1st Croatian Conference on Earthquake Engineering
1CroCEE
22-24 March 2021 Zagreb, Croatia

DOI: https://doi.org/10.5592/CO/1CroCEE.2021.148

Comparative behaviour analysis of fixed and base isolated RC building during seismic event

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Abstract

Every man-made structure induce more or less seismic energy through it's foundations, but the most of the human casualties happens in residential buildings. Unfortunately, although most of the old houses and buildings are seismically vulnerable by default, many of the new design structures also represent threat during seismic event to their residents. Conventional aseismic standards imply the concept of increasing resistance capacity for all structural members, with fixed support to the foundation. Modern, but not yet widely accepted aseismic approach is to apply systems for base isolation, which can be active or passive. Both types can be used in residential buildings, but the cheaper investment and easier maintenance provides initial advantages to passive base isolation. This paper presents the results of nonlinear response of a multi-storey reinforced concrete building imposed to seismic actions, which is modelled using ETABS software. Comparative behaviour analysis has been established onto two separate models: one with the fixed supports and the other with base isolation system incorporated into foundations. This system consists of rubber isolators and energy dissipaters, and experimental data for their nonlinear stiffness and yield strength are inputted into time-history analysis. The behaviour of structural elements in plastic range is defined through performance-based seismic design. Comparative diagrams of vibration modes, required reinforcement, frame displacement and inter-story drifts are given as results of behaviour analysis. Also, obtained results are compared with EC8 criteria, focusing on limit drifts in both models and their role in preventing and limiting structural damage depending on desired structural performance.

Key words: behaviour analysis, nonlinear analysis, base isolation, frame building, inter-story drift

1 Introduction

From all load cases, correct seismic loading is the most significant input regarding global stability and optimization of the structural model for frame residential building. The use of computers has enabled working in the field of nonlinear analysis and plastic deformations through many iterations, especially in the case of reinforced concrete structures; in order to maximize the potential of all structural materials applied [1]. The use of such iterative steps quickly results in a new stiffness matrix at each stage of the nonlinear analysis.

Still, linear analysis can also provide the correct results for dimensioning typical structures. Whether it is a linear analysis based on strength (linear-static analysis), or on the basis of response-spectrum (dynamic linear analysis) [2], the method of calculation is much simpler compared to non-linear analysis, with a shorter calculation time. The best results are obtained by using time-history-analysis, because the load in this case is a function of time, and so the equations of motion can be set for each time step. The application of time-history-analysis can simultaneously take into account material nonlinearity and P-Δ effects [3].

Since the earthquake primarily represents a process of transmission, absorption and dissipation of energy where structures are mainly demolished due to the high input energy, this fact has led to a new philosophy in seismic engineering, which consists of developing methods for identifying possibilities for modification and reduction of seismic effects on structures [2]. As important public buildings, (like hospitals, schools, police and fire stations, bridges), should remain functional after the earthquake event, the concept of protection using base isolation, i.e. passive control of structures, has been widely applied [4]. Flexible structures are more susceptible to seismic actions, especially when there is no possibility of additional energy dissipation. Depending on the control mode, there are three main systems of protection against the earthquakes: passive, active and hybrid (semi-active) [5]. Passive systems do not use additional external energy for their work, while active systems use controllable systems which induce additional energy. Hybrid systems combine passive and active systems of protection.

In this paper, passive system has been used for numerical modelling [6]. Base isolation is installed at the base of the building, uncoupling a structure from the ground and reducing thereby the transmission of seismic forces from the ground. Comparative analysis of 3D structural behaviour of RC building is also provided with and without using passive system of protection and includes composite isolators and steel dissipaters.

2 Materials and methods

After several strong earthquakes in major cities (Loma Prieta in 1989 and Northridge in 1994 in California, as well as the 1995 Kobe earthquake in Japan), human casualties with material damage (especially technical equipment in buildings), as well as costs of repairs and relocation of business and commercial activities in densely populated urban areas became unacceptably high [7]. Seismic design based on performances represents new flexible philosophy [5] and modern comprehensive approach to seismic design of buildings and other structures, which enables structural performances to be ensured for several different levels of seismic hazard. In 1995, under the supervision of the Federal Emergency Management Agency, recommendations and guidelines were issued for the first time in the United States for seismic design as a document FEMA-273, along with the later released documents the US/FEMA-350, FEMA-356, FEMA-440, ASCE-31 and ASCE-41 [7].

With dynamic nonlinear analysis (Time history) a detailed calculation can be generated using either Fast Nonlinear Analysis (FNA) based on modal analysis, or the method of direct integration, where the equations of motion are set at each iterative step [8]. By assigning seismic loads on the structure through ground displacement, velocity or acceleration based on time histories records, behaviour of connections, elements and the structure as a whole under the effect of a given earthquake can be accurately calculated [9]. Depending on the type of building importance (residential, hospitals, schools, public institutions, ancillary buildings, temporary facilities) and estimated intensity of potential earthquakes, a designer determines how the structure should be "protected" or which degree of damage is permissible for permanent deformations [10].

The philosophy of the base isolated structure is aimed at extending the fundamental period of vibration, which reduces the earthquake induced shear force at the base, providing additional damping of or reducing the relative displacement along the isolator itself. More benefit from base isolation system is achieved in rigid structures where the fundamental period of vibration of the fixed structure is less than 1.0 second. In these structures, the fundamental period can be extended to 1.5 to 2.5 seconds by installing a base isolation system [4]. This technique is applicable in low and medium-high buildings, and is less effective in very tall buildings, given that the fundamental periods of vibration increase with the height of the building.

3 Structural response with and without base isolation – a case study

Using all previous research and methods, a numerical sample of an RC multi-storey building is made here by using the ETABS software [11]. A comparative analysis of results provides better insight in nonlinear response of building structure, with useful conclusions and recommendations. Results will be given for modelling with and without base isolation.

The case study concerns a multi-story RC building shown in Fig. 1. The building has a basement with height of 3.0m, ground floor with height of 4.5m and 4 stories each with height of 3.0m. The building appears a mostly regular story plan, with 5 frames on 5.0 m in the X direction, and 5 frames on 4.0 m in the Y direction.

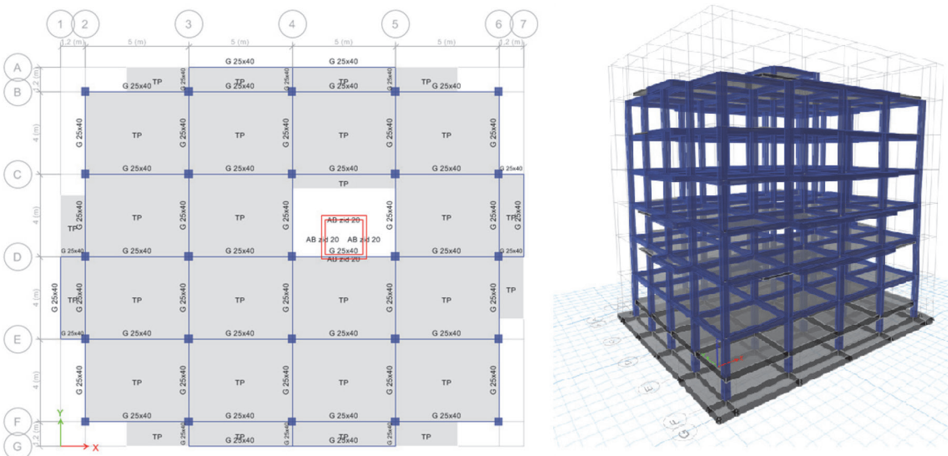

Figure 1. Building plan and isometric view

The section dimensions of all columns are 40 x 40 cm, while the cross-section of beams is 25/40 cm. RC slabs have thickness of 20cm. Every structural element is made of concrete class C30/37 and reinforcement class B500. In the first sample there is no base isolation at the basement level, while in the second sample there are rubber isolators and energy dissipaters above the ground floor slab.

The nonlinear analysis was conducted in the CSI ETABS 2015 software (CSI Knowledge base, 2014) using time-history record for El Centro earthquake (Imperial Valley, California, 1940), for duration of 12 s, with the maximum acceleration peaks occurring between 1.5 s and 2.5 s of the earthquake duration. The time-step of applying the acceleration is 0.01 sec.

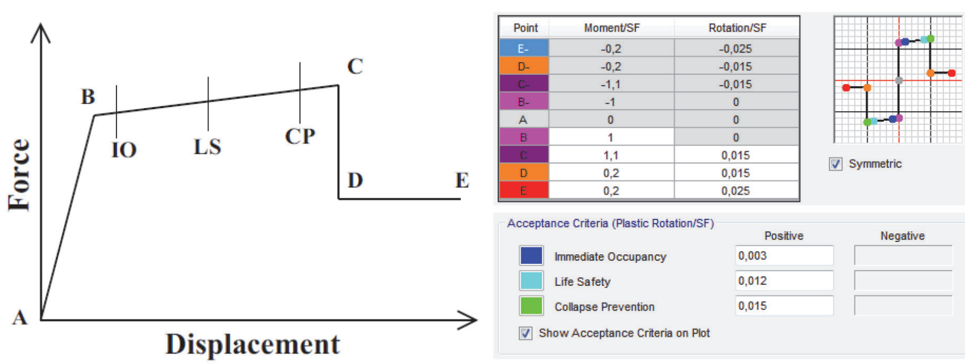

Figure 2. Force-displacement diagram used in ETABS 2015 (left), with points of acceptance criteria for seismic performance on M-ϕ diagram (right)

Plastic hinges at beam ends were set for the bending moment around the major axis M3, while in columns concentrated plastic hinges at the nodes were set for three degrees of freedom (P-M2-M3). The behaviour of structural elements in the plastic range is defined using a force-displacement diagram (Figure 2), with the marked points that correspond to the limit states defined through performance-based seismic design (PBSD) as: immediate occupancy (IO), life safety (LS) and collapse prevention (CP).

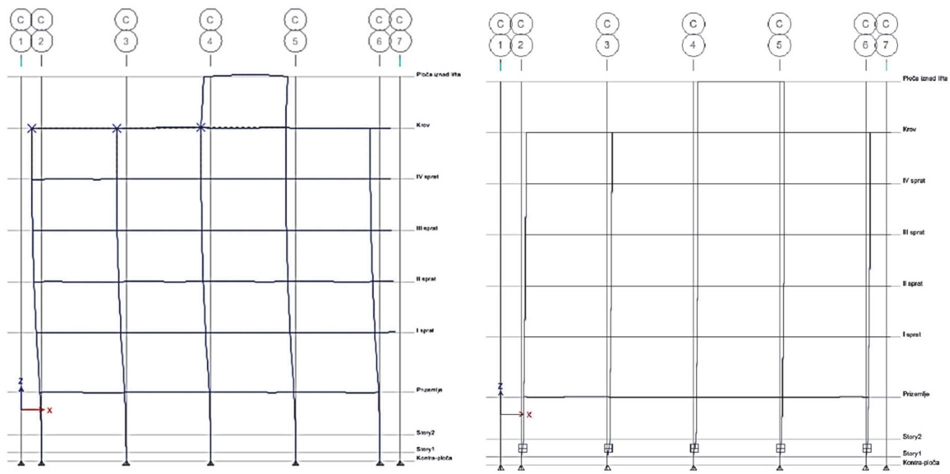

Figure 3. First vibration mode on sample without isolation (left) and with isolation (right)

Firstly, a modal analysis was conducted on both samples – without and with base isolation. Rubber isolators are modelled with linear effective stiffness and nonlinear stiffness and yield strength in X and Y direction, while in Z direction they behave linearly and have only effective stiffness. These isolators are placed under each supporting column. The modal analysis results in a very different behaviour and response values.
As can be seen on Figure 3, the forms for the first vibration mode are very different for the regular structure in comparison to the seismically isolated structure. The main difference is in the first modal period, since it is expected that devices for base isolation enlarge the horizontal movement of the entire structure. The second and third periods of vibration are also similar in comparison, see Table 1.

Table 1. Comparison between periods of vibration for samples with and without isolation

Mode	**First period of vibration** [s]	**Second period of vibration** [s]	**Third period of vibration** [s]
Structure without isolation	0,659	0,611	0,598
Structure with isolation	0,980	0,730	0,689

Axial forces can also be compared between models (Figure 4). In both cases, central columns accumulate greater axial forces, but range of minimum and maximum forces are quite different. Namely, while in the model without isolators peak axial forces in one of the central columns are from 2500 kN to 803 kN (in pressure), in the same column

these values goes from 1615 kN to 1339 kN in the model with isolators. It means that during seismic event columns in bottom stories of isolated building will be compressed with smaller deviations in peak values about 20 %, relative to the columns in unisolated building which will could have deviations in absolute pressure forces up to 300 %.
The differences between designing conventional and seismically isolated structure can be seen also in the required longitudinal reinforcement (Figure 5). In the sample without isolators, the required longitudinal reinforcement reaches 2 % of column cross section, while in the sample with isolators the main reinforcement is accepted as 1 % of column cross section.

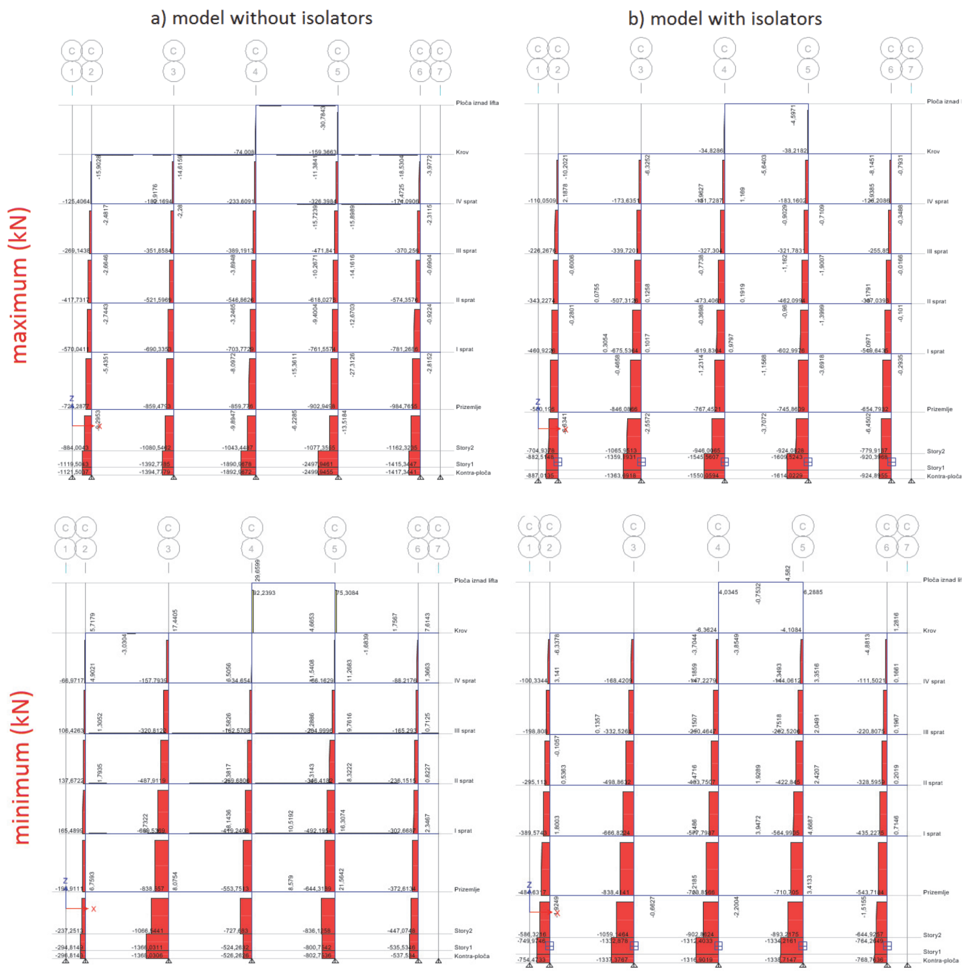

Figure 4. Axial forces in central frame of two models, depending on minimum and maximum values

At the beams, the situation is the same: although at the middle span the required reinforcement is almost the same in both cases, on supports 2 to 3 times as much reinforcement is required in the sample without isolators. Since the structural members are the same in both samples, it can be concluded that dimensions and reinforcement of the structural members in combination with seismic isolator can be reduced, which in most cases will justify slightly higher costs of isolation.

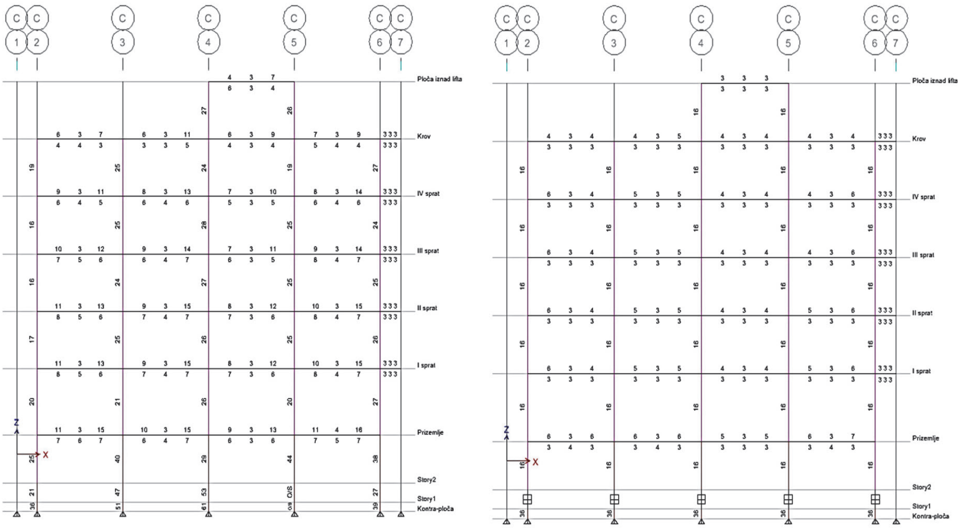

Figure 5. Longitudinal reinforcement in the central frame of the two samples (left – sample without isolation, right -sample with isolation)

The frame global displacement differences between the two samples can be also analysed. For weak and relatively moderate earthquakes, the displacements on all building floors, and especially on upper floors, are mostly larger when seismic isolators are used. This is the first and main guidance point when an engineer decides which system will be used for reducing seismic input into the building. But, when a structure is subjected to a moderate or strong earthquake, a seismically isolated structure remains within an acceptable domain of lateral movement, while conventional buildings do experience large lateral movement, which, in combination with P-Δ effect, can induce unacceptable influences into structural members, mostly into columns.

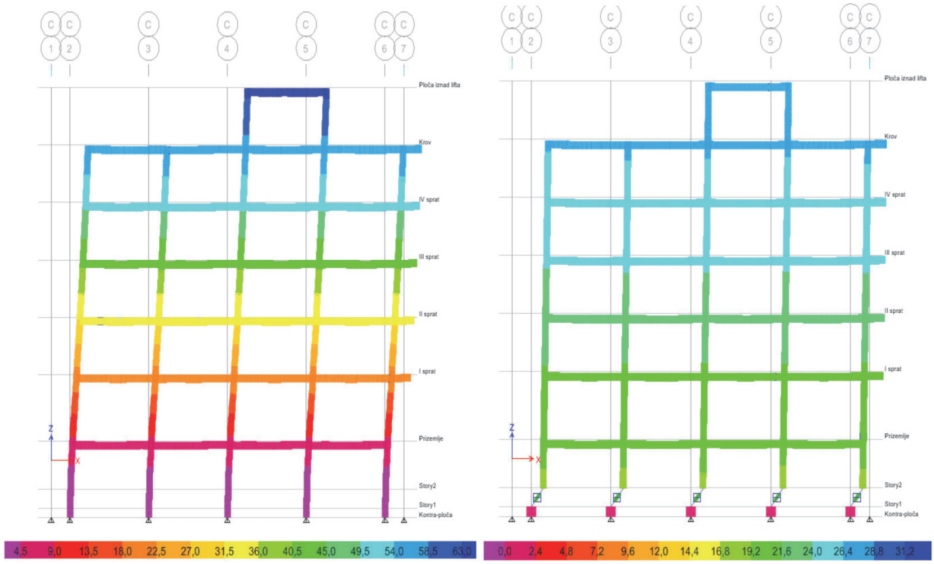

Figure 6. Frame C displacements of the two samples under the El Centro seismic load case (left - sample without isolation, right -sample with isolation)

The two samples frame displacements under El Centro earthquake are shown on Figure 6, and it can be seen that they are almost doubled in the sample without isolation. But, it is not only that: the inter-story drift is also a problem which appears next to large scale frame displacement on the sample without isolators. In Figure 7 the maximum story drifts are displayed in unit less diagrams. On the isolated sample, the maximum inter-story drift appears on the ground level (where isolators end) and on the upper floors it is almost negligible. On the sample without isolators, the inter-story drifts are at maximum on the first floors above ground. This results in much lower bending and shears forces in columns of the isolated structure, which is in correlation with the required reinforcement and dimensions of structural members.

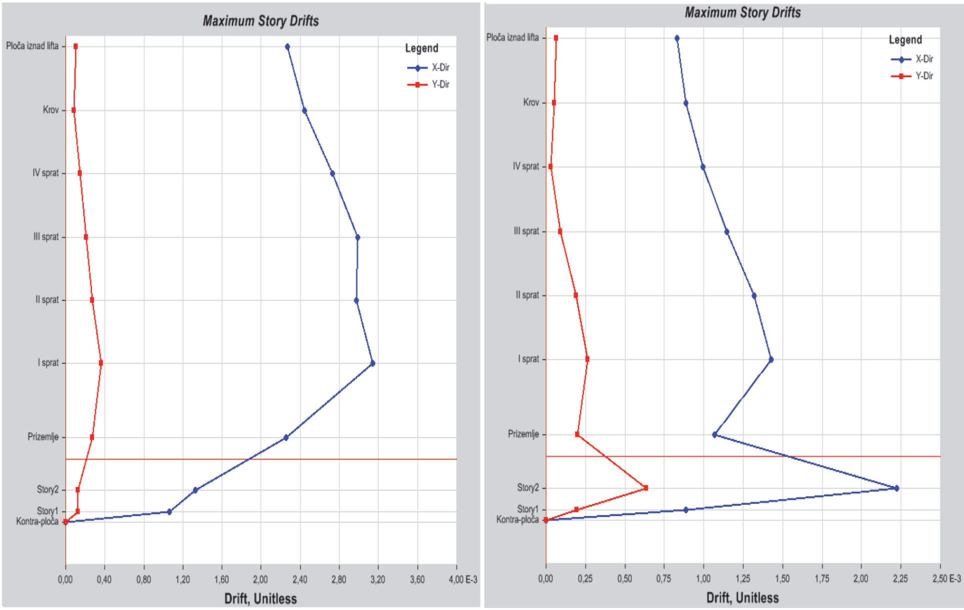

Figure 7. Inter-story drifts of the two samples under the El Centro seismic load case (left - sample without isolation, right -sample with isolation)

4 Conclusions and sugestions

- Ductility of columns should always be high, and their brittle failure should be avoided (especially of short columns resulting from parapets, and the like). The largest axial gravity load in columns should be at the level of "balance point" in order to enable equal expansion to occur in concrete and reinforcement, which is necessary for the simultaneous failure across the concrete and reinforcement. The bending stiffness of beams should be minimum 25 to 40 % lower than that of the column in the joints in order to ensure proper development of plastic hinge and reception of the moment of plasticity in the beam instead of the column.
- The nonlinear response of a reinforced concrete building, after applying a base isolation system in combination with devices for energy dissipation, has been computationally investigated by the ETABS rule. On the example of two 3D structural samples exposed to the El Centro earthquake, the main difference is in the first modal period in the two samples. As it is expected, devices for base isolation enlarge horizontal movement of entire structure compared to non-isolated sample. Second and third period of vibration have also similar comparison.
- In the sample without seismic isolation difference between minimum and maximum values of pressure forces in bottom column are enormous, which results in required longitudinal reinforcement up to 2 % of column cross section in the non-isolated sample, while in the sample with isolation the main reinforcement is accepted as 1 %

of column cross section. The situation is the same for beams: although at the middle span required reinforcement is almost identical in both cases, on supports there is 2 to 3 times more reinforcement in the sample without isolators.

- On the isolated sample, the maximum story displacement appears on the ground level, where isolation ends, whereas on the upper floors it is almost negligible. On the sample without isolators, the drifts are at maximum on first floors above ground. This results in a much lower bending and shears forces in columns of the isolated structure, which is in correlation with required reinforcement and dimensions of structural members.
- Since the structural members are the same in both models, it can be concluded that structural members in combination with passive seismic isolation can be reduced in dimensions and reinforcement, which will justify slightly higher costs for isolation system purchase in most cases.

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