



## **SEISMIC PERFORMANCE EVALUATION OF AN IRREGULAR HIGH-RISE BUILDING**

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### **ABSTRACT**

In this paper, the seismic performance of an irregular high-rise building with two large openings (20m by 20m) in elevation was studied. There were two transfer stories in the building, which were set for structural requirement as well as architectural function. The analytical model of the building was first established in the finite element program of Strand7<sup>R</sup>. Plate element and beam element were employed for the structural walls, columns and beams, respectively. Some points on member skeleton curves of structural members were obtained using the software named Section Builder<sup>R</sup>, and Takeda constitutive rule included in the Strand7 was applied for the constitutive rule of the members. Then, nonlinear time-history analysis of the structure under multi-earthquake inputs was carried out. The dynamic properties and displacement responses were compared to the results of the dynamic model test.

Compared to the test, it was concluded that the nonlinear dynamic responses can be accurately reflected by the analytical model developed in this paper. Further conclusions come that the analytical parameters could be logically obtained by calculating member skeleton curve in Section Builder and then inputting them in the Strand7 model. Seismic performance of the irregular high-rise building was evaluated on both the analytical responses and experimental results. Up to now, the construction of the target building with improved design has been completed.

**Keywords:** Irregular high-rise building, performance evaluation, Strand7, Section Builder

### **INTRODUCTION**

Detailed study is necessary to verify the seismic safety and reasonableness of the structural design. For significant buildings, feasible research methods are shaking table test, nonlinear static and dynamic analysis. With the popularity of the shaking tables around the world, dynamic test procedure is becoming one of the most useful tools to learn the structural response under earthquake simulations. (Katayama, 2005; Pavese and Amaris, 2005; Tremblay et al., 2005) For structural analysis, seismic design of buildings is increasingly using nonlinear dynamic procedures to demonstrate structural performance because of the analytical feasibility and reasonableness.

In this paper, the irregular building of interest is a high-rise building with two large openings (20m by 20m) in elevation, which is designed beyond the prescriptive provisions of the code. First, nonlinear dynamic analysis was done by calculating member skeleton curve in specified software (Section Builder) and inputting them in the finite element program (Strand7). Then, the analytical results,

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including dynamic properties and displacement, were compared to the experimental results (Zhou et al., 2004). The earthquake-resistant performance of the structure was evaluated by the analytical results with the test verification.



Figure 1. Elevation of the building model

### **DISCRIPTION OF THE IRREGULAR STRUCTURE**

The high-rise building of interest is a 30-story residential building located at Huaihai Road in Shanghai, China. It has a rectangular plan with the dimension of 69.0m by 18.15m. The building has a total structural height of 96.55m and its typical story height is 3.05m except that its first story is 8.1m high (Figure 1). There are 24 steel reinforced concrete (SRC) columns and 3 reinforced concrete (RC) core walls in the ground floor, which allows for an open public area to diversify architectural functions of the building (Figure 2). In the second floor and above, short-length shear walls are needed for the residential space (Figure 3) thereby a RC-steel composite transfer beam is placed between the first two stories. In the medium seven stories from story 17 to story 23, some slabs are eliminated to build a long suspended gymnasium reflecting the special appearance of the building. The second composite transfer story is designed above the openings. The maximum height of transfer beam even adds up to the story height. In elevation, three core walls stretch from the bottom to the top and extrude 6.2m out of the roof floor.

Structural engineers prefer regular buildings for its simple force-bearing mechanism. Regularity limitations on height, plan and elevation of buildings are thus established in China Code for Seismic Design of Buildings (CSDB, 2001). For the columns-supported shear wall system, the maximum height of the building is 100m and the height to width ratio is 6. The layout of this building does not conform to the code geometrical requirement. In addition, buildings in Shanghai should be designed to sustain earthquakes of intensity seven (roughly equivalent to a modified Mercalli intensity of seven) with ordinary repair or without repair.

Given these irregularity and complexity of the structure, the owner entrusted the State Key Laboratory for Disaster Reduction in Civil Engineering at Tongji University to perform a detailed study to verify the seismic safety and reasonableness of the design.

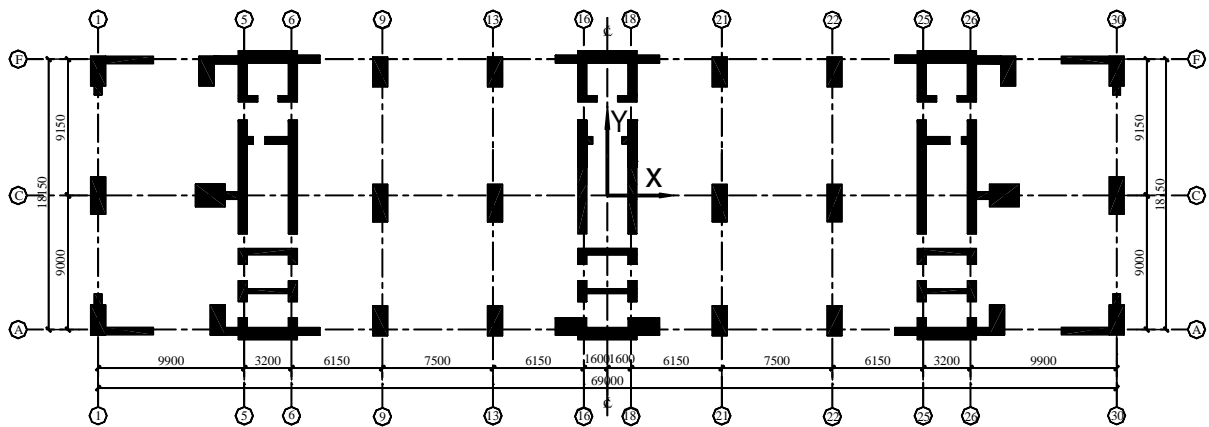


Figure 2. First floor plan

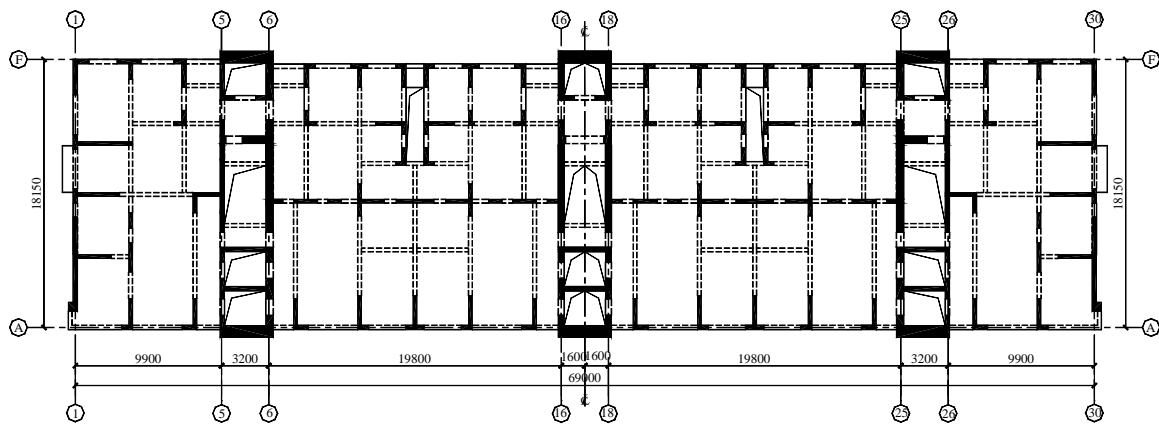


Figure 3. Standard floor plan

### NONLINEAR ANALYSIS

Seismic design of buildings is increasingly using nonlinear analysis procedures. While code and guidelines requirement exist, there still remain many undefined aspects for which additional guidance would be helpful. Current buildings codes contain provisions that allow for use of alternative procedures. For example, UBC (1997) states in 1629.10.1:

Alternative lateral-force procedures using rational analysis based on well-established principles of mechanics may be used in lieu of those prescribed in these provisions.

CSDB (2001) states as follows:

Elasto-plastic deformation of a weak story (or location) of a structure under the rarely occurred earthquake may be determined by the static elasto-plastic analysis method and the time-history analysis.

Buildings are expected to respond nonlinearly under maximum considered earthquake level ground motions. Therefore, nonlinear dynamic analysis, properly executed and interpreted, is one of the best ways to identify nonlinear dynamic response characteristics, including yielding mechanisms, associated internal forces, deformation demands, and detailing requirements.

In China, it has been used on many occasions in actual building designs to demonstrate through nonlinear analysis combined with experimental evidence that building system performance will not exceed or equal performance intent of the prescriptive provisions of the code. (Lu et al., 1999; Lu et al., 2006) Examples include innovative structural systems, conventional systems built beyond that permitted by code provisions, and more effective conventional designs.

Experimental and numerical studies of nonlinear dynamic response demonstrate that, because the behaviour is nonlinear, internal actions cannot be scaled directly from linear analysis results; similarly, nonlinear behaviour at one hazard level cannot be scaled from nonlinear results at another hazard level. Additionally, conventional capacity design approaches can underestimate internal forces in some structural systems (and overestimate them in others) because lateral force profiles and deformation patterns change as the intensity of ground shaking increased (Priestley and Amaris, 2003). Generally, nonlinear dynamic analysis procedures require: an understanding of the relation between performance and nonlinear modeling, selection and manipulation of ground motions appropriate to design hazard levels; selection of suitable nonlinear models and analysis procedures; and interpretation of results to determine design quantities based on nonlinear dynamic analysis procedures (Moehle, 2005).

The structure of interest in the paper was far beyond that permitted in the code. According to the analysis above, the preferred research approach is to study the response of the model building to representative ground motions at the target hazard level using nonlinear dynamic analysis. For this purpose, a detailed nonlinear model of the building was established using appropriate computer software, that Strand7 was employed here. Scaled El-centro, Pasadena, and Shanghai accelerograms, similar to the test input (Zhou et al., 2004), were used as the ground motions in the analysis. Nonlinear relations of members were calculated by the program named Section Builder. Structural dynamic response were analysed and compared to the experimental results.

### **Analytical software – Strand7**

Strand7 is a general-purpose finite element analysis system developed by Strand7 Pty Ltd. (Strand7, 2005) It is a stand-alone system comprising pre-processing, post-processing and solver functionality. Solver capabilities in Strand7 include linear and non-linear static, linear and non-linear transient dynamic (with re-start), linear buckling, natural frequency, harmonic response, spectral response, linear and non-linear steady-state heat transfer, linear and non-linear transient heat transfer (with re-start). Beam and wall elements are included in Strand7 to be selected by various professional users.

### **Analytical model and nonlinear relations**

Structural dynamic response is, by its very nature, nonlinear beyond the region of elasticity. It can be seen that structural elastic state is the original state and nonlinear member relations are then introduced to do the nonlinear analysis. Therefore, nonlinear analysis procedure includes: establishment of the original elastic analytical model; introduction of the nonlinear member rules; and analysis of the nonlinear time-history response.

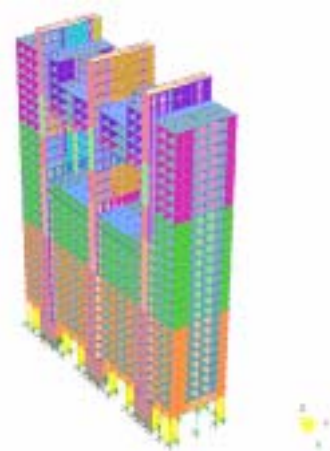


Figure 4. Analytical Model

In this paper, analytical model was developed as Figure 4, in which beam element was used for the columns and beams, and plate element for structural walls. The total number of nodes, beam elements and plate elements is 7483, 4816 and 9154, respectively.

Based on the elastic analytical model, dynamic properties were achieved and compared to the experimental ones as listed in Table 1. From Table 1, it can be found that only little dispersion existed in the first five frequencies and accordingly the original elastic state was well simulated. Figure 5 shows the relationship between the vibration shape and the mode participation factor. The summation of mode participation factor adds up over 80% at the 5<sup>th</sup> mode while 90% at the 31<sup>st</sup> mode. According to CSDB (2001), the vibration shape number for analysis is taken the number when the summation of mode participation factor at least adds up to 90%. For this model, however, the first several modes are enough to catch the dynamic characteristics of the whole structure in spite of the subsequent local vibration modes.

Table 1. Comparison of dynamic properties

Vibration Mode		Frequency (Hz)	Vibration shapes
1	Test	5.634	Translation of Y
	Analysis	5.570	Translation of Y
	Dispersion	1%	-
2	Test	5.822	Translation of X
	Analysis	5.825	Translation of X
	Dispersion	1%	-
3	Test	6.949	Torsion
	Analysis	6.891	Torsion
	Dispersion	1%	-
4	Test	18.404	Translation of X
	Analysis	17.353	Translation of X
	Dispersion	6%	-
5	Test	22.160	Translation of Y
	Analysis	22.007	Translation of Y
	Dispersion	1%	-

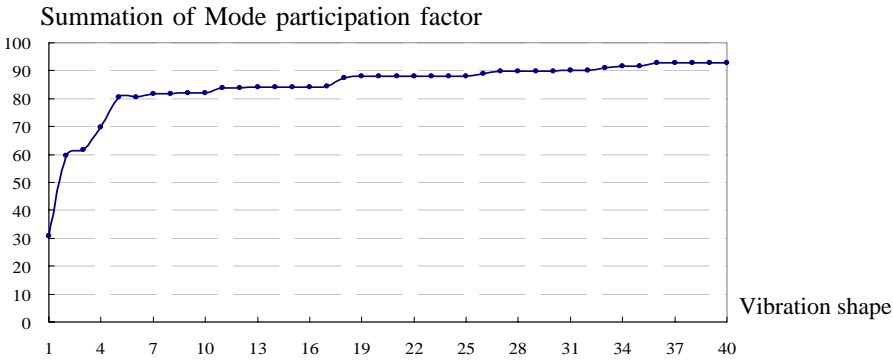


Figure 5. Summation of the modal participation factor of the analytical model

There are two keys in the nonlinear analysis: the selection of the member nonlinear relation, and the stability and convergence of the solver. Nowadays, several efficient algorithms are usually involved in finite element software, such as self-adaptive approach, arc-length method. It is noted that selection of generalized load-deformation properties is more important to the final result. In this paper, for beam moment-curvature skeleton curve key points was calculated by the program Section Builder (Section Builder, 2002) and for wall stress-strain curve by confined concrete model (Mander, 1988). Takeda

model involved in Strand7 was applied for the constitutive rule of the nonlinear model, which can be widely used for the structural column, beam and wall (Eto and Takeda, 1973; Hwang and Jaw, 1990).

### Nonlinear response with test verifications

#### Time-history analysis

Figure 6 ~ Figure 8 shows the roof displacement time-history curve of the analytical model under frequent, basic, rare occurrence earthquake, respectively. It is concluded that:

- Under frequent earthquake level, the analytical curves meet well with the experimental results. The model stays in elastic at this stage and the analytical parameters are suitable to the model.
- Under basic and rare occurrence earthquake input, the time-history curves agree well at the beginning while difference appears with the lapse of time. The reason that the experimental result is larger than the analysis lies in the damage accumulation in the test.

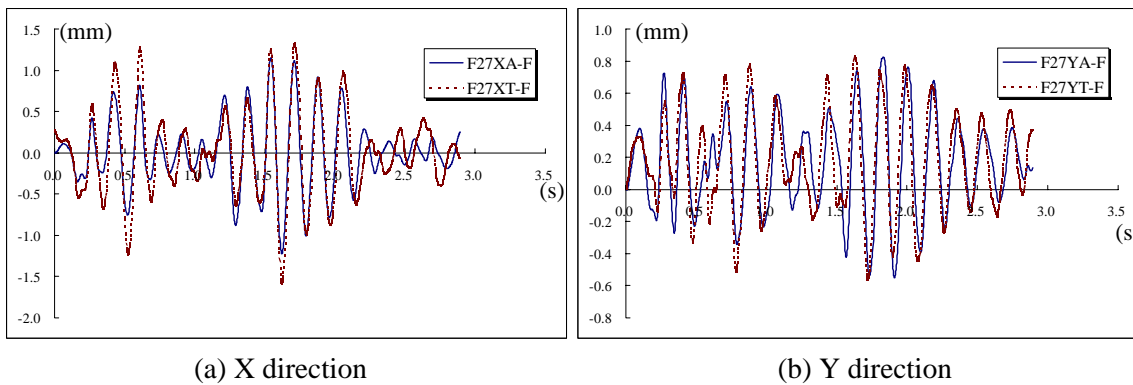


Figure 6. Roof displacement time-history under El Centro earthquake input of frequent occurrence

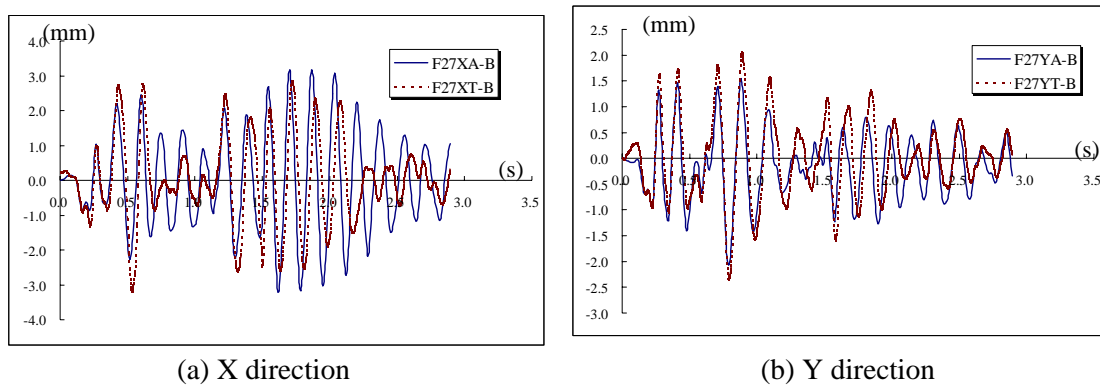


Figure 7. Roof displacement time-history under El Centro earthquake input of basic occurrence

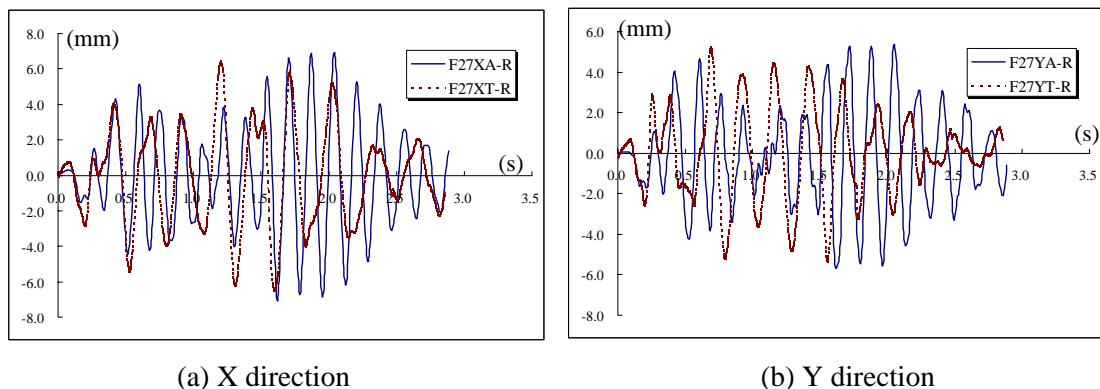


Figure 8. Roof displacement time-history under El Centro earthquake input of rare occurrence

### Strain Distribution in the structure

Strain distribution in the structure when suffering the earthquake inputs can be easily checked as shown in Figure. 9. The maximum strain located at the ends of the building, middle height of the tubes, and the joints of the upper transfer beams.

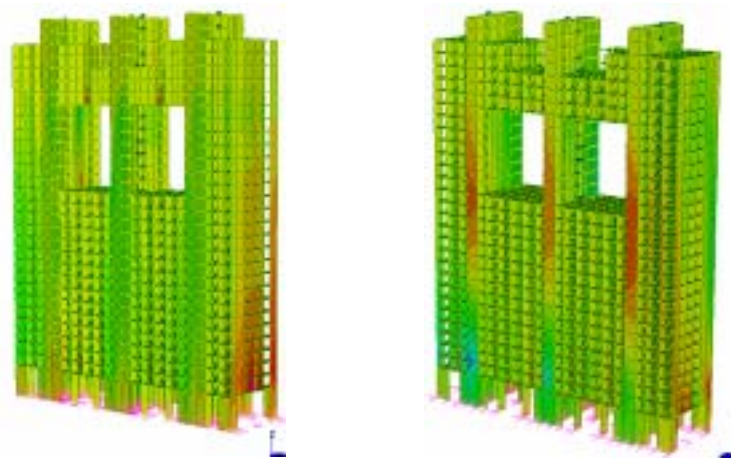


Figure 9. Strain distribution in the structure

### Inter-story drift envelopes of the model structure

Figure 10 shows the ratio of inter-story drift envelopes of the model structure. It can be concluded that the ratio of inter-story drift envelopes under several inputs could match the experimental results better than under one ground input. The reason lies in that the peak value was more likely to be simulated because of the appropriately selected parameters at the beginning of the analysis. With the lapse of time, damage accumulation lead to the response difference, as shown in Figs. 6, 7, and 8.

The difference appears at Floor 2 ~ Floor 16 at Y direction owing to the shortage of accelerometers in that direction. The big dispersion existing at the top of the building suggested the extruded tube design should be paid special attention in the structural design. For the joints of transfer beam and core wall, a suggested section design is shown in Figure 11 to regulate the stiffness and ductility of the joints. Structural design has been improved and the building construction has been completed, as shown in Figure 12, on the basis of the detail design suggestion.

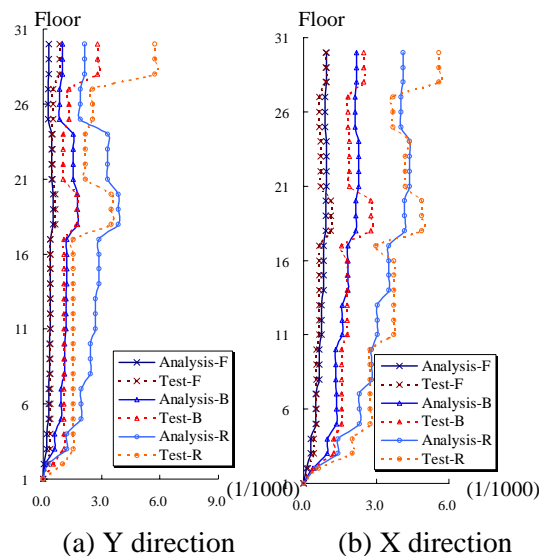


Figure 10. Ratio of inter-story drift envelope of the model structure

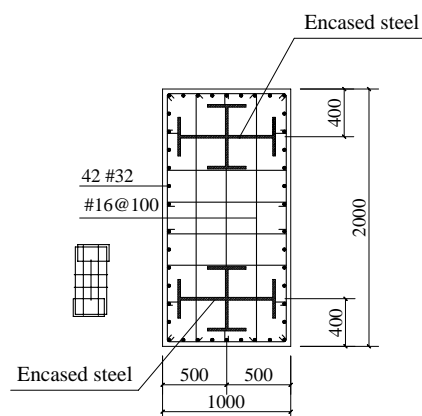


Figure 11. Suggested reinforcement of a transfer beam (Units: mm)



Figure 12. Construction of the irregular building

## CONCLUSIONS

In this paper, the seismic performance of an irregular building, with two large openings in elevation, was evaluated by nonlinear dynamic analysis with test verification. Both the analytical and the experimental results showed that:

1. In spite of the big openings in the elevation, the structural elastic frequencies and displacements in direction Y were close to direction X, verifying reasonable stiffness design of the overall structure. The irregular structure was designed for resisting earthquakes of intensity seven and it can resist frequent earthquakes without damage, resist basic earthquakes with some structural cracking, and resist rare earthquakes without collapse, but with some severe structural as well as non-structural damages.
2. The first five analytical natural frequencies of the structure were in good agreement with the experimental results. The torsion period of the design structure meets the requirement of the code.
3. Structural ratio of inter-story drifts increase abruptly at the rigid stories. Rigid members and those closely connected with the rigid stories were suggested to strengthen to fit for the force concentration at the typical stories.



This paper conducted the nonlinear dynamic analysis of an irregular model building in three steps: establishment of original elastic model; input of nonlinear member relation; and time-history analysis. With test verification, it can be concluded that it is a useful way to evaluate the seismic performance of irregular buildings. Ongoing studies will continue to improve our understanding of the requirements for nonlinear analysis in support of performance-based earthquake engineering in the years ahead.

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