Stretto di Messina

Concessionaria per la progettazione, realizzazione e gestione del collegamento stabile tra la Sicilia e il Continente Organismo di Diritto Pubblico
(Legge n° 1158 del 17 dicembre 1971, modificata dal D.Lgs. n°114 del 24 aprile 2003)

EurolinK

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Unità Funzionale	OPERA DI ATTRAVERSAMENTO	PB0033_F0
Tipo di sistema	STUDI DI BASE	
Raggruppamento di opere/attività	STUDI AERODINAMICI	
Opera - tratto d'opera - parte d'opera	Basic Studies	
Titolo del documento	Wind Tunnel Tests, Towers	

CODICE: C G 1 0 0 0 | P | R G | D | P | S B | S 3 | 0 0 | 0 0 | 0 0 | 0 0 | 0 1 | F0

REV	DATA	DESCRIZIONE	REDATTO	VERIFICATO	APPROVATO
F0	20/06/2011	EMISSIONE FINALE	ADME	ALN	ALN/EYA

NOME DEL FILE: PB0033_F0

INDICE

1 Executive Summary

Section model wind tunnel tests have been carried out with a 1:100 scale model of the Messina Bridge tower structure for determination of the wind load coefficients with respect to the structural design as well as provide an indicative assessment of wind effects on the tower as vortex induced vibrations and aerodynamic stability.

Furthermore, full aeroelastic model tests have been carried out at 1:200 scale in two different wind tunnel facilities, to access the effects of wind and verify tower response to boundary layer wind flow. The primary focus of the investigation at The Boundary Layer Wind Tunnel Laboratory (BLWTL), The University of Western Ontario Canada, was to provide verification of the tower behaviour as obtained at BMT Fluid Mechanics, England.

One of the main objectives of the wind tunnel tests was to identify the level of structural damping necessary to mitigate vortex shedding response.

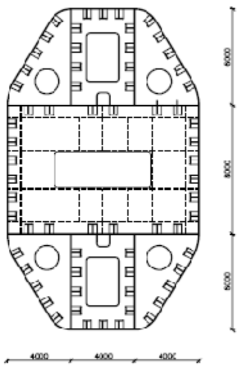
The detailed tests of the tower structure lead to the following conclusions:

- In smooth flow the tower section model displayed vortex induced oscillations in the non-dimensional wind speed range $5 < V/f_bB < 10.0$.
- RMS response for tower section model can be mitigated by increasing level of structural damping.
- Tower section model is aerodynamically stable up to and above the maximum design speed at tip of the tower.
- The static wind load coefficients appear to be independent of Reynolds' Number for the 1:100 scale section model in the wind speed range tested and is almost unaffected by turbulence.
- Vortex induced vibrations for the aeroelastic tower model are observed in both bending and torsion degree of freedom.
- The aeroelastic tower response was at BMT found to be almost unaffected by turbulence while the BLWTL investigations indicated that turbulence generally results in a reduction in the magnitude of vortex shedding induced peaks, but increases buffeting responses at higher wind speeds. The turbulence intensity was around 3% larger at BLWTL.

- Vortex shedding response of the aeroelastic model of the tower, in-service configuration, in along bridge axis, primary bending mode, were measured for all configurations between 0º and 20º for wind speeds lower than design wind speed.
- By increasing structural damping level of bending mode up to 4% rel-to-crit., for tower in service configuration, the response can be mitigated to an RMS acceleration level of approximately 0.5 m/s^2 as required by the specifications.

2 Tower Geometry and Dynamic Properties

The tower model considered for sub-tests T1, T2 and T3 wind tunnel test programme, Figure 1, is identical to the design presented in the Tender Design, with the exception that the tower height has been increased with 16.4 m (Progetto Definitivo). Two twin-leg towers, where each leg is of constant octagonal section, are canted in towards each other at the top, Figure 2.



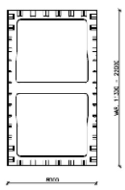


Figure 1 Left hand side: tower section geometry investigated in wind tunnel, right hand side: cross beam section geometry.

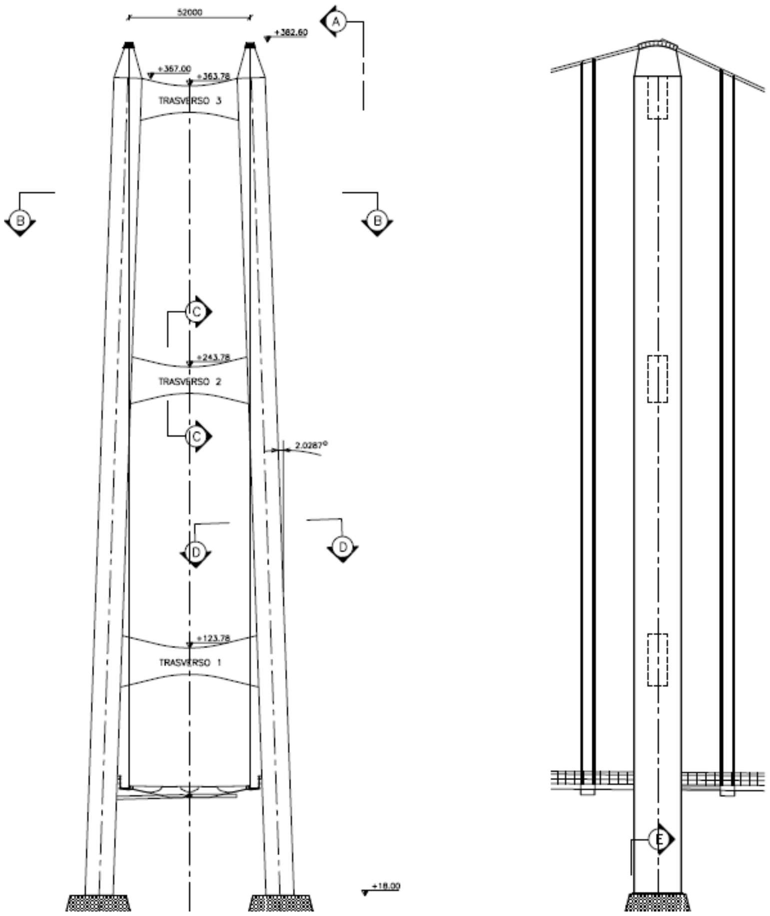


Figure 2 Tower geometry investigated in wind tunnel, along and across deck view.

2.1 Sub-test T1 and T2, section model

The tower model sub-test T1 and T2 wind tunnel tests were carried out at BMT Fluid Mechanics UK. The test setup and results are reported in [1].

The tower leg model of the Messina Strait Bridge was constructed to the geometrical scale of $1:\lambda_L = 1:100$ yielding a model tower leg width B = 20 m / 100 = 0.2 m. Investigation are carried out in 2.7m wide wind tunnel with one tower leg cross sections and assembly of two tower leg cross sections representative of the 70% of full tower height.

A picture of the tower leg model is shown in Figure 3.

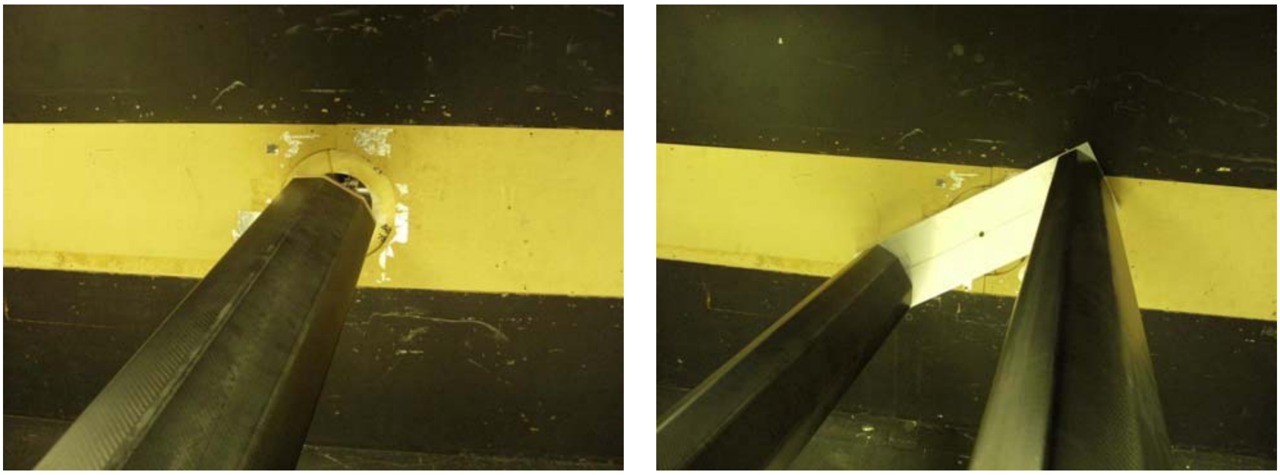


Figure 3 Tower section model in 1:100 scale. Left hand side of the figure reflects single leg configuration, right hand side reflects double leg system.

2.1.1 Dynamic scaling of the section wind tunnel model

A combination of geometrical, mass and stiffness considerations resulted in the selection of a λ_L = 1:100 geometrical scale for the tower model of the Messina Bridge. Thus, the 2.7 m long section model represented 270 m of the tower and modelled all the geometrical details that were thought to have an influence on the aerodynamics of the structure. For static tests only geometrical scale is applicable.

2.2 Sub-test T3, Aeroelastic model

The tower model sub-test T3 wind tunnel tests were carried out at BMT Fluid Mechanics and at The Boundary Layer Wind Tunnel Laboratory BLWTL. The test setup and results are reported in [2] and [3], respectively.

2.2.1 BMT tests

The tower model of the Messina Strait Bridge investigation was carried out in BMT's 4.8x2.4m cross section boundary layer wind tunnel. To ensure accurate description of wind effects and verification of the tower response three different models were investigated. The models are geometrically identical with different dynamic properties.

Four structural conditions were investigated

- Completed tower, free standing condition
- Completed tower, pinned at top simulating the effect of main cables prior to deck installation
- Construction phase immediately before mounting of top cross beam
- Completed tower, in service condition, pinned at top simulating effect of main cable, deck installed

Dynamic properties of the prototype and aeroelastic models are as given in [2], Appendix B.

A picture of the tower section model at BMT is shown in Figure 4.

Figure 4 Full aeroelastic model prier to the tests at BMT, left side reflecting a freestanding tower, right side reflecting in service tower with pinned at the top.

2.2.2 BLWTL tests

The full aeroelastic models of the bridge tower were studied at the main boundary layer test section of BLWT II. Two full aeroelastic models were designed and constructed, one Froude and one non-Froude scaled model.

The tests included measurements of the response of the full aeroelastic model to smooth and turbulent wind with two configurations:

- Completed tower, free standing condition
- Completed tower, pinned at the top to simulate the effects of the main cables and tie back.

Dynamic properties of the prototype and aeroelastic models are as given in [3].

2.2.3 Dynamic scaling of the full aeroelastic wind tunnel model

The test configurations were investigated using differently scaled aeroelastic models. A combination of geometrical, mass and stiffness considerations resulted in the selection of a λ_L = 1:200 geometrical scale for all aeroelastic tower models of the Messina Bridge.

SdM specifications required that model tests with one aeroelastic system shall obey Froude scaling. This means that the ratio of model frequencies to prototype frequencies is fixed as the square root of the geometric scale $f_m / f_p = \sqrt{\lambda_L}$, which in turn yields that prototype wind speeds are obtained as model wind speeds multiplied by model scale wind speeds multiplied by the square root of the geometric scale $V_p = V_m \cdot \sqrt{\lambda_L}$.

Whereas Froude scaling is a necessary condition for correct representation of fluid / structure systems in which gravity plays a significant role, such as a full aeroelastic model of a suspension bridge, it is not required for an elastically suspended wind tunnel section model which operates independent of gravity. Dimensional analysis of the important forces acting on the elastically sprung section model demonstrates that the frequency ratio f_m / f_p can be chosen independently of geometrical scale and that prototype wind speeds are obtained as model wind speeds multiplied by the geometric scale and the inverse of the frequency $V_p = V_m\ \lambda_L \cdot f_p / f_m = V_m \cdot \lambda_V$.

For the present sub-test T3 the wind speed scale factor was chosen as λ_V = 4.1 and λ_V = 6.0 at BMT and BLWTL, respectively, for the stability (and vortex shedding tests at BLWTL) tests to ensure full utilisation of the speed range of the wind tunnel and thus as high Reynolds' Numbers as possible.

For the vortex shedding tests at BMT the wind speed scale factor was chosen as λ_V = 2.2 to ensure that vortex shedding was captured at wind tunnel speeds above 2 m/s.

For the in-service vortex shedding tests Froude scaling was chosen giving λ_V = 14.2 for the bending mode.

3 Results, Sub-test T1

Sub-test T1 was split in three parts according to the scope of work. A vortex shedding phase designed to identify wind effects on the tower model, a damping phase to verify effect of increased structural damping and a verification phase documenting the aerodynamic stability of the double leg tower configuration.

Different configurations of the tower leg were investigated as indicated in [2], Table 2.2. Mitigation of the vortex shedding excitation is done by increasing structural damping.

3.1 Vortex induced response

Vortex induced oscillations of the tower leg in smooth flow were measured for both configurations, single and double leg, at each angle of attack.

The measurements were carried out by varying the wind speed in the non-dimensional range 1.0< V/f_bB < 10 at increments of approximately 1.0. At wind speeds where the section model displayed oscillatory response the wind speed increments was decreased to ensure capture of the full lock-in range.

In smooth flow the tower section model displayed vortex induced oscillations in the non-dimensional wind speed range 5 < V/f_bB < 10.0.

For single leg configuration worst case RMS displacement for a damping level of 0.1% rel-to-crit., of about 1.16m occurs at angle of attack 0º and 5º.

The amplitude measured for double leg configuration are greater then those for single leg configuration. At 0º, with level of damping of 0.1% rel-to-crit., the double leg reached amplitude of 1.54m.

3.2 Mitigation of Vortex induced response

To mitigate vortex shedding excitation additional structural damping was added to both configurations. A copper vane was supported from the arms of the dynamic rig, between poles of electromagnet. By varying the current feeding the electromagnet, different levels of damping can be obtained.

At 0º, single leg configuration, RMS displacements are reduced to 0.24m by damping level of 2% rel-to-crit, and for the double leg configuration RMS displacement at 5º are reduced to 0.13m by damping level of 2.5% rel-to-crit.

3.3 Aerodynamic stability

The critical wind speed of T1 double leg tower configuration was measured for angles of attack between 0^0 and 90^0 in smooth flow (I = 0.3%) using the same dynamic rig applied in the vortex shedding tests and reported in [1].

From results it is noted that the T1 double leg tower section is aerodynamically stable at full scale smooth flow wind speeds up to and above the maximum design speed of $80ms^{-1}$ at tip of the tower.

4 Results, Sub-test T2

The tower leg configurations were subjected to wind load tests in smooth flow ($I_{u,w}$ = 0.3%) and turbulent flow (I_u = 4.8% and I_v = 3.7%) for verification of the aerodynamic performance [1]. These tests comprised:

- Single and double leg configuration, measurement of wind load coefficients C_L, C_D, C_M as functions of angle of attack η.

4.1 Wind load coefficients

The wind load coefficients are defined as the lift, drag force $F_{L,D}$ and overturning moment F_M acting on the section model made non-dimensional through normalisation with the dynamic head $½\rho V^2$, and model tower width B (lift and drag) or tower width squared B^2:

$$C_{L,D} = \frac{F_{L,D}}{½\rho V^2 B}$$

$$C_M = \frac{F_M}{½\rho V^2 B^2}$$

Measurement of C_L, C_D, C_M for the verification was carried out with the section model suspended in a high frequency 6 component force balance. Plots of C_L, C_D, C_M vs. the angle of attack in the range $0^0 < \eta < 90^0$ obtained in smooth and turbulent flow extracted from [1], figure 3.2 are shown in Figure 5 **Errore. L'origine riferimento non è stata trovata.** and Figure 6.

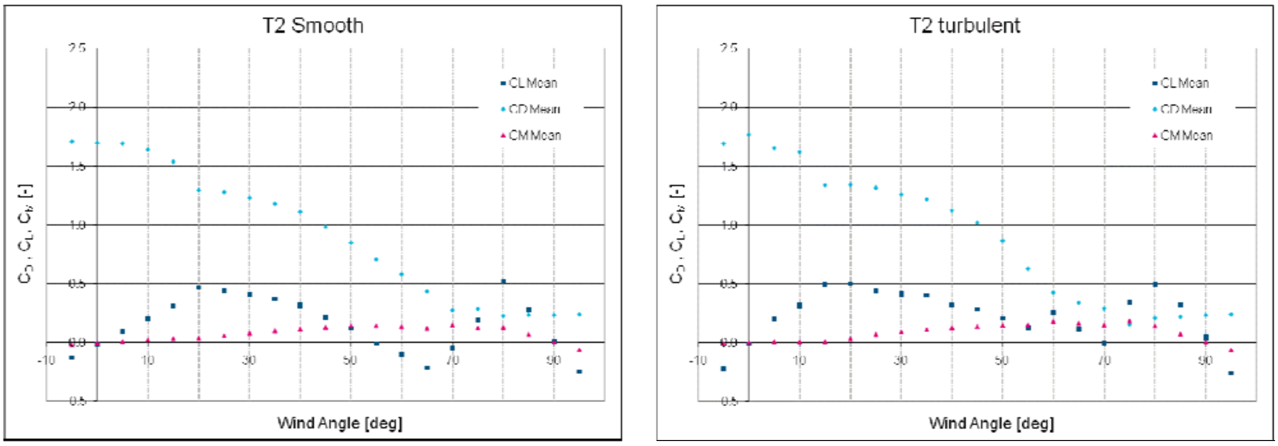


Figure 5 Wind load coefficients for the T2 one leg system configuration obtained in smooth and turbulent flow at Reynolds number of $5{\cdot}10^5$.

From Figure 5**Errore. L'origine riferimento non è stata trovata.** it is noted that the drag coefficients does not change significantly with the change in flow conditions from smooth to turbulent.

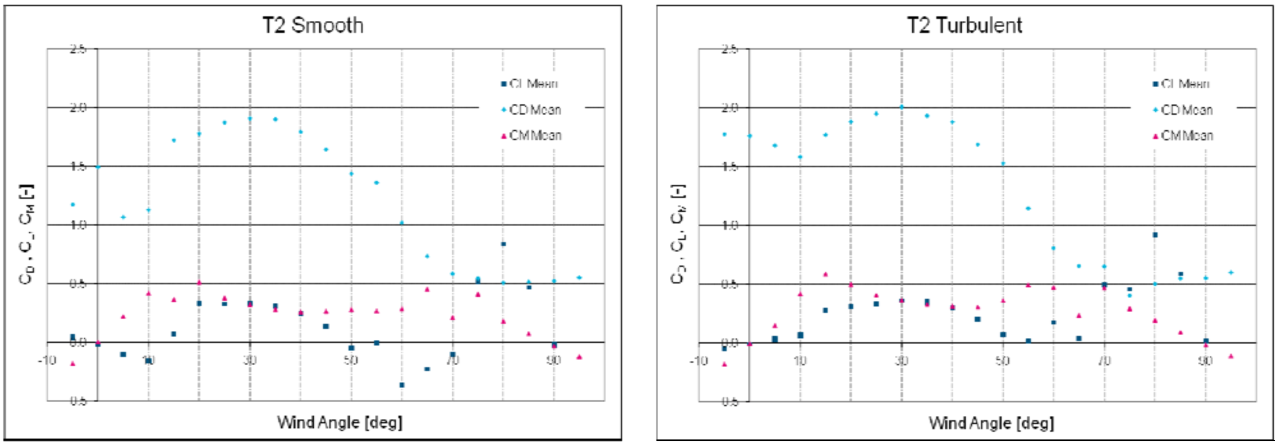


Figure 6 Wind load coefficients for the T2 double leg system configuration obtained in smooth and turbulent flow at Reynolds number of $5{\cdot}10^5$.

From Figure 6 it is noted that trend of the measured lift and moment coefficients are same as for one leg configuration in the angle of attack higher then 30º. At lower angles of attack where downstream leg is in the wake shed from the upstream leg some discrepancies are noted. Furthermore, drag coefficients is found to be largely unaffected by the levels of turbulence for all angles of attack higher then 10º.

To determine to what extend the static drag coefficients are subjected to scale effects to additional models of single leg configuration, one at scale of 1:50 and one at scale of 1:200, have been investigated at higher wind speed settings with Reynolds number up to 1×10^6 for 4 angles of attack, 0º, 30º, 60º and 90º [1]. This observation indicates that the wind loads are reasonably independent of Reynolds' Number for the present model scale of 1:100.

5 Results, Sub-test T3

The aeroelastic model was subjected to more detailed tests in smooth flow ($I_{u,w}$ = 0.3% at BMT and I_u = 1% at BLWTL) and turbulent flow (I_u = 6.9% and I_v = 5.2% at BMT and I_u = 10% at BLWTL) for verification of the aerodynamic performance, [2] and [3]. These tests, for the structural conditions given in section 2.2, comprised:

- Measurement of structural response at increasing wind speeds in the range of 5m/s-80m/s full scale at wind directions between 0º-90º in steps of 10º. The angle of attack increment is decreased to 2.5º between the two directions yielding the highest response.

- Measurement of critical wind speed for tower model and confirmation of aerodynamic stability.

5.1 Vortex induced response

The measurements were carried out by varying the wind speed in the model scale range 1.0< V_{MS} < 15 at increments of approximately 1.0. At wind speeds where the section model displayed oscillatory response the wind speed increments was decreased to ensure capture of the full lock-in range.

Based on free standing tower test results p.18 [2] the tower response is unaffected by the turbulence effect but comparing figure 3.1 and figure 3.7 in [3] turbulence effect is observed and the second peak in the longitudinal direction, 0º wind, around V_{FS}=40m/s is mitigated. First peak in longitudinal direction about V_{FS}=17m/s is of same magnitude and unaffected by the turbulence effect.

In service condition, comparing longitudinal response figure 3.4 and figure 3.8 in [3], the tower response is unaffected by the turbulence effect.

Vortex shedding response of the tower in along bridge axis, primary bending mode, were measured for all configurations between 0º and 20º for wind speeds lower design wind speed.

For the first three configurations given in section 2.2, the worst vortex shedding peak occurrence in along bridge axis bending, smooth flow, found at BMT Fluid Mechanics [2] is given in **Errore. L'origine riferimento non è stata trovata.**.

Table 1 Worst case vortex shedding peaks, smooth flow, along bridge axis bending, BMT.

Configuration	Wind direction [º]	RMS acceleration MS [m/s^2]	Damping rel-to-crit. [%]
Freestanding tower	0	60	0.16
Prior to cross beam installation	15	35	0.32
Completed tower, with cables installed	20	12	0.32

BLWTL investigations showed that the maximum response in the under construction condition (free standing tower) for almost all tests occurred in tower torsion. The largest tower response is found to occur in the 20º wind direction tests in turbulent flow at wind speed of V_{FS}=46m/s where the tests were stopped due to large buffeting responses.

Wind speeds between 50-63 m/s were skipped in the BLWTL in-service configuration tests due to large tower responses.

In service configuration with a Froude scaled model of the tower have demonstrated that severe vortex shedding of the tower legs in along bridges axis bending is likely to occur at wind speed lower than V=71 m/s corresponding to the SILS condition at z=250m level. The worst response in smooth flow occurred at a wind direction of 2.5º and 5º with the normal to bridge line.

The first series of vortex shedding test done at BMT for in service configuration did not show the same response as obtained from the Froude scaled model. To investigate this issue the Froude scaled model was tested as a freestanding tower to assess the effect of Reynolds number on the response of the tower. Froude scaled and non-Froude scaled tower yields identical response in free standing condition, Figure 7.

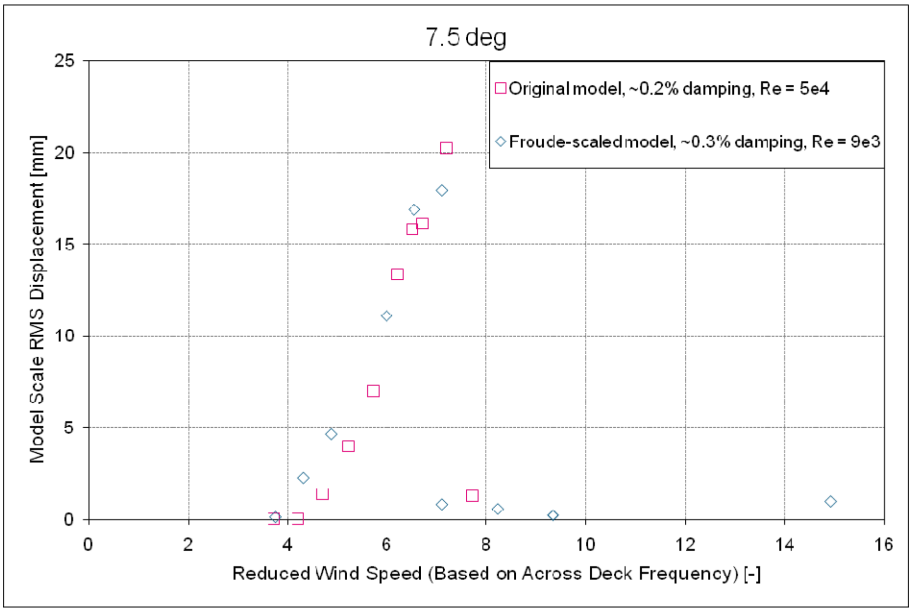


Figure 7 Comparison of free standing tower with original and Froude scaled model [2].

Comparison between Reynolds numbers for freestanding and in service configurations with old and new model indicate insensitivity of the model to Reynolds number effects, **Errore. L'origine riferimento non è stata trovata.** Table 2 and Figure 8. The old tests appeared to be incorrect.

Table 2 Comparison of Reynolds number for 1st bending mode in along bridge axis.

Configuration	Reynolds number
Freestanding, old stiff model	$9.0 \cdot 10^3$
Freestanding, Froude scaled model	$5.0 \cdot 10^4$
In service, Froude scaled model	$3.1 \cdot 10^4$
In service, old stiff model	$6.5 \cdot 10^4$

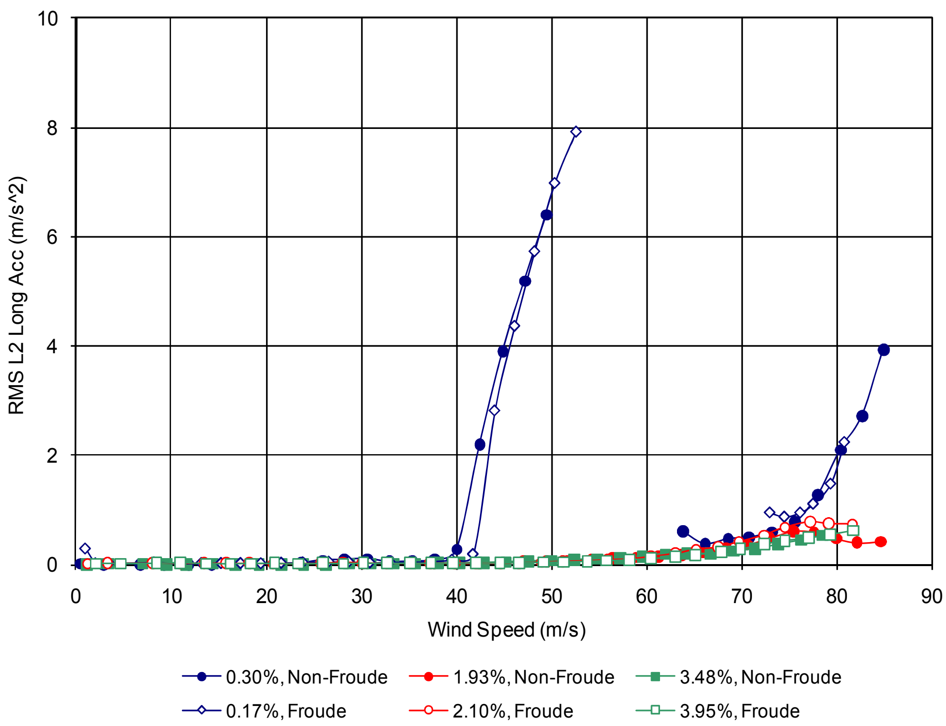


Figure 8 Comparison of the tower responses in smooth flow for 0 of the tower responses in smooth flow for 0º wind, in-service condition, BLWTL.

5.2 Mitigation of Vortex induced response

To mitigate vortex shedding excitation additional structural damping was added. At BMT a copper vane was supported through a carbon-fibre pushrod from tower, between poles of electromagnet. By varying the current feeding the electromagnet, different levels of damping can be obtained.

For the first three configurations, the worst vortex shedding peak, smooth flow, occurrence in along bridge axis bending given in **Errore. L'origine riferimento non è stata trovata.** can be reduced down to a level given in Table 3.

Table 3 Worst case vortex shedding peaks, along bridge axis bending with additional structural damping added, BMT.

Configuration	Wind direction [º]	RMS acceleration MS [m/s²]	Damping rel-to-crit. [%]
Freestanding tower	0	10	0.47
Prior to cross beam installation	15	<5	0.47
Completed tower, with cables installed	20	-	-

By increasing structural damping level of bending mode up to 4% rel-to-crit., for tower in service configuration, the response can be mitigated to an RMS acceleration level of approximately 0.5 m/s^2 as required by the specifications. The worst case vortex shedding occurrence in full scale with additional structural damping is shown in Figure 9. The figures are showed in [2] (figure 3.11) in model scale and full scale. Scaling factors used are given by $\lambda_{acc} = \left(f_{FS} / f_{MS}\right)^2 \cdot \lambda_L$ and $\lambda_v = \left(f_{FS} / f_{MS}\right) \cdot \lambda_L$.

Using 1st bending frequencies $f_{FS} = 0.477 Hz$ and $f_{MS} = 6.7 Hz$ gives scale factors of $\lambda_{acc} = 1.01$ and $\lambda_v = 14.24$.

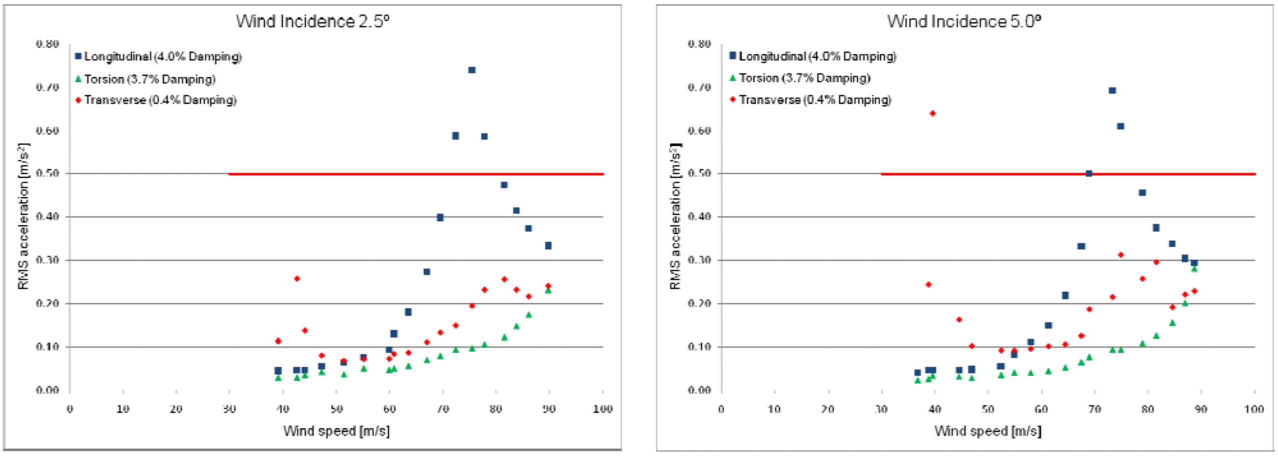


Figure 9 Worst case vortex shedding with additional structural damping of 4% rel-to-crit, BMT.

Transverse response for in service configuration with 5º wind slightly exceeds the SdM requirement of 0.5 m/s^2. However this mode is not faithfully represented in the wind tunnel model as model mass of the full bridge structure in service is more then 3 times higher than that of the pinned tower restrained from moving at the top in the along axis direction. Accounting for the modal mass difference , a maximum RMS response of about 0.2 m/s for transverse direction is found.

It can been seen from the BLWTL tests that the turbulent boundary layer flow with 10% turbulent intensity is effective in eliminating nearly all of the vortex shedding peaks. The exception to this conclusion is the peak between 53-60m/s, which was omitted in both smooth and turbulent flow tests due to excessive tower response.

Turbulence generally results in a reduction in the magnitude of vortex shedding induced peaks, but increases buffeting responses at higher wind speeds.

It has been observed from the smooth flow tests that the vortex shedding peaks between 53-60m/s can effectively be eliminated by adding extra structural damping, Figure 10.

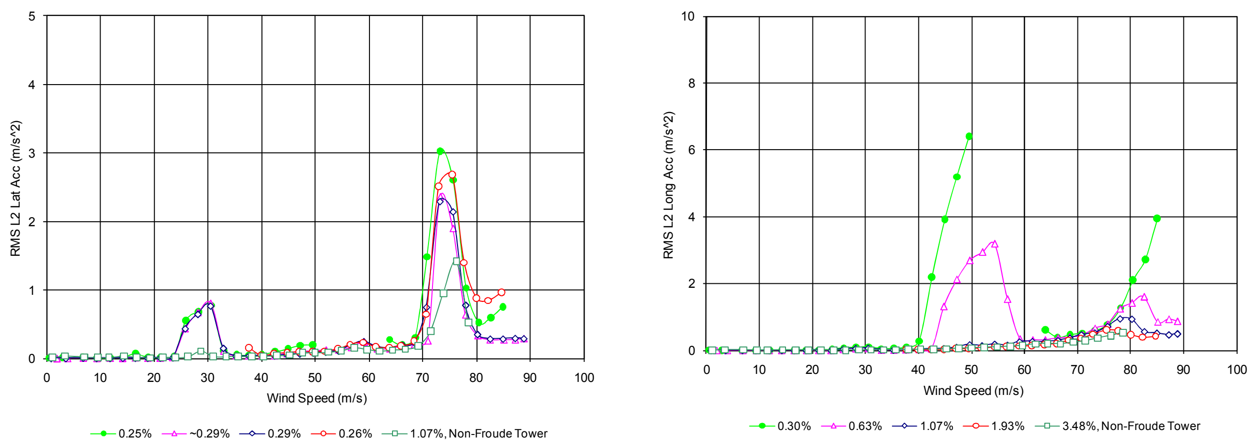


Figure 10 Tower response in smooth flow for 0º wind, in service condition with additional structural damping, BLWTL.

In general, with 4% rel-to-crit. structural damping the investigations at BLWTL indicated that the tower response is below SdM requirement of 0.5 m/s^2 for wind speeds up to design wind speed of 80 m/s.

The structural damping in lateral direction (across deck) was largely unaffected by the additional damping in the longitudinal (along deck) and torsional directions. The damping level in the lateral direction was about 1% for the tests with 4% additional damping in longitudinal direction. The lateral response slightly exceeds the SdM requirement of 0.5 m/s^2.

5.3 Aerodynamic stability

The critical wind speed of T3 for two configurations, free standing tower and tower prior to crossbeam installation, was measured for angles of attack in range of 0^0 and 90^0 in smooth flow (I = 0.3%) and reported in [2].

From the investigation in [2] it is noted that the tower is aerodynamically stable at full scale smooth flow wind speeds up to the maximum design speed of $80ms^{-1}$ at tip of the tower.

Most of the test conducted for the construction stage configuration at BLWTL [3] reached a mean hourly wind speed at tower height of 50m/s. Some tests were terminated early due to significant buffeting response.

From the in-service investigation in [3] it is seen that the tower is aerodynamically stable for wind speeds up to the design wind speed of 80m/s at tower height. Due to large tower response in the tests with inherent damping, the wind speeds between 50-63 m/s were omitted.

6 References

1 BMT Fluid Mechanics, Project No. 431163/00 Messina Straits Crossing, Towers, Section Model Studies, 10th November 2010

2 BMT Fluid Mechanics, Project No. 431163/00 Messina Straits Crossing, Towers, Full Aeroelastic Studies, 10th November 2010

3 BLWTL The University of Western Ontario, BLWT-SS1-2011 Messina Strait Bridge, Italy, Non-Froude and Froude Scaled Aeroelastic Models of Tower - Sub-Test T3

Appendix - Scope of Works