CivilEng

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Wind Forces on Medium-Span Bridges: A Comparison of Eurocode 1 Part 4 and Computational Fluid Dynamics

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Abstract: Bridges often have complicated geometries in complex terrain where they can be exposed to high wind loading. Current practice in designing for wind can be conservative. The drive for more lean construction motivates the study of computational modelling as an alternative to traditional methods of determining these wind loads. This paper compares wind forces determined using Eurocode 1 Part 4 with those determined by CFD modelling for a given bridge geometry, taking variations in altitude, location, wind speed and wind direction into account. Results indicate that the exposure factors used in Eurocode 1 Part 4 inflate the net wind force values. It was also found that the directional factor is conservative for wind forces on bridge decks but ineffective for wind forces on bridge piers in the x-direction. Furthermore, the Reynolds-Averaged Navier–Stokes equations (CFD) appear to produce smaller values of net wind force than Bernoulli's equation (Eurocode). Bernoulli's equation can only be applied to an ideal fluid, and Reynolds-Averaged Navier–Stokes equations can be applied to any viscous fluid—a further concern with the current practice.

Keywords: bridge; wind; CFD; Eurocode

Citation: Moore, N.; Keenahan, J. Wind Forces on Medium-Span Bridges: A Comparison of Eurocode 1 Part 4 and Computational Fluid Dynamics. *CivilEng* **2022**, *3*, 794–808. https://doi.org/10.3390/civileng3030046

Academic Editor: Francesco D'Annibale

Received: 28 July 2022
Accepted: 6 September 2022
Published: 9 September 2022

1. Introduction

Wind is random and spatiotemporally variable and is therefore very difficult to predict [1]. All structures are exposed to wind, and wind is an important consideration in the design of structures. Bridges often have complicated geometries and are located in complex terrain where they can be exposed in all directions to wind loading as well as hazards [2]. For mid- to long-span bridges, the effect that wind has on their stability is the most important consideration. There are several ways in which wind on bridges can be assessed: experimentally [3], numerically using the equations of motion [4], physically, using wind tunnel tests and, in recent years, through the use of Computational Fluid Dynamics [5].

The Eurocodes were created in 1975 to replace design codes of individual countries and create harmonized standards for structural design in Europe [6]. The purpose of the Eurocodes was to coordinate technical specifications and remove technical obstacles in order to promote harmonious trade between EU member states [6]. Two Eurocodes, EN 1991-1-4 and EN 1993-3-1, apply to wind actions on bridges, the former governing wind actions on structures and the latter governing wind actions on masts and towers [7]. Long-span bridges are considered to be bridges over 300–500 m in span [8]. Eurocode 1 Part 4 only governs bridges with no span greater than 200 m, provided they are not cable-supported, and none of the following are under investigation: torsional vibrations, bridge deck vibrations from transverse wind turbulence, or vibrations where more than the fundamental mode needs to be considered [6]. In complex cases, Eurocode 1 Part 4 recommends the use of wind tunnel testing to determine wind actions on bridges, and wind tunnel testing has been used to determine constants, factors and coefficients within Eurocode 1 [6].

With the recent expansion in computational power, there has been a growing demand to computationally simulate climate phenomena rather than measure it in situ or with physical models. Computational Fluid Dynamics (CFD) has the potential to provide structural engineers with an accessible method of recreating wind effects, which are often the governing consideration when designing long-span bridges. Currently, the Eurocode on wind actions [6] provides guidance on calculating wind effects under specific conditions with sets of equations, and recommends wind tunnel testing in all other conditions. CFD is not yet specified in the Eurocode as a means of estimating wind effects on long-span bridges, and consequently, it is not widely used in Europe. As revisions to the Eurocode are currently being considered, it is timely to consider the potential of CFD in this area. The draft of the revised Eurocode 1 Part 4 acknowledges CFD and provides guidance for its use in 'Annex K-Guidance on derivation of design parameters from wind tunnel tests and numerical simulations' [9]. It states that wind tunnel testing can be used throughout the preliminary design and detailed design stages, whereas CFD may be used in the preliminary design stage and only for detailed design in cases of pedestrian comfort, pollution dispersal and topographical studies [9]. The reasoning is that CFD cannot be relied upon to give inputs of absolute values of parameters in the design of civil engineering structures. It is interesting to note that the draft states that the appropriateness of the computational model can only be assessed with validation cases that compare wind tunnel test results with those of the computational model. It also does not take into consideration cases where field data are available, which would negate the need for wind tunnel testing. Compared with wind tunnel testing, CFD has the potential to have shorter lead times, no scaling issues and no issues with the physical presence of sensors disrupting the flow. Furthermore, the Eurocode is known to be conservative. As we, as a society, are becoming more conscious of the impact the construction industry has on the environment, there is a push for more lean construction, which is a further potential advantage of CFD.

The aim of this paper is to compare two methods of calculating the wind forces on medium-span bridges in this Irish context: the Eurocode computational method and the CFD modelling method, for different wind directions, altitudes, and wind velocities. Eurocode 1 [6] is widely used and understood amongst designers. By comparing the known with the unknown, this paper aims to expand perceptions, ultimately expediating the advancement of such a promising area of research. Due to the conservative nature of the Eurocode and the unpredictable nature of wind, different combinations of the two methods will also be compared. This will delineate a clearer picture of the differences between the two methods and allow for a more nuanced comparison to take place. As consideration is given to the inclusion of CFD in the Eurocode as a method of determining wind effects on long-span bridges, the differences between these two methods are becoming a more relevant issue. Knowing the appropriate use case for each will be paramount.

2. Bridge Details

A simple bridge geometry was used to facilitate a comparison between the Eurocode method and the CFD method of determining wind forces. The bridge length, l, was taken as 200 m, and the width of the bridge, b, was taken as 30 m. The depth of the bridge, d, was 2.5 m with a degree of inclination from the vertical, α_1, of 30°. These dimensions correspond to those presented in Figure 8.2 of Eurocode 1 [6], and the form of the cross-section was as given in Figure 8.1 of Eurocode 1 [6]. The bridge was supported by five piers (Figure 1) with a span/depth ratio of 1/20 and a clearance height of 20 m. The length of each pier, t, was taken as 10 m, the width, b, was taken as 4 m and the height, h, was taken as 16 m. The z-axis was taken as acting positively upwards and the x-axis was acting perpendicular to the length of the bridge. The return period for the design of a bridge, T, is 100 years. The annual probability of exceedance, p, is therefore 1/100 or 0.01.

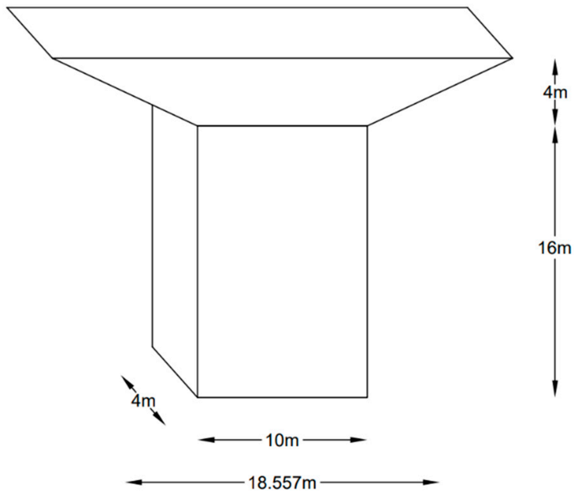


Figure 1. Pier dimensions in meters.

3. Eurocode Analysis

Eurocode 1 Part 4 [6] provides guidance on wind actions on structures. It plays an advisory role with the final decision left to the expertise of the design engineer. As such, it is important to be aware of where these equations come from and their sources of inaccuracy. Eurocode 1 Part 4 and the accompanying Irish National Annex [6] provide guidance on quantifying the nature of wind and the way in which it acts on structures. Wind is unpredictable, but analysing the factors that influence its speed and turbulence could help in its understanding. Air is considered to be a fluid; wind, being the movement of air, is therefore also a fluid. Wind is Newtonian in that the viscosity of wind remains constant for a given temperature [10]. Viscosity is the measure of a fluid's resistance to flow, and gases have negligible viscosity [10]. In this instance, wind is also considered to be incompressible in that it undergoes a negligible change in volume and its density remains constant [10]. The methodology of Eurocode 1 Part 4 [6] is based on the application of Newton's First Law to a gas, which is accurate for steady flow conditions [10]. This is acknowledged at the beginning of the code with the stipulation that the code does not give guidance on torsional vibrations, bridge deck vibrations from transverse wind turbulence, cable-supported bridges and vibrations where more than the fundamental mode needs to be considered [6]. Eurocode 1 Part 4 [6] acknowledges the atmospheric boundary layer, where wind speed gradually increases with height, through the use of an altitude factor, c_{alt} [11]. The polynomial equations that govern the altitude factor, known as the Harris and Deaves model, are derived from real-world measurements [12]. A directional factor, c_{dir}, recognizes the way in which the speed of wind decreases as the angle between its direction and the direction of the prevailing wind increases. A seasonal factor, c_{season}, recognizes that certain times of year are more prone to high wind speeds than others. A probability factor, c_{prob}, addresses the probability that the prescribed wind speed will be exceeded over the design life of the structure. The velocity of wind near the ground, and its rate of increase with height, depend on how much friction energy has been extracted from the upwind terrain [11]. Rough terrain upstream makes the flow more turbulent and reduces the mean velocity downstream [11]. Turbulence superimposes peaks and troughs on the mean wind speed, increasing the peak pressures to be designed against [11]. The velocity pressure values represent the pressure generated by bringing the flow to a standstill [11]. Each of the factors has been determined through experimental evidence with the use of wind tunnel testing [11]. The factors in Eurocode 1 Part 4 [6] were derived from extreme value analysis of integrated multiple instantaneous pressure measurements, and they are generally presented in graphical or tabular form for different arrangements [11]. Bridges with spans over 200 m, bridges that do not satisfy the criteria for dynamic response, and cable-supported bridge all fall outside the scope of the Eurocode wind calculations, and wind tunnel testing is advised [6].

3.1. Eurocode Parameters

This research studied three different locations in the Republic of Ireland: Dublin, Cork and Galway, each of which has different values for the fundamental basic wind velocity, $v_{b,map}$, according to Figure NA. 1 of Eurocode 1 Part 4 [6]. The values are approximately 24.9 m/s for north of Dublin city, Co. Dublin, 25.9 m/s for east of Galway city, Co. Galway, and 26.9 m/s for north of Skibbereen, Co. Cork. The locations are situated in *Country Terrain* as a combination of the *Terrain Category I* and *Terrain Category II* [6]. This type of terrain is categorized by its lack of obstacles or the presence of isolated obstacles, with separation of at least twenty obstacle heights, as well as its low to negligible vegetation. The choice of location also affects the distance upwind to the shoreline, which varies at each location, depending on the direction of the wind.

Arbitrary values were selected for the altitudes: 25 m, 50 m and 100 m above sea level. A range of wind directions were chosen in increments of 30°. They represent the worst possible case: 240° clockwise from due north is the prevailing wind in Ireland, and the next four worst possible cases: 30° and 60° from the prevailing wind in both the clockwise and anticlockwise directions. This produces a range of values between 180° and 300° clockwise from due north: 180°, 210°, 240°, 270° and 300°. It should be noted that the angle of attack of the wind, i.e., the angle of the wind in the x–z and y–z planes, θ, was kept at zero. The values of distance upwind to the shoreline for each location and the corresponding wind direction clockwise from due north are detailed in Table 1.

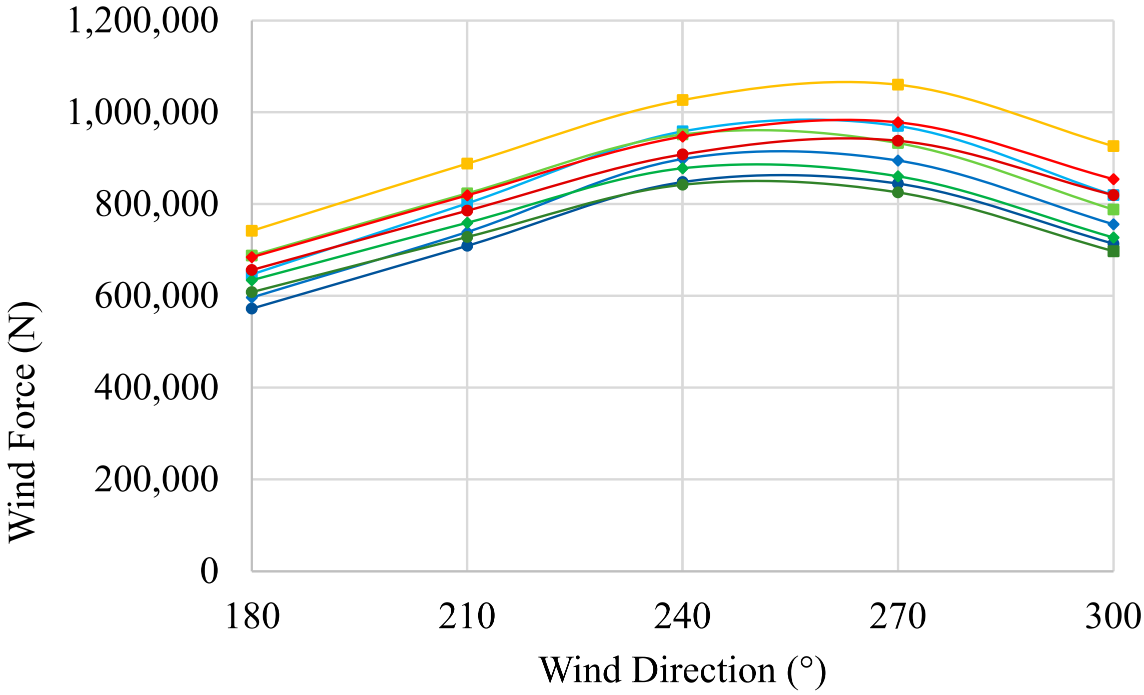
Table 1. Table of distance upwind to the shoreline depending on the location and the direction of the wind clockwise from due north.

Location	Wind Direction Clockwise from Due North (Degrees)	Distance Upwind to Shoreline (km)
Dublin	180	40
	210	20
	240	6
	270	3
	300	3
Galway	180	110
	210	230
	240	270
	270	190
	300	210
Cork	180	170
	210	430
	240	270
	270	16
	300	8

The seasonal factor, c_{season}, is taken as 1 for January and $c_s c_d$ was also taken as 1.0, as the structural factor was not required in this study. The orography factor, $c_o(z)$, was neglected so as to not further enhance the net wind force values beyond that of the CFD modelling method, and as such, the average upwind slope is assumed to be less than 3° [6].

3.2. Eurocode Values for Wind Actions

The methodology of Eurocode 1 Part 4 [6] was used to determine the wind forces acting on the bridge deck in the x-direction (Figure 2a) and z-direction (Figure 2b) and on the bridge piers in the x-direction (Figure 2c) for sites in Dublin, Cork and Galway at a variety of different altitudes with winds coming from different directions.



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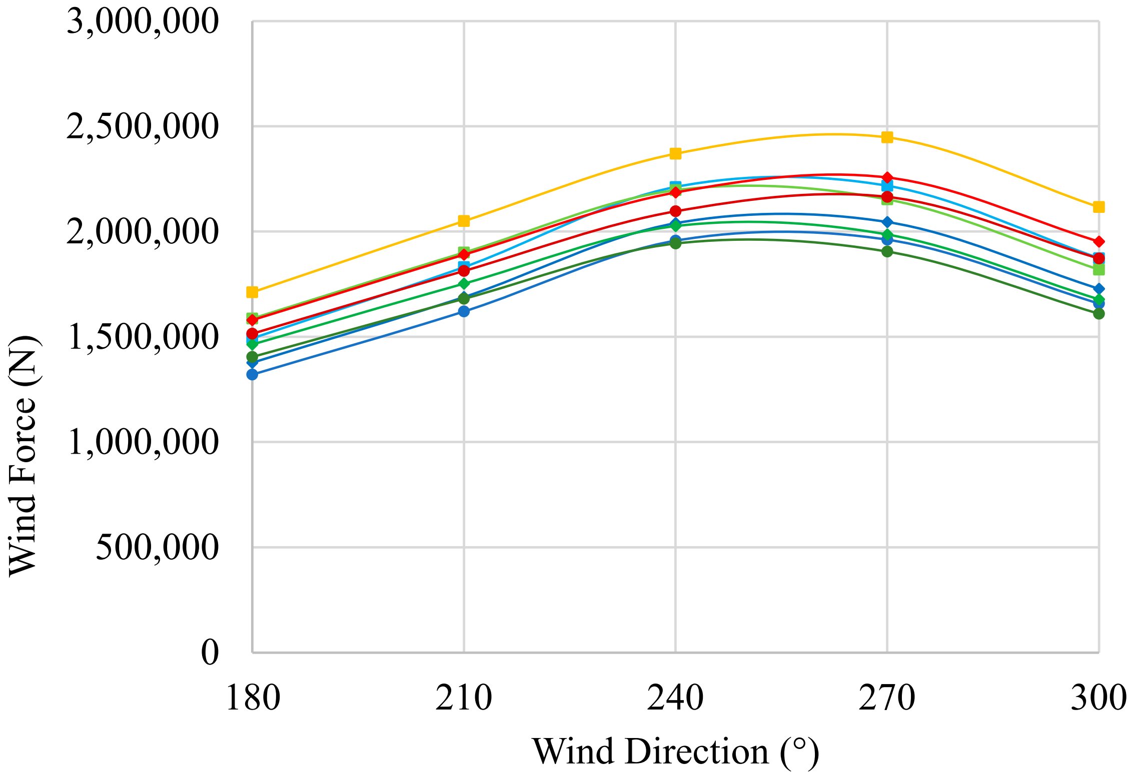

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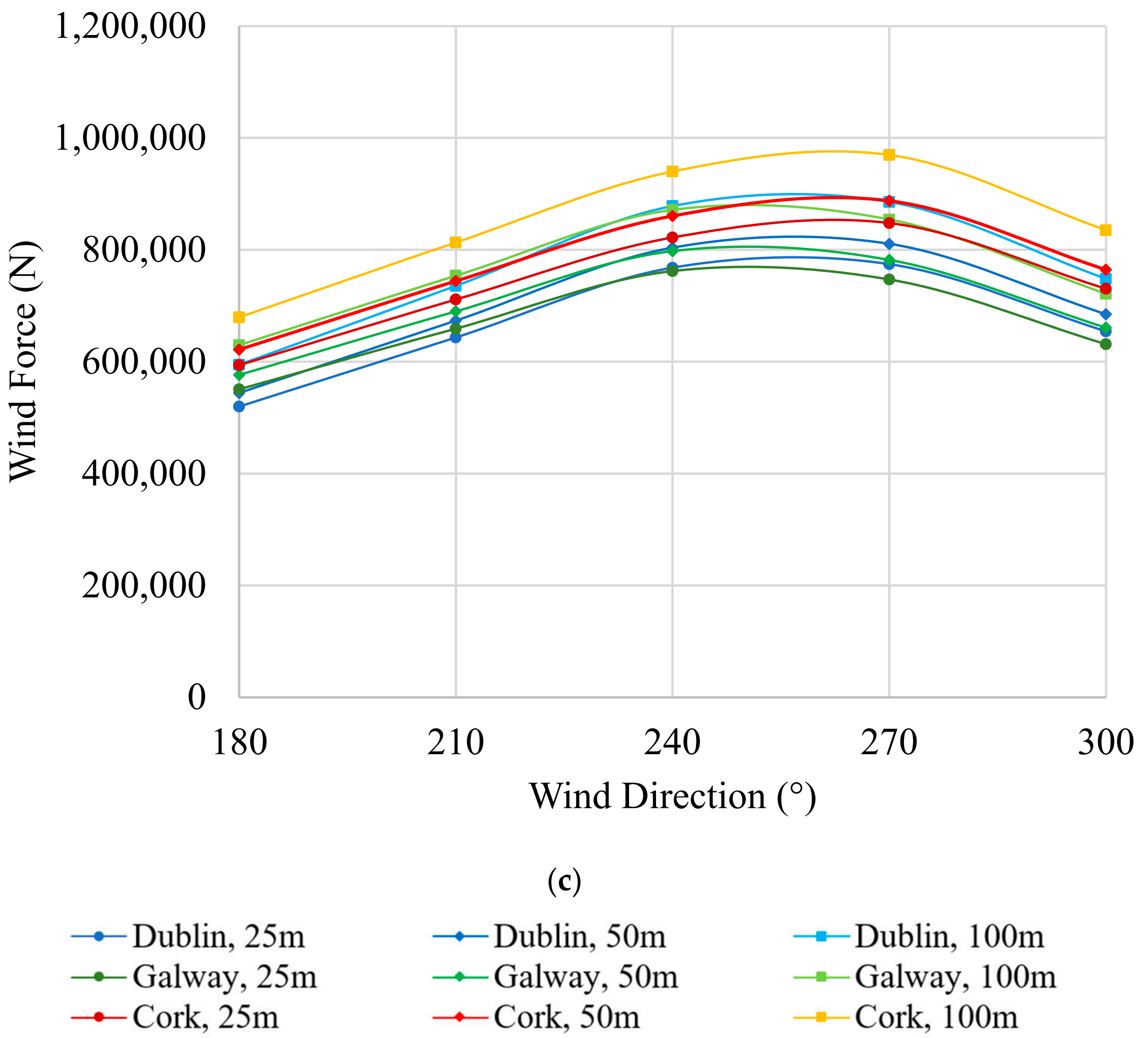


Figure 2. Wind force plotted against wind direction for (**a**) Deck in the x-direction; Wind force acting on the deck in the x-direction; (**b**) Deck in the z-direction; Wind force acting on the deck in the z-direction; (**c**) Piers in the x-direction; Wind force acting on the piers in the x-direction.

Each of the Eurocode cases, regardless of whether the x-direction or the z-direction is examined, follows the same shape trend: skewed slightly to the left due to the uneven distribution of wind across different directions. This is due to the uneven distribution of the wind forces with an emphasis on the directions clockwise from due north of the prevailing wind. This is caused by the directional factors, c_{dir}, for the angles 180° to 300° clockwise from due north being 0.85, 0.93, 1.00, 0.99, and 0.91, respectively.

The values of net wind force in the x-direction vary from 572,436 N to 1,060,299 N, with a mean of 812,221 N. In the z-direction, the values vary between 1,321,005 N and 2,446,845 N, with a mean of 1,869,964 N. The wind force in the z-direction represents the uplift as a result of the horizontal force in the x–y plane, with forces upwards being positive and forces downwards being negative. The reason for these high values is that in the absence of an equation for uplift, the characteristic peak velocity pressure, $q_p(z)$, for wind travelling horizontally at the reference height of the bridge, was applied to the reference area of the bridge in the z-direction, $A_{ref,z}$. This represents a scenario where the wind is travelling vertically upwards at the same peak magnitude that it would horizontally: an unlikely scenario but also not the scenario being investigated. Wind in these cases is strictly travelling horizontally. However, the force coefficient in the z-direction, $c_{f,z}$, is applied to reduce the net wind force in order to more realistically represent the effect that horizontal wind would have in the z-direction. For the deck cross-section in question, a value of ±0.25

was used. As is the nature of all factors in the Eurocodes, this factor is likely a conservative value. It is likely that this factor does not do enough to prevent an overestimation of net wind forces on the deck in the z-direction, but further analysis is required. Where the z-direction was the worst case for the deck, the x-direction is the worst case for the piers. The net wind force values vary from 519,926 N to 969,618 N, with a mean of 738,467 N.

Some of the curves, Dublin—25 m, Dublin—50 m and Dublin—100 m, follow a slightly different pattern where the net wind force values at 300° are greater than the values at 210°. Some of the curves, Cork—25 m, Cork—50 m and Cork—100 m, also follow this pattern but additionally have net wind force values at 270° that are greater than the values at 240°. This is not in line with the theory that the shape of the graph is solely dictated by the directional factor, c_{dir}. In these calculations, the exposure factor, $c_e(z)$, increases the pressure and subsequently the force values for 270° and 300° clockwise from due north. The locations are relatively close to the upwind shoreline for the directions of 270° and 300° clockwise from due north, as seen in Table 1. The exposure factor, $c_e(z)$, also has the effect of altering the order of the lines representing each location and altitude. If 180° clockwise from due north and 300° clockwise from due north are taken, the effect can be observed. From lowest to highest, the net wind forces for 180° clockwise from due north are Dublin—25 m, Dublin—50 m, Galway—25 m, Galway—50 m, Dublin—100 m, Cork—25 m, Cork—50 m, Galway—100 m and Cork—100 m. This follows the logical pattern of 'lowest velocity—lowest altitude', 'middle velocity—lowest altitude', 'lowest velocity—highest altitude', 'highest velocity—lowest altitude', 'middle velocity—lowest altitude' and 'highest velocity—highest altitude' that one would expect to see given the distances upwind to the shoreline for Dublin, Galway and Cork for this angle are 40 km, 120 km and 170 km, respectively. All those distances are relatively close on the logarithmic graph, which determines the exposure factor, given any distances over 100 km are to be taken as 100 km, and so the upwind shoreline distance has little effect, and the effect of the velocity governs. From lowest to highest, the net forces for 300° clockwise from due north are Galway—25 m, Dublin—25 m, Galway—50 m, Dublin—50 m, Galway—100 m, Dublin—100 m, Cork—25 m, Cork—50 m and Cork—100 m. This pattern is more affected by the diverse upwind to shoreline distances: 3 km, 210 km and 8 km for Dublin, Galway and Cork, respectively. Clearly, the factors with the most influence on the shape of the graphs are the directional factor and the exposure factor.

4. CFD Analysis

CFD uses the computational power of computers to solve the partial differential equations that govern the conservation of mass, momentum, and energy of fluids, which are also known as the Navier–Stokes equations. A RANS simulation (steady state) with an appropriate turbulence model can provide sufficiently accurate results in the study of time-averaged wind effects if cases do not have large flow separations or vortex shedding, such as these ones [13]. This study used the Reynolds-Averaged Navier–Stokes (RANS) equations to solve for the velocity and pressure at all points within the fluid:

$$(\delta\bar{u})/\delta t + (\bar{u})\ \nabla\bar{u} = -\nabla p^{-} + \nu\nabla\hat{}2\ \bar{u} + g + \nabla\cdot(-(u\hat{}'\ u\hat{}')^{-}) \quad (1)$$

$$\nabla\cdot u = 0 \quad (2)$$

where $\bar{u}$ is the time-averaged velocity, p^{-} is the mean kinematic pressure and u' is the fluctuation velocity. The Reynolds stress must be approximated using a turbulence model to close the equation. For the purpose of this structural engineering application, a simple turbulence model that allows for complex geometry is sufficient. The most commonly used turbulence models in bridge aerodynamics are eddy-viscosity models, in which the Boussinesq hypothesis is applied so that the Reynolds stress can be calculated by the mean velocity field and the turbulence viscosity. These models normally contain one or two transport equations, and so the computational cost is relatively low. The k-ε models are particularly favoured in applications related to civil and structural engineering [14–16]. A k-ε model was used which allows prediction of near-wall flow phenomena without changes to constants or functions, where k is the turbulence energy and ε is the dissipation rate of turbulence [17]. It has been shown that a RANS simulation with the k-ε model can reproduce the velocity field and pressure field measured in wind tunnel tests [13,17]. Simulations in this paper were performed using the open-source software OpenFOAM.

4.1. Model Description

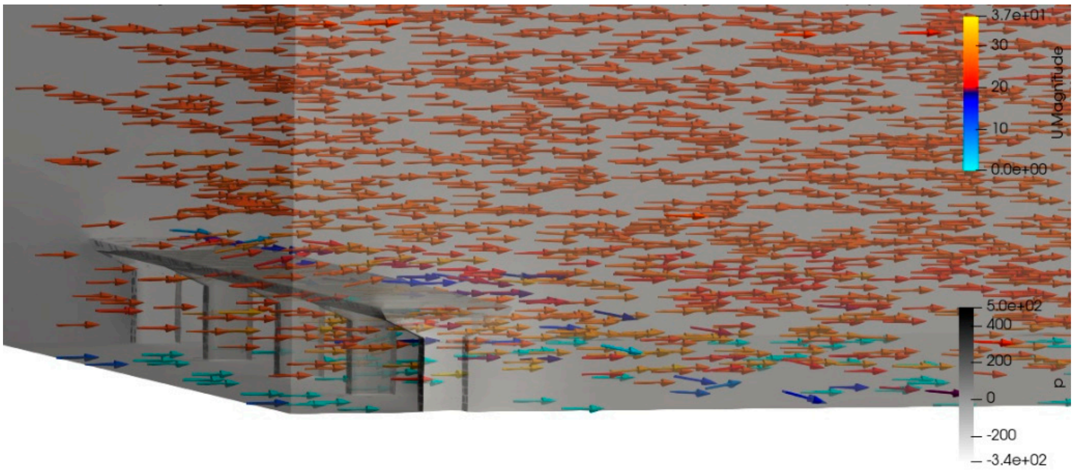
The geometry of the bridge was created in a 3D Computer-Aided Design software and imported as an STL file to OpenFoam. A rectangular domain was used: 350 m long (in the x-direction), 204 m wide (in the y-direction) for geometry placed perpendicularly to the direction of flow, and 140 m high (in the z-direction). The 350 m length enabled the bridge geometry to be placed 20 m from the inlet to allow the flow to adjust and 330 m from the outlet to allow the geometry to be rotated without a change in the domain length. The 204 m width was dictated by the length of the bridge. The 140 m height is between five and ten times the height of the bridge, 22.5 m. The steady-state solver simpleFoam was used to solve for incompressible, turbulent flow [18]. The density of air was set to 1.226 kg/m^3 [18], which is the same value recommended in Eurocode 1 Part 4 [6]. The kinematic viscosity of air was set to 1.5×10^{-5} m^2/s. Discretization is based on Gauss's theorem which allows for a smooth and accurate evaluation of the displacement gradient outlined in the momentum equation [18]. The value of ε was taken to be 0.03, and the value of k was taken to be 1.5. The pressure, p, in simulations was set to *zeroGradient*, meaning the normal gradient of pressure was zero [18].

4.2. Wind Input Values—From Met Eireann Data

The inlet of the velocity in CFD simulations was determined using weather data from Met Eireann data [19]. Weather data for the locations of interest in this study were available from the weather stations at Dublin Airport, Athenry in County Galway and Cork Airport [19]. A historical analysis of wind speeds over the past ten years from these weather stations revealed the annual average peak wind velocities of 25.8 m/s for Dublin, 22.5 m/s for Galway and 26.8 m/s for Cork. In each case, the altitude of the individual weather stations had to be used in the simulations: 71 m for Dublin Airport, 40 m for Athenry in Galway and 155 m for Cork Airport. The other patch velocities were set to zero using the *noSlip* function.

4.3. CFD Values for Wind Actions

A suite of fifteen different simulations were performed with three different locations, their associated velocity and altitude variables, and five different wind direction variables. Figure 3 shows the pressure acting on the bridge as a result of the wind (from 240°) at Dublin. It illustrates one of the key advantages of CFD modelling in that results are obtained for the entire domain and not just at discrete sensor locations, as would be the case in field testing or wind tunnel testing. Figure 3a illustrates the velocity magnitude and direction of the wind flows around the bridge in the form of coloured arrows. Figure 3b illustrates the pressure acting on the bridge.



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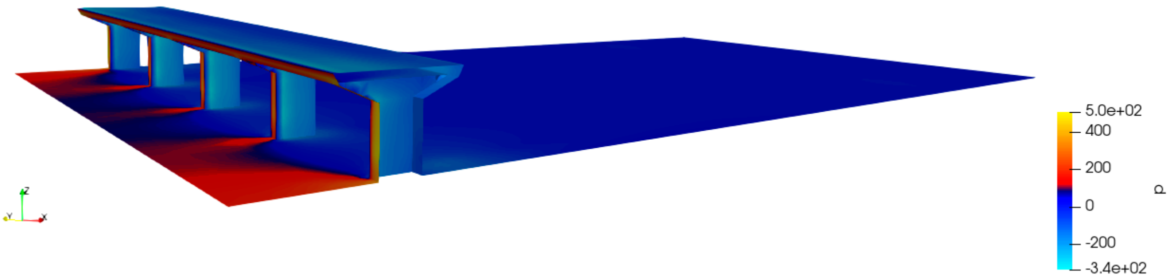
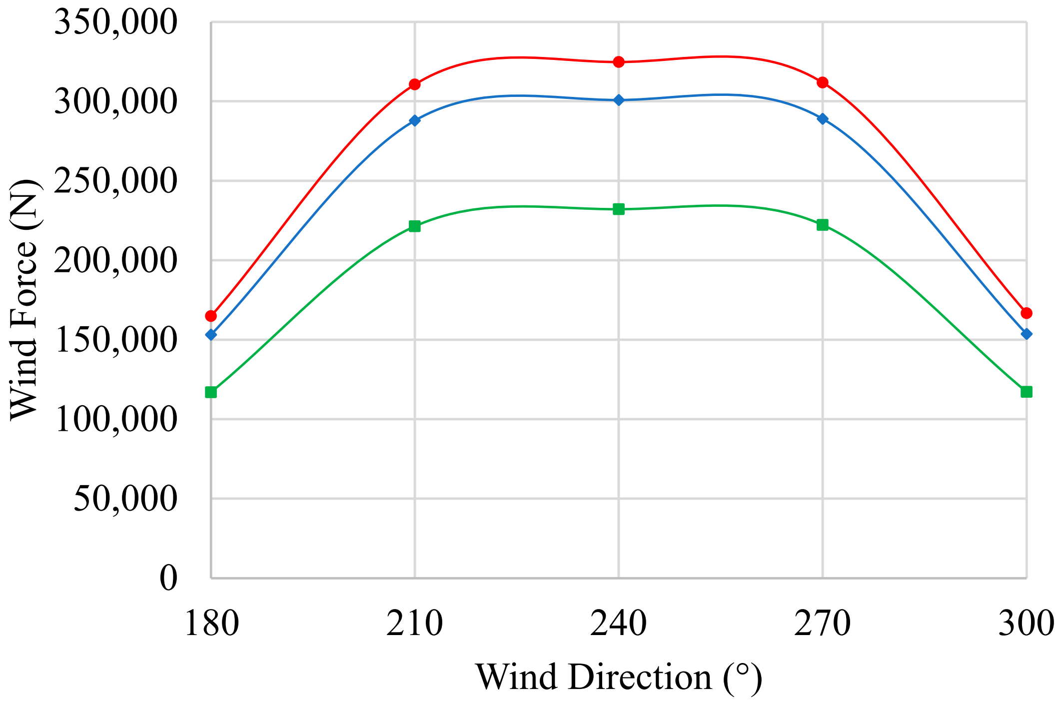


(**b**)

Figure 3. Results from CFD modelling: (**a**) Pressure on the bridge in black and white, and the velocity magnitude and direction in the form of coloured arrows; Velocity magnitude and direction of the wind flows around the bridge(**b**) pressure on the bridge in colour; Pressure acting on the bridge.

Figure 4 plots the wind force against wind direction for the bridge deck in the x-direction and the z-direction and the piers in the x-direction. Each point on a graph represents a simulation that was performed: red circles for Cork, blue diamonds for Dublin and green squares for Galway. In Figure 4a, there appear to be negligible differences between the net wind force values for the 180° and 300° wind directions and the 210° and 270° wind directions, as the wind direction is changed by rotating the geometry of the bridge within the CFD model and not through the skewed Eurocode directional factors. It is interesting to note that the Galway wind force values are lower than those in Dublin and Cork, which is likely due to its lower altitude. Similar trends are apparent in Figure 4b for the deck in the z-direction. Interestingly, the shape trend for the piers in the x-direction is inverted. This is likely an effect of rotating the geometry of the piers in the CFD model; the more the wind is rotated away from the direction that is perpendicular with the piers, the more area of the piers the wind will come into contact with. This is especially true given that unlike the deck, only the shorter dimension of the piers is exposed to wind travelling perpendicularly to the bridge deck, whereas both the shorter and longer dimensions are exposed to the other four wind directions. This is reflected in the wind directions 60° from the perpendicular direction. For example, the cases that are 180° and 300° clockwise from due north have the highest net wind force values. The cases with the wind directions 30° from the perpendicular direction, 210° and 270° clockwise from due north, have the second highest net wind force values. Finally, the perpendicular direction, 240° clockwise from due north, has the lowest net wind force values.



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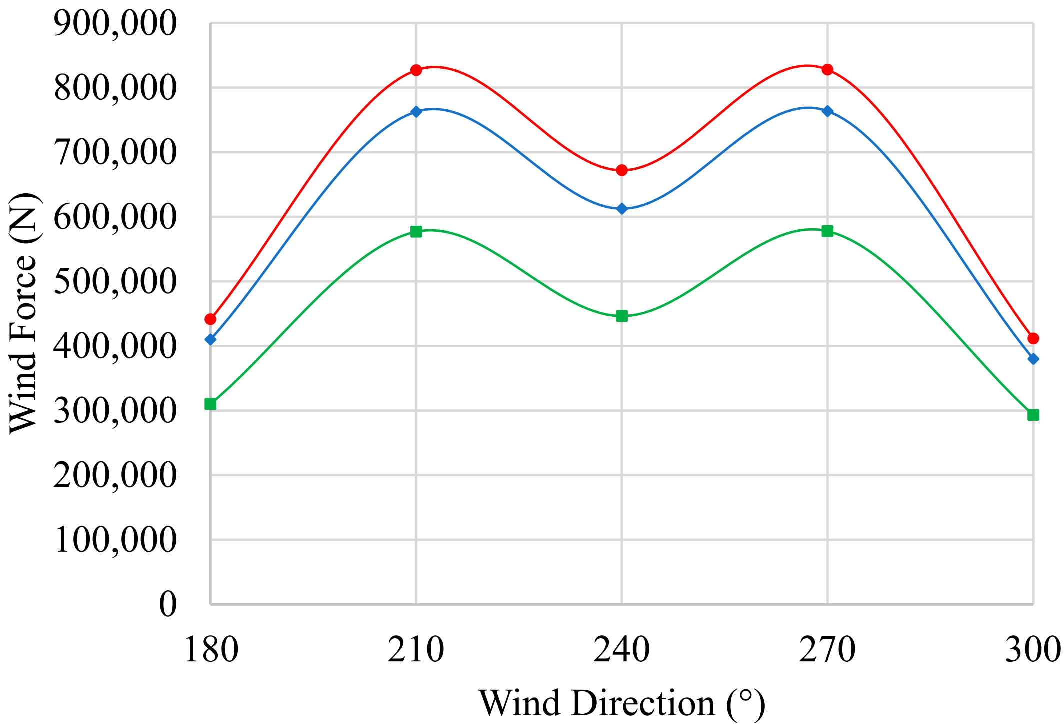

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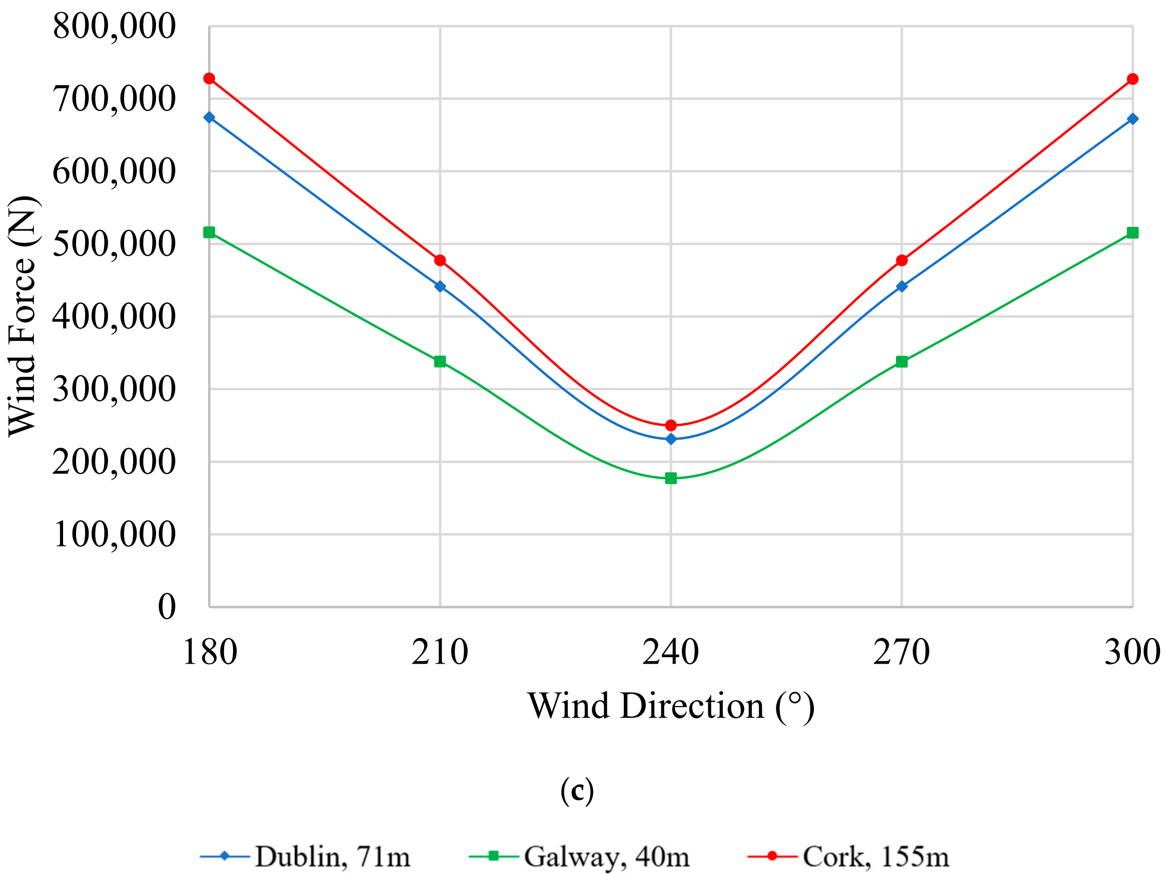


Figure 4. Wind force plotted against wind direction for (**a**) Deck in the x-direction; Wind force acting on the deck in the x-direction; (**b**) Deck in the z-direction; Wind force acting on the deck in the z-direction; (**c**) Piers in the x-direction; Wind force acting on the piers in the x-direction.

5. Comparison of the Eurocode and CFD Wind Actions

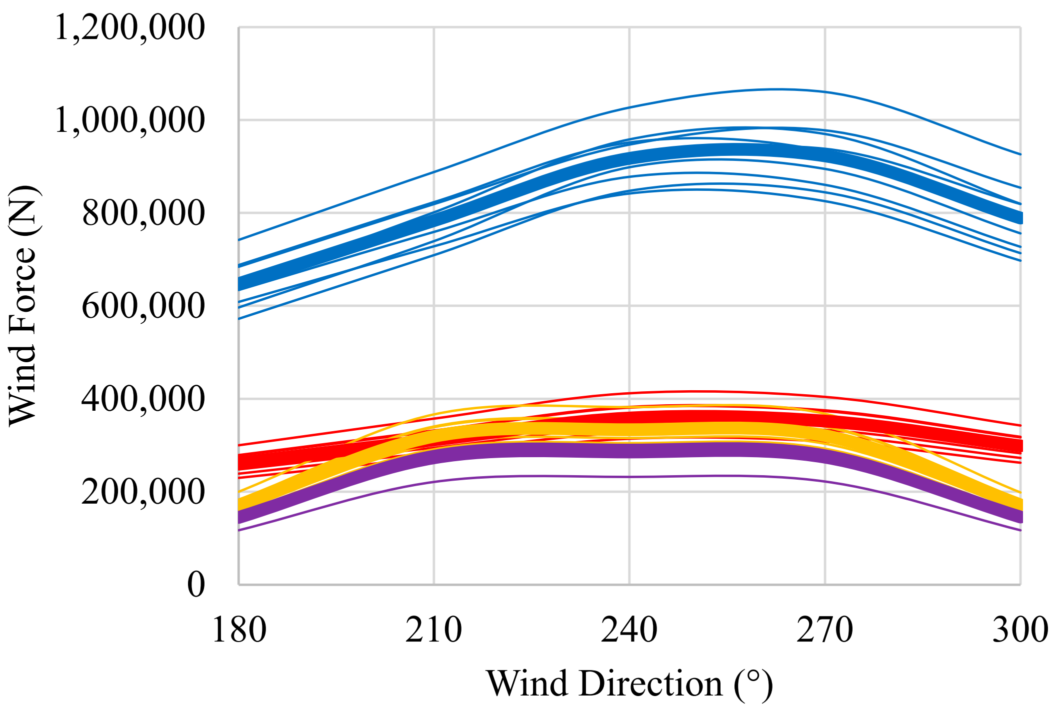
In addition to the two methodologies presented thus far, the Eurocode method (Section 3) and the CFD method (Section 4), two further CFD modelling scenarios were considered. The first scenario (CFD Case 1) uses the basic wind velocity, v_b, calculated using Eurocode 1 Part 4 [6], which is influenced by the altitude factor and directional factor. The directional factor is changed to simulate the changes in wind intensity for different directions. The wind forces are then determined using CFD modelling. The second scenario (CFD Case 2) uses the fundamental basic wind velocity, $v_{b,0}$, which was calculated using Eurocode 1 Part 4 [6] and influenced by the altitude factor only. Here, the direction of the wind is changed by rotating the bridge in the x–y plane within the CFD model. Again, the wind forces are determined using CFD modelling. Table 2 summarises the scenarios investigated in this study and the relevant wind parameters used in each case, where information in the light grey cells are the parameters determined by the Eurocode, and information in the darker grey cells are determined using CFD modelling.

Figure 5 plots the wind force against wind direction for all four cases (Eurocode Case, CFD Case, CFD Case 1 and CFD Case 2) for the bridge (a) deck in the x-direction and (b) the z-direction and the (c) piers in the x-direction. The thick blue line represents the mean of all nine Eurocode simulations presented previously in Figure 2. The thick purple line represents the mean of the three CFD simulations previously presented in Figure 4. The set of red lines represents the nine simulations preformed for CFD Case 1, with the corresponding mean plotted as a thick red line. The set of yellow lines represents the nine simulations performed for CFD Case 2, again with the corresponding mean plotted as a thick yellow line.

Table 2. Differences between individual cases: Eurocode Case, CFD Case 1, CFD Case 2 and CFD Case 3, in terms of the factors that influence the wind force values, and the method by which these factors are determined.

Case	Altitude	Wind Direction	Wind Velocity	Wind Force
Eurocode Case	Altitude factor used to show effect of altitude on wind intensity	Directional factor changed to simulate the changes in wind intensity for different directions	V_b value used, which is influenced by the altitude factor and directional factor [1]	F_w determined using the Eurocode calculation
CFD Case	Altitude of each Met Eireann weather station is observed	Direction of the wind changed by rotating the bridge in the x–y plane within the CFD model	Velocity values generated from historical Met Eireann data	Net wind force determined using CFD models
CFD Case 1	Altitude factor used to show effect of altitude on wind intensity	Directional factor changed to simulate the changes in wind intensity for different directions	V_b value used, which is influenced by the altitude factor and directional factor [1]	Net wind force determined using CFD models
CFD Case 2	Altitude factor used to show effect of altitude on wind intensity	Direction of the wind changed by rotating the bridge in the x–y plane within the CFD model	$V_{b,0}$ value used, which is influenced by the altitude factor only.	Net wind force determined using CFD models

[1] Direction factor influenced by distance upwind to shoreline.



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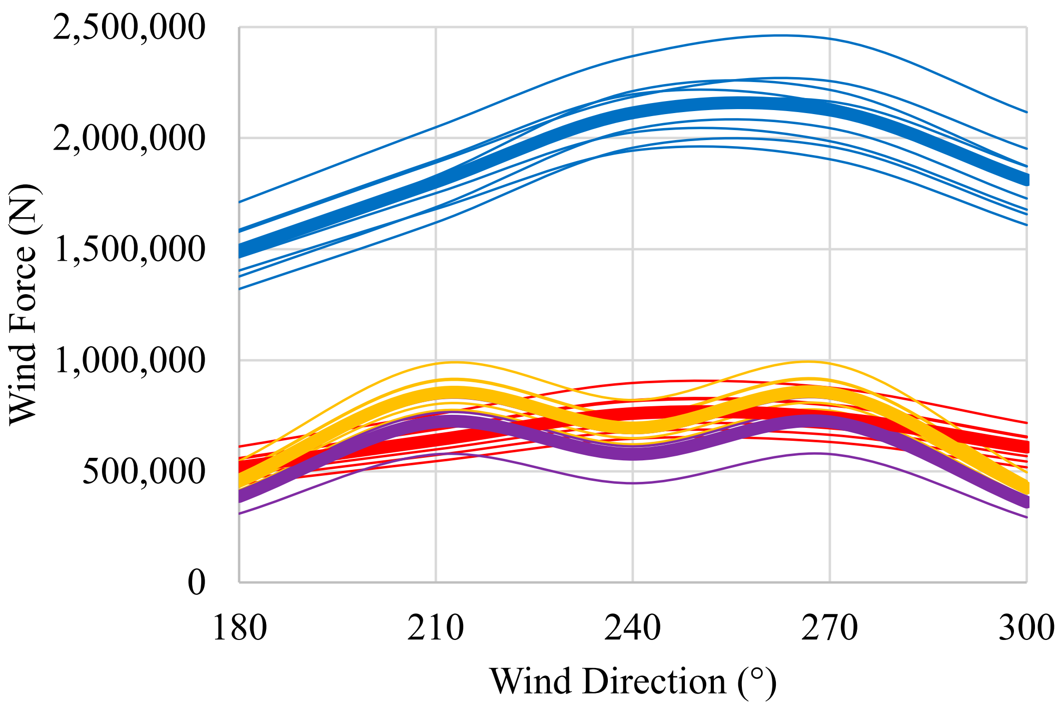

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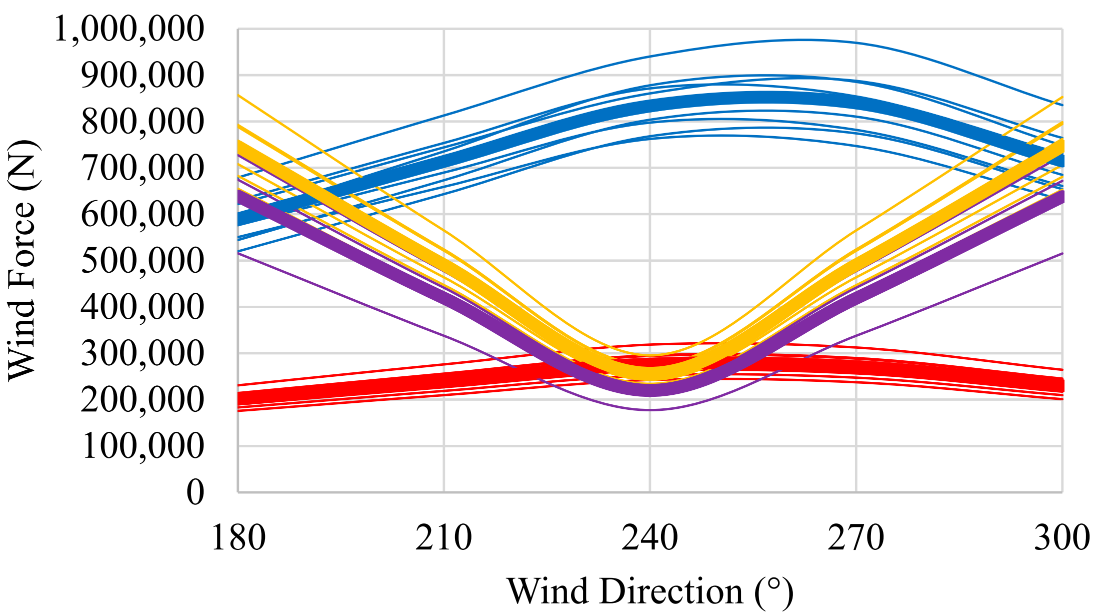

(**c**)

Figure 5. Wind force plotted against wind direction for (**a**) Deck in the x-direction; Wind force acting on the deck in the x-direction; (**b**) Deck in the z-direction; Wind force acting on the deck in the z-direction; (**c**) Piers in the x-direction; Wind force acting on the piers in the x-direction.

Both the Eurocode Case and CFD Case 1 followed the same shape trend for the deck in the x- and z-directions and the piers in the z-direction. Thus, the Eurocode does not accurately reflect the wind profile that wind would have on a deck in the z-direction and piers in the x-direction. The mean of the net wind force for the deck in the x-direction was larger for CFD Case 1 than for CFD Case 2. Reynolds-Averaged Navier–Stokes equations appear to produce smaller values of net wind force than Bernoulli's equation. Bernoulli's equation can only be applied to an ideal fluid, and Reynolds-Averaged Navier–Stokes equations can be applied to any viscous fluid. Thus, the Eurocode overestimates net wind force not intentionally by applying factors but unintentionally by its choice of calculation method.

The mean of the net wind force values for the CFD Case was lower than each of the other cases for the deck in the x- and z-directions and for the piers in the x-direction. This is because calculating a wind velocity based on past wind velocities, without attempting to project future wind velocities, is not a recognized method of calculating such values. Thus, given that the design life of a bridge is 100 years, the method described in the CFD Case is not recommended for calculating net wind force values unless a safe wind velocity can be determined.

The means and ranges of the Eurocode Case are larger than those of CFD Case 2 and the CFD Case for the deck in the x-direction. Thus, the CFD modelling method allows for more accurate net wind force values; the Eurocode method increases the range of values while not allowing them to be relatively small, ensuring that bridges in areas less prone to high winds are more overly engineered than bridges in areas more prone to high winds.

For the deck in both the x- and z-directions, the CFD Case, CFD Case 1 and CFD Case 2 have similar means and ranges, despite different factors being applied, while the Eurocode Case has much larger means and ranges. This is because of the exposure factor. For CFD and the Eurocode to be integrated so that the CFD modelling method has the same level of conservatism as the Eurocode, an exposure factor would need to be developed that could be applied earlier in the net wind force calculation.

For the piers in the x-direction, the CFD Case has a larger mean and range than CFD Case 1. This is despite the CFD Case not having any factors applied and not being conservative. Thus, CFD Case 1, by using the directional factor, despite using other factors, does not produce usable net wind force values for design purposes because it does not apply the directional and force coefficient factors that would inflate the net wind force values.

For the piers in the x-direction, the CFD Case and CFD Case 2 show that the wind directions 30° and 60° from the wind direction perpendicular to the bridge should have greater net wind force values. However, the directional factor reduces the net wind force values in these instances. This is not an issue when the Eurocode method is carried out in full but would be an issue for integrating the Eurocode with CFD.

6. Conclusions

This paper compared two methods of calculating the wind forces on medium-span bridges: the Eurocode computational method and the CFD modelling method, for different wind directions, altitudes and wind velocities. The Eurocode case had net wind force values far larger than any other case. This is partly due to the application of factors but also due to the method of calculation itself. The Eurocode is limited in its capabilities and presents a conservative method for wind analysis for bridges. Results indicate that the Eurocode prioritizes conservativeness over accuracy. It is clear that the exposure factor in particular inflates net wind force values. It was also found that the directional factor is conservative for wind forces on bridge decks but ineffective for wind forces on bridge piers in the x-direction.

The current Eurocode 1 Part 4 [6] is only applicable to bridges with spans no greater than 200 m. For long-span, complex bridges, it is hoped that future iterations of the Eurocode will provide guidance on the use of CFD. Perhaps there is an opportunity to combine the factors, coefficients and constants that provide the Eurocode with its conservativeness, with CFD. This paper performed calculations that combined these two methods. However, these factors, coefficients and constants were derived from wind tunnel testing and real-world measurements. As society moves towards a greater priority on sustainable, lean engineering design, greater consideration ought to be given to the derivation of these factors and coefficients. The intended impact of this study is to highlight the opportunities of CFD modelling with the intention of them becoming rigorously verified and validated and ultimately becoming adopted in the design and operational analysis of wind effects on long-span bridges.

Author Contributions: Conceptualization, J.K. and N.M.; methodology, J.K. and N.M.; software, N.M.; validation, N.M.; formal analysis, N.M.; investigation, N.M.; resources, N.M.; data curation, N.M.; writing—original draft preparation, N.M.; writing—review and editing, J.K.; visualization, N.M.; supervision, J.K.; project administration, N.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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