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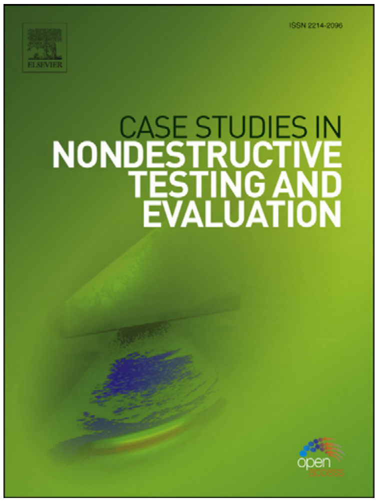

Serviceability assessment of the Góis footbridge using vibration monitoring

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Serviceability assessment of the Góis footbridge using vibration monitoring

Rolando Salgado[a,1], Jorge M. Branco[b], Paulo J.S. Cruz[b] and Gustavo Ayala[c]

[a]*University of Veracruz, Boca del Río, México, e-mail: rosalgado@uv.mx*

[b]*University of Minho, Campus Azurém, Guimarães, Portugal, e-mails: jbranco@civil.uminho.pt and pcruz@civil.uminho.pt*

[c]*Institute of Engineering, UNAM, México, D.F., e-mail: GAyalaM@iingen.unam.mx*

Abstract

Footbridges are structures that may experience vibration amplification problems caused by pedestrian and/or wind actions. Design codes deal with these phenomena limiting the natural frequencies and the maximum accelerations expected. Aiming at taking into consideration these dynamic phenomena, current procedures to evaluate the structural performance of light-weight bridges based on experimental dynamic analysis are evaluated in this study. To achieve this, the dynamic response of three pedestrians walking, running and jumping was obtained. Maximum comfort limits of dynamic responses were then determined. The results indicate that codes could overestimate the level of vibration in this kind of footbridge.

Keywords: Dynamic tests; structural evaluation, serviceability assessment.

1. Introduction

Short and medium span footbridges do not usually endure heavy loads, and are generally sufficient, slender cross-sections. Moreover, many footbridges have natural frequencies that are similar to those detected when pedestrians walk. A similar problem has been detected when wind gusts excite footbridges at frequencies close to their natural ones. Under these conditions, vibration amplification problems may cause discomfort to people and may even result in damage to structural elements and connections. In this study, we identified that currently few codes and design guidelines address these vibration problems.

The most extensive research on the dynamic analysis of footbridges was conducted after the Millennium Bridge, in London [1] started experiencing vibration problems. In this context, Živanovic et al. [2] presented a state-of-the-art about the serviceability conditions of footbridges under pedestrian excitation. Their work addresses important issues such as numerical structural modeling of a footbridge, load models for pedestrians walking, pedestrian-footbridge dynamic interaction, human perception to bridge vibration, recommendations for design codes and measures to avoid excessive vibration.

Caetano et al. [3] carried out the dynamic analysis on the Pedro e Inês footbridge in Portugal. Here, they discovered that the footbridge presented a lock-in effect phenomenon resulting in high lateral accelerations when pedestrians tried to cross it. A numerical model of the footbridge was updated with information from experimental dynamic tests to support the definition of the

[1] *Corresponding author at: Faculty of Engineering, Campus Veracruz, University of Veracruz, Calzada Adolfo Ruiz Cortines no. 455, Fracc. Costa Verde, Boca del Río Veracruz, C.P. 94294, phone number: +(52) 229 775 2000*

corrective intervention. At the final stage of the study, control devices (tuned mass dampers) were installed to reduce the level of accelerations below recommended values given by codes.

Van Nimmen et al. [4] carried out a comparison of the serviceability evaluation of several footbridges according to the European guideline HiVoSS and the French guideline Sétra. They discovered that evaluations made by codes are highly sensitive to small variations in predicted natural frequencies. The authors have therefore suggested a modified load model that accounts for uncertainty in predicted natural frequencies in design stage. Moreover, they recommended that a modal identification of the footbridge should be carried out once the footbridge is built in order to achieve a more reliable comfort level.

In this paper, we present the serviceability assessment of a light-weight footbridge, using its dynamic response. This proposed procedure is exemplified in the Góis footbridge. Dynamic parameters obtained from experimental results are used to evaluate several recommendations provided by codes and other authors.

2. Footbridge description

The footbridge under investigation is a timber arch structure located in the Baião Park in the village of Góis, in central Portugal, 40 km East of Coimbra. The footbridge was built by the local administration as a pedestrian crossing over the Ceira River. Only a few pedestrians cross the footbridge daily and most of them are students from a nearby high-school. Fig. 1 shows the footbridge under investigation and its location in the village of Góis.

a) General view of the footbridge b) Location of the footbridge

Fig. 1. Timber arch footbridge of Góis.

3. Modal analysis

Dynamic tests were performed on the Góis timber arch footbridge in order to determine its dynamic parameters. Ambient vibration tests (AVTs) were conducted on the footbridge on 30th March and 2nd April 2007. Ambient loading excitation was mainly caused by wind (with speeds between 8 to 12 km/h). Weather during tests was cloudy with light rain with an average temperature between 11.9°C to 13.3°C, and average humidity between 63% to 69.4%.

To obtain an appropriate mode shape definition 31 measuring points were chosen on the footbridge. To cover the total number of points with the 8 available accelerometers, 6 sensor setups with three reference sensors were required. 14 measuring points were set up in the vertical direction (in the platform), while 17 were located in the transversal direction (platform and arch).

The acceleration response was obtained using a sampling frequency of 100 Hz and 900 s of recorded time for each setup. Using the recorded acceleration history, modal parameters of the Góis footbridge were obtained using the enhanced frequency domain decomposition method ([5] and [6]). To accomplish this, the acceleration history was filtered using a butterworth low pass filter at 30 Hz with an slope of 60 dB/octave. Moreover, acceleration response was not decimated. Spectral density matrices were estimated with a frequency line spacing of 0.0245 Hz, an overlap of 66.67% and using a Hanning window function.

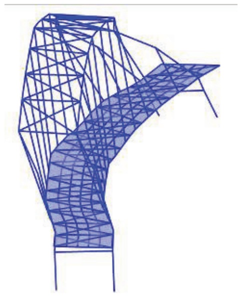
Six mode shapes in the frequency range of interest were found. The frequencies and damping ratios and their standard deviations for the selected mode shapes are shown in Fig. 2. Modes 1, 2 and 4 are in the transversal direction, while modes 3, 5 and 6 are in the vertical direction. Fig. 2 indicates that structure is more flexible in the transversal direction.

The obtained frequencies associated to the mode shapes have a very low standard deviation, which indicates a highly accurate estimation. Standard deviation of damping ratios are more disperse, as it frequently occurs. Therefore, this parameter can also be considered to have a good approximation. Moreover, the modal parameters were consistent with those obtained through a preliminary numerical model, which confirms the good correlations of the results obtained [7].

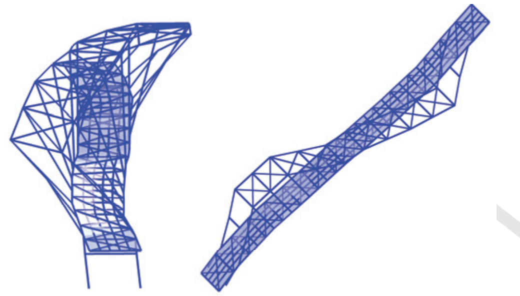
In order to determine the level of accelerations under pedestrian excitation, three cases were evaluated: a) pedestrians walking at frequencies between 1.4 and 1.8 Hz. b) pedestrians running at frequencies between 2.7 and 3.10 Hz and c) pedestrians jumping at frequencies between 2.0 and 2.5 Hz. The acceleration history for these cases was recorded with a sampling frequency of 100 Hz and a recorded time of 900 s.

3.1. Limits of vibration comfort for the Góis timber arch footbridge

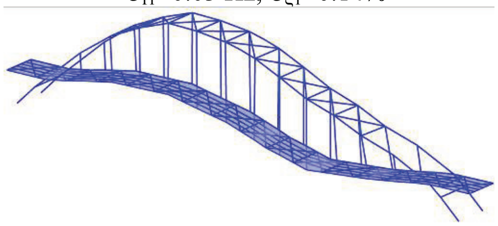
The comfort vibration evaluation of the Góis timber arch footbridge was performed comparing the results obtained from the dynamic tests under pedestrian excitation with the comfort limits recommended in codes, standards and several other publications listed in Tables 1 to 3 (taken from [8], [9], [10], [11] and [12]).



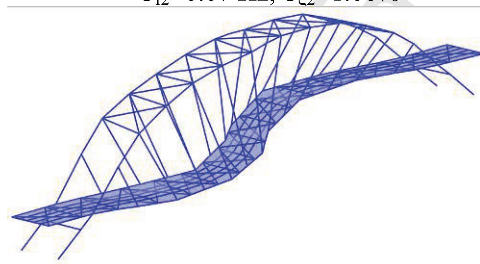
Mode 1. f_1=2.46 Hz, ξ_1=1.49 %,
σ_{f1}=0.03 Hz, $\sigma_{\xi 1}$=0.14%



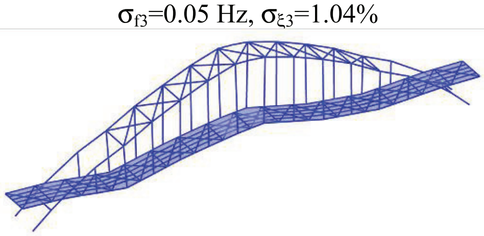
Mode 2. f_2=4.51 Hz, ξ_2=1.92 %,
σ_{f2}=0.07 Hz, $\sigma_{\xi 2}$=1.06%



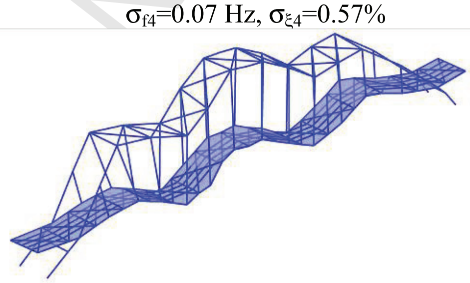
Mode 3. f_3=5.15 Hz, ξ_3=1.71 %,
σ_{f3}=0.05 Hz, $\sigma_{\xi 3}$=1.04%



Mode 4. f_4=7.72 Hz, ξ_4=0.57 %,
σ_{f4}=0.07 Hz, $\sigma_{\xi 4}$=0.57%



Mode 5. f_5=8.09 Hz, ξ_5=1.28 %,
σ_{f5}=0.03 Hz, $\sigma_{\xi 5}$=0.32%



Mode 6. f_6=22.76 Hz, ξ_6=0.60 %,
σ_{f6}=0.08 Hz, $\sigma_{\xi 6}$=0.28%

Fig. 2. Mode shapes of Góis footbridge from the AVTs.

Table 1 confirms that the natural frequencies of the Góis timber arch footbridge are in accordance with the limit values recommended by several codes therefore avoiding the risk of resonance. Only the frequency limits suggested by Eurocode 5 [13] are not fulfilled in the horizontal direction. This does not mean that based on Eurocode 5 the structure is not acceptable, but instead it means that a more detailed confirmation should be obtained. Consequently, the comfort verification of the footbridge was complemented with the study of the vertical (Table 2) and horizontal (Table 3) accelerations for the Eurocode 5 (compulsory) and for the remaining codes to verify if accelerations found in the dynamic tests are in accordance to the maximum allowable values.

Table 1. Verification of comfort vibration by frequency limit values

Codes	Limit values		Verification.
	Vertical (f_v=5.15 Hz)	Horizontal (f_h=2.46 Hz)	
American Guide Spec.	<3 Hz		OK
Eurocode 2 (ENV 1992-2)	1.6 Hz – 2.4 Hz	0.8 Hz – 1.2 Hz	OK
DIN-Fachbericht 102	1.6 Hz - 2.4 Hz, 3.5 Hz – 4.5 Hz		OK

Eurocode 5 (ENV 1995-2)	< 5 Hz	< 2.5 Hz	DV*
SIA 260 (Switzerland)	1.6 Hz – 4.5 Hz	<1.3 Hz transverse <2.5 longitudinal	OK
BS 5400 (G.B.)	< 5 Hz		OK
Austroroads (Australia)	1.5 Hz – 3 Hz		OK
Japanese Footbridge Design Code (JFDC)	1.5 Hz – 2.3 Hz		OK
Sétra	1.7 Hz – 2.1 Hz	0.5 Hz – 1.1 Hz	OK
Hivoss	1.25 Hz – 2.3 Hz	0.5 Hz – 1.2 Hz	OK

* DV more detailed verification of the comfort criteria may be needed.

Table 2. Vertical acceleration limits for the Góis footbridge

Reference	Application	Criteria	Limit value (f_v=5.15 Hz)
International Standard Organization, ISO 2631 -2	outdoor footbridges	expressed in rms accelerations (1-4 Hz) a_{rms}=10-5/3f (%g) (4-8 Hz) a_{rms}=5%g	$a_{rms} \leq 5\%g$
Eurocode 1	footbridges	$a_{máx} \leq \min\begin{cases}5.1\sqrt{f_v} \\ 7.0\end{cases}$ (%g)	$a_{max} \leq 7.0\%g$
BS 5400	bridges	$a_{max} \leq 5.1\sqrt{f_v}$ (%g)	$a_{max} \leq 11.57\%g$
Eurocode 5	bridges	$a_{max} \leq 7.0\%\,g$	$a_{max} \leq 7.0\%g$
Ontario Code	bridges	$a_{max} \leq 2.55 f_1^{0.78}$ (% g)	$a_{max} \leq 9.16\%g$
Bachmann	footbridges	$a_{max} \leq 5$ to $10\%\,g$	$a_{max} \leq 7.0\%g$*
Stoyannoff	footbridges	$a_{max} \leq 7.0\%\,g$	$a_{max} \leq 7.0\%g$
Japanese Code (JFDC)	footbridges	$a_{max} \leq 10\%\,g$	$a_{max} \leq 10\%g$
DIN Fachbericht 102	bridges	$a_{max} \leq 5.1\sqrt{f_v}$ (%g)	$a_{max} \leq 11.57\%g$
Sétra	footbridges	$a_{máx} \leq 10\%g$ (average comfort)	$a_{máx} \leq 10\%g$
Hivoss	footbridges	$a_{máx} \leq 10\%g$ (average comfort)	$a_{máx} \leq 10\%g$

* suggested value within the proposed interval. g is the acceleration due to gravity (9.81 m/s^2).

Table 3. Horizontal acceleration limits for the Góis footbridge

Reference	Application	Criteria	Limit value (f_h=2.46 Hz)
Eurocode 5	standing individuals	$a_{máx} \leq 2\%\,g$ applicable for f_v<2.5 Hz	$a_{max} \leq 2.0\%g$
Eurocode 1	footbridges	$a_{máx} \leq \min\begin{cases}1.4\sqrt{f_h} \\ 1.5\end{cases}$ (%g)	$a_{max} \leq 1.5\%g$
International Standard Organization ISO 2631-2	vibrations	(1 -2 Hz) $a_{rms} \leq 1.7$ (%g) (2-80 Hz) $a_{rms} \leq 0.83 f_h^{1.04}$ (%g)	$a_{rms} \leq 2.12\%g$
Bachmann	footbridges	$a_{máx} \leq 1$ *to* $2\%\,g$	$a_{max} \leq 2.0\%g$*
Stoyannoff	footbridges	$a_{máx} \leq 2.0\%\,g$	$a_{max} \leq 2.0\%g$
Sétra	footbridges	$a_{máx} \leq 3.0\%g$ (average comfort)	$a_{máx} \leq 3.0\%g$
Hivoss	footbridges	$a_{máx} \leq 3.0\%g$ (average comfort)	$a_{máx} \leq 3.0\%g$

* suggested value within the proposed interval. *g* is the acceleration due to gravity (9.81 m/s^2).

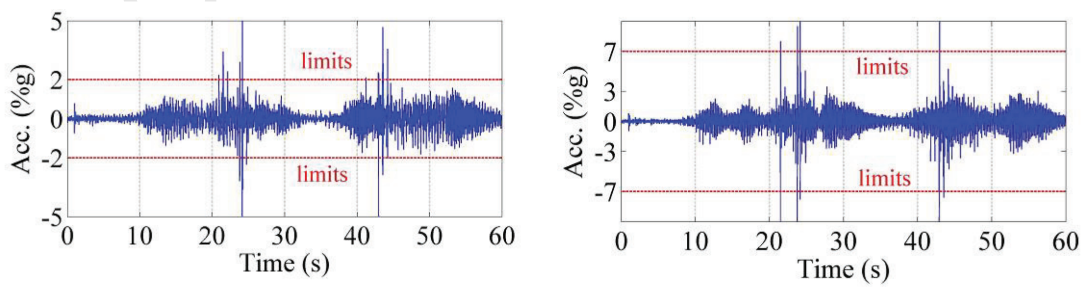
Most conservative references listed in Table 2 define values near 7.0%g for the vertical acceleration limit while the ISO 2631 (after [8]) specifies the acceleration limits in terms of root mean square (rms) values of accelerations with a maximum value of 5%g rms.

In the case of the transversal acceleration limits shown in Table 3, the most unfavorable case was determined in accordance with Eurocode 1 [14], which limits the maximum transversal acceleration to 1.5%g. This value is considered very conservative for footbridges with natural frequencies close to the upper frequency limit value (such as in this case). Therefore, if the maximum acceleration is not taken into account, the maximum transversal accelerations calculated accordingly [14] can increase up to 2.19 %g. The rest of the analyzed methods propose a horizontal acceleration limit of 2.0%g. In conclusion, a maximum transversal acceleration of 2.0%g and an rms acceleration value of 2.1 %g were adopted for the comfort limit verification in terms of horizontal acceleration.

3.2. Evaluation of the vibration level

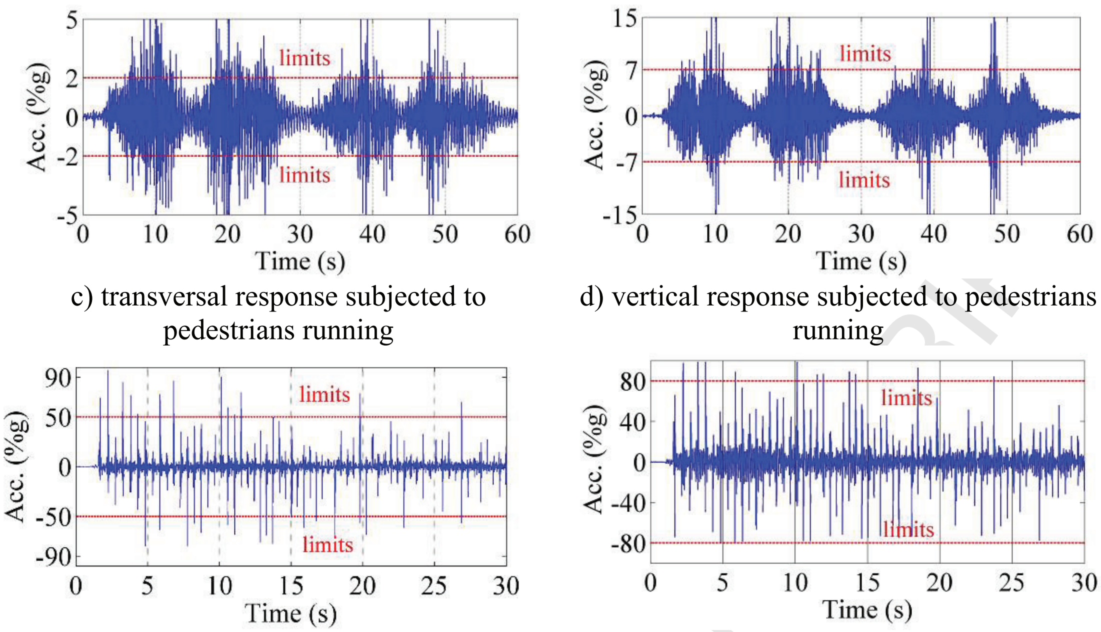
Acceleration responses of pedestrian walking are shown in Figs. 3a and 3b for the transversal and vertical direction, respectively. The maximum measured acceleration values in transversal and vertical direction were 5.1%g and 7.14%g (0.52 m/s^2 and 0.70 m/s^2), respectively. The maximum acceleration values were higher than the comfort limit for both directions (7%g vertical and 2%g transversal). Two facts may explain this behavior: the vertical and transversal accelerations increased when the pedestrians approached the mid-span of the footbridge and the accelerometers also registered the ambient sound and the local impact vibrations caused by the pedestrian steps.

As for pedestrian running (see Figs. 3c and 3d), the same behavior in the acceleration response, compared with pedestrians walking, was observed when pedestrians approached the mid-span of the footbridge. For this second load case, the acceleration values were higher than the comfort limit for the transversal direction even when impulse accelerations were disregarded. In the vertical direction, accelerations (eliminating local peaks) were very close to the comfort limit. Even when the acceleration values in the transversal direction were higher than the comfort limit (see Fig. 3c), no significant discomfort was felt by individuals standing at the mid-span of the footbridge during the dynamic tests.



a) transversal response subjected to pedestrians walking

b) vertical response subjected to pedestrians walking



c) transversal response subjected to pedestrians running

d) vertical response subjected to pedestrians running

e) transversal response subjected to pedestrians jumping

f) vertical response pedestrians subjected to jumping

Fig. 3. Acceleration response for pedestrian loadings. Key: ········ Comfort limit

As for the last case analyzed (see Figs. 3e and 3f), pedestrians simultaneously jumped for thirty seconds. The accelerations produced by pedestrians jumping reached values close to 100 %g (9.81 m/s^2) in both directions. Discomfort was felt at the location where pedestrians were jumping (mid-span), but this sensation ceased immediately after the jumping stopped. It became evident that the accelerations were higher than the maximum recommended values for the ULS (50%g for transversal accelerations and 80%g for vertical accelerations.

Even though the individuals who were standing on the structure during the tests could feel the movement of the deck, the acceleration response did not reach any degree of instability no high demands were caused in the footbridge by this forced excitation. Therefore, it can be concluded that the Góis timber arch footbridge is safe to the excitation caused by acts of vandalism.

The comfort limit evaluation using the ISO 2631 requirements is reported in Table 4. The rms acceleration values were obtained considering all frequencies included in the acceleration history for all considered directions. The acceleration limits defined by this standard in the vertical (5.0%g) and transversal (2.12%g) directions are higher than the measured maximum rms acceleration values for pedestrian walking (1.11%g vertical and 0.56%g transversal) and also for pedestrian running (2.89%g vertical and 1.34%g transversal). Therefore, one of the conclusions drawn from this research is that, under pedestrian walking and running, levels of accelerations comply with the recommended limits proposed by ISO 2631 [8]. These results are in accordance with the pedestrian perception of vibrations during these tests. No pedestrian experienced unsafe conditions while crossing the footbridge.

Table 4. Root mean square (rms) accelerations for the pedestrian excitation

Event	Vertical $a_{rms,v}$ (%g)	Transversal $a_{rms,h}$ (%g)

walking	1.11	0.56
running	2.89	1.34
jumping	15.54	11.04

4. Conclusions

According to the ambient vibration tests, six mode shapes associated to frequencies between 2 and 23 Hz were identified in the structure with good confidence. In agreement with the preliminary numerical model, with low standard deviation of frequency and obtained damping ratios between those calculated with similar timber structures. It can be pointed out that the footbridge is more flexible in the transversal direction than in the vertical direction.

Among the several codes used to verify the comfort vibration of the footbridge, only [8] recommends a more detailed revision, concerning not only the natural frequency values, as considered for the remaining standards, but also the acceleration assessment.

Regarding the vibration level of the footbridge under (experimental) pedestrian excitation, it can be concluded that the Góis timber arch footbridge is in accordance to vertical and transversal acceleration limits when pedestrians were walking and running if we eliminate peaks caused by local impact of pedestrian steps. In the case of pedestrians jumping, maximum accelerations were higher than maximum values. Nevertheless, the footbridge did not reach any degree of instability. Using rms accelerations comparison eliminate acceleration peaks and give us a better parameter of the comfort level of the footbridge. Taking account these results, this footbridge is not prone to suffer harmful effects caused by the pedestrian-footbridge dynamic interaction. On the contrary, the vibration level determined with codes and standards indicate that the footbridge can bear an important pedestrian interaction.

It can be concluded that current codes are not fully applicable to all kind of footbridges, particularly when they have frequencies near those, which are considered to have vibration problems. A more comprehensive study of these structures is recommended, such as the procedure that we propose in this study in order to detect or discard possible vibration problems in light-weight bridges.

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