

CFD aerodynamic assessment of deck alternatives for a cable-stayed bridge

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ABSTRACT: The present document reports the CFD analyses carried out for a set of four different deck cross-sections considered at the preliminary design of the Forth Replacement Crossing: a single box girder with and without wind shields and a twin box girder with and without wind shields. In order to assess the aerodynamic performance of these alternative designs the force coefficients, the shelter provided by the wind shields and the low-speed vortex shedding response of the static deck have been computed. The results obtained are compared with experimental data available in the literature for similar cross-sections finding a good general agreement. It can be concluded that CFD can provide designers with valuable qualitative information at an early design stage for the set of alternative designs considered.

KEYWORDS: CFD, force coefficients, wind shields, vortex shedding, cable-stayed bridges.

1 INTRODUCTION

Focusing on the wind action response, at the early design stage of long span bridges several alternatives for the deck are usually considered. The expected aerodynamic and aeroelastic response must be assessed in order to choose the most feasible alternative for each specific project. Usually engineers rely on previous experiences with similar cross-sections and only in the most challenging projects it is possible to test in the wind tunnel some of the considered preliminary designs. On the other hand, the use of computer-based aerodynamic analysis in real cases is scarce in spite of the growing number of applications in recent times [1, 2].

The aim of the present work is to employ CFD tools to assess the aerodynamic response of two deck types considered at the early design stage of the Forth Replacement Crossing. In order to recreate the constraints in the real design process, where the available resources are limited, 2D models with a limited size are employed. In the absence of published experimental data of the considered cross-sections the results are partially validated using experimental results of similar decks available in the literature. It must be remarked that this application aims to qualitatively evaluate the aerodynamic response of the set of cross-sections and to identify potential problems to focus on in a comprehensive wind tunnel campaign of a candidate design. It is out of discussion the requirement of extensive experimental campaigns to ascertain the performance of any bridge final design. Finally, it is worth recalling that the alternative selected by Transport Scotland for the final design of the Forth Replacement Crossing was the single box girder with wind shields [3].

2 ANALYSIS STRATEGY

2.1 Deck types

Two different deck types, from the ones considered for the Forth Replacement Crossing two corridor functional cross section, have been chosen as the specimens for this study: namely, single

box girder (SBG) and twin box girder (TWBG). The data required for the geometric definition of the cross sections of the aforementioned deck types have been obtained from published documents [4, 5] while the geometric definition of the 50% porosity wind shields has been obtained from Ozkan et al. [6].

In the forthcoming sections the results obtained computationally for the two different deck types, with and without wind shields (WS standing for wind shields and BD standing for bare deck respectively), are going to be presented. This means that a benchmark of four different configurations will be analysed. In figure 1 the geometric definition of the cross sections studied suited with wind shields can be inspected (dimensions in m at real scale). It can be remarked that the purpose of the simulations has been to reproduce numerically the real sectional model wind tunnel tests at a 1:80 geometric scale.

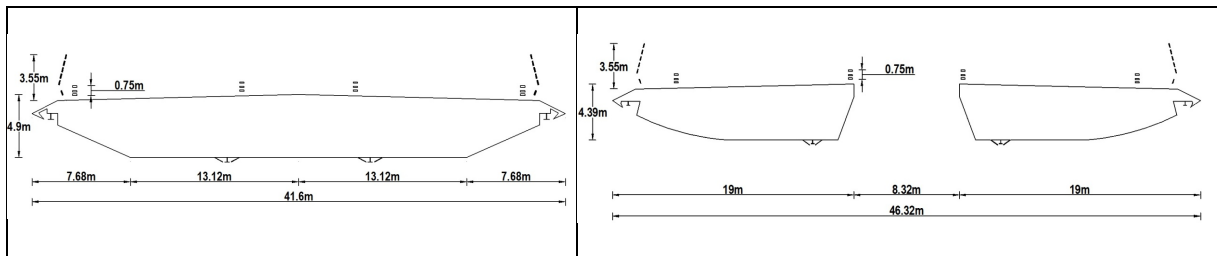


Figure 1. Geometry of the deck types

2.2 Aerodynamic assessment approach

The first step to ascertain the aerodynamic response of the set of considered deck types has been the computation of the force coefficients.

$$C_d = \frac{D}{\frac{1}{2}\rho U^2 B}; \quad C_l = \frac{L}{\frac{1}{2}\rho U^2 B}; \quad C_m = \frac{M}{\frac{1}{2}\rho U^2 B^2} \quad (1)$$

In fact, force coefficients play a very significant role because to avoid one degree of freedom instability the first derivative of lift and moment coefficients must be positive according to the criteria of figure 2; additionally, the greater the value of those derivatives is the lower the flutter critical wind speed of the structure is [7, 8]. Moreover, the force coefficients allow the quantification of the effect caused by the wind shields in the overall aerodynamic performance of each particular cross-section, for instance in the increase of the drag coefficient or the changes in the slope of the lift and moment coefficients.

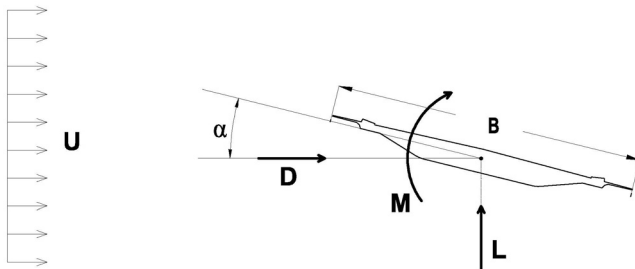


Figure 2. Sign criteria for the force coefficients

Besides this, the computer simulations also allow the evaluation of the level of shelter created by the wind shields in the vehicles' circulation zone on the deck.

Another critical issue to be addressed in the conceptual design stage of a cable supported bridge is the risk of low-speed vortex shedding excitation. In this study a number of flow velocities are considered in the unsteady simulations carried out, and the effect of the wind shields in the oscillatory lift forces suffered by the deck has been analysed.

In this work the CFD simulations for the single box girder are in the Reynolds number range ($4.33\text{e}+04$, $5.3\text{e}+05$) based on the girder width, while for the twin box girder deck the Reynolds number based on the one box chord length is in the range ($1.19\text{e}+04$, $2.37\text{e}+05$). It has been assumed that the deck is static throughout the simulations.

3 COMPUTATIONAL MODELLING

The flow around the deck has been computed using the incompressible, unsteady Reynolds averaged Navier-Stokes equations in 2D and the $k-\omega$ SST turbulence model has been chosen. Dirichlet conditions are imposed at the inlet and outlet while no-slip boundary condition has been imposed at the deck surface and the upper and lower limits of the fluid domain as the purpose of the simulations is to reproduce real sectional wind tunnel tests. The corners are modelled as perfectly sharp. The turbulent intensity prescribed at the inlet is 1.1% while the turbulent length scale is about 0.1 times the width of the single box girder design [9]. The flow domain considered in this work is $26.9B$ by $3.8B$ (being B the single box girder width), similar to existing wind tunnel facilities.

A commercial finite volume solver has been used to numerically evaluate the flow field. A quadrilateral mesh using the map scheme near walls, and pave scheme in the main part of the flow domain, was utilised. As the target of this study is the preliminary analysis of a set of tentative designs it has been intended to avoid high density meshes. Additionally it has been intended to employ only one mesh for each deck type with similar temporal and spatial discretization, thus the boundary layer grid resolution has been a compromise between the requirements associated to each Reynolds number. As a consequence the ratio of the height of the first grid layer attached to the deck and the single girder width is $\delta_1/B=5.8\text{e}-5$ for all the cases analyzed, which is close to the value prescribed by Ribeiro [10] and one order of magnitude higher than the values adopted by Mannini and co-workers [11] and Fransos and Bruno [12]. In tables 1 and 2 the time averaged values of $y^+ = \delta_1 u_\tau / \nu$ (y^+) averaged along the boxes, the traffic barriers and the windward wind shield are presented along with the time averaged maximum value of y^+ ($y^+_{\max}$) for the same parts of the deck.

Table 1. Single box girder grids y^+ characteristics

	SBG_BARE			SBG_WS		
	$Re=4.3\text{e}+4$	$Re=1.0\text{e}+5$	$Re=5.2\text{e}+5$	$Re=4.3\text{e}+4$	$Re=1.0\text{e}+5$	$Re=5.2\text{e}+5$
y^+ box	0.05	0.11	0.49	0.07	0.10	0.41
$y^+_{\max}$ box	0.30	0.60	2.81	0.56	0.88	2.92
y^+ traffic barriers	0.14	0.28	0.85	0.11	0.19	0.67
$y^+_{\max}$ traffic barriers	0.64	1.20	3.44	0.61	1.22	3.25
y^+ windward WS				0.24	0.49	1.54
$y^+_{\max}$ windward WS				0.73	1.47	3.95

Table 2. Twin box girder girders y^+ characteristics

	TWBG_BARE			TWBG_WS		
	$Re=1.2e+4$	$Re=4.7e+4$	$Re=2.4e+5$	$Re=1.2e+4$	$Re=4.7e+4$	$Re=2.4e+5$
y^+ windward box	0.05	0.14	0.62	0.05	0.13	0.57
$y_{\max}^+$ windward box	0.22	0.70	2.52	0.23	0.80	2.50
y^+ leeward box	0.05	0.14	0.48	0.03	0.08	0.25
$y_{\max}^+$ leeward box	0.27	0.78	2.57	0.19	0.62	1.77
y^+ traffic barrier	0.12	0.33	1.04	0.08	0.19	0.57
$y_{\max}^+$ traffic barrier	0.43	1.18	3.43	0.41	1.17	3.32
y^+ windward WS				0.17	0.49	1.61
$y_{\max}^+$ windward WS				0.55	1.51	4.13

4 GRID AND TIME-STEP REFINEMENT

As a first step in the verification of the numerical simulations a grid and time-step refinement study has been carried at $Re=5.3e5$ and 0° angle of attack for both single box girder arrangements and at $Re=2.4e5$ for the twin box girder with and without wind shields, in order to analyze the changes in several variables.

Regarding the spatial discretization study, in tables 3 to 6 the main characteristics of the set of grids considered are presented along with the results obtained for the mean force coefficients (C_d , C_l and C_m) and the standard deviation of the fluctuating force coefficients (C'_d , C'_l and C'_m). The number of cells is increased by a factor of 1.5 while the characteristics of the structured layer attached to the deck, described in the previous section, are the same in all the cases.

Table 3. Grid refinement study of the single box girder without wind shields

Mesh	total cells	total nodes	δ_1/B	Incr s	C_d	C_l	C_m	C'_d	C'_l	C'_m
coarse	173396	175396	5.8E-05	2.88E-03	0.069	-0.071	0.018	0.0008	0.0005	0.00004
medium	257717	262242	5.8E-05	2.88E-03	0.069	-0.073	0.017	0.0012	0.0114	0.0025
fine	378123	381099	5.8E-05	2.88E-03	0.069	-0.087	0.016	0.0018	0.0010	0.0002

Table 4. Grid refinement study of the single box girder with wind shields

Mesh	total cells	total nodes	δ_1/B	Incr s	C_d	C_l	C_m	C'_d	C'_l	C'_m
coarse	219414	222275	5.8E-05	2.88E-03	0.143	-0.223	-0.013	0.0049	0.0126	0.0026
medium	349250	352322	5.8E-05	2.88E-03	0.142	-0.223	-0.013	0.0058	0.0158	0.0034
fine	511717	514949	5.8E-05	2.88E-03	0.145	-0.227	-0.011	0.0060	0.0169	0.0037

Table 5. Grid refinement study of the twin box girder without wind shields

Mesh	total cells	total nodes	δ_1/B	Incr s	St	C_d	C_l	C_m	C'_d	C'_l	C'_m
coarse	171705	174350	5.8E-05	2.53E-03	0.149	0.136	-0.140	0.033	0.0327	0.2677	0.0200
medium	255248	258626	5.8E-05	2.53E-03	0.151	0.140	-0.131	0.030	0.0318	0.2815	0.0231
fine	384587	387368	5.8E-05	2.53E-03	0.149	0.132	-0.134	0.031	0.0340	0.2385	0.0267

Table 6. Grid refinement study of the twin box girder with wind shields

Mesh	total cells	total nodes	δ_1/B	Incr s	C_d	C_l	C_m	C'_d	C'_l	C'_m
coarse	230611	233501	5.8E-05	2.53E-03	0.130	-0.087	0.026	0.0064	0.0222	0.0061
medium	345674	348613	5.8E-05	2.53E-03	0.132	-0.084	0.027	0.0063	0.0230	0.0063
fine	508476	511641	5.8E-05	2.53E-03	0.132	-0.081	0.028	0.0064	0.0288	0.0073

From the results presented in the tables above it can be concluded that there are not substantial differences in the mean values of the force coefficients obtained with the medium and fine grids for the single box girder with wind shields, and the twin box girder deck with and without wind shields. Therefore the medium mesh will be used in the simulations hereafter. It is worth remarking that for the single box girder without wind shields there is a non-negligible difference in the value computed for the mean lift coefficient as a 20% discrepancy exists between the medium and fine mesh results, furthermore the standard deviation of both lift and moment coefficients is about one order of magnitude lower when the fine grid is adopted. Further studies are required to set an accurate spatial discretization for the single box girder case without wind shields, nevertheless at the present stage of the investigation it has been decided to adopt the medium mesh to keep coherency with the other cases studied, in the understanding that the level of accuracy can be compatible with the purpose of this work, which is the preliminary assessment of a set of alternative designs. The twin box girder without wind shields shows a strong vortex shedding; thus the Strouhal number (St) has been included in table 5 for comparison.

For the ascertaining of the time step adequacy, the mean values and standard deviation of the force coefficients are computed using the medium grid, considering two different non-dimensional time steps: 2.88e-03 and 1.44e-03, for the single box girder cases, and 2.53e-03 and 1.23e-03 for the twin box girder cases. The results are presented in tables 7 to 10.

Table 7. Time step refinement study of the the single box girder without wind shields

Mesh	δ_1/B	Incr s	C_d	C_l	C_m	C'_d	C'_l	C'_m
medium	5.80E-05	2.88E-03	0.069	-0.073	0.017	0.0012	0.0114	0.0025
medium	5.80E-05	1.44E-03	0.069	-0.069	0.017	0.0017	0.0117	0.0024

Table 8. Time step refinement study of the the single box girder with wind shields

Mesh	δ_1/B	Incr s	C_d	C_l	C_m	C'_d	C'_l	C'_m
medium	5.80E-05	2.88E-03	0.142	-0.223	-0.013	0.0058	0.0158	0.0034
medium	5.80E-05	1.44E-03	0.144	-0.224	-0.009	0.0055	0.0136	0.0030

Table 9. Time step refinement study of the the twin box girder without wind shields

Mesh	δ_1/B	Incr s	St	C_d	C_l	C_m	C'_d	C'_l	C'_m
medium	5.80E-05	2.53E-03	0.151	0.140	-0.131	0.030	0.0318	0.2815	0.0231
medium	5.80E-05	1.26E-03	0.153	0.133	-0.153	0.026	0.0338	0.2671	0.0235

Table 10. Time step refinement study of the the twin box girder with wind shields

Mesh	δ_1/B	Incr s	C_d	C_l	C_m	C'_d	C'_l	C'_m
medium	5.80E-05	2.53E-03	0.132	-0.084	0.027	0.0063	0.0230	0.0063
medium	5.80E-05	1.26E-03	0.133	-0.083	0.026	0.0059	0.0182	0.0051

For the twin box girder without wind shields a 17% difference in the mean lift coefficient along with a 5% difference in the mean drag coefficient have been found while the Strouhal number and the standard deviation of the three force coefficients are in good agreement. These differences are considered assumable at the present stage for the intended purposes of the investigation. For the other three deck types, no substantial discrepancies are presented. As a consequence $2.88\text{e-}03$ and $2.53\text{e-}03$ non-dimensional time steps are selected for the computation of the complete set of mean force coefficients which are going to be presented next. However for the low-speed vortex shedding simulations $1.44\text{e-}03$ and $1.26\text{e-}03$ non-dimensional time steps have been chosen for the sake of higher accuracy in evaluating this unsteady response.

5 NUMERICAL EVALUATION OF THE FORCE COEFFICIENTS

5.1 Single box girder with and without wind shields

In figure 4 the computed mean force coefficients of the single box girder deck with and without wind shields at $Re=5.2\text{e}5$ are presented along with the experimental force coefficients of section H4.1 of the candidate cross-sectional shapes considered in the early design of the Great Belt Bridge [13] for validation.

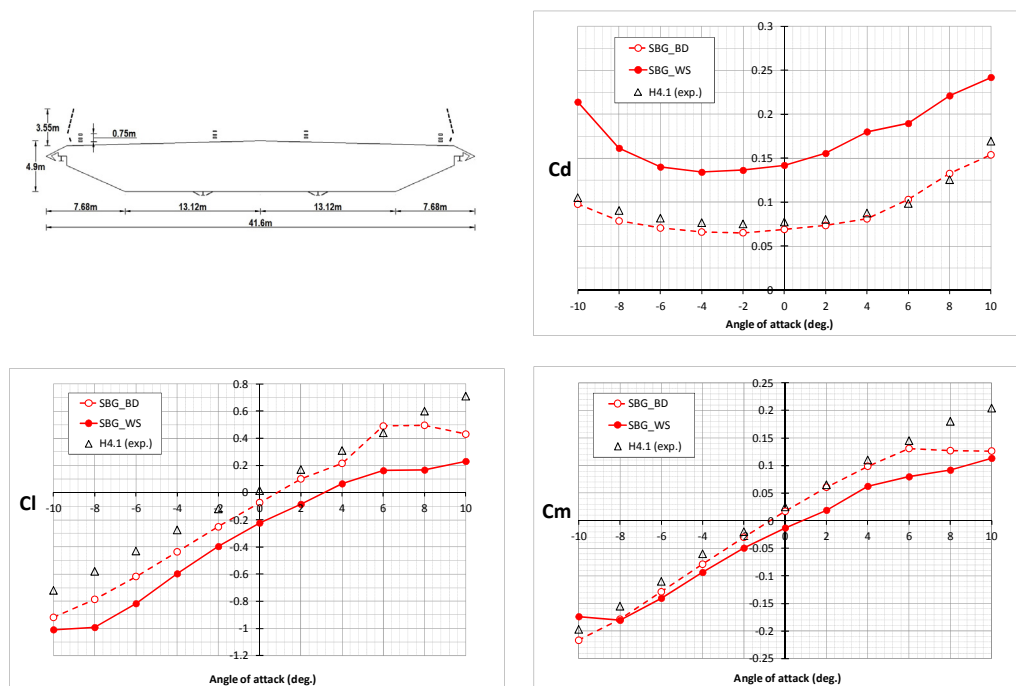


Figure 4. Force coefficients of the single box girder with and without wind shields

From figure 4 it can be concluded that mean force coefficients of the single box girder without wind shields are in good agreement with the experimental data of the H4.1 section. This is important due to the poor results of the grid convergence study for this particular deck type. Besides this the wind shields cause an important increment in the drag coefficient, which is about twice the drag coefficient for the bare section at 0° angle of attack. Furthermore the lift co-

efficient shifts down about 0.15 units keeping the same slope in the range of angles of attack (-8° , 6°) and the slope of the moment coefficient decreases slightly.

5.2 Twin box girder with and without wind shields

The computed mean force coefficients at $Re=2.4e5$ for the twin box girder deck types are presented in figure 5. In this case, the experimental force coefficients of two twin box girder decks as the Xihoumen Bridge [14], with a geometrical arrangement similar to the studied specimen, and the Stonecutters Bridge [15], with curved box lateral plates, are also included for the sake of indirectly validating the numerical results.

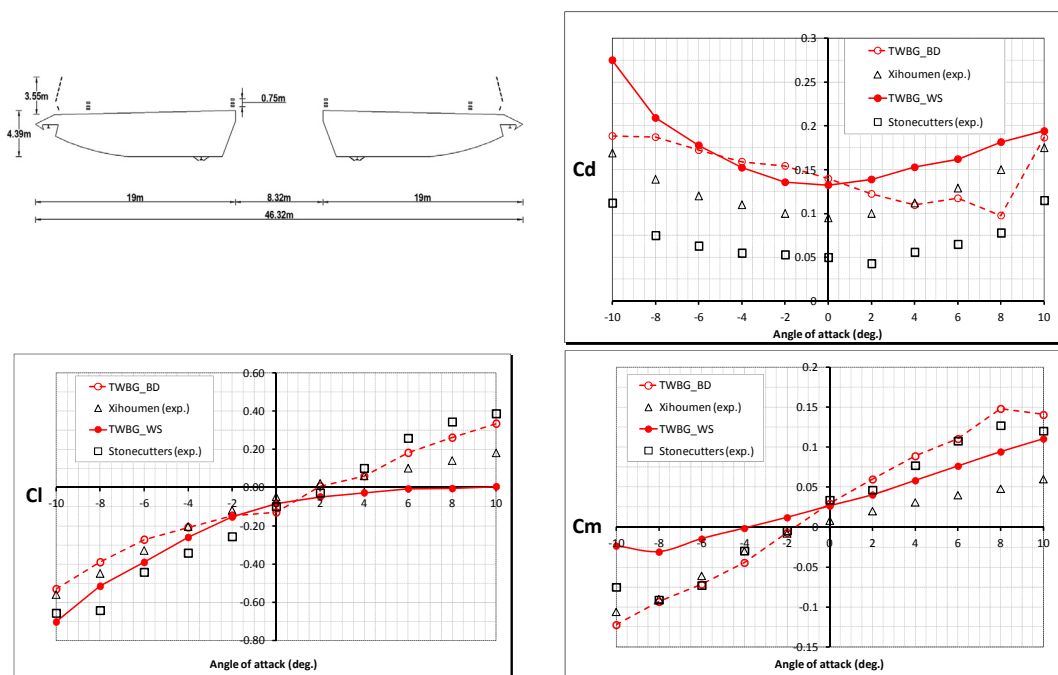


Figure 5. Force coefficients of the twin box girder with and without wind shields

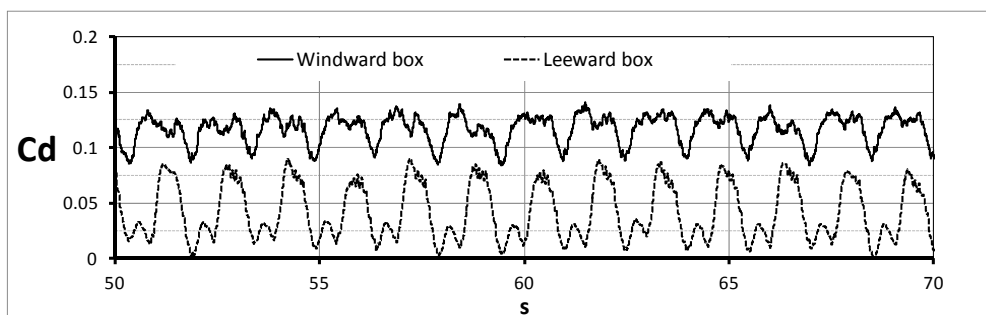


Figure 6. Time history of the disaggregated drag coefficient for TWBG without wind shields at -4° angle of attack.

The twin box girder without wind shields shows lift force coefficient close to the Xihoumen Bridge in the range of angles of attack between -10° and 4° and the differences increase for higher angles of attack. The computed moment coefficient shows good agreement with the Xihoumen Bridge experimental data from -10° to -2° angle of attack. Besides this, for the positive angles of attack the computational results are in agreement with lift and moment coeffi-

cients of the Stonecutters Bridge. Nevertheless it must be remarked the abnormal patter of the drag coefficient which is far from the parabolic shape typical of this force coefficient. Another important characteristic is the high value of the drag coefficient which is similar to the values of the wind shield configuration for the angles of attack between -8° and 2° . Analyzing the computed disaggregated drag forces acting on the windward and leeward boxes it has been found that they are nearly in phase as it can be perused in figure 6. In the absence of a precise experimental validation, this result must be taken as a work hypothesis to be confirmed in the experimental wind tunnel tests to carry out in case of this alternative progressing along the design process.

On the other hand the drag coefficient computed for the twin box girder with wind shields shows a parabolic shape, with values higher than those corresponding to the Xihoumen Bridge. The effect caused by the wind shields in the lift coefficient is the decrement in the slope of the Cl for the positive angles of attack. Regarding the moment coefficient, the wind shields cause the decrement of the coefficient slope for the complete range of studied angles of attack.

6 SHELTER EFFECT OF WIND SHIELDS

The purpose of windshielding in bridges is to provide shelter to vulnerable vehicles, in order to avoid restrictions in bridge operation such as the imposition of lane closures [16].

For the single box girder and the twin box girder alternatives for the Forth Replacement Crossing, computational simulations were carried out for a 3.0 m/s flow speed, which corresponds to a 26.3 m/s free stream velocity at real scale, which is above the wind speed values triggering restrictions in the operation of long span bridges. In figure 7 the normalized wind velocities (ratio of the velocity magnitude to the reference velocity at any point) fields between wind shields are presented for both the single box girder and the twin box girder deck types. The origin of coordinates x and y is set at the connection between the windward wind shield and the box deck. In the charts the horizontal and vertical coordinates are normalized employing the height of the wind shield (H)

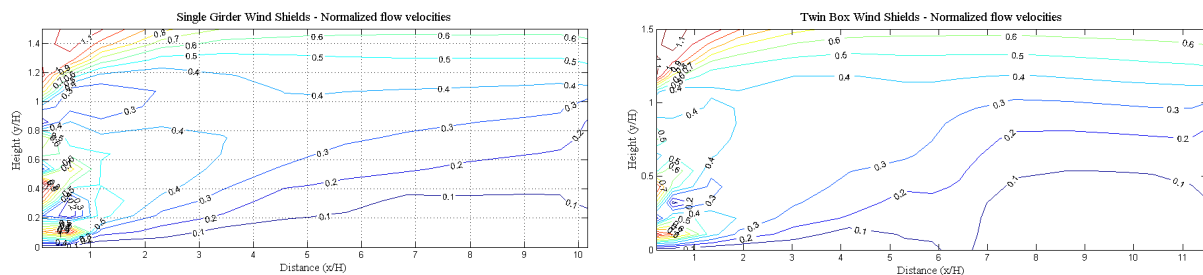


Figure 7. Normalized flow velocities at 0° angle of attack.

The numerical results are compared with the experimental tests reported by Kwon and co-workers [17] who tested an expanded metal barrier with a porosity ratio of 53.7% and a folded porous plate with a porosity ratio of 50% at a 1:10 geometric scale. The numerical results are about a 15%-20% lower than the normalized velocities obtained in the wind tunnel. This can be due to several causes: in the experimental tests the size of the mesh and the holes of the porous plate were not scaled to prevent scale effects, furthermore in the wind tunnel tests only a windward barrier was considered, nevertheless in the present computation both windward and leeward barriers along with the four traffic barriers have been included in the model, which justifies an additional decrement in the flow velocities. Additional studies are required for an accurate as-

assessment of the shelter provided by the wind shields as Reynolds number effects cannot be dismissed beforehand.

7 VORTEX SHEDDING RESPONSE

The preliminary assessment of the vortex-induced vibration risk of the different deck types proposed for the Forth Replacement Crossing at the early design stage has an obvious interest as it would allow the identification of potential aerodynamic concerns. Special attention must be paid to the twin box girder arrangement as bridges with this configuration such as the Stonecutters [18] or the Xihoumen [19] Bridges required mitigation strategies to tackle this phenomenon.

Several simulations considering a static deck have been carried out at low speed and 0° angle of attack for the set of deck types considered in this work. The fluctuating lift coefficient has been analyzed in order to identify strong peaks on the spectrum, indicative of vortex shedding excitation risk. For the single box girder with and without wind shields the fluctuating lift coefficient does not show important peaks on the spectrum. However for the twin box configuration without wind shields a single and extremely high pick has been identified at a St between 0.152 and 0.160 for all the flow velocities considered (0.75 m/s, 1.25 m/s, 1.75 m/s, 2.25 m/s and 3 m/s) which clearly indicates a vortex excitation risk and is in agreement with the experimental results reported in the literature. On the other hand, when the twin box girder is fitted with wind shields, it does not show a single strong peak in the spectrum of the lift coefficient for the same set of wind speeds. This indicates a beneficial effect of the wind shields in the vortex shedding response of twin box decks as it has been reported by Ge and co-workers [19].

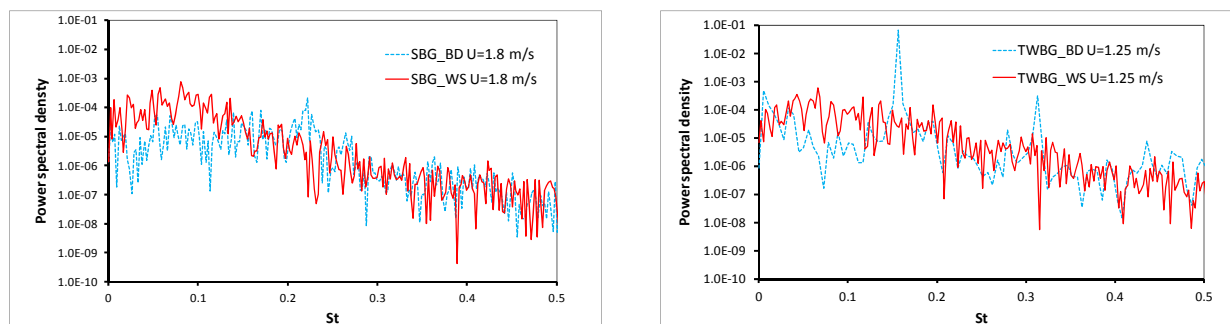


Figure 8. Power spectral density of the fluctuating lift coefficient at 0° angle of attack for the single box girder and the twin box girder with and without wind shields.

8 CONCLUSIONS

CFD techniques have been employed to study the aerodynamic response of two different deck types, with and without wind shields. The force coefficients have been computed, along with the shelter provided by the wind barriers and the vortex shedding response at low-speed.

The verification studies have shown a poor grid convergence for the single box girder without wind shields and some discrepancies were found for the twin box girder without wind shields refining the time step. On the other hand both decks fitted with wind shields showed a good grid and time step convergence.

The force coefficients for the decks without wind shields presented results close to other designs whose experimental data are available in the literature, except for the drag coefficient of the twin box which must be further studied. The decks fitted with wind shields showed a strong increment in the drag coefficient and a slight decrement in the slopes of lift and moment coefficients.

The shelter provided by the 50% porosity wind shields is higher than the existing results in the literature. However, the presence of the leeward wind shield and the traffic barriers justifies lower wind speeds at deck level.

Vortex shedding excitation risk was detected for the twin box girder without wind shields which is in agreement with the published literature. Also the beneficial effect of the wind shields has been pointed out, which is also in agreement with the results published for the Xihoumen Bridge.

9 ACKNOWLEDGEMENTS

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