

PONTE SULLO STRETTO DI MESSINA



PROGETTO DEFINITIVO

EUROLINK S.C.p.A.

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<p><i>Unità Funzionale</i></p> <p><i>Tipo di sistema</i></p> <p><i>Raggruppamento di opere/attività</i></p> <p><i>Opera - tratto d'opera - parte d'opera</i></p> <p><i>Titolo del documento</i></p>	<p>OPERA DI ATTRAVERSAMENTO</p> <p>STUDI DI BASE</p> <p>STUDI AERODINAMICO (ANALITICI E SPERIMENTALI)</p> <p>Basic Studies</p> <p>Wind Tunnel Tests, Girder</p>	<p>PB0034 F0</p>
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Wind Tunnel Tests, Girder		<i>Codice documento</i> PB0034_F0.docx	<i>Rev</i> F0	<i>Data</i> 20/06/2011

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1 Introduction

A series of section model wind tunnel tests have been carried out for the girder of the Messina Bridge with the following objectives:

- optimize the original Tender Design
- validate the resulting design with respect to vortex induced vibrations and aerodynamic stability
- obtain wind load coefficients with and without traffic and for different wind attack angles
- obtain aerodynamic admittance and aerodynamic derivatives for use in buffeting and aeroelastic stability calculations

The wind tunnel tests are referred to as sub-tests D1, D2, D3, D4, D5, D6, D7 and D8. The scope of works for the tests can be found in Appendix A.

This report summarises the salient results of the tests.



2 Executive summary

The optimization phase of the girder wind tunnel test programme resulted in selection of a deck (C5/63) carrying 1.8 m high safety screens of 55% air void along the outer roadway crash barriers, 2.4 m high safety screens of 55% air void along the inner roadway crash barriers and 1.8 m high solid safety screens along the railway inspection lanes. Furthermore, the preferred deck configuration carries a soffit plate having 30% air void below the railway inspection lanes and an inclination of the railway side panels of 63° with horizontal.

This deck configuration was then subjected to rigorous testing at three independent wind tunnel laboratories, BWLTL in Canada, BMT in England and Force in Denmark.

The results are summarised below:

- Static wind load coefficients for use in design were taken from the turbulent flow tests at Force (except the drag, which was taken as a mean value so not to be too conservative), as they were the more conservative set. Turbulent flow is considered representative for full scale conditions.

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- The differences between the static load coefficients at the laboratories appear to lie in the modelling of barriers and screens, as the construction stage configuration shows almost identical results.
- The tests demonstrated that the girder is aerodynamically stable up to the required limit of 75 m/s and that the required levels of residual damping are obtained. For one traffic configuration, the girder showed limited amplitude responses for wind speed exceeding 50 m/s in smooth flow. For turbulent flow, this disappeared entirely.
- The vortex shedding tests showed that the necessary damping required to reduce the vortex shedding response to below the requirements was approximately 0.3% of critical. A mesh between roadway girders and railway girder was seen to reduce the vertical vortex shedding peak. This is further discussed in [10]. Further the vortex shedding tests demonstrated that turbulence had a distinct mitigating effect on vortex shedding excitation.

3 Optimization of deck geometry


The objective of Sub-tests D1 and D7 was optimization of the deck geometry. This was done in two steps:

- In sub-test D1, the effects of omitting some or all of the screens and varying the porosity of screens and plates were examined.
- In sub-test D7, the railway girder shape was optimized in order to improve the vortex shedding performance.

3.1 Sub-test D1

3.1.1 Deck Section Geometry and Dynamic Properties

The deck section considered for the sub-test D1 wind tunnel test programme is identical to the layout presented in the Tender Design, with the exception that the slope of the roadways has been changed from 2% inwards slope (Tender Design) to 2% outwards slope (Progetto Definitivo). Different configurations of the internal protection screens of along the roadway crash barriers and the railway inspection lanes and the soffit plate below the railway inspection lanes were investigated as indicated in Figure 3.1 and the corresponding Table 3.1.

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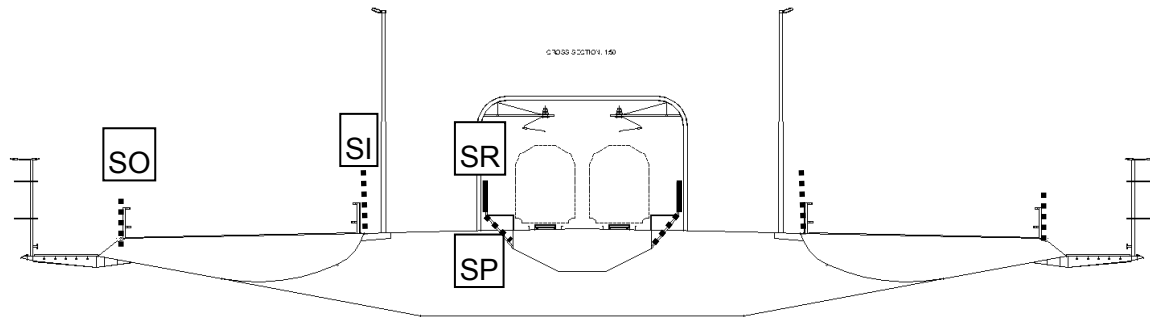




Figure 3.1 Deck section geometry investigated in wind tunnel section model sub-test D1 identifying safety screens SO, SI, SR and railway inspection lane soffit plate SP.

Table 3.1 Configurations of safety screens / soffit plate tested.

Configuration	Outer safety screen SO: 55%, h = 1.8 m	Inner safety screen SI: 55%, h = 2.4 m	Railway safety screen SR: solid, h = 1.8 m	Soffit plate SP
C1	Off	Off	On	Off
C2	Off	Off	On	air void 30%
C3	Off	Off	On	Solid
C4	On	Off	On	air void 30%
C5	On	On	On	air void 30%
C6	On	Off	Off	air void 30%
C7	Off	Off	Off	air void 30%

The section model sub-test D1 wind tunnel tests were carried out at FORCE Technology. The test setup and results are reported in [1].

The section model of the Messina Strait Bridge was constructed to the geometrical scale of $1:\lambda_L = 1:80$ yielding a model deck width $B = 60.4 \text{ m} / 80 = 0.75 \text{ m}$. The model spanned the 2.55 m wide wind tunnel yielding an aspect ratio $L_A / B = 3.4$ in compliance with the SdM requirements [2]. Wind

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and safety screens were designed to be easily replaceable and to offer a pressure loss coefficient of 2.7, thus simulating a porosity or an air void of 55% full scale.

A picture of the deck section model is shown in Figure 3.2.

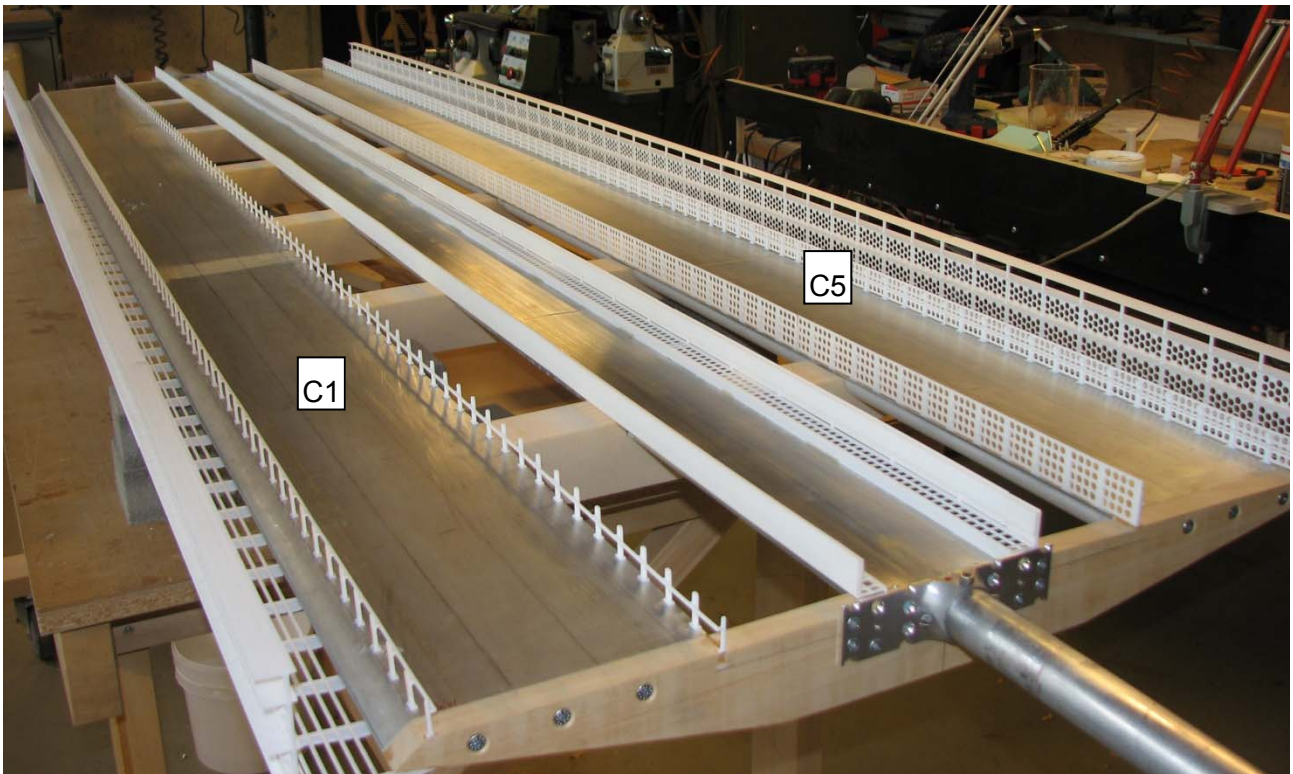


Figure 3.2 1:80 Scale section model utilized in sub-test D1. Right hand side of the model reflects configuration C5, left hand side reflects configuration C1.

The dynamic properties of the section model reflected the Tender Design having inertia and basic eigenfrequencies corresponding to cable sag to span ratio of 1/11. A recent increase of the cable sag to a ratio of 1/10.5 have changed the dynamic properties slightly as shown in Table 3.2, but these changes are estimated to be negligible for the aerodynamic properties of the bridge.



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Table 3.2 Dynamic properties of the Messina deck section as tested (sag / span ratio 1/11) and agreed for the Progetto Definitivo (sag / span ratio 1/10.5).

Sag ratio	Mass	Mass mom. of inertia	1st assym bending freq.	1st assym torsion freq.
1/11	53200 kg/m	26500000 kgm ² /m	$f_v = 0.0645$ Hz	$f_T = 0.0831$ Hz
1/10.5	54330 kg/m	26650000 kgm ² /m	$f_v = 0.0648$ Hz	$f_T = 0.0832$ Hz

3.1.2 Dynamic scaling of the wind tunnel model



The specifications [2] require that model tests with aeroelastic systems 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 mode 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 D1 the wind speed scale factor was chosen as $\lambda_V = 6.5$ for the stability 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 the wind speed scale factor has been chosen as $\lambda_V = 2.2$ to ensure that vortex shedding was captured at wind tunnel speeds above 2 m/s. In case Froude scaling was chosen vortex shedding excitation would have occurred at wind tunnel speeds of approximately 0.5 m/s at which the speed setting is difficult to control with accuracy.

3.1.3 Optimization

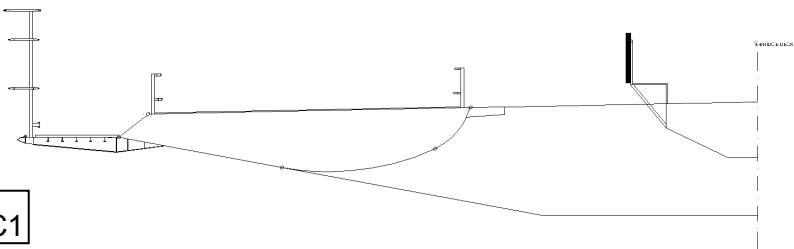
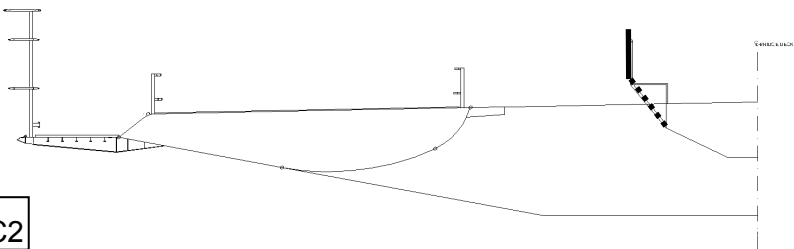
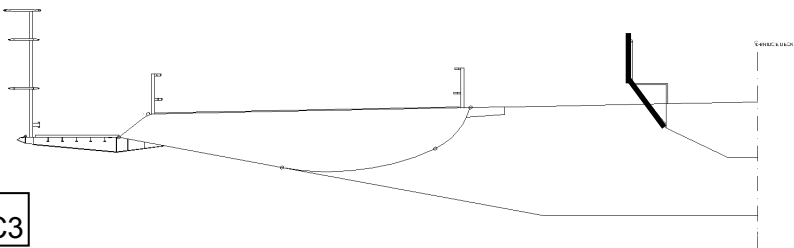
The optimization phase was aimed at identifying the aerodynamically most desirable safety screen / soffit plate configuration among C1 - C7 presented in Figure 3.1. The tests comprised

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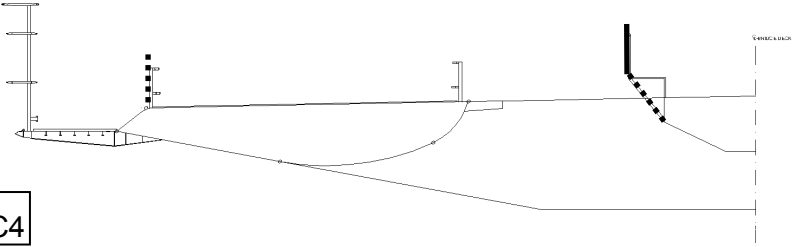
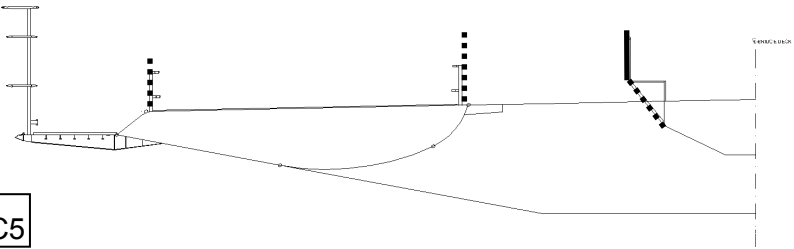
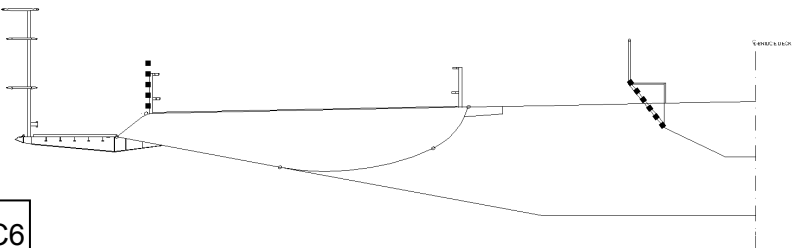
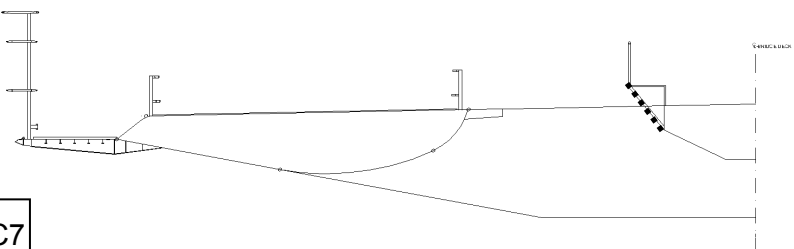
measurement of drag, lift and moment coefficients as functions of angle of attack and measurement of aerodynamic stability at 0° angle of attack in smooth flow. The section model was suspended in a 3-component force balance for measurement of C_L , C_D , C_M and in a two degree of freedom elastic suspension for measurement of the critical wind speed using a soft spring suspension yielding a velocity scale $\lambda_V = 6.5$. The mechanical damping of the elastic suspension was 0.3% rel.-to-crit. for the vertical degree of freedom and 0.2% rel.-to-crit. for the torsion degree of freedom fulfilling the SdM requirement [2] of mechanical damping to be less than 0.5%.

The results in terms of critical wind speed for onset of flutter V_c and moment slope $K_M = dC_M/d\eta$ averaged over the angle of attack range $-6^{\circ} < \eta < 6^{\circ}$ are summarized in Table 3.3.

Table 3.3 Summary of critical wind speeds and moment slopes for deck configurations investigated.

Deck configuration	V_c [m/s]	K_M [rad ⁻¹]
 C1	122	0.133
 C2	116	0.159
 C3	116	0.178



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 <div style="border: 1px solid black; padding: 2px; width: 30px; height: 30px; display: flex; align-items: center; justify-content: center; margin-top: 5px;">C4</div>	90	0.252
 <div style="border: 1px solid black; padding: 2px; width: 30px; height: 30px; display: flex; align-items: center; justify-content: center; margin-top: 5px;">C5</div>	>124	0.142
 <div style="border: 1px solid black; padding: 2px; width: 30px; height: 30px; display: flex; align-items: center; justify-content: center; margin-top: 5px;">C6</div>	94	0.23
 <div style="border: 1px solid black; padding: 2px; width: 30px; height: 30px; display: flex; align-items: center; justify-content: center; margin-top: 5px;">C7</div>	114	0.217

From

it is noted that the critical wind speed of all deck configurations exceeds the stability requirement of 75 m/s set by SdM [2]. The C5 configuration offers the highest critical wind speed of $V_c > 124$ m/s, thus the C5 configuration was chosen as the preferred deck section.

It is further noted that all deck configurations tested displayed sufficient stability to comply with the SdM criteria indicating that the bridge will remain stable should the safety screens along the roadway crash barriers and railway inspection lanes be removed at some point in the future.

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3.2 Sub-test D7

Section model sub-test D7 was carried out at BMT in a model scale of 1:65, [2]. This sub-test series which featured a very stiff carbon fibre model was commissioned because sub-test D1 featuring a 1:80 scale model failed to identify vertical vortex shedding due to Reynolds' number effects and the bending response recorded for the 1:30 scale model of sub-test D2, [5], was judged by SdM to be contaminated by bending of the model. The sub-tests D7 focused on vortex induced vibrations at 0° inflow angle in smooth flow and static wind load coefficients. Three inclination angles, Figure 3.3, of the railway girder side panels were tested to improve the vortex shedding performance of the bridge girder: 28° (the original inclination, as shown in Figure 3.1), 45° and 63°. The test setup and results are reported in [3].

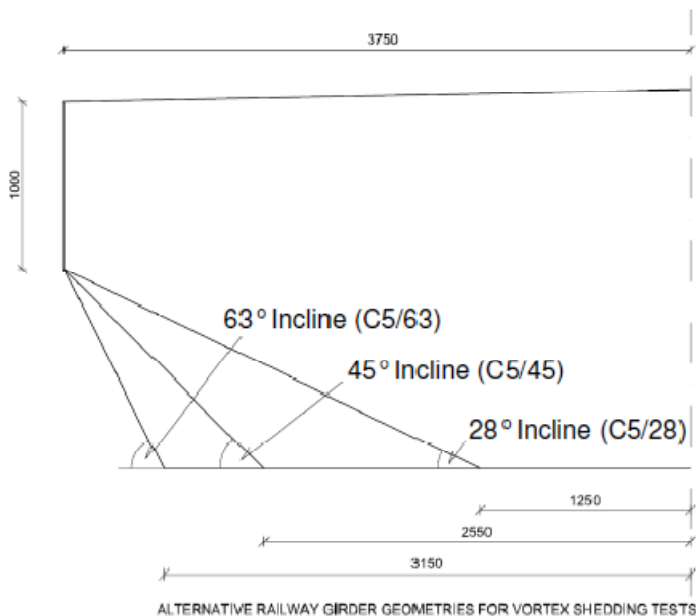




Figure 3.3 The three railway girder configurations.

The tests were carried out in smooth flow at 0° wind angle and for structural damping levels between 0.1% and 0.5% of critical.

3.2.1 Vortex induced vibrations

For the original configuration, denoted C5/28, four vortex shedding peaks were observed: two vertical bending peaks and two torsional peaks. Increasing the angle to 45° (C5/45) reduced the magnitude of the torsional peaks and removed the second vertical bending peak to higher wind

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speeds. No change was seen for the first vertical bending peak. The 63° configuration (C5/63) showed a further reduction of torsional peaks and no effect on the first bending peak. A structural damping level of 0.4% of critical was necessary to eliminate this vertical bending peak.

Results for the lowest structural damping levels, 0.11% of critical, are shown in Figure 3.6. The 63° configuration was selected based on these tests.

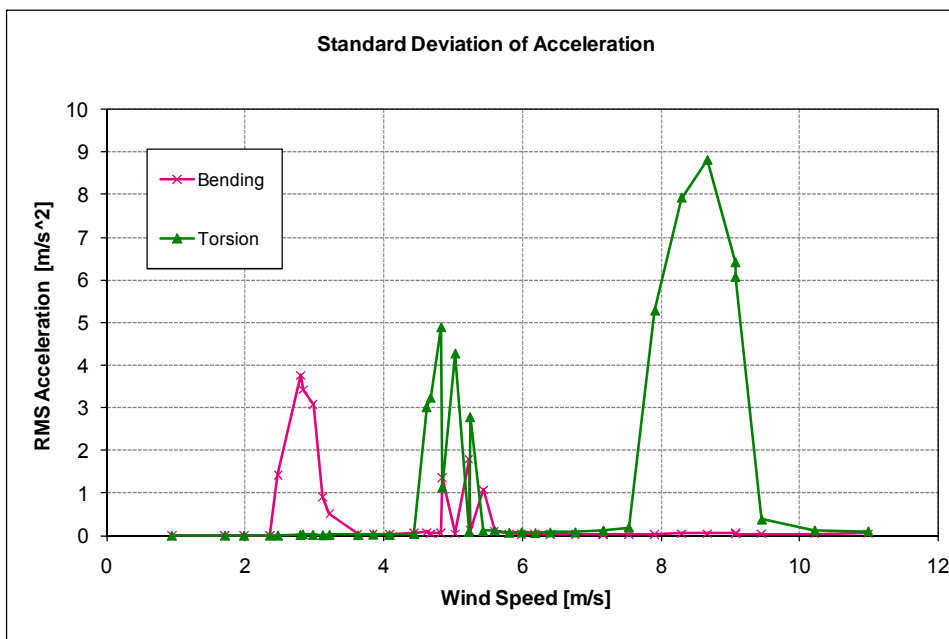




Figure 3.4 Vortex shedding responses for configuration C5/28, model scale. Damping 0.11% of critical.

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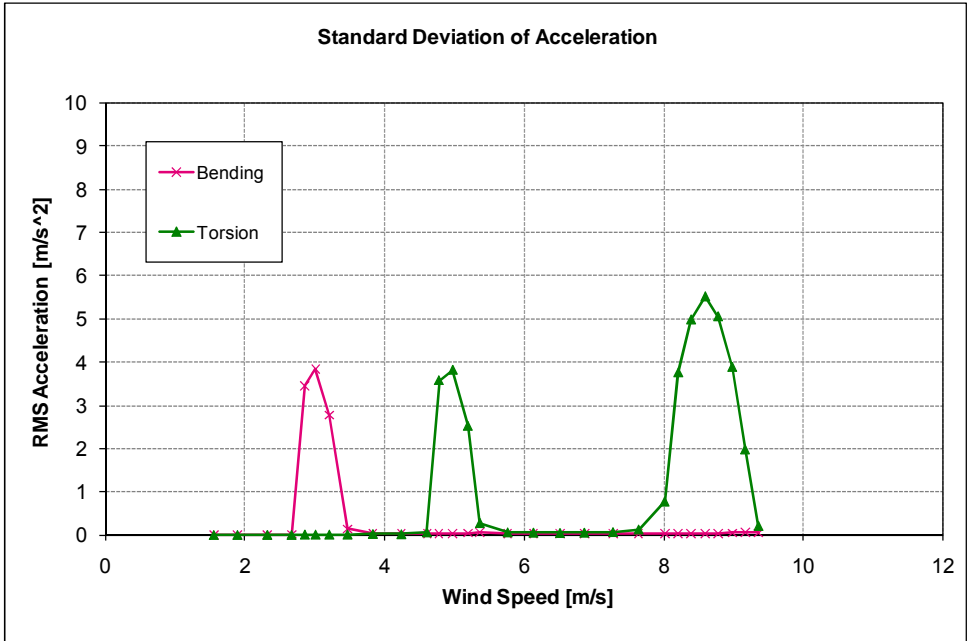


Figure 3.5 Vortex shedding responses for configuration C5/45, model scale. Damping 0.11% of critical.

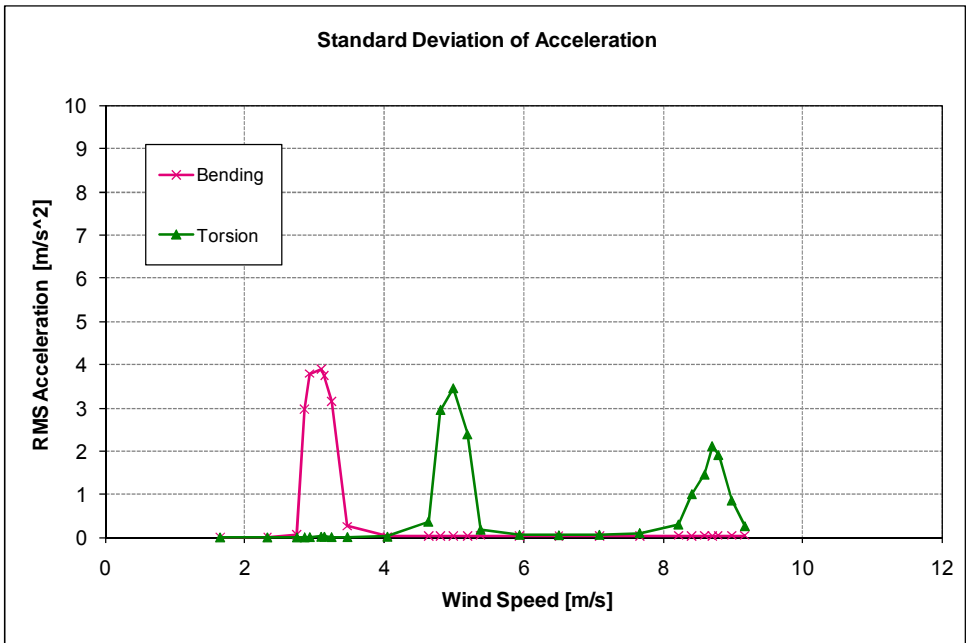



Figure 3.6 Vortex shedding responses for configuration C5/63, model scale. Damping 0.11% of critical.

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3.2.2 Aerodynamic stability

The critical wind speeds are presented in the following for the three railway girder configurations for angles of attack of -4° , 0° and 4° in smooth flow ($I = 0.5\%$) and turbulent flow ($I = 7.5\%$, NRC tests $I = 2-4\%$ though). The 45° inclination was tested at NRC in scale 1:30, sub-test D2 [5], and the 28° and 63° inclinations were tested at FORCE in scale 1:80, sub-test D1, [1] and [4]. Also the compound damping ζ rel.-to-crit. (mechanical damping + aerodynamic damping in torsion and vertical bending averaged) at full scale wind speeds of 54 m/s and 75 m/s were measured. A comparison of the measured critical wind speeds with SdM criteria is shown in Table 3.4 below. A comparison of the measured averaged compound damping (torsion and vertical bending) and the SdM criteria [2] are summarized in Table 3.5 and Table 3.6.



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Table 3.4 Critical wind speeds for the C5 deck section in smooth and turbulent flow for the three different inclinations of the railway girder side panel. *For $\eta = -4^{\circ}$ in turbulent flow tests were stopped at full scale wind speeds of 76 m/s as the model response exceeded the physical response limits set by the wind tunnel walls. **low damping in the range $18 < U_r < 22$ but stable.

Deck configuration C5	Flow	η [deg]	V_c [m/s]	V_c [m/s]	V_c [m/s]
Railway girder variation			C5/28	C5/45	C5/63
	smooth	-4	> 113 m/s	> 90 m/s	> 125 m/s
		0	> 123 m/s	> 90 m/s	119** m/s
		+4	> 124 m/s	> 90 m/s	120 m/s
	turbulent	-4	> 76* m/s	> 90 m/s	83* m/s
		0	> 124 m/s	> 90 m/s	81 m/s
		+4	> 122 m/s	> 90 m/s	126 m/s
SdM requirement			75 m/s		

From the table it is noted that all three deck configurations are aerodynamically stable at full scale smooth and turbulent flow wind speeds above the SdM stability criterion.



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Table 3.5 Averaged compound damping in smooth flow for the three different inclinations of the railway girder side panel at full scale wind speeds of 54 m/s and 75 m/s. Configuration C5.

Smooth flow (I = 0.5%)	η [deg]	V [m/s]	ζ [rel-to-crit.]	ζ [rel-to-crit.]	ζ [rel-to-crit.]
Railway girder variation			C5/28	C5/45	C5/63
	-4	54	2.05%	3.6%	2.4%
	-4	75	1.45%	3.0%	1.55%
	0	54	3.35%	3.15%	3.65%
	0	75	2.9%	3.05%	1.9%
	+4	54	4.6%	4.1%	3.55%
	+4	75	4.25%	5.6%	1.9%
SdM requirement		54	> 2%		
		75	> 1%		



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Table 3.6 Averaged compound damping in turbulent flow for the three different inclinations of the railway girder side panel at full scale wind speeds of 54 m/s and 75 m/s. Configuration C5.

Turbulent flow (I = 7.5%)	η [deg]	V [m/s]	ζ [rel-to-crit.]	ζ [rel-to-crit.]	ζ [rel-to-crit.]
Railway girder variation			C5/28	C5/45	C5/63
	η [deg]	V [m/s]	ζ [rel-to-crit.]	ζ [rel-to-crit.]	ζ [rel-to-crit.]
	-4	54	3.4%	-	1.75%
	-4	75	5.05%	-	0.65%
	0	54	3.6%	-	2.5%
	0	75	3.35%	-	1.0%
	+4	54	3.65%	-	2.9%
	+4	75	7.25%	-	1.3%
SdM requirement		54	> 2%		
		75	> 1%		

From Table 3.5 and Table 3.6 it is noted that the measured compound damping (mechanical + aerodynamic) in smooth and turbulent flows at angles of attack of -4° , 0° and 4° complies with the SdM criteria for aerodynamic stability except for -4° in turbulent flow.

3.3 Conclusions

The preferred deck C5/63 was selected as the configuration carrying 1.8 m high safety screens of 55% air void along the outer roadway crash barriers, 2.4 m high safety screens of 55% air void along the inner roadway crash barriers and 1.8 m high solid safety screens along the railway inspection lanes. Further the preferred deck configuration carries a soffit plate having 30% air void below the railway inspection lanes and an inclination of the railway side panels of 63° with horizontal.

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4 Verification of deck geometry

Sub-tests D2, D3, D4, D5, D6 and D8 were carried out to further verify the deck geometry, obtain design values for static wind load coefficients and aerodynamic admittance as well aerodynamic derivatives for numerical calculations of aerodynamic stability and aerodynamic damping levels. The tests were carried out at NRC (sub-test D2), BLWTL (sub-tests D3, D5 and D6), FORCE (sub-test D1 and D4) and BMT (sub-test D8) and are reported in [1], [4], [5], [6], [7], [11] and [13].

4.1 Aerodynamic stability

Table 4.1 summarises the measured critical flutter wind speeds from the three sets of wind tunnel tests, D1 [4], D3 [6] and D8 [13]. The D8 tests were carried out with two types of wind screens: type B with circular etched holes, type A made of stretch metal. Both the Force and the BLWTL screens correspond to type B.

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Table 4.1 Measured critical wind speeds for the deck section in smooth and turbulent flow.
*For $\eta = -4^\circ$ in turbulent flow tests were stopped at full scale wind speeds of 76 m/s as the model response exceeded the physical response limits set by the wind tunnel walls.

		D1 Force	D3 BLWTL	D8 BMT		D3 BLWTL		
		No traffic	No traffic	No traffic, screen A	No traffic, screen B	Train & road vehicles, upwind girder	Road vehicles	Train alone
Flow	η [deg]	V_c [m/s]	V_c [m/s]	V_c [m/s]	V_c [m/s]	V_c [m/s]	V_c [m/s]	V_c [m/s]
smooth	-4	> 124 m/s	> 114 m/s	-	-	> 100 m/s	> 100 m/s	> 105 m/s
	0	91 m/s	> 120 m/s	108 m/s	> 118 m/s	50 m/s	> 100 m/s	> 105 m/s
	+4	117 m/s	84 m/s	-	-	93 m/s	83 m/s	94 m/s
turbulent	-4	83* m/s	-	-	-	-	-	-
	0	81 m/s	99 m/s	-	-	> 100 m/s	> 99 m/s	> 97 m/s
	+4	126 m/s	-	-	-	-	-	-
SdM requirement		75 m/s				54 m/s		

It is seen from Table 4.1 that the deck satisfies the criteria without traffic and only the situation with both road traffic and train present falls below the requirements in smooth flow for 0° wind angle. The corresponding critical wind speed in the turbulent flow test is above 100 m/s which indicate that the presence of just a little more turbulence in the wind than in the smooth flow tests will increase the critical wind speed significantly. It is recommended that this aspect is investigated in further detail in the Progetto Esecutivo phase.

The D8 tests also investigated the effect of the horizontal meshes between the girders (see the following section on vortex shedding vibrations for further explanation) for the case with wind screens of type A, with and without turbulence in the oncoming flow. The critical wind speeds obtained were 92 m/s and 103 m/s, respectively. The horizontal meshes thus do not compromise aerodynamic stability.





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Table 4.2 summarises the averaged compound damping from the three sets of wind tunnel tests, D1, D3 and D8. A structural damping of 0.3% of critical is assumed for the BLWTL tests.

*Table 4.2 Averaged compound damping in smooth flow for the deck section at full scale wind speeds of 54 m/s and 75 m/s. *torsional damping negative. **uncertainty in measurements.*

Smooth flow (I = 0.5%)		D4 Force	D3 BLWTL	D8 BMT		D3 BLWTL including traffic		
						Train & road vehicles, upwind girder	Train & road vehicles, downwind girder	Train alone
η [deg]	V [m/s]	ζ	Z	ζ	ζ	ζ	ζ	ζ
-4	54	2.4%	4.3%	-	-	3.7%	3.9%	5.3%
-4	75	1.55%	5.7%	-	-	5.5%	5.8%	8.2%
0	54	3.65%	2.1%	4.8%	2.8%	2.1%*	2.5%	1.4%**
0	75	1.9%	3.1%	5.0%	2.9%	2.1%	2.8%	2.1%*
+4	54	3.55%	2.4%	-	-	2.4%	2.6%	1.8%
+4	75	1.9%	2.2%	-	-	2.2%	2.5%	1.9%
SdM requirement	54	> 2%				> 1%		
	75	> 1%				-		

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4.2 Vortex induced vibrations

Vortex induced vibrations were measured as part of sub-test D7 at BMT, see Section 3.2.1, and in greater detail as part of sub-test D8 for deck section C5/63 featuring three screen layouts. The wind and safety screen elements tested included two stretched metal screens (A) similar to the screen elements applied for the Soluzione D model by PoliMi in 2004, and one plate screen (B) having etched circular holes. The pressure drop coefficient for the two screen A elements were $k = 2.7$ and $k = 3.7$, respectively, while $k = 2.7$ was measured for screen element B.

Figure 4.1 displays the model vortex shedding responses for the lowest damping level of 0.095% corresponding to a Scruton number $Sc = 0.079$, which fulfils the SdM requirement to the tests of $Sc < 0.3$. It is noted that the deck section model responds in vertical bending at a non-dimensional wind speed of approximately 0.4 (2.5 m/s model scale) and in torsion at wind speeds of approximately 0.8 (6.5 m/s model scale) and 1.35 (11 m/s model scale).

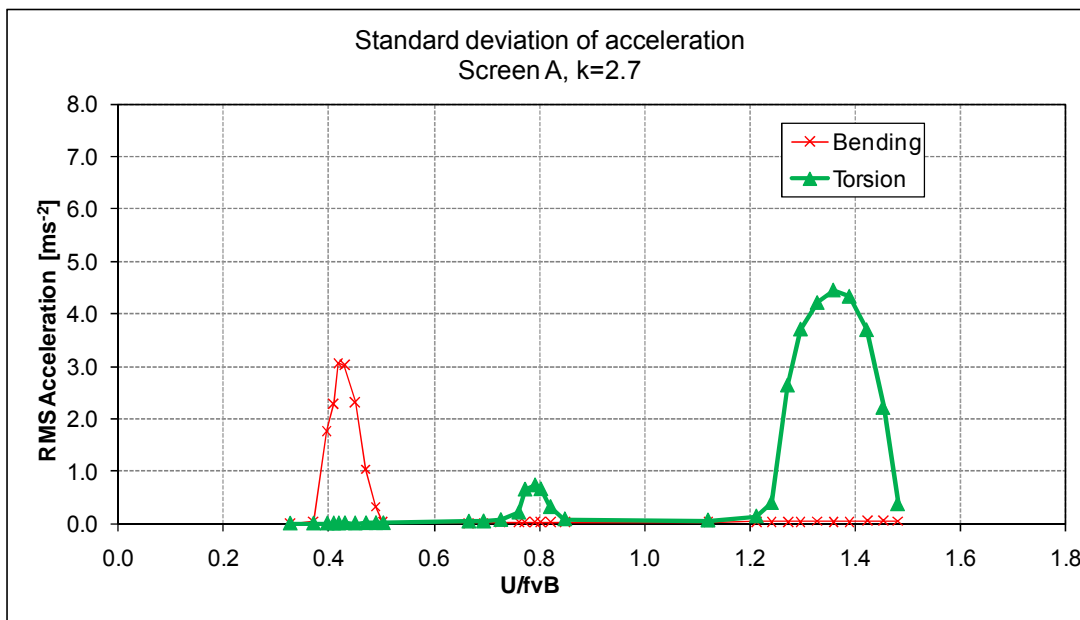




Figure 4.1 Model scale vortex shedding responses for configuration C5/63, Screen A, $k = 2.7$ as function of non-dimensional wind speed. Damping 0.095% of critical, $Sc = 0.079$.

Figure 4.2 displays the vortex shedding response for the C5/63 model fitted with the stretch metal screen elements (A) having a pressure drop coefficient $k = 3.7$ at the lowest possible damping

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(0.095% ret-to-crit., $Sc = 0.079$). It is noted that the bending a second torsion peak decreases relative to the $k = 2.7$ screen, but that the first torsion peak increases.

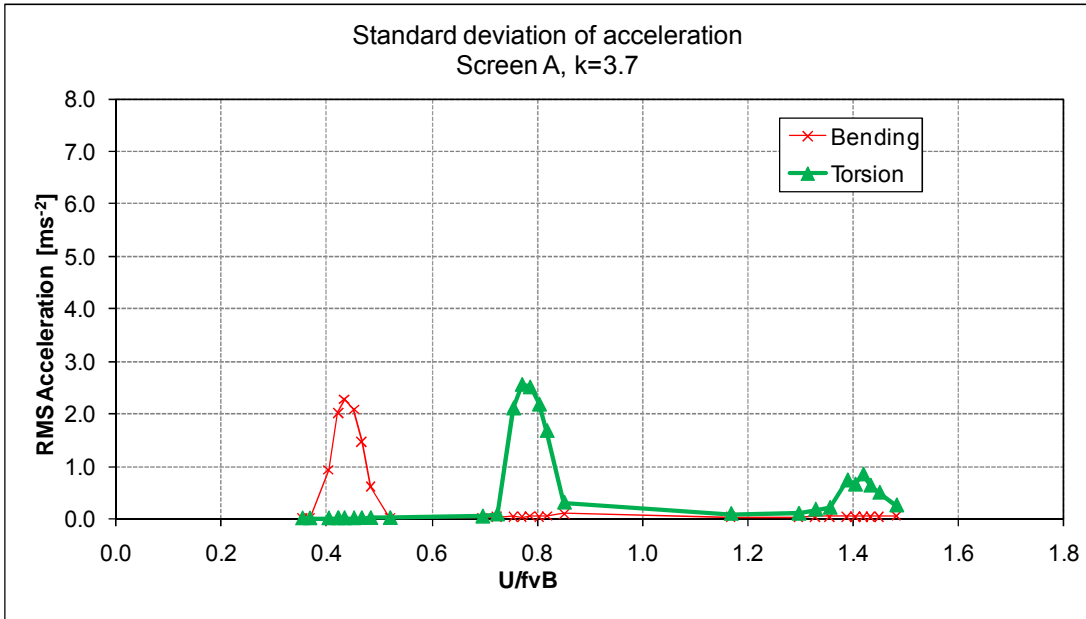


Figure 4.2 Model scale vortex shedding responses for configuration C5/63, Screen A, $k = 3.7$ as function of non-dimensional wind speed. Damping 0.095% of critical, $Sc = 0.079$.

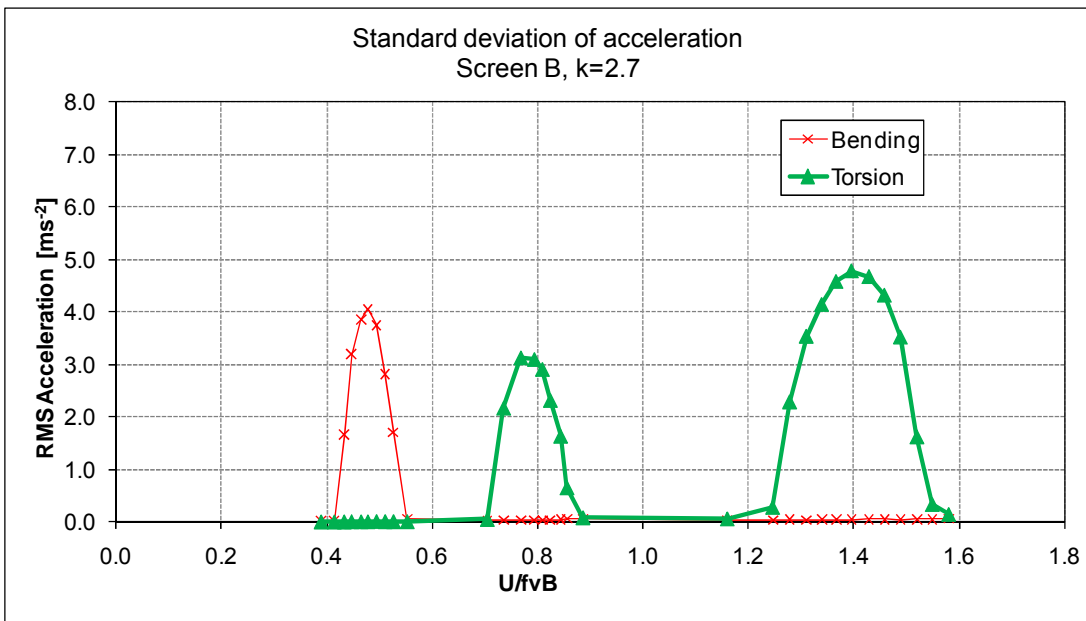




Figure 4.3 Model scale vortex shedding responses for configuration C5/63, Screen B, $k = 2.7$ as function of non-dimensional wind speed. Damping 0.095% of critical, $Sc = 0.079$.

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From Figure 4.3 it is noted that the vortex response of the C5/63 deck section fitted with the screen B with etched circular hole is slightly higher than for the model with the stretched metal mesh screens.

Increasing the damping level eliminates the torsion response fairly quickly for the deck fitted with the A screen elements having $k = 3.7$ whereas the vertical bending peak is less influenced by the damping level. For the other configurations tested both the bending and torsion responses are more persistent and more difficult to mitigate by means of damping. An overview of the effect of structural damping on vortex shedding response is given in Figure 4.4 which shows the vertical rms response and edge deflection due to torsion normalized by deck width B as function of Scruton number. From this figure it is noted that the SdM requirements of non-dimensional edge deflections of 10^{-4} is only strictly fulfilled for the deck section fitted with the stretch metal screen elements A having $k = 3.7$ and assuming a structural damping of 0.3% rel-to-crit. corresponding to Scruton numbers in bending $Sc_b = 0.24$ and torsion $Sc_t = 0.033$ based on the section mass and mass moment of inertia.

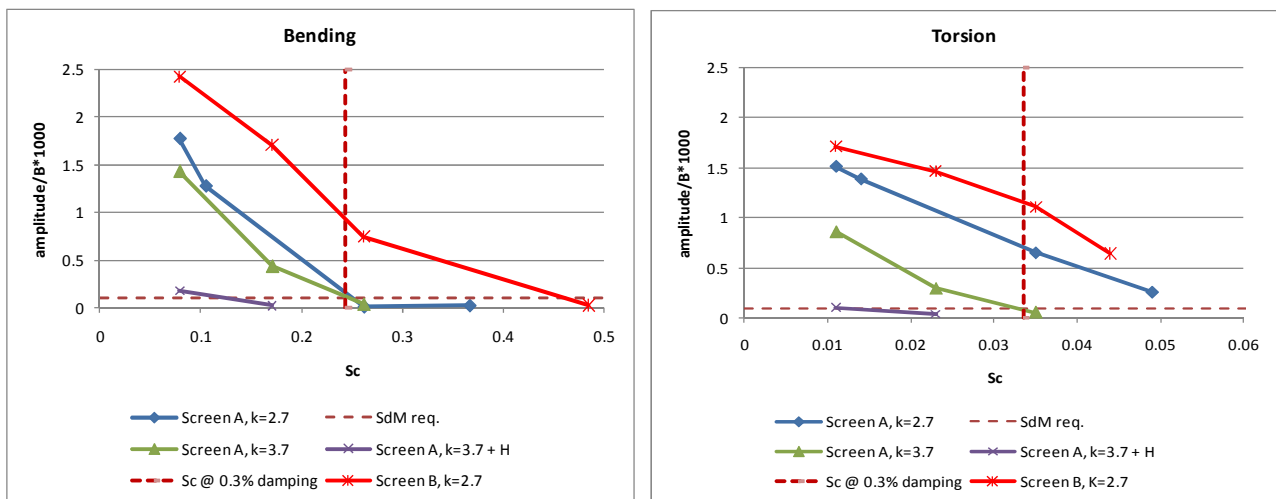




Figure 4.4 RMS bending and edge deflection due to torsion as function of Scruton number.

Fitting a horizontal perforated mesh between the railway and road girders as shown in Figure 4.5 is very efficient in eliminating vertical response as is demonstrated in Figure 4.4 (Screen A, $k = 3.7 + H$). Looking at the vortex shedding response as function of wind speed for the deck section fitted with the B screens, Figure 4.6, it is noted that the horizontal screens between the railway and road girders are only efficient in vertical bending but has little effect on the torsion response. Finally it

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should be noted that light turbulence having along wind and vertical turbulence intensities $I_u = 4.8\%$ and $I_w = 3.7\%$ substantially decreases the vortex shedding response.



Figure 4.5 Deck section C5/63 with A screens and horizontal mesh between roadway and railway girders.

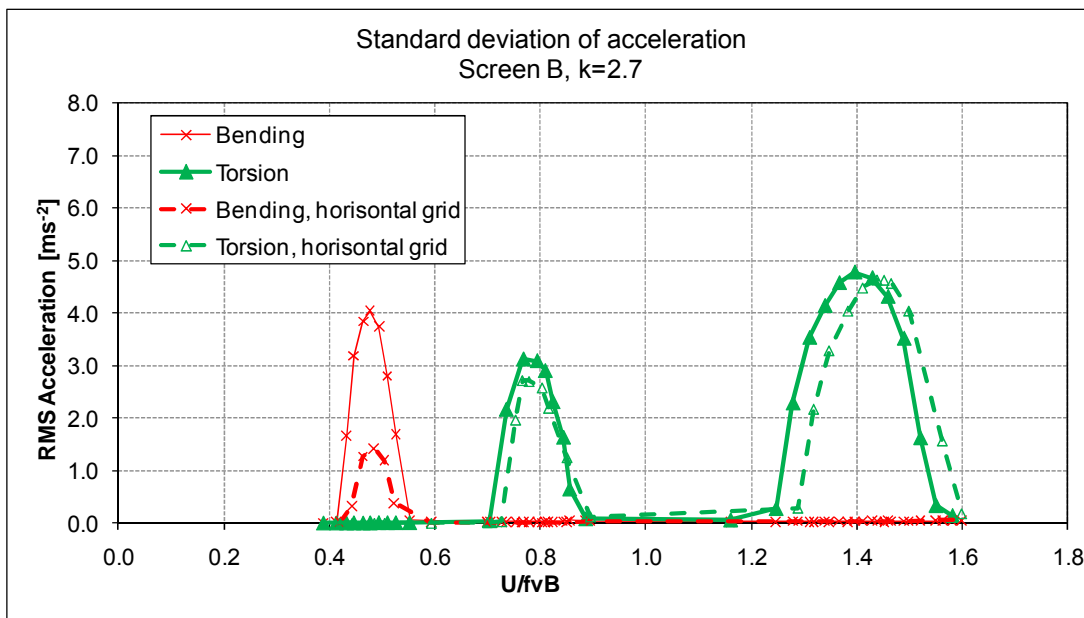




Figure 4.6 Comparison of vortex shedding responses for configuration C5/63, B screens, $k = 2.7$ with and without horizontal meshes added between the roadway girders and the railway girder. Model scale accelerations as function of non-dimensional wind speed. Damping 0.13% of critical.

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Having demonstrated in the sub-test D8 that the vortex shedding response of the deck is highly dependent on the detailed layout of the wind and safety screen meshes and not only a function of the pressure loss coefficient, *it is proposed to study this effect further either prior to or during the esecutivo phase with a view to finding the optimum wind screen configuration combining vortex shedding mitigation and shelter effects.*

4.3 Static 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 $\frac{1}{2}\rho V^2$, model span length L_A and model deck width B (lift and drag) or deck width squared B^2 :

$$C_{L,D} = \frac{F_{L,D}}{\frac{1}{2}\rho V^2 L_A B}$$

$$C_M = \frac{F_M}{\frac{1}{2}\rho V^2 L_A B^2}$$

Static wind load coefficients were measured as part of sub-tests D3, D4 and D8 (wind perpendicular to the girder, no traffic) and sub-test D5 (with traffic, wind under skew angles). Figure 4.7 and Figure 4.8 show a comparison of the measured values at the laboratories for smooth and turbulent flow, respectively. The D8 tests were only carried out in smooth flow and for the service condition.

The results from FORCE, sub-test D4, are seen to be the more conservative set of coefficients and were therefore used in the buffeting verification calculations, [8].

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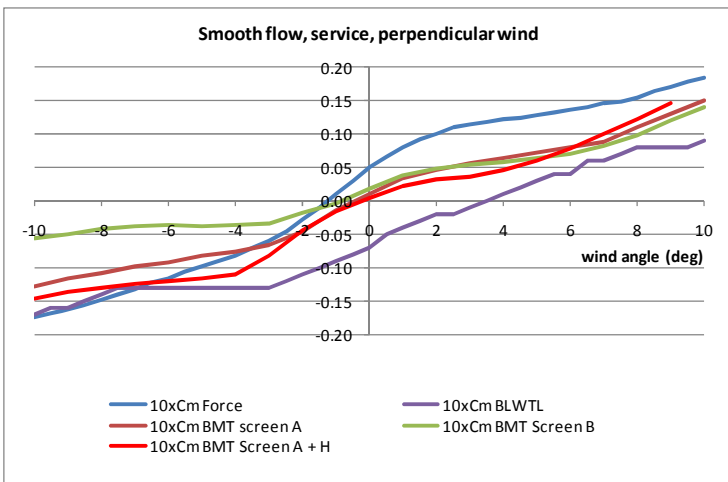
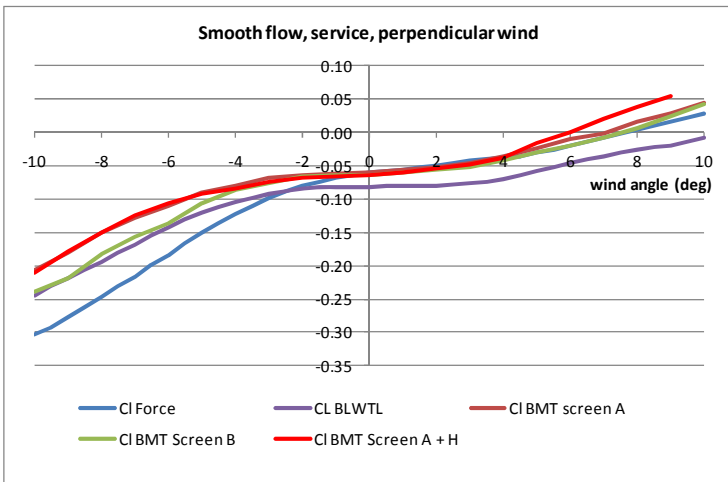
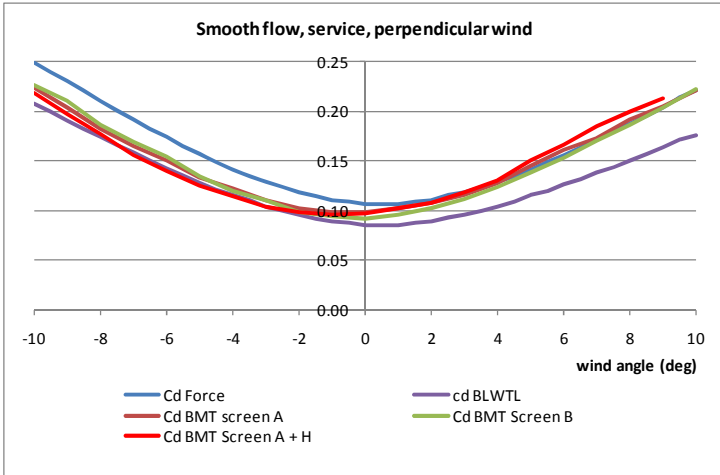




Figure 4.7 Static wind load coefficients from the three parallel tests (sub-tests D3, D4 and D8), no traffic. Smooth flow, perpendicular wind.

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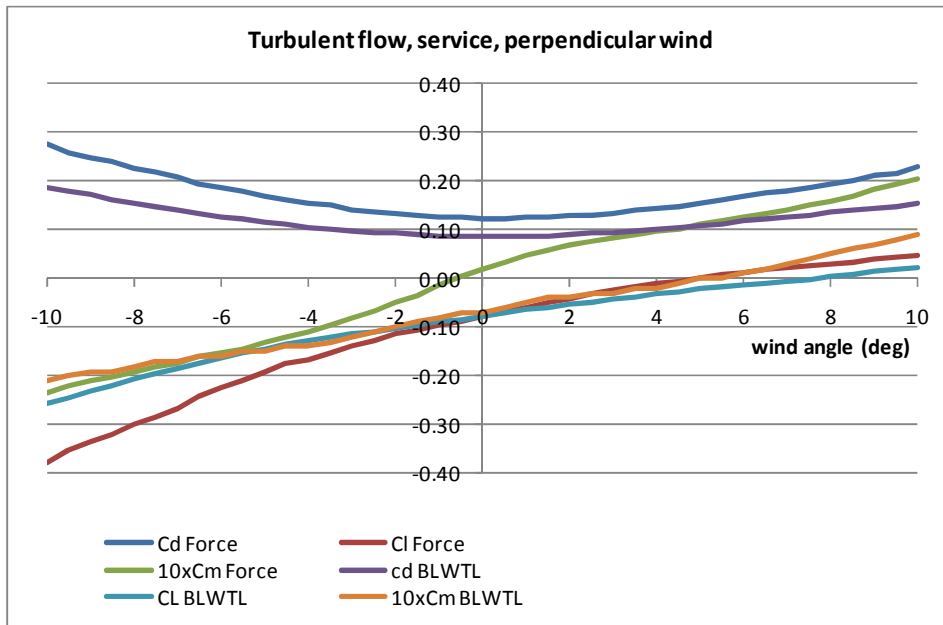




Figure 4.8 Static wind load coefficients from the two parallel tests (sub-tests D3 and D4), no traffic. Turbulent flow, perpendicular wind.

It is interesting to compare the results from the two test laboratories Force and BLWTL for the construction stage where no railings, wind screens or crash barriers are present on the deck section, see Figure 4.9. Then the measured drag coefficients become almost identical, the differences in the lift coefficients and in particular the lift slope become much smaller, and also the agreement between moment coefficients and moment slopes is much better. This strongly suggests that the differences between the two sets of measurements are primarily caused by differences in the way that railings, screens and barriers are modelled even though both models satisfy the requirements for pressure loss and porosity of the wind screens. The test results from the D8 tests at BMT seem to confirm the dependence of the drag coefficients on the screen configuration, as the drag coefficients in these tests lie between the drag coefficients from Force and from BLWTL in the service condition.

Different roughnesses of the models may also play a role. A rougher surface can be said to represent a somewhat higher Reynolds number for a curved surface, similar to the well-known translation of the drag crisis towards lower Reynolds numbers for rougher surfaces, but as seen from the construction stage results, this does not seem to play a large role in the present case as

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the results are quite similar.

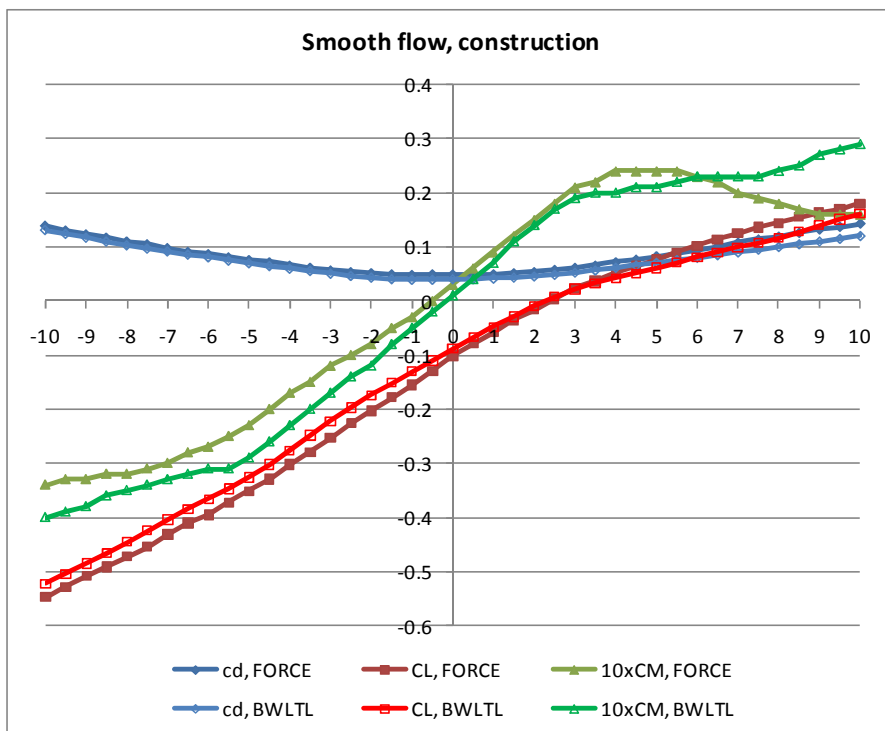
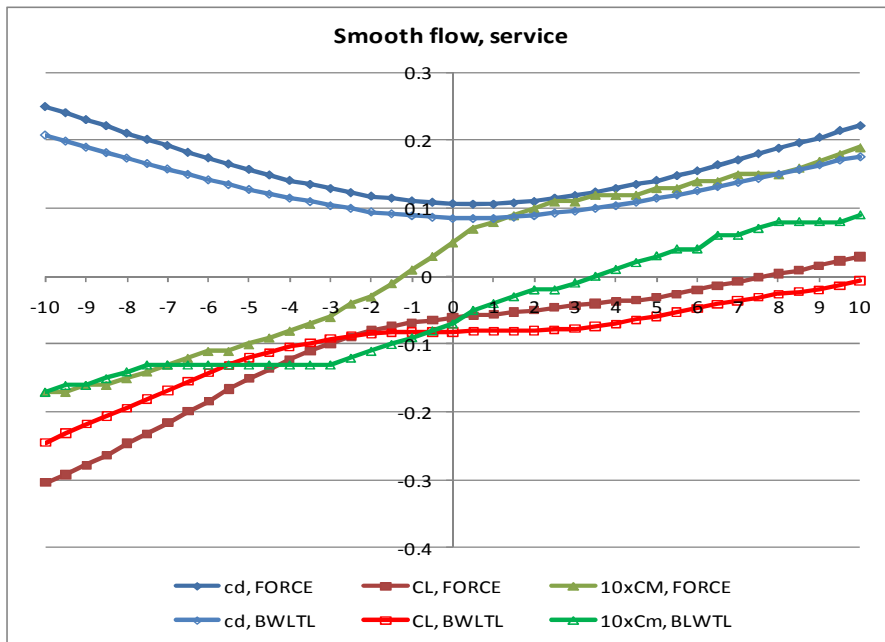




Figure 4.9 Static wind load coefficients from the two parallel tests (sub-tests D3 and D4), no traffic. Smooth flow, perpendicular wind. Service and construction.

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The test conducted in scale 1:30 at NRC in Canada, [5], for the 45° inclination (see Section 3), is compared with the 1:80 scale tests at Force of the same configuration (C5/45) in Figure 4.10. It is seen that the drag decreases a little when the Reynolds number increases just as expected while the lift and the moment coefficients around horizontal wind attack are very similar. The moment slope is, however, much smaller in the large scale tests and whether this is a genuine scale feature or a post-processing issue is still unresolved.

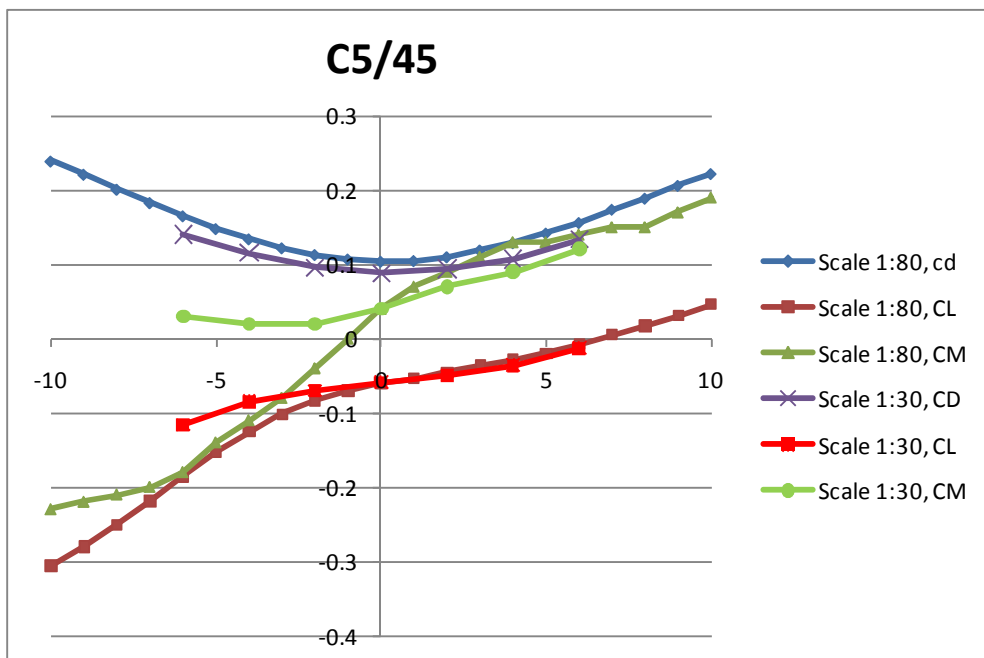



Figure 4.10 Static wind load coefficients from two different scale tests (sub-tests D1 and D2), no traffic. Smooth flow, perpendicular wind. Service.

It is concluded, based on the above discussions, that the static wind load coefficients obtained from Force's 1:80 scale tests can be viewed as representative though a little conservative for the full bridge. Regarding the drag coefficient, it is thought better to use a mean value of the drag coefficient of 0.107 in design in order not to be too conservative but otherwise the turbulent flow values from Force is used.

SdM requirements [2] stipulate that the slope of the lift and moment coefficients $K_L = dC_L/d\eta$, $K_M = dC_M/d\eta$ shall be within certain limits, where η is the wind angle with horizontal:

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$$1/10 \cdot 2\pi < K_L < 1/5 \cdot 2\pi \text{ and } 1/10 \cdot \pi/2 < K_M < 1/5 \cdot \pi/2.$$

in the range $-6^\circ < \eta < 6^\circ$ without traffic and

$$0 < K_L \text{ and } 0 < K_M$$

in the range $-3^\circ < \eta < 3^\circ$ with traffic.

In coordination meetings during the design process it was accepted by Stretto di Messina that lift and moment slopes could deviate from the required values provided the deck fulfilled the stability requirements.

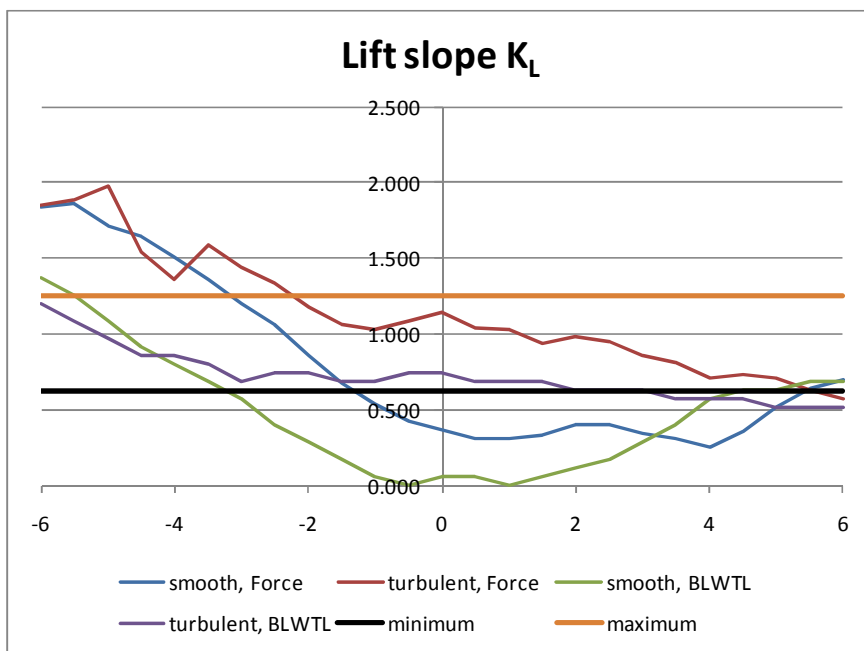




Figure 4.11 Lift slopes from the two parallel tests (sub-tests D3 and D4), no traffic. Perpendicular wind. The minimum and maximum values according to [2] are shown.

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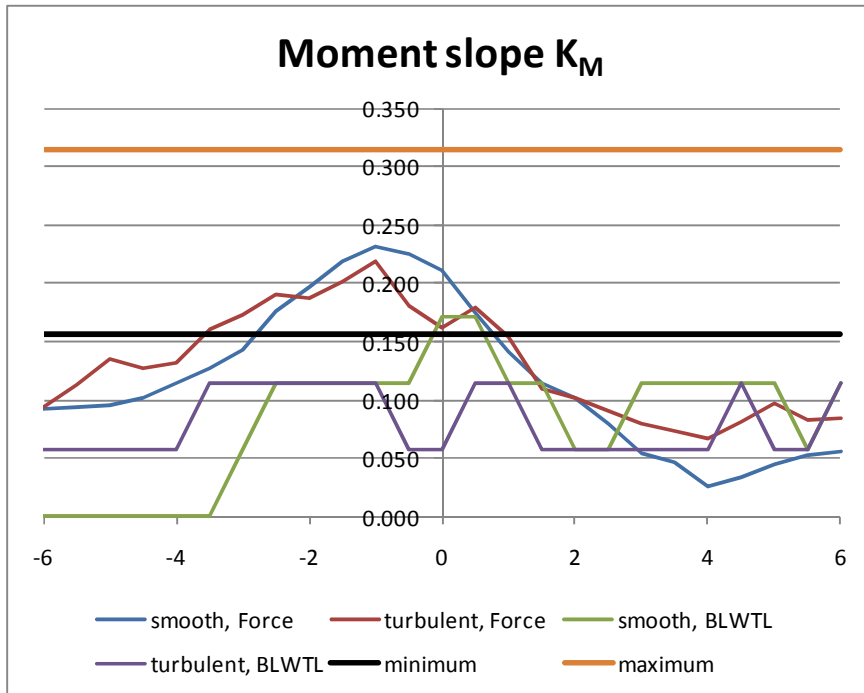


Figure 4.12 Moment slopes from the two parallel tests (sub-tests D3 and D4), no traffic. Perpendicular wind. The minimum and maximum values according to [2] are shown.



It is seen that the lift slopes are generally small but larger than zero in all the tests. The moment slopes are also all above zero in the entire range, though small. Galloping instabilities are thus not indicated.

For the three traffic configurations, the static wind load coefficients and the slopes are shown in Figure 4.13 to Figure 4.16. The traffic configurations are numbered as follows:

Traffic 1: roadway traffic on upwind girder, train.

Traffic 2: roadway traffic on downwind girder, train.

Traffic 3: train only.

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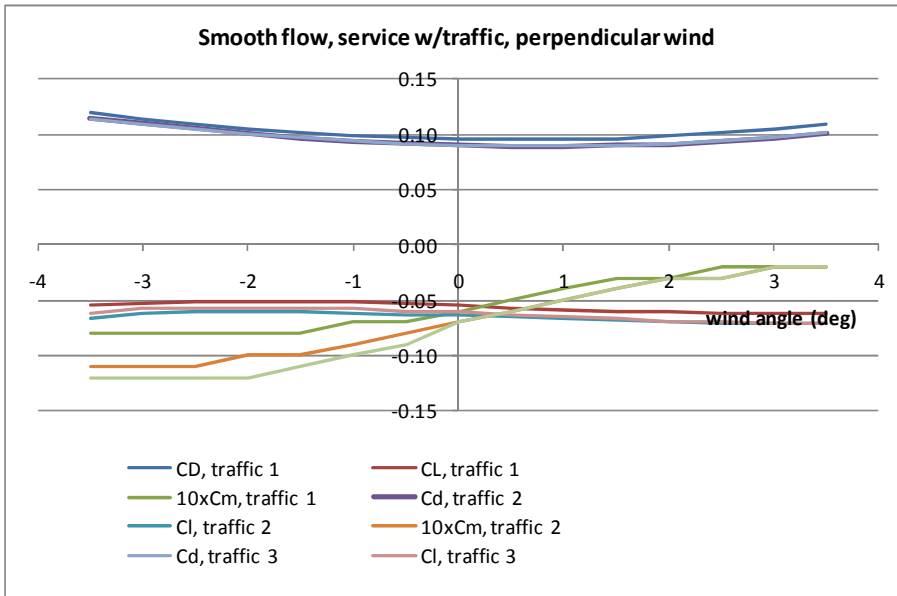


Figure 4.13 Static wind load coefficients with traffic. Smooth flow, perpendicular wind.

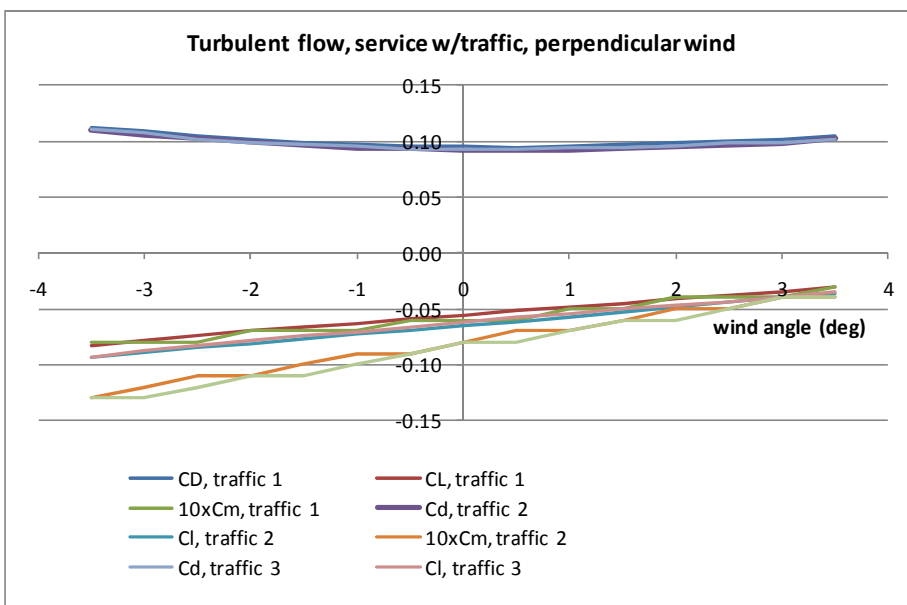


Figure 4.14 Static wind load coefficients with traffic. Turbulent flow, perpendicular wind.



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Figure 4.15 Lift slopes, traffic.



Figure 4.16 Moment slopes, traffic.

There is seen to be very little difference between wind load coefficients for the various traffic configurations. Except for the smooth flow lift slopes, all slopes are positive.

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4.4 Aerodynamic admittance

Aerodynamic admittances were measured both at FORCE (sub-test D4, [7]) and at BLWTL (sub-test D3, [11]) for the in-service and construction stages. Admittances for all three degrees of freedom: lift, drag and moment, were measured in turbulent flow with $I_U = 7.5\%$ and $I_W = 7\%$.

For horizontal wind, the measured admittances are shown in the following figures. Functional fits to the measurements are shown in blue. The fits have been optimised for the range $fB/U = 0.05$ to 0.5 . There are significant differences between the measured admittances at the two laboratories which may be due to the differences in the way measurements are carried out. At BWLTL, measurements are done for one strip (distance equal to distance between cross beams) while Force measures at each end, i.e. includes the whole length.

It was decided to neglect the aerodynamic admittances in the buffeting calculations as this proved the most conservative, [8]. It was also seen that the differences between the measured aerodynamic admittances only have small influence on the buffeting responses, as exemplified in

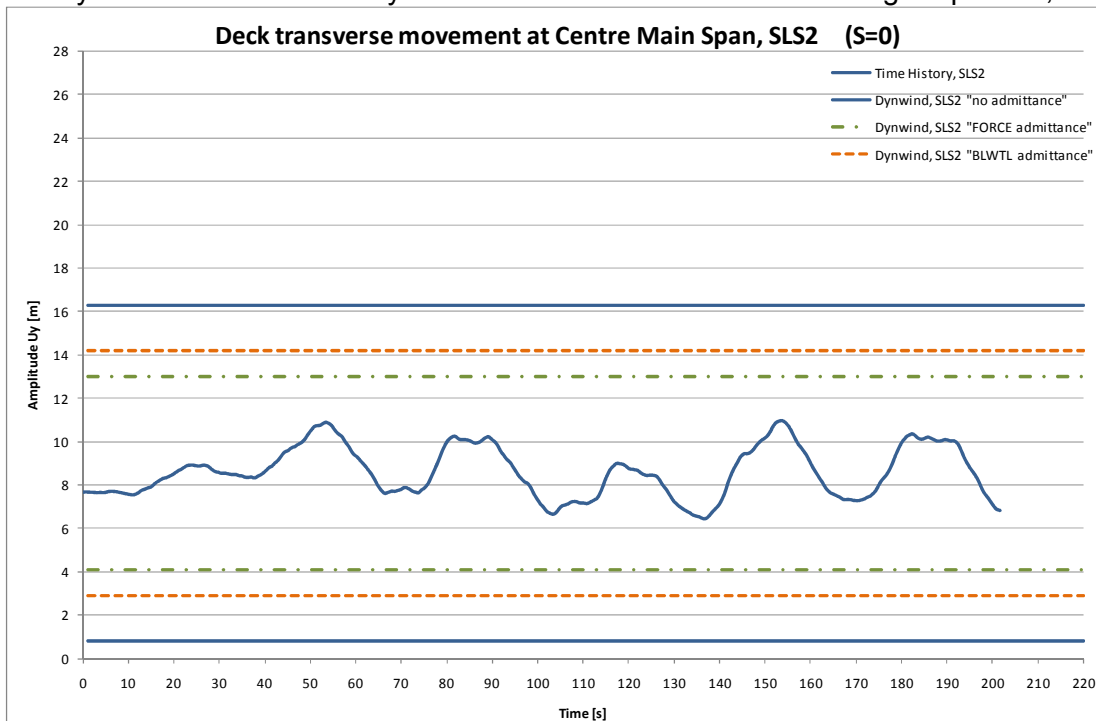




Figure 4.17.

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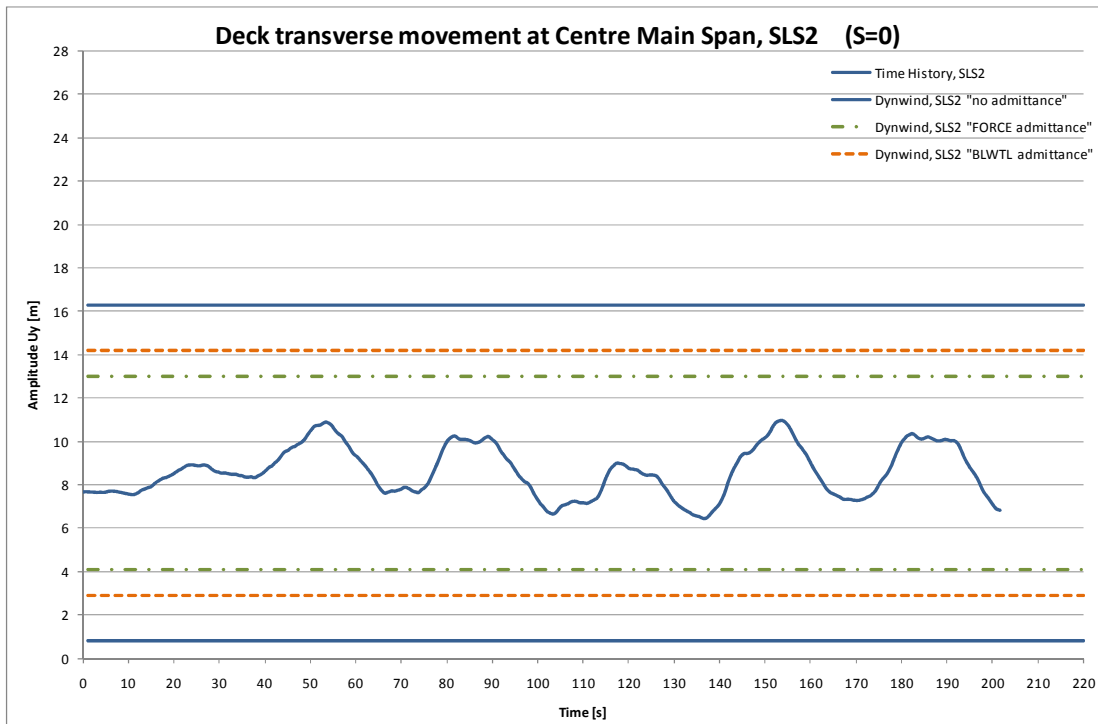




Figure 4.17 Buffeting responses for three types of admittance: none, BLWTL measured and Force measured. From [8].

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Wind Tunnel Tests, Girder		<i>Codice documento</i> <i>PB0034_F0.docx</i>	<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="text-align: left;"><i>Rev</i></th> <th style="text-align: left;"><i>Data</i></th> </tr> </thead> <tbody> <tr> <td style="text-align: left;"><i>F0</i></td> <td style="text-align: left;"><i>20/06/2011</i></td> </tr> </tbody> </table>	<i>Rev</i>	<i>Data</i>	<i>F0</i>	<i>20/06/2011</i>
<i>Rev</i>	<i>Data</i>						
<i>F0</i>	<i>20/06/2011</i>						

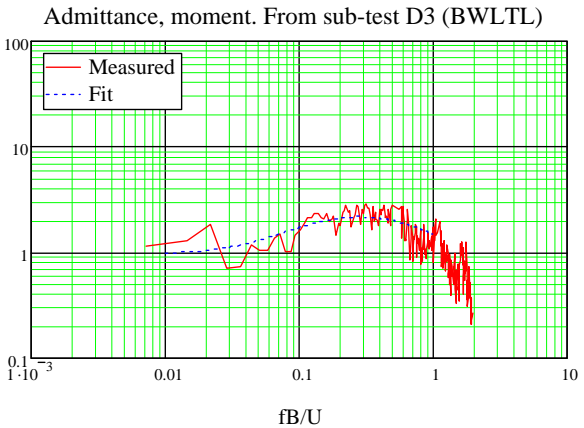
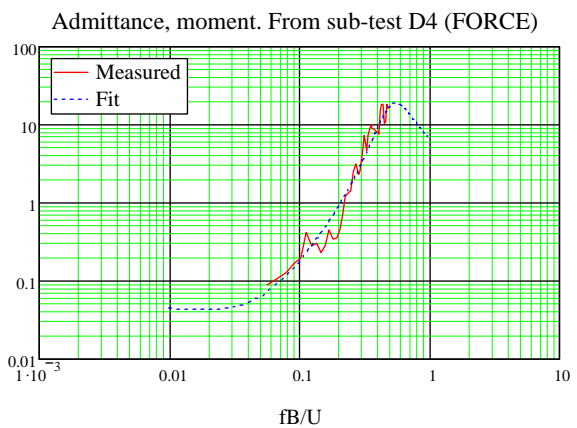
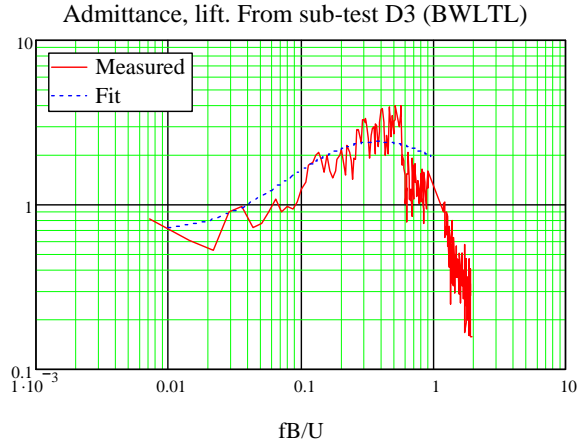
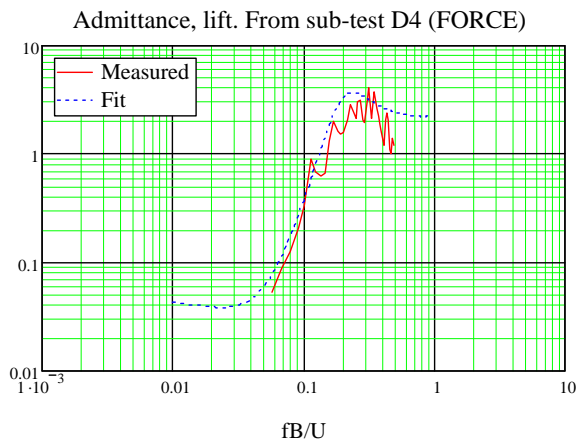
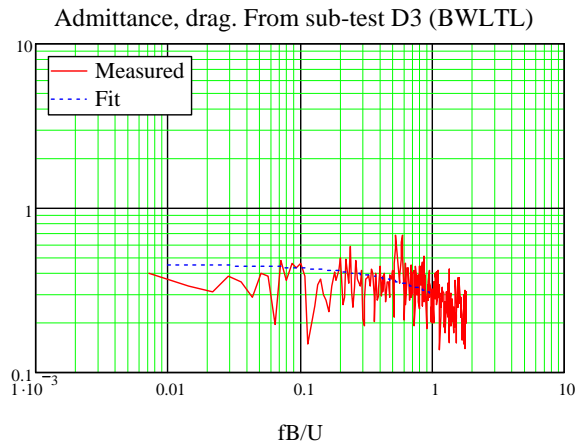
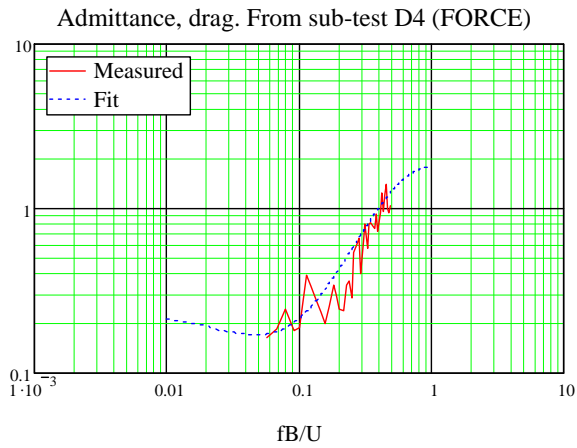




Figure 4.18 Measured and fitted aerodynamic admittances, from sub-tests D3 and D4.

		Ponte sullo Stretto di Messina PROGETTO DEFINITIVO		
Wind Tunnel Tests, Girder		<i>Codice documento</i> PB0034_F0.docx	<i>Rev</i> F0	<i>Data</i> 20/06/2011

4.5 Aerodynamic derivatives

Aerodynamic derivatives were measured both at FORCE (sub-test D4, [7]) and at BLWTL (sub-test D3, [11]) for the in-service and the construction stages for wind angles between -6° and 6° . The aerodynamic derivatives for 0° are compared in Figure 4.19 and Figure 4.20. They are given according to the formulation of Scanlan [12]:

$$D = \frac{1}{2} \rho U^2 (2B) \left(KP_1^* \frac{\dot{y}}{U} + KP_2^* \frac{B\dot{\theta}}{U} + K^2 P_3^* \theta + K^2 P_4^* \frac{y}{B} + KP_5^* \frac{\dot{h}}{U} + K^2 P_6^* \frac{h}{B} \right)$$

$$L = \frac{1}{2} \rho U^2 (2B) \left(KH_1^* \frac{\dot{h}}{U} + KH_2^* \frac{B\dot{\theta}}{U} + K^2 H_3^* \theta + K^2 H_4^* \frac{h}{B} + KH_5^* \frac{\dot{y}}{U} + K^2 H_6^* \frac{y}{B} \right)$$

$$M = \frac{1}{2} \rho U^2 (2B^2) \left(KA_1^* \frac{\dot{h}}{U} + KA_2^* \frac{B\dot{\theta}}{U} + K^2 A_3^* \theta + K^2 A_4^* \frac{h}{B} + KA_5^* \frac{\dot{y}}{U} + K^2 A_6^* \frac{y}{B} \right)$$

with the vertical axis h positive downwards. K is the reduced frequency, $K = \omega B/U$, U is wind speed and ω is the circular frequency.

The relationship with the aerodynamic derivatives required by SdM and defined by Zasso [9], in small caps, is given below:

$P_1^* = -\frac{1}{2} \frac{V}{\omega B} p_5^*$	$P_2^* = -\frac{1}{2} \frac{V}{\omega B} p_2^*$	$P_3^* = \frac{1}{2} \left(\frac{V}{\omega B} \right)^2 p_3^*$	$P_4^* = \frac{1}{2} \frac{\pi}{2} p_6^*$	$P_5^* = \frac{1}{2} \frac{V}{\omega B} p_1^*$	$P_6^* = -\frac{1}{2} \frac{\pi}{2} p_4^*$
$H_1^* = -\frac{1}{2} \frac{V}{\omega B} h_1^*$	$H_2^* = \frac{1}{2} \frac{V}{\omega B} h_2^*$	$H_3^* = -\frac{1}{2} \left(\frac{V}{\omega B} \right)^2 h_3^*$	$H_4^* = \frac{1}{2} \frac{\pi}{2} h_4^*$	$H_5^* = \frac{1}{2} \frac{V}{\omega B} h_5^*$	$H_6^* = -\frac{1}{2} \frac{\pi}{2} h_6^*$
$A_1^* = \frac{1}{2} \frac{V}{\omega B} a_1^*$	$A_2^* = -\frac{1}{2} \frac{V}{\omega B} a_2^*$	$A_3^* = \frac{1}{2} \left(\frac{V}{\omega B} \right)^2 a_3^*$	$A_4^* = -\frac{1}{2} \frac{\pi}{2} a_4^*$	$A_5^* = -\frac{1}{2} \frac{V}{\omega B} a_5^*$	$A_6^* = \frac{1}{2} \frac{\pi}{2} a_6^*$

Figure 4.21 and Figure 4.22 show the derivatives in the SdM formulation. The full set of derivatives in both formulations is shown graphically and in tabular form in the two test reports, [7] and [11].

As seen from Figure 4.19 and Figure 4.20, or Figure 4.21 and Figure 4.22, some differences exist between the two sets of measurements. As the data from sub-test D4 covers the full range of relative wind speeds (up to 30), they were applied in the calculations of aerodynamic stability, [10], and in the calculation of modal aerodynamic damping and stiffness reductions for the buffeting calculations, [8].

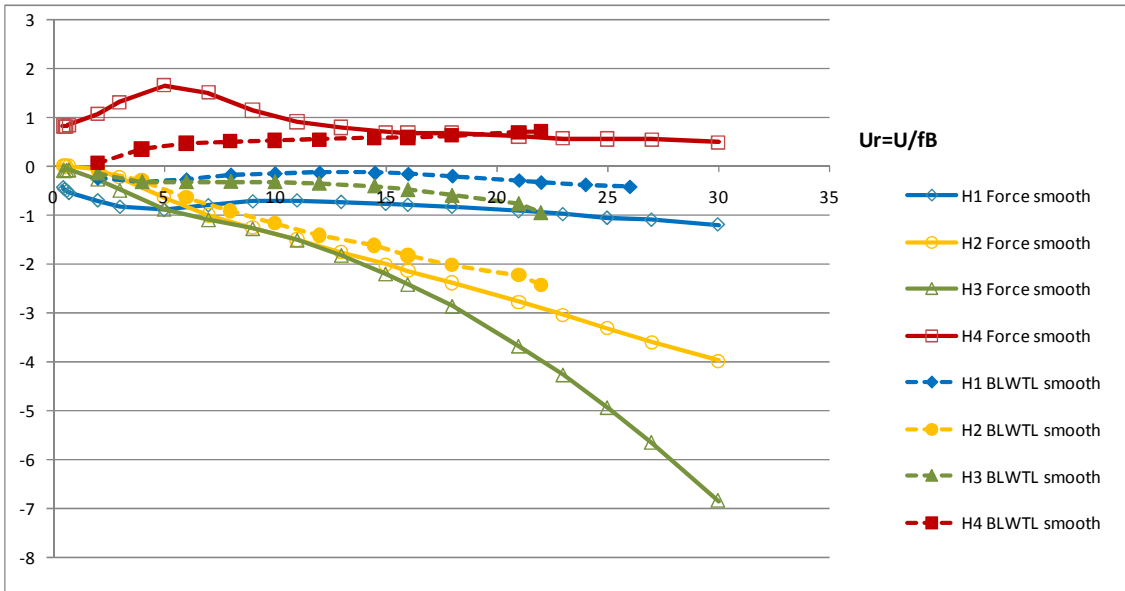


Figure 4.19 Measured aerodynamic derivatives (H_{1-4}^*) at FORCE (sub-test D4) and at BWLTL (sub-test D4), smooth flow. Wind angle 0° . Scanlan notation.

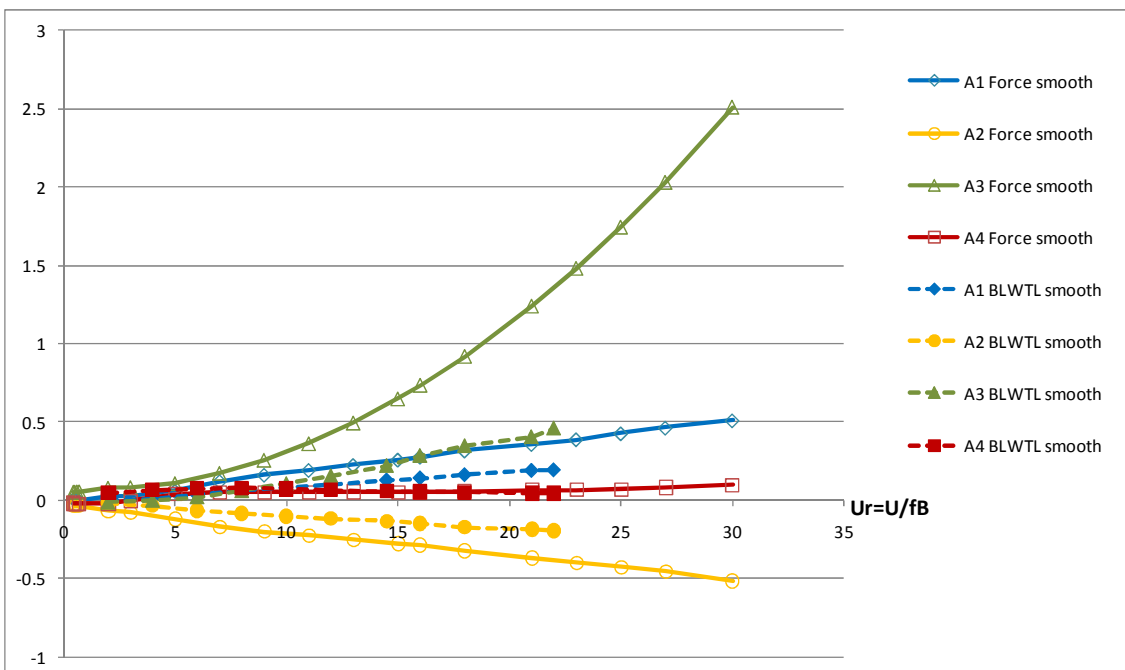




Figure 4.20 Measured aerodynamic derivatives (A_{1-4}^*) at FORCE (sub-test D4) and at BWLTL (sub-test D3), smooth flow. Wind angle 0° . Scanlan notation.

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Wind Tunnel Tests, Girder	<i>Codice documento</i> PB0034_F0.docx	<i>Rev</i> F0	<i>Data</i> 20/06/2011

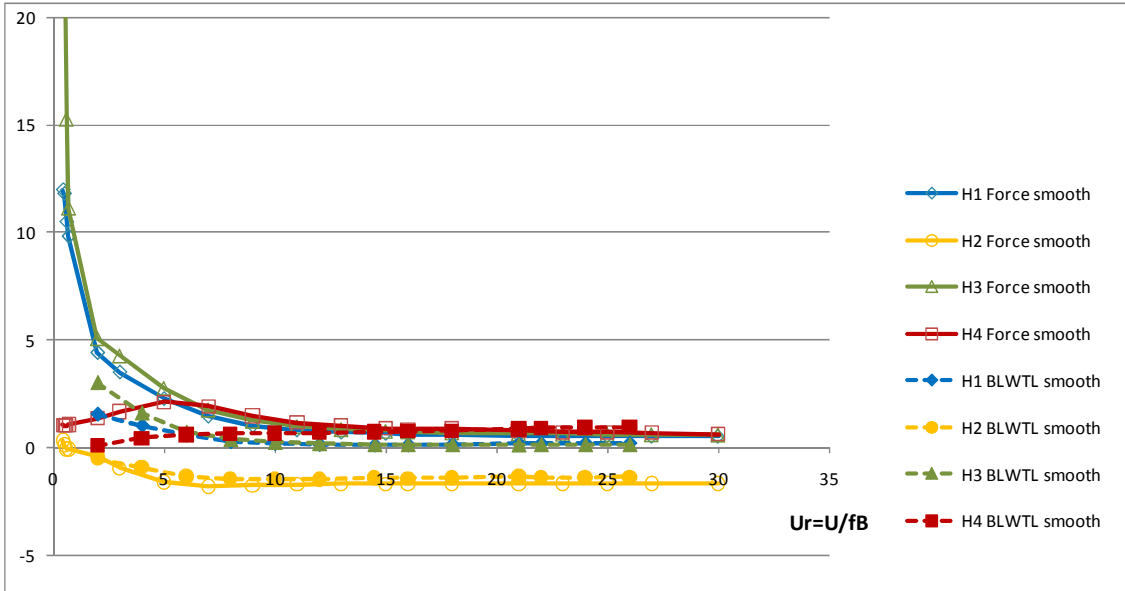




Figure 4.21 Measured aerodynamic derivatives (H_{1-4}^*) at FORCE (sub-test D4) and at BWLTL (sub-test D4), smooth flow. Wind angle 0° . SdM (Zasso) notation.

		Ponte sullo Stretto di Messina PROGETTO DEFINITIVO		
Wind Tunnel Tests, Girder		Codice documento <i>PB0034_F0.docx</i>	Rev <i>F0</i>	Data <i>20/06/2011</i>

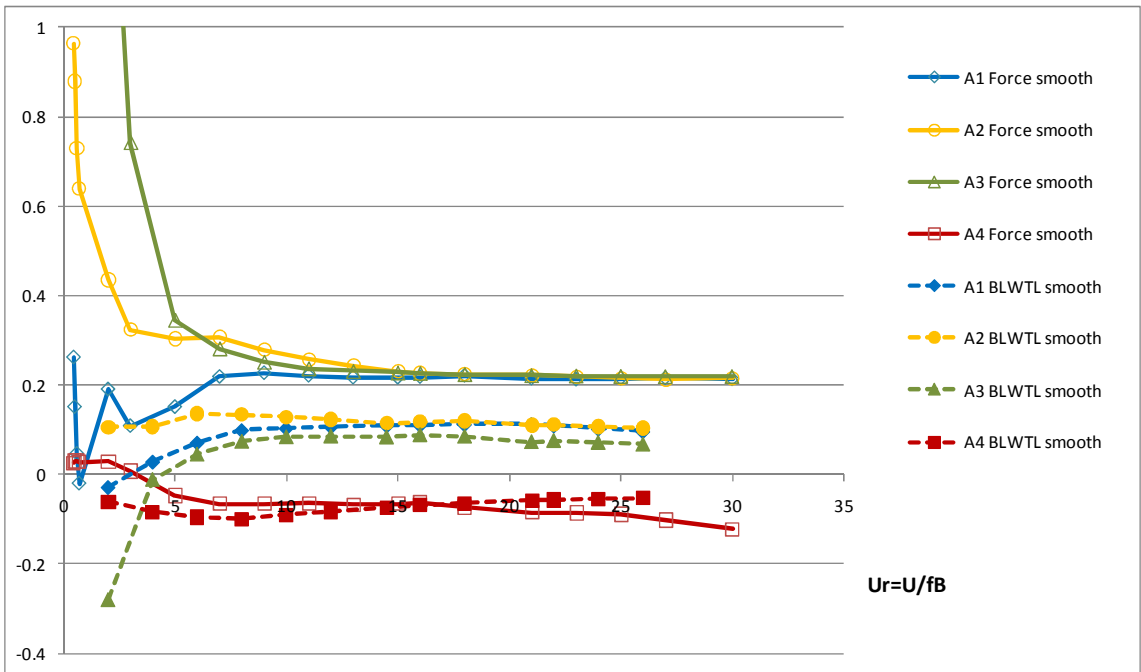
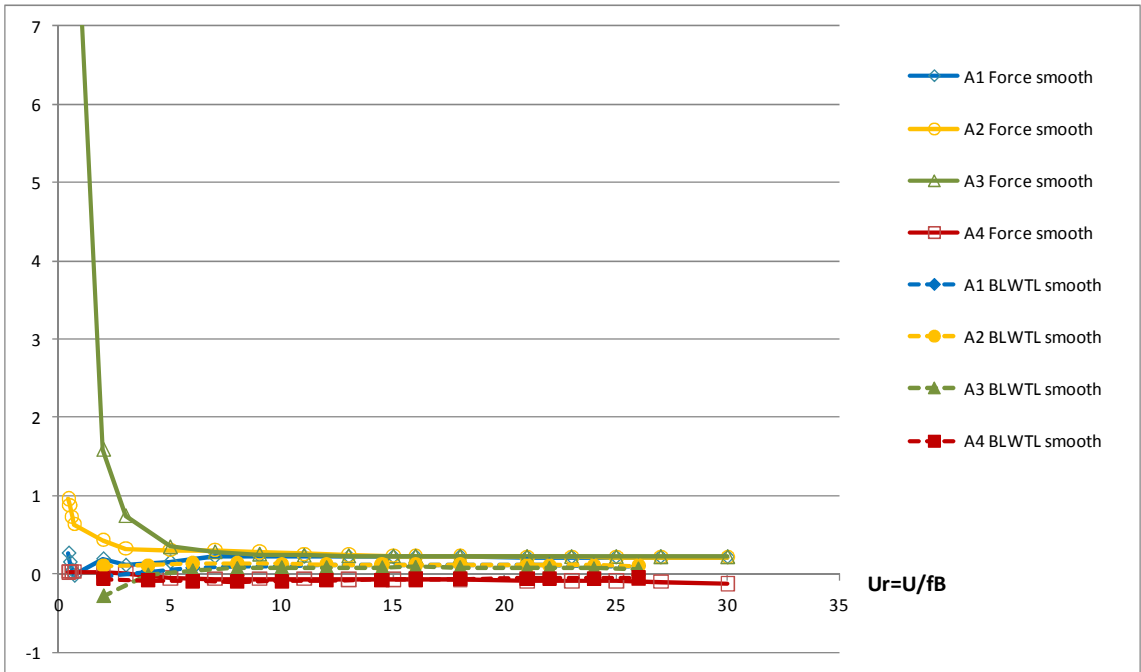




Figure 4.22 Measured aerodynamic derivatives (A_{1-4}^*) at FORCE (sub-test D4) and at BWLTL (sub-test D3), smooth flow, with close-up (bottom graph). Wind angle 0° . SdM (Zasso) notation.

		Ponte sullo Stretto di Messina PROGETTO DEFINITIVO		
Wind Tunnel Tests, Girder		<i>Codice documento</i> PB0034_F0.docx	<i>Rev</i> F0	<i>Data</i> 20/06/2011

5 References

- 1 FORCE Technology. Sub-test 1 Section Model Tests for the Messina Strait Bridge. Report no. 110-25465, Rev. 1, June 2010.
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- 10 EUROLINK S.C.p.A. CG1000-P-CL-D-P-SB-S3-00-00-00-00-02, Rev. B/ 2011-03-07, Aerodynamic calculations, girder. 2011.
- 11 BLWTL. A study of wind effects for the Messina Strait Bridge, Italy, deck section model - subtests D3, D5 and D6. BLWTL-SS42-2010/Draft 4. January 2011.
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<p align="center">Wind Tunnel Tests, Girder</p>		<p><i>Codice documento</i> PB0034_F0.docx</p>	<p><i>Rev</i> F0</p>	<p><i>Data</i> 20/06/2011</p>

Appendix A - Scope of Works

Memo

Title Wind tunnel tests, Sub-test 1, Scope of work
Date 22 April 2010
To Eurolink, EYA
Copy SAMI
From ALN

COWI A/S

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1 Introduction

This memo details the scope of work for section model tests, sub-test 1 optimisation, following the overall aerodynamic design methodology for the Progetto Definitivo phase.

The objective of the tests is to optimise the aerodynamic properties of the bridge deck cross section for the new configuration having 2% outwards slope of the roadways.

2 Requirements to testing

The tests will be carried out as conventional deck section model tests covering:

- Aerodynamic stability, soft spring suspension
- Steady state aerodynamic coefficients, force gauges
- Vortex shedding excitation, stiff spring suspension

The pressure loss coefficient for the permanent external wind screens must be experimentally verified to be 2.7.

The tests are in general to be carried out in smooth flow. However, a confirmatory test for the best performing cross section shall be carried out in turbulent flow with intensity $I = 7\%$.

The spring suspension for the stability tests must be designed in such a way that full scale wind speeds of 120 m/s full scale can be reached.

The spring suspension for the vortex shedding tests must be designed in such a way that the wind speed is larger than 2 m/s model scale at lock-in.

The model mechanical damping shall be less than 0.3% logarithmic decrement.

3 Configurations to be tested

The geometry and layout of the bridge deck section to be tested is given in the enclosed drawings: 100 - 104. The external wind screens at the tips of the service lanes shall always be included.

The following variants of the deck section shall be tested:

- C1 Deck without internal safety screens and rail walkway soffit plates
- C2 Deck without internal safety screens but including rail walkway porous soffit plates
- C3 Deck without internal safety screens but including rail walkway solid soffit plates
- C4 Deck with internal inner safety screens and rail walkway soffit plates (porous or solid according to results for C2, C3).
- C5 Deck with internal inner and outer safety screens and rail walkway soffit plates (porous or solid according to results for C2, C3).
- C6 Deck configuration selected according to results for configurations C1 - C5 but with solid railway screens removed.
- C7 Optional: A combination of the above appendages not tested above.

4 Test programme

The test programme is split in two parts:

- 1 Optimisation of configuration
- 2 Verification of optimum configuration

4.1 Optimisation of configuration

Optimisation of the configuration is carried out by comparing the critical wind speed for aerodynamic instability (flutter) for the spring suspended section model at 0° wind angle and steady state wind load coefficients C_D , C_L , C_M at wind inflow angles with horizontal of -10° - $+10^{\circ}$, obtained for configurations C1 - C7 in smooth flow.

Based on the above results a preferred configuration will be chosen for verification.

4.2 Verification of configuration

Verification of the preferred configuration will involve measurement for aerodynamic stability at angles of incidence, and vortex shedding excitation of a spring suspended model.

4.2.1 Aerodynamic stability

The critical wind speed for onset of aerodynamic stability (flutter) shall be measured by slowly incrementing the wind speed until instability is observed. The static and dynamic response of the section is recorded for documentation. Tests are to be carried out in smooth and turbulent flow.

The tests are carried out for 3 inflow angles with horizontal of: -4° , 0° , $+4^{\circ}$.

The aerodynamic damping in vertical motion and torsion motion are derived from decay tests in smooth flow at full scale wind speeds of 54 m/s and 75 m/s.

4.2.2 Reynolds' Number test

The steady state drag, lift and moment coefficients shall be verified in smooth and turbulent flow and at a minimum of 3 wind speeds at wind inflow angles with horizontal of -10° - $+10^{\circ}$.

4.2.3 Vortex shedding excitation

Vortex shedding excitation, if any, is expected to occur in the non-dimensional wind speed range $0.5 < V/fB < 2.0$ where V is wind speed, f is the deck eigen-frequency in vertical bending or torsion and B is the over all deck width $B = 60.74$ m.

The wind speed range and bending and/or torsion response amplitudes due to vortex shedding excitation shall be measured by slowly incrementing the wind speed and recording the dynamic response.

The measurements are to be carried for 0° wind angle and in smooth and turbulent flow.

5 Model parameters

The section model shall be built to faithfully replicate the attached drawings.

Preliminary inertia and frequencies to be modelled are as follows:

- Full scale mass $m = 53.2 \cdot 10^3$ kg/m
- Full scale mass moment of inertia $I = 26.5 \cdot 10^6$ kgm²/m
- First bending frequency $f_b = 0.0645$ Hz
- First torsion mode $f_t = 0.0831$ Hz

Minor adjustments to the data, if any, will be given prior to start of the tests.

6 Data analysis and reporting

The results of test runs shall be documented in a data report, which shall also documents the particulars of the section model.

The results of the analyses shall be reported with a complete documentation of the applied procedures and observations made in course of the tests.

Test data shall be provided in digital form upon request.

Memo

Title Wind tunnel tests, Sub-test D2, Scope of work
Date 29 June 2010
To Eurolink, EYA
Copy SAMI
From ALN

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1 Introduction

This memo details the scope of work for large scale section model tests sub-test D2 (deck), following the overall aerodynamic design methodology for the Progetto Definitivo phase.

The objective of these tests is to verify the validity of the aerodynamic properties of the deck at high Reynolds Numbers.

2 Requirements to testing

The tests shall be carried out as a conventional deck section model test covering:

- Aerodynamic stability, soft springs
- Steady state wind load coefficients, force gauges
- Vortex shedding excitation, stiff springs

The pressure loss coefficient for the permanent external wind screens must be experimentally verified to be 2.7 with a 5% error margin.

The tests are to be carried out in smooth flow.

The spring suspension system for the stability tests must be designed in such a way that full scale wind speeds of 90 m/s full scale can be reached.

The model mechanical damping shall be less than 0.5% rel.-to-crit.

A model scale of 1:30 is selected to match existing model suspension rigs.

A model aspect ratio $L/B = 2.75$ is selected to match existing support structures in the wind tunnel.

3 Configuration to be tested

The geometry and lay out of the bridge deck section to be tested is given in the enclosed drawings 100 - 104. The configuration of the internal safety screens and railway barriers are subject to optimisation by conventional section model tests and will be announced early June 2010.

4 Test programme

The high Reynolds Number sub-test 2 programme shall include the elements outlined in the following sections.

4.1 Aerodynamic stability

The critical wind speed for onset of aerodynamic stability (flutter) shall be measured by slowly incrementing the wind speed until instability is observed. The static and dynamic response of the section model shall be recorded for documentation.

The aerodynamic damping in vertical and torsion motion shall be derived from decay tests at full scale wind speeds of 54 m/s and 75 m/s as a minimum.

The tests are to be carried out for five inflow angles with horizontal: -4, -2, 0, 2, 4 deg.

The results shall be presented in diagrams giving the dynamic root mean square and static response as function of wind speed. The result of the damping measurements shall be given in tabular form.

4.2 Steady state wind load coefficients

Steady state wind load coefficients C_L , C_D , C_M yielding lift, drag and overturning moment are to be measured at five inflow angles with horizontal of -4, -2, 0, 2, 4 deg. and at 10 different wind speeds spanning a Reynolds Number range: $0.8 \cdot 10^6 < Re < 6.0 \cdot 10^6$ based on over all deck width.

The results shall be given in diagrams displaying the wind load coefficients C_L , C_D , C_M as function of inflow angle with Reynolds Number as parameter.

4.3 Vortex shedding excitation

Vortex shedding excitation, if any, is expected to occur in the non-dimensional wind speed range $0.5 < V/fB < 2.0$ where V is wind speed, f is deck bending frequency in vertical motion and B is the over all deck width of 60.74 m.

The wind speed range and bending and/or torsion response amplitudes due to vortex shedding excitation shall be measured at 0 deg. of inflow angle with horizontal.

The measurements shall be made by slowly incrementing the wind speed and recording the dynamic response. A minimum of 40 measurement points shall be taken over the wind speed range.

The results shall be presented in diagrams giving the dynamic root mean square response as function of wind speed.

5 Model parameters

The section model shall be built to faithfully replicate the attached drawings.

Preliminary inertia and frequencies to be modelled are as follows:

- Full scale mass $m = 54.33 \cdot 10^3 \text{ kg/m}$
- Full scale mass moment of inertia $I = 26.65 \cdot 10^6 \text{ kgm}^2/\text{m}$
- First bending frequency $f_b = 0.0648 \text{ Hz}$
- First torsion mode $f_t = 0.0832 \text{ Hz}$

6 Data analysis and reporting

The results of test runs shall be documented in a data report, which shall also documents the particulars of the section model.

The results of the analyses shall be reported with a complete documentation of the applied procedures and observations made in course of the tests.

The report shall be accompanied by high quality video recordings of selected test runs.

Test data shall be provided in digital form upon request.

Memo	Eurolink s.c.p.a.	COWI A/S
Title	Wind tunnel tests deck, Sub-tests D3, D5 and D6, Scope of work	Parallevej 2 DK-2800 Kongens Lyngby Denmark
Date	5 July 2010	Tel +45 45 97 22 11
To	Eurolink, EYA	Fax +45 45 97 22 12
Copy	SAMI	www.cowi.com
From	ALN	

1 Introduction

This memo details the scope of work for conventional scale section model tests sub-test D3, D5 and D6 (deck), following the overall aerodynamic design methodology for the Progetto Definitivo phase.

The objective of these tests is to verify the aerodynamic properties of the preferred deck configuration for the in-service condition as well as during erection.

2 General Requirements

The geometrical scale of the section models shall be 1:80 or larger.

The model length to deck width ratio (aspect ratio) shall be larger than 3.

The blockage ratio of the wind tunnel shall be less than 10% for deck angles of attack in the range -10^0 - $+10^0$ with horizontal.

The pressure loss coefficient for the permanent external wind screens must be experimentally verified to be 2.7 with an error margin of 5%.

Smooth flow conditions in the wind tunnel shall be verified to have a turbulence level less than 2%.

Turbulent flow shall be verified to have a turbulence intensity of approximately 7%.

For elastically suspended models the spring suspension system must be designed in such a way that full scale wind speeds of 120 m/s can be reached.

The mechanical damping of spring suspended section models shall be less than 0.5% rel.-to-crit.

3 Sub-test D3

Sub-test D3 shall measure steady state wind load coefficients, aerodynamic derivatives and aerodynamic admittances for the preferred deck layout in the service condition as well as during erection.

3.1 Steady state wind load coefficients

Steady state lift, drag and moment coefficients shall be measured in the angle of attack with horizontal in the range $-10^{\circ} < \alpha < +10^{\circ}$ at increments of 0.5° .

The sensitivity of the load coefficients to Reynolds' Number shall be checked by expanding one of the test runs at a selected angle of attack, say 0° , to measure the load coefficients in a range of wind speeds.

The tests shall be carried out in smooth and turbulent flow.

The results shall be presented in graphs giving the lift, drag and moment coefficients in a deck (C_L , C_D , C_M) and fixed (C_Z , C_X , C_M) frame of reference relative to the mean wind.

3.2 Aerodynamic derivatives

Aerodynamic derivatives a^*_{1-6} , h^*_{1-6} , p^*_{1-6} following the convention given by Stretto di Messina (SdM) in ref. 1 shall be measured by the free decay method at deck angles of attack of $\pm 6^{\circ}$, $\pm 4^{\circ}$, $\pm 2^{\circ}$, 0° with horizontal.

Conversion of aerodynamic derivatives obtained from the common Scanlan convention to the Stretto di Messina convention is presented in the appendix.

The tests shall be carried out in smooth flow only.

Tests shall be carried out at sufficiently high wind speeds to allow capture of flutter of the elastically suspended model and at sufficiently low wind speeds to identify vortex shedding excitation.

Each test run shall be repeated at least 10 times to increase the accuracy of the identification procedure.

The results shall be presented in graphs and as curve fits giving the aerodynamic derivatives as function of non-dimensional wind speed V/fB .

3.3 Aerodynamic admittance

The aerodynamic admittances for lift, drag and twisting moment shall be measured by as the transfer functions between the incoming turbulent wind fluctuations and the resulting load fluctuations on the deck. The measurements shall be carried out by the force balance method and at deck angles of attack of $\pm 6^{\circ}$, $\pm 4^{\circ}$, $\pm 2^{\circ}$, 0° with horizontal.

The tests shall be carried out in turbulent flow only.

The results shall be presented in graphs and as curve fits giving the aerodynamic admittances as function of non-dimensional frequency fB/V .

The spectral distribution and the root coherence of the along wind and vertical turbulence shall be documented.

Requirements to the measurement of aerodynamic admittances given in ref. 1 can not be honoured by measurements techniques, such as the force balance method, commonly employed by wind tunnel laboratories. In order to partially fulfil the SdM requirements it has been agreed to supply simultaneous time histories of forces on the deck model and along wind and vertical wind speeds measured by two fast responding anemometers located one deck width apart in the span wise direction and one half deck width upwind of the model for the angles of attack investigated. A minimum of one set of time series must be presented for each angle of attack.

4 Sub-test D5

Sub-test D5 shall measure steady state wind load coefficients with and without traffic and at skew wind directions relative to the bridge line. Further the sub-test shall measure the mean wind and turbulence profiles at selected positions on the road and railways.

4.1 Steady state wind load coefficients

Steady state lift, drag and moment coefficients shall be measured for the wind direction perpendicular to the bridge line $\psi = 0^\circ$ and in skew wind directions $\psi = 10^\circ, 20^\circ, 30^\circ$ and 45° at angles of attack with horizontal in the range $-10^\circ < \alpha < +10^\circ$ at increments of 0.5° . The measurements for $\psi = 0^\circ$ shall be carried out for 3 different traffic set-ups to be defined and the measurements at skew angles $\psi = 10^\circ, 20^\circ, 30^\circ, 45^\circ$ shall be carried out for 3 traffic set-ups and for no traffic.

The load tests shall be carried out in smooth and turbulent flow.

The results of the load tests shall be presented in graphs giving the lift, drag and moment coefficients in a deck (C_L, C_D, C_M) and fixed (C_Z, C_X, C_M) frame of reference relative to the mean wind.

4.2 Wind profiles

Vertical profiles of the mean wind and turbulence intensity ranging from deck level to 8-7 m above (full-scale) shall be measured by means of a hot wire probe at 8 stations across the deck corresponding to the centre of the roadway and railway lanes. The profile measurements shall be made for wind perpendicular to the bridge, $\psi = 0^\circ$, and at an angle of attack $\alpha = 0^\circ$. The wind profile measurements shall be made without traffic and in selected positions with 3 traffic configurations present.

The wind profile measurements shall be carried out in turbulent flow only.

The results of the wind profile measurements shall be presented in graphs giving the mean wind normalized by the free stream wind speed and turbulence intensity as function of height above roadway / railway surface for the various stations across the bridge deck.

5 Sub-test D6

Sub-test D6 shall provide experimental data for verification of aerodynamic calculations of aerodynamic stability and buffeting responses using the three degree of freedom spring suspended section model.

5.1 Aerodynamic stability and buffeting

The critical wind speed for onset of aerodynamic stability (flutter) and the buffeting responses shall be measured by slowly incrementing the wind speed until instability is observed. The static and dynamic response of the section is recorded for documentation.

The tests are carried out for 3 inflow angles with horizontal of: -4° , 0° , $+4^{\circ}$ in smooth flow and at 0° for turbulent flow.

Response measurements in turbulent flow shall be supplemented by simultaneous measurements of time histories of along wind and vertical flow fluctuations by means of two fast responding anemometers at one deck width spacing in the span wise directions and half a deck width upwind of the model, i.e. a similar set-up requested for the admittance tests. Simultaneous time series of vertical, twist and along wind response are delivered in calibrated form for processing by the client.

The aerodynamic damping in vertical motion and torsion motion are derived from decay tests in smooth flow at full scale wind speeds of 44, 47, 54, 60 and 75 m/s.

The tests are to be carried out for the deck without traffic as well as for the three traffic configurations investigated in sub-test D5.

The results of the stability/buffeting tests shall be documented in graphs giving the mean and root mean square vertical, along wind and torsion response of the deck section as function of full scale wind speed.

Aerodynamic damping levels measured at full scale wind speeds of 44, 47, 54, 60 and 75 m/s are reported in tabular form.

5.2 Documentation of turbulent flow

Buffeting response is linked to the spatial and spectral distribution of the wind turbulence, thus these properties shall be fully documented.

The documentation comprises power spectral densities of along wind and vertical turbulence and their cross wind horizontal (along span) root coherences to

be obtained at the reference point for turbulence spectra applied for calculation of the aerodynamic admittances in sub-test D3.

6 Model parameters

The section model representing the in-service condition shall be built to faithfully replicate the attached drawings.

Inertia and frequencies to be modelled for the service condition are as follows:

- Full scale mass $m = 54.33 \cdot 10^3 \text{ kg/m}$
- Full scale mass moment of inertia $I = 26.65 \cdot 10^6 \text{ kgm}^2/\text{m}$
- Frequency of first asymmetric vertical bending mode $f_v = 0.0648 \text{ Hz}$
- Frequency of first asymmetric torsion mode $f_t = 0.0832 \text{ Hz}$
- Frequency of first asymmetric horizontal sway mode $f_h = 0.055 \text{ Hz}$

Minor adjustments to the above data and corresponding data for the erection condition will be given prior to start of the tests.

7 Data analysis and reporting

The results of test runs shall be documented in a data report, which shall also document the particulars of the section model.

The results of the analyses shall be reported with a complete documentation of the applied procedures and observations made in course of the tests.

The report shall be accompanied by high quality video recordings of selected test runs.

Test data shall be provided in digital form upon request.

8 References

- 1 Stretto di Messina. Technical specifications for the final and the executive plan of the bridge. Requirements and guidelines for the development of the project - Aerodynamic Design. Doc. code. F.05.03, 22 Oct. 2004.

9 Appendix - Aerodynamic Derivatives

The self excited forces, drag D, lift L and moment M acting on bridge decks are commonly expressed as aerodynamic derivatives P^*_{1-6} , H^*_{1-6} , A^*_{1-6} following Scanlan's original definition:

$$D = \frac{1}{2} \rho V^2 (2B) \left(KP_1^* \frac{\dot{y}}{V} + KP_2^* \frac{B\dot{\theta}}{V} + K^2 P_3^* \theta + K^2 P_4^* \frac{y}{B} + KP_5^* \frac{\dot{h}}{V} + K^2 P_6^* \frac{h}{B} \right)$$

$$L = \frac{1}{2} \rho V^2 (2B) \left(KH_1^* \frac{\dot{h}}{V} + KH_2^* \frac{B\dot{\theta}}{V} + K^2 H_3^* \theta + K^2 H_4^* \frac{h}{B} + KH_5^* \frac{\dot{y}}{V} + K^2 H_6^* \frac{y}{B} \right)$$

$$M = \frac{1}{2} \rho V^2 (2B^2) \left(KA_1^* \frac{\dot{h}}{V} + KA_2^* \frac{B\dot{\theta}}{V} + K^2 A_3^* \theta + K^2 A_4^* \frac{h}{B} + KA_5^* \frac{\dot{y}}{V} + K^2 A_6^* \frac{y}{B} \right)$$

with a vertical axis h, and thus L, positive *downwards*. K is the reduced frequency, $K = \omega B/V$.

Reference 1 defines the aerodynamic derivatives p^*_{1-6} , h^*_{1-6} , a^*_{1-6} as follows:

$$D = \frac{1}{2} \rho V^2 B \left(-p_1^* \frac{i\omega z}{V} + p_4^* \frac{\pi}{2V^{*2}} \frac{z}{B} - p_2^* \frac{i\omega B\theta}{V} + p_3^* \theta - p_5^* \frac{i\omega y}{V} + p_6^* \frac{\pi}{2V^{*2}} \frac{y}{B} \right)$$

$$L = \frac{1}{2} \rho V^2 B \left(-h_1^* \frac{i\omega z}{V} + h_4^* \frac{\pi}{2V^{*2}} \frac{z}{B} - h_2^* \frac{i\omega B\theta}{V} + h_3^* \theta - h_5^* \frac{i\omega y}{V} + h_6^* \frac{\pi}{2V^{*2}} \frac{y}{B} \right)$$

$$M = \frac{1}{2} \rho V^2 B^2 \left(-a_1^* \frac{i\omega z}{V} + a_4^* \frac{\pi}{2V^{*2}} \frac{z}{B} - a_2^* \frac{i\omega B\theta}{V} + a_3^* \theta - a_5^* \frac{i\omega y}{V} + a_6^* \frac{\pi}{2V^{*2}} \frac{y}{B} \right)$$

Assuming harmonic motion $h = h_0 e^{i\omega t}$ $y = y_0 e^{i\omega t}$ $\theta = \theta_0 e^{i\omega t}$ and inserting $h = -z$ into the Scanlan expressions yields the following relationships between the SdM form (p^*_{1-6} , h^*_{1-6} , a^*_{1-6}) and Scanlan form (P^*_{1-6} , H^*_{1-6} , A^*_{1-6}) of aerodynamic derivatives:

$P_1^* = -\frac{1}{2} \frac{V}{\omega B} p_5^*$	$P_2^* = -\frac{1}{2} \frac{V}{\omega B} p_2^*$	$P_3^* = \frac{1}{2} \left(\frac{V}{\omega B} \right)^2 p_3^*$	$P_4^* = \frac{1}{2} \frac{\pi}{2} p_6^*$	$P_5^* = \frac{1}{2} \frac{V}{\omega B} p_1^*$	$P_6^* = -\frac{1}{2} \frac{\pi}{2} p_4^*$
$H_1^* = -\frac{1}{2} \frac{V}{\omega B} h_1^*$	$H_2^* = \frac{1}{2} \frac{V}{\omega B} h_2^*$	$H_3^* = -\frac{1}{2} \left(\frac{V}{\omega B} \right)^2 h_3^*$	$H_4^* = \frac{1}{2} \frac{\pi}{2} h_4^*$	$H_5^* = \frac{1}{2} \frac{V}{\omega B} h_5^*$	$H_6^* = -\frac{1}{2} \frac{\pi}{2} h_6^*$
$A_1^* = \frac{1}{2} \frac{V}{\omega B} a_1^*$	$A_2^* = -\frac{1}{2} \frac{V}{\omega B} a_2^*$	$A_3^* = \frac{1}{2} \left(\frac{V}{\omega B} \right)^2 a_3^*$	$A_4^* = -\frac{1}{2} \frac{\pi}{2} a_4^*$	$A_5^* = -\frac{1}{2} \frac{V}{\omega B} a_5^*$	$A_6^* = \frac{1}{2} \frac{\pi}{2} a_6^*$

Relation between aerodynamic derivatives following Scanlan's original definition and the definition preferred by Stretto di Messina.

It is noted that in later work Scanlan changed the definition of the aerodynamic derivatives in accordance with the following definition which yields a factor of 2 between the original and the new definition of the aerodynamic derivatives.

$$D = \frac{1}{2} \rho V^2 B \left(KP_1^* \frac{\dot{y}}{V} + KP_2^* \frac{B\dot{\theta}}{V} + K^2 P_3^* \theta + K^2 P_4^* \frac{y}{B} + KP_5^* \frac{\dot{h}}{V} + K^2 P_6^* \frac{h}{B} \right)$$

$$L = \frac{1}{2} \rho V^2 B \left(KH_1^* \frac{\dot{h}}{V} + KH_2^* \frac{B\dot{\theta}}{V} + K^2 H_3^* \theta + K^2 H_4^* \frac{h}{B} + KH_5^* \frac{\dot{y}}{V} + K^2 H_6^* \frac{y}{B} \right)$$

$$M = \frac{1}{2} \rho V^2 B^2 \left(KA_1^* \frac{\dot{h}}{V} + KA_2^* \frac{B\dot{\theta}}{V} + K^2 A_3^* \theta + K^2 A_4^* \frac{h}{B} + KA_5^* \frac{\dot{y}}{V} + K^2 A_6^* \frac{y}{B} \right)$$

Memo	Eurolink s.c.p.a.	COWI A/S
Title	Wind tunnel tests deck, Sub-tests D4, Scope of work	Parallevej 2 DK-2800 Kongens Lyngby Denmark
Date	25 June 2010	Tel +45 45 97 22 11
To	Eurolink, EYA	Fax +45 45 97 22 12
Copy	SAMI	www.cowi.com
From	ALN	

1 Introduction

This memo details the scope of work for conventional scale section model tests sub-test D4 (deck), following the overall aerodynamic design methodology for the Progetto Definitivo phase.

The objective of this test is to verify the aerodynamic properties of the preferred deck configuration obtained from sub-test D3.

2 General Requirements

The geometrical scale of the section models shall be 1:80 or larger.

The model length to deck width ratio (aspect ratio) shall be larger than 3.

The blockage ratio of the wind tunnel shall be less than 10% for deck angles of attack in the range -10^0 - $+10^0$ with horizontal.

The pressure loss coefficient for the permanent external wind screens must be experimentally verified to be 2.7 with an error margin of 5%.

Smooth flow conditions in the wind tunnel shall be verified to have a turbulence level less than 2%.

Turbulent flow shall be verified to have a turbulence intensity of approximately 7%.

3 Sub-test D4

Sub-test D4 shall verify steady state wind load coefficients, aerodynamic derivatives and aerodynamic admittances for the preferred deck layout in the service condition as well as during erection.

3.1 Steady state wind load coefficients

Steady state lift, drag and moment coefficients shall be measured in the angle of attack with horizontal in the range $-10^0 < \alpha < +10^0$ at increments of 0.5^0 .

The sensitivity of the load coefficients to Reynolds' Number shall be checked by expanding one of the test runs at a selected angle of attack, say 0^0 , to measure the load coefficients in a range of wind speeds.

The tests shall be carried out in smooth and turbulent flow.

The results shall be presented in graphs giving the lift, drag and moment coefficients in a deck (C_L , C_D , C_M) and fixed (C_Z , C_X , C_M) frame of reference relative to the mean wind.

3.2 Aerodynamic derivatives

Aerodynamic derivatives a^*_{1-6} , h^*_{1-6} , p^*_{1-6} following the convention given by Stretto di Messina (SdM) in ref. 1 shall be measured by the forced oscillation method at deck angles of attack of $\pm 6^0$, $\pm 4^0$, $\pm 2^0$, 0^0 with horizontal.

Conversion of aerodynamic derivatives obtained from the common Scanlan convention to the Stretto di Messina convention is presented in the appendix.

The tests shall be carried out in smooth flow as well as in turbulent flow.

Tests shall be carried out at sufficiently high wind speeds to allow capture of flutter of the elastically suspended model and at sufficiently low wind speeds to identify vortex shedding excitation.

Each test run shall be repeated at least 10 times to increase the accuracy of the identification procedure.

The results shall be presented in graphs and as curve fits giving the aerodynamic derivatives as function of non-dimensional wind speed V/fB .

3.3 Aerodynamic admittance

The aerodynamic admittances for lift, drag and twisting moment shall be measured by as the transfer functions between the incoming turbulent wind fluctuations and the resulting load fluctuations on the deck. The measurements shall be carried out by the force balance method and at deck angles of attack of $\pm 6^0$, $\pm 4^0$, $\pm 2^0$, 0^0 with horizontal.

The tests shall be carried out in turbulent flow only.

The results shall be presented in graphs and as curve fits giving the aerodynamic admittances as function of non-dimensional frequency fB/V .

The spectral distribution and the root coherence of the along wind and vertical turbulence shall be documented.

Requirements to the measurement of aerodynamic admittances given in ref. 1 can not be honoured by measurements techniques, such as the force balance method commonly employed by wind tunnel laboratories. In order to partially fulfil the SdM requirements it has been agreed to supply simultaneous time histories of fluctuating forces on the deck model and along wind and vertical wind

speeds measured by two fast responding anemometers located one deck width apart in the span wise direction and one half deck width upwind of the model. A minimum of one set of time series must be presented for each angle of attack investigated.

4 Model parameters

The section model representing the in-service condition shall be built to faithfully replicate the attached drawings.

Inertia and frequencies to be modelled for the service condition are as follows:

- Full scale mass $m = 54.33 \cdot 10^3 \text{ kg/m}$
- Full scale mass moment of inertia $I = 26.65 \cdot 10^6 \text{ kgm}^2/\text{m}$
- Frequency of first asymmetric vertical bending mode $f_v = 0.0648 \text{ Hz}$
- Frequency of first asymmetric torsion mode $f_t = 0.0832 \text{ Hz}$
- Frequency of first asymmetric horizontal sway mode $f_h = 0.055 \text{ Hz}$

Minor adjustments to the above data and corresponding data for the erection condition will be given prior to start of the tests.

5 Data analysis and reporting

The results of test runs shall be documented in a data report, which shall also documents the particulars of the section model.

The results of the analyses shall be reported with a complete documentation of the applied procedures and observations made in course of the tests.

The report shall be accompanied by high quality video recordings of selected test runs.

Test data shall be provided in digital form upon request.

6 References

- 1 Stretto di Messina. Technical specifications for the final and the executive plan of the bridge. Requirements and guidelines for the development of the project - Aerodynamic Design. Doc. code. F.05.03, 22 Oct. 2004.

7 Appendix - Aerodynamic Derivatives

The self excited forces, drag D, lift L and moment M acting on bridge decks are commonly expressed as aerodynamic derivatives P^*_{1-6} , H^*_{1-6} , A^*_{1-6} following Scanlan's original definition:

$$D = \frac{1}{2} \rho V^2 (2B) \left(KP_1^* \frac{\dot{y}}{V} + KP_2^* \frac{B\dot{\theta}}{V} + K^2 P_3^* \theta + K^2 P_4^* \frac{y}{B} + KP_5^* \frac{\dot{h}}{V} + K^2 P_6^* \frac{h}{B} \right)$$

$$L = \frac{1}{2} \rho V^2 (2B) \left(KH_1^* \frac{\dot{h}}{V} + KH_2^* \frac{B\dot{\theta}}{V} + K^2 H_3^* \theta + K^2 H_4^* \frac{h}{B} + KH_5^* \frac{\dot{y}}{V} + K^2 H_6^* \frac{y}{B} \right)$$

$$M = \frac{1}{2} \rho V^2 (2B^2) \left(KA_1^* \frac{\dot{h}}{V} + KA_2^* \frac{B\dot{\theta}}{V} + K^2 A_3^* \theta + K^2 A_4^* \frac{h}{B} + KA_5^* \frac{\dot{y}}{V} + K^2 A_6^* \frac{y}{B} \right)$$

with a vertical axis h, and thus L, positive *downwards*. K is the reduced frequency, $K = \omega B/V$.

Reference 1 defines the aerodynamic derivatives p^*_{1-6} , h^*_{1-6} , a^*_{1-6} as follows:

$$D = \frac{1}{2} \rho V^2 B \left(-p_1^* \frac{i\omega z}{V} + p_4^* \frac{\pi}{2V^{*2}} \frac{z}{B} - p_2^* \frac{i\omega B\theta}{V} + p_3^* \theta - p_5^* \frac{i\omega y}{V} + p_6^* \frac{\pi}{2V^{*2}} \frac{y}{B} \right)$$

$$L = \frac{1}{2} \rho V^2 B \left(-h_1^* \frac{i\omega z}{V} + h_4^* \frac{\pi}{2V^{*2}} \frac{z}{B} - h_2^* \frac{i\omega B\theta}{V} + h_3^* \theta - h_5^* \frac{i\omega y}{V} + h_6^* \frac{\pi}{2V^{*2}} \frac{y}{B} \right)$$

$$M = \frac{1}{2} \rho V^2 B^2 \left(-a_1^* \frac{i\omega z}{V} + a_4^* \frac{\pi}{2V^{*2}} \frac{z}{B} - a_2^* \frac{i\omega B\theta}{V} + a_3^* \theta - a_5^* \frac{i\omega y}{V} + a_6^* \frac{\pi}{2V^{*2}} \frac{y}{B} \right)$$

Assuming harmonic motion $h = h_0 e^{i\omega t}$ $y = y_0 e^{i\omega t}$ $\theta = \theta_0 e^{i\omega t}$ and inserting $h = -z$ into the Scanlan expressions yields the following relationships between the SdM form (p^*_{1-6} , h^*_{1-6} , a^*_{1-6}) and Scanlan form (P^*_{1-6} , H^*_{1-6} , A^*_{1-6}) of aerodynamic derivatives:

$P_1^* = -\frac{1}{2} \frac{V}{\omega B} p_5^*$	$P_2^* = -\frac{1}{2} \frac{V}{\omega B} p_2^*$	$P_3^* = \frac{1}{2} \left(\frac{V}{\omega B} \right)^2 p_3^*$	$P_4^* = \frac{1}{2} \frac{\pi}{2} p_6^*$	$P_5^* = \frac{1}{2} \frac{V}{\omega B} p_1^*$	$P_6^* = -\frac{1}{2} \frac{\pi}{2} p_4^*$
$H_1^* = -\frac{1}{2} \frac{V}{\omega B} h_1^*$	$H_2^* = \frac{1}{2} \frac{V}{\omega B} h_2^*$	$H_3^* = -\frac{1}{2} \left(\frac{V}{\omega B} \right)^2 h_3^*$	$H_4^* = \frac{1}{2} \frac{\pi}{2} h_4^*$	$H_5^* = \frac{1}{2} \frac{V}{\omega B} h_5^*$	$H_6^* = -\frac{1}{2} \frac{\pi}{2} h_6^*$
$A_1^* = \frac{1}{2} \frac{V}{\omega B} a_1^*$	$A_2^* = -\frac{1}{2} \frac{V}{\omega B} a_2^*$	$A_3^* = \frac{1}{2} \left(\frac{V}{\omega B} \right)^2 a_3^*$	$A_4^* = -\frac{1}{2} \frac{\pi}{2} a_4^*$	$A_5^* = -\frac{1}{2} \frac{V}{\omega B} a_5^*$	$A_6^* = \frac{1}{2} \frac{\pi}{2} a_6^*$

Relation between aerodynamic derivatives following Scanlan's original definition and the definition preferred by Stretto di Messina.

It is noted that in later work Scanlan changed the definition of the aerodynamic derivatives in accordance with the following definition which yields a factor of 2 between the original and the new definition of the aerodynamic derivatives.

$$D = \frac{1}{2} \rho V^2 B \left(KP_1^* \frac{\dot{y}}{V} + KP_2^* \frac{B\dot{\theta}}{V} + K^2 P_3^* \theta + K^2 P_4^* \frac{y}{B} + KP_5^* \frac{\dot{h}}{V} + K^2 P_6^* \frac{h}{B} \right)$$

$$L = \frac{1}{2} \rho V^2 B \left(KH_1^* \frac{\dot{h}}{V} + KH_2^* \frac{B\dot{\theta}}{V} + K^2 H_3^* \theta + K^2 H_4^* \frac{h}{B} + KH_5^* \frac{\dot{y}}{V} + K^2 H_6^* \frac{y}{B} \right)$$

$$M = \frac{1}{2} \rho V^2 B^2 \left(KA_1^* \frac{\dot{h}}{V} + KA_2^* \frac{B\dot{\theta}}{V} + K^2 A_3^* \theta + K^2 A_4^* \frac{h}{B} + KA_5^* \frac{\dot{y}}{V} + K^2 A_6^* \frac{y}{B} \right)$$

Memo

Title Wind tunnel tests, Sub-test D7, Scope of work
Date 12 August 2010
To Eurolink, EYA
Copy SAMI
From ALN

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1 Introduction

This memo details the scope of work for 1:65 scale section model tests sub-test D7 (deck), following directions given by Stretto di Messina.

The objective of these tests is to verify the validity of the vortex shedding excitation performance of the deck using a very stiff model.

2 Requirements to testing

The tests shall be carried out as a conventional deck section model test covering:

- Steady state wind load coefficients, force balance
- Vortex shedding excitation, stiff springs

The pressure loss coefficient for the permanent external wind screens must be experimentally verified to be 2.7 with a 5% error margin.

The tests are to be carried out in smooth flow.

The spring suspension system for the vortex shedding tests must be designed in such a way that the model wind speed in the tunnel must be above 2 m/s at a non-dimensional wind speed $V/fB = 0.5$ where f is model bending frequency and B is over all deck width = 60.4 m.

The model mechanical damping shall be less than 0.5% rel.-to-crit.

A model scale of 1:65 is selected to match existing model suspension rigs and the over all dimensions of the wind tunnel.

The model must be built in such a way that the lowest natural frequency in vertical bending of the model is above 10 Hz.

3 Configurations to be tested

The general lay out of the bridge deck section to be tested is given in the enclosed drawings 100 - 104. The configuration of screens constitutes external wind screens of 55% void with airfoil dampers, internal safety screens of 55% void attached to the roadway crash barriers and solid railway screens attached to the handrails of the railway inspection walkway. This screen configuration is referred to as C5.

Three different geometries of the railway girder shall be investigated having different width of the horizontal bottom plate and thus inclinations of the lower inclined side panels.

For the C5/28 configuration the angle between the inclined lower side panels and horizontal is approximately 28 deg.

For the C5/45 configuration the angle between the inclined lower side panels and horizontal is approximately 45 deg.

For the C5/63 configuration the angle between the inclined lower side panels and horizontal is approximately 63 deg.

The different railway girder configurations are shown in the enclosed drawings.

4 Test programme

The sub-test 7 programme shall include the elements outlined in the following sections.

4.1 Verification of pressure loss coefficient, wind screens

It must be verified that the perforated plates used for modelling of the 55% void screens displays a pressure loss coefficient of 2.7

4.2 Steady state wind load coefficients

Steady state wind load coefficients C_L , C_D , C_M yielding lift, drag and overturning moment are to be measured in smooth flow for the C5/63 configuration at inflow angles of - 10 deg. to , + 10 deg. at increments of 1 deg.

The results shall be given in diagrams displaying the wind load coefficients C_L , C_D , C_M as function of inflow.

4.3 Vortex shedding excitation

Vortex shedding excitation, is expected to occur in the non-dimensional wind speed range $0.5 < V/fB < 2.0$ where V is wind speed, f is deck bending frequency in vertical motion and B is the over all deck width of 60.4 m.

The wind speed range and bending and/or torsion rms response amplitudes due to vortex shedding excitation shall be measured in smooth flow at 0 deg. of inflow angle with horizontal.

The measurements shall be made for configurations C5/28, C5/45 and C5/63 by slowly incrementing the wind speed and recording the dynamic response. A minimum of 40 measurement points shall be taken over the wind speed range.

For each configuration the rms amplitudes shall be measured for the inherent damping level of the dynamic rig as well as for three higher damping levels where the highest damping level is chosen such that the vortex response is just eliminated.

The results shall be presented in diagrams giving the dynamic root mean square displacements as function of non-dimensional wind speed with Scruton number as parameter. The Scruton number being defined as:

$$Sc = \frac{\delta m}{\rho B^2}$$

Where δ is mechanical damping (logarithmic decrement), m is deck unit mass or mass moment of inertia, ρ is air density and B is deck width.

5 Model parameters

The section model shall be built to faithfully replicate the attached drawings.

Preliminary inertia and frequencies to be modelled are as follows:

- Full scale mass $m = 54.33 \cdot 10^3 \text{ kg/m}$
- Full scale mass moment of inertia $I = 26.65 \cdot 10^6 \text{ kgm}^2/\text{m}$
- First bending frequency $f_b = 0.0648 \text{ Hz}$
- First torsion mode $f_t = 0.0832 \text{ Hz}$

6 Data analysis and reporting

The results of test runs shall be documented in a data report, which shall also documents the particulars of the section model.

The results of the analyses shall be reported with a complete documentation of the applied procedures and observations made in course of the tests.

The report shall be accompanied by high quality video recordings of selected test runs.

Test data shall be provided in digital form upon request.

Memo

Title Eurolink s.c.p.a.
Title Wind tunnel tests, Sub-test D8, Scope of work
Date 28 February 2011
To Eurolink, EYA, LSJ
Copy SAMI
From ALN

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1 Introduction

This memo details the scope of work for 1:65 scale section model tests sub-test D8 (deck), following directions given by Stretto di Messina.

The objective of these tests is to verify by duplication the validity of the vortex shedding excitation performance of the deck using a very stiff model (similar sub-test D7) and in addition investigate the effect of horizontal grids between the railway and roadway girders on the vortex shedding excitation, the aeroelastic stability and the static wind load coefficients.

2 Requirements to testing

The tests shall be carried out as a conventional deck section model test covering:

- Steady state wind load coefficients, force balance
- Vortex shedding excitation, stiff springs, at an inflow angle of 0 deg. and for a minimum of 4 damping levels.
- Critical wind speed for onset of flutter instability at inflow angles of -4, -2, 0, + 2, +4 deg. and measurement of the aerodynamic damping at full scale wind speeds of 54 m/s and 75 m/s

The tests shall be carried out for two configurations of the permanent external wind screens both fulfilling the SdM requirement for the pressure loss coefficient of 2.7 with a 5% error margin corresponding to 55% porosity.

The tests are to be carried out in smooth flow.

The spring suspension system for the vortex shedding tests must be designed in such a way that the model wind speed in the tunnel must be above 2 m/s at a non-dimensional wind speed $V/fB = 0.5$ where f is model bending frequency and B is over all deck width = 60.4 m.

A model scale of 1:65 is selected to match that of the existing section model.

3 Configurations to be tested

The general lay out of the bridge deck section to be tested is given in the enclosed drawings 100 - 104. The configuration of screens constitutes external wind screens of 55% perforation with airfoil dampers, internal safety screens of 55% void attached to the roadway crash barriers and solid railway screens attached to the handrails of the railway inspection walkway. This screen configuration is referred to as C5.

Three tests are carried out for the C5/63 configuration. The angle between the inclined lower side panels and horizontal is approximately 63 deg.

The different railway girder configurations are shown in the enclosed drawings.

4 Test programme

The sub-test 8 programme shall include the elements outlined in the following sections.

4.1 Verification of pressure loss coefficient, wind screens

It must be verified that the two sets of perforated plates used for modelling of the 55% void screens displays a pressure loss coefficient of 2.7 with a 5% error margin.

4.2 Vortex shedding excitation

Vortex shedding excitation, is expected to occur in the non-dimensional wind speed range $0.5 < V/fB < 2.0$ where V is wind speed, f is deck bending frequency in vertical motion and B is the over all deck width of 60.4 m.

The wind speed range and bending and/or torsion rms response amplitudes due to vortex shedding excitation shall be measured in smooth flow at 0 deg. of in-flow angle with horizontal.

The measurements shall be made for configuration C5/63 by slowly incrementing the wind speed and recording the dynamic response. A minimum of 40 measurement points shall be taken over the wind speed range.

For each configuration the rms amplitudes shall be measured for the inherent damping level of the dynamic rig as well as for three higher damping levels where the highest damping level is chosen such that the vortex response is just eliminated.

The results shall be presented in diagrams giving the dynamic root mean square displacements as function of non-dimensional wind speed with Scruton number as parameter. The Scruton number being defined as:

$$Sc = \frac{\delta m}{\rho B^2}$$

Where δ is mechanical damping (logarithmic decrement), m is deck unit mass or mass moment of inertia, ρ is air density and B is deck width.

4.3 Steady state wind load coefficients

Steady state wind load coefficients C_L , C_D , C_M yielding lift, drag and overturning moment are to be measured in smooth flow for the C5/63 configuration at inflow angles of - 10 deg. to , + 10 deg. at increments of 1 deg.

The results shall be given in diagrams displaying the wind load coefficients C_L , C_D , C_M as function of inflow.

4.4 Aerodynamic stability

The measurements shall be made for configuration C5/63 by slowly incrementing the wind speed starting at a wind speed below 54 m/s full scale and ending when divergent response is encountered. The aerodynamic damping is recorded at full scale wind speeds of 54 m/s and 75 m/s as is the divergent dynamic response at the instability limit.

The model mechanical damping for the stability tests shall be less than 0.3% rel.-to-crit.

4.5 Overview of tests

The following table gives an overview of tests carried out as part of the sub-test D7 programme and new tests to be carried out during sub-test D8

Configuration	Static	Vortex	Stability
Screens A	√	√	+
Screens A + H	+	√	+
Screens B	+	+	+

Outer wind screens A: As tested during sub-tests D7

Horizontal screens H: As tested during sub-tests D7

Outer wind screens B: To be tested during sub-tests D8

√: Tests replicating sub-test D7

+: New tests D8

5 Model parameters

The section model shall be built to faithfully replicate the attached drawings.

Preliminary inertia and frequencies to be modelled are as follows:

- Full scale mass $m = 57.66 \cdot 10^3$ kg/m
- Full scale mass moment of inertia $I = 28.89 \cdot 10^6$ kgm²/m

- First bending frequency $f_b = 0.063$ Hz
- First torsion mode $f_t = 0.080$ Hz

6 Data analysis and reporting

The results of test runs shall be documented in a data report, which shall also documents the particulars of the section model.

The results of the analyses shall be reported with a complete documentation of the applied procedures and observations made in course of the tests.

The report shall be accompanied by high quality video recordings of selected test runs.

Test data shall be provided in digital form upon request.

7 Wind Tunnel Crew

It is a condition that the wind tunnel crew executing the sub-test D8 and analysing the data are different from the crew that executed sub-test D7.