

Experimental study of vortex-induced vibrations on H-shaped sections

Abraham S. Corriols ^a, Miguel A. Astiz ^a, Antonio Barrero ^a

^a *Technical University of Madrid, Prof. Aranguren s/n, Spain*

ABSTRACT: Experimental results of aeroelastic tests carried out with H-section models, aiming to study in detail the aeroelastic phenomena associated with vortex shedding, are presented through this paper. Such phenomena led to the oscillations of Alconétar arch bridge during its construction in 2006. The facility used is a small, simple wind tunnel built at the Ignacio Da Riva Institute, School of Aeronautics, Technical University of Madrid. Also a comparison with data from rectangular tandem section tests that conform to the geometry of the bow section of the Alconétar Bridge and some conclusions are outlined.

KEYWORDS: Aerodynamics, Vortex shedding, Vibration, Tandem section, H-shaped section

1 INTRODUCTION

The oscillations observed in the Alconétar steel arch bridge during its construction in January 2006 before placing the superstructure [1], led to the initiation of a research aimed at studying in detail the aeroelastic phenomena related to the vortex shedding that resulted in such an event [2].

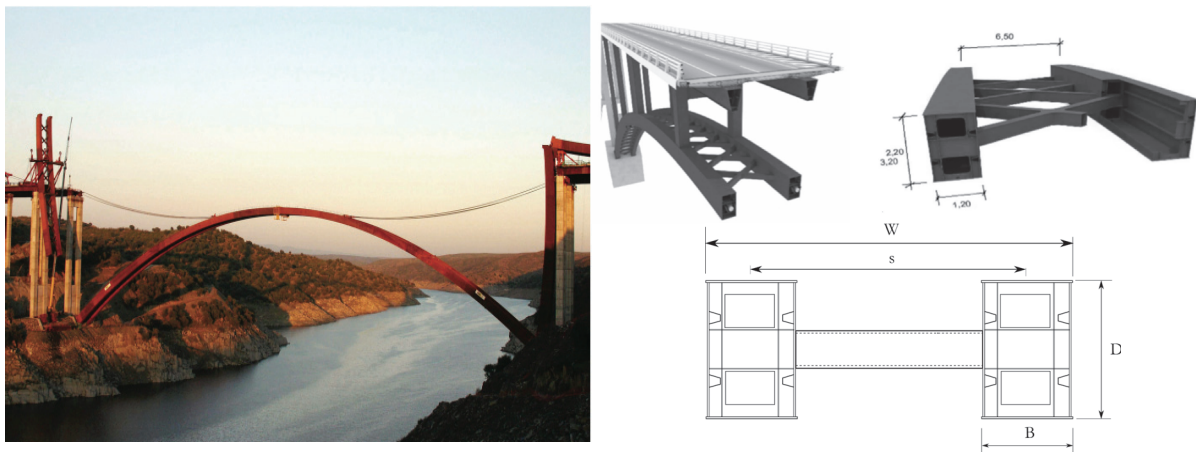


Figure 1. Alconétar bridge during erection (left) and cross-section with main dimensions (right)

The maximum amplitude reached was 80 cm on the vertical axis [1]. The box depth corresponding to the maximum amplitude value is $D=2.41$ m, the box width is $B=1.2$ m and the total width is $W=7.74$ m, giving a side ratio of $W/D = 3.21$. Measured wind speeds during the Alconétar Bridge vibration episode did not exceed 30 km/h, so the corresponding reduced frequency was close to 0.21, typical from a H-shaped section with the same side ratio. [3]. The modal mass is 1,133 kg/m and the damping ratio of critical, 0.003.

It is well known that bluff bodies behave very differently than streamlined bodies with the passage of air flow. In high curvature surfaces, an adverse pressure gradient is added to the retardant action of friction surface, which can cause the flow to be interrupted and retreat to a region adjacent to the surface. This results in the emergence of a back flow region, and a detached boundary layer appears below. For sufficiently high Reynolds numbers (say, above 10^3), the region due to the separation flow becomes unstable and an oscillating wave composed of large-scale eddies, known as Von Karman vortex street, is formed downstream of the body.

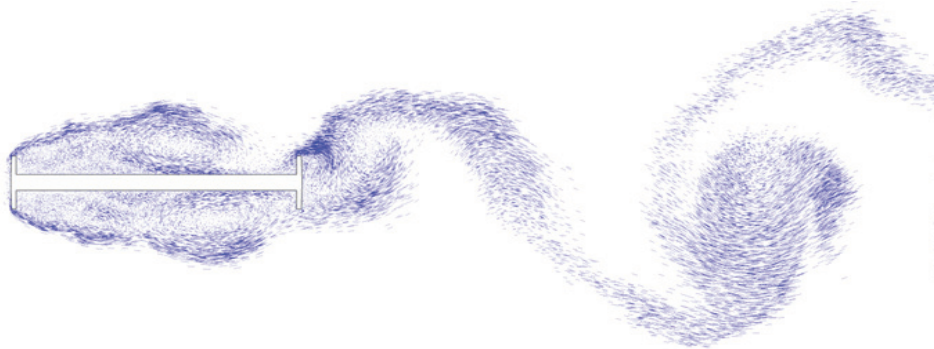


Figure 2. Visualization of the vortex shedding phenomenon through a numerical simulation code

The vortex shedding typically develops with great regularity showing a dominant frequency, which is characterized by the Strouhal number, according to the following expression:

$$St = \frac{fD}{U_{\infty}} \quad (1)$$

where D is the section depth, and U_{∞} , the speed of the current incident. The Strouhal number (St) mainly depends on the geometry of the object.

When the natural frequency of the structure is close to the value of the vortex shedding frequency, the periodic forces caused by the alternate shedding can give rise to resonance oscillations, resulting in a complex coupling between the motion of the structure and the wake pattern (e.g., the spacing between the vortices can change). Usually these type of oscillations are classified as instability induced excitations (IIE) [3]

When analysing the effect of vortex-induced oscillations, it is important to note that the amplitude of the structure is self-limited [3]. There is an upper threshold with a maximum equal to the vertical dimension of the body. Nevertheless, these types of oscillations can be considered as problematic for the serviceability of the structure. Thus, it is necessary to limit the level of vibrations in structures to ensure an appropriate standard of comfort for the users and avoid fatigue damage over time.

2 EXPERIMENTAL SET-UP

Tests were conducted in a small, simple wind tunnel built at the Ignacio Da Riva Institute, School of Aeronautics, Technical University of Madrid (see fig. 2). The installation has a rotor capable of generating an air flow that can reach a maximum speed of 1.40 m/s, driven by an AC motor. The regulation of the flow speed is achieved through a variable transformer capable to get speed increments of 0.01 m/s (the same as the tolerance of the hot wire anemometer used for

measuring the flow speed values). A laser device to measure the oscillation amplitudes of the models is employed. An oscilloscope has been connected in order to allow a better visualization of periodic movements.

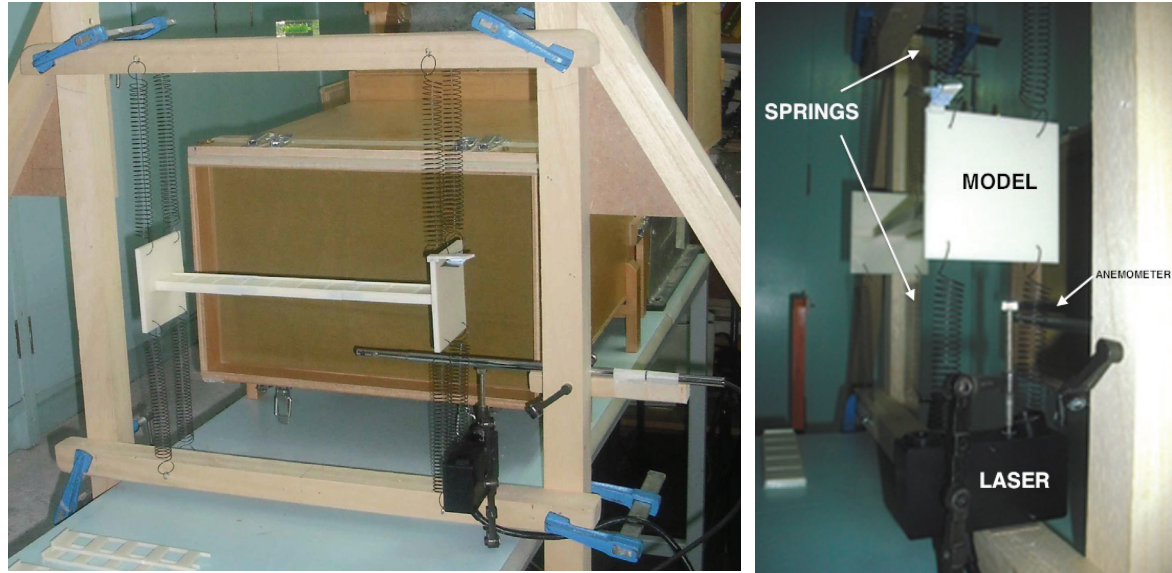


Figure 3. General view of the installation (left). Detail of springs, laser and hot wire anemometer (right)

Eight springs support the model elastically normal to the air flow. Linearity of the mechanical properties for every model was checked. These properties ready for testing are listed in Table 1.

Compared to the real section of Alconétar Bridge, it has a scale factor of $1/240$. The Reynolds number range is between 67 and 930. Typical Reynolds numbers for real bridges are between 10^5 and 10^7 , so it creates a turbulent wake behind the section. For Reynolds numbers less than 10^3 as the case is, viscous forces are still important, so it will be necessary to consider this fact to draw the appropriate conclusions and compare the results with other tests performed.

3 MODELS TESTED

Table 1 summarizes the geometry properties of the models used, being W/D the width/depth ratio corresponding to each model.

Table 1. Geometry of models tested

Model	Length (L) mm	Width (W) mm	Depth (D) mm	W/D
H-SHAPED 2.0	300	20	10	2.0
H-SHAPED 2.5	300	25	10	2.5
H-SHAPED 3.0	300	30	10	3.0
H-SHAPED 4.0	300	40	10	4.0
H-SHAPED 5.0	300	50	10	5.0
H-SHAPED 6.0	300	60	10	6.0
H-SHAPED 7.5	300	75	10	7.5

Dynamic properties to characterize frequency and damping for each W/D ratio are presented below.

Table 2 summarizes dynamic parameters of models tested

MODEL	W/D	D	f	m	ξ	m^*	$m^*\xi$
	-	m	Hz	Kg/m	%	-	-
H-SHAPED 2.0	2.0	0.01	4.73	0.1017	0.110	813.5	0.8957
H-SHAPED 2.5	2.5	0.01	4.69	0.1031	0.107	825.1	0.8830
H-SHAPED 3.0	3.0	0.01	4.80	0.0982	0.131	785.4	1.0296
H-SHAPED 4.0	4.0	0.01	4.76	0.1011	0.131	809.1	1.0568
H-SHAPED 5.0	5.0	0.01	4.76	0.1046	0.101	837.2	0.8456
H-SHAPED 6.0	6.0	0.01	4.75	0.1038	0.141	830.5	1.1705
H-SHAPED 7.5	7.5	0.01	4.80	0.1042	0.133	833.3	1.1091
H-SHAPED 4.0 POROSITY 0%	4.0	0.01	4.33	0.0994	0.076	794.8	0.6065
H-SHAPED 4.0 POROSITY 10%	4.0	0.01	4.60	0.0867	0.129	693.5	0.8397
ALCONÉ TAR BRIDGE	3.21	2.41	0.70	1131	0.300	153.9	0.4616

where W/D=width/depth ratio; f=the vibration frequency of the model; m=linear mass associated to the model; ξ =damping ratio; m^* =mass ratio ($=m/\rho D^2$); $m^*\xi$ =reduced damping. In order to achieve a realistic comparison, not only depending on the W/D ratio, similar values of damping ratio in all models have been sought. In this case, the values are all close to unity.

A model with a porosity ratio of 10% (related to overall surface and distributed in hollow strips parallels to the air flow direction) has also been tested, in order to compare the amplitude of oscillations with solid models. Also another model with a lower reduced damping ($m^*\xi$) have been considered to check the dependency of the amplitude of oscillations as a function of reduced damping. Lastly, real data from Alconétar Bridge are also included.



Figure 4. Model with of W/D=4.0 and porosity ratio of 10% ready to be tested

4 RESULTS

Figure 5 shows a series of plots corresponding to the amplitude spectrum of lift coefficient oscillations (left) and temporal registration of vertical movements (right) that identify the process of vortex-induced vibration of the model with a W/D = 4.0, for a given range of air flow speeds. Frequency range of the spectrum is 20 Hz, and the time interval considered is one minute, always leaving two minutes at each speed interval prior to the start of data recording to ensure that the steady state is reached.

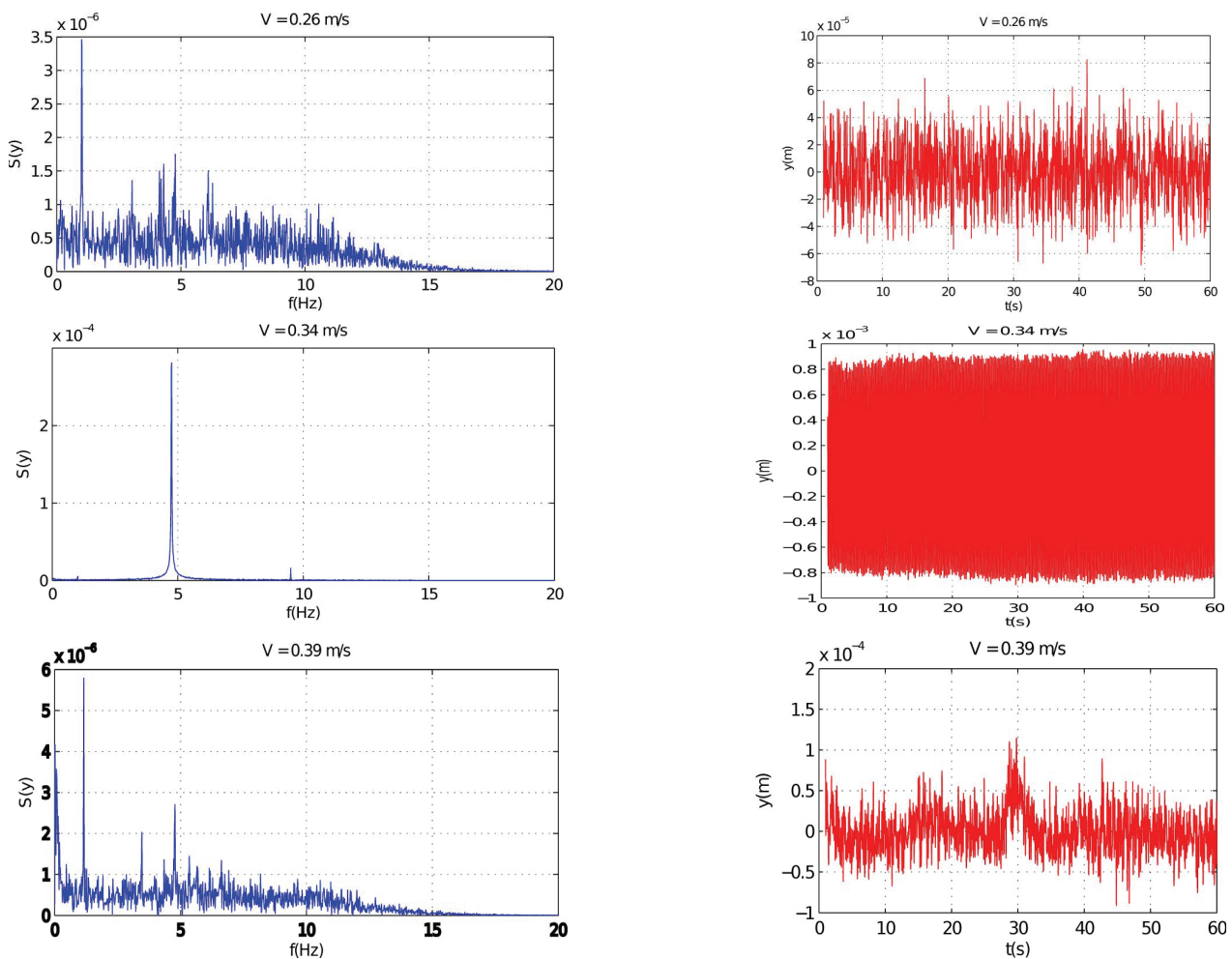


Figure 5. Amplitude spectrum of lift coefficient oscillations (left) and temporal register of vertical displacements within the wind speed range of VIV (right). Model with side ratio of $W/D=4.0$

Figure 5 ($v = 0.26$ m/s) shows that the excited frequency range is quite broad, which indicates that the model is vibrating slightly. However, there is no coupling between the natural vibration frequency and the vortex shedding frequency. The oscillations are small, not exceeding the threshold of $6 \cdot 10^{-5}$ m of amplitude ($y/D < 0.6\%$). As the wind speed increases, the vortex shedding frequency approaches the natural frequency. Oscillations become more regular and their amplitude increases, reaching a value close to 10^{-4} m ($y/D = 1.0\%$) for an air flow speed value of 0.28 m/s. This value can precisely be considered as the starting speed of vortex-induced vibration phenomenon (v_0), which occurs within an air flow speed range between 0.28 m/s and 0.37 m/s. Critical air flow speed (v_{crit}) is 0.34 m/s, associated to the peak value of vertical oscillations, around $9 \cdot 10^{-4}$ m ($y/D = 9\%$). From 0.37 m/s, air flow speed considered as the end of the coupling phenomenon (v_e), small peaks in the spectrum different to the natural oscillation frequency begin to appear, decreasing the amplitude of the oscillation gradually and losing the regularity simultaneously, turning back to the prior oscillation state.

Figure 6 shows the root mean square (RMS) of the amplitude of oscillation as a function of the reduced speed for each model. The range of reduced speeds in which the phenomenon of vortex-induced vibration (VIV) occurs when the W/D ratio varies from 2.0 to 7.5, is between 3.0 and 15.5. For the comparison to be effective and not depend only on the W/D ratio, similar low values of damping ratio (or Scruton number, which is an equivalent parameter) in all models has been sought to achieve.

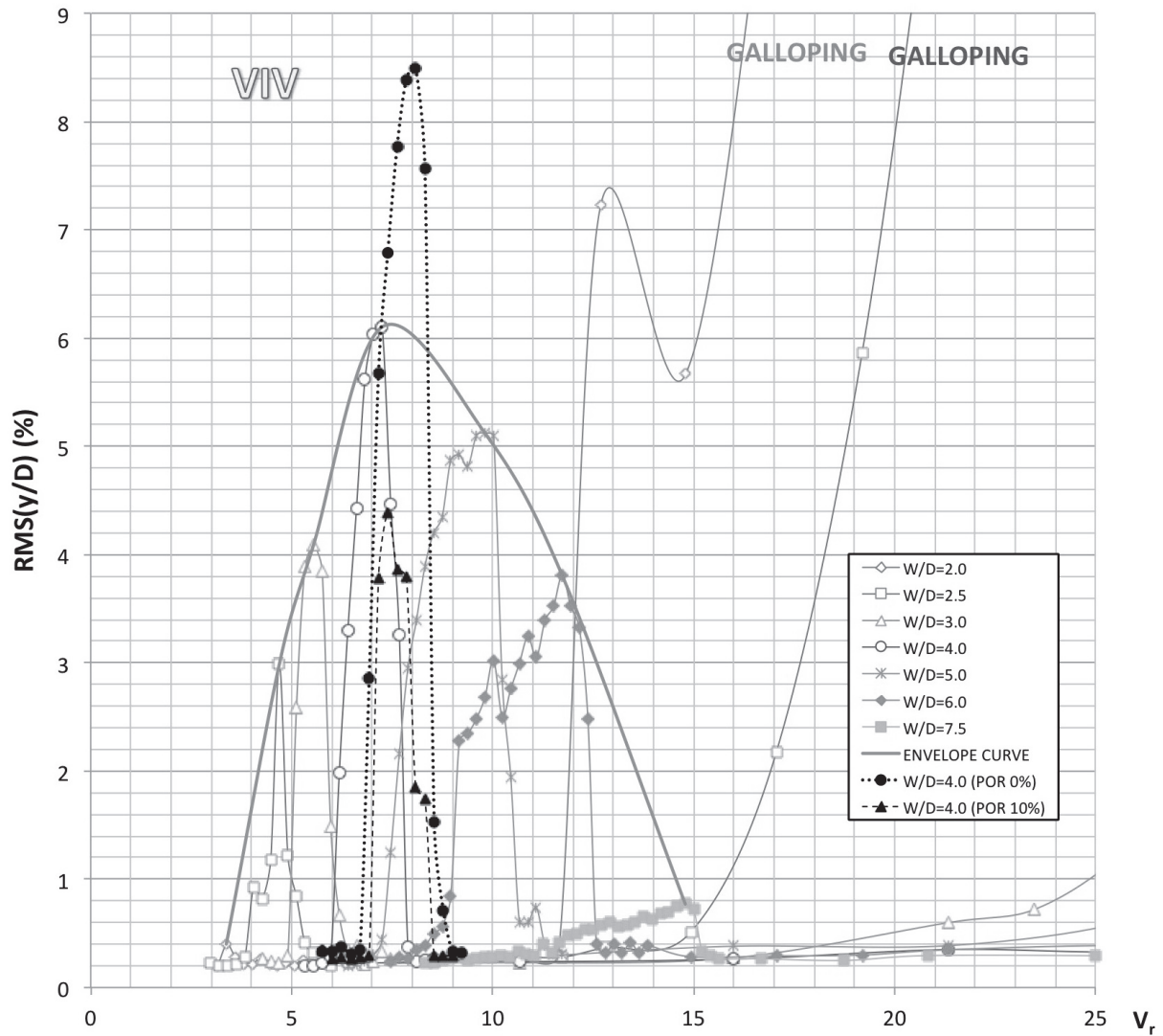


Figure 6. RMS non-dimensional amplitude ($RMS(y/D)\%$) as a function of the reduced speed, v_{red} of models tested

Table 3 collects the most important data represented in figure 6.

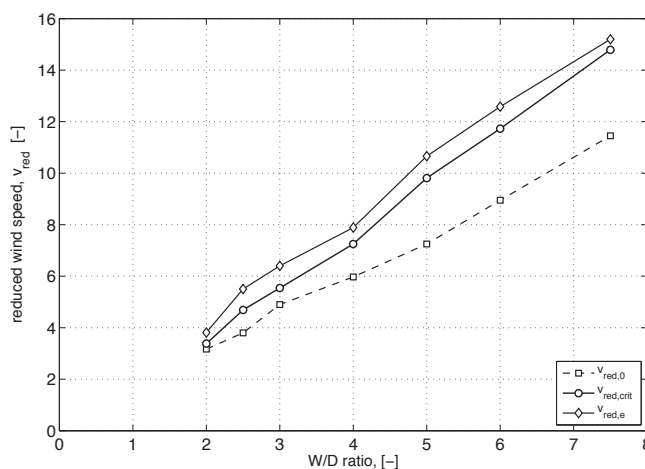
Table 3 summarizes main results extracted from the tests

MODEL	$V_{red,crit}$	$V_{red,0}$	$V_{red,e}$	Band-width	$RMS(y)_{max}(\%)$	Sc
	-	-	-	-	-	-
H-SHAPED 2.0	3.38		3.81	0.64	0.40	11.26
H-SHAPED 2.5	4.69	3.17	5.50	1.70	2.99	11.10
H-SHAPED 3.0	5.54	3.80	6.40	1.50	4.09	12.94
H-SHAPED 4.0	7.25	4.90	7.89	1.92	6.10	13.28
H-SHAPED 5.0	9.81	5.97	10.66	3.41	5.12	10.63
H-SHAPED 6.0	11.73	7.25	12.58	3.63	3.81	14.71
H-SHAPED 7.5	14.79	8.95	15.20	3.74	0.08	13.94
H-SHAPED POROSITY 0%	8.08	6.93	8.61	1.68	8.49	7.62
H-SHAPED POROSITY 10%	6.96	6.82	9.02	2.20	4.39	11.23
ALCONÉTAR BRIDGE	≈ 5.0	-	-	-	≈ 16.60	5.80

where $v_{red,crit}$ =critical reduced wind speed ($v_{red,crit}=U/fD$, being U =air flow speed corresponding to the maximum amplitude of oscillation); $RMS(y)_{max}$ =root mean square of the maximum amplitude of oscillation; $RMS(y/D)_{max}(\%)$ =root mean square of non dimensional maximum amplitude; Sc =Scruton number ($Sc = 4\pi m \cdot \xi$)

The most important fact to note is the variation of the maximum response as a function of W/D ratio. As shown in figure 6, the response increases as the W/D relationship increases, up to a maximum, which reaches a non dimensional amplitude of 6.10% for a given side ratio of $W/D=4.0$. From this value, the response amplitude decreases while W/D increases, so that, with a side ratio of 7.5, the effects of vortex-induced vibrations on the H-shaped section are not significant. The evolution of the response and its dependence on W/D can be explained by the coalescence phenomena of vortices that occur when the air flow interacts with the model [4]. It has been shown that models with $W/D=2.0$ and $W/D=2.5$ experience vibrations associated with the phenomenon of transverse galloping at excessively high reduced speeds. It would be interesting to test other models at higher speeds, and thus verify if they might undergo transverse galloping as well at certain air flow speeds.

Figure 7 shows the critical reduced speed, $v_{red,crit}$, the onset reduced speed, $v_{r,0}$, and the ending reduced speed, $v_{red,e}$, as a function of the W/D ratio. All these parameters keep a linear dependence on the W/D ratio. Expressions obtained by least squares adjustment are also given by the following expressions:



$$v_{red,crit} = 2.06 \cdot \frac{W}{D} - 0.67 \quad (2)$$

$$v_{red,0} = 1.47 \cdot \frac{W}{D} - 0.18 \quad (3)$$

$$v_{red,e} = 2.05 \cdot \frac{W}{D} - 0.08 \quad (4)$$

Figure 7. Reduced speeds as a function of W/D ratio for H-shaped section models

H-shaped section models represent a transition between rectangular sections and two prisms in tandem arrangement. In this case, the vortex shedding pattern presents a peculiar behaviour as described below and depicted in figure 8 with the aid of a CFD code, a very useful tool for understanding the vortex shedding mechanism. For small side ratios the central spacing between section borders do not have any influence and behaves as an equivalent rectangular section. For side ratios greater than 2.0, vortex shedding mechanism responds to the ILEV type [3] That is due to the appearance of convection cells in the upper and lower gap, which maintains the detached boundary layer and favours the formation of impinging leading edge vortices along the surface (ILEVcc). This effect is less important as the side ratio increases. Furthermore, according to figure 8, with side ratios between 2.0 and 4.0, a transition zone between normal ILEV pattern and that caused by convection cells (ILEVcc) gives rise to a dual vortex shedding frequencies, thus we conclude that the resonant effect may occur for two different horizontal wind speeds.

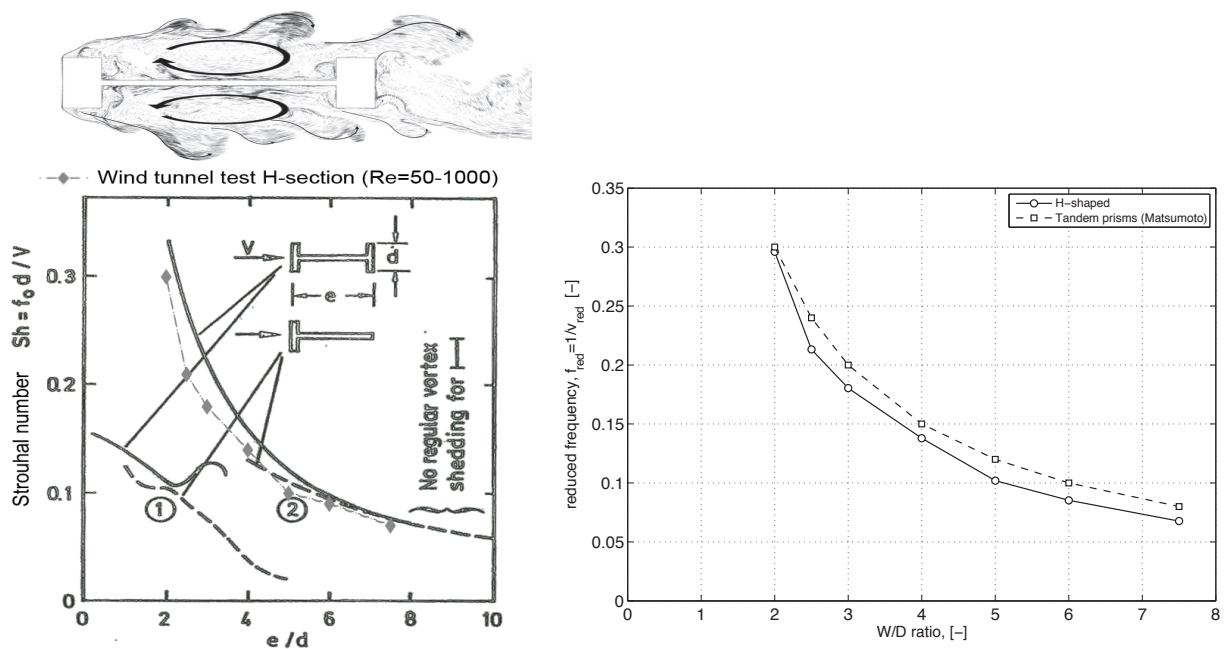


Figure 8. CFD flow visualization and Strouhal number for different H-section side ratios (After [5], p. 129), with present results added (left). Reduced frequency of VIV p as a function of W/D ratio (right)

5 COMPARISON WITH OTHER EXPERIMENTAL RESULTS

Experimental wind tests similar to that described in this paper were carried out by Matsumoto and other researchers with rectangular sections in tandem configuration [4] are shown in figure 9. The model tested consist in two prisms in tandem arrangement with $W/D=4.0$, $B/D=1.0$ and a splitter plate behind the prism downstream. Two vortex shedding patterns are identified: the movement induced excitation (MIE) and Karman Vortex (KV). MIE pattern can be associated to the ILEV mechanism, as described previously.

The upper curve on the right (see figure 8) corresponds to the onset reduced frequency ($f_{red,o}=1/v_{red,o}$) of MIE vibrations type, characterized by Matsumoto and experienced by rectangular tandem sections. Their values are very close to the lower curve, which relates the reduced

frequency with the W/D ratio for H-shaped section models. Results for H-shaped section correlate well with those obtained by the Japanese researcher.

Figure 9 shows the value of non dimensional amplitude, η/D , based on the reduced speed obtained by Matsumoto [4]. Peaks amplitudes are located close to 15%. In the case of H-shaped sections, the maximum peak amplitude registered was 9.0% for 'H-SHAPED $W/D=4.0$ ' and 12.1% for 'H-SHAPED $W/D=4.0$ POROSITY=0%'. The maximum RMS value was 6.1% and 8.5%, respectively. Both models have the same geometry but different values of reduced damping: $m^*\xi=1.06$ for 'H-SHAPED $W/D=4.0$ ' and $m^*\xi=0.61$ for 'H-SHAPED $W/D=4.0$ POROSITY=0%'. Matsumoto's model has a total value (two prisms) of $m^*\xi=1.66$ ($m^*\delta=5.2$ per prism, being $\delta=2\pi\xi$). The larger reduced damping is, the smaller the smaller amplitudes of oscillation are. However, H-shaped section and two prisms in tandem cannot be compared, since their force coefficients are not equivalent and the amplitude of oscillation significantly depends on the lift coefficient as well.

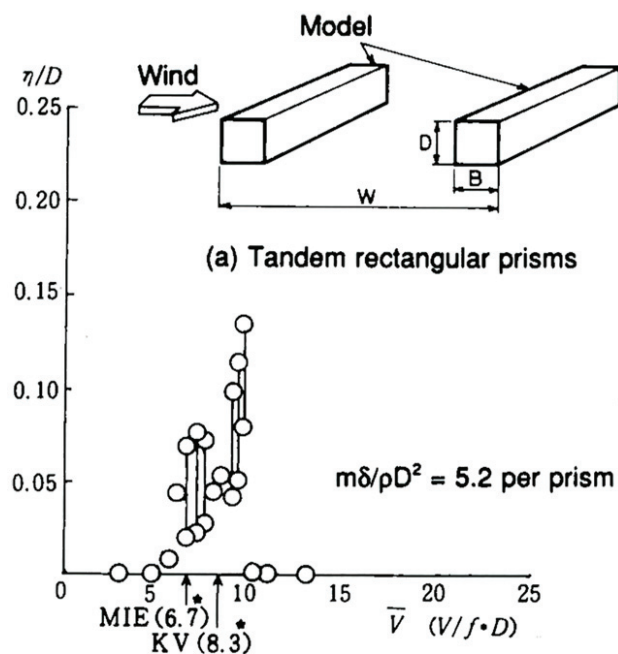


Figure 9. Non dimensional amplitude of oscillation as a function of reduced speed for prisms in tandem arrangement (from [4])

6 CONCLUSIONS

Vortex-induced vibrations identified in the H-shaped section models are not due to alternating shedding of vortices, or Von Karman vortices (KV, according to the description made by Matsumoto in [4]) as it might be initially thought, but an excitation induced by the movement of the structure itself. The vortices originated from the interaction between the air flow and the studied section also come into play different from alternating shedding of vortices. As in the rectangular tandem sections, the aerodynamic forces acting on the H-shaped section models seem to be largely conditioned by the section oscillations.

This issue highlights the importance to understand the mechanism that causes the aerodynamic phenomenon and thus take the required measurements to eliminate or minimize vibrations as they can endanger the integrity of certain structures such as bridges, if the circumstances occur. The vibration episode of Alconétar Bridge might be explained through two possible vortex shedding patterns analyzed herein.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

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