

Full-Size Testing of Stay Cable Damping for the Assessment of Viscous Damper Efficiency



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Abstract Full-scale stay cable tests for viscous damping assessment at the Guadiana International Bridge are presented and discussed in this article. The tests carried out involved a pull-and-release method which allowed a repeatable damping assessment. Based on this, stay cable damping was identified by an exponential function fit to acceleration data. Measured stay cable damping ratios confirmed the viscous damper design, achieving a minimum of 4% logarithmic decrement total damping in accordance with fib89.

Keywords Full-size testing · Stay cable damping · Viscous damper · Damper efficiency

1 Introduction

Cable-stayed bridges have become a popular construction type over the last few decades, resulting in increased span lengths, tower heights, and cable lengths. For the design of cable-stayed bridges, cable vibrations must be limited to avoid structural damage. Therefore, the risk of excessive cable vibrations due to parametric excitation and various wind phenomena (such as buffeting, vortex shedding, galloping and rain-wind induced vibrations) can be investigated. To limit the cable amplitudes, a required stay cable damping can be defined for each investigated case (sometimes by using the Scruton number). To achieve the required damping, the use of viscous dampers is state of the art [1].

For damper design, analytical solutions for the eigenvalue analysis of the partial differential equation of the cable provide a well-established basis for predicting the stay cable damping achieved by viscous dampers [2, 3]. However, based on full-scale test results on various cable-stayed bridges, it is known that the actual damping provided is lower than the predictions based on the above theory, which is sometimes referred to as damper efficiency. This leads to two important issues: (a) how to perform

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reliable full-scale damping assessment tests and (b) what damping efficiencies can be considered for damper design.

For some cable-stayed bridges, the theoretically calculated damping is just above the damping requirements. Therefore, further development of accurate damping assessment methods and full-scale damping assessment examples are needed by the industry. Therefore, this article presents damping assessment tests carried out by DYWIDAG-Systems International GmbH (in the following DYWIDAG) at the Gadiana International Bridge (Spain-Portugal). The tests were carried out in 2021 after replacement of the stay cables. A pull-and-release method was used to assess the stay cable damping by viscous dampers. Measurements were analyzed using an exponential function fit of free vibrations and tests were performed three times to show repeatability. In conclusion, the calculated damper efficiency results are within the range reported in the scientific community for other cable-stayed bridges.

2 Damping Tests at Gadiana Bridge (Spain-Portugal)

The Gadiana International Bridge is located on the border between Spain and Portugal (between the towns of Ayamonte, in the district of Huelva, and Castro Marim, in the district of Faro). It has a total length of 666 m, a central span of 324 m, and the structure consists of two 100 m high pylons. The bridge deck is supported by 128 stay cables, made up of between 22 and 55 strands, ranging in length from 50 to 170 m. Built between 1985 and 1991, the Gadiana International Bridge remains one of the most iconic cable-stayed bridges on the Iberian Peninsula (see Fig. 1).



Fig. 1 Aerial view of Gadiana International Bridge during stay cable replacement works [4]



Fig. 2 During inspection water leakage at deck anchorages was found (left); Deck anchorages after removal (middle); Installation of new stay cables with ConTen system (right)

2.1 Inspection and Stay Cable Replacement at Guadiana International Bridge

After two strands broke in recent years (a third broke in March 2019), inspections and non-destructive testing were carried out in 2018. The inspection results suggested a complete replacement of the stay cable system (originally installed by a competitor). The following work was therefore carried out by DYWIDAG (see Fig. 2 and [4]):

1. Removal of the existing stay cables and anchorages.
2. Adjustments in existing elements.
3. Installation of new stay cables, including external viscous dampers.
4. Installation of cable force monitoring system.

After replacing the stay cables, the Guadiana International Bridge has been repaired and is safe again.

2.2 Damping Tests

Newly installed stay cables were also equipped, where necessary, with external viscous dampers based on a conducted viscous damper design. After the installation of the dampers, damping tests were carried out to check the validity of the damping system in order to comply with fib89 [5], which recommends 3–4% logarithmic decrement total damping (0.48–0.64% damping ratio) for cables longer than 80 m. Standard testing methods for stay cable damping are (a) rhythmic pulling (e.g. by hand or machine) and (b) the pull-and-release method. The latter was used on the Guadiana International Bridge, where the cable was pulled with a rope and then released (see Fig. 3). The rope was attached at a height of approximately 11 m above

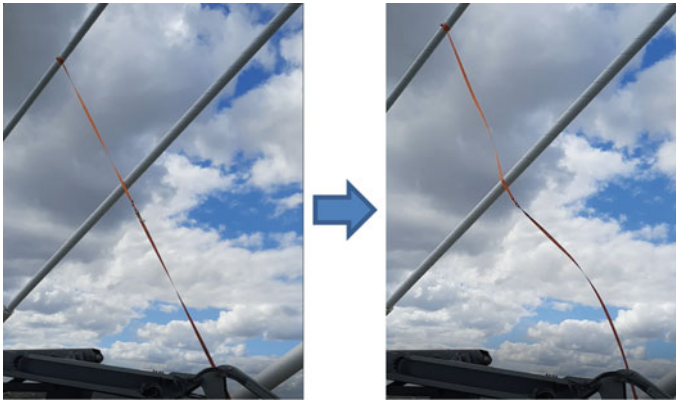


Fig. 3 Pull-and-Release method for damping assessment at Guadiana International Bridge

Table 1 Parameters of tested stay cables

Cable	Chord length L [m]	Chord angle θ [°]	Strands [-]	Unit mass m [kg/m]	Tension H [kN]	Damper c-value [kNs/m]	Damper position x_c/L [-] (%)
2N28	132.800	29.4	37	51.45	3091	65	3.13
2N29	141.550	28.2	37	51.45	2948	65	3.03
2N30	150.360	27.1	37	51.45	3246	65	2.93
2N31	159.220	26.1	37	51.45	3300	65	2.87
2N32	168.120	25.3	55	75.38	4873	95	2.79

deck and the rope was pulled until the cable moved at least 10 mm at the damper position (to ensure damper activation). Once released, the free vibrations of the stay cable were measured using an accelerometer attached on top of the stay cable at approximately 10 m height.

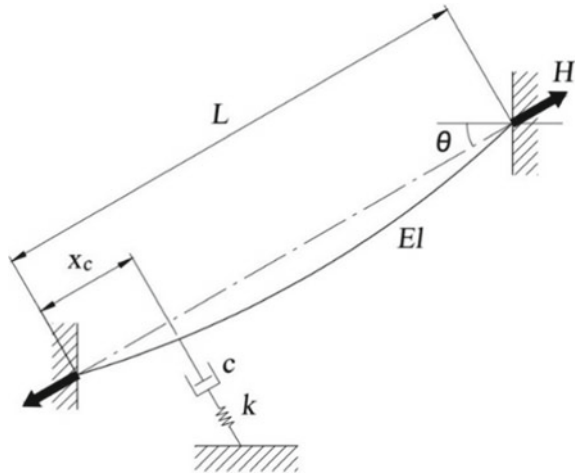
For cables 2N28...2N32, damping tests were carried out three times (see Table 1), which are analyzed in Sect. 4. The tests were carried out under similar environmental conditions (approximately 25 °C air temperature).

3 Assessment of Viscous Damper Efficiency

3.1 Viscous Damper Design

State-of-the-art damper design theory is based on the work of Krenk et al. [2, 3] and is well-known for its high accuracy and applicability. This theory is based on the mechanical model shown in Fig. 4. The damper is modelled as a Maxwell element to

Fig. 4 Mechanical model of viscous damper design



incorporate the damper support stiffness [1]. The mechanical model “cable-damper” allows for the calculation of the additional damping ratio ζ (the cable itself is modelled without inherent damping).

From this model, the reduction in damper efficiency due to bending stiffness, cable sag, and equivalent damper support stiffness are derived. For the analyzed stay cables of the Guadiana International Bridge, the sag has a negligible influence and is therefore not considered in the following.

Based on the stay cable parameters, a curve of the achievable damping ratio ζ is calculated, based on the universal damping curve [1]. For a chosen viscous damping coefficient c , several curves separately show the damping ratio for different vibration modes of the stay cable.

An example of the universal damping curve for cable 2N28 is shown in Figs. 5 and 6. The design curves are shown using a security coefficient $\gamma_\zeta = 0.75$ (see Sect. 4). Importantly, there is no linear damper with an optimal damper configuration for all modes. Within this detailed design, it is shown that dampers with a chosen damping coefficient c lead to different damping ratios for each mode.

It is well known that the actual damping provided is less than the predictions based on the above theory, sometimes referred to as damper efficiency [1]. Therefore, full-scale test results are required for accurate damper design.

3.2 Damping Assessment

To calculate the stay cable damping, the measured data must be processed, usually using free vibration acceleration measurements (see Sect. 2.2). At the Guadiana International Bridge, the mechanical system “cable-damper” acts almost linear, therefore the free decay of the cable $w(t)$ due to an initial deflection is theoretically known as

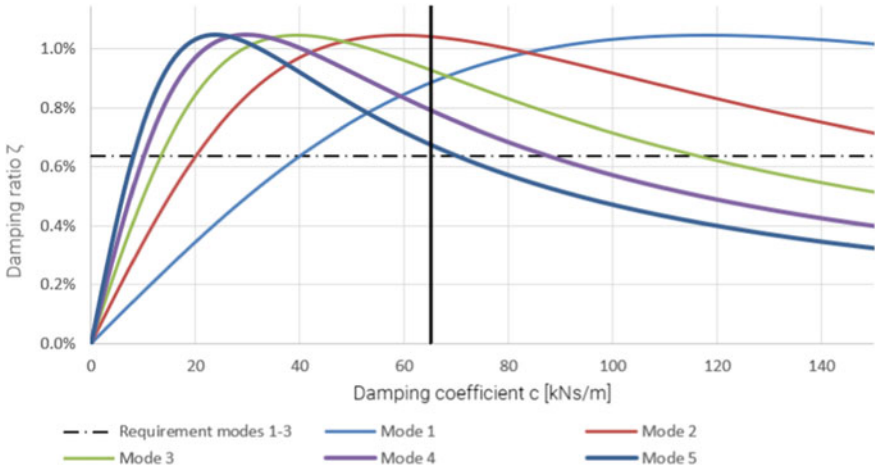


Fig. 5 Viscous damper design for stay cable 2N28: Additional design damping ratio can be seen at the intercepts of design curves at the chosen damper c -value of 65 kNs/m (vertical black line)

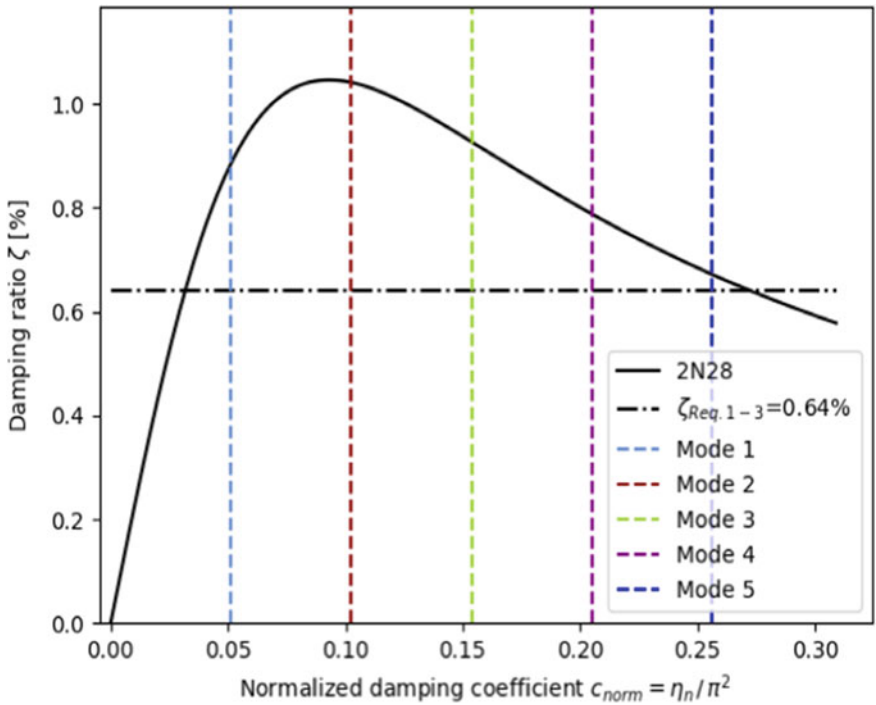


Fig. 6 Normalized viscous damper design for stay cable 2N28: Additional design damping ratio can be seen at the intercepts of design curve and normalized c -values following $c = 65\text{kNs/m}$ ($\eta_n = n\pi(x_c/L)c/\sqrt{Hm}$; vertical colored line for mode n); Identical calculated damping ratios as in Fig. 5

$$w(t) = e^{-\omega_0 \zeta t} (A \cdot \sin(\omega_d t) + B \cdot \cos(\omega_d t)), \omega_d = \omega_0 \sqrt{1 - \zeta^2} \tag{1}$$

A and B indicate general factors and are not required to calculate the damping ratio ζ . Further, undamped and damped angular frequencies ω_0/ω_d are very similar for small damping ratios ζ , vibration “peaks” can be modelled by

$$g(t) = a \cdot e^{-bt} + c \tag{2}$$

By identifying $g(t)$, it is straightforward to estimate ζ . Since the stay cable vibrates at several frequencies (modes), it is necessary to analyse each frequency separately. Hence the following procedure for damping assessment has been used (see Figs. 7 and [6]):

1. Bandpass filtering with FIR filters (filter design by window method with Hamming window) to extract a single mode (modes 1–5 were analysed).
2. Identification of half-wave maxima (“peaks”).
3. Fitting the “peaks” with an exponential function.
4. Damping ratio ζ follows from the exponential function fit.

As damping assessment can lead to scattered results [6], damping tests were performed three times per cable and the average is used below.

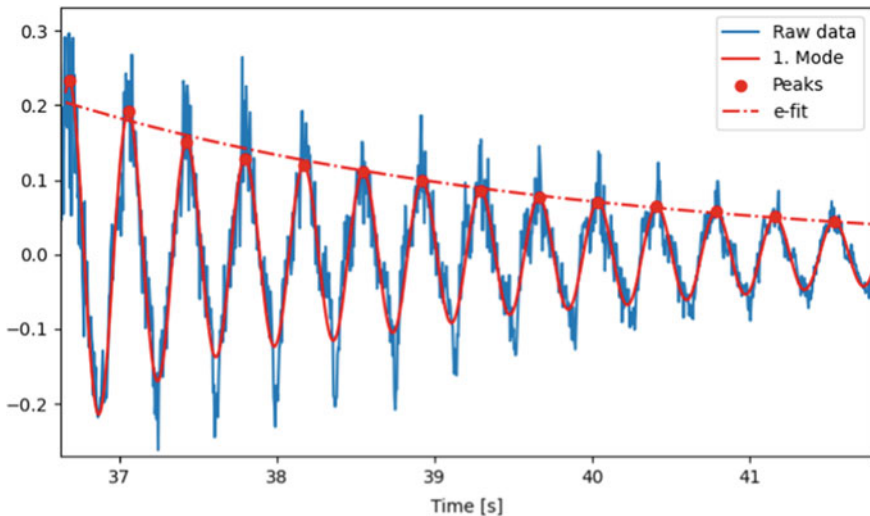


Fig. 7 Principle of damping assessment by exponential function fitting

4 Results: Damper Efficiency at Guadiana International Bridge

This section brings together the viscous damper design from Sect. 3.1 and the test results from Sect. 3.2 to show the measured damper efficiency.

Viscous damper design. For the viscous damper design, a security coefficient $\gamma_\zeta = 0.75$ has been used by $\zeta_{\text{design}} = \gamma_\zeta \cdot \zeta_{\text{calculation}}$ following general recommendations [1]. Further, the stiffness of the damper support was chosen based on experience. For comparison with measured “total” damping ratios, the design values have been increased by an assumed inherent damping of 0.1%.

Damping test results. Measured mean damping ratios are so-called “total damping ratios” (damper + inherent damping). For some modes, damping ratios could not be analyzed (and therefore are not shown), probably due to test conditions (the reasons could not be fully explained).

As can be seen in Fig. 8, all measured damping ratios are above the design universal damping curve (to be comparable an inherent damping of 0.10% is added; security coefficient has been applied). Therefore, the damping tests carried out confirm that

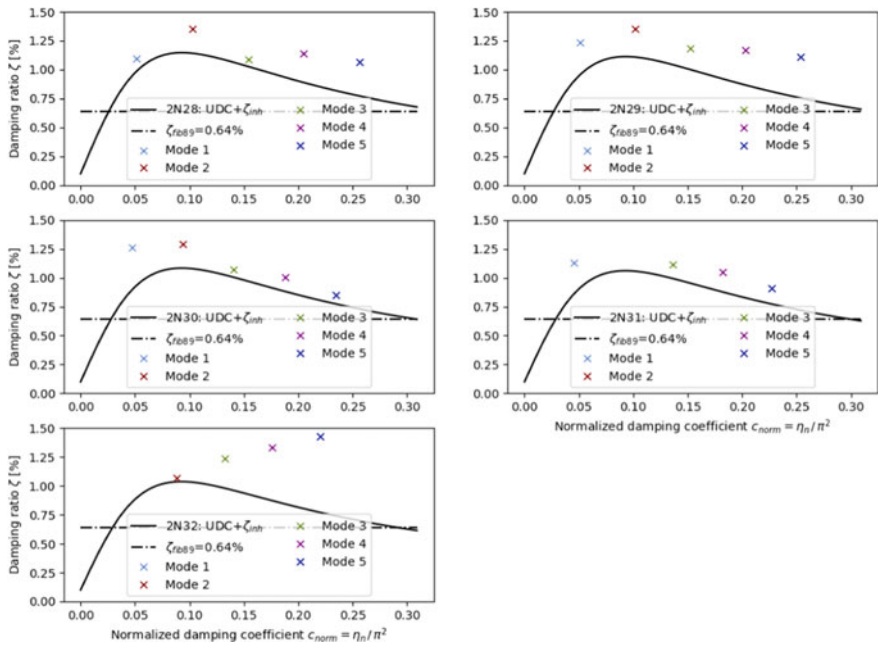


Fig. 8 Results of damper efficiency at Guadiana International Bridge: Measured “total” damping ratios (colored crosses) are above the universal design curve (to be comparable an inherent damping of 0.10% is added; black line, see Sect. 3.1) for each tested cable (subplot)

the viscous damper design complies with fib89 [5] (total damping larger than 4% logarithmic decrement).

From a theoretical point of view, it is important to note that the measured damping ratios follow the general shape of the universal damping curves for stay cables 2N28, 2N29, 2N30 and 2N31, which reinforces the conducted viscous damper design.

5 Conclusions

This paper presents and discusses full-scale stay cable tests carried out at the Gadiana International Bridge to assess viscous damping. A pull-and-release method was used to allow repeatable damping tests. The measured data were then processed using exponential function fitting to identify the stay cable damping. Considering the test results, all measured damping ratios confirmed the viscous damper design to achieve a minimum of 4% logarithmic decrement according to fib89 [5].

The security coefficient applied is a pragmatic and simple approach to considering damper efficiency and is consistent with the damping efficiencies reported by Caetano [1]. The identified damping efficiency is considered specific to the Gadiana International Bridge and may not be general for other cable-stayed bridges. Therefore, it is recommended that the scientific community publishes more measurement data (i.e., further full-scale damping assessment involving different test methods and other cable-stayed dampers) to allow for even more accurate damper design and improved cable-stayed bridge design.

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