Study of Aerodynamic Effect on Skybridges Connecting Tall Buildings: A Computational Fluid Dynamic Approach

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Abstract: **Many cities have developed with the rapid growth of the population. Due to the shortage of land, tall buildings have to be implicit closeness. In the recent past due to various advantages, skybridges are adopted widely to connect adjacent buildings in the case of wind-induced motion, the vortex shedding causes a periodic driving force across the skybridge structure. Flutter and buffeting are the main aerodynamic instabilities in flexible bridges. In this research, a numerical simulation based on CFD was used to investigate the aerodynamic performance of skybridges. The numerical simulation was adopted using ANSYS/Fluent software to analyze four different skybridge configurations subjected to various wind forces. Throughout the simulation process that was carried out, the interaction of wind speed and cross-section of the skybridge deck was examined. All three aerodynamic forces showed an increment when the velocity increases. Results revealed that when the edges of the deck cross-section get smoother, aerodynamic forces acting on the skybridge get smaller. Hence, the model with curved edges gives the optimum cross-section for the construction of a skybridge.**

Keywords: Skybridges, Aerodynamic effects, Tall buildings, Computational Fluid Dynamics

I. INTRODUCTION

As technology advances, civil engineering tends to construct sophisticated structures like tall buildings and long-span bridges. Skybridges provide links between two tall buildings to move horizontally to another. Skybridges are high-level linkages that improve both the level of life safety for building residents and the economic feasibility of these "dead" spaces[1]. The structural behavior of skybridges depends on the location of the linkage, stiffness, mass, connection configuration with the building, and internal planning[2]. And the aerodynamic effect on the skybridge should be also examined.

II. AERODYNAMIC EFFECTS

The wind is one of the important forces acting upon civil structures. Structural damage and discomfort for the individuals inside become the principal issues caused by wind. Vortex shedding is a wind-induced phenomenon that occurs when wind streams over a structure, and strong swirls of air magnify the damaging effect of wind. The natural frequency includes in every single object tends to sway when that matches with the frequency of the vortex shedding.

As long as a structure is exposed to wind, the smooth wind flow is disturbed and separates around the body resulting in shedding vortices. Generally, the wind has a low viscosity. Flow gets deformed and it varies randomly. This generates forces on the body and forms vortices in the wake region.

Pressure changes as a result of the occurrence of alternative shedding vortices. The body tends to vibrate and it causes structural deflections on the body.

Furthermore, resonance due to flutter and buffeting should be inspected as they cause instability of aerodynamics. A flutter of a skybridge defines the vibration at a higher frequency of the bridge surface due to vortex shedding and twisting the bridge itself. Buffeting occurs when shedding vortices create vertical or lateral vibrations and it is caused by an impulse of load increasing[2].

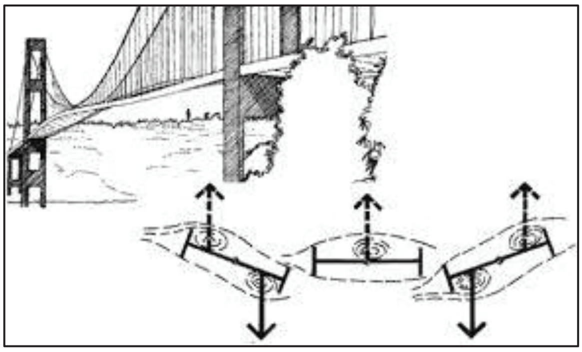

Fig.1 Flutter across a bridge deck[9]

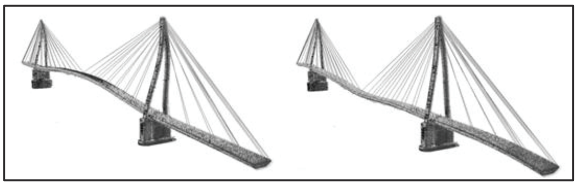

Fig.2. Buffeting across a bridge deck[8]

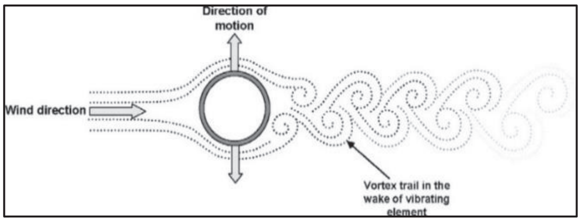

Fig.3. Shedding vortices across a structure[7]

III. Numerical Simulation

The aerodynamic effect on the structure of various configurations under different flow conditions can be evaluated by Computational Fluid Dynamic (CFD). Verification of numerical results can be done with wind tunnel test results on scaled models or real field data. Although CFD is not widely used in the construction industry, it is applied in the aerospace industry. As a result, we must do a CFD analysis to determine the stability.

ANSYS is one of the main software packages used by professionals in the building.

In comparison to the conventional method of wind tunnel tests for modeling and analysis, numerical study saves both money and time. The computer simulation is used as a rapid design tool to generate essential design information more efficiently relative to the wind tunnel experiments, allowing for more design trials to be completed in less time. It also makes it easier to investigate the effects of modified structural configurations and variations of cross-section geometries. As a result, a faster design cycle decreases design risk and makes actual bridge designs more cost-effective[3].

IV. Aerodynamic Stability of Skybridges

Instability phenomena have two types such as aerostatic instability and aerodynamic instability. Vortex shedding, Galloping, and Flutter are the most relevant aerodynamic instability phenomena. The creation of shedding vortices has caused vibrations in the deck and leads to feeling discomfort for pedestrians and material fatigue. In a vertical bending mode (Galloping) and a torsional mode (Torsional Flutter), these include modifying the global damping[4].

Flutter and buffeting are actions against the stability of the skybridges that occur when the structure is subjected to aerodynamic forces. When the bridge is exposed to the flutter effect, the bridge gets twisted due to a coupled motion of translation The bridge's stability against flutter is checked by holding the bridge's two adjacent natural frequencies at least 2.5 times apart

In buffeting, shedding vortices cause vertical and lateral vibrations while the efficiency of buffeting is checked using the techniques of spectral density analysis. Structural girders can be covered by proper

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profiling to reduce vortex shedding and buffeting[2].

V. PRACTICAL ISSUES RELATED TO AERODYNAMIC INSTABILITY

The Tacoma Narrow bridge in the USA was the third-longest suspension bridge with a central span of 2800 feet and two side spans of 1100 feet each. It was originally built in 1940 and with the collapse after four months, aerodynamic stability for bridges got a concern. It got swayed and bent even with the normal wind along its length. Resonance due to aeroelastic flutter where the frequency of shedding vortices that matched with the structure's natural frequency contributed to the failure under torsional mode. Moreover, the motion had transformed from rhythmically rising and sinking to a two-wave twisting as the torsional vibration amplitude increased. After both of these movements, the bridge center stayed rigid, while the other two halves twisted in opposite directions as shown in **Fig. 4.** Visible fractures developed there until the entire bridge collapsed into the river[5].

Fig. 4. Tacoma Bridge response with the Torsional Motion[5]

The primary cause of the Tacoma Narrows Bridge failure was an aeroelastic flutter. The wind flow pattern induced Vortex Shedding because the crosswind had to go over or under the bridge portion due to the existence of I-Girders. At the same time, bending vibration frequency and torsional frequency are almost closer [5].

VI. FLOW PARAMETERS

Prameters such as the Reynolds number, coefficient of drag force, lift force, and moment characterize the flow. Those parameters are defined as follows [6].

$$R_e = \frac{VB}{\upsilon} \qquad \ldots(1)$$

$$C_d = \frac{F_d}{0.5\,\rho V^2 D} \qquad \ldots(2)$$

$$C_l = \frac{F_l}{0.5\,\rho V^2 B} \qquad \ldots(3)$$

$$C_m = \frac{F_m}{0.5\,\rho V^2 B^2} \qquad \ldots(4)$$

F_d - Drag force
F_l - Lift force
F_m - Moment force
C_d - Drag coefficient
C_l - Lift coefficient
C_m - Moment coefficient
B - Breadth between the edges of both fairings
D - Height between upper and lower faces at the girder center
V - Velocity
υ - Kinematic viscosity
ρ - Density

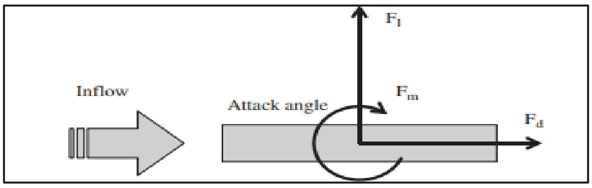

Fig. 6. Coordinate axis of aerodynamic forces[6]

VII. SELECTION OF DECK GEOMETRIES

Aerodynamic forces are the most significant loads acting on the skybridge due to its high elevation above the ground level. And they are mainly generated by the deck of the skybridge. Hence, aerodynamic forces are depending on the cross-section of the skybridge deck. Four different cross-sections were decided according to past research and those geometries were modeled using ANSYS/ Fluent. Cross sections generally adopted for the skybridge aerodynamic shaping were selected for this study based on the literature [2] as a qualitative description of bridge geometries for aerodynamic instabilities.

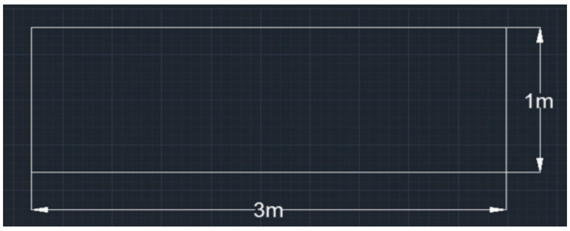

Fig.7. Deck 01 cross section

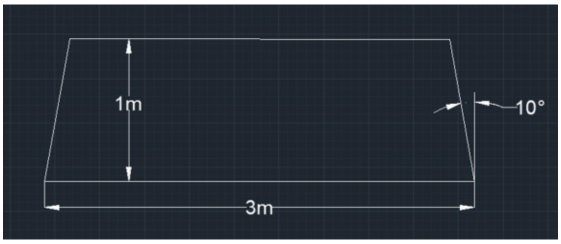

Fig.8. Deck 02 cross section

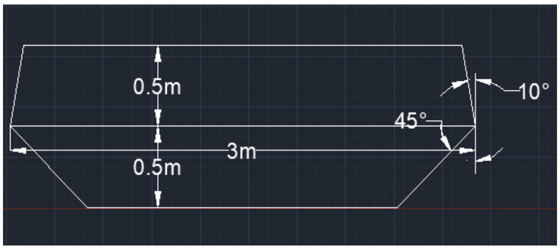

Fig.9. Deck 03 cross section

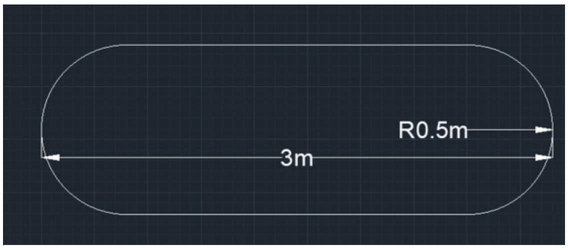

Fig.10. Deck 04 cross section

VIII. Modelling Process

ANSYS/Fluent software package was used to generate the models, which is one of the tools common computational fluid dynamic studies. A two-dimensional transient-state study was done on each deck for selected sky bridge cross sections. The aerodynamic forces for drag, lift, and torsional moment are one of the most essential parameters for this kind of load. Concerning these forces, the dimensionless aerodynamic coefficients for drag, lift, and the moment was calculated at various inlet velocities (40m/s – 60m/s). A section model with a 1m section depth is considered for the study.

Simulating CFD problems in ANSYS / Fluent usually consists of five main configurations.

1) Geometry
2) Grid generations
3) Setup
4) Solution
5) Results

This simulation's geometry consists of a large domain with the skybridge cross-section. Each geometry was created under the dimensions that were specified. The computational domain was sized for this study according to Watanabe and Fumoto[6].

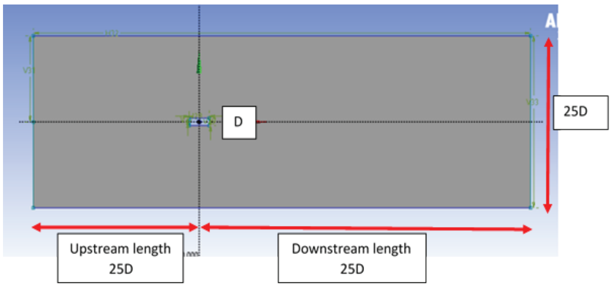

Fig.11. Fluid domain size

The domain region is divided into a finite number of computational elements to form computational grids. Grids can be either unstructured or structured. An unstructured grid is best adopted for complex geometries while a structured grid is only for simple geometries. Although the flow around the skybridge is significant and complex, these models should have a very fine unstructured grid in this region. Some of the edges were named here to make it easier to construct boundary conditions for the mesh.

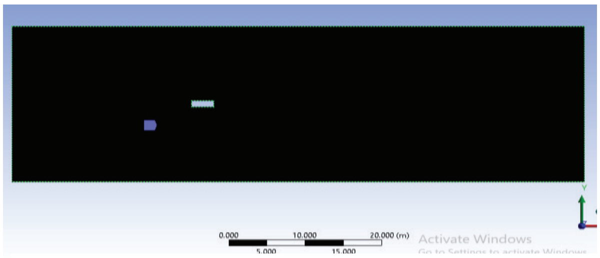

Fig.12. Meshing details of the skybridge cross section and the fluid domain

This proceeds to set up the model by defining the fluid, setting the boundary conditions, and solving the simulation. The Density-Based option is defined as the solver. The density of the fluid was 1.225 kg/m3. Various velocities ranging from 40m/s to 60m/s were entered.

During the Post-processing of the computed data, numerical models were

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generated to calculate the aerodynamic forces acting on the skybridge deck. Diagrams of velocity contour, pressure contour, and streamlines were obtained which are relevant to each model with varying velocities.

IX. WIND TUNNEL TESTING

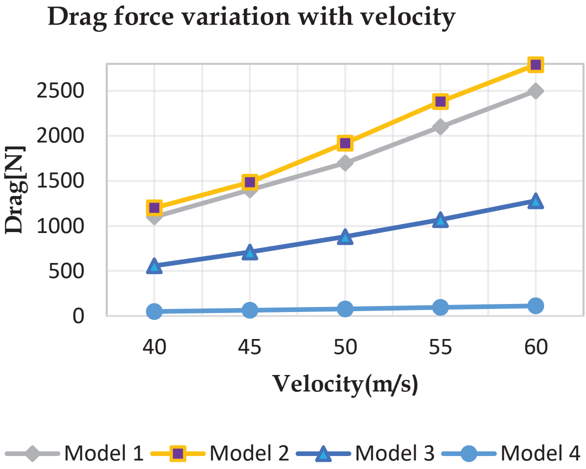
Despite the fact that the science of theoretical fluid mechanics is highly established and computational methods are applied, wind tunnel tests are still required to obtain insight into complicated processes related to wind effects on structures. A wind tunnel test, will not immediately give a bridge design or an ideal deck shape to maintain aerodynamic stability. It will assist in determining whether or not the design is acceptable from an aerodynamic standpoint, if not in identifying the source of undesired oscillations[6].

A variety of wind tunnels are utilized for different types of reduced models. Each of these serves a unique function. In this research validation, a closed-circuit wind tunnel was used with a section model to obtain results. Testing using sectional models is frequently used for analytical investigations of bridge behavior under the impact of wind. Which is perfect for this research. Furthermore, these tests must be carried out with the least amount of turbulence allowed[6].

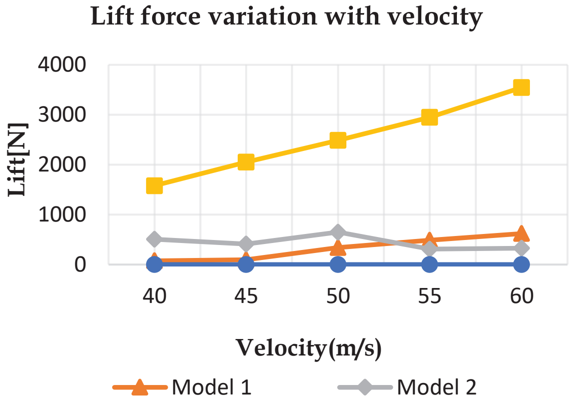
X. RESULTS AND DISCUSSION

In this study numerical simulation was carried out for four different sky bridge deck geometries with varying velocities. The effect of the wind speed that causes aerodynamic instabilities was investigated by generating the models for a quality mesh configuration. The solution strategies used to solve the governing equations of the model are sensitive to errors as the wind flow is very complex and irregular. The results for drag force, lift force, and moment acting on the bridge deck were tabulated and analyzed separately.

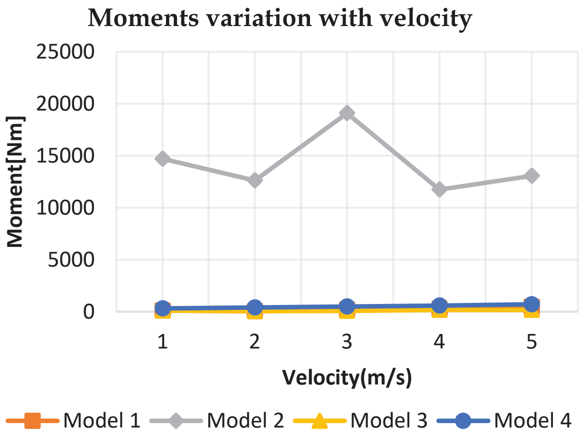
Magnitude values for the drag force gradually increase when the velocity increases. This reveals that drag force is directly dependent on the velocity. The fact behind this is that the faster the wind flows, the acting force on the skybridge in the flow direction gets increases. Furthermore, the model with a trapezoidal cross-section (Model 02) has the highest and the model with a curved edges cross-section (Model 04) has the lowest magnitude in the drag force.



Lift force is acting on the skybridge in the transversal to wind flow direction. From the results, it was identified that Model 03 has a significantly higher magnitude of lift force while Model 04 has the lowest. The difference in pressure generated above and below the skybridge as it travels through viscous air is measured as the lift force and the model with the least magnitude of lift force occupies the safest design. If there is a greater pressure difference, people affect discomfort. Therefore, Model 04 which is with curved edges has the highest aerodynamic stability.



The moment of a body through a fluid is defined as the torsional moment occurring at the center of gravity. The results show an increase in the magnitude of the moment as the velocity increases. Model 02 has a relatively greater moment than other models.

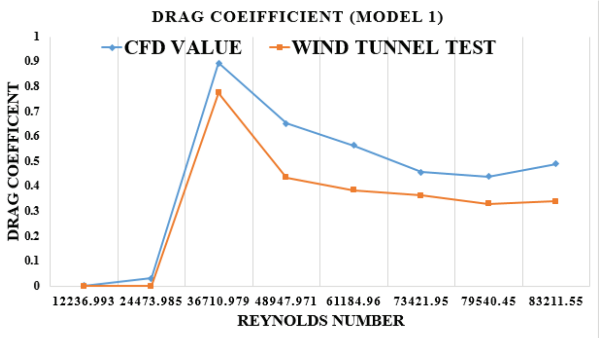


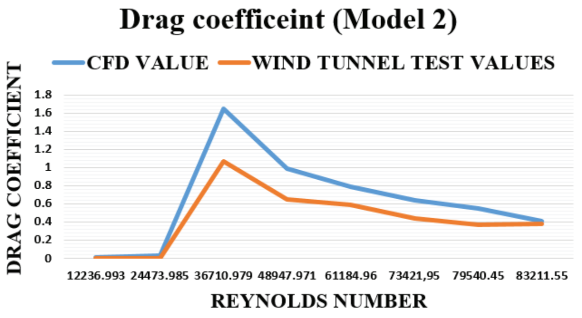
To ensure the accuracy of the results, a validation procedure will be followed. The objective of this procedure is to assess if the appropriate model has been chosen for the specific application of interest based on the experimental results. The numerical simulation results were compared against wind tunnel data collected during scale model testing. Results verified that the same Model 04 which is with curved edges has the highest aerodynamic stability.

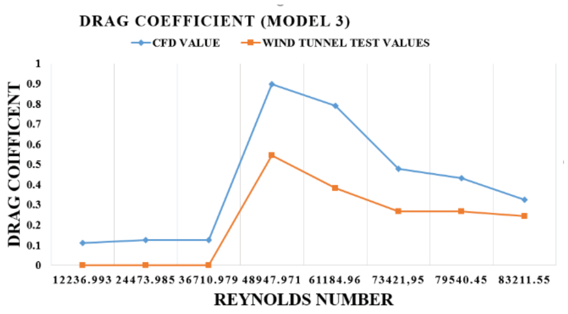
XI RESULTS COMPARISON

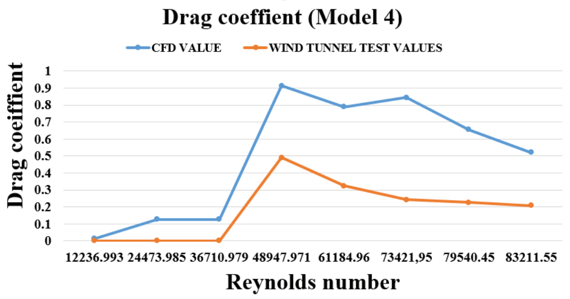
For result validation, the coefficients will have to be the same as for the results taken from the wind tunnel testing

A *Drag coefficient*



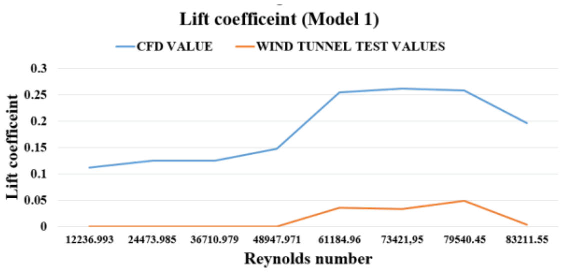


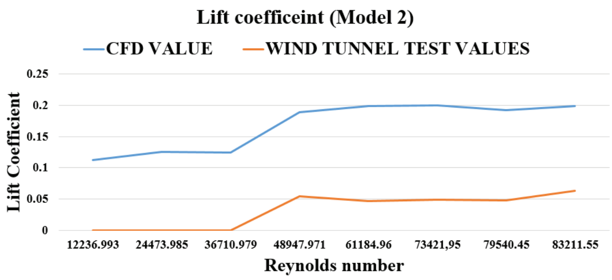


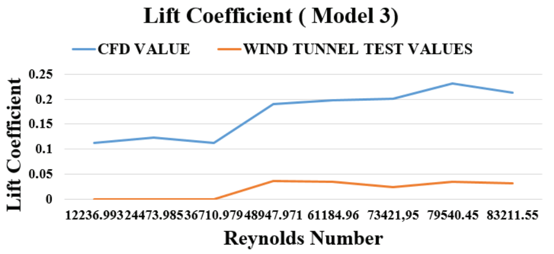


Both the CFD model values and the wind tunnel findings, when compared, have produced an identical optimal model. However, the lack of adequate facilities for wind tunnel testing appears to have an impact on the outcome since you can detect a difference between the final drag coefficient values

B *Lift force*







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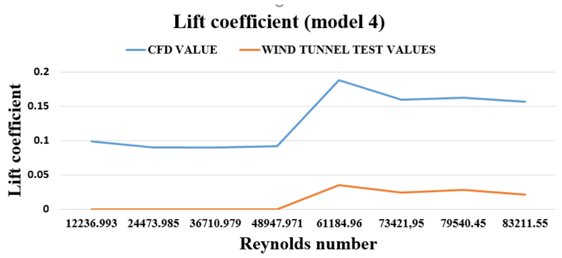
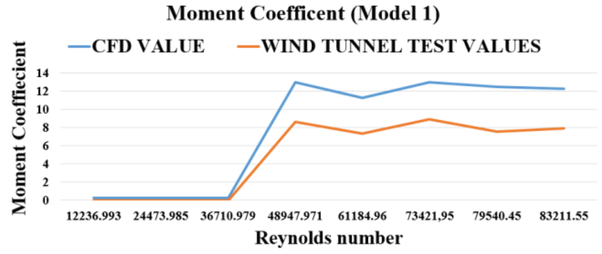
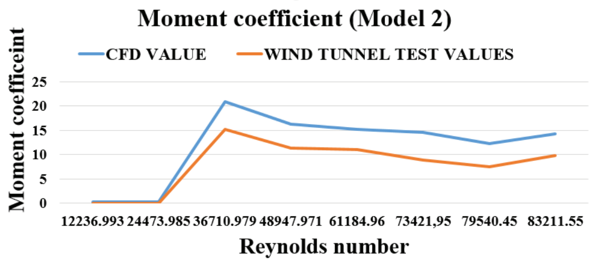
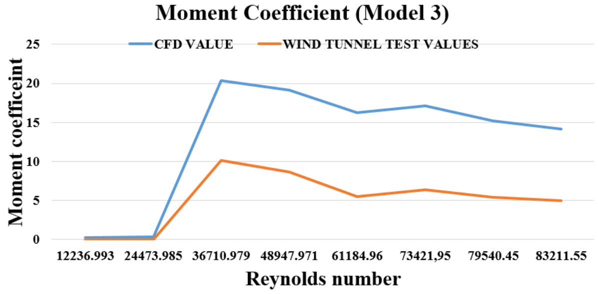


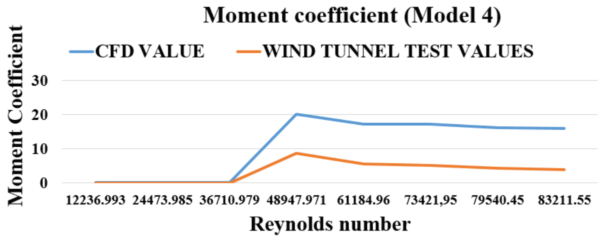
Both the CFD graph and the wind tunnel graph appear to have roughly the same shape when it comes to the lift force. however, they don't cross across. According to the final results, both models appear to have the same optimal form.

C *Moment*









Both the CFD model and the wind tunnel section model have produced the identical optimal geometrical form for the moment created by the model at zero angles of attack.

Overall, the number of scaled-down models was limited when using the available wind tunnel test section for wind tunnel testing. The force detector's accuracy may have had an impact on how the CFD model results and wind tunnel results varied. However, for the majority of the test, both the wind tunnel test and the CFD model appear to demonstrate the same pattern of aerodynamic coefficient patterns.

XII CONCLUSIONS

A numerical simulation of the aerodynamic effect around the skybridge was performed using the CFD approach. Four cross-sections were analyzed by running ANSYS/Fluent software package. Models were developed to examine the fluid-structure interaction at different velocity levels. Related parameters were entered to generate the mesh and setup procedures. Results for three main aerodynamic variables, namely F_d, F_l, and F_m were calculated and plotted. These obtained results were compared with each cross-section to find the optimum geometry. Furthermore, the models were able to report the velocity and pressure contours as well as streamlines around the skybridge section. Wind flow patterns were observed based on those outputs. All three aerodynamic forces showed an increment when the velocity increases. The drag force, lift force, and moment have a mathematical relationship with the square of the velocity if other parameters keep constant.

$$F_d \alpha V^2 \qquad \ldots(5)$$

$$F_l \alpha V^2 \qquad \ldots(6)$$

$$F_m \alpha V^2 \qquad \ldots(7)$$

Results revealed that when the edges of the deck cross-section get smoother, aerodynamic forces acting on the skybridge get smaller. Hence, the Model 04 with curved edges gives the optimum cross-section for the construction of a skybridge.

The validation procedure results indicate that the aerodynamic coefficients fluctuate slightly between CFD and wind tunnel tests. The Source of errors in these variations can be due to the quality of the mesh, inadequate time steps in CFD, and human errors during the experimental process.

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