Theoretical and Experimental Study of Twin-tower Tall Building Connected with Damper-supported Corridor under Seismic Excitation

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ABSTRACT:
The twin-tower tall building connected with space corridors is applied more and more popular. When the corridors are soft-connected with damper supports, the seismic performance may be better than rigid connected scheme. To evaluate relative displacement of the damper under server seismic excitation, which is the key problem to prevent collapse of the corridor, theoretical and experimental research are performed. 3-DOF model is established, in which the twin towers and the corridor are represented with 1-DOF respectively. The transfer function and the RMS of relative displacement of damper are deduced in frequency domain. The seismic excitation spectrums include white noise and Kanai-Tajimi spectrum. Parameter study indicates that the resonance between corridor and each tower in vibration frequency will lead to big relative support displacement, that the mass ratio between corridors to tower will decrease the relative support displacement, that the damping ratio of support will decrease the relative support displacement as well. The vibration frequency of corridor should be calculated under restrained of both supports. Experiments of steel frames connected with spring support corridor are performed on dynamic simulator. The test result proves the theoretical conclusion, and indicates that to eliminate the relative support displacement, the adequate damping ration of the corridor should be least.

KEYWORDS: Damper, Twin-tower, Tall building, Seismic, Dynamic simulator, Resonance

1. FOREWORD

In last decade, the twin-tower tall buildings, which are connected with space corridors, are applied more and more popular. With the design concept of giant gate, they always bring impact in version and make themselves become landmarks in local regions, even a few of them have entered the tallest buildings list in the world. Current research and practice indicates that if the towers are connected with corridor rigidly, the towers' seismic response will couple, in some case even become worst than that of non-connected multi-tower scheme. On the other hand, if they are connected with damper-supported corridors, the complicated and coupled response will be reduced (HOU, 2006), but the calculation of relative displacement of the damper under server seismic excitation will be the key problem. If the relative displacements exceed the limitation of the damper's deformation, the collapse of the corridor from space may occur. Present researches on twin-connected-tower tall buildings focus on reducing seismic response of towers with dampers (Xu, 2000), but in practice the towers' stiffness can be increased by the lateral resistance system themselves, and the relative support displacement is not good evaluated. This paper tries to find out the most sensitive factor to the relative support displacement by theoretical research and shaking table test.

2. THEORETICAL RESEARCH

2.1. Dynamic Equation of 3-DOF

The basic vibration mode participation factor of single tower is normally greater than 80%, thus 1-DOF model is applied to represent each tower as well as the rigid body vibration of corridor restrained under two damper supporters, 3-DOF dynamic equations set is given as Figure 1, and the meaning of each parameter is shown in Table 1

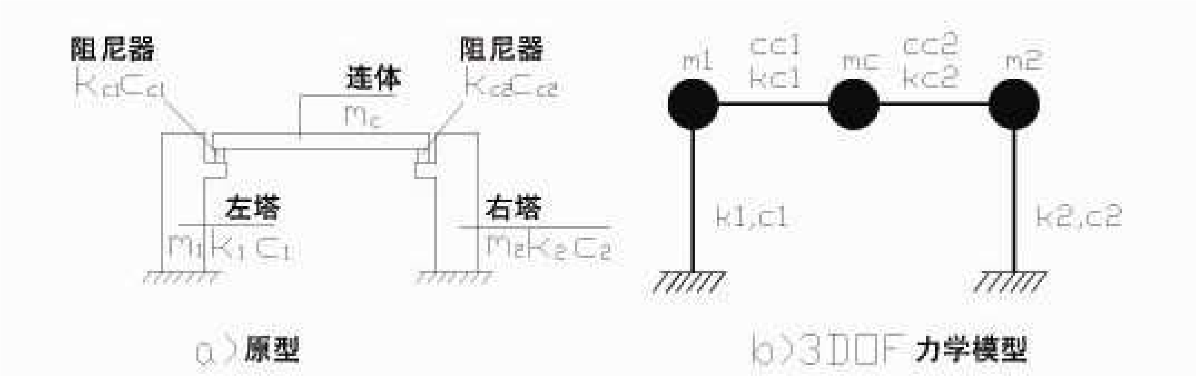

Figure 1 Analysis model of 3-DOF

Table 1 Meaning of each parameter in 3-DOF model

	Mass	Stiffness	Damping Ration
Left Tower	m_1	k_1	c_1
Right Tower	m_2	k_2	c_2
Left Support of Corridor	m_c	k_{c1}	c_{c1}
Right Support of Corridor		k_{c2}	c_{c2}

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=-[M][I_n]\{\ddot{x}_g\} \quad (1)$$

In which, $$[M]=\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_c \end{bmatrix} \quad (2)$$

$$[C]=\begin{bmatrix} c_1+c_{c1} & 0 & -c_{c1} \\ 0 & c_2+c_{c2} & -c_{c2} \\ -c_{c1} & -c_{c2} & c_{c1}+c_{c2} \end{bmatrix} \quad (3)$$

$$[K]=\begin{bmatrix} k_1+k_{c1} & 0 & -k_{c1} \\ 0 & k_2+k_{c2} & -k_{c2} \\ -k_{c1} & -k_{c2} & k_{c1}+k_{c2} \end{bmatrix} \quad (4)$$

2.2. Transfer Function and RMS Displacement

Eq.(1)left-multiplied with [M^{-1}], substituding $\omega_1^2={k_1}/{m_1}$, $\omega_2^2={k_2}/{m_2}$, $\omega_{c1}^2={k_{c1}}/{m_c}$, $\omega_{c2}^2={k_{c2}}/{m_c}$, $\xi_1={c_1}/{2\omega_1 m_1}$, $\xi_2={c_2}/{2\omega_2 m_2}$ $\xi_{c1}={c_{c1}}/{2\omega_{c1} m_c}$, $\xi_{c2}={c_{c2}}/{2\omega_{c2} m_c}$, $\lambda={m_2}/{m_1}$, $\lambda_c={m_c}/{m_1}$, $D_1=2\omega_1\xi_1$, $D_2=2\omega_2\xi_2$, $D_{c1}=2\omega_{c1}\xi_{c1}$, $D_{c2}=2\omega_{c2}\xi_{c2}$ in it, we get:

$$[I_{3x3}]\{\ddot{x}\}+[M^{-1}][C]\{\dot{x}\}+[M^{-1}][K]\{x\}=-[I_{3x3}][I_n]\{\ddot{x}_g\} \quad (5)$$

$[I_{3x3}]$is 3x3 unit matrix, $[I_n]=\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$;

ω_1, ω_2 are vibration circle frequencies of left and right towers;

ω_{c1}, ω_{c2} are vibration circle frequencies of corridor restrained under left or right support;

ξ_1, ξ_2 are damping ratios of left and right towers;

ξ_{c1}, ξ_{c2} are damping ratios of left and right support of corridor;

λ, λ_c are mass ratio between right tower to left tower and ratio between corridor to left tower;

Apply Fourier transfer to Eq.(5), we get:

$$[A]\{X(i\omega)\}=[I_n]\{X_g(i\omega)\} \quad (6)$$

In which, $[A]=[I_{3x3}](i\omega)^2+\left[M^{-1}\right][C](i\omega)+\left[M^{-1}\right][K]$ (7)

$$\{X(i\omega)\}=\begin{Bmatrix}X_1(i\omega)\\X_2(i\omega)\\X_c(i\omega)\end{Bmatrix},\quad X_j(i\omega)=\int_{-\infty}^{\infty}x_j e^{-i\omega t}dt\text{ , } j=1\text{, }2\text{, }c \quad (8)$$

$$\left\{X_g(i\omega)\right\}=-\int_{-\infty}^{\infty}\ddot{x}_g e^{-i\omega t}dt \quad (9)$$

Eq.(6) is left-multiplied with $[A]^{-1}$ and right-multiplied with $\left\{X_g(i\omega)\right\}^{-1}$, we get

$$\begin{Bmatrix}X_1(\omega)/X_g(\omega)\\X_2(\omega)/X_g(\omega)\\X_c(\omega)/X_g(\omega)\end{Bmatrix}=[A]^{-1}\begin{Bmatrix}1\\1\\1\end{Bmatrix} \quad (10)$$

The transfer function expresses the transfer relationship of input and output variables in a linear system in frequency domain. Thus, we get:

$$\{H(i\omega)\}=\begin{Bmatrix}H_{x_1}(i\omega)\\H_{x_2}(i\omega)\\H_{x_c}(i\omega)\end{Bmatrix}=[A]^{-1}\begin{Bmatrix}1\\1\\1\end{Bmatrix} \quad (11)$$

$$\begin{cases}H_{x_1}(i\omega)=\dfrac{B_{14}(i\omega)^4+B_{13}(i\omega)^3+B_{12}(i\omega)^2+B_{11}(i\omega)+B_{10}}{Det(A)}\\H_{x_2}(i\omega)=\dfrac{B_{24}(i\omega)^4+B_{23}(i\omega)^3+B_{22}(i\omega)^2+B_{21}(i\omega)+B_{20}}{Det(A)}\\H_{x_c}(i\omega)=\dfrac{B_{34}(i\omega)^4+B_{33}(i\omega)^3+B_{32}(i\omega)^2+B_{31}(i\omega)+B_{30}}{Det(A)}\end{cases} \quad (12)$$

$$Det(A)=A_6(i\omega)^6+A_5(i\omega)^5+A_4(i\omega)^4+A_3(i\omega)^3+A_2(i\omega)^2+A_1(i\omega)+A_0 \quad (13)$$

This research focuses on the relative displacement. The relative displacement between left tower and corridor is expressed in dx_1, and relative displacement of right tower and corridor in dx_2. In this paper, dx_1, dx_2 are not the differential of x_1, x_2:

$$dx_1=x_1-x_c \quad (14)$$

$$dx_2=x_2-x_c \quad (15)$$

Since x_1, x_2, x_c are all independence variables, apply Fourier transfer to Eqs. (14)、 (15), and based on the linear relation of Fourier transfer, we get:

$$\tilde{F}(dx_1)=\tilde{F}(x_1-x_c)=\tilde{F}(x_1)-\tilde{F}(x_c) \quad (16)$$

$\tilde{F}$ represents Fourier transfer.

$$DX_1(i\omega)=X_1(i\omega)-X_c(i\omega) \quad (17)$$

$$DX_2(i\omega)=X_2(i\omega)-X_c(i\omega) \quad (18)$$

Similar steps, we get

$$[A_d]\{DX(i\omega)\}=[I_n]\left\{X_g(i\omega)\right\} \quad (19)$$

$$\{DX(i\omega)\}=\begin{Bmatrix}DX_1(i\omega)\\DX_2(i\omega)\\X_c(i\omega)\end{Bmatrix} \quad (20)$$

$$\{H_d(i\omega)\} = \begin{Bmatrix} DX_1(\omega)/X_g(\omega) \\ DX_2(\omega)/X_g(\omega) \\ X_c(\omega)/X_g(\omega) \end{Bmatrix} = [A_d]^{-1} \begin{Bmatrix} 1 \\ 1 \\ 1 \end{Bmatrix} \quad (21)$$

The seismic input $\ddot{x}_g$ is random load. If the ground motion acceleration is assumed to be white noise with zero mean value, the spectrum density of the acceleration is:

$$S_g(\omega) = S_0 \quad (22)$$

According to random dynamic theory, the mean square of the displacement response is:

$$E[x^2(t)] = R_x(0) = \int_{-\infty}^{+\infty} S_x(\omega) d\omega = \int_{-\infty}^{+\infty} |H(i\omega)|^2 S_g(\omega) d\omega \quad (23)$$

In which, $R_x(\tau)$ is the autocorrelation function of displacement $x(t)$, $S_x(\omega)$ is the spectrum density of structural displacement, S_0 is the spectrum density of ground motion and constant. Thus the mean square of the displacement and relative displacement are:

$$\begin{cases} E\left[x_1^2\right] = S_0 \int_{-\infty}^{+\infty} \left|H_{x_1}(i\omega)\right|^2 d\omega \\ E\left[x_2^2\right] = S_0 \int_{-\infty}^{+\infty} \left|H_{x_2}(i\omega)\right|^2 d\omega \\ E\left[x_c^2\right] = S_0 \int_{-\infty}^{+\infty} \left|H_{x_c}(i\omega)\right|^2 d\omega \\ E\left[dx_1^2\right] = S_0 \int_{-\infty}^{+\infty} \left|H_{dx_1}(i\omega)\right|^2 d\omega \\ E\left[dx_2^2\right] = S_0 \int_{-\infty}^{+\infty} \left|H_{dx_2}(i\omega)\right|^2 d\omega \\ E\left[x_{c2}^2\right] = S_0 \int_{-\infty}^{+\infty} \left|H_{x_{c2}}(i\omega)\right|^2 d\omega \end{cases} \quad (24)$$

In which $E\left[x_c^2\right]$、$E\left[x_{c2}^2\right]$ are both the mean square of corridor displacement and expressed with different transfer function.

2.3. Parameter Study

Based on theoretical research above, vast amount of parameter study is applied to investigate the regularity between relative displacement and some parameter mentioned above, including circle frequencies, mass ratios, damping ratios etc. Some main study cases are listed in Table 2.

The following conclusions are drawn from all parameter study cases:

1) For the symmetric towers situation, the corridor and towers' performance are similar with tuned mass damper (TMD). When the corridor and towers have close frequencies, the vibration of corridor will be strengthened, the displacement of corridor will increased, the vibration of tower will be reduced and displacement decreased. When increasing the mass ration between corridor to tower or damping ratios of corridor support, the displacement of towers and corridor to the ground all decreased, the relative displacement of corridor supports is reduced as well. For the situation of medium to high frequency tower, the displacement of tower is rather small, the relative support displacements of corridor supports mainly come from the displacement of corridor to the ground, and thus it will be effective way to adjust the parameters of corridor.

2) For the unsymmetrical towers situation, when corridor has close frequency with any one of the tower's, resonance occurs, vibration of tower reduce and of corridor increase. The mass ratio between corridor and tower and damping ratio of corridor supports lead to similar performance in symmetric tower situation. The great difference with symmetric tower situation is the asynchronous driving principle, that is, the absolute displacement of corridor is excited by softer tower, but the big relative displacement of corridor support will occur between corridor and stiffer tower.

Table 2 Main Parameter Study Cases*

Case	ω_1	ω_2	ω_{c1}	ω_{c2}	ξ_{c1}	ξ_{c2}	λ_c	Remark	
F3	3	3	1~7@1	ω_{c1}	0.03	0.03	0.05	Symmetric towers	Change ω_{c1}, ω_{c2}
F4	1~7@1	ω_2	3	3	0.03	0.03	0.05		Change ω_1, ω_2
F5	3	3	1~7@1	2.23	0.03	0.03	0.05		Change ω_{c1}
F6	3	3	1~3@0.5	$\sqrt{3^2-\omega_{c1}^2}$	0.03	0.03	0.05		Change ω_{c1}, ω_{c2} keep $\omega_{c2}^2+\omega_{c1}^2=3^2$
F8	3	3	2.12	2.12	0.10	0.10	0.01~0.61 @0.10		change λ_c ,corridor & towers resonance
F10	3	3	2.12	2.12	2^k/100,k =1~7	$=\xi_{c1}$	0.05		change ξ_{c1}, ξ_{c2}, corridor & towers resonance
F11	3	3	2.12	2.12	2^k/100, k=1~7	0.05	0.05		change ξ_{c1} , corridor & towers resonance
F12	1.41	4.23	1~7@1	ω_{c1}	0.03	0.03	0.05	Unsymmetrical Towers	change ω_{c1}, ω_{c2}, keep $\omega_{c2}=\omega_{c1}$
F13	1~7@1	5	3.54	3.54	0.03	0.03	0.05		Change ω_1
F14	3	5	0.49* (k-0.95), k=1~7	$\sqrt{3^2-\omega_{c1}^2}$	0.03	0.03	0.05		Change ω_{c1}, ω_{c2} keep $\omega_{c2}^2+\omega_{c1}^2=3^2$
F16	3	5	2.12	2.12	0.10	0.10	0.01~0.61 @0.10		Change λ_c, corridor & left tower resonance
F16a	3	5	2.12	2.12	0.10	0.10	0.05		corridor & left tower resonance, $\lambda=10^{(0.3k-1.3)}$, k=1~7
F17	3	5	2.12	2.12	2^k/100, k=1~7	$=\xi_{c1}$	0.05		change ξ_{c1}, ξ_{c2}, corridor & left tower resonance,
F18	3	5	2.12	2.12	2^k/100, k=1~7	0.05	0.05		Change ξ_{c1}, corridor & left tower resonance,
F19	3	5	2.12	2.12	0.05	2^k/100, k=1~7	0.05		change ξ_{c2}, corridor & left tower resonance,
F20	3	5	(k-0.95)* 0.49, k=1~7	$\sqrt{3^2-\omega_{c1}^2}$	2^k/100, k=1~7	0.05	0.05		ξ_{c1}, ξ_{c2} ω_{c1}, ω_{c2} Change Corridor & left tower resonance
F21	1~7@1	5	3.54	3.54	0.03	0.03	0.05		K-T Spectrum, other same as F13
F22	1.41	4.23	1~7@1	ω_{c1}	0.03	0.03	0.05		K-T Spectrum, other same as F12

* In Table 2 @ represents step of variables, unit of circle frequencies is rad/s. Unless specified, some parameters are $\xi_1=\xi_2=0.05$,λ=1.

3) The principles under excitation of white noise and K-T spectrum are similar, besides the white-noise leads

to overestimate displacement at low frequency range.

3. EXPERIMENTAL RESEARCH

3.1. Experiment Design

Experiment of dynamic simulator was performed at Earthquake Resistance Research Centre of Guangzhou University in January 2008. The model is steel slab-column structure, the slabs made from steel plate and columns from steel rebar, they are connected with bolts. This type of model has the following advantages: 1) Accurate mass, 2) Adjustable height and stiffness, 3) Vibration frequencies suitable to be excited by dynamic simulator (Figure 3~Figure 4).

The damper supports of corridor are simulated with different stiffness tension spring pairs and small wheels. The tension spring pairs provide various stiffness and the wheels support the corridor when moving (Figure2).

Figure 2 Damper support

Figure 3 Unsymmetrical model

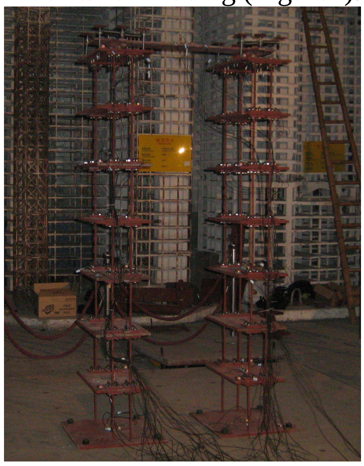

Figure 4 Symmetric model

This type of mechanism has been design in this way based on following consideration:

1) The tension spring is more stable than compression spring;

2) spring pair can keep internal force balance and no extra influence to tower stiffness;

According to theory analysis, the spring pair provides fix stiffness under working tension range, and the stiffness is calculated as:

$$k_{1+2} = k_1 + k_2 \qquad (25)$$

In Eq.(25) k_1, k_2 are two single spring's stiffness, and k_{1+2} is stiffness of spring pair. The outer diameters of spring range from 14~22mm. Varies corridor frequencies are obtained with different spring pairs supports. In the experiment cases of this paper, the corridor is movable along two towers' center line and fixed perpendicular to the center line.

The dynamic simulator has size of 3m x 3m at table and can excite the model in 3 directions and 6-DOF, the team operating the machine has rich experience.

The waves used to excite the model include white-noise, El-Centro, Taft, Northridge and simple harmonic wave. The harmonic wave frequencies are selected according to structural frequencies. Since the model's basic frequency is within 5 Hz, the seismic records were compressed in time with scale of 1:5.

3.2. Experiment Result

Totally more than 80 experiment cases are applied in damper support model, symmetric and unsymmetrical, under horizontal excitation. The corridor time history proves the above conclusion by theoretical analysis at stationary stage. The data will be published in other paper due to words limitation. The experiment not only proves the conclusion from theoretical study, but also brings further understanding to this interesting topic.

3.2.1 Equivalent Damping Ratio

The half band width of power curve method (R.Clough, 2003) is applied to test the damping ratio of models restrained with different corridor supports.

$$\xi = \frac{f_2 - f_1}{f_2 + f_1} \quad (26)$$

f_1， f_2 is the values of frequencies at frequency-response curve where the peak of amplifier multiplying $1/\sqrt{2}$, and in Figure 5 they are the values of the intersection between the curve and *x* axis. Results of 5 cases are shown in Table 3，it is interesting that, for the 3 cases of the 7 stories symmetric towers， the equivalent damping ratios are ordered in T79，T73，T85. The phenomena shows that when the frequencies'' ratio between corridor to tower is close to 1, the damping ratio of whole structure is bigger, even can reach 5 times of single tower. The corridor acts as energy absorber of tower.

Table 3 Equivalent Damping Ratio

工况	Peak	Peak $/\sqrt{2}$	Resonance Freq f	f_1	f_2	ξ
5 story single tower T1	257.70	182.22	5.625	5.606	5.644	0.34%
7 story single tower T61	82.88	58.61	3.656	3.608	3.676	0.93%
7 story twin tower T73	538.77	380.97	3.219	3.151	3.243	1.40%
7 story twin tower T79	59.75	42.25	3.281	3.2925	3.270	0.34%
7 story twin tower T85	700	495	3.125	3.03	3.35	5.02%

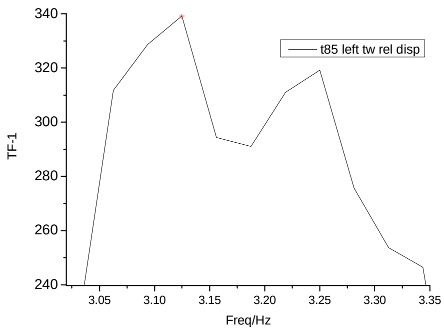

Figure 5 Damping Ratio tested by half band width power method

3.2.2 Nonstationary State

When the first peak of ground motion arrives and the corridor is not excited thoroughly, the relative big displacement between corridor and tower may occur. But at stationary stage, the corridor will be driven and move synchronous. Thus it is important to control the support displacement at nonstatoinary stage, it is effective method to avoid resonance to tower vibration and increase the stiffness or damping ratios of supports. (Figure 6)

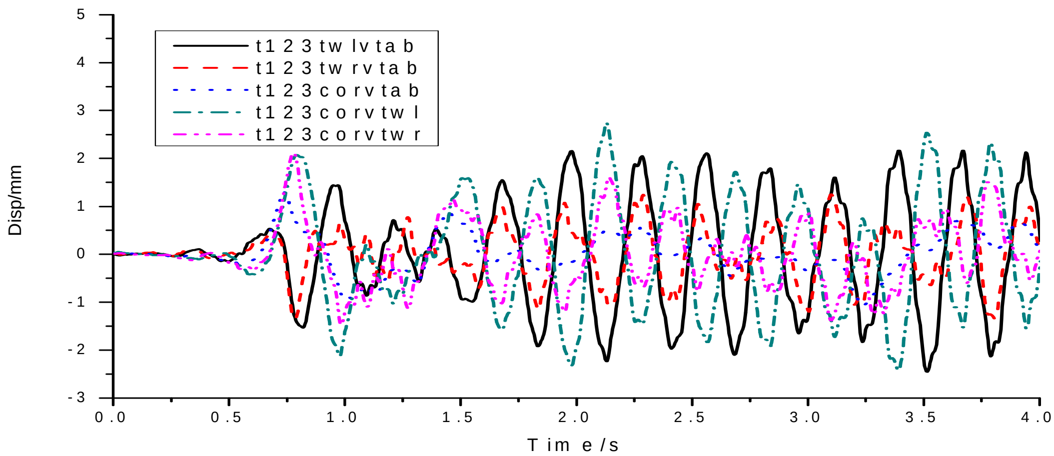

Figure 6 T123 Displacement Time History

4. CONCLUSION

The theoretical and experimental research of twin-tower connected with damper-support corridor indicates that:

1) At stationary stage, resonance between corridor and tower frequencies should be avoid to minimize the relative displacement between corridor and towers. Increasing the damping ratio of supports or mass ratio between corridor to tower will be helpful as well. The working mechanics is to avoid the corridor acting as energy absorber of tower;
2) At nonstationary stage, first peak of ground motion may lead to large support displacement, and some measurement should be applied, e.g. adjusting the parameters of corridor or some equipment to limit the displacement of supports.

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