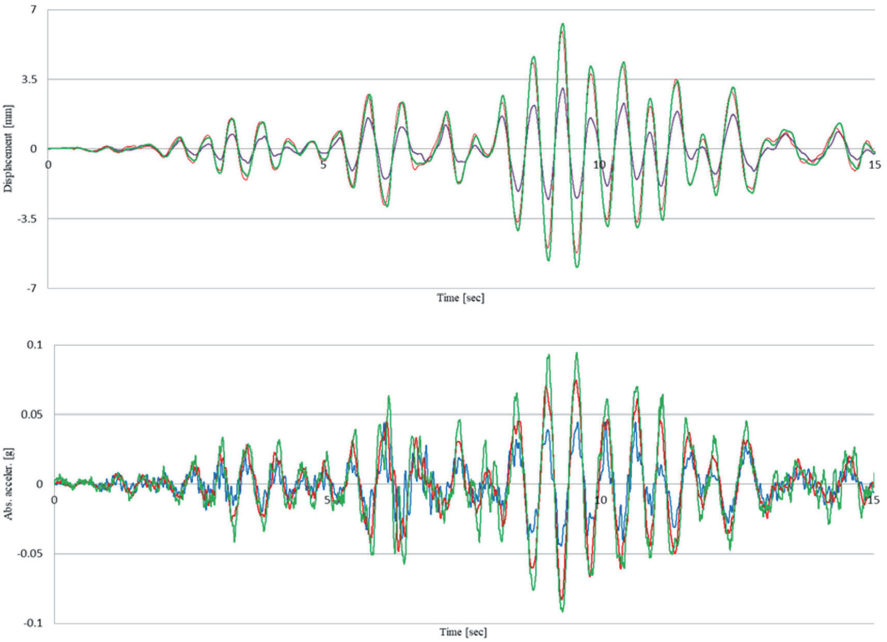

Figure 6. Experimentally obtained time history of relative displacement and accelerations for the RCF1 + LFT2 model (test 26, EQ Landers)

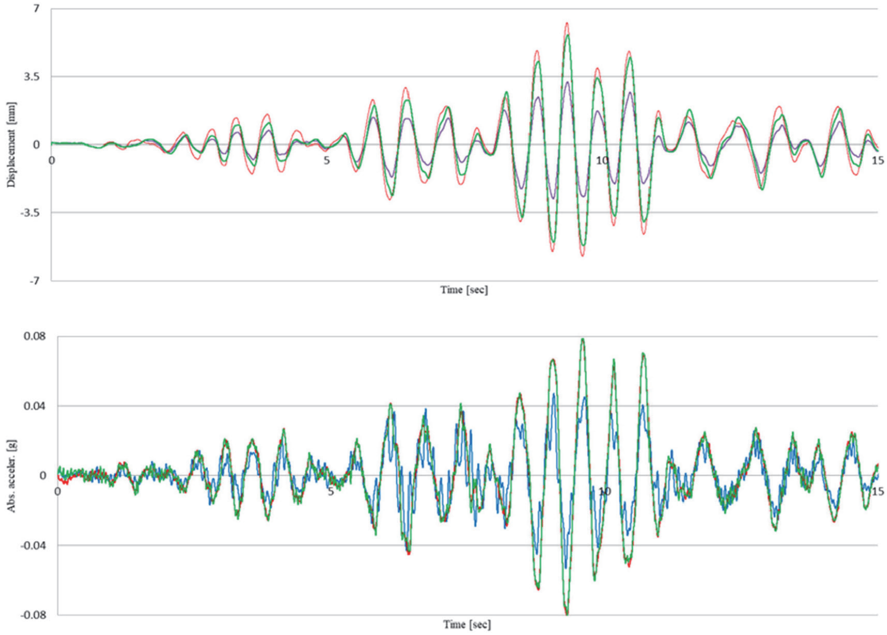

Figure 7. Experimentally obtained time history of relative displacements and accelerations for the RCF1 + GLS model (test 30, EQ Landers)

5 Conclusion

From this research, as observed from the tested specimens, it can be concluded that all upgrades differently contribute to the overall dynamic response of the integral systems. The steel frame (STL) upgrade has been shown to behave in a very flexible manner (particularly at the connections) because of its smaller stiffness compared to the stiffness of the two-story RC structure. In this case, the influence of higher modes has been shown to be significant. The light-frame timber upgrade (LFT) showed a somewhat improved behavior compared to the steel frame, however, the most favorable behavior due to compactness and properly distributed stiffness along the height has been observed in the case of the X-Lam panel upgrade (XLAM):

The connections with the concrete slab had certainly an impact on the response mechanism in the case of all types of upgrades that varied depending on whether they were strong or flexible. In future, a more detailed elaboration of these conclusions supported by numerical verification will be presented.

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