Project No. 431185/00
Messina Straits Crossing, Italy
Deck

Wind Tunnel Testing

Section Model Studies

(22nd December 2010)

For
Eurolink S.C.p.A.

Report Title	**Messina Straits Crossing Deck Wind Tunnel Testing, Section Model Studies**		
Client:	**Eurolink S.C.p.A.**		
Document No:	**431185rep1v3**	**Release: 3**	**Copy No:**
Status	**Final**		
Report Date:	**22nd December 2010**		
Holds:			

	Name:	**Signature:**	**Date:**
Prepared by:	**Mr J Osman**		**22-12-10**
Checked by:	**Miss A Bagnara**		**22-12-10**
Approved by:	**Dr V Buttgereit**		**22-12-10**

Distribution:	**Copy no.**	**to**	**Client**
	Copy no.	**to**	**BMT Records**

Previous Release History:	**Release No:**	**Status:**	**Date:**
431185rep1v1	**1**	**Draft Report for Internal Review**	**26/11/10**
431185rep1v2	**2**	**Draft Report for Client Review**	**29/11/10**

Messina Straits Crossing
Deck
Wind Tunnel Testing
Section Model Studies

Contents

EXECUTIVE SUMMARY

Background

This document has been prepared by BMT Fluid Mechanics Limited (BMT) for COWI, acting on behalf of Eurolink S.C.p.A. to summarise the results of section model testing commissioned to study the wind effects relevant to the design of the deck of the Messina Straits Crossing in Italy.

The wind tunnel studies were carried out to derive a detailed quantification of the static wind loading and aerodynamic stability with regards to vortex shedding of the bridge deck by way of section model wind tunnel testing.

The wind tunnel tests were carried out in BMT's aeronautical wind tunnel using a 2-dimensional, 1:65 scale section model of the bridge deck. The tests were conducted with a varying angle of incline of the underside of the rail deck.

Results

The main results of the wind tunnel testing are as follows:

VORTEX SHEDDING RESPONSE

The vortex shedding response of the bridge deck was measured for three configurations, characterised by a different angle of incline of the underside of the rail deck (all tested at 0° wind angle).

The maximum vortex shedding response is observed in both the vertical and torsional modes of the bridge for all configurations, at model scale windspeeds [ms^{-1}] and accelerations [ms^{-2}] as follows:

Configuration	Wind Angle	Max Vertical		Max Torsion	
		Windspeed [m/s]	RMS Acceleration [m/s^2]	Windspeed [m/s]	RMS Acceleration [m/s^2]
C5/28	0°	2.8	3.8	8.7	8.8
C5/45	0°	3.0	3.8	8.6	5.5
C5/63	0°	3.1	3.9	5.0	3.5

N.B torsional accelerations are measured at a point 0.46m from the centre line of the bridge model (the location of the outer wind barriers)

STATIC WIND LOADING

- Static load coefficients were measured for the C5/63 configuration for wind angles in the range ±10° in 1° increments

- The static load coefficients, measured for Reynolds number of ~$1.8x10^6$ based on the width of the section (60.4m at full scale) at 0° wind incidence, are as follows:

Configuration	Wind Angle	C_L	C_D	C_{Mz}	$\delta C_L/\delta \alpha$
C5/63	0°	-0.170	0.232	0.000	0.008

Messina Straits Crossing Deck Wind Tunnel Testing

1. Introduction

1.1. Background

This document has been prepared by BMT Fluid Mechanics Limited (BMT) for COWI, acting on behalf of Eurolink S.C.p.A. to summarise the results of section model testing commissioned to study the wind effects relevant to the design of the deck of the Messina Straits Crossing in Italy.

1.2. Site / Structure Details

1.2.1. Proposed Development / Location

The Messina Straits Crossing is a suspension bridge linking the Island of Sicily with mainland Italy, and has a total length of ~3300m. Two twin-leg towers, 399m tall, support the suspension cables. The bridge has a triple deck configuration; a rail deck in the centre, with two traffic/pedestrian decks on either side. The total width of the deck is 60.4m, including the 2 gaps of 8.0m between the rail deck and traffic deck. Figure 1.1 shows the arrangement of the deck and the relevant geometrical features.

1.3. Requirements for Wind Tunnel Study

The main requirements of the studies are as follows:

- Provide an assessment of the vortex shedding response for three proposed arrangements of the bridge deck.
- Provide an assessment of the static wind loading for one proposed arrangement of the bridge deck.

1.4. Methodology

1.4.1. Structural and Dynamic Properties

The structural properties of the proposed Messina Bridge section were supplied by COWI and are detailed in Appendix A.

1.4.2. Section Model Studies

The following methodology has been adopted for the section model studies.

1.4.2.1. BMT's Aeronautical Wind Tunnel & Flow Conditions

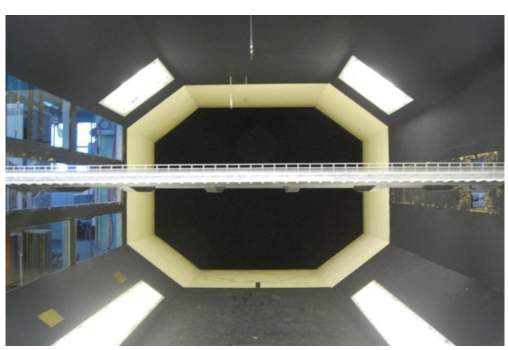
The section model tests have been conducted in BMT's aeronautical wind tunnel facility. The tunnel has an octagonal cross section test section, which is 2.74 m wide x 2.14 m high. The controllable wind speed range is between 0.2 m/s - 65 m/s. All wind tunnel tests were conducted in smooth flow. The maximum level of turbulence inherent in smooth flow in the wind tunnel is below 0.5%.

1.4.2.2. Wind Tunnel Models

A rigid model of the bridge deck was designed and constructed in high-modulus carbon-fibre at a scale of 1:65, based on drawing information supplied by COWI. Further details on model design & construction are provided in Appendix B. The governing criteria for section model design and dynamic rig were as follows:

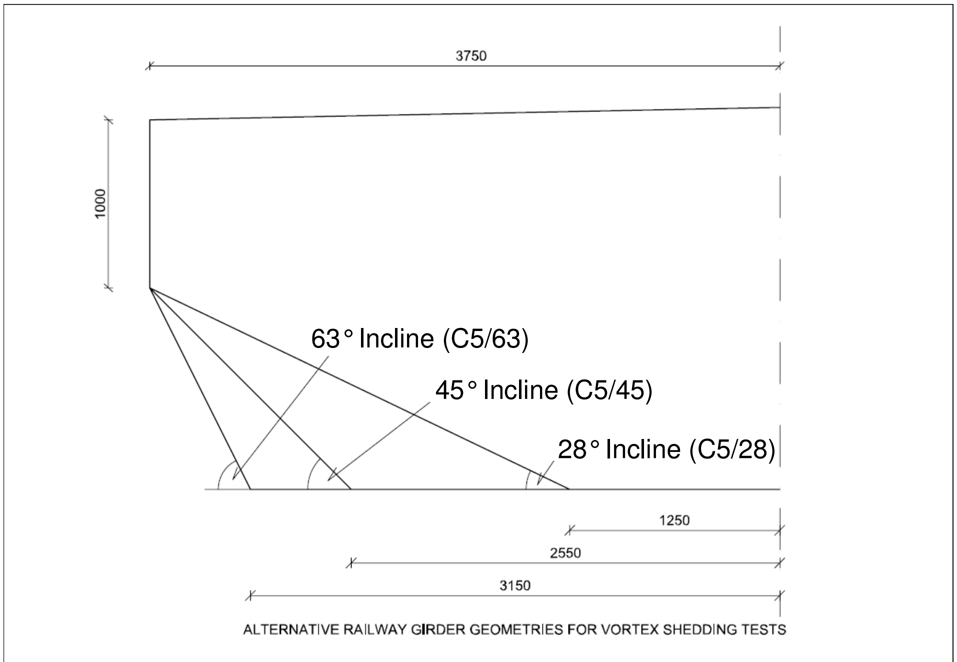
- Geometric representation of all aerodynamically active features at a scale of 1:65
- First bending frequency of the model fully restrained at both ends to be higher than 10 Hz
- Conservation of non-dimensional inertia parameters as defined in Appendix D
- Compatibility between controllable wind speed range of the wind tunnel facility and the full scale design wind speed range in smooth flow

The following photograph shows the wind tunnel model:



1.4.2.3. Model Configurations and Test Matrix

The deck section was tested with 3 configurations of the lower side panel of the rail deck, as illustrated below:



431185 Messina Straits Crossing Deck Cross-Section	BMT Fluid Mechanics	Drawing no.: 431185-FIG-2	Status: Preliminary	By: J Osman Date: 29-Nov-10

A fourth configuration, with a 55% porous mesh between the rail and vehicle decks, for the C5/28 Config was also tested for 1 level of damping.

The test matrix is detailed below:

Static Tests			
Run	**Config**	**Wind Angles [Deg]**	**Reynolds Number**
1	C5/63	0	2.1.E+5 to 2.4.E+6
2	C5/63	-10 to 10 in 1 deg steps	1.8E+06

Dynamic Tests				
Run	**Config**	**Wind Angles [Deg]**	Damping Level [%]	
			Bending	Torsion
3	C5/28	0	0.11	0.11
4	C5/28	0	0.35	0.40
5	C5/28	0	0.21	0.22
6	C5/28	0	0.48	0.48
7	C5/45	0	0.11	0.11
8	C5/45	0	0.35	0.40
9	C5/45	0	0.21	0.22
10	C5/63	0	0.11	0.11
11	C5/63	0	0.21	0.22
12	C5/63	0	0.35	0.40
13	C5/63	0	0.48	0.48
14	C5/63	0	0.11 - 0.48	-
15	C5/63 + Mesh	0	0.11	0.11
16	C5/28	0	0.11 - 0.48	-
17	C5/45	0	0.11 - 0.48	-

2. Dynamic Response

2.1. Details of Measurement

The objective of the tests was to investigate the vortex shedding response of the bridge deck. Dynamic responses were measured in terms of bending and torsion, based on a model scale bending frequency of f_b=6.9Hz and a model scale torsional frequency of f_t=9.0Hz, at a wind angle of 0°, with a level of structural damping varied from 0.1% to 0.5% of critical

Figure 2.1 Shows the wind angle and sign convention

Details of the experimental set-up and instrumentation are included in Appendix D.

2.2. Vortex Shedding Results

The vortex shedding response of the deck was measured for the following four configurations:

C5/28 – Lower side panel of rail deck inclined at 28°

C5/45 – Lower side panel of rail deck inclined at 45°

C5/63 – Lower side panel of rail deck inclined at 63°

An additional run was conducted for the C5/63 Configuration with a 55% porous mesh covering the gaps between decks.

Results show the variation of model scale RMS acceleration against wind speed for all configurations and are presented in graphical format in Figures 2.2 to 2.5.

Torsional accelerations are measured at a point 0.46m from the centreline of the bridge model.

3. Static Wind Loading

3.1. Details of Measurement

Static wind loads were measured in terms of the mean lateral force, mean normal force and pitching moment about the centre of rotation of the deck and are reported as static wind load coefficients in wind axis (C_D, C_L, C_M) defined as follows:

$$C_D = \frac{D}{\frac{1}{2}\rho U^2 B} \qquad C_L = \frac{L}{\frac{1}{2}\rho U^2 B} \qquad C_M = \frac{M}{\frac{1}{2}\rho U^2 B^2}$$

where D, L and M are the wind axis along force, across wind force and pitching moment respectively.

U is the mean wind speed, ρ is the density of air and B is the reference dimension (Full Scale deck width B=60.4m).

Figure 2.1 details the sign convention adopted for the data presentation.

Details of the experimental set-up and instrumentation are included in Appendix C.

3.2. Results

The static load coefficients were measured for the following configuration:

C5/63 – Underside of rail deck inclined at 63°

The static load coefficients were measured for a Reynolds numbers of $1.8x10^6$. The measurements were taken in 1° increments covering an angle range of –10° to 10°.

Results showing the variation of drag, lift and moment coefficients with wind angle in smooth flow are presented in graphical format in Figure 3.1.

In addition, drag coefficients were also plotted against Reynolds Number and are presented in graphical format in Figure 3.2. For the Reynolds Number range explored the variation of C_D with Reynolds Number is negligible.

4. Discussion Of Results

Vortex Shedding

The vortex shedding response of the bridge is observed to occur at multiple windspeeds for each configuration. The baseline case, with an angle of inclination of the underside of the rail deck of 28° sees four vortex shedding peaks: two in bending and two in torsion, which is typical of multiple deck bridges. The effect of increasing this angle to 45° is a reduction in the magnitude of the torsional peaks, and eliminates the second bending peak (occurring at the greater windspeed). The first bending peak is unaffected by this change of angle. Likewise, increasing the angle further to 63° decreases the two torsional peaks further, and again, has no effect on the first bending peak.

It is noted that increasing the level of structural damping in the system reduces the magnitude of each vortex-shedding peak. The first peak of vortex shedding in the vertical bending mode is the most resistant to damping (and unaffected by the angle of the underside of the rail deck), and a level of damping of 0.04% eliminates this.

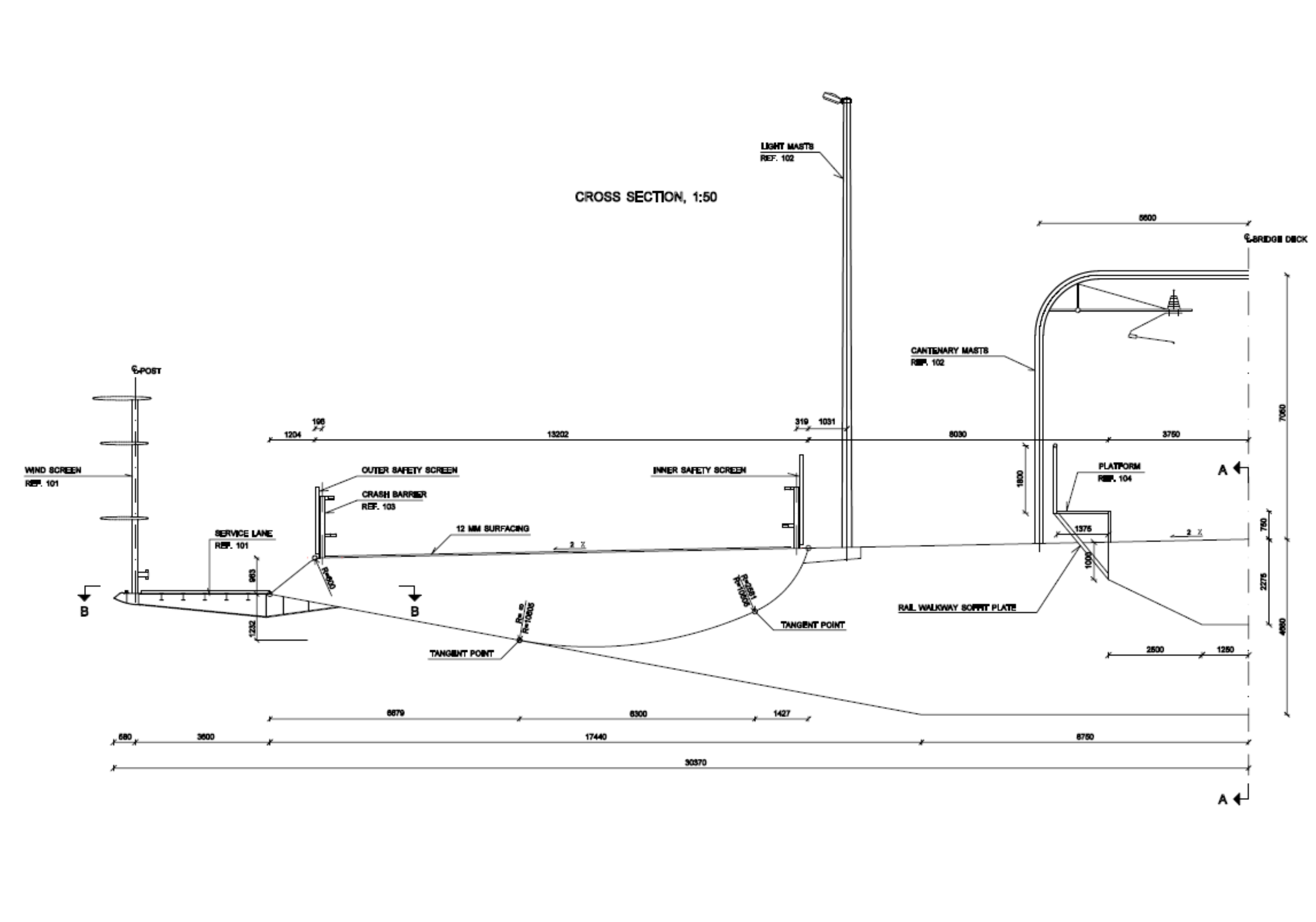
The introduction of a 55% porous mesh, spanning the gaps between the rail deck and each vehicle deck reduced the magnitude of the first two (low speed) vortex-shedding peaks close to half of their original values. The torsional peak, occurring at a higher wind speed was slightly increased in magnitude as a result of the introduction of the mesh. The critical speed for vortex-shedding was unaffected by the mesh.

5. References

[1] Scope of work, Deck wind tunnel tests, Sub-tests D7. ALN0002153.doc

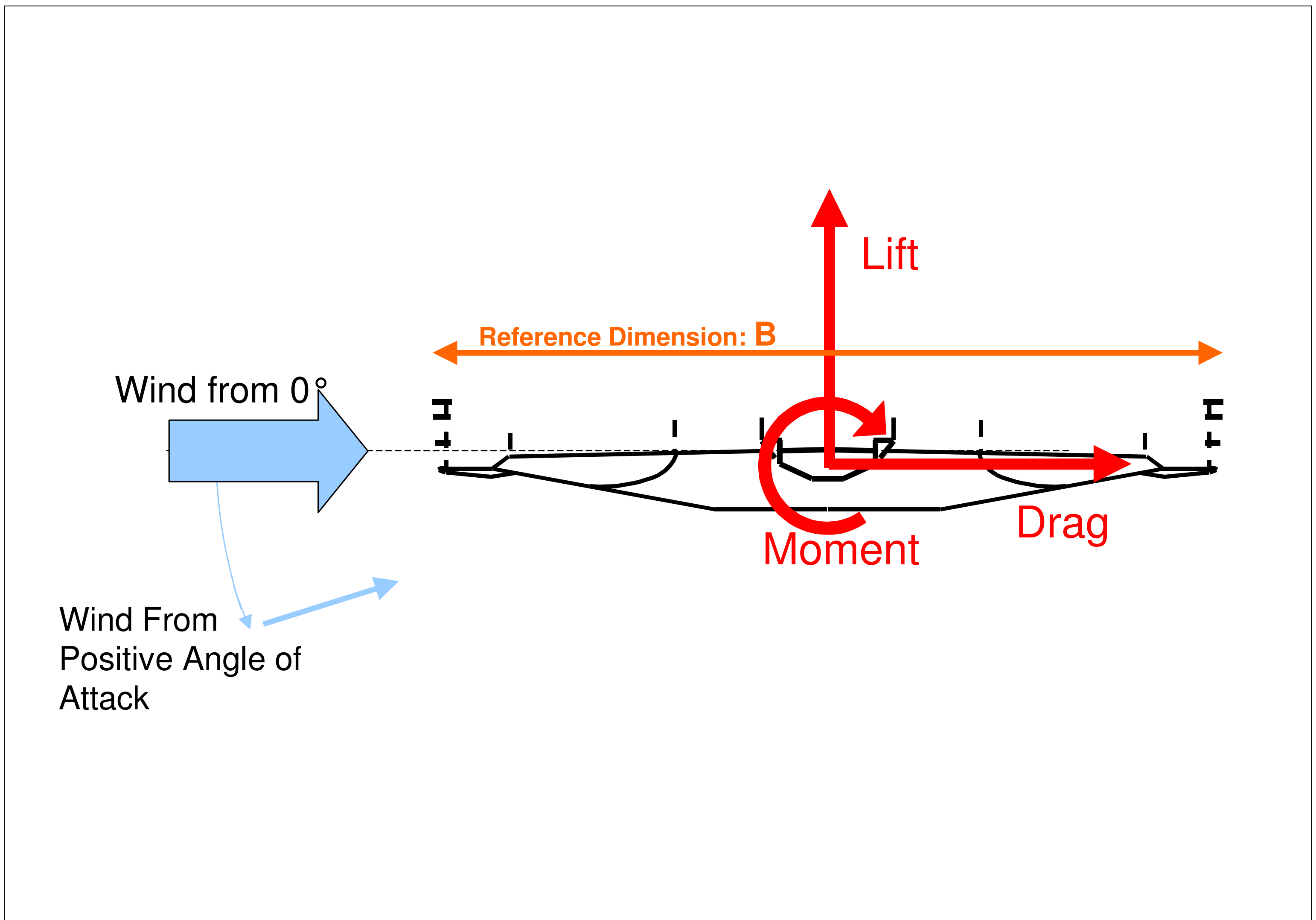
Figures

Figure 1.1: Messina Straits Crossing – Deck Section



431185 Messina Straits Crossing Deck Cross-Section	BMT Fluid Mechanics	Drawing no.: 431185-FIG-2	Status: Preliminary	By: J Osman Date: 26-Nov-10

Figure 2.1 Sign Convention



431185 Messina Straits Crossing Deck Axis System Definition	BMT Fluid Mechanics	Drawing no.: 431185-FIG-1	Status: Preliminary	By: J Osman Date: 29-Nov-10

Figure 2.2 Config C5/28– Variation of MS RMS Acceleration with MS Wind Speed for Various Levels of Damping & Variation of RMS Acceleration with damping at 3ms^{-1}

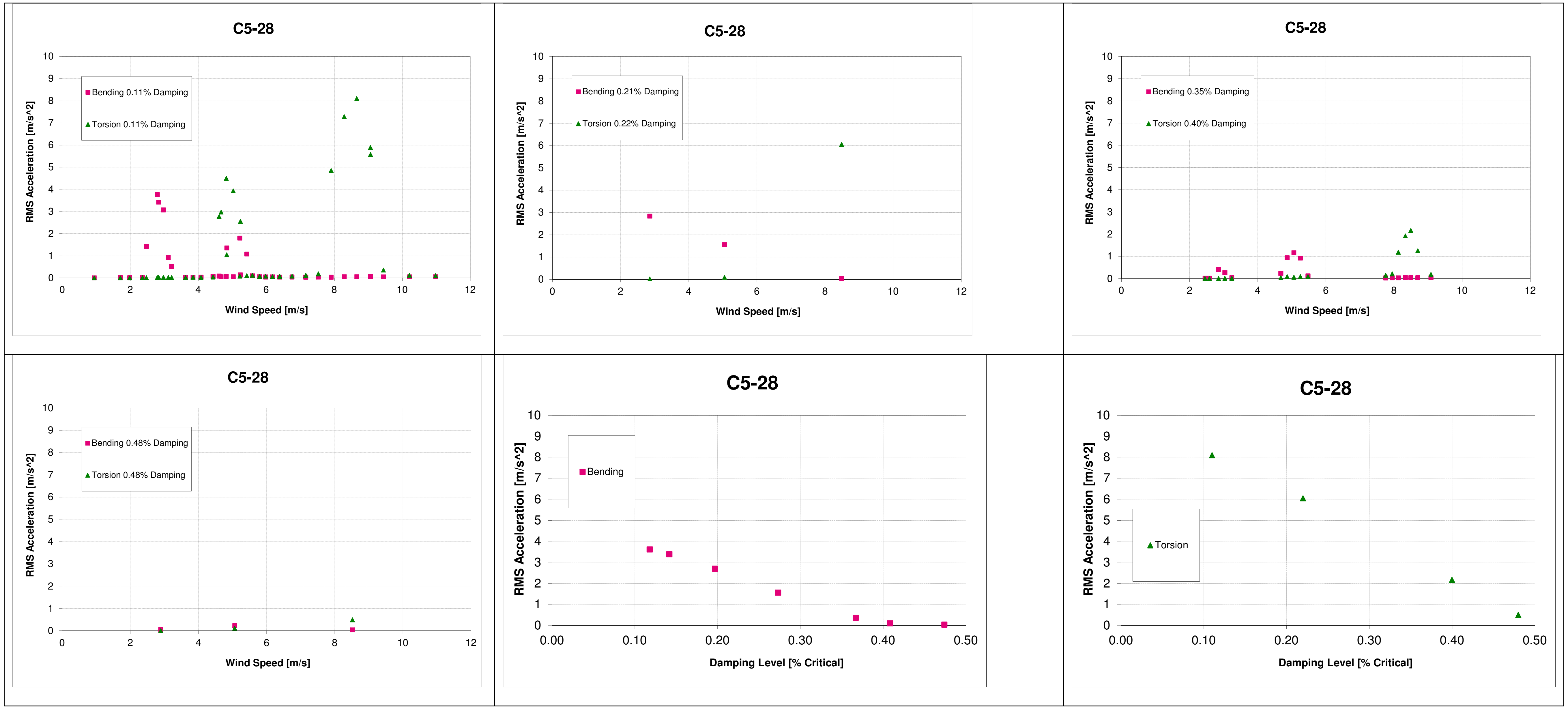


Figure 2.3 Config C5/45– Variation of MS RMS Acceleration with MS Wind Speed for Various Levels of Damping & Variation of RMS Acceleration with damping at 3ms^{-1}

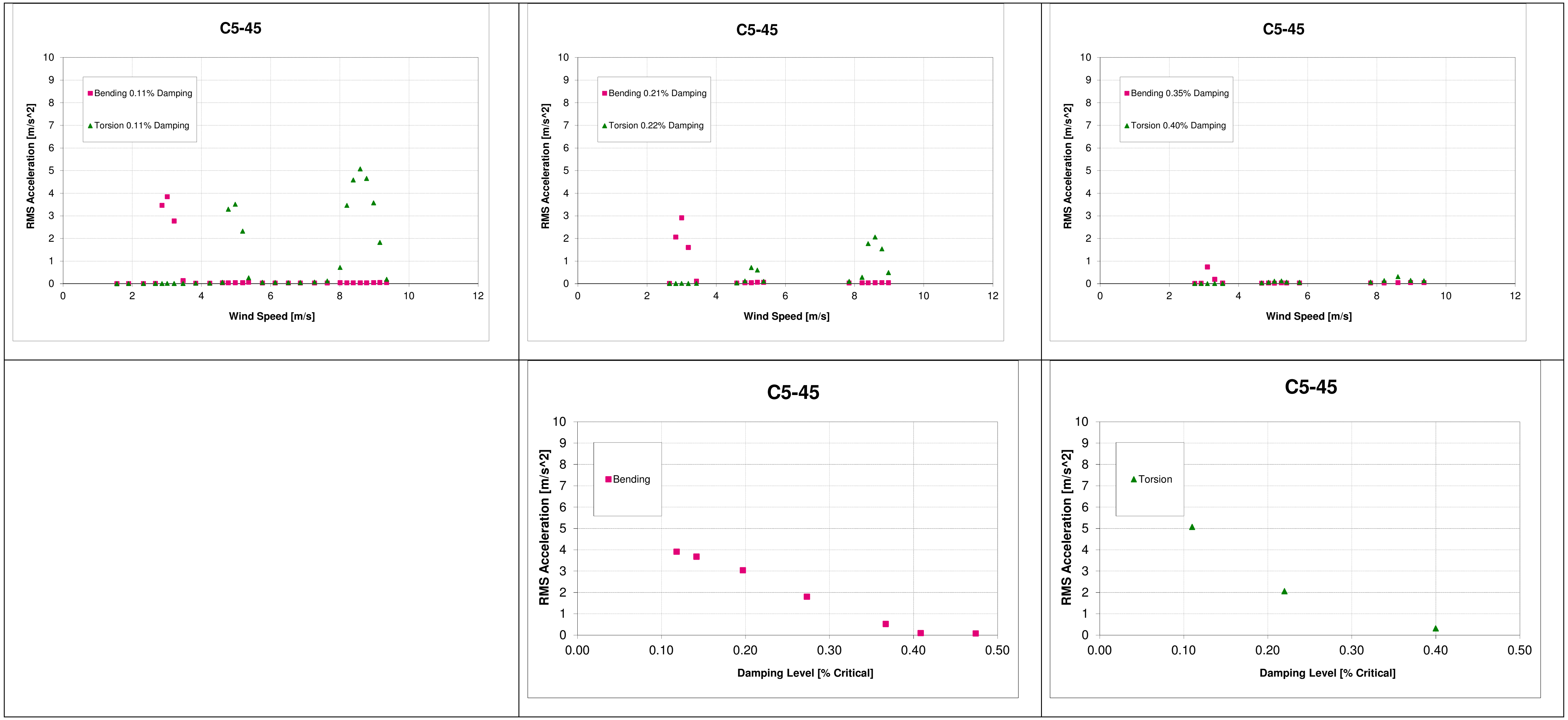


Figure 2.4 Config C5/63– Variation of MS RMS Acceleration with MS Wind Speed for Various Levels of Damping & Variation of RMS Acceleration with damping at 3ms^{-1}

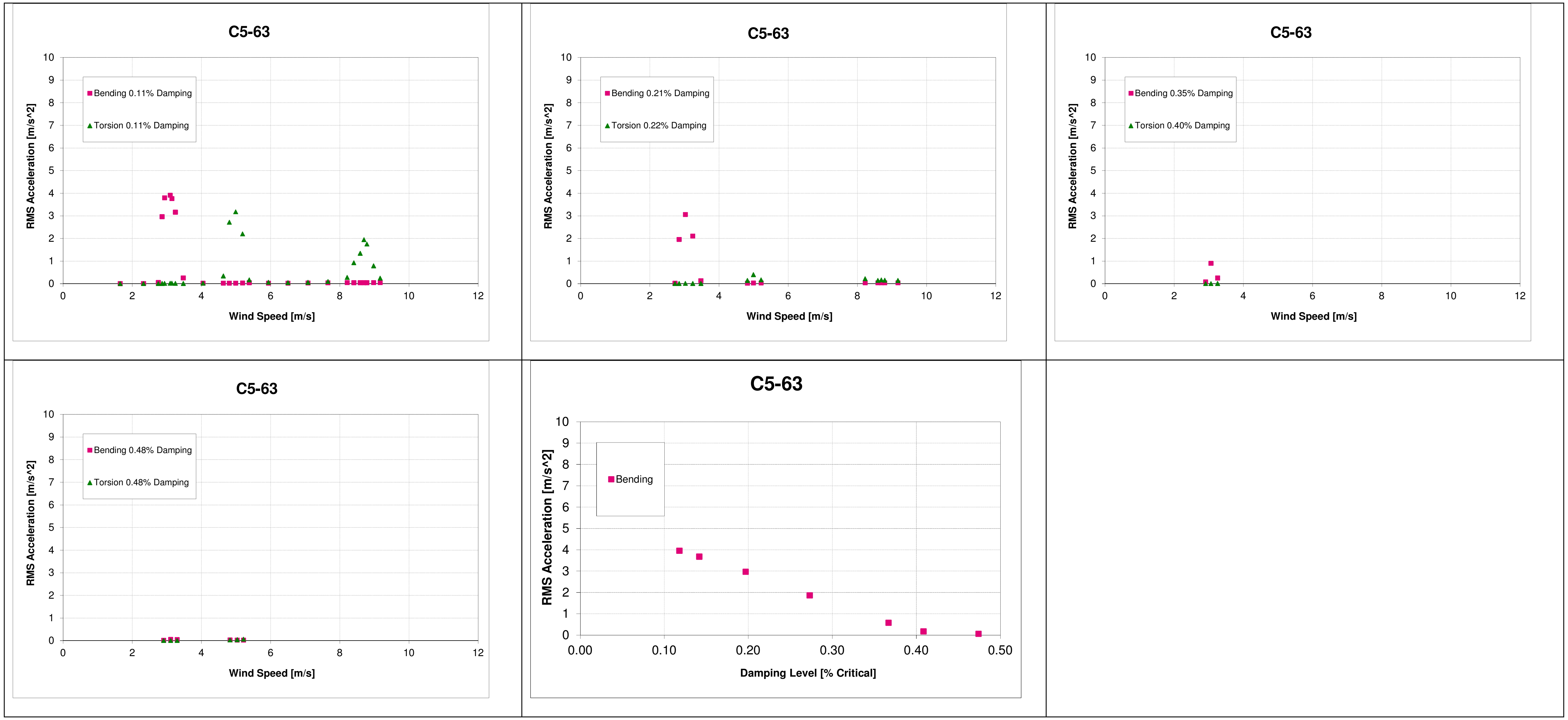


Figure 2.5 Config C5/63 With 55% Porous Mesh Covering the Gaps Between Decks – Variation of MS RMS Acceleration with MS Wind Speed for Damping Level 0f 0.11%

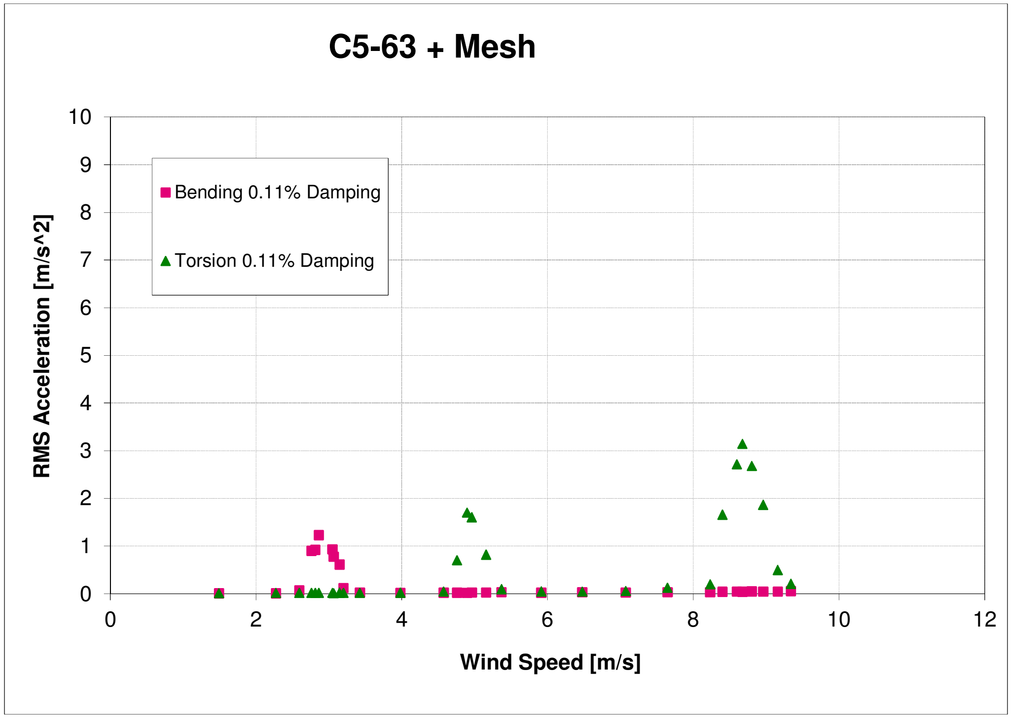


Figure 3.1 Static Wind Loading - Variation of Wind Load Coefficients with Wind Angle

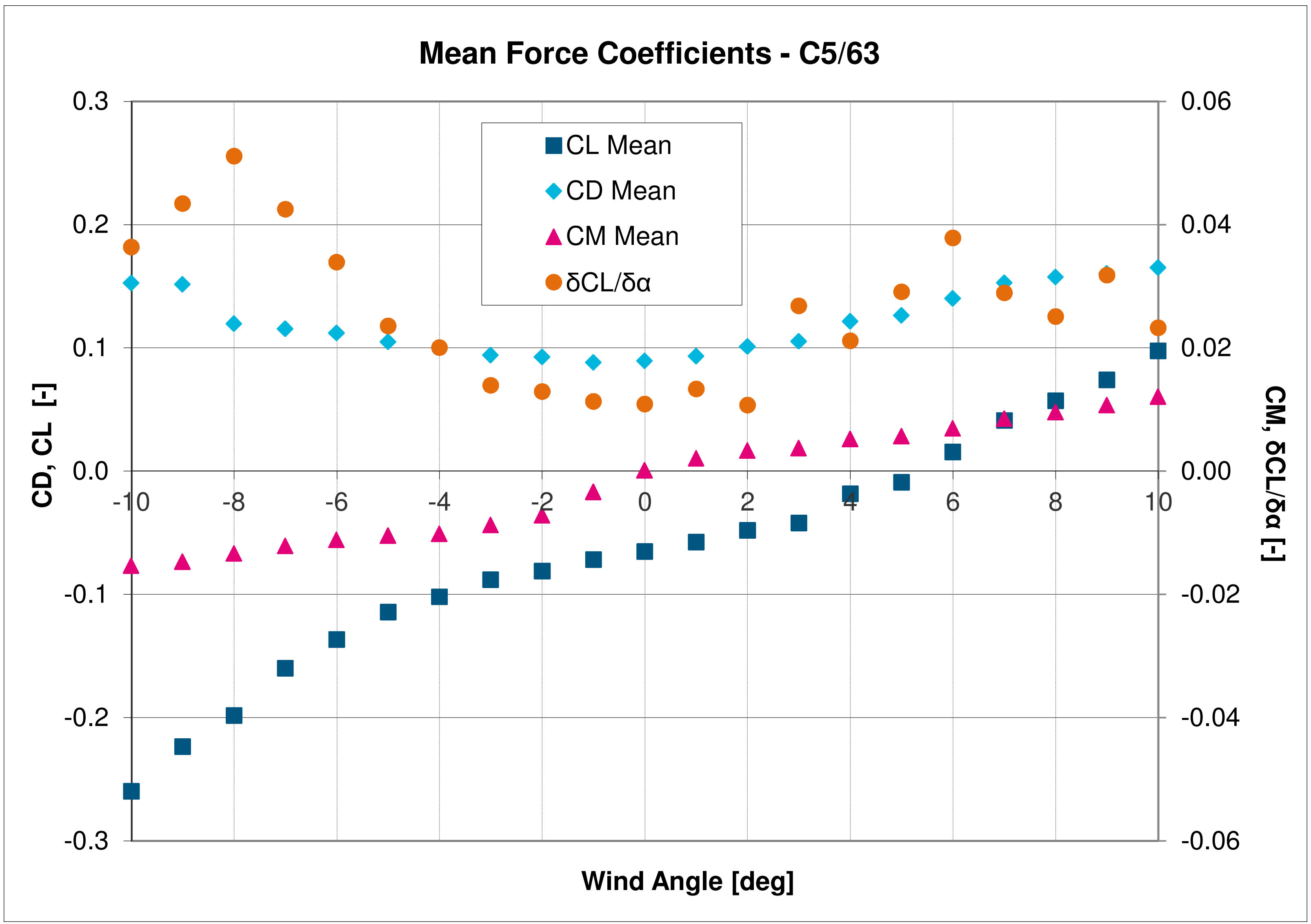
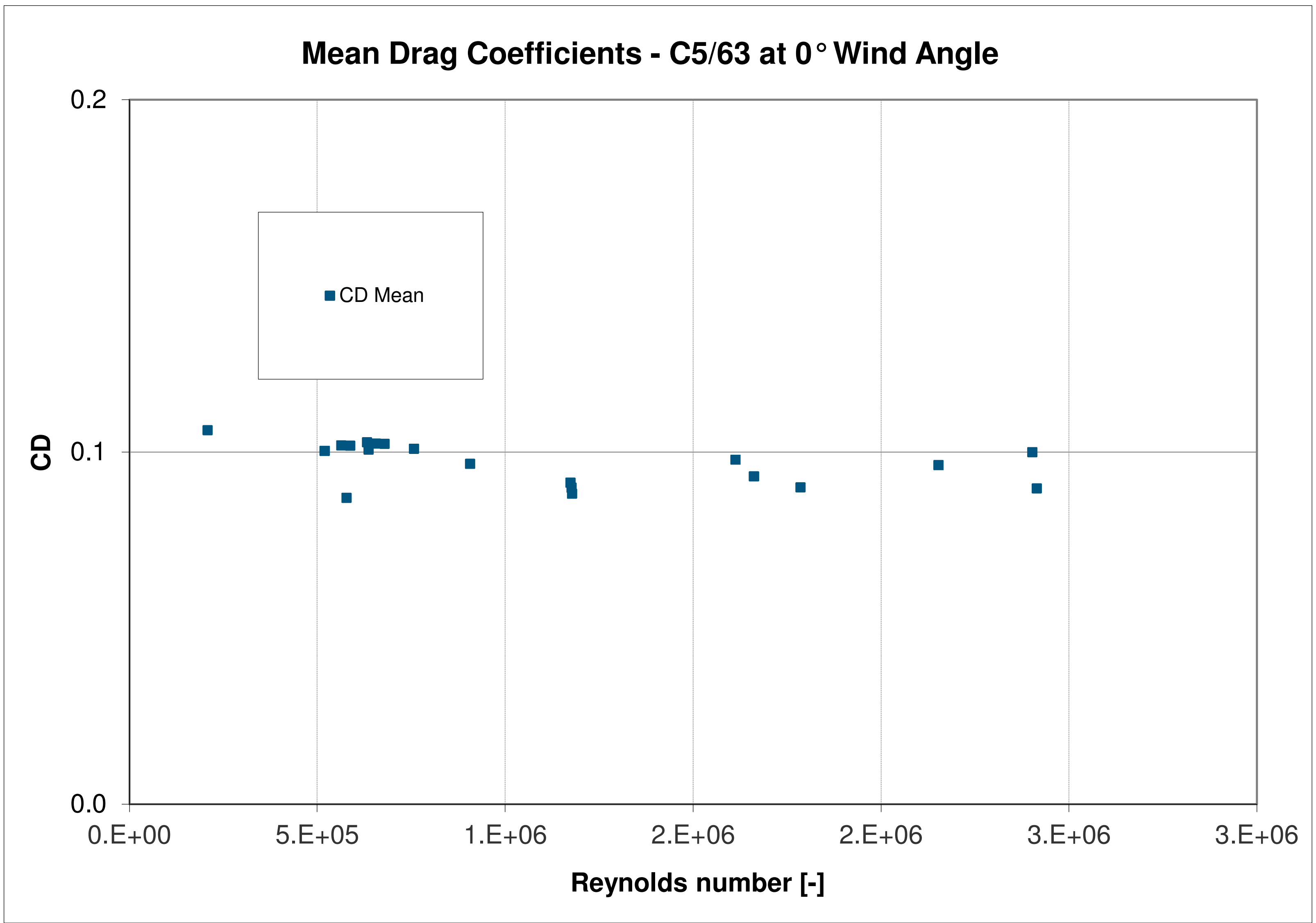


Figure 3.2 Static Wind Loading - Variation of Drag Coefficients with Reynolds Number



APPENDIX A. STRUCTURAL AND DYNAMIC PROPERTIES

A.1. Structural and Dynamic Properties

The following properties were provided by COWI for the purpose of the current study:

Full Scale reference dimension (B)	60.4m
Full Scale first bending frequency (fb)	0.0647Hz
Full Scale first torsional frequency (ft)	0.0806Hz
Full Scale Mass	58100kg/m
Full Scale Torsional Inertia	28930000kgm^2/m

APPENDIX B. MODEL DESIGN AND CONSTRUCTION

B.1. Basis for Design and Construction

The model was designed and constructed based on drawing information of the bridge deck supplied by COWI. Table B.1 summarises the drawings used for the models design and construction.

Table B.1: Drawing Information

Drawing Name/No.	Date Received
100-03.dwg	17th September 2010
101-02.dwg	17th September 2010
102-01.dwg	17th September 2010
103-02.dwg	17th September 2010
104-03.dwg	17th September 2010
106-01.dwg	17th September 2010

B.2. Models Design and Construction

The section model, as designed, was suitable for dynamic wind tunnel testing.

The model was constructed at a linear model scale of 1:65. At this scale the model allows detailed representation of all geometric features of the bridge deck that are expected to affect the wind flows around the bridge at full scale.

In order to achieve the model scale target mass and frequency/stiffness, a carbon fibre construction was adopted. In particular the carbon fibre material was specifically chosen to have the highest Young's Modulus in order to ensure that the frequency of the model was in excess of 10Hz, as specified by COWI. The first bending natural frequency of the model fully restrained at both ends was measured to be 23.5Hz.

The following items were designed in built in aluminium and hard plastic:

- Pedestrian/cycle deck
- Wind Shields
- Vehicle Crash Barriers
- Rail Deck Parapets

The mesh was designed and built to have a pressure loss coefficient equal to 2.7 as specified in the testing brief. Section B.2.1 shows the results of the pressure loss coefficient measurements for the mesh, which were reviewed and approved by COWI prior to testing.

Photographs of the wind tunnel model are as follows:

- Figures B.1 to B.3 show a general view of the model in the wind tunnel.
- Figures B.4 to B.6 show the detail of the varying angle of inclination of the underside of the rail deck.

Figure B.1: Wind Tunnel Model – General View

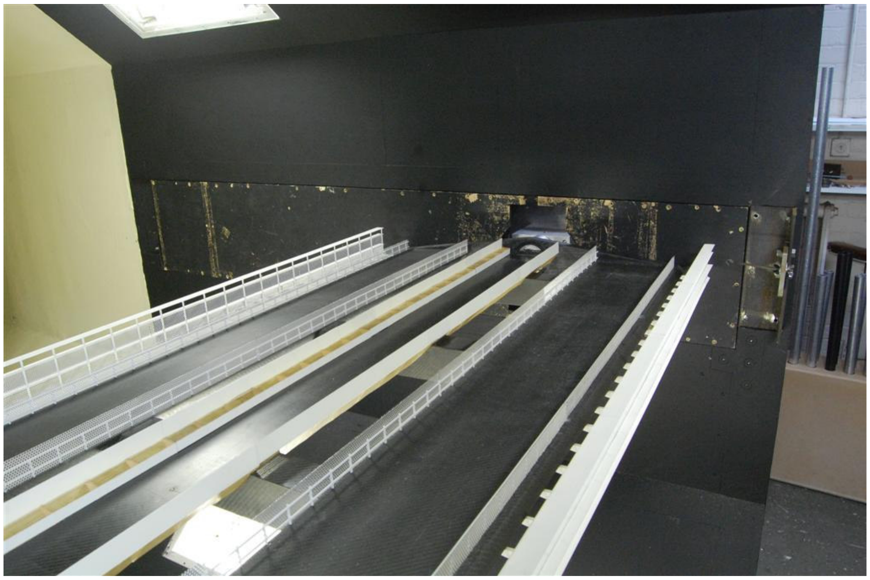


Figure B.2: Wind Tunnel Model – Close up View of the Wind Barriers

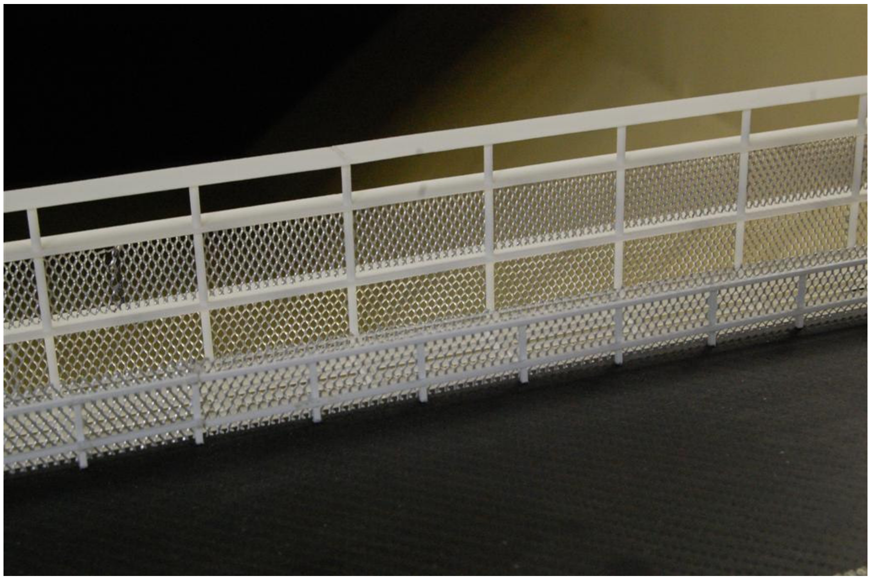


Figure B.3: Wind Tunnel Model - Close-Up View of Underside of Model C5/28

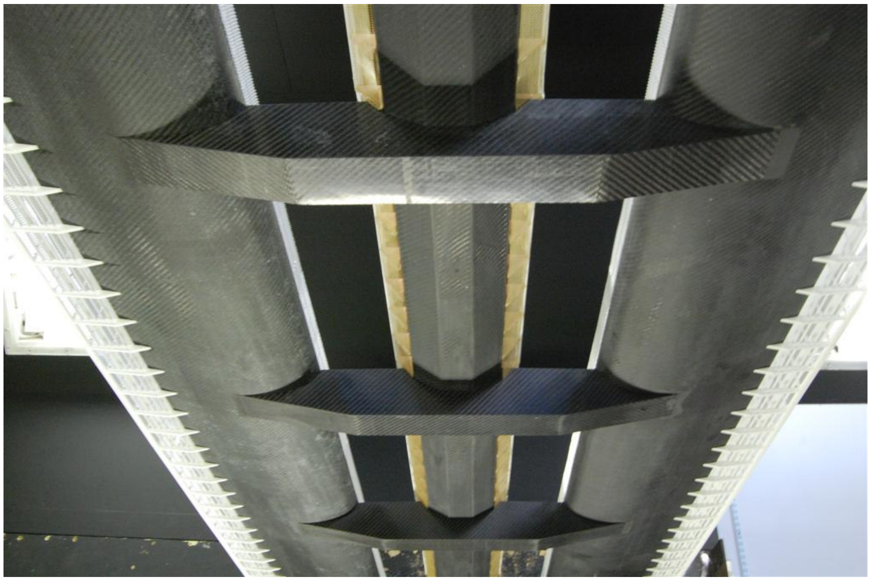
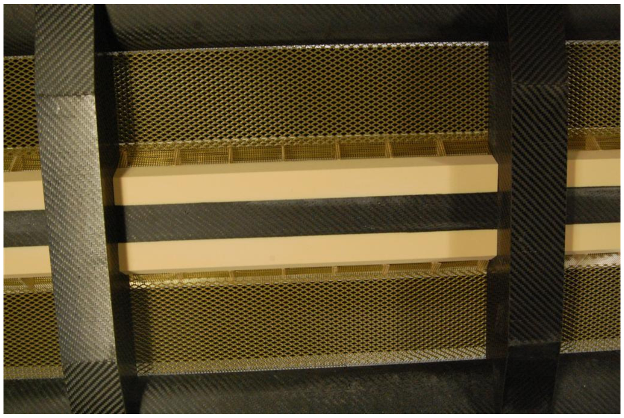


Figure B.4: Wind Tunnel Model - Close-Up View of Underside of Model C5/45

Figure B.5: Wind Tunnel Model - Close-Up View of Underside of Model C5/63

Figure B.6: Wind Tunnel Model - Close-Up View of Underside of Model C5/63 with mesh added



B.2.1. Pressure Drop Coefficient Data

The pressure loss coefficient of the semi-porous wind barriers and crash barriers was specified by COWI to have a value of 2.7, with a 5% error margin. The pressure loss coefficient, *K* is defined as:

$$K = \frac{p_{Upstream} - p_{Downstream}}{\frac{1}{2}\rho V^2}$$

Where:

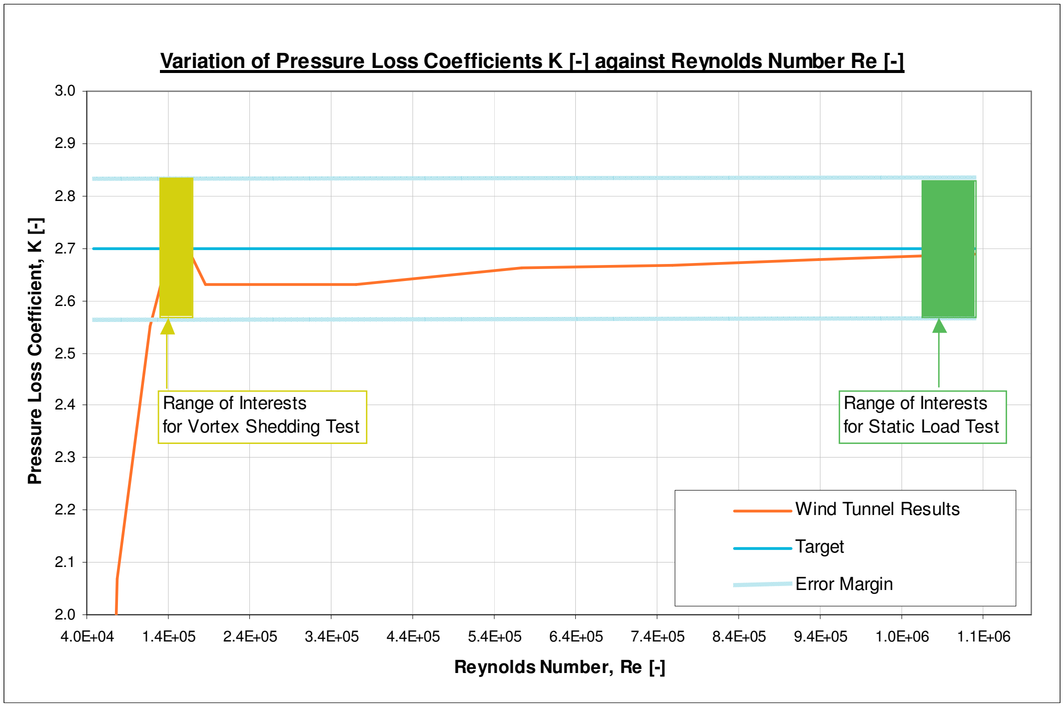
$P_{Upstream}$ = Upstream Pressure [Pa]

$P_{Downstream}$ = Downstream Pressure [Pa]

ρ = Density of Air [kgm^{-3}]

V = Upstream Velocity [ms^{-1}]

The results of wind tunnel tests of a sample of the mesh used in the modelling of these components are displayed below and show that the criteria are satisfied for the Reynolds number ranges of interest.



B.3. Model Approval

The wind tunnel models were reviewed and approved by COWI prior to testing.

APPENDIX C. STATIC WIND LOADING STUDIES

C.1. Model Mounting & Instrumentation

For measurement of the static wind load coefficients the model was mounted across the 2.74 m width of the wind tunnel on a force balance rig.

The force balance rig consists of a pair of 3-component strain-gauged force transducers placed on either side of the wind tunnel test section and on which the wind tunnel model is accurately rigged via precision-machined fittings. The model is rotated through the test wind angles on the balances so that the wind loads are measured directly in model axes.

Load balance checks were carried out prior to the experiments over the expected range of forces and moments coefficients. Further checks including repeatability checks, showing agreement on forces and moments, and symmetry checks.

APPENDIX D. DYNAMIC RESPONSE STUDIES

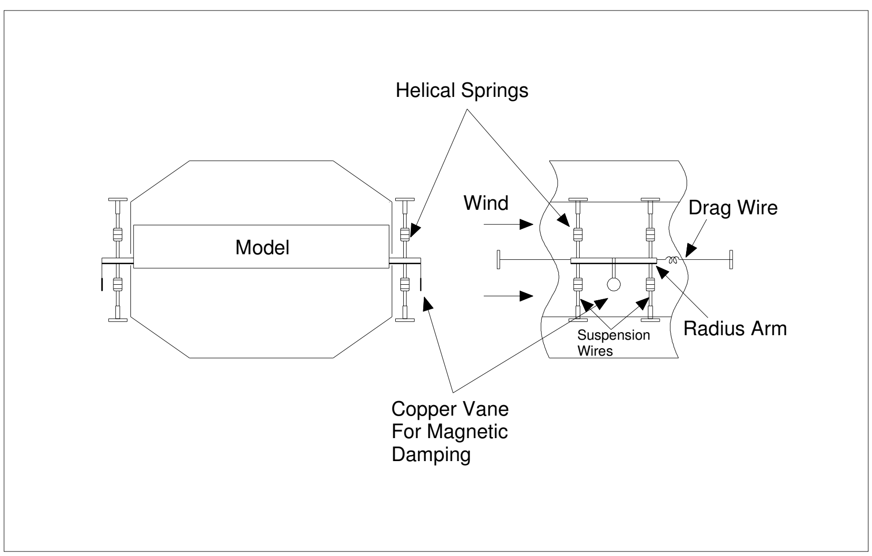
D.1. Model Mounting & Instrumentation

D.1.1. Dynamic Rig

For the dynamic response tests the models were mounted across the 2.74 m width of the wind tunnel on a dynamic rig consisting of a system of springs allowing 2 degrees of freedom (vertical bending and torsional motion). The models were restrained from moving in the other directions by a combination of light steel wires.

The layout of the dynamic rig for this configuration is shown in Figure D.1 below.

Figure D.1: Layout of the Dynamic Rig



For dynamic response measurements, the test rig was instrumented with four small accelerometers one mounted at either end of each suspension arm external to the wind tunnel and positioned to resolve the vertical bending and rotational motion through the sum and the difference of the signals digitised simultaneously. A further two accelerometers were placed at the centre of one of the rig arms and the centre of the deck model, in order to monitor the stiffness of the setup. From the acceleration time histories the amplitude response of the models was determined.

D.2. Experimental Conditioning

D.2.1. Scaling Requirements

For the dynamic rig tests it was required to reproduce the full-scale behaviour of the bridge deck by imposing the correct structural properties on the wind tunnel models subject to scaling laws detailed below.

For dynamic similarity, equality of the following non-dimension parameters is required between model-scale and full-scale:

$$i)\ \frac{I_z}{\rho B^2} \qquad ii)\ \frac{I_\vartheta}{\rho B^4}$$

$$iii)\ \frac{U}{f_b B} \qquad iv)\ \frac{U}{f_t B}$$

$$v)\ \delta_z \qquad vi)\ \delta_\vartheta$$

Where:

I_z is the mass per unit length of the bridge deck

I_ϑ is the mass moment of inertia of the bridge deck

B is the reference dimension taken as the bridge deck width

ρ is the density of air

U is the mean hourly wind speed

f_b is the bending natural frequency

f_t is the torsional natural frequency

δ_z is the logarithmic decrement of the structural damping corresponding to the bending frequency

δ_{ϑ} is the logarithmic decrement of the structural damping corresponding to the torsional frequency

The combined structural and inertial parameters for single degree of freedom sinusoidal motions are as follows:

$$vii)\frac{I_z\delta_z}{\rho B^2} \qquad viii)\frac{I_{\vartheta}\delta_{\vartheta}}{\rho B^4}$$

A departure from the correct frequency ratio can be obtained for single degree of freedom motions providing different values of U and hence different wind speed scales for vertical bending and torsional motion.

With the above parameters correctly modelled, values of U/fB obtained from wind tunnel measurements will be directly applicable to full scale. The responses measured in the wind tunnel can be related via the model scale.

D.2.2. Dynamic Response

Table D.1 contains target and achieved values of non-dimensional inertia for the dynamic tests. The target parameters were based on the full-scale data supplied by COWI.

Table D.1 Target & Achieved Non-Dimensional Quantities

Target Values			Achieved Values		
$\frac{I_z}{\rho B^2}$	$\frac{I_\theta}{\rho B^4}$	$\frac{f_b}{f_t}$	$\frac{I_z}{\rho B^2}$	$\frac{I_\theta}{\rho B^4}$	$\frac{f_b}{f_t}$
13.00	1.77	1.25	15.39	1.76	1.30

Table D.2 Achieved Model Scale Frequencies

	Bending	Torsion
Model Scale Frequency [Hz]:	6.9	9.0

D.3. Model Calibration

The model dynamic properties in terms of natural bending and torsional frequencies and structural damping were measured prior to each set of tests.

The dynamic properties of the models were measured by resonating the models in a natural mode via the deck using a vibrator through a light spring or by hand.

The bending and torsional frequencies were measured by oscillating the models at constant amplitude.

The structural damping associated with the rig system was measured in amplitude decay tests.

D.4. Damping Devices

Controlled additional damping to simulate the effect of a damping device was also provided for the vortex-shedding tests. A copper vane was supported from the arms of the rig, between the poles of an electromagnet. The current generated in the copper vane interacts electromagnetically to provide additional damping. By varying the current feeding the electromagnet, different levels of damping can be obtained.

APPENDIX E. FULL SET OF RESULTS

The main results of the studies are provided in a series of Excel spread sheet tables and plots attached:

431185 Messina Deck Dynamic Section Results.xls

431185 Messina Deck Static Section Results.xls