CSCE Annual Conference

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Laval (Greater Montreal)

June 12 - 15, 2019

FLOW-CONDITIONING OF THE WIND TUNNEL AT RYERSON UNIVERSITY TO MODEL BOUNDARY LAYER FLOWS

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Abstract:

This study aims at modeling boundary layers (BLs) encountered by tall buildings (i.e. open, suburban and urban) at the subsonic Wind Tunnel (WT) at Ryerson University (RU). This WT was solely used for aerospace applications, thus had negligible turbulence. A flow-conditioning system to generate proper turbulence at the WT was designed in a previous study conducted by the authors. The system consists of roughness blocks and spires equipped with movable slats to control the generated boundary layer. The system was recently constructed and installed at the WT. This study focuses on validating the system and characterizing the resulting BLs. The study reveals capability of the system to accurately generate BLs for various terrain conditions (i.e. open, suburban and urban) for wide range of length scale. The study also shows that the resulting BLs are naturally developed, which is important for testing flow aerodynamics around civil structures.

Keywords: Wind Tunnel (WT), Flow Conditioning System, Boundary Layer (BL).

1 INTRODUCTION

Wind is the main loading case for tall buildings. Design codes such as NBCC (2015), ASCE (2016), Eurocode (2010) and AS/NZs (2010) can be used for load evaluation however, the codes have limitations with respect to the building height, shape and surrounding configuration. Wind tunnel (WT) can overcome these limitations. WTs have been used in studying tall buildings since mid-sixties when Alan Davenport investigated wind effects on the old-world trade center. Afterwards, WTs were used extensively to study the behavior not only for tall buildings (Ishizaki and Nishimura, 1992; Irwin, et al. 2012), but also for low-rise buildings (Kim et al. 2013), bridges (Tanaka and Davenport, 1983) and flexible energy infrastructure (Aboshosha, et al., 2016 ;Elawady et al. 2017; Jubayer and Hangan, 2016). Ryerson University operates a subsonic WT which has a closed loop with a test cross section of approximately 1m x 1m. The wind tunnel is suitable for smooth flow (i.e. aerospace applications) with a maximum turbulence intensity of 0.5% (Carroll, 2017; Barcelos 2015). This is significantly less than the turbulence intensities encountered by tall buildings which are engulphed in atmospheric Boundary Layer (BL) (ESDU 2001-2002). It is essential for accurate wind load-evaluation to properly simulate the BL with the proper turbulence (Davenport, 2002; Cermak, 2003). This study focuses on validating a system that was developed by the research team that enabled the subsonic WT at RU to model proper BL flows for different terrain conditions (i.e. open, suburban and urban) (Ghazal et al,2019).

Most BL WTs have a contraction zone to streamline the flow at the upstream followed by a flow-conditioning system to generate the target turbulence. Typically, this system consists of spires, barrier(s) and roughness blocks. There are extensive studies in the literature related to generating proper BLs in WTs. Systems used to generate the BL can be categorized under three categories: (i) Category 1 - Passive system with spires, barriers and blocks, (ii) Category 2 - Passive system with grids only and (iii) Category 3 - Active system with a dynamic grid (moving louvers) and blocks. Researchers started to use Category I (Passive system with spires, barriers and blocks) after the early studies by Davenport, (1961) and Counihan, (1969a, b, 1973). The system which is referred to as Counihan system, generates a proper BL with near-zero pressure gradient and is shown in Figure 1. This figure represents a photo taken from inside the BL WT at University of Western Ontario and shows the 3 components of the system (spires, barrier and roughness blocks). Robins (1979), used Counihan's system to determine the length of the streamwise fetch necessary for the flow development. The study concluded that a fetch length of 12 to 15 times the BL height is typically needed to achieve a well-developed BL (naturally grown zero pressure gradient BL). This can be a challenge for WTs with limited space such as the tunnel at RU.

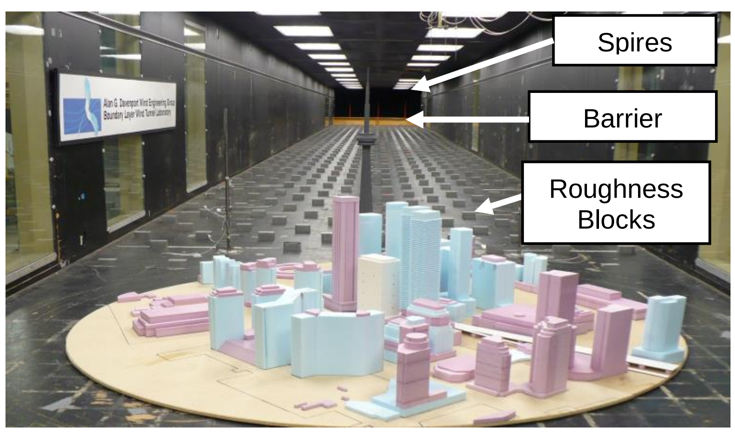

Figure 1: Category I (Counihan System) of generating Proper Turbulence, Photo from BLWT

Inspired by Counihan, (1969) and Robins, (1979), Farell and Iyengar, (1999) succeeded to simulate urban BL using quarter-elliptic constant wedge angle spires, a castellated barrier and roughness elements in a staggered arrangement. Irwin (1981) characterized the flow generated from Counihan system and developed semi-analytical design equations for the spires depending on the target scale, tunnel dimensions, and target BL. These equations were validated by Irwin, (1981), and others (e.g. De Paepe et al. 2016) to be useful in achieving proper BLs. However, the equations typically lead to a BL with a limited acceptable depth (i.e. ~ 40% of the tunnel height, e.g. ~ 43 cm out of 108 cm for the WT at RU), which is not adequate for studying tall building aerodynamics at a suitable scale.

Cheng and Castro, (2002) and Schultz et al., (2005) conducted wind tunnel studies for BLs resulting from multiple upstream terrains. Salizzoni et al., (2008) studied the interaction between large scale (i.e buildings) and small-scale (i.e. street-level obstacles and elements on the facades and roofs) roughness and their effect on the flow in the urban BL. They used spires similar to Counihan and Irwin systems, but utilized multiple barriers and mounted the roughness blocks (small scales) on the top of the barriers, with the aim of modeling parallel canyons in the built-environment. They found a modest effect of the added small-scale roughness when the large-scale obstacles are closely packed (increase the turbulence intensities and momentum transfer). Kozmar, (2011) re-designed the spires of Counihan ignoring the tunnel height, but truncated the part above the tunnel height (above 1.7 m), to fit inside the tunnel. This led to spires coving the entire height of the tunnel, which is not the case for the original Counihan or Irwin's system (Counihan, 1969; Irwin, 1981). A highly calibrated BL with a depth covering ~ 95% of the tunnel height (1.7 m out of 1.8m) was achieved by this, which is very useful for tunnels with low height such as the WT at RU.

Varshney, (2012) conducted a parametric study on the passive turbulence generating elements (spires, barrier, roughness blocks) in addition to slots at the nozzle of the wind tunnel upstream of the spires and managed to generate all major types of BLs. The study showed that to generate a deep BL extending to a larger portion of the tunnel height (which is the target for the WT at RU), additional turbulence generating element (i.e. slots with variable width) is needed beside the typical system of spires, roughness blocks and barrier. Shojaee, et al., (2014) used an aerospace WT to simulate BL. Because the tunnel had a shorter fetch length, a system of custom-designed spires was employed at the inlet followed by cubical surface roughness elements to create the proper BL for three main exposures. Aly et al., (2011) used a system of airfoils, and/or adjustable plank mechanism with or without grids to simulate hurricane winds in the open jet facility wall of wind (i.e. WoW) at Florida International University. They achieved proper BLs and identified acceptable range of model location and size to fit within the BLs. They found out that the model height should be within 1/3 of the generated BL thickness to allow for accurate pressures on the roof. This 1/3 constrain results from the freedom of the air movement in the open jet where no bounding walls exist. Mooneghi et al., (2014) used WoW facility to generate different BLs employing triangular spires, floor roughness elements to examine the uplifting of concrete roof pavers for low rise buildings. Pires et al., (2013) generated an open terrain BL on a short tunnel (i.e. 465 × 465 x 1200 mm) utilizing turbulence generating elements: spires, screens (grid) and floor mats individually and in-combinations. The results showed that the spires and screen achieved proper BL with least occupied tunnel area suitable for tunnels with short test chambers. De Paepe et al., (2016) generated the BLs using 2 systems: (i) Truncated Counihan ellipses, a grooved barrier and roughness elements and (ii) Truncated Irwin spires followed by roughness elements. Both truncated systems led to proper deep BLs (i.e. up to 80% of the tunnel height), but Irwin's spires achieved slightly better results.

Category 2 of the turbulence generating systems (i.e. employing passive grids) was utilized by many researchers in studying wind effects on sections of bridges and buildings. This system is capable for generating a kind of uniform turbulence intensity suitable for simulating a portion of the BL. Although, this is enough to study aerodynamics of the cross section of a building or a bridge, it is not suitable to study an entire building engulphed in BL (Davenport 1961; Ishizaki and Nishimura 1992; ESDU 2001; Sun et al. 2017; Liu et al., 2017) investigated the turbulent parameters (i.e. turbulence intensity and wind speed) generated by using two different grids with different dimensions (i.e. width, thickness and height). The distance required for flow stabilization as well as obtaining a uniform turbulence intensity for both grids were determined. Vita et al., (2018) employed grids to generate proper turbulence and investigated the effect of tunnel expansion (diffusing) on the turbulence characteristics. Category 3 of the turbulence generating systems (i.e. with active elements) typically consists of dynamic louvers at the inlet with/without roughness blocks. This system is typically utilized in wide wind tunnel with short fetch length to rapidly induce target turbulence. For example, Jubayer and Hangan, (2018) used a system of louvers with turning vanes to impose turbulence at the inflow to characterize the wind field in complex terrains. Most of the studies belong to category I or II (passive with spires, barrier and roughness blocks or passive with grid only). Those studies provide a very good insight about the effect of each of the turbulence generating elements on the resulting BL. These insights were utilized to design a flow-conditioning system to generate target BLs at the subsonic WT at RU with suitable depth to allow for testing of tall buildings (Ghazal et al., 2019). This new system is validated in this study at RU WT.

The study is divided into 5 sections. Section 1 (this section) provides an introduction about BL modeling, while section 2 provides details about the Flow conditioning system at RU WT. Section 3 discusses the experimental setup and Section 4 shows results of the generated BLs. Conclusions and recommendation are provided in section 5.

2 FLOW CONDITIONING SYSTEM AT RU WT

Ryerson University currently operates a large subsonic, closed-loop WT for aerospace applications which is shown **Error! Reference source not found.**. This wind tunnel was refurbished in 2014/2015 to improve runtime and flow quality (Barcelos 2015; Carroll, 2017). The tunnel is equipped with a large fan that pushes air at the north side of the tunnel as shown in **Error! Reference source not found.**a. The pushed air passes through turning vanes and then through a contraction zone to streamline the flow at the south side before the test section. The test section has dimensions of 91 x 91cm, with very smooth flow (Turbulence intensity of 0.5% or less). Located behind the test section is a diffuser zone with dimensions varying from 91x91cm to 108x108cm. It was planned to utilize the south section of the tunnel to simulate BL flows (from the contraction zone to the diffuser zone) as marked in **Error! Reference source not found.**. The original test section right after the contraction was utilized to generate the turbulence using the flow conditioning system, while the diffuser zone is utilized to characterize the flow and test building models.

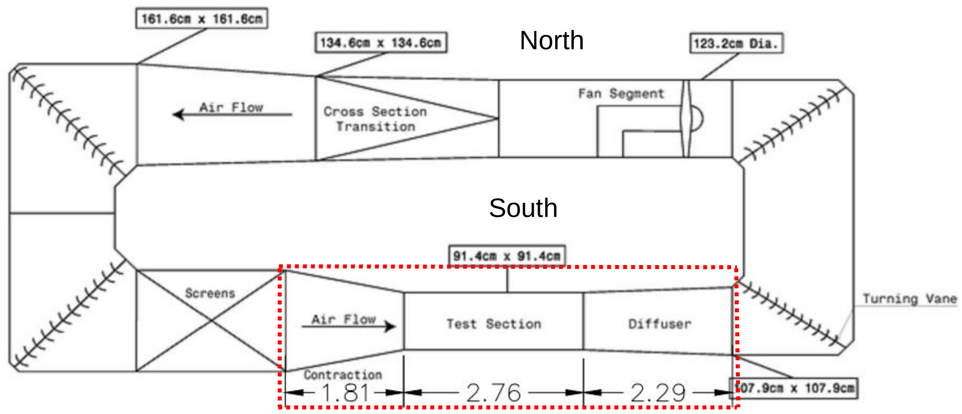

Figure 2: Subsonic Wind Tunnel at RU (Barcelos, 2015)

The newly designed flow conditioning system consists of two-layer spire-slat system, as shown in Figure 3, and 10 cm roughness staggered roughness blocks distributed over 6 rows. The slats system has two layers (i) a fixed upwind layer with a 40% blockage (highlighted in green in Figure 3a) and (ii) movable downwind layer with also 40% blockage (highlighted in orange in Figure 3b). This system allows for controlling the blockage between the range of 40-80%. When the two-layer system is fully open, the overall blockage is just 40% (i.e. second layer is completely shielded), but when the system is fully closed the overall blockage increases to 80%, where the second layer is fully exposed to wind. This two-layer system was used to control the blockage ratios in order to generate BLs matching suburban and urban terrains. Slats are grouped into 4 groups with 2 slats in each group. Each group can move at a different distance (or at a different rate) independently. This was achieved by connecting each group to a rotary shaft using links connected at different radii. The larger the radius of movement, the greater the distance the slat group travels. Since larger slats are located at the bottom, larger radii were used with lower slat groups. Table 1 summarizes the slat movement required to achieve best BLs matching suburban and urban exposures. It was found out that the system with no slat movement leads to the best matching BL for open terrain.

Table 2: Slat Group Movement with Respect to Open Terrain Slat Configuration

	Open Terrain	Suburban Terrain	Urban Terrain
Slat Groups	**Slat Movement (mm)**		
Group 1 (bottom)	0	8	13
Group 2	0	6	10
Group 3	0	2	4
Group 4 (top)	0	2	3

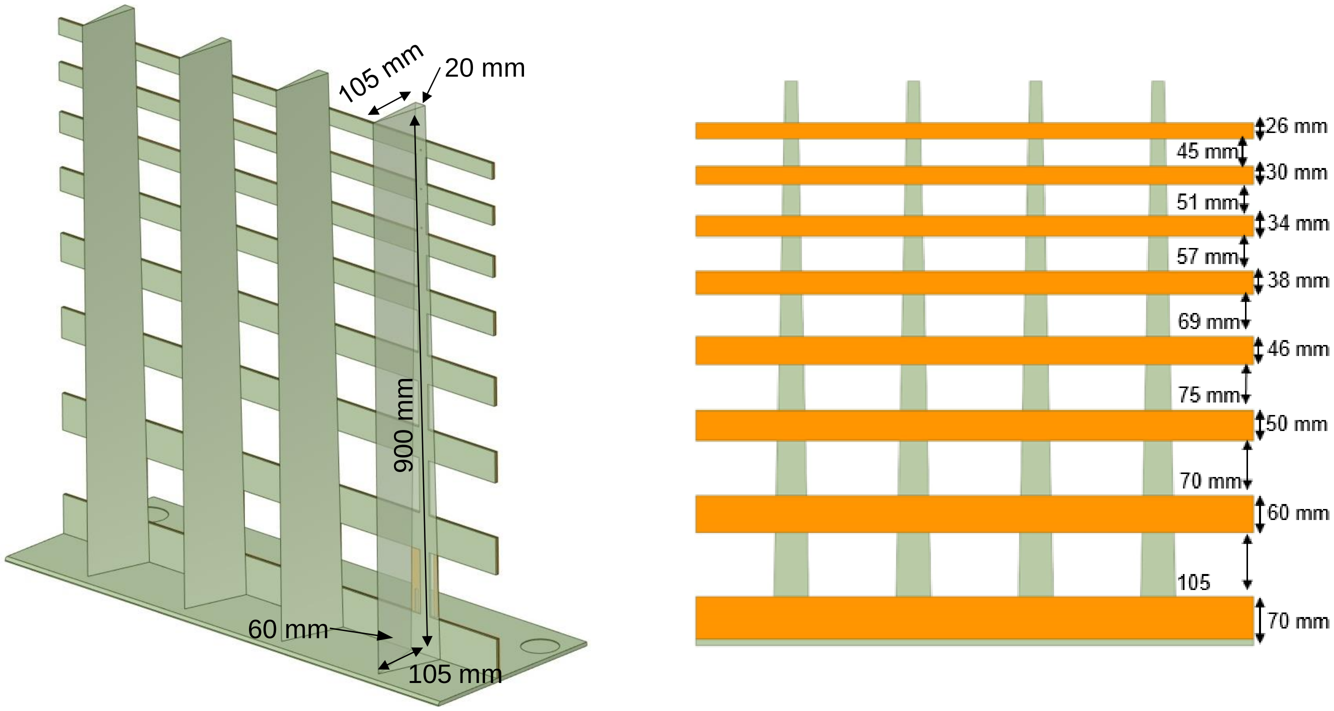

Figure 3 a) Spire Slat System b) Slat Arrangement covering 40%

3 EXPERIMENTAL SETUP

The flow conditioning system was constructed and installed at RU wind tunnel as shown in Figure 4. Figure 4a shows component of the spire-slat system, while Figures 4b,c show the system at the fully open and fully closed positions. This system is controlled using a stepper motor (NEMA 34), with a high torque of 1100 oz-in (7.8 N.m) capable of moving the slats smoothly at wind speeds up to 60 m/s.

Turbulent wind speed profiles in the tunnel were characterized using 2 multi-hole pressure probe (Cobra Probes) namely Probe A and Probe B as shown in Figure 5. In order to confirm repeatability of the results obtained from the tunnel, Probe A was always kept at a same location at the center of the turntable at 0.2 m high. Probe B was the movable probe and utilized to acquire the turbulent speeds at different heights and locations of the tunnel. Those probes have a sampling frequency of 1250 hz and are capable of capturing inclined turbulent speeds within ±45° from the main flow direction. The probes were utilized to characterize the turbulent speeds at 8 heights (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 and 0.8 m). Quality of the resulting flow at the turntable was investigated using Cobra Probes. This was conducted by acquiring the turbulent velocities at 4 locations shown in Figure 6. The four locations are taken at (i) the middle of the tunnel at the center of the turntable and denoted by “M”, (ii) quarter of the turntable to the left and detonated by “L”, (iii) quarter of the turntable and denoted by “R”, and (iv) upstream the turntable at the middle and denoted by “U”. Probe B was utilized to obtain wind velocity records at the four locations at various heights. Images showing sample probe layouts are provided in Figure 7.

a) b) c)

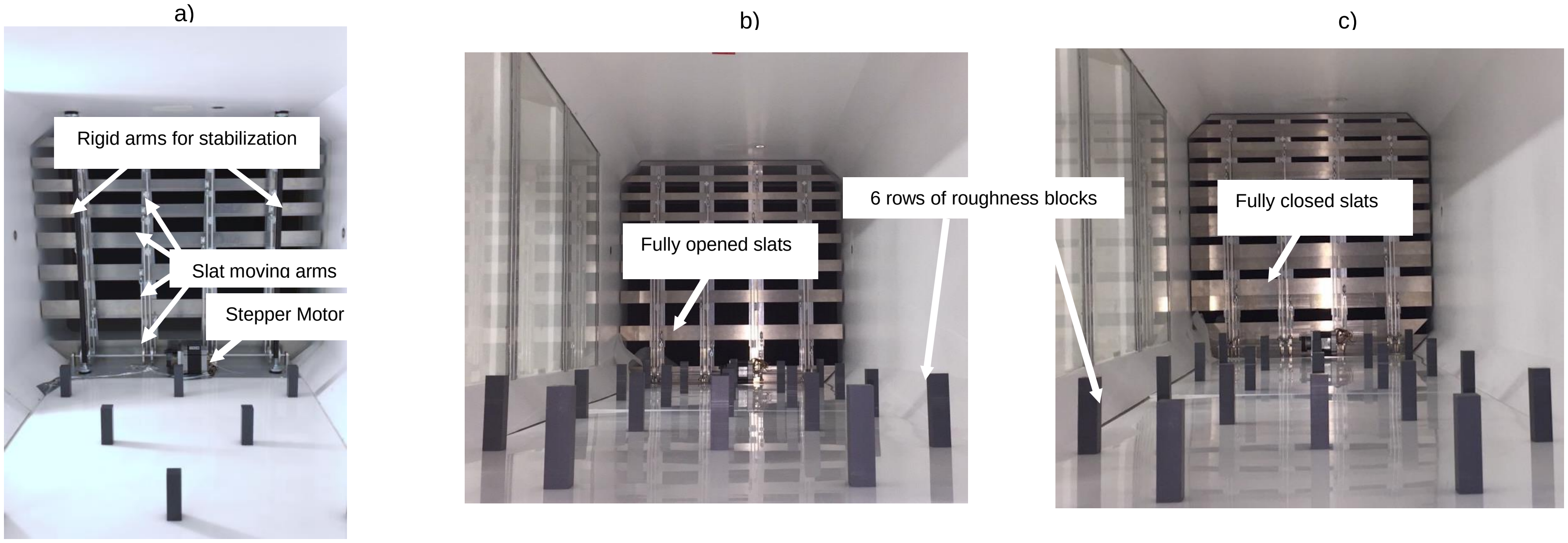

Figure 4: Flow conditioning system a) Elevation view showing the stepper motor b) Slats fully opened (40% blockage) c) Slats fully closed (80% blockage) c) Slats fully closed

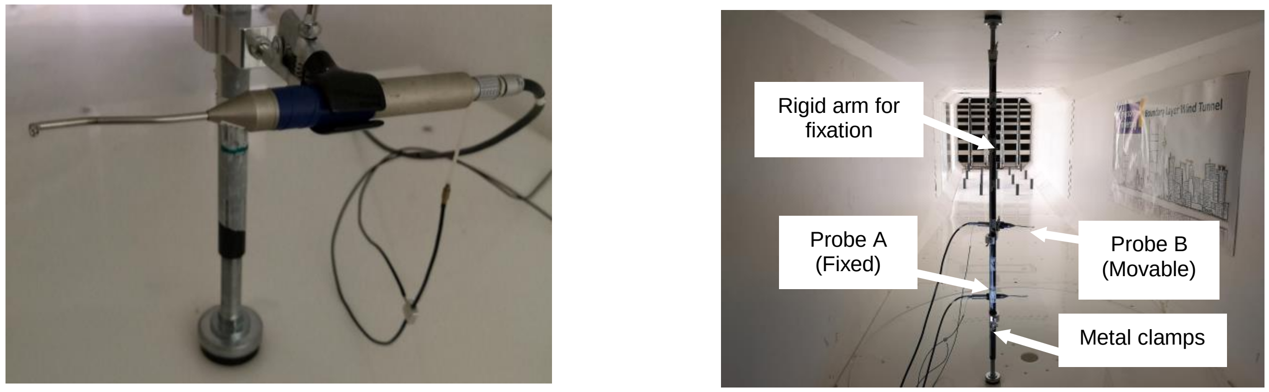

Figure 5: Probes setup and fixation

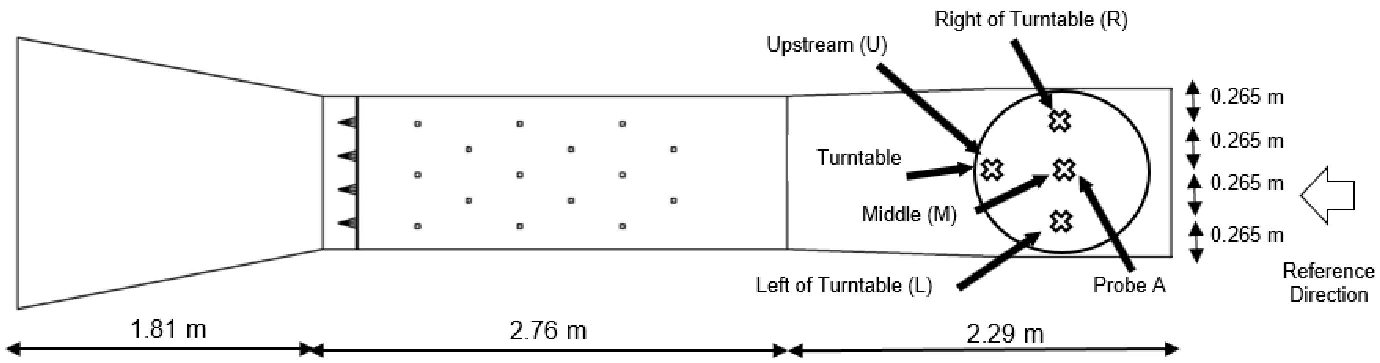

Figure 6: Uniformity test location

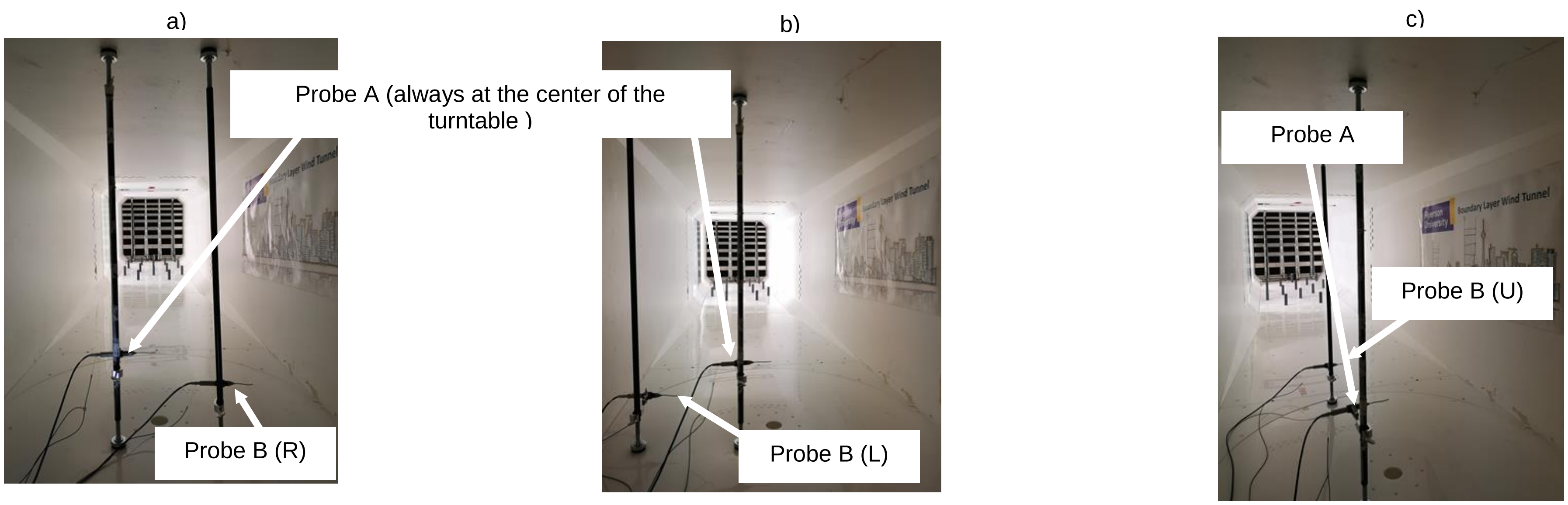

Figure 7: Uniformity test at different locations a) Probe B on the right b) Probe B on the left c) Probe B upstream

Mean longitudinal wind velocities and longitudinal turbulence intensities where evaluated for the fully open wind spire-slat system and plotted in Figure 8 at the four selected locations. The figure indicates that the obtained four profiles are in a reasonable agreement with each other and, therefore it can be concluded that uniformity of the obtained flow field is acceptable at the test zone (i.e. within the limits of the turntable).

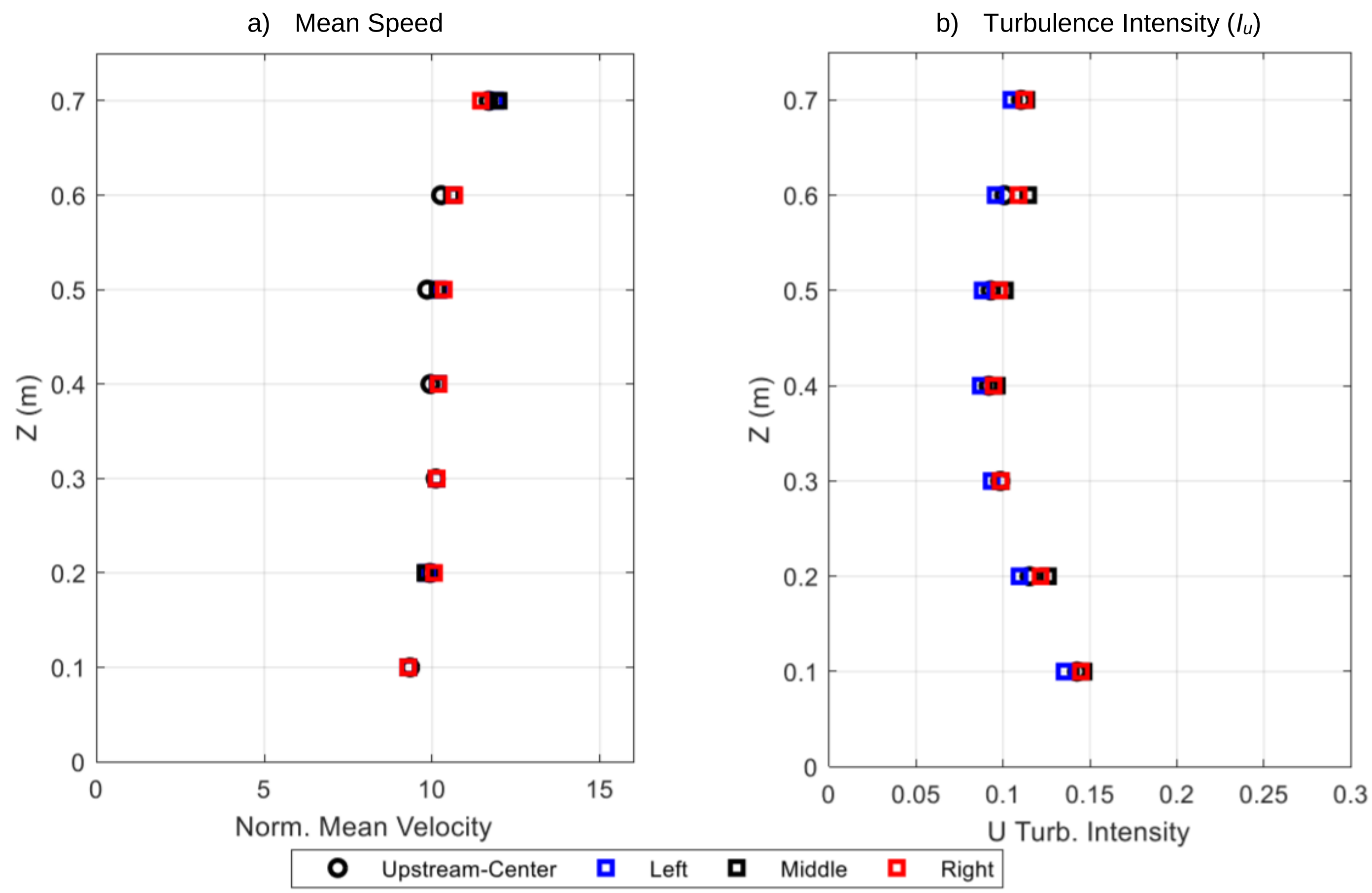

Figure 89: Mean speed and turbulence intensity at four locations in the turntable

4 VALIDATING THE RESULTING BL WIND FIELD

Turbulent velocity records in the longitudinal u, transverse v, and vertical w directions were acquired at the center of the turntable at various heights considering different Spire-slat openings. Slat-openings were adjusted according to (Ghazal et al., 2018) and the profiles were compared with the target profiles according to the ESDU. Target profiles were taken considering two sample length scales typically used for tall buildings (i.e. 1:500 and 1:250). Figure 9 shows the resulting profiles at the center of the turntable for an open terrain exposure for a length scale of 1:500. As shown in the figure, longitudinal mean velocity, turbulent intensities Iu, Iv and Iw and Reynolds stress <u'w'> are plotted and compared with the target. In addition, sample longitudinal velocity time history at 0.4m is plotted and its spectra was generated and compared with target according to the ESDU (2010). It can be seen from Figure 29 that resulting flow field characteristics match those of the ESDU with a very good agreement. There is a slight overestimation of the Iw component, but this is expected to have a minor effect on the building pressures and associated later loads.

Similarly Figures 10 and 11 show the resulting wind field from the system at a length scale of 1:500 compared to the target suburban and urban ESDU profiles, respectively. The two figures show very good match which validates the designed system. Similar to Figures 9-11, Figures 12-14 present characteristics of the resulting flow field compared with the ESDU for open, suburban and urban terrain exposures, respectively, at a length scale of 1:250. Those figures also confirm the accuracy of the system in generating target BL winds. The effective blockage for each of the cases presented in Figures 9-14 is shown on the figure caption. It can be seen that, that the required blockage to achieve length scale of 1:250 is in general greater than blockage needed for the length scale of 1:500. Since the urban profile at the 1:250 (largest turbulence intensity) length scale was obtained at an effective blockage of only 70%, which is lower than the maximum blockage achievable by the system (i.e. 80%), it is expected that the system will work also with higher length scales which needs more turbulence.

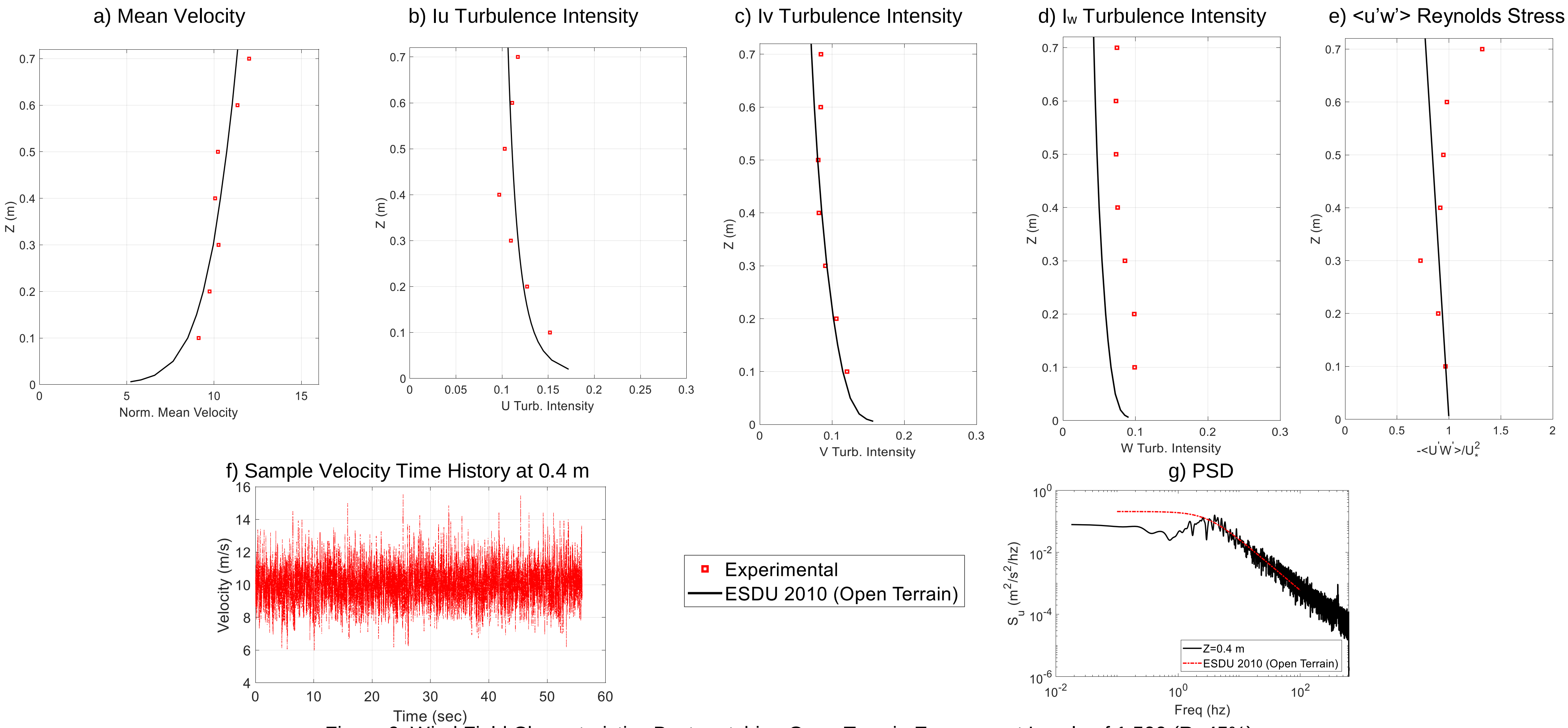

Figure 9: Wind Field Characteristics Best matching Open Terrain Exposure at Lscale of 1:500 (R=45%)

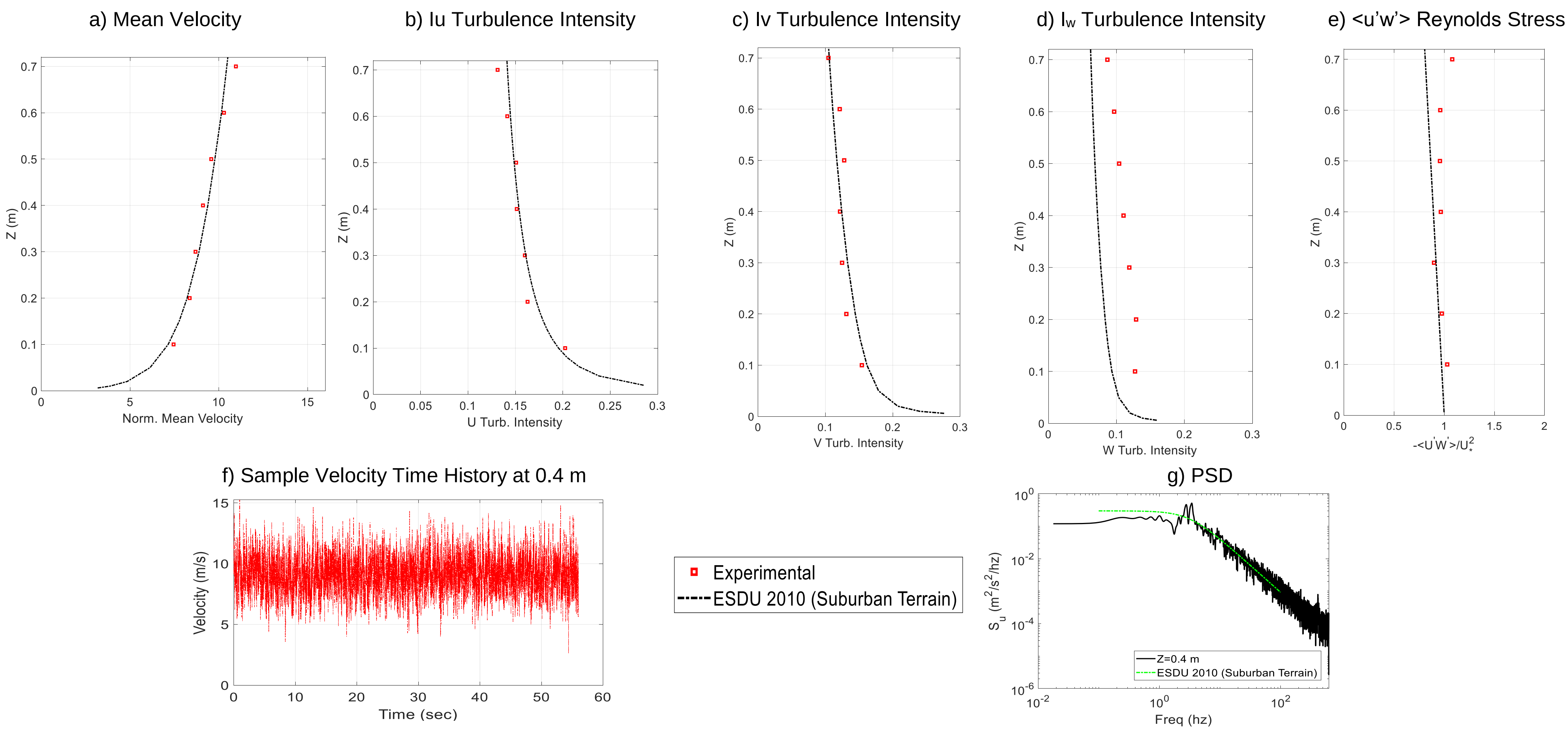

Figure 10: Wind Field Characteristics Best matching Suburban Terrain Exposure at Lscale of 1:500 (R=55%)

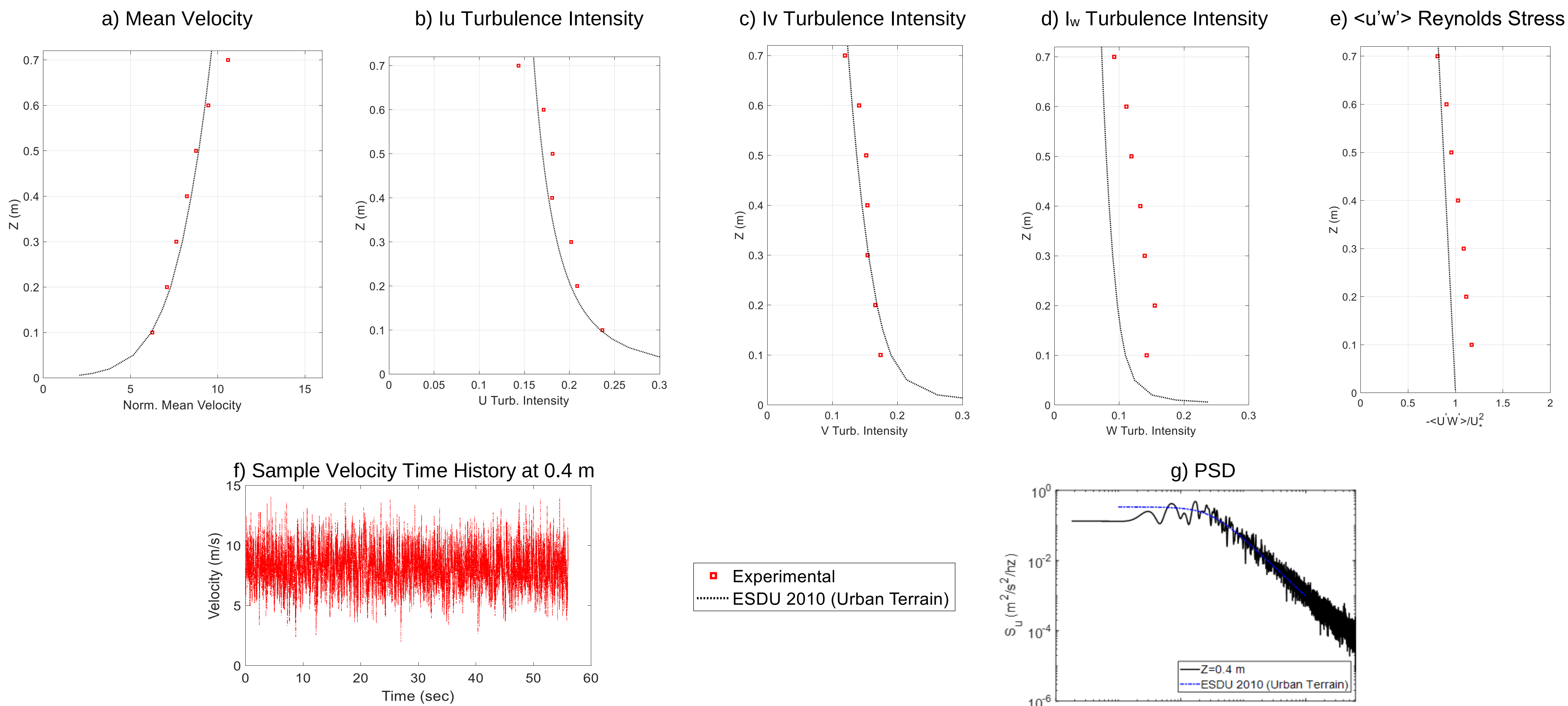

Figure 11: Wind Field Characteristics Best matching Urban Terrain Exposure at Lscale of 1:500 (R=63%)

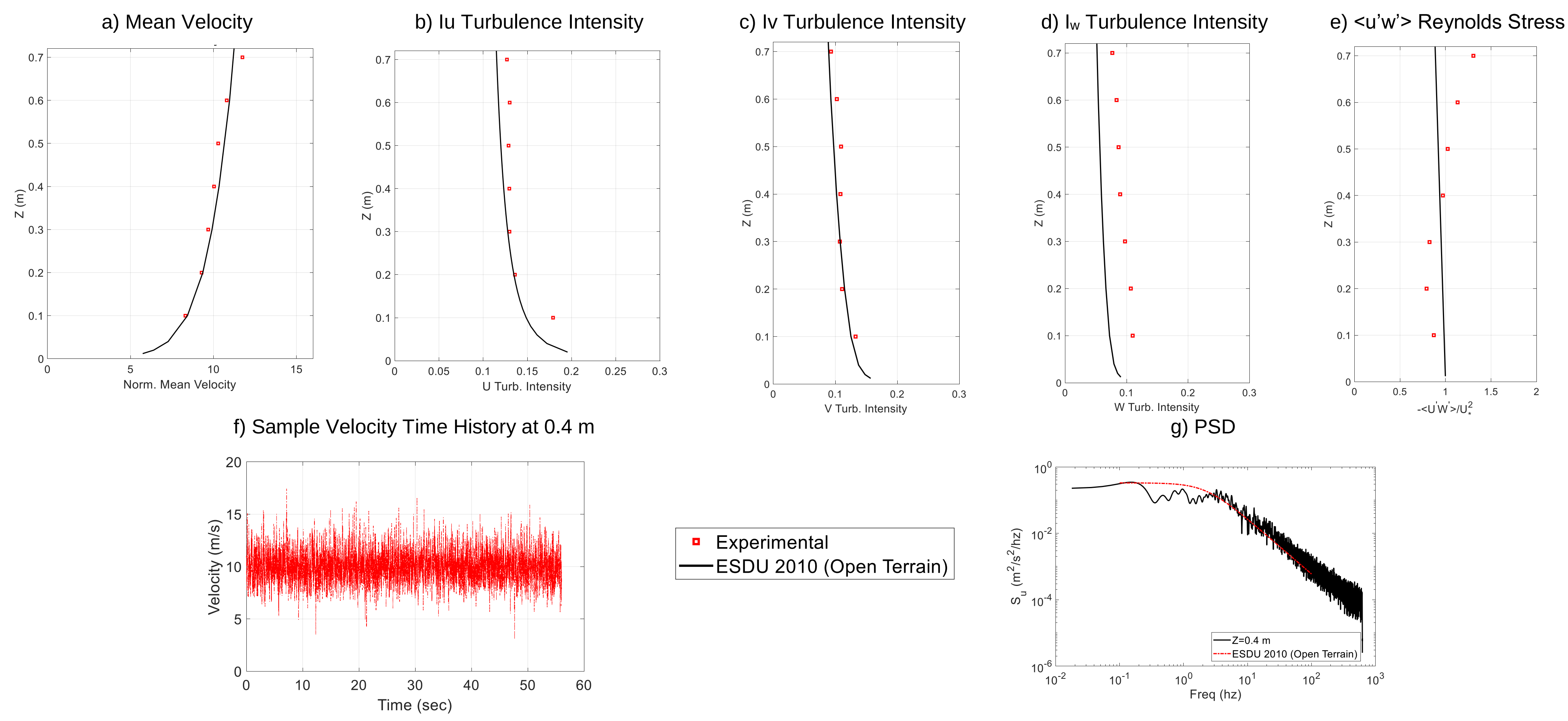

Figure 12: Wind Field Characteristics Best matching Open Terrain Exposure at Lscale of 1:250 (R=48%)

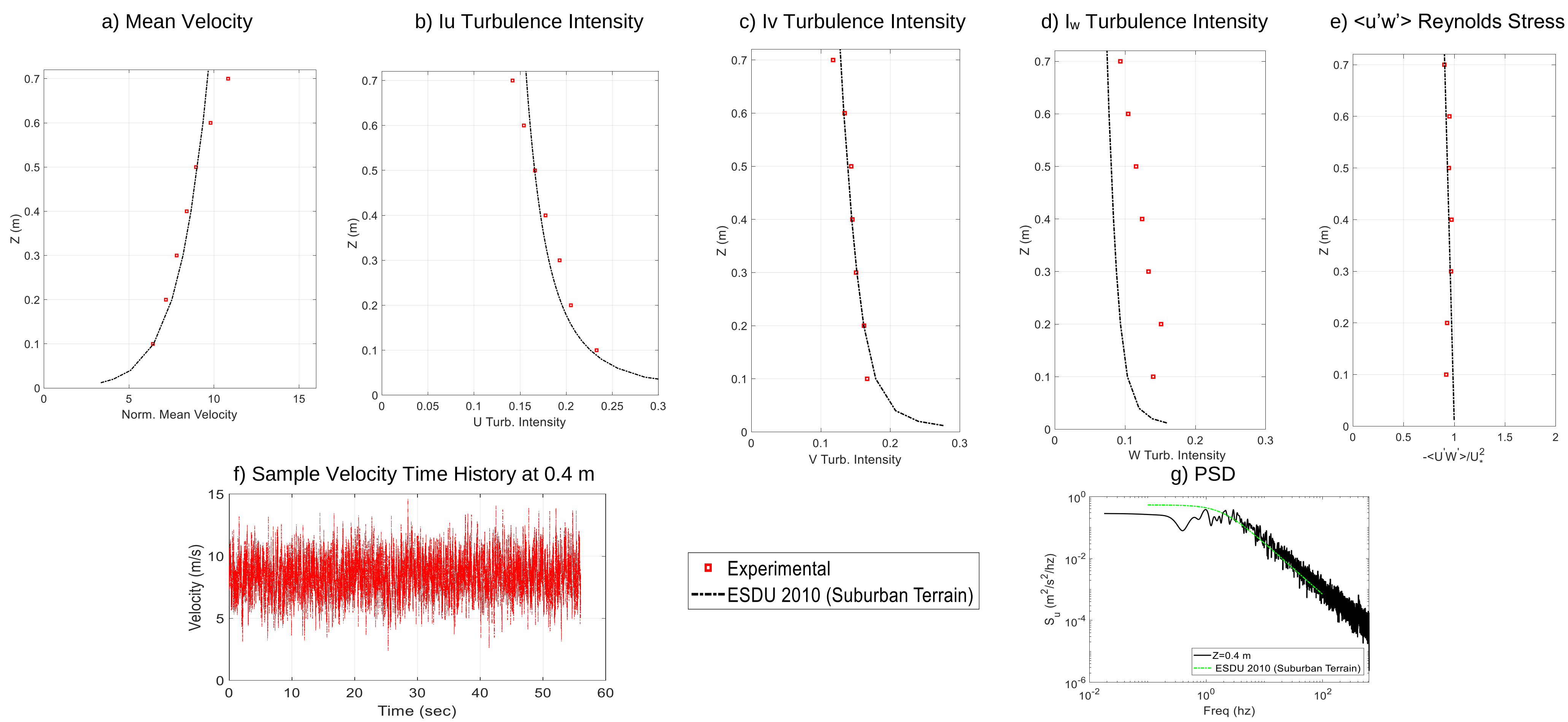

Figure 13: Wind Field Characteristics Best matching Suburban Terrain Exposure at Lscale of 1:250 (R=62%)

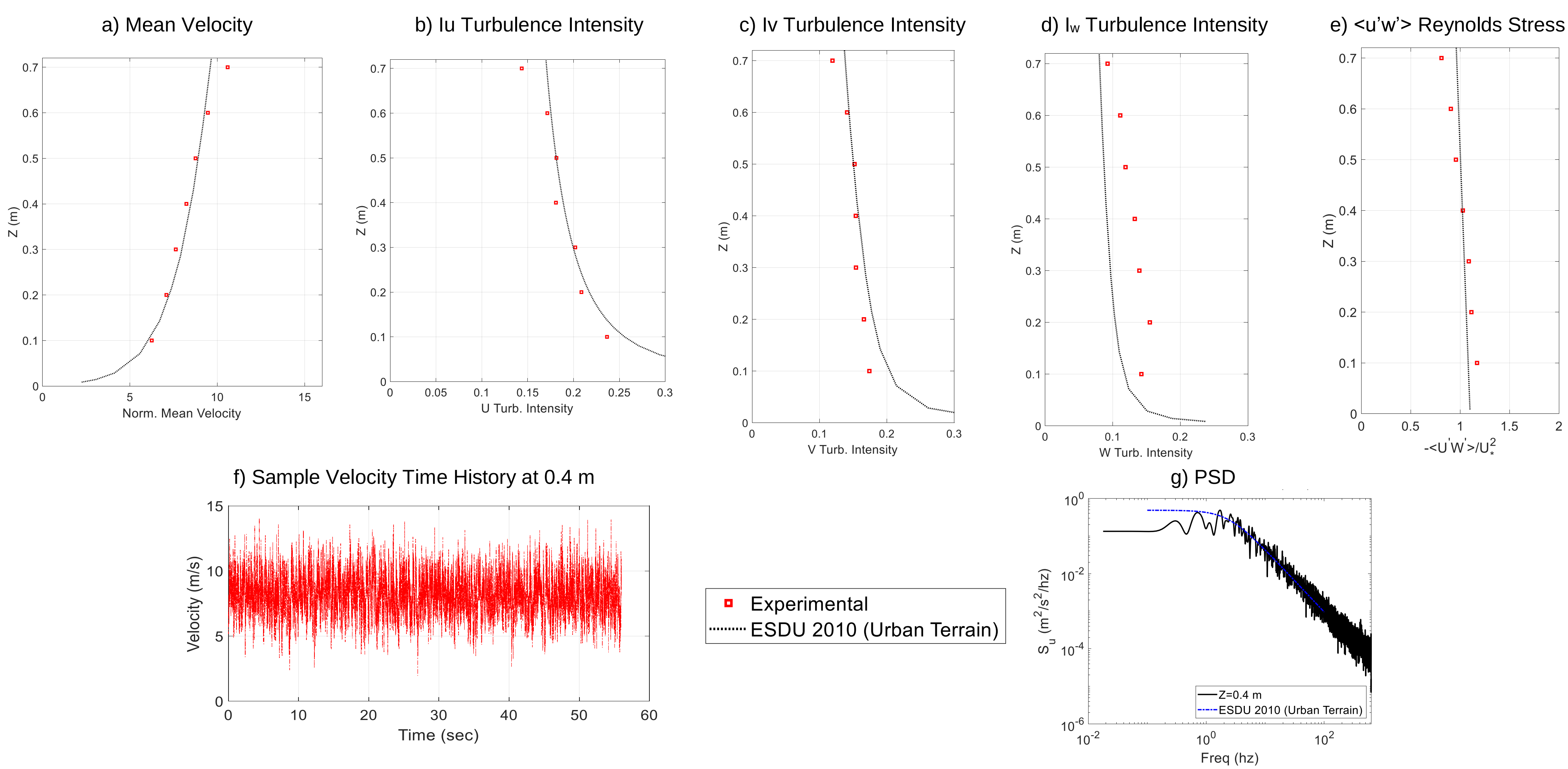

Figure 14: Wind Field Characteristics Best matching Urban Terrain Exposure at Lscale of 1:250 (R=70%)

5 CONCLUSIONS

In this study, a flow-conditioning system to model various Boundary Layers BLs for typical terrain conditions at the sub-sonic wind tunnel at Ryerson University was validated experimentally. The system consisted of a two-layer spire slat system (one fixed and one movable) in order to control the blockage ratio to model different BL's (open, suburban and urban terrains), in addition to10 cm roughness blocks distributed over 6 rows. Characteristics of the resulting flow field were compared with the target characteristics based on the ESDU at two typical length scales (1:500 and 1:250). The system achieved a very good match with the target characteristics which prove the accuracy of the system and capability of generating accurate BL profiles for various terrain exposures.

ACKNOWLEDGEMENT

The authors would like to thank Ryerson University for the funding of this project through the start-up and equipment grants of the last author. Also, the authors are thankful to the team at the WindEEE research institute for kindly lending the Cobra Probe system.

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