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Experimental Investigations on Behaviour of Steel Structure Buildings

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ABSTRACT: In this study, design, building and commissioning procedure of a scale steel structure building model has been developed for practical applications in shaking table test programmes. To validate the model, shaking table tests and numerical time history dynamic analyses were carried out under the influence of different scaled earthquake acceleration records. Comparing the numerical predictions and experimental values of maximum lateral displacements, it became apparent that the numerical predictions and laboratory measurements are in a good agreement. Thus, it is concluded that the physical model is a valid and qualified model with sufficient accuracy which can be employed for further experimental shaking table investigations.

1 INTRODUCTION

Many researchers (e.g. Zhang et al., 1998; Fallahi et al., 2004; Rodríguez et al., 2006; Ziemian et al., 2010) have performed shaking table tests to determine linear and nonlinear dynamic response of scale structural models subjected to various earthquake records. However, none of the past research works presented the process of design and commissioning of building structural models. As a result, in order to employ structural models in testing programmes, researchers may need to spend substantial amount of time and effort to properly design and produce construction detail drawings for their structural models, in particular for tall building structural models. In response to this need and in order to save time and energy, in this study, a comprehensive procedure for detail design, building and commissioning of scale tall building structural models has been developed and presented for practical applications in shaking table test programmes.

2 BUILDING STRUCTURAL MODEL

The prototype of the experimental tests is a two dimensional fifteen storey steel moment resisting building frame. The building frame height and width are 45 and 12 metres, respectively and spacing between the frames into the page is 4 metres. The building is resting on a footing which is 4 meters wide and 12 meters long. The natural frequency of the prototype building is 0.384 Hz and its total mass is 953 tonnes. The utilised scaling relations for the variables contributing to the primary modes of system response are shown in Table 1. The mentioned scaling relationships have been employed by many researchers (e.g. Meymand, 1998; Turan et al., 2009; Moss et al., 2010; Sulaeman, 2010; Lee et al., 2012; Tabatabaiefar et al., 2015) in their shaking table tests and are very well established and well known among the seismic engineering researchers. Geometric scaling factor (λ) of 1:30 is adopted for experimental shaking table tests on the scale tall building model in this study. Employing geometric scaling factor of 1:30, height (H), length (L), and width (W) of the structural model are determined to be, 1.50 m, 0.40 m, and 0.40 m, respectively. Referring to Meymand (1998) principal test conditions, in order to achieve dynamic similarity, in addition to geometric dimensions, the natural frequency of the prototype should be scaled by an appropriate scaling relation and the density of the model and the prototype should be equal. Dynamic similarity describes a condition where homologous parts of the model and prototype experience homologous net forces. In this way, prototype structure may be modelled more accurately in shaking table tests. The mentioned two parameters play key roles in the scaling process, and scaling them deemed to be adequate.

According to Table 1, the scaling relationship between natural frequency of the model ($\boldsymbol{f_m}$) and natural frequency of the prototype ($\boldsymbol{f_p}$) is:

$$\frac{f_m}{f_p} = \lambda^{-1/2} = 5.480 \tag{1}$$

Table 1: Scaling relations in terms of geometric scaling factor (λ)

Mass Density	**1**	Acceleration	**1**	Length	**λ**
Force	**λ^3**	Shear Wave Velocity	**$\lambda^{1/2}$**	Stress	**λ**
Stiffness	**λ^2**	Time	**$\lambda^{1/2}$**	Strain	**1**
Modulus	**λ**	Frequency	**$\lambda^{-1/2}$**	EI	**λ^5**

The natural frequency of the prototype structure is f_p = 0.384 Hz. Therefore, the required natural frequency of the structural model ($\boldsymbol{f_m}$) can be determined as follows:

$$f_m = 5.480 \times f_p = 5.480 \times 0.384 = 2.11 \ Hz$$

The determined natural frequency of the model is conforming with the approximated value of average frequency of the building equal to 2.95 Hz, calculated by Equation 6.2(7) of AS 1170.4-2007.

Scaling relationship between density of the model (ρ_m) and density of the prototype (ρ_p), based on Table 1, is:

$$\frac{\rho_m}{\rho_p} = 1 \Rightarrow \rho_m = \rho_p \tag{2}$$

Density of the prototype structure (ρ_p) can be determined as follows:

$$\rho_p = \frac{m_p}{V_p} = \frac{953{,}000}{45 \times 12 \times 4} = 441 \, kg/m^3 \tag{3}$$

where, m_p is the mass of the prototype structure and V_p is the volume of the prototype structure. Substituting the density of the prototype structure (ρ_p) from Equation (3) into Equation (2), the mass of the structural model (m_m) can be estimated as:

$$m_m = \rho_m \times V_m = 441 \ kg/m^3 \times \ (1.50 \ m \ \times 0.40 \ m \times 0.40 \ m) = 106 \ kg \tag{4}$$

where, V_m is the volume of the structural model. Based on the above mentioned discussions, the required characteristics of the structural model is summarised in Table 2.

Table 2: Characteristics of the structural model

Total Height (m)	Total Length (m)	Total Width (m)	Natural Frequency (Hz)	Total Mass (kg)
1.50	0.40	0.40	2.11	106

3 DESIGN AND CONSTRUCTION OF BUILDING MODEL

Knowing the required characteristics of the structural model, its 3D numerical model has been created in SAP2000 software using two dimensional shell elements to model columns and floors as shown in Figure 1. The numerical model consists of fifteen horizontal steel plates as the floors and four vertical steel plates as the columns. Steel plate grade 250, according to AS/NZS 3678-2011 (Structural Steel), with the minimum yield stress of 280 MPa and minimum tensile strength of 410 MPa, has been adopted in the design. The thickness of the steel plates have been determined in design process after several cycles of trial and error in order to fit the required natural frequency and mass as summarised in Table 2. After the numerical modelling and design, construction detail drawings were prepared to reflect the design requirements of the structural model. Construction details of the structural model are illustrated in Figure 2. The numerical results of the analysis show that the designed structure has the natural frequency of f_m =2.13Hz and the calculated total mass is 105.6 kg, which are both in good agreement with the requirements in summarised Table 2.

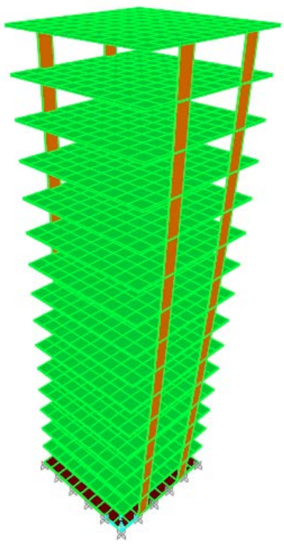

Fig. 1: 3D numerical model of the structural model in SAP2000

In the building phase, the detail drawings were passed on to the engineering workshop. At the workshop, the steel plates were cut and drilled according to construction detail drawings and then sent to the structures laboratory to be assembled. Afterwards, the steel plates were assembled in order to form the structural model using stainless sheet metal screws with 2.5 mm diameter and 25 mm length. Figure 3 shows the completed structural model. The mass of the model (mm), without the base plate, was measured to be 104 kg which matches the required structural mass (Table 2). Total measured mass of the structural model considering the mass of the base plate is 115kg.

Fig.2. Completed building model

4 SCALING OF ADOPTED EARTHQUAKE ACCELERATION RECORDS

Four earthquake acceleration records including Kobe, 1995 (Figure 3a), Northridge, 1994 (Figure 4a), El Centro, 1940 (Figure 5a), and Hachinohe, 1968 (Figure 6a) have been adopted for the shaking table tests. The first two earthquakes are near field ground motions and the latter two are far field motions. These earthquakes have been chosen by the International Association for Structural Control and Monitoring for benchmark seismic studies (Karamodin and Kazemi, 2008). According to Table 1, as determined by Equation (1), scaling relationship between natural frequency of the model (f_m) and natural frequency of the prototype (f_p) is 5.48 while scaling relations between the model and prototype accelerations is 1.0. It means that the earthquake magnitude remains the same as the prototype based on the first principle of "dynamic similarity" (Meymand, 1998; Turan et al., 2009) which defines model and prototype accelerations to be equal (Table 1). Therefore, for scaling the earthquake records, it is required to reduce the time steps of the original records by a factor of 5.48. As a result, the original time steps of Kobe, Northridge, and El Centro earthquake acceleration records were shifted from 0.02 to 0.00365, while for Hachinohe earthquake record, the original time steps of 0.01 shifted to 0.001825. The scaled acceleration records of the four adopted earthquakes are illustrated in Figures 6b to 9b.

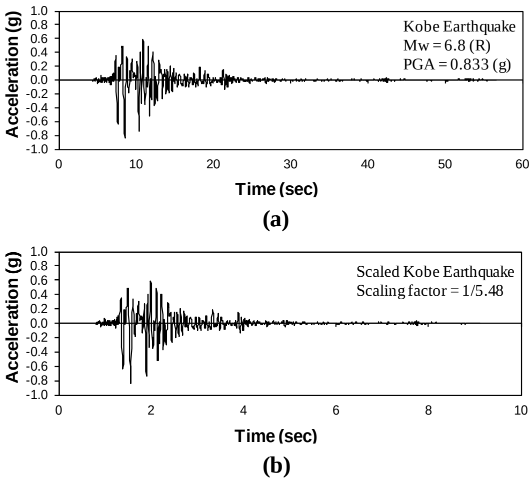

Fig.3. Kobe earthquake (1995)
a) original record; (b) scaled record

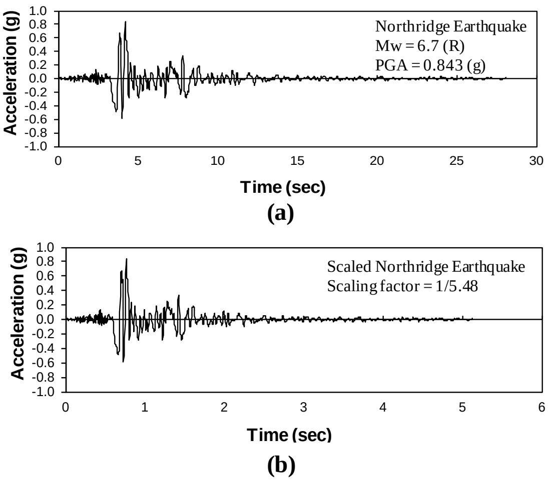

Fig.4. Northridge earthquake (1994)
a) original record; (b) scaled record

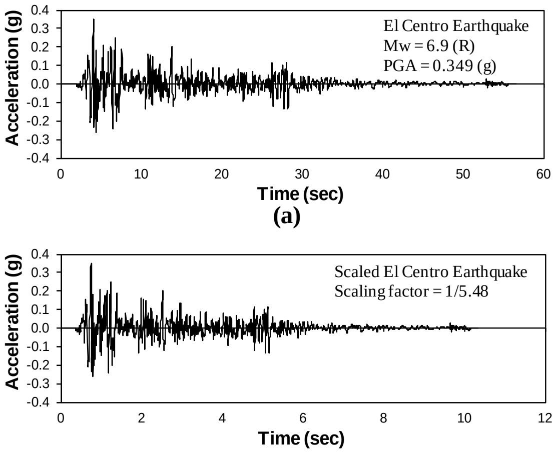

Fig.5. El Centro earthquake (1940)
a) original record; (b) scaled record

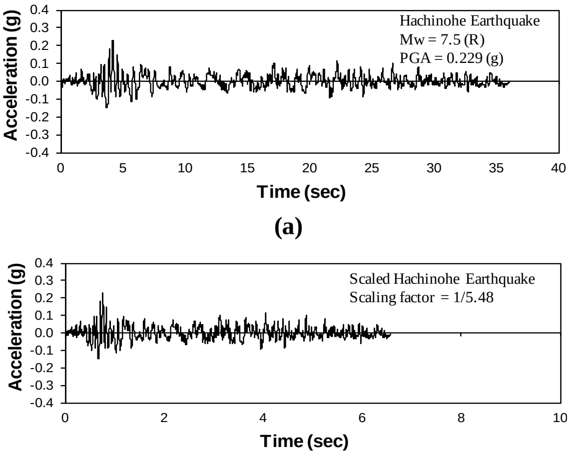

Fig.6. Hachinohe earthquake (1968)
a) original record; (b) scaled record

5 SHAKING TABLE TESTS PROCEDURE

Shaking table tests have been performed on the scale tall building structural model which has been directly fixed on top of the shaking table in order to:

- Ensure the structural model possesses targeted natural frequency;
- Determine the damping ratio of the structural model; and
- Obtain seismic response of the structural model to be used for numerical verification purposes.

To achieve the above, the structural model was fixed and secured on the shaking table as shown in Figure 11. After securing the structural model on the shaking table, instrumentations including displacement transducers and accelerometers were installed on the structure in order to monitor the behaviour of the structure and to primarily measure structural lateral displacements. It should be noted that in addition to the displacement transducers installed at levels 3, 5, 7, 11, 13, and 15, eight accelerometers were installed at levels 3, 5, 7, 9, 11, 13, and 15 so as to check the consistency of the recorded displacements. Displacement, acceleration and velocity in time domain are closely related to each other. If the measured parameter is acceleration, displacement can be found through a double integration in time domain. Therefore, displacements of the various levels were determined by integrating the corresponding accelerations, measured by the accelerometers, in time domain and checked against the recorded displacements to ensure the consistency and accuracy of the obtained records. Figure 7 illustrates the final arrangement of the displacement transducers and accelerometers at different levels of the structural model.

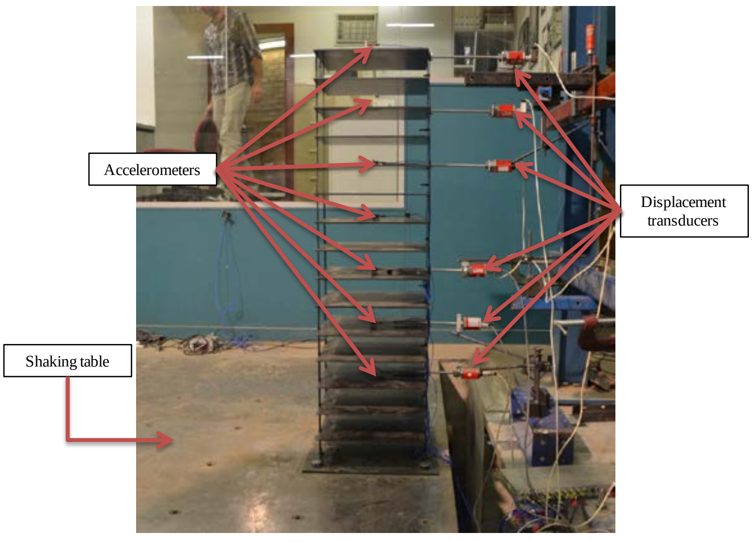

Fig.7. Final arrangement of the measuring instruments of the fixed base model (Tabatabaiefar et al., 2014)

Initially, Sine Sweep test was performed on the structural model to determine the natural frequency of the model. Sine Sweep test involves a logarithmic frequency sweep holding a specified acceleration constant at the base of the structure. For the current Sin Sweep test, frequency of the shaking table has increased from 0.1 Hz to 50 Hz. The first resonance between the shaking table and structural model frequencies showed the fundamental natural frequency of the model. The test was repeated three times to ensure the determined natural frequency is adequately accurate. The resulting natural frequency of the constructed structural model obtained from sin sweep test results was 2.19 Hz which is in a very good agreement with the desired natural frequency of structural model (Table 2). Therefore, the constructed structural model, with the natural frequency (f_m) of 2.19 Hz and the total mass (m_m) of 104 kg, possesses the required characteristics as summarised in Table 2, to meet the dynamic similarity criteria. After ensuring adequacy of the structural model characteristics, shaking table tests were performed by applying scaled earthquake acceleration records of Kobe, 1995 (Figure 6b), Northridge, 1994 (Figure 7b), El Centro, 1940 (Figure 8b), and Hachinohe, 1968 (Figure 9b) to the tall building structural model.

The estimated value of the structural damping ratio of the constructed structural model has been determined from the free vibration lateral displacement records of the structural model using the following Taylor series expansion (Roy et al., 2006):

$$\frac{U_n}{U_{n+m}} = e^{2\pi m\xi} = 1 + \sum_{n=1}^{\infty} \frac{(2\pi m\zeta)^n}{n!} = 1 + 2\pi m\xi + \frac{(2\pi m\xi)^2}{2!} + \ldots \tag{5}$$

where, ξ is the structural damping ratio and U_n and U_{n+m} are two positive peaks of the free vibration response of the structure which are m cycles apart. Substituting the values of U_n and U_{n+m} for the two positive peaks of the free vibration lateral displacement records in Equation (5), which are 10 cycles apart, and repeating the whole process several times, the estimated structural damping ratio (ξ) is 1.1%. The results of the performed shaking table tests under the influence of four scaled earthquake acceleration records in terms of maximum lateral deflections are determined and presented in Figures 8a to 8d. In determination of the lateral deflections, the movement of the shaking table has been subtracted from storey movements. Therefore, all the records are in comparison to the base movements. It should be noted that for the sake of accuracy and consistency, the recorded displacements using displacement transducers, verified against the calculated displacements from accelerometer records, are presented.

6 NUMERICAL VERIFICATION

The numerical model of the constructed structural model has been created in SAP2000 using dimensions of the physical model. After building the geometry of the structural model, the required structural parameters including cross-sectional area of the beams (A_b), moment of inertia of the beams (I_b), cross-sectional area of the columns (A_c), moment of inertia of the columns (I_c), cross-sectional area of the foundation slab (A_s), moment of inertia of the foundation slab (I_s), modulus of elasticity of steel (E), density (ρ), and structural damping ratio (ξ), summarised in Table 3, were extracted from the construction detail drawings and specifications and adopted in the numerical simulation of the structure in SAP2000. After creating the numerical model, time history dynamic analyses were performed under the influence of four scaled earthquake acceleration records including Kobe, 1995 (Figure 3b), Northridge, 1994 (Figure 4b), El-Centro, 1940 (Figure 5b), and Hachinohe, 1968 (Figure 6b) and the results in terms of maximum lateral deflections are determined and shown in Figures 8 to 11. Geometric nonlinearity of the structures, capturing P-Delta effects, has been accommodated in the structural analysis.

Table 3: Adopted parameters for numerical simulation of the structural model

A_b (m^2)	I_b (m^4)	A_c (m^2)	I_c (m^4)	A_s (m^2)	I_s (m^4)	E (kPa)	ρ (kg/m^3)	ξ (%)
0.002	4.16E-9	1.6E-4	5.33E-11	0.005	4.16E-8	2.0E8	7850	1.1

7 RESULTS AND DISCUSSION

The numerical predictions and experimental values of the maximum lateral displacements of the scale structural model are presented and compared in Figures 8a to 8d. Average values of the numerical predictions and experimental values are determined and compared in Figure 9.

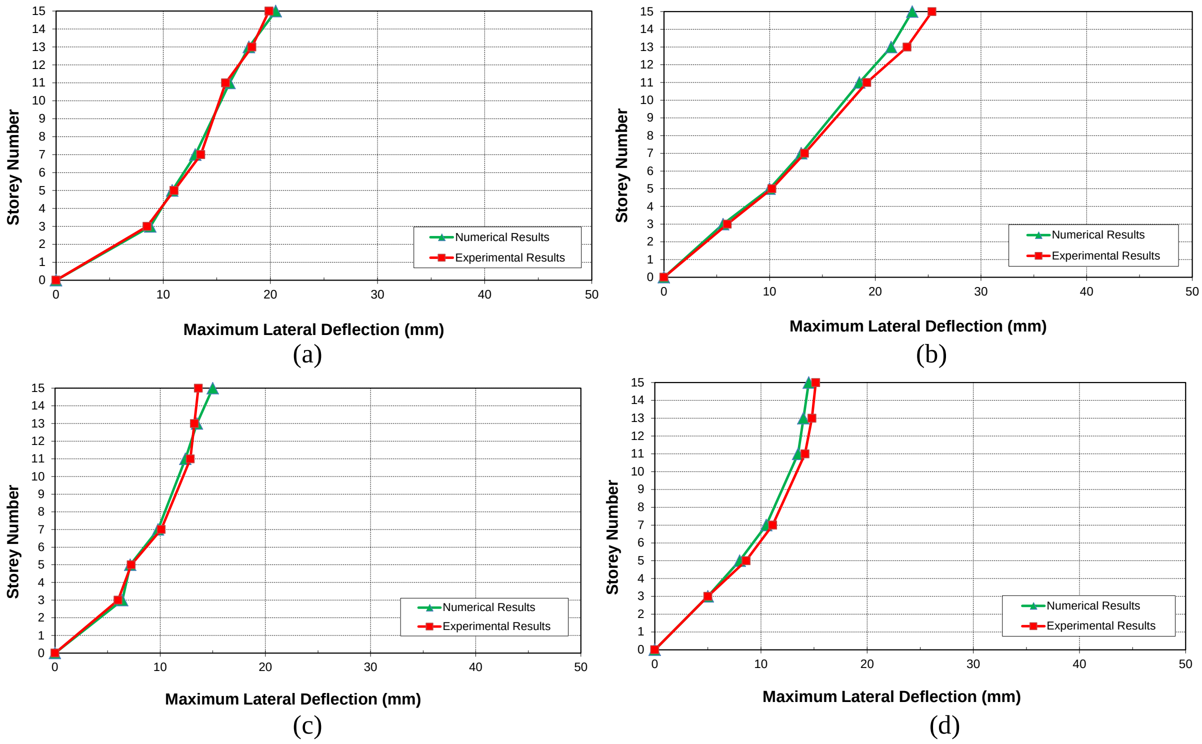

Fig.8. Numerical and experimental maximum lateral displacements under the influence of (a) Kobe (1995) earthquake; (b) Northridge (1994) earthquake; (c) El Centro (1940) earthquake; (d) Hachinohe (1968) earthquake

Comparing the predicted and observed values of the maximum lateral displacements, the accuracy of the experimental shaking table test results is examined. Reviewing the average maximum lateral deflections (Figure 9), it becomes apparent that the numerical predictions and laboratory measurements are in a good agreement (less than 5% difference). Accordingly, it becomes apparent that the trend and the values of the experimental shaking table test results are in good agreement and consistent with the numerical predictions. The observed discrepancy between the numerical predictions and laboratory observations could be due to energy absorption at the bolted connection of the base in the physical laboratory model which cannot be captured by rigid base assumption of the numerical model.

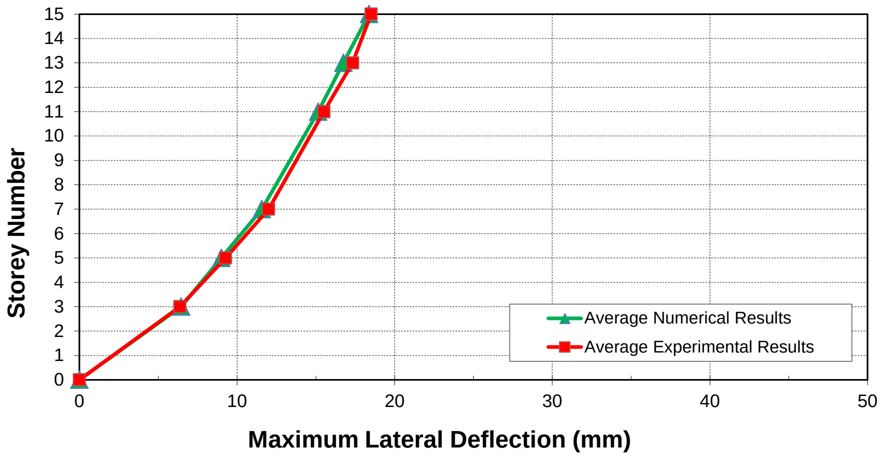

Fig.9. Average values of numerical predictions and experimental values of the maximum lateral displacements

8 CONCLUSIONS AND RECOMMENDATIONS

In this study, a comprehensive procedure for detail design, building and commissioning of a scale tall building structural model has been developed and presented for practical applications in shaking table test programmes. Shaking table tests under the influence of four scaled earthquake acceleration records have been performed on the scale model and the results in terms of maximum lateral deflections were determined. Afterwards, the numerical model of the constructed structural model has been created and time history dynamic analyses were performed under the influence of the mentioned four scaled earthquake acceleration records. Then maximum lateral deflections were determined and compared with the experimental results. Comparing the numerical predictions and experimental values of the maximum lateral displacements of the scale structural model, it became apparent that the numerical predictions and laboratory measurements are in a good agreement (less than 5% difference). It is concluded that the scale structural model is a valid and qualified model with sufficient accuracy which can be employed for further experimental shaking table investigations.

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