Shaping Effects on Long Span Bridge Deck Aerodynamics

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Abstract- An aerodynamic circumstance of wind pressure surrounding the long-span bridge allocates many theoretical and experimental research to this topic. Determination of the materials and optimal cross-sectional shape of bridge decks that affected a dynamic behavior of long span bridge deck is still included in current research issues and works to be continued in this path. These include the Lack of sufficient awareness of wind forces, stemming from complex nature, and the unpredictability of the wind nature. In this study, in addition to recognizing the aerodynamic behavior of the flutter, the acting pressure forces on the bridge deck are investigated. The geometrical shape of decks, wind velocity, and flutter conditions are adopted as design variables that affected the dynamic forces exerted on bridge decks. A common type of geometric sections of the long-span bridge deck and effective aerodynamic phenomena are examined. The hollow box steel suspended deck and double cells box girder linked via upper flanges and cells linked via the top and bottom flanges are adopted for Computational Fluid Dynamic (CFD) approach. Thus, aerodynamic instability and turbulent torsional flutter flows, as well as a trail of shedding vortices around the bridge decks, are investigated. By changing some geometrical parameters of commonly used bridge sections, the optimal cross-section in terms of turbulence created above and below the deck section is examined and an optimal cross-sectional shape variable is proposed. The shape variable and section dimensions adopted for CFD-Simulations are similar to the dimensions and materials used in previous laboratory specimens of wind tunnels to be able to interpret the results and possibly verify them with the result of the current study.

Keywords: Wind load, hollow box steel suspended deck, box girder deck, aerodynamic instability, trail of shedding vortices.

1. Introduction

Construction of bridges with long spans on valleys, lakes is increasingly underway and in turn, new techniques must be adopted to calculate and estimate the forces acting on bridge components, building materials, and the type of bridge deck cross-section, both in the design and construction phase. One of the major forces acting on bridges is wind pressure. Lack of sufficient knowledge and careful study of the forces applied by the wind loads can cause severe vibrations on the bridge deck and may occurrence of a resonance condition that can lead to complete failure of the bridge. The collapse of the Tacoma Bridge in the United States (1940) and Brington Bridge in China (1879) are the examples of a bridge collapse due to unexpected wind loads.

In general, the effect of wind depends on factors such as geographical location, height of the area above sea water level, topography of the bridge site, and geometric characteristics of the bridge. The wind speed increases at higher elevations above ground level, and thus we face more air pressure at higher elevations. Since the fluctuations caused by turbulent wind currents on bridges are of great importance, the study of the geometric shape of the bridge deck is one of the most important issues in bridge engineering and requires more comprehensive studies. The compressive pressure is exerted on the windward surface, while there is the suction on the leeward sides or parallel surfaces of the wind flow, and the wind does not flow steadily, the air particles collide with the turbulence as they move. Vortex shedding tails is created which put more local pressure around bridge components. This is reason that an additional local pressure is created around the decks and should be taken into consideration in structural design process.

In general, wind load is dynamic in nature, meaning that its magnitude varies with time and space. As a result, the analysis and modeling of such a load and its relative effects on structures can be complex, and requires a great deal of knowledge in mathematics, CFD, and structural analysis. For instance, the structure starts to fluctuate with the wind flow and then following the deck vibration itself affects the wind flow interactively, sometimes its increases and sometimes its decreases turbulence currents. Such an inactive effect can be examined by CFD-Simulation and experimental procedures like wind tunnel tests.

The regulations for the design of bridges against wind forces, such as European EN-1991-1-4 (Eurocode 1), [1] have special design criteria for structural designers against incoming wind forces on surfaces of structures, dynamic and static responses of long-span bridges. Despite the complex nature of wind forces, the regulation proposes relatively simple methods for the modeling of wind flutter phenomena and their corresponding effects on bridge structures, as well as determine the aeroelastic and dynamic responses of structures. However, sufficient knowledge of the context and logic applied in the simplified proposed method is required for using these criteria. It should be ensured that the results of the hypotheses and limitations of the suggested methods should reflect the real conditions at the bridge construction site. On the other hand, the relationships provided for the responses toward wind direction and the reciprocal wind responses (outside the wind direction) are not considered in simplified method. According to the regulation criteria, single bridges with a main span length of more than 50 meters need to be dynamically checked and the wind load coefficients provided by simplified method is not accurate enough for use in practice. The simplified criteria are true for bridges with a simple geometric shape with the dominant first mode. More precise dynamic analysis is required for several complex deck shapes such as long span suspension bridge decks exposed to strong turbulent wind flow.

The aerodynamic stability of bridges is determined largely based on wind tunnel tests. Since CFD-Simulations methods have developed, it has been used as a complement to test ways. Although very time consuming and costly, wind tunnels have become popular with researchers and bridge design engineers. The use of CFD simulation is not a reliable alternative to wind tunnel testing and verification by experimental results is required. Nevertheless, it can be used as a powerful tool for documenting and examining various scenarios prior to laboratory simulations. This is also easily done by changing the modeling input parameters.

The main purpose of this study is to examine the aerodynamic stability of long span bridge decks subjected to strong wind flutter condition. The effects of the geometry of the bridge deck on the pressure distribution on the deck surface is also examined. In addition to introducing and examining the shape of common decks, an attempt has been made to estimate pressure caused by tail of vortex shedding. The CFD approach, assumptions and domain size considered in the analyzes are introduced. The effect of the geometric shape of the deck on the dynamic behavior under the influence of the wind current is evaluated and compared. Thus, recommendations on the optimal deck cross-sectional shape are introduced. As mentioned before, numerical simulations of wind flow will be valid and reliable if they can be reproduced by experimental tests. In this study, the author tried to construct structural models similar to laboratory samples tested in previous research in order to compare, adapt and validate the results obtained.

2. Literature Review on Previous Works

The following is a brief description of the papers used with the topic of the flutter phenomenon and the impact of deck shaping under wind flows and wind tunnels experiments.

The aerodynamic static coefficients of the 2-edge sloped box beam were assessed by Lee *et al.*, [2]. The static wind load coefficient sensivity angle of attack was evaluated for 2-edge sloped box girder. A series of wind tunnel tests were conducted by changing the the box slope angle from 0° to 17°, whereas the attack angle was arranged in between -10° to 10°. The consequences illustrated that the lateral wind force decreased significantly with increasing box slope angle, except when the physical angle was 8°–11°. For the practical range of angle of attack, the box slope must be greater than 15° to minimize the aerodynamic static lateral force on the beam. Ying *et al.*, [3] comprehensively investigated the limit cycle flutter characteristics of a bridge deck through use a fluid-structure interaction model. Its precision was confirmed by the flutter reactions of a thin plate with theoretical solutions. The aeroelastic responses of a bridge deck was numerically simulated. As the angle of attack increases, the section shape turns into much blunter, so it becomes more prone to limit cycle flutter. The advanced numerical simulation supplyes a robust instrument for limit cycle flutter analyses of bridges with large span. The sufficient precision of the numerical models is verified by comparison with the experimental results.

The flutter performance of a twin-box bridge girder at large angles of attack were investigated. Several central slot widths were taken into consideration. The stationary and dynamic flow field characteristics were changed. The results of both CFD-simulations and wind tunnel testing are compared (Tang *et al.*) [4]. The analysis results imply that the presence of the central slot benefits the bridge flutter stability at null angle of attack. However, the flow field around the girder is varied at large angles of attack. The incoming flow may run through the central slot and act on the vortex connecting to the girder. The upstream box draws energy from the wind flow easier than downstream, thus leading the bridge to torsional flutter instability at lower wind velocities. Montoya *et al.*, [5], proposed a methodology for performing the aerostructural design of bridges with large span in early design phases by taken into account a number of parameter variation to analyze the relations in between the geometric shape of deck and the buffeting repercussions. This information is used to tailor the deck shape aiming at keeping the buffeting response under a given threshold. This outcome is applied to adapt the shape of the deck, which aims to keep the buffeting response below a certain threshold.

Kusano *et al.*, [6] carried out the CFD simulations of a single-box deck section to investigate the significance of railings and vortex attenuation tools on the bridge reaction subjected to wind pressure. Several cross section of bridge deck were investigated like a bare section and deck sections with attenuation tools and altering the width of deck. Coefficients of aerodynamic force get through CFD simulations were then applied to calculate flutter derivatives on the basis of quasi-steady formula. Flutter speed was computed for several cross sections. The deck section with the greatest width to depth ratio has the highest efficiency towards instability of flutte phenomenon. Although it appears the vortex attunation tools be in tendency to develop the aerodynamic behavior of the bridge through changing the flow field around the bridge deck. Liu *et al.*, [7] presented the properties of self-excited forces are in both in the time-domain and frequency-domain. The flutter calculation is performed subjected to both smooth flow and turbulent flow to evaluate the impact of wind turbulence on the instability condition of the flutter. By comparing of the results of several turbulence severites with that of the smooth flow, it was concluded that the turbulence has a stabilizing impact on flutter condition of bridge. The turbulence can alter the vibration patterns and decline the spatial vibration correlation in some degree. Consequently, the critical flutter speed could be augmented by 5% to 10%.

Yang *et al.*, [8] examined two critical flutter and vortex-induced vibration performance performance of closed-box girder bridges with lower inclined web angles and various wind fairing angles by experimental research and theoretical studies by performing a theoretical analysis and wind tunnel testing results. The results indicate that for a given inclined web angle, a closed box girder with a sharper wind fairing angle of 50° has better flutter and vortex-induced vibration performance than 60°, while a 14° inclined web angle reduces the best vortex-induced vibration performance. Furthermore, a wind fairing angle of 50° reduces a preferable flutter output by causing a single vortex shape and a balanced distribution of the strength of vorticity in both lower and upper sides of the wake zone.

Hansen, [9-11] analyzed the critical wind velocities of the flutter phenomenon on the bridge during the construction of the Great Belt East. This research was commissioned by Steinman Co. with the aim of reviewing the work done by COWI Consulting Engineers. The research report was based on wind tunnel experiments and they concluded that the most critical stage of construction is when the fifth section of the bridge is installed. The deck of the bridge at that stage was 249 meters long. The results of this research indicated the critical wind speed of the flutter is at about 43.3 m/s^2. They also observed that the phenomenon of vibration occurs at the collision of two characteristic modes of torsional and vertical transition. Frandsen, [12] conducted extensive studies on fluid dynamics analysis and proposed several structural fluid formulations to find the critical float velocities of the built bridges. Although the fluid range was relatively large, the results were surprisingly good. In that study, even the smallest mesh elements had a characteristic length of approximately one meter. He observed the beginning of the vortex shedding behind the bridge deck. The fluid range of 1900 nodes was modeled in an irregular mesh structure. The critical wind velocity of the float was calculated between 65 m/s and 70 m/s, which was slightly lower than the values measured from the Danish Maritime Institute's wind tunnel test in 1992 and 1993. The results of fluid dynamics analysis through the finite element model of structures to estimate the critical float wind speeds were presented with sufficient accuracy, but not enough to the extent that there is no need to conform and adapt to the laboratory results of wind tunnels.

Awruch and Braun [13] used two different methods to find flutter critical wind speeds. The forced vibration test was performed on a numerical model and the oscillations were simulated by altering the input wind angle. The experiment was performed to find aerodynamic derivatives and the critical wind velocity of the floater was 73 m/s. They also performed structural-fluid interaction analyzes. The analysis resulted in a critical flutter wind speed of 69 m/s. Both of these results were in good agreement with the quantities obtained from the wind tunnel test. The Strohall number was $S_t = 0.18$, which was close to the quantities of wind tunnel test measurements.

Cigada *et al.*, [14] introduced a new approach to simulate the bridge deck response to turbulent winds. The results show that the wind tunnel test has an important and fundamental role in determining the values of variables used in bridge deck simulation software against turbulent and tornado loads. The aerodynamic acceptance function is one of the hardest variables to estimate because it depends on the control of the incoming tornado spectrum as well as the ratio of the average wind-to-deck angle that varies in time and space. Larsen *et al.*, [15] examined a variety of box beam deck models and determined the optimal geometric shape to prevent the formation of wind vortex response. All models of this research have been made and tested in the laboratory and in the wind tunnel. The results indicated that a deck could be obtained without virtual vibration and also the angle between the lower horizontal plane of the deck and the sloping side plate is a fundamental variable to achieve this goal (Larsen *et al.*) [15].

Larsen *et al.*, [16] examined the dynamic effects of wind on two types of suspension and cable bridges. This study addresses the different types of wind dynamic effects that usually occur on suspension and cable bridges with emphasis on the importance of understanding the dynamics of the bridge structure. Anina *et al.*, [17] performed an experimental and analytical research of load coefficients and free vibrations of bridge decks. The results of the analysis are firstly compared with the quantites get from the wind tunnel and validated. In this model, two-dimensional model analysis is assumed and, in the analysis, the deck cross-section used in the wind tunnel was used. Han *et al.*, [18] investigated the impacts of aerodynamic variables on the dynamic response of road and deck vehicles and bridges under vertical wind loads on vehicle direction. At first, they simplified the vehicle and the forces applied from the wind to the vehicle using mathematical formulas, and then the result of these forces was applied to the bridge deck, and finally, the effects of wind on the bridge deck were obtained using mathematical calculations. The results show the different and often increasing effects of these vehicles on the output of deck forces. Some recent literature review on the impact of deck cross section under wind loads are described in the following:

Pindado *et al.*, [19] investigated the impact of the cross-sectional deck shape on the aerodynamics of the uniform deflection-rotational torques of the cantilever bridges during construction. The oscillating torque applied on the deck of a reinforced concrete box was made experimentally, using a balanced cantilever installation method, during the bridge installation operation. The impact of the shape of the box beam deck was tested by wind tunnel using four models based on the different cross section for box bridges with different angles of the box girder. The parameter was taken to be a = 0.02 m (Fig. 4). The results of their experiments showed that the reduction of deflection oscillation torque coefficients decreases with the linearization of the bridge deck shape and when the length of the deck is close to twice the width of the deck, the Yawing moment coefficient attains its maximum quantity. Larose *et al.*, [20] performed laboratory measurements on the forces of wind blowing for different models of bridge decks at the Danish Maritime Research Center in Denmark. The results of the wind tunnel test were reported to investigate the volumetric distribution of wind loads as a function of deck width and sudden turbulent flow for different sections of the bridge deck. For the geometric variable of the cross-section, the ratio of width to height of the cross-section was considered, and laboratory models were tested with ratios of 5, 7.5, 10, and 12.67 (Fig. 6). They examined and reported a more detailed relationship between aerodynamic flow direction and forces along the bridge span.

Larsen and Wall [15] conducted research on the effect of deck shape to prevent vortex shedding from responding to the aerodynamics laboratory at the Ottawa National Research Center in Canada. The side edge angle of trapezoidal box decks was a geometric variable in the models tested for their research work (Fig. 7). The authors showed that free decks can be obtained from virtual vibration and that the angle between the bottom surface of the deck and the inclined side is a significant parameter to achieve this aim. The results of their experiments showed that the trapezoidal cross-section of the bridge deck can be adopted to prevent the formation of vortex shedding for specific structural damping. The experiments were performed for relatively small Reynolds numbers, but subsequent tests also confirmed the results for high Reynolds numbers. It was observed that the angle between the bottom plate and the side panel is about 15 degrees, which is almost the optimal value for the trapezoidal cross-section of the bridge deck. The vortex shedding was just below the side panel.

3. Aerodynamics and Wind-Induced Forces on Long Span Bridge Decks

In this section, a brief introduction to the load phenomena emerging on long-span bridge decks is expressed. This study focuses on the flutter phenomenon, but an understanding of other phenomena is necessary for fully grasping the nature of the wind-induced motions. The impacts that occured when long-span suspension bridges are under wind-induced forces can be rather excessive and in critical situations causing the full collapse of the bridge. The effect of the wind loads is dependent on the aerodynamic characteristics of the bridge deck. A bridge deck entangled in a flow interacts with the flow, and is, as a result, exposed to compressive or suction surface pressures. The applying turbulent flow will produce the dynamic forces on the bridge deck which causes the time-dependent lift force, drag force, and moment loads on bridge decks. The forces are classified into static forces, related to the mean wind speed, and forces associated with the pressure fluctuations (buffeting), due to the turbulence.

Wind-induced loads on long-span bridge decks are classified into three separate groups: (a) Extraneously induced excitation covers dynamic loads due to turbulence with very large movements in the applying wind. The motions due to fluctuating winds are called buffeting. (b) Instability due to turbulence developed by the bridge deck itself goes by the name of signature turbulence. This covers the well-known Von Kármán’s Street which is likely to be in resonance with the bridge structure. (c) Aerodynamic instability (negative damping), where motion-induced wind loads arise on the bridge structure. This covers phenomena such as galloping and flutter. (Morgenthal) [21-22]. The origin of the loads can be classified into the motionless and moving bridge deck. An explanation of the wind-induced loads expressed in the following sections.

3.1 Aerodynamic Instability (Galloping and flutter phenomenon)

Flutter and galloping both occur for the wind which does not act in resonance with the structure, both are described as aerodynamic instability phenomena. In addition, the phenomena are independent of the turbulence of the incoming wind but can arise in a uniform flow. Galloping is the phenomenon occurring when the structural vibrations are almost perpendicular to the incoming wind and are characterized by negative aerodynamic damping as the driving force. Flutter is a combination of a coupled vertical motion and a rotational motion. It is important for the coupled flutter vibration, that there is a phase difference between the torsional and the vertical movement. If there is no phase difference between the two movements, the resulting work is zero. Flutter is said to occur when the energy input, from the wind velocity, is equal to the energy dissipated. This velocity is known as the critical flutter wind velocity. The aerodynamic damping loads become negative when exceeding the critical flutter wind velocity, and thereby further increasing the vibration amplitudes. For flutter to occur, the torsional frequency must exceed the vertical frequency for the bridge movements, but only marginally. This ensures the continued energy transfer to the system which is crucial for the phenomenon to arise. Other than, the energy transfer will dissipate due to structural damping. (Hansen and Dyrbye) [23].

Depending on the cross-section of the bridge deck, increasing wind velocity leads to aerodynamic instability. If the aerodynamic effects are continuous and gradually stronger due to aerodynamic forces in some places, they will experience self-induced increasing oscillating movements, which is called flutter. The flutter is basically a stability problem that causes the bridge to experience large and increasing vibrations (intensifying) to the point of failure.

In Fig. 1, a schematic flow around a stationary bridge deck profile is presented. On the windward side of the profile, a point of stagnation is expected for a bridge at rest. On the first two edges, the flow is expected to separate, forming two standing vortices. Due to the relatively large afterbody, it is expected that the flow reattaches to the bridge deck. This is expected as the width of the bridge is larger than the vortex formed on the edge. The global forces on the bridge deck are very sensitive to the reattachment, as this dictates the size of the vortex where the relative pressure is large. After the reattachment a turbulent boundary layer builds up until the end of the profile is reached. Due to the sharp edges on the leeward side of the profile, vortices are expected to be shed periodically forming a well-known vortex street in the wake. Strong adverse pressure gradients are expected to arise when the wind passes over the sharp edges on the top and bottom of the bridge. This will cause the flow to separate from the boundary, forming two standing vortices. The vortex on the top side of the bridge is formed on a sharper edge, resembling a backward-facing step.

Periodic movements of a structure may happen when the vortices formed around the body is shed at a frequency close to the eigenfrequency of the structure. Both vertical and torsional modes should be considered. Vortex induced motions can be avoided by providing that the frequencies of the vortices created are widely separated from the structure's natural frequencies. This is performed by altering the geometry of the bridge design or changing the natural frequencies. The shedding frequency is usually defined by the use of Strouhal's number. The necessary values for the determination of Strouhal's number for the bridge deck can be found by the use of two contour plots from the simulation, one illustrating the horizontal velocity and one illustrating the vortices. The Strohall number is a function of the Reynolds number:

$$R_e = \frac{VD\rho}{\mu} \quad (1)$$

In this expression, V is wind velocity, D is the diameter of the cross-section, or in this instance the height of the deck, ρ is the specific gravity of air, μ is the coefficient of kinematic viscosity of air.

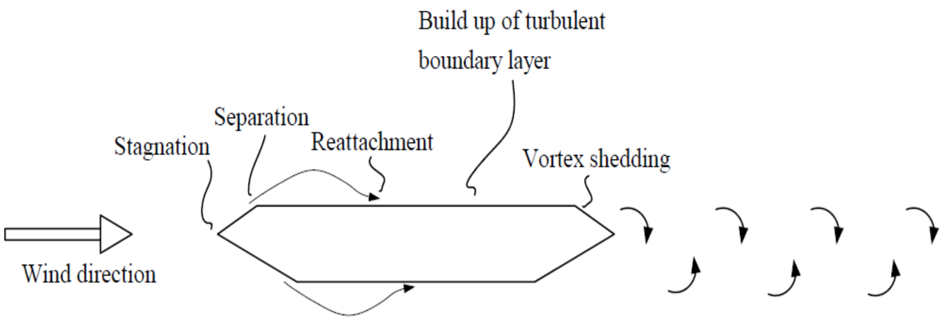


Fig. 1. Schematic view of the wind flow around the bridge deck

4. Basic Assumptions in Fluid Dynamics Analysis

To compute the critical flutter wind speed of the bridge deck float, the cross-sectional area of the box bridges and the flat deck with different edge angles have been adopted for CFD Simulation. In modeling, the cross-section is modeled as a rigid body. For this reason, the deformation of the bridge deck itself is not considered in the CFD-simulations. Since the deformations of the deck itself are very small compared to the vibrations of the bridge, it is assumed that they have very little effect on the movements created by wind loads.

The formation of periodic variable vortices The von Karman's vortex road, following the bridge deck, is very dependent on the meshing around the surface of the windward deck. Since eddies are formed by several meshing elements, the size of the eddies naturally determines the meshing size. In the shape of the road, a fully formed eddy current can be seen. Numerical models lead to more accurate results by increasing the mesh density and reducing the size of the loading steps. But the point is that the optimum mesh size and loading steps also lead to sufficiently acceptable results, but less time is spent solving the equations. Numerical models are less sensitive to the effects of boundary layers.

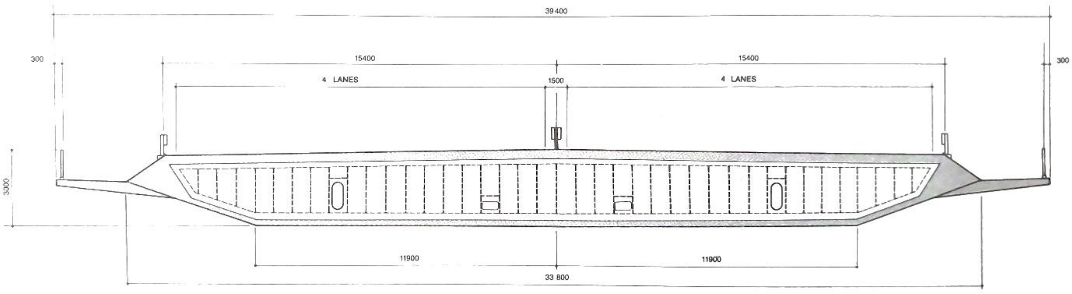
4.1 Design variables for selected flat trapezoidal and box girder decks

Design engineers use streamlined, box, and twin girders or the trapezoidal flat section types according to architectural issues and structural needs in the relevant project. The cross-section of bridges used in this study is divided into three main categories: simple trapezoidal, box girder beams, and double box girder types. The suspended deck of Fatih Sultan Mehmet Bridge over the Bosphorus strait is an example of flat trapezoidal used in this study as shown in Fig. 2. The main span between its towers is 1090 m. The underside of the deck is 64 m above sea level. The steel suspended deck is a hollow box composed of orthotropic, stiffened panels, having an aerodynamic cross-section. The deck has a 33.80 m x 3.00 m box section and two cantilever side walks of 2.8 m at each side. The total width of the deck is 39.40 m. Length of deck unit are variable and their weights are between 115-230 tons. Multiple advantages lie with this box form compared with the classical stiffened truss. Much less steel is required in the boxes which means less material in the cables, towers, anchorages, and foundations. The “steam lined” shape improves aerodynamic performance and reduces the wind loading on the bridge. The large flat uncluttered surfaces are much easier to maintain than the truss girder. The deformation caused by the movements caused by the wind flow is the maximum value in the middle part of the bridge span, so it is assumed that the sections that are under flutter in the analysis of dynamic analysis are adopted from the middle part of the long-span bridge.

The selected section dimensions adopted for CFD-Simulations are similar to the dimensions and materials used in previous laboratory samples of wind tunnels to be able to interpret the results and possibly verify them with the result of the current study. Important parameters affecting the shape and behavior of both trapezoidal flat girders and box girders are examined. By changing the dimensional sectional ratios, the effect of shapes on wind flow around deck is investigated. In order to find the most suitable cross-sectional shape, the pressure distribution caused by the wind flow has been clarified.

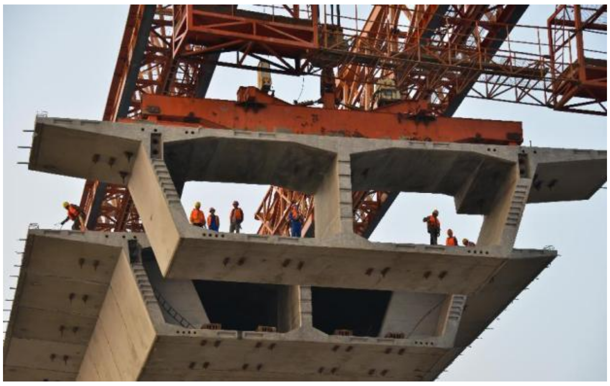
The impact of the box beam deck was tested by Pindado *et al.*, [19] in a wind tunnel using four models based on the different cross-sections for box bridges with different angles of box girders are adopted for CFD-Simulations. The parameter was taken to be a = 0.02 m (Fig. 4). Trapezoidal flat cross-section models used by Larose *et al.*, [20] are adopted for this study. For the geometric variable of the cross-section, the ratio of width to height of the cross-section is considered, and simulation models are prepared with ratios of 5, 7.5, 10, and 12.67 (Fig. 6), similar to those used in experimental test specimens. The section dimension and deck shape (side edge angle) effects of trapezoidal box deck models conduced by Larsen and Wall, [15] are adopted for this research. The dimension details and geometric variables in the models tested for their research work shown in Fig.

(a)



(b)

Fig. 2. (a) Deck view and (b) section from the deck of Fatih Sultan Mehmet Bridge



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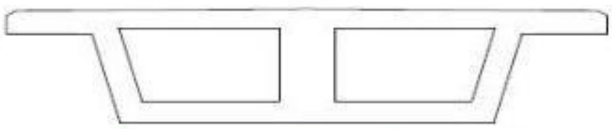


(a)

(c)

Fig. 3. Box girder with cells linked by upper flanges and cells linked to both lower and upper flanges

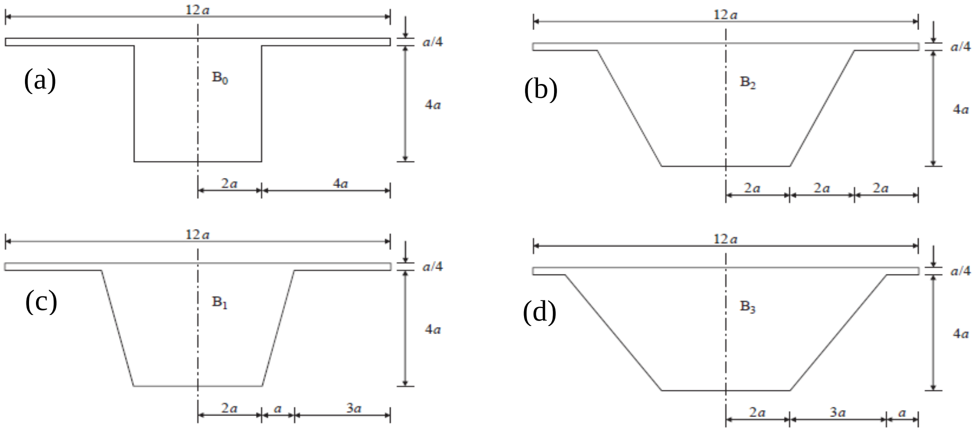


Fig. 4. Bridge deck model designed for CFD-Simulations wind analysis, with different cross section for bridges with different angles of box girder (a = 0.02m)

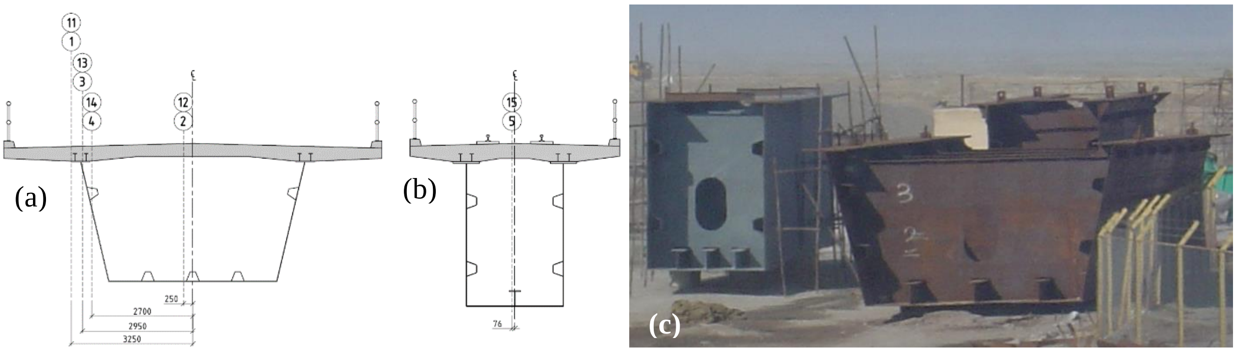


Fig. 5. Trapezoidal cross section bridge deck model with different length to width ratio (5,7.5, 10 and 12.67)

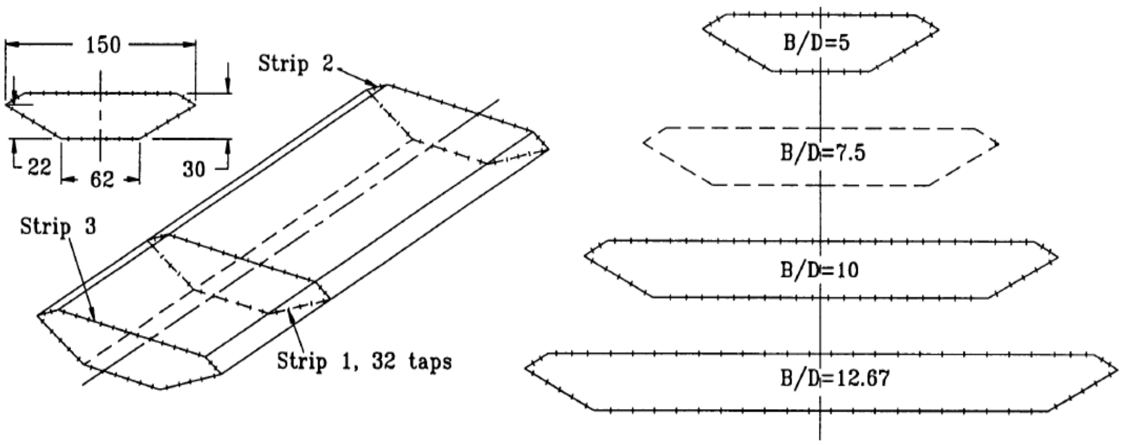


Fig. 6. Trapezoidal cross section model of bridge deck with different length to width ratio (5,7.5, 10 and 12.67)

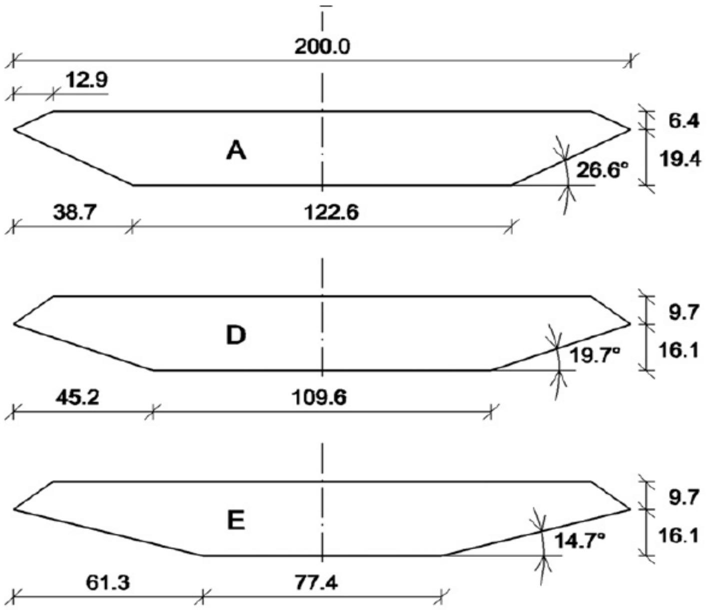


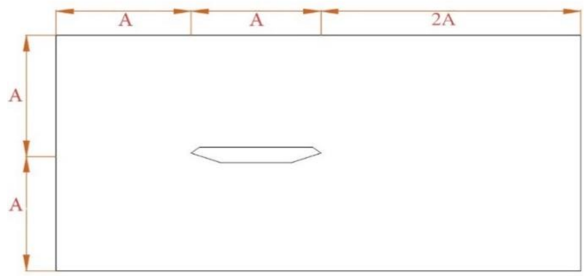
Fig. 7. Trapezoidal cross section model of bridge deck with different side angles $(26.6°,\ 19.7^{\circ},\ 14.7^{\circ})$

5. Fluid Dynamic Analysis

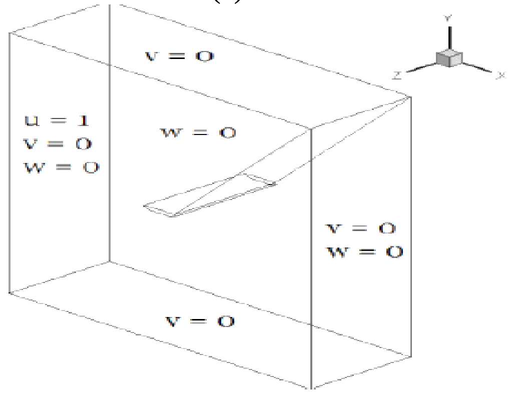
This analysis is a suitable tool for analyzing fluid flow in two-dimensional and three-dimensional modes. In a fluid analysis, the following seven general steps must be followed: (1) to identify the physical condition of the problem, (2) to determine the fluid regime, (3) to prepare a mesh model of finite elements, (4) to apply the border conditions. At this stage, it is necessary to adjust the parameters related to the dynamic analysis of the fluid, (5) perform analysis and problem-solving. In this step, the results are reviewed and the effect of each of the analysis variables is evaluated, and thus the optimal cross-sectional area of the bridge can be judged.

In fluid dynamic solution problems (CFD-Simulations), first, it is necessary to draw the fluid domain (wind flow) to be analyzed and then the solid domain (which in this research is the cross-section of the bridge deck) from the fluid domain.

The shape of the wind fluid domain and the cross-section of the deck for the model of bridges with box girders are shown in Fig. 8. The fluid domain is assumed that the distance between the upper and lower boundary plates and also the incoming flow is at the distance of the nominal diameter of the surface (D) of the cross-section from the center of gravity of the deck and the boundary surface of the flow outlet is at the distance (4D). The air temperature is considered to be 30 degrees Celsius. The characteristics of fluid (air) for atmospheric pressure at 30° C are given in Table 1. The element size around the bridge deck plays an important role in the forming of vortices behind the bridge. Very high values of velocity gradients near the surface require a very fine mesh. The vortices form in the sharp-edged body of the deck.



(a)



(b)

Fig. 8. (a) The size of the flow domain used for wind dynamic analysis, (b) Boundary conditions of current domain

Table 1. The characteristics of air for atmospheric pressure at 30° C

	VALUE
Mass density	1.166
Conductivity	0.0264
Specific Heat	1.005
Viscosity	1.604E-005
Expansion Coeff.	0.003315

The airflow is assumed to be uniform. The air pressure at the outlet edge is assumed to be zero. The behavior of the air on the deck wall is very important and the parameters related to the deck will need to be introduced to the program accurately. In both turbulent or turbulent fluid analyzes, it is necessary to calculate the pressure and flow distributions in two- or three-dimensional geometry. In these cases, the density and viscosity of the fluid need to be determined. Boundary conditions applied to different levels of the flow range are shown in Fig.8. Since the parameters are dimensionless, the upper bound has a unit velocity in the x-direction and is not a component in the y and z directions. And periodic boundary conditions are used in the z-direction. The output edge is assumed to be zero pressure. Non-slip conditions are considered on the deck surface.

In applying the boundary conditions of the edge in which the incoming flow into the domain. The incoming velocity is applied in one direction and equal to 100 km/h as per to the Iranian bridges loading code (139 regulation). The average speed wind at a height of 10 meters above the ground or river equal to 100 kilometers per hour is suggested. In the analyzes, the effect of wind velocity has also been investigated, for which wind velocities of 60, 100, and 120 km/h have been considered for dynamic analysis, respectively.

The transient flow from the float can be considered as slow or turbulent flow. In the slow flow of the fluid, the field velocity of the fluid changes slightly. This type of flow occurs in the field of fluid flow with high viscosity and low velocity. For example, fluids such as oil have such a flow field. In fluids, turbulent flow occurs if the velocity is high enough and the viscosity is low. Results of fluid dynamics analysis, comparison, and interpretation are expressed in the following section.

6. Results of Fluid Dynamics Analysis, Comparison and Interpretation

In this section, the shape of the flutter mode, the critical flutter wind velocity contour, the pressure distribution contours around the bridge deck of the trapezoidal flat bridges and the box girder are presented and examined. For different Reynolds numbers, the back-to-wind flow also follows different patterns, so that in very small amounts of Reynolds number $R_e \cong 1$, the flow remains parallel to the cylindrical body after passing through the deck body. As the Reynolds number increases up to $R_e \cong 20$ the flow around the body becomes symmetrical, but the flow separates from the deck body and large vortices shedding are formed at the lower surface of the deck body. At last, for $30 \leq R_e \leq 5000$ ranges, vortex street occurs downstream of the body (Benard-von Karman Vortex Street. Laboratory and theoretical research of this phenomenon for different cross-sections are still ongoing. In the following, the flow lines of the behind the bridge deck and the pressure distribution around the cross-section of the deck are examined.

6.1 Pressure contours around flat decks with different web edge angles (α=14.7, 19.7, 26.6 deg)

The variation of the web edge angle of the flat trapezoidal deck under the turbulence flow around the bridge decks is investigated in this section. Fig. 9 shows the velocity flow at the wind velocity of 100 km/h for different web edge angles (α=14.7, 19.7, 26.6 deg). The wind flow passes above and below the deck surface uniformly and the separation of the flow is not observed at the point of contact with the wall. By reduction of the side web edge angle, wind flow passes the deck steadily. Fig. 10 shows the pressure contours around flat decks with different outer edge angles. The pressure distribution around the cross-section reduces at a smaller web angle. It is observed that a smaller angle of approximately 15 degrees between the bottom plate and the side edge is the optimal value for the trapezoidal deck cross-section. It has a positive effect on the uniform passage of airflow around the deck and prevents oscillating flows to form vortex shedding behind the deck body and in turn, reduce the incoming forces and the probability of resonance condition.

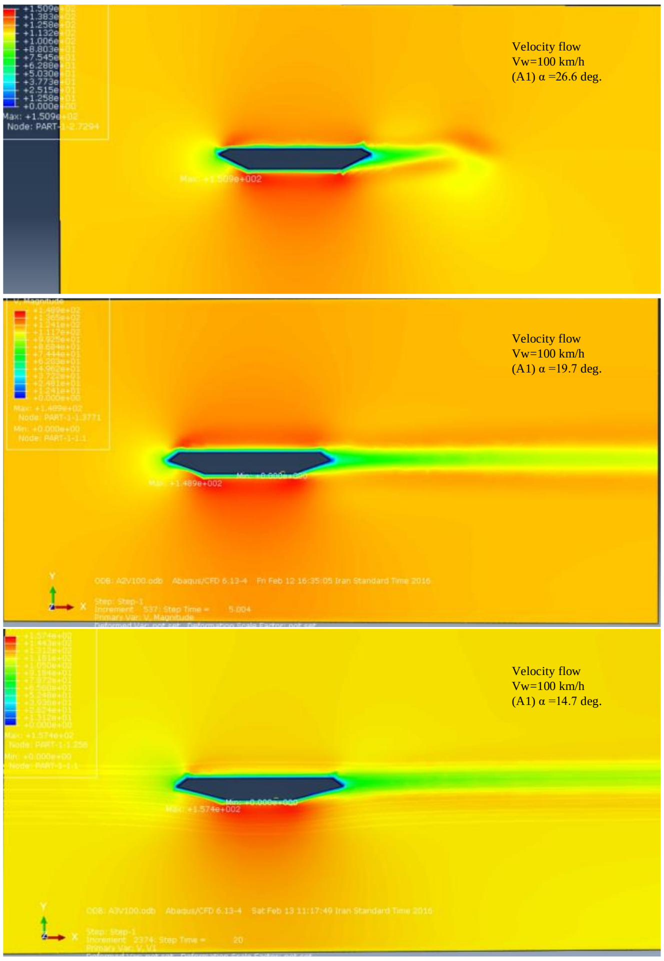


Fig. 9. Flow velocity on flat decks with different lateral edge angles (α=14.7, 19.7, 26.6 deg)

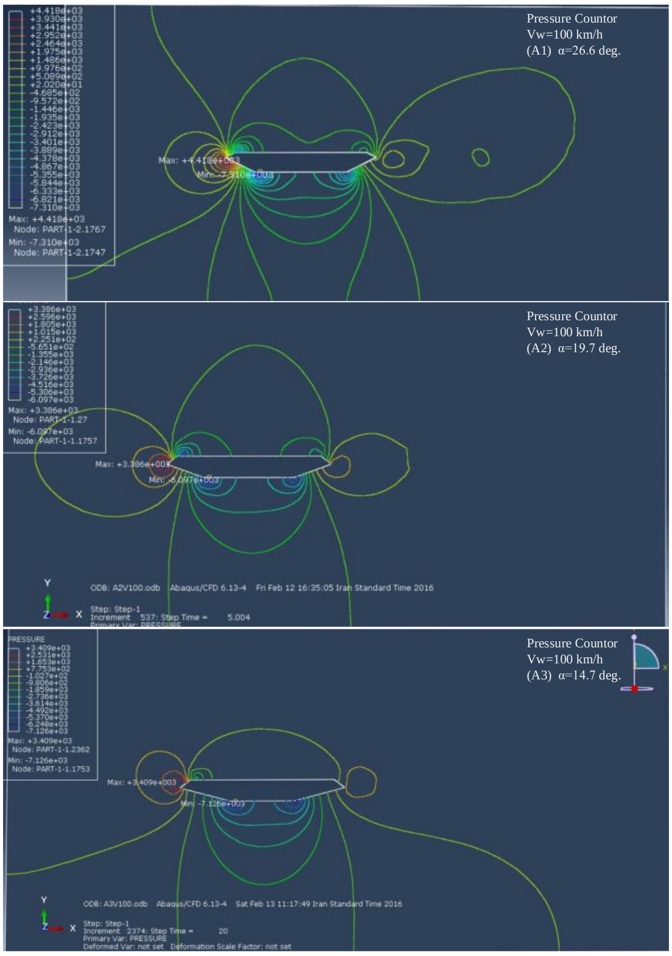


Fig. 10. Pressure contours around flat decks with different outer edge angles (α=14.7, 19.7, 26.6 deg)

6.2 Variation of Flow velocity and Pressure contours in flat decks with different width to height ratio of cross section (B/D ratio=12.67, 10, 7.5, 5)

The flow rate around the different flat decks with the ratio of width-to-height (B/D ratio = 5, 7.5, 10, 12.67) is examined in Fig. 11. By increasing this ratio, the velocity flow passes steadily up and down the deck without disturbing. A vortex road can be seen at low ratios, which causes shocks and severe vibration of the bridge deck. In general, by increasing the ratio of width to height of trapezoidal flat sections, the transient current crossing is improved and less vortex shedding is generated. It leads to a degradation of shocks and vibration on the bridge deck and fewer dynamic forces are applied to the surface of the deck.

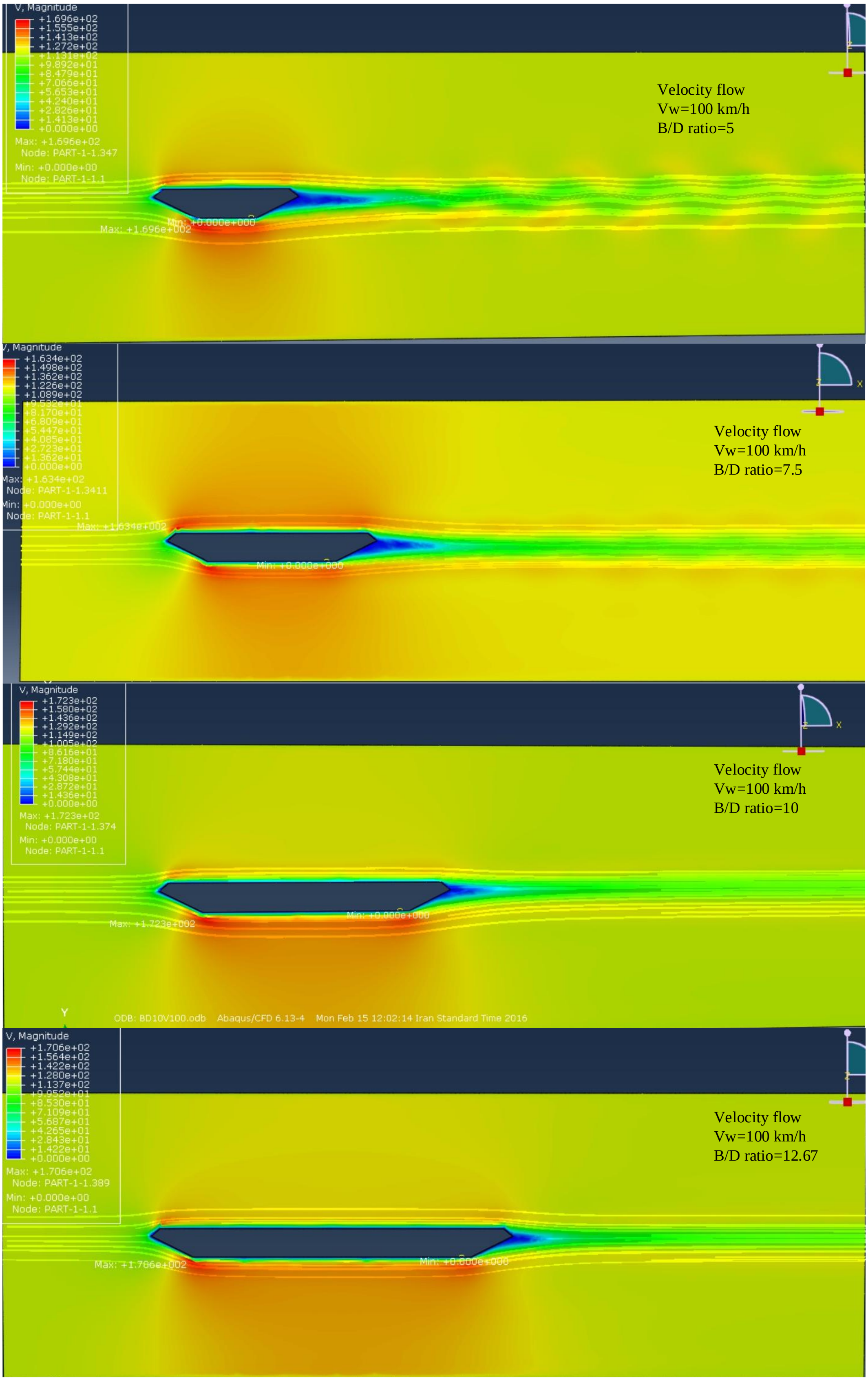


Fig. 11. Flow velocity in flat decks with different width to height ratio of cross section (B/D ratio=12.67, 10, 7.5, 5)

6.3 Variation of Flow velocity and Pressure contours around the box decks with different web angles (α=53, 63, 76, 90 deg)

The angle of the web plate to the vertical line is one of the important features of box decks. Despite the good performance of box bridges against the gravity and seismic loads, their performance against strong wind forces also needs further investigation. In particular, the geometric characteristics of the deck section are among the important parameters that affected the aerodynamic behavior of bridge structures. In Fig. 12, box girders with various web angles (α = 53, 63, 76 90 degrees to the bottom flange are adopted to CFD-simulations. Generation of moving vortex shedding on the back of section at the upper side of the deck. The occurrence of such turbulences flow causes impact motions (Galloping) and severe vibration on the deck surface, which will lead to dynamic forces. The most critical case is the box section with a vertical web case. Vortex shedding operates in a counterclockwise direction to rotate the section body. Fig. 13 shows the pressure countors of the single-cell box section with different web angles. The pressure distribution around the section indicates that the pressure applied to the section with the vertical web is 25% higher than in the case where the web plate position at an angle of 53 degrees toward the bottom flange.

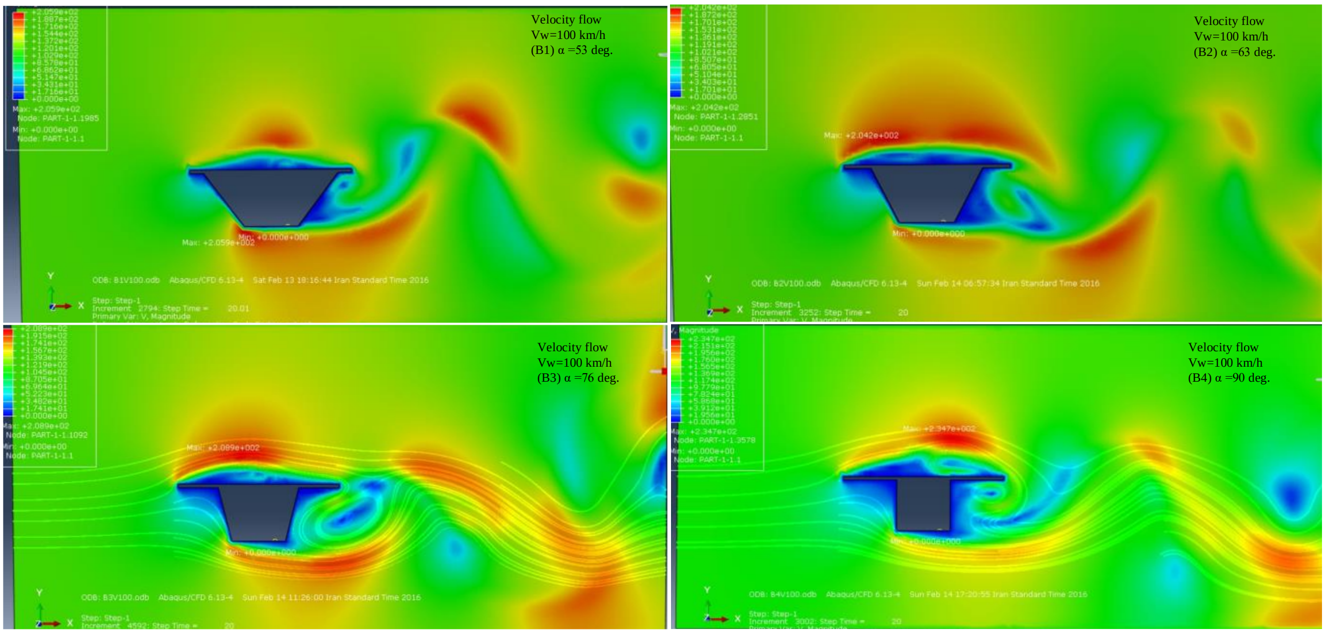


Fig. 12. View the flow velocity around the box decks with different web angles (α=53, 63, 76, 90 deg)

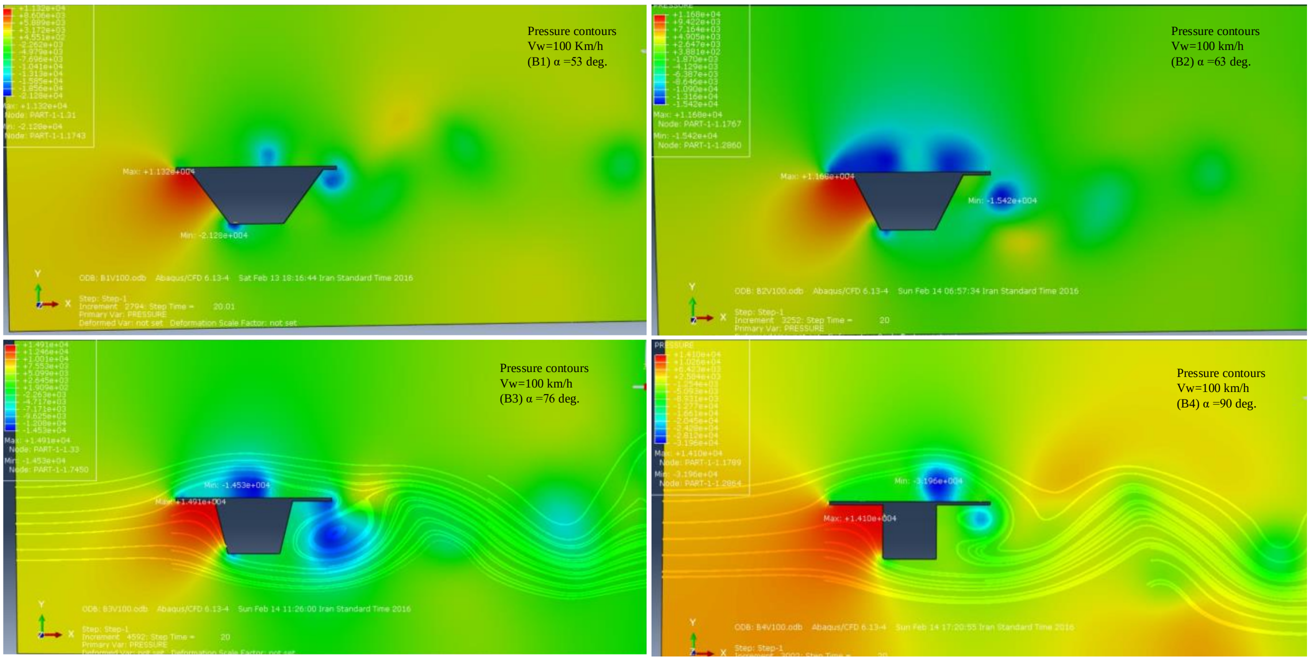


Fig. 13. Distribution of pressure and flow lines around box decks with different life angles (α=53, 63, 76, 90 deg)

6.4 Distribution of pressure and flow lines around box decks with different web angles due to increasing wind velocites

In this section, an attempt has been made to investigate the effect of increasing the critical flutter wind velocity on the box section with various web angles. To this aim, the flutter wind velocity is increased from 60 to 100 km/h. Fig. 14 shows the contours of wind flow lines around single-cell box decks. It can be seen that the wind turbulence condition has become more critical with increasing the box web angle. At an angle of 76 and above, a vortex shedding is formed on the leeward side of the deck. Increasing the flutter wind velocity causes the formation of longer vortices street leeward side of the deck section. The maximum flow velocity values at the top and bottom of the section cause severe vibration motions and in turn greater forces. The pressure distribution around the deck wall is also plotted for the same models (See Fig. 15). It is shown that with increasing flutter wind velocity, the pressure on the wall facing the wind increases by about 4.5 times so that this increase is more critical in the vertical wall and has increased up to 5 times. It is seen that increasing suction pressure on the leeward side of the deck generates the moment forces to rotate the section counterclockwise direction. The pressure distribution conditions around the decks indicate that the uplift forces applied at the windward edge of the deck. Vortices shedding on the leeward side of the deck are caused by negative pressures and acts against the uplift-edged pressure. The distributed negative pressure field affects the bridge deck almost uniformly. The pressure field increases due to the counterclockwise rotation moments. By vortex shedding of moving the vortex to the right side of the deck, an increase in positive moments is seen.

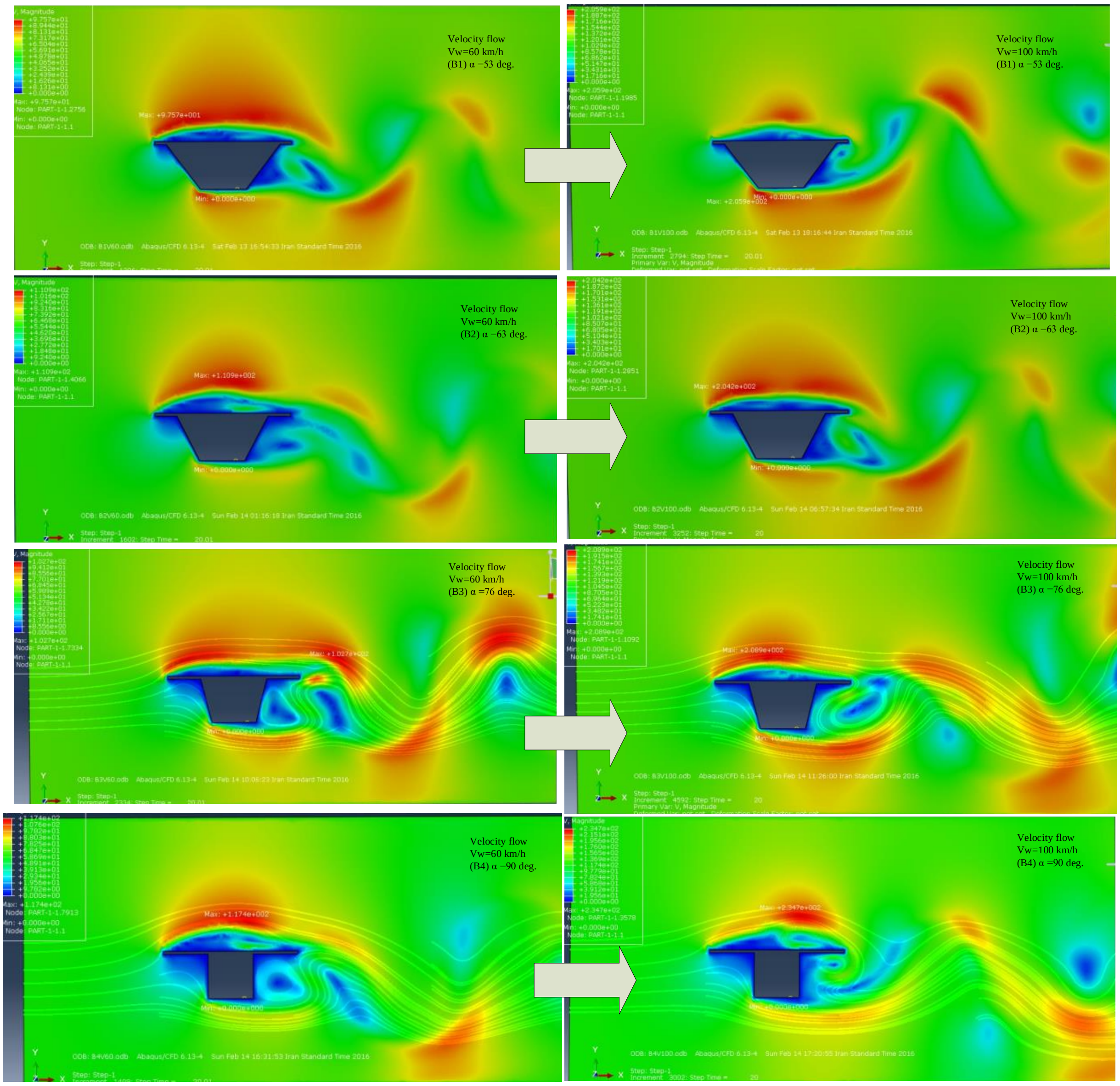


Fig. 14. Flow lines around box decks with different web angles with increasing the wind speed

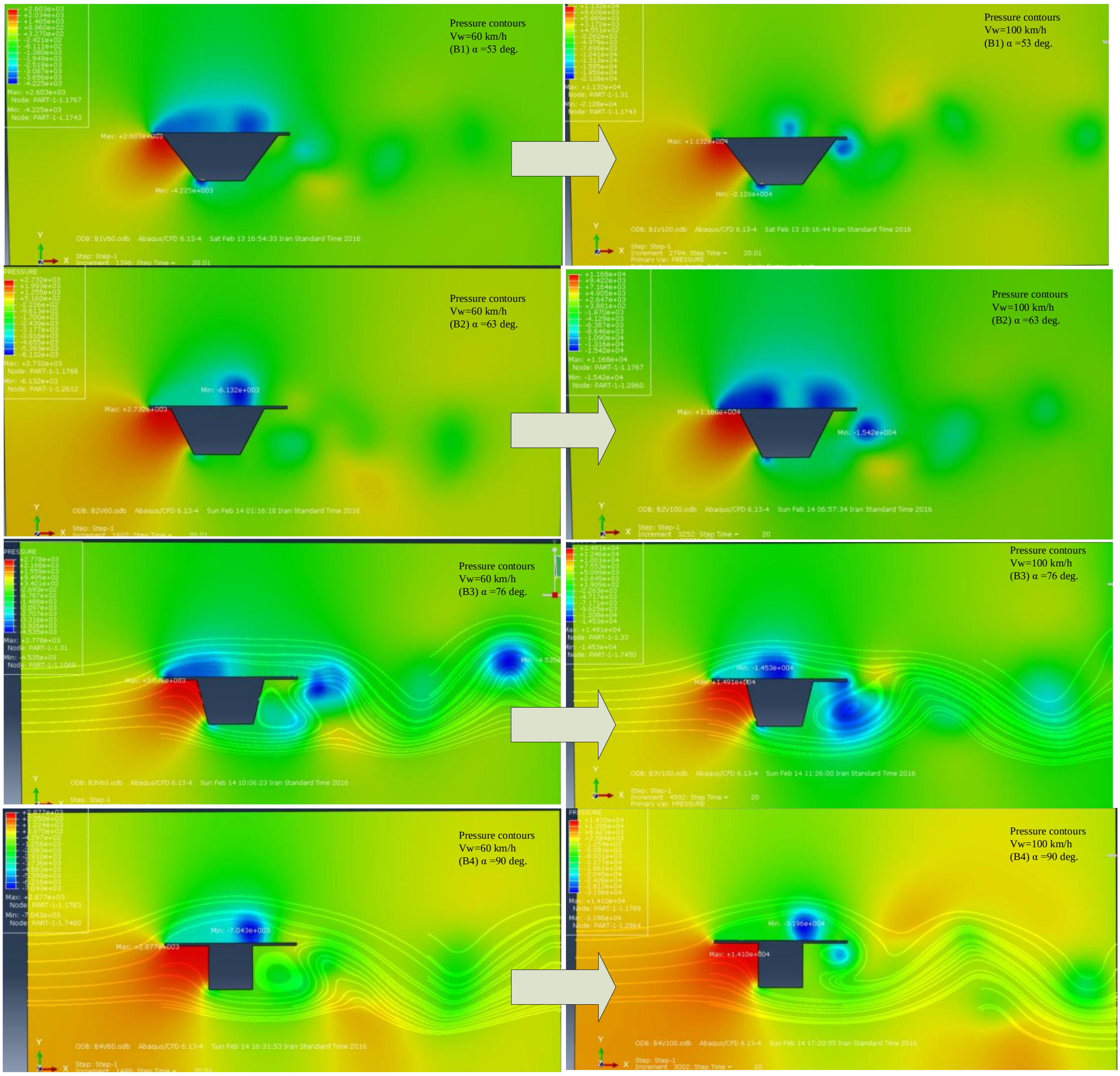


Fig. 15. Distribution of pressure and flow lines around box decks with different web angles under the influence of increasing wind speed

6.5 Variation of Flow velocity and Pressure contours around the box girder with (a) cells linked by top flanges and (b) cells linked both by top and bottom flanges

Both models of continuous cell box beam (with cells linked both by the top and bottom flanges) and double cells box beam (with cells linked by top flanges) are made and put them subjected to flutter condition at a wind speed of 100 km/h (See Fig. 16). The vortex shedding path at the back of the wind in both sections is similar. Fig. 17 shows how the pressure is distributed around the deck cross-section. According to pressure countors, there is no appreciable force in the gap area between the cells. In general, the pressure distribution is similar for both sections. The single cell box or a pair of cells will not have much effect on the turbulence of the flow around the wall of the deck. The goal in deck section designing is to establish a more uniform flow around the section as much as possible. In general, fixed vortex currents can be used to push the laminar flows and wind energy dissipation to get the optimal section. In this case, maybe the fixed vortex shedding formed between the two modules plays a positive role in dissipating incoming wind energy.

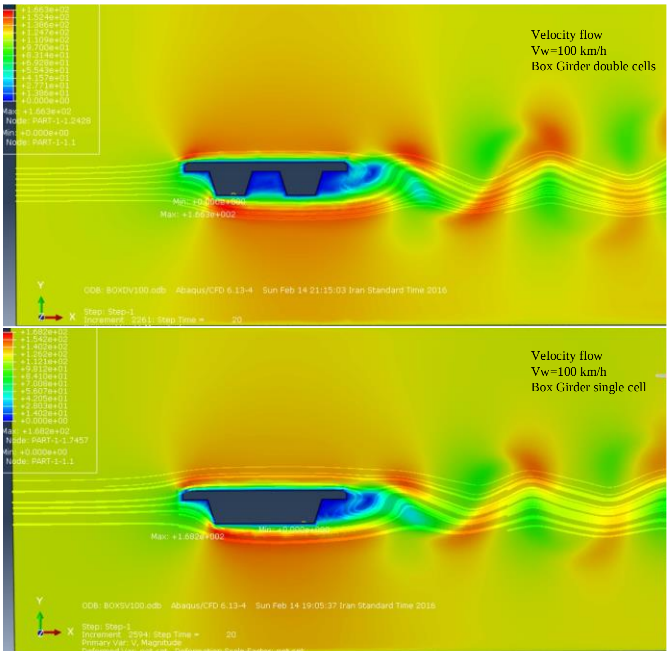


Fig. 16. The velocity of the flow around the box girder with (a) cells linked by top flanges and (b) cells linked both by top and bottom flanges

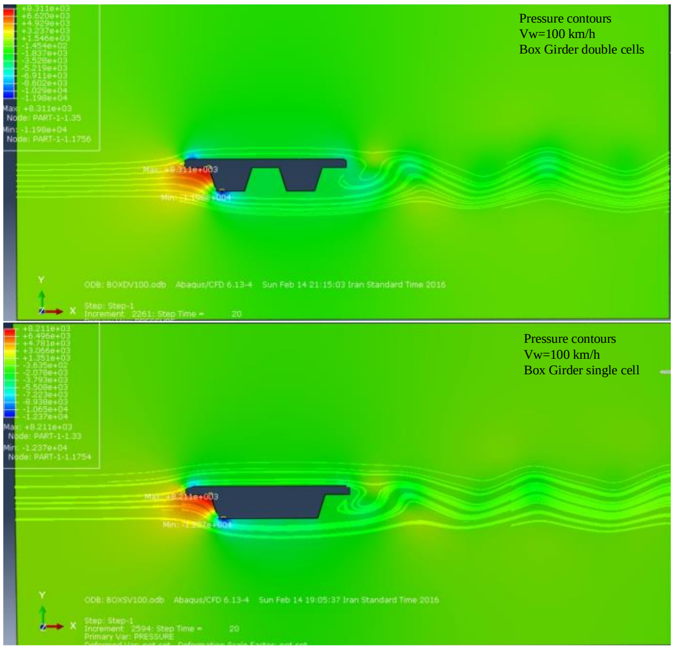


Fig. 17. The pressure countor of the flow around the box girder with (a) cells linked by top flanges and (b) cells linked both by top and bottom flanges

6.6 Comparison of velocity vector around the bridge decks with different cross sections

Bridges with flat trapezoidal decks have a higher critical flutter wind velocity compared to closed box section decks. Due to aerodynamic characteristics of sharp-edged trapezoidal decks, wind flows cross around the deck uniformly. The absence of turbulence and all kinds of vortex shedding causes fewer flactuations and impact loads to the deck. In brief, the flat shape of the deck improves the dynamic balance of the bridge. But in the case of box decks, turbulent flows due to the cross-sectional shape leads to the formation of vortex shedding at the leeward side of the deck section which imposed additional dynamic forces on the deck and even leads to resonance conditions.

It has been observed that the high ratio of the width of the section to its height has a positive role in the wind flow passing above and below the section. In trapezoidal deck sections with a higher ratio of width to height, wind flow crosses the contact surface of the deck without creating severe vortices, which in turn will cause fewer vibrations. The vortex road formed in the leeward side of box sections indicates the need for further investigations and tests in using single-cell box sections for long-span bridges, particularly those prone to strong winds.

Fig. 18 shows the velocity vectors inside the flow domain. It is found that the wind flows cross above and below the flat deck uniformly and the separation of the wind flow is not observed at the point of contact with the wall and leeward side. However, the separation of the wind flow from the upper surface of the deck is clearly seen in single-cell box sections. The most critical condition is related to the single-cell box section with vertical webs. Vortex shedding on the deck cause vibrations and in turn dynamic forces at the entrance sector of the deck. The wind flow separation of single-cell box decks is seen clearly when wind flow cross-section.

Using Equation (1) and the values provided for air at 30°C (Table 1), the Reynolds number values for the proposed sections can be calculated. This value of Reynolds number is obtained for trapezoidal flat deck section, box sections with one double cell, and box sections with single-cell, 5’250’490, 6’058’256 and 14’135’932 respectively. As can be seen, Reynolds’ values are relatively large, increasing by about 14 million, leading to severe vortex shedding leeward the sections. The calculation of turbulent wind flows for large-size and sections with real dimension gives the large Reynolds numbers. On the other hand, it is known that the flow patterns and the consequent pressure and wind forces change with Reynolds numbers. This also makes it difficult to use wind tunnel results directly on real structures. Qualitative treatments of wind flow over a deck section depends largely on the Reynolds number; similar wind flow patterns often appear when the shape and Reynolds number is matched. Other factors such as surface roughness have a serious effect as well. CFD-Simulation methods also have some deficiencies for large Reynolds numbers and require additional measures for use in practical work.

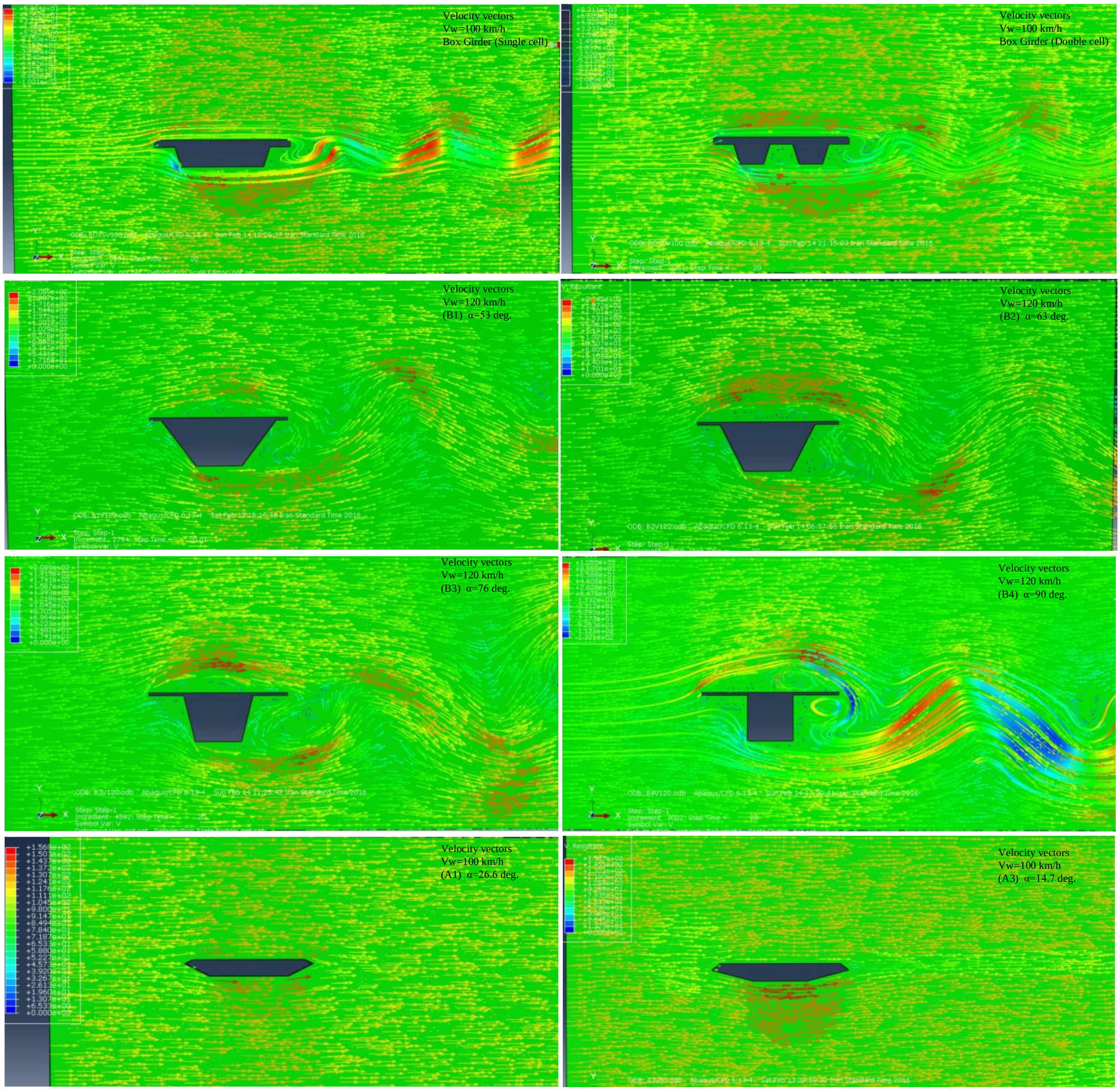


Fig. 18. Flow velocity vector in the perimeter of bridge decks with different cross section

7. Conclusions

A brief overview of laboratory experiments and modeling of bridge deck air flutter is discussed. The geometry of the deck cross-section and their aerodynamic behavior are considered in the present study. The main focus is the geometric parameters of the sections were considered as a design variable and previously tested in wind tunnels. An attempt has been made to compare and validate the results of the dynamic analysis of the current study with identical laboratory results.

- The phenomena of wind flow, turbulence, vortex shedding, and aerodynamic instability of the wind in flutter are introduced. Then, the assumptions used in fluid dynamics analysis, including deck design variables, wind flutter domain, boundary conditions, and meshing, are described and interpreted. The steps of performing dynamic analysis and the parameters and material properties introduced to ABAQUS platform V6.14 [24] are presented and the results of the analyzes are compared and interpreted. Based on the results obtained from several bridge deck models under wind flutter conditions and fluid dynamic analyzes, the following results can be mentioned.
- Due to the relatively long length of the deck, wind currents are expected to stick to the deck surface. Then the eddy boundary layers are reattached to the end of the deck. The sharp edges facing the bridge deck, vortices are expected to form periodically behind the deck, which is called (vortex road). To obtain all these phenomena, a fine-grained mesh is needed.

- Long-span Bridges with flat trapezoidal decks have a higher critical flutter wind speed than closed box decks, owing to the wind flows smoothly pass through the top and bottom of the deck. In the case of box decks, turbulent currents due to the section shape causes the occurrence of vortex shedding behind the section (See Fig. 17). In other words, the flat trapezoidal shape of the deck improves the dynamic instability of the bridge.
- The shape of the bridge deck is very important for dynamic responses. The aerodynamic behavior of trapezoidal flat sections under the influence of wind forces is better than box sections. That's why, the majority of long-length modern suspension bridge decks were constructed using a variety of trapezoidal flat sections (or sections with sharp edges), when compared to box sections. The results show the high sensitivity of the aerodynamic behavior of the bridges to changes in the geometry of the end edges of the decks.
- Calculating turbulent flows for large and real size sections yields large numbers. The flow patterns and the consequent pressure/wind forces that change with Reynolds numbers reduces the reliability of direct use of wind tunnel results. Dynamic flow calculations for large Reynolds numbers show that as Reynolds values increase, the vortex shedding behind the cross-section becomes more severe.
- In the study of the aerodynamic effect of the geometric shape of the bridge deck, the angle of the web plate of a box girder relative to the vertical line, which is one of the important characteristics of box decks is examined. The results showed that the pressures applying to rotate the cross-section acts counter-clockwise direction, increase with rising angle, and the most critical state is related to the vertical upright position (Fig. 13). The pressure on the box girder web in the vertical position is about 25% higher than the case where the web position is at an angle of 53 degrees to the bottom flange.
- By increasing the width-to-height ratio of trapezoidal flat sections, the uniform flow conduction is improved and less vortex shedding is seen. By reducing shocks and oscillating movements on the bridge deck, fewer dynamic forces are applied to the surface of the bridge deck (Fig. 12).
- The lower angle (approximately 15 degrees between the bottom flange plate and the side web panel is the optimal value for the side edge of flat trapezoidal cross-section, has a positive effect on the uniform passage of airflow around the deck, and the lack of vortex shedding around the cross-section reduces the oscillating vibrations and in turn decrease the applied forces and probability of resonance condition. (Fig. 9).
- In the investigation of the effect of increasing flutter velocity on box sections with different web angles, it is observed that with increasing the speed of the flutter, the pressure on the wall facing the wind is about 4.5 times, so that this increase is more critical in the vertical upright webs up to 5 times.
- An increase in suction pressure in the opposite direction of the wind is also seen, and the torsional moments rotate the section counterclockwise. The pressure distribution around the decks showed that the existing pressure creates lifting forces at the loaded edge of the deck. Negative pressures cause the vortex shedding on the right of the deck and act against the edge pressure towards the wind. The distributed negative pressure field affects the bridge deck almost uniformly. The pressure field increases due to the counterclockwise rotation. Considering these works, it can be seen as a result of moving to the right of the vortices on the deck. When they are scattered from the deck surface when an increase in the positive moment is observed.

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