AN INVESTIGATION ON EFFECTIVENESS OF TUNED MASS DAMPER (TMD) DEVICE IN MITIGATING STRUCTURE VIBRATION: A CASE STUDY OF SMALL-SCALE STEEL BEAM

Tran Dinh Minh*, Vo Duy Hung, Nguyen Phu Quang Quan, Ho Manh Hung

The University of Danang – University of Science and Technology, Danang. Vietnam

*Corresponding author: tdminh@dut.udn.vn

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Abstract - TMD devices are considered a reasonable solution to enhance the bearing capacity of the structures under unpredictable impacts from external forces because their operating principle is quite simple and does not vary the main structure. This paper investigated the influence of the TMD device, including its mass and stiffness, on the vibration reduction of the primary structure, a basic steel beam. In which, a small-scale steel beam model with boundary conditions through experiments was carried out. Then, simulated the experiment using MATLAB based on the experimental results to study the effect of TMD on the vibration of the structure. The results exhibit that the vibration-damping capacity of the main structure increases as the TMD mass increases. The stiffness of the main structure is less than 1,8*k* for both TMD 3% and 5%, resulting in the rapid increase of oscillation reduction efficiency.

Key words - Tuned Mass Damper; Steel Beam Bridge; Vibration Control; Stiffness; Initial Excitation Force

1. Introduction

A Tuned Mass Damper (TMD) is essentially an integrated system, consisting of mass, spring, and damping, linked into the main structure to minimize its vibration response [1]. TMD is one of the oldest oscillation control devices and a popular choice thanks to its simplicity and ease of application [2-3]. The TMD is an externally mounted device, does not change the mechanics of the main structure, and uses its self-weight to create relative motion. In addition, the TMD operates by dissipating energy through relative motion between the main structure and its mass as an oscillating frequency is excited [4]. Thus, the greater the inertia force of the TMD acts on the main structure, the greater the relative motion increases [5]. Therefore, the effectiveness of the TMD device depends on its mass of it. When the mass of the TMD increases, it will increase the interaction of the TMD with the main structure. However, the mass of the TMD that is too large affects the main structure [6]. Normally, the optimal mass of TMD is in the range of 2%-5% of the mass of the main vibration system in the structure [7]. The effectiveness of the TMD device is to reduce the vibration significantly as the main structure has a weak damping coefficient. For the main structure to prosper function, the TMD device and the dampers need to have properly selected characteristics [6].

After Frahm invented a vibration control device, which he patented in the United States, TMD became known for the first time as a damper [8]. The TMD model was applied to reduce the ship's rolling motion and showed the installation of a dynamic absorber to reduce the oscillation for the main system based on the stiffness and mass adjustment of the absorber such that the natural frequency of the absorber is the same as the harmonic excitation frequency. Subsequently, Den Hartog developed a theoretical model of TMD with a dynamic absorber that added drag and discussed in detail the optimal TMD parameters in terms of damping (c_d), stiffness (k_d), and mass (m_d) [9-10]. Based on the model of Den Hartog, the researchers have extended the model to many different cases of control target and vibration patterns. Showdown proposed different types of absorbing dampers for efficient structural systems [11]. Falcon developed a model with the main system having dampers [12]. Warburton carried out the statistics of the optimal parameters of dynamic absorbers for many cases [13]. Tsai and Lin conducted an experimental investigation to find the optimal damper parameters [14]. In the field of structural control, the dynamic absorber is often referred to as TMD. The word "Tuned" was added to distinguish it from other vibration-damping devices such as active control and mass-coupled control [6].

TMD devices have been used in many fields requiring unforeseen vibration reduction. In particular, large projects need to mitigate vibrations caused by wind and seismic impacts. In civil engineering, TMD is commonly used in buildings to reduce their displacement and acceleration caused by the dynamic response [15-16]. In Japan, new high-rise building projects are equipped with different damping systems to reduce vibrations caused by small or medium earthquakes. For large bridges such as cable-stayed and suspension bridges, the TMD device is used to reduce vibrations in towers and improve structural performance [17]. In recent years, the application of TMD in pedestrian bridge construction has been applied more [3]. Daniel found that the TMD device added to the pedestrian bridge improved its vibration-damping ability and increased its lifespan [18]. Carpineto proposed to reduce human-induced vibrations in pedestrian suspension bridges by applying multiple TMD [19]. In addition, for large-span bridges, the application of TMD also increases the efficiency of the construction, but there has not been an in-depth study on the optimal parameters of the dampers for bridge constructs, but mainly focused on research for building construction [20].

Fatigue failures of steel bridges are frequently recorded around the world. The most common cause is to relate vibration-induced fatigue and fracture [21]. Thus, the analysis and control of the structure vibration are necessary to increase the lifespan of the steel bridge. However, improving or changing the response of the structure after checking and analyzing structure parameters that significantly affect the dynamic response needs to be suitable to obtain economic efficiency. Selecting the optimal parameters of dampers TMD is an effective way to control the dynamic response and preserve the integrity of the construction. Therefore, this paper investigates by experiment and simulation using MATLAB the influence of parameters of TMD, related to the change in its mass and stiffness, on the vibration-damping effect of a simple steel beam under different initial displacement excitation forces. In addition, the determination of the vibration reduction effect of TMD on small-scale steel beam model serves as a basis to apply further research to existing buildings to reduce maintenance costs. Firstly, the validation work will be carried out to compare the theoretical model with experimental results. After that, the effect of steel beam stiffness on the effectiveness of TMD will be elucidated. In addition, the impact of initial excitation displacement on the effectiveness of TMD will also be investigated clearly. Finally, some of the significant findings will be presented in the conclusion.

2. Experimental and theoretical model

2.1. Test Apparatus

A simple experimental model has been proposed to investigate the damping effect of the TMD device on the main structure. The general configuration of the experimental apparatus is shown in figures 1a and 1b. It consists of a simple steel beam, a TMD device, an oscilloscope of Bridge Diagnostics Inc (BDI), and a data acquisition system.

a) *b)*

Figure 1. *Test Apparatus: a) without TMD; b) with TMD*

A steel beam that has a length of 556 mm, a width of 25 mm, and a thickness of 2 mm is supported by two supports consisting of one rigid and one movable bearing which used hinge joints to create the links. The movable bearing has rotational displacement and fix horizontal and vertical displacements, and the rigid bearing allows horizontal and vertical displacements and fix rotational displacements (see Figure 1a). In addition, its mass and stiffness are shown in Table 1.

Table 1. *Parameters of steel beam*

Mass of steel beam *m* (kg)	**Length *l* (mm)**	**Width *b* (mm)**	**Thickness *h* (mm)**	**Stiffness *k* (N/m)**	**Viscous coefficient *c* (N.s/m)**
0.238	556	25	2	931	1.05

A simple TMD device with a mass of 3% or 5% of a steel half-beam mass attached to a spring (see Table 2). The TMD device is linked to the middle of the steel beam during experimental testing. The BDI oscilloscope is used to determine the vibration of the steel beam without TMD or with TMD when the steel beam is subjected to an excitation force corresponding to an initial displacement in the middle of the span. The BDI oscilloscope consists of an LVDT sensor used to collect data in terms of the vibration of the steel beam at the half-span position under the effect of the initial displacement (see Figure 1b) and the parameters of BDI are presented in detail in [22]. In addition, data collection software is written by the staff of Bridge Diagnostics Inc. The software automatically measures the vibration based on the strain sensor located in the middle of the span during the test.

Table 2. *Parameters of TMD device*

Ratio mass $\bar{m}$ (%)	**Damping mass m_d (kg)**	**Optimal frequency f_{opt}**	**Stiffness k_d (N/m)**	**Damping coefficient c_d (N.s/m)**
3%	$3.57.10^{-3}$	0.941	24.73	0.30
5%	$5.95.10^{-3}$	0.913	38.80	0.50

2.2. Test procedures

Figure 2 illustrates an arrangement of the experimental devices. After the preparation of the testing apparatus, the experiment was carried out with an initial vertical excitation displacement of 4,85 mm directed downwards at the center of the steel beam. When the wire is released, the vibration of the middle of the span of the steel beam is recorded by the BDI oscilloscope until the steel beam stops completely. The test sequence is performed for each case of steel beams without TMD, with TMD for 3% and 5% of a half weight of the steel beam.

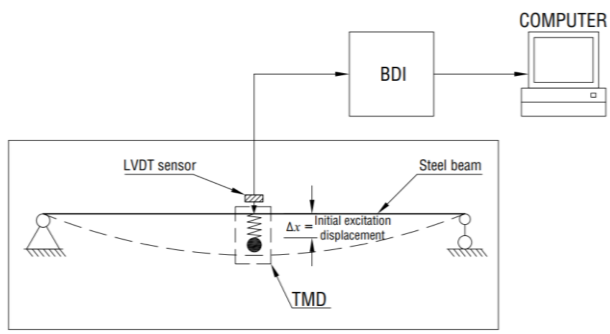

Figure 2. *Schematic of the test device*

2.3. Theoretical model

Figure 3a shows the single degree of freedom (SDOF) of the main structure, consisting of the stiffness k, mass m_1, and viscous coefficient c while the stiffness k_d, damping mass m_d, and damping coefficient c_d in Figure 3b are of the TMD device of the system of SDOF with TMD (SDOF-TMD). The equation of motion for the SDOF-TMD system, that the main structure is subjected to an external excitation force, is presented as follows [23].

For simple steel beam:

$$m_1\ddot{x} + c\dot{x} + kx - c_d\dot{x}_d - k_d x_d = p \quad (1)$$

For TMD device:

$$m_d\ddot{x}_d + c_d\dot{x}_d + k_d x_d + m_d\ddot{x} = 0 \quad (2)$$

Parameters of the simple beam and TMD are computed as follows:

$$k = \omega^2 m_1 \quad (3)$$

$$c = 2\xi\omega m_1 \quad (4)$$

$$k_d = \omega_d^2 m_d \quad (5)$$

$$c_d = 2\xi_d \omega_d m_d \quad (6)$$

$$\omega_d = f_{opt}\omega \quad (7)$$

And the ratio mass TMD:

$$\bar{m} = \frac{m_d}{m_1} \quad (8)$$

Whereas the damper is located at the midspan of the steel beam. According to Connor, the corresponding mass m_1 is equal to $m/2$, and m is the mass of the steel beam [23]. The optimal frequency f_{opt} is determined based on the damping ratio of the main structure and the fitting curve [14]. The frequency of the TMD is ω_d and the frequency of the main structure is ω. The viscous coefficient values of the main structure c and the TMD device c_d are determined based on experimental results and Matlab simulation. Parameters of the steel beam and TMD device are shown in Tables 1 and 2, respectively.

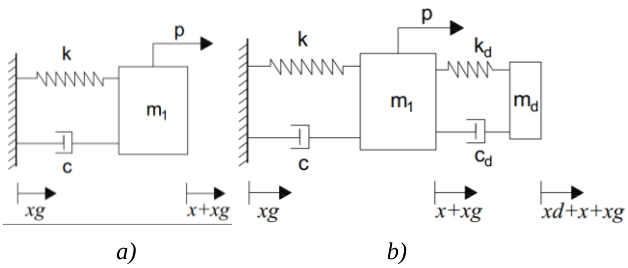

Figure 3. *System: a) Single degree of freedom (SDOF) b) SDOF – TMD [23]*

3. Experimental results and validation

3.1. Experimental results

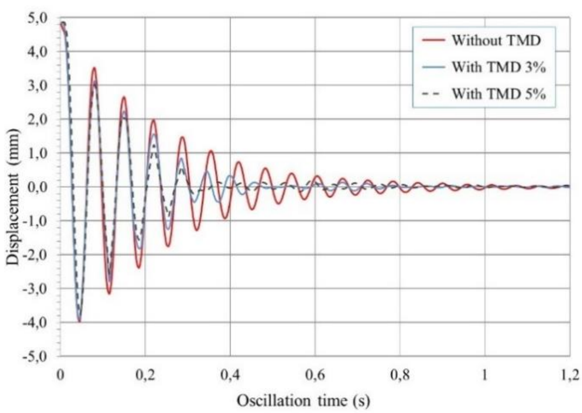

Figure 4. *Vibrations with initial excitation displacement 4,85mm for without TMD, with TMD 3%, and TMD 5%*

Figure 4 shows the vibration pattern of the steel beam at mid-span without TMD, with TMD of 3% and 5% under the initial excitation displacement of 4.85 mm. The results show that the oscillation fades and almost stops after 1.2s for 3 cases. The steel beam with TMD has a greater reduction in vibration amplitude than when not fitted with TMD. In addition, the vibration reduction effect for TMD 5% is greater than that for TMD 3%. This effect is explicitly shown starting from the oscillation period 2.5T.

3.2. Model validation

Figure 5 compares the vibration of steel beams without TMD, with TMD 3%, and TMD 5% between the experimental result and the simulated result in Matlab with an initial excitation displacement of 4.85 mm. The viscous coefficient c of the main structure is tuned from the experimental data for the SDOF, i.e. the value of c is assumed so that the simulated vibration curve is the same as the experimental vibration curve. The result shows that c corresponding to 1.05 (N.s/m) gives the closest curve to the experimental data (see Figure 4). Thus, the above viscosity coefficient value is used in the theoretical model.

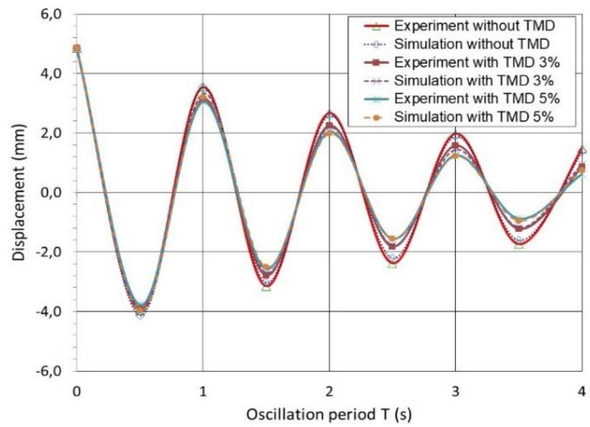

Figure 5. *Comparison of the present model and experiment data*

In the same manner, for SDOF-TMD, the damping coefficient c_d of TMD 3% and 5% was determined through a comparison between simulation in Matlab and experiment data. The results show that the values of the damping c_d with the TMD 3% and 5% are 0.3 (N.s/m) and 0.5 (N.s/m), respectively. With these values, the model results are closest to the experimental results.

In addition, a very high correlation coefficient can be seen in Table 3. In general, the correlation coefficients of the predicted and experimental values [24] for all three cases are 0.9994. The results generated by this model have a high degree of congruence with the experimental data in terms of the displacement value as well as trend lines for three separate scenarios. As a result, a theoretical model can be successfully applied for the purpose of further estimation.

Table 3. *Parameters of steel beam*

Validation Metric	Without TMD	With TMD 3%	With TMD 5%
Correlation coefficient	0.9994	0.9994	0.9994

4. Results and discussions

4.1. Steel beam stiffness k on the effectiveness of TMD

To investigate the effect of beam stiffness on the efficiency of the TMD device, a series of Matlab simulations at the initial excitation displacement of 4.85 mm was carried out with the same parameters (m_1, c, and c_d) but varying the steel beam stiffnesses: 0.5k; 1.0k; 1.5k; 2.5k; 5.0k; *and* 10.0k. Figure 6 and Figure 7 illustrate the vibrations of beam steel without TMD, with TMD 3% and TMD 5% for stiffnesses 1.0k and 5.0k, respectively.

For the SDOF, it is clear that the number of oscillation periods increases with k but the value of the amplitude of the oscillation is the same over time.

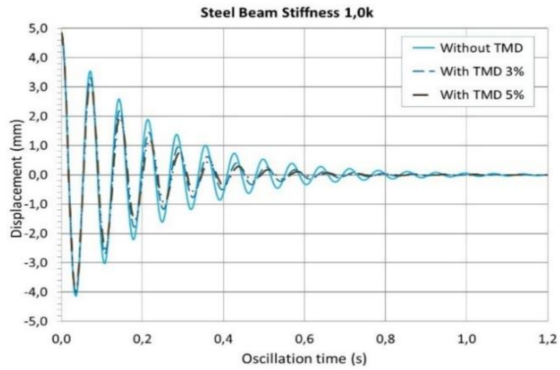

Figure 6. *Effectiveness of TMD for beam stiffness 1.0k*

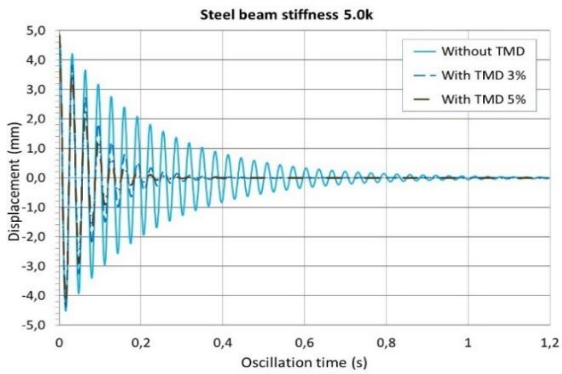

Figure 7. *Effectiveness of TMD for beam stiffness 5.0k*

For the SDOF - TMD, it is shown that decreasing oscillation amplitude occurs with the increasing *k*. Thus, As stiffness increases, the effect of vibration reduction of the main structure with TMD is greater than that without TMD. Based on the simulation results, the displacement in the middle of the steel beam in the 1st oscillation period according to different stiffnesses and TMD mass was determined to evaluate the influence of *k* on the effectiveness of TMD (see Table 4).

Table 4. *Oscillation at the center of steel beam at 1st oscillation period*

	Oscillation amplitude at the mid-span of the steel beam at 1st oscillation period (mm)					
Stiffness / TMD	**0.5*k***	**1.0*k***	**1.5*k***	**2.5*k***	**5.0*k***	**10.0*k***
Without TMD	3.11	3.54	3.75	3.98	4.21	4.39
With TMD 3%	2.95	3.32	3.48	3.65	3.82	3.95
With TMD 5%	2.87	3.19	3.31	3.46	3.61	3.71

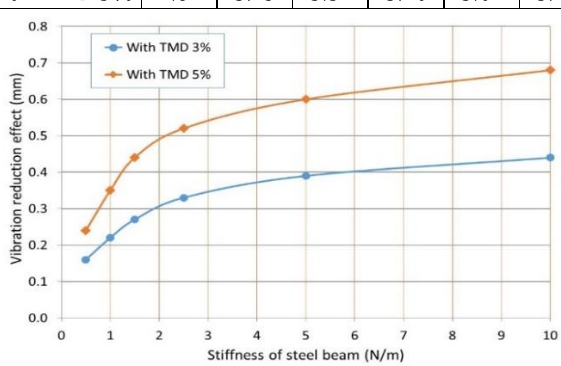

Figure 8. *Vibration reduction with different beam stiffnesses for SDOF – TMD*

Figure 8 shows TMD 3% and 5% vibration reduction effects with different beam stiffnesses. For SDOF-TMD, the efficiency of vibration damping of the main structure increases with *k*. For TMD 5%, it is more effective than TMD 3%. In addition, the evolution of oscillation reduction performance of TMD 5% is higher than TMD 3%. The efficiency of reducing vibration can be categorized into two distinct trends: the first is a rapid increase in efficiency when the stiffness is less than 1,8*k* for both TMD 3% and 5%; the second is a negligible increase in efficiency as k increases beyond the aforementioned values.

4.2. Initial displacement on the effectiveness of TMD

A series of Matlab simulations were performed with varying initial excitation forces, namely the initial displacement change, to investigate the vibration mitigation effect of the TMD. Similar to investigating the influence of beam stiffness, the initial displacements were changed by 2.85 mm; 3.85 mm; 4.85 mm; 7.85 mm; 10.85 mm; and 13.85 mm for the SDOF - TMD system. Figures 9 and Figure 10 illustrate the vibrations of beam steel without TMD, with TMD 3% and TMD 5% for initial displacements of 3.85 mm and 10.85 mm, respectively.

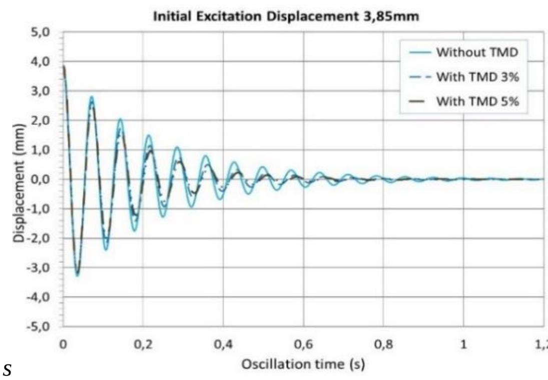

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Figure 9. *Effectiveness of TMD for the initial excitation displacement of 3.85 mm*

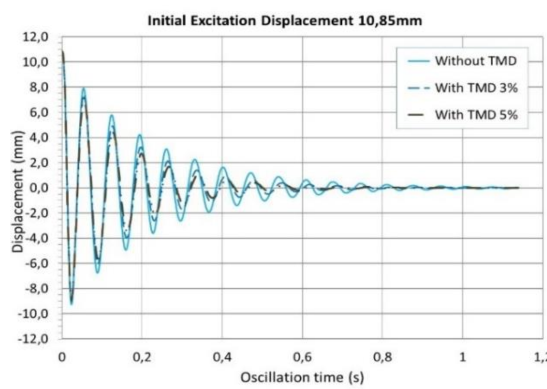

Figure 10. *Effectiveness of TMD for the initial excitation displacement of 10.85 mm*

Table 5 displays the displacement in the middle of the steel beam at the 1st oscillation period corresponding to TMD 3% and 5% with the difference of the initial excitation forces. The percentage of oscillation reduction efficiency was determined based on the ratio of the difference value of amplitude at the 1st oscillation period to the initial excitation displacement. The results elucidate that the vibration reduction efficiency for the TMD 5% system is higher than that for the TMD 3% system (see Figure 11). In addition, for each mass ratio TMD, the effect of the initial excitation displacement does not significantly affect the vibration reduction efficiency. However, the vibration reduction efficiency reaches a peak at the initial excitation displacement of 7.85 mm. TMD 3% had an efficient percentage of 4.71%, whereas TMD 5% had 7.26%.

Table 5. *The mid-span amplitude with the different initial excitation displacements*

Initial Displacement (mm) / TMD	Oscillation amplitude at the mid-span of the steel beam at 1st oscillation period (mm)					
	2.85	**3.85**	**4.85**	**7.85**	**10.85**	**13.85**
Without TMD	2.08	2.80	3.54	5.72	7.90	10.08
With TMD 3%	1.95	2.63	3.32	5.35	7.43	9.45
With TMD 5%	1.88	2.53	3.19	5.15	7.14	9.10

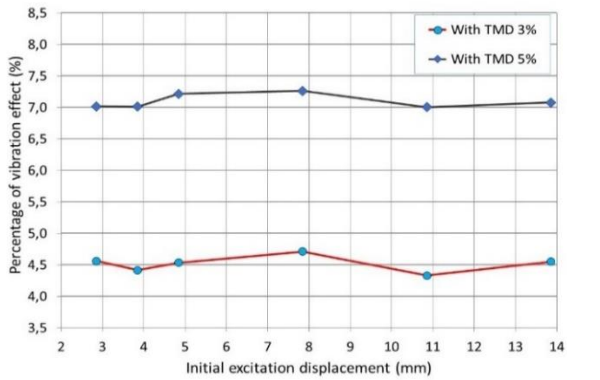

Figure 11. *Vibration mitigation efficiency of TMD 3% and 5% at different displacements*

5. Conclusion

TMD devices can reduce structural vibrations. Thus, the influence of TMD is explored, including mass ratio TMD and initial excitation displacement. Experiments are also carried out to validate the theoretical model. The findings obtained from this paper are as follows: the effect of reducing vibration for the simple supported steel beam by adding the TMD device is recorded according to the experimental results in the article.

- A significant increase in vibration mitigation efficiency of the main structure was observed when the stiffness of the steel beam for both TMD 3% and 5% is less than 1.8*k*.

- Compared to TMD with 3% of the main structure's mass, TMD with a mass ratio of 5% has a greater effectiveness in reducing vibration.

- The excitation force does not have a considerable impact on the efficiency of the vibration reduction for the main structure throughout all mass ratios TMD.

TMD devices provide effective vibration reduction. However, steel beams equipped with TMD devices contribute to their increased weight, which in turn leads to increased static moments and displacements. Thus, consideration should be given to using TMD devices with an appropriate mass ratio. Therefore, the design of the TMD should incorporate the appropriate mass ratio to achieve the desired effect of suitable damping, economy, and avoidance of impact on the main structure.

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