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APPROACHES OF REPRODUCING APPROPRIATE SEISMIC INPUTS TO FAÇADE SYSTEM IN SHAKING TABLE TESTS

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Abstract

Shaking table testing methods are usually used to investigate the seismic performance of structures and non-structural components. A shaking table test for a granite façade system was performed in this paper. In practical construction, façade systems are supported by the main structure at different points both horizontally and vertically, so that they are excited by the combined responses of several locations of the main structure other than a single point. However, in shaking table tests, façade systems are usually excited by the supporting frame on the shaking table, in which it is hard to reproduce the waves to the façade system from the supporting system and the real main structure, and the approaches to generate the seismic inputs to façade systems with the supporting frame on the shaking table are usually diversified and uncertain. The testing approaches of reproducing appropriate seismic inputs to the façade system were studied, which including generating appropriate motions and exciting sequences. Typical specimens of granite facade systems were installed to a specially designed and fabricated steel supporting frame on the shaking table. Seven records, including five natural earthquake records and two artificial waves, were rigorously selected or generated as seismic inputs in the test. They comply with the seismic demands of the façade system, which related to the main structure's maximum floor accelerations and inter-story drifts, dynamic properties of the granite façade system and the steel supporting frame. A multi-stage exciting procedure was erected, and the selected motions with different peak values were generated as different quake levels and input to excite the granite façade system with its supporting frame for reproducing the seismic responses of granite façade system. With the testing results, the realization of seismic demands was verified, he response differences between cases using various records were studied, and the spectrum of the supporting frame was compared with the floor spectrum. An improved method to generate table inputs using a more appropriate spectrum was proposed with the consideration of the transfer functions of the supporting frame. A finite element model of the supporting frame, together with the tested specimen, was established and analyzed to approve this improved method to be a better realization of floor spectrum characteristics in shaking table tests.

Keywords: shaking table test, granite façade system, seismic demand, seismic input, wave reproduce.

1. Introduction

Economic losses in buildings because of nonstructural damage or malfunction can be much more significant than those directly related to structural performance [1]. In historical earthquakes, the curtain wall exhibited some damages in panels or connections when deformation exceeded designed limits [2]. To evaluate the seismic performance of curtain walls, many simulation studies or tests, for example, cyclic loading tests and shaking table tests have been done [3-7].

The input excitation is one of the most critical consideration in shaking table tests, but there is no common senses and approaches of reproducing appropriate time histories. The approaches to generate seismic inputs in the tests are affected by the test setup. Two different methods can be used to install NCs in shaking table tests, one is somehow to install NCs in a full-scale structure [8-9] the other is to install NCs directly on the table with supporting frames [10]. The advantages of the former method include that it can reproduce realistic input excitation for NCs and take the interaction between NCs, boundary conditions, and floor system vibration into consideration [8]. Ground motions are selected as the seismic inputs, and NCs experience the excitation from the full-scale structure. However, such tests have great requirements on the shaking table capacity. NCs shaking table tests without main structures are much easier to carry out. In some of these tests, series of linear or nonlinear time history analyses using selected ground motions were carried out to generate floor motions, which are used as inputs for shaking table tests. Some other tests use artificial waves generated from floor spectrum. Seismic demands of NCs (e.g., peak acceleration) are also achieved by increasing the shaking intensities. If the supporting frame exists, the spectrum of input excitations to NCs is different from the spectrum of input motions at shaking tables. Seismic inputs to façade systems in shaking table tests are usually diversified and uncertain. However, this effect has not been clearly quantified.

A shaking table test to evaluate the seismic performance of the specimen of the granite façade system is introduced, and the seismic inputs and response in the tests are also analyzed. An attempt to match the response spectrum on NCs with the design floor spectrum is carried out.

2. Seismic inputs and spectrum realization in a shaking table test

2.1 Test setup

Two granite cladding system specimens were installed on the opposite two sides of a steel supporting frame fixed on the shaking table. Totally 36 accelerometers and 11 ASM displacement sensors were placed in critical locations to get the response of the supporting frame and the façade specimen. The completed test specimen is shown in Fig. 1.

Fig. 1 - Test setup

A steel frame was designed for the installation of the facade specimen and the transfer of the excitation to the specimen. The supporting function could also be realized by a concrete tube, which could be more rigid but of much weight [11]. The frame, on the one hand, is expected to be strong enough to resist the possible large inertia force of the façade system and to generate certain acceleration or drifts between hanging points. On the other hand, the frame should be light enough to accommodate the bearing capacity of the shaking table.

It is known that the supporting frame is not supposed to simulate a certain floor where the cladding is installed on, but to transfer the seismic inputs from the shaking table to the hanging façade system. Therefore, the dynamic properties of the supporting frame (e.g., vibration frequencies, modes, and damping ratio) is critical. The dynamic properties of the supporting frame are shown in Table 1.

Table 1- Dynamic characteristics of the supporting frame (with façade system)

cases	Fundamental Frequency in X direction (Hz)			Fundamental Frequency in Y direction (Hz)		
	Mode 1	Mode 2	Mode 3	Mode 1	Mode 2	Mode 3
1	3.25	11.50	22.25	4.75	12.25	32.75
9	3.25	11.25	22.25	4.75	12.25	31.25
17	3.25	11.75	22.25	4.00	11.75	31.25
25	3.25	11.75	23.00	5.00	10.25	23.00
33	3.25	11.75	22.75	4.75	——	——
Average	3.25	11.75	22.25	4.75	12.25	31.23

2.2 Seismic inputs and response in the test

Seismic inputs should consider the design of the main structure and nonstructural components. Artificial waves should be fitted according to the actual seismic response spectrum of the selected location of curtain wall specimens (Shaking table test method for seismic performance of curtain wall GB/T 18575-2017, 2017) [12]. The Floor Response Spectrum (FRS) method consists of first obtaining the response spectrum at the location in the structure where a nonstructural component is attached (the floor response spectrum) and then using this response spectrum to estimate its seismic response [13]. This test explores a simpler method to design input motions in the shaking table test without a FEM model of the main structure.

The object of the motions is to excite the façade system together with the supporting frame to achieve design performance level, specifically, the required acceleration and drift ratio. The peak values of the horizontal seismic response of each floor of the main structure are extracted, and the performance evaluation level index of the façade system in the test is determined. At each peak level, the El Centro and other ground time histories, artificial ground waves fitted by response spectrum, and artificial floor waves are selected as seismic inputs, which make the seismic input typical.

Five records are directly chosen from the seven records for main structure analysis and the remaining 2 time histories, including El Centro wave and an artificial wave. The artificial wave is generated according to the modified spectrum (Fig. 2, codified spectrum in black and modified spectrum in blue). The difference between the codified spectrum and the modified spectrum is that the platform extends from 0.1 s-0.9 s, where 0.9 s is the site period, to 0.06-0.9 s for that fundamental period of façade system is 0.075s.

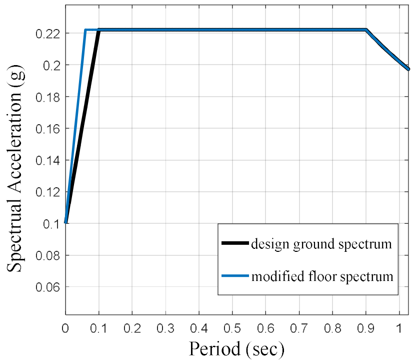

Fig. 2 - standard design ground spectrum and modified spectrum

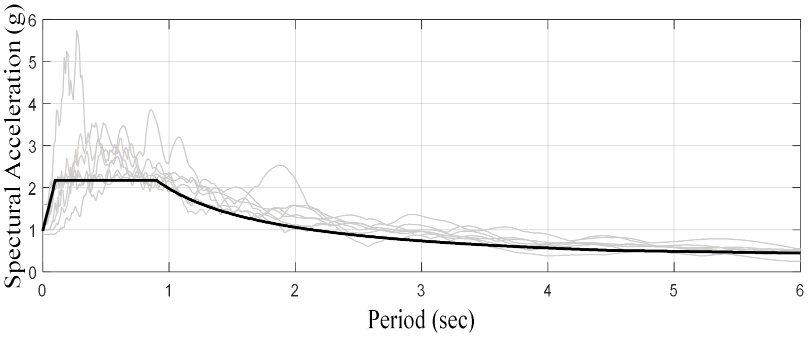

Fig. 3 - standard design ground spectrum and acceleration spectrum of input motions

2.3 Spectrum in the test

To get the real seismic inputs in the test, the shaking table capacity should be considered. In this test, that is to make sure that the time history of the record is within the table's displacement limits(100mm). By filtering the records with a cut-off frequency of approximately 1 Hz, new time histories can be produced, of which the acceleration spectrum is shown in Fig.5. The bold black line in the figure shows the average spectrum of real seismic inputs in the tests, and it is quite similar to the design ground spectrum in short periods and much lower in longer periods because of the use of a high pass Butterworth filter.

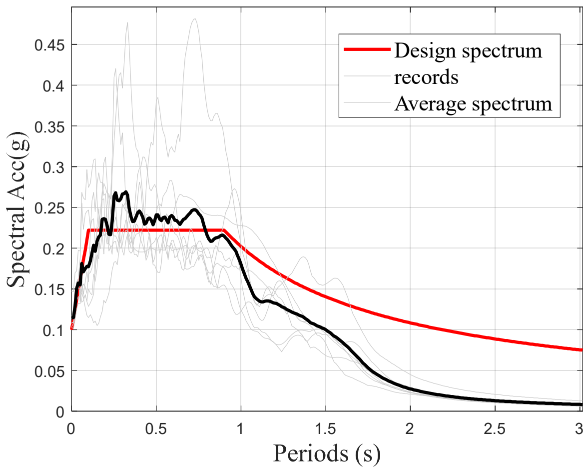

Fig. 4. standard design ground spectrum and seismic inputs in the test

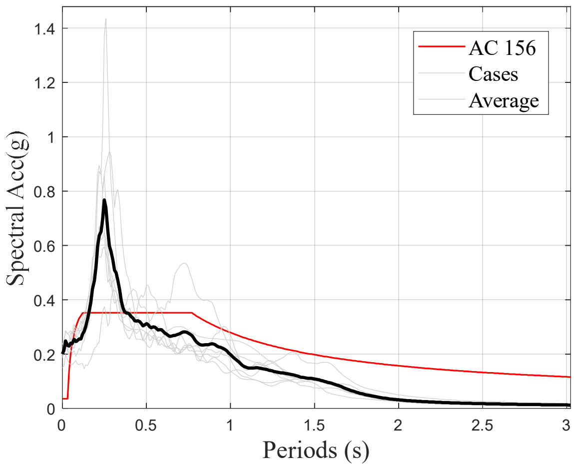

Fig. 5. AC 156 floor spectrum and frame response in the test

As is shown in fig. 5, the spectral characteristics of frame response are different from that of seismic inputs. It is also reported in other researches but has not been quantified. In this test, the response spectrum is lower than the recommended AC 156 spectrum [14] but higher near 0.21s. It is mainly because of the existence of the supporting frame. A sharp increase of spectral acceleration occurs near the natural frequency of the supporting frame as a result of the interaction between the supporting frame and the shaking table. A spectrum ratio was employed to show how the existence of a supporting frame affects the spectral characteristics, which is defined as the result of the frame spectrum (in Fig. 5) over the input spectrum (in Fig.4).

It is clearly shown that the amplification effects of white noise and natural records are similar (as the spectrum ratio shown in Fig. 6). The ratio has an amplitude of 3.0 near the natural frequency of the supporting frame, and the maximum amplification factor of spectral acceleration is about 3. For periods longer than 0.6s, the amplification factor is about 1.2. There also exists some difference in short periods. That is may because that white noise has a constant energy spectrum in different periods while it has large spectral acceleration in short periods compared with natural records. The spectrum of white noise cases is shown in Fig. 7, and the cases of 7 records are shown in Fig. 8. The differences between those cases are easily observed, especially in short periods.

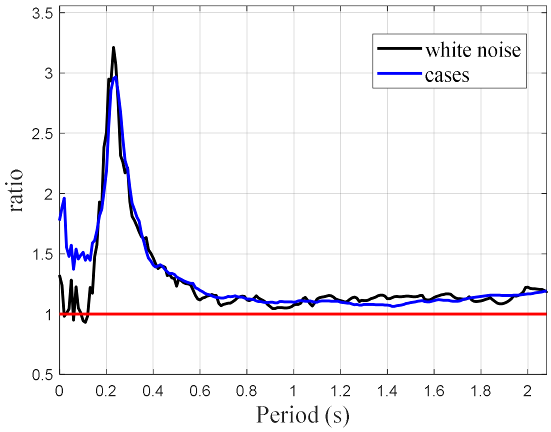

Fig. 6 - Spectrum ratio of white noise cases and natural records cases

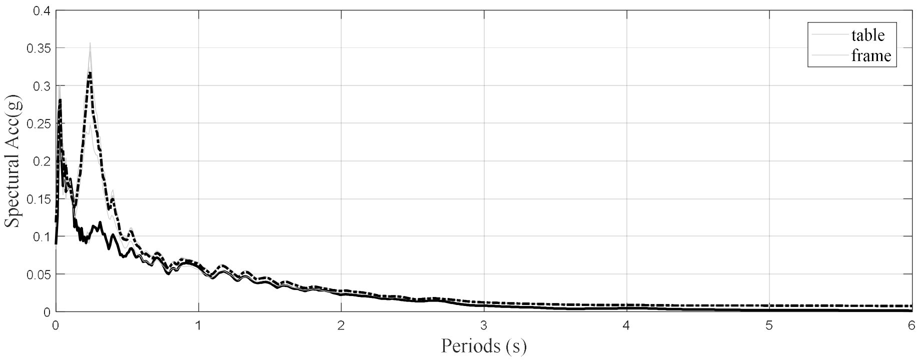

Fig. 7 - Acceleration spectrum of input and the response in white noise cases

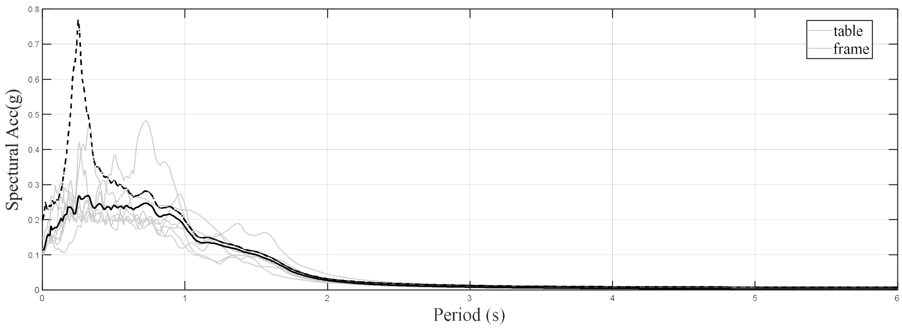

Fig. 8 - Acceleration spectrum of input and the response in natural records cases

3. An approach of a better realization of spectrum characteristics

The difference between spectrum in tests and design spectrum exists, and the approaches for a better realization of spectrum properties relies on modifying the input motions. A procedure is proposed to generate time history according to the dynamic properties of the supporting frame.

Since the white noise cases can be done before the test, the spectrum ratio of frame spectrum over the input spectrum is obvious. Then the spectrum ratio can be used to estimate the frame response under time histories. A procedure to adjust seismic input to get the desired floor spectrum is developed, as is shown in Fig. 9.

To follow this procedure, all the calculations and evaluations shall be performed after the test is set, and before the input of excitation starts. First, one or several white noise tests are carried out to get the basic dynamic properties and the spectrum ratio between hanging points and the table. Then, the average target spectrum can be calculated with the design floor spectrum. When compared with the average spectrum of initial seismic inputs, the target spectrum of each record can be judged to be either the same or different but with an average spectrum as the average target spectrum. Finally, records are adjusted in the frequency domain to match the target spectrum.

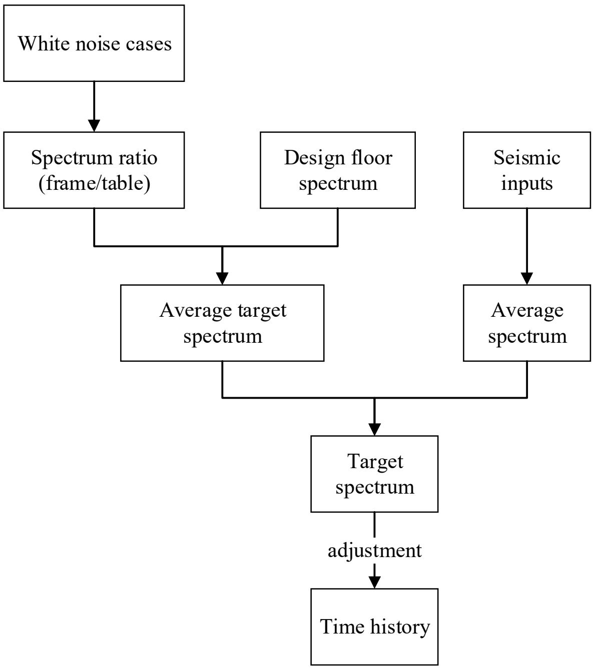

Fig. 9 - Flowchart of modifying time history

To get the time history, spectral acceleration S_a and the Fourier spectrum amplitude A of initial records should be obtained and modified as the amplitude of Fourier spectrum at control periods as Eq. (1).

$$A'(\omega_i) = A(\omega_i) \cdot \frac{S_{a,target}(T_i)}{S_a(T_i)} \quad (1)$$

Since one iteration has limited effect, the Fourier spectrum can be repeatedly modified till the acceleration spectrum matches the target spectrum. A good indicator of a matched spectrum is that ε is smaller than 0.05. ε is defined as the following equation, where N is the number of control periods.

$$\varepsilon = \sqrt{\frac{\sum_{i=1}^{N} [1 - \frac{S_a(T_i)}{S_{a,target}(T_i)}]^2}{N}} \quad (2)$$

4. A case study of an improved approach

The shaking table test results are collected, and the approach of modifying time history is applied. The average target spectrum is shown in Fig.10. The floor spectrum is in the red line, the initial input spectrum is in the blue line, and the average target spectrum is in the black line.

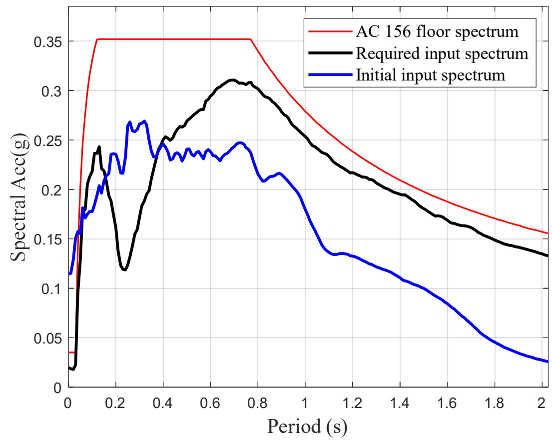

Fig.10 - Initial input spectrum and average target spectrum

The control periods are 0-1s, which is easier for the shaking table to reproduce the excitation since a longer period component will increase the peak displacement and is not harmful to NCs. One modified time history of El Centro wave and its spectrum are shown in Fig.11, and Fig. 12. The modified time history matches the target spectrum well in control periods of 0-1s.

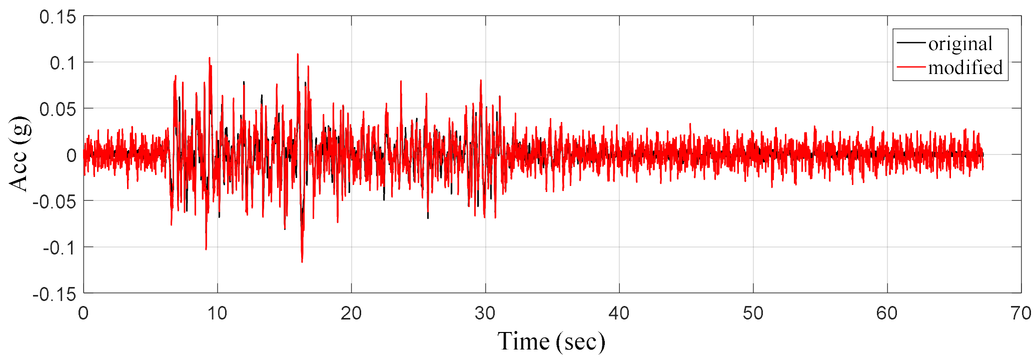

Fig. 11 - Time history of initial records and modified records

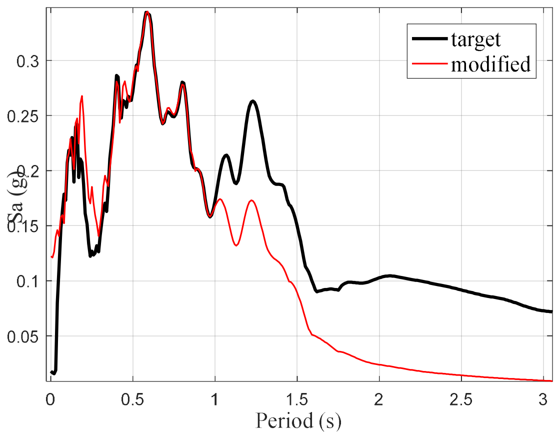

Fig. 12 - Time history of initial records and modified records

A simplified finite element model is established according to the configuration and characteristics of the supporting frame (Figure 13). The joints which are actually connecting four frame-blocks are simplified as the same section characteristics in the middle of the column, and the façade system is considered as the lumped mass on the hanging point while the complex connecting is not considered in this FEM model.

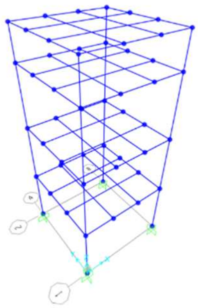

Fig. 13 - FEM model of the test system

The result of the simulation shows a better realization of the spectrum properties. The response spectrum of the modified El Centro wave is shown as Fig. 14. There is no obvious sharp amplitude around the natural period of the supporting frame when compared with the spectrum in the test. The result of all 7 records after modification can be seen in Fig.15. The response spectrum on the supporting frame matches well with the AC156 floor spectrum in control periods.

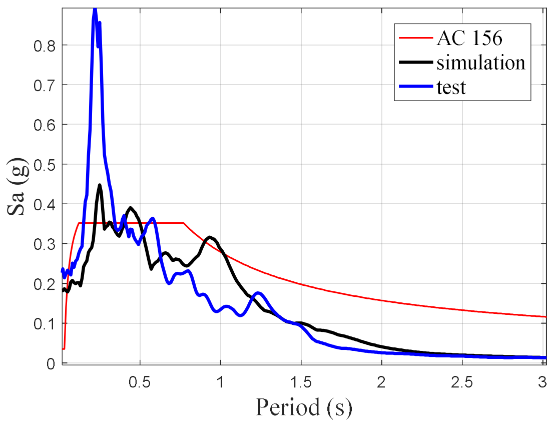

Fig.14 - Spectrum realization of El Centro wave

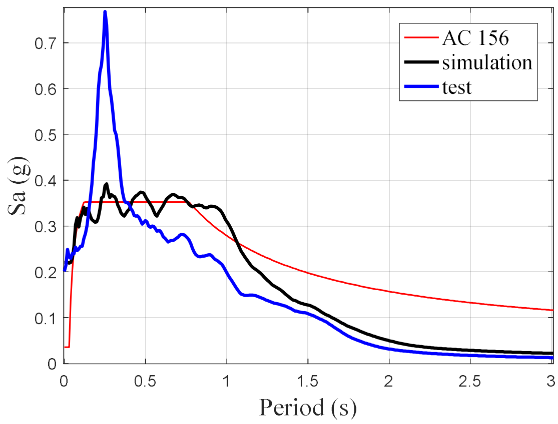

Fig.15 - Spectrum realization of all 7 records

5. Conclusions

The seismic inputs and responses in a shaking table test for evaluating the seismic performance of the unit granite façade system are introduced, and the difference of spectrum is compared. A procedure is proposed to match the response spectrum on NCs with the design floor spectrum. The approaches of reproducing appropriate seismic inputs to façade system in shaking table tests are summarized as follows.

1. Seismic inputs in shaking table tests for NCs should consider both ground motion characteristics and dynamic properties of main structures. Natural records can be used as input motions, while the spectrum on supporting frames could be different from that of input motions.
2. Spectrum ratio between supporting frame and input motion has several factors, e.g., the natural frequency of the supporting frame, mass and stiffness of NCs, and also the spectrum of input motions.
3. A new approach to better realize the floor spectrum by modifying the Fourier spectrum and the time history of input motions are proved to be accessible by simulation.

6. Acknowledgment

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