CIVL4160 ADVANCED FLUID MECHANICS

WIND LOADS ON BUILDINGS - PHYSICAL MODELLING IN AN INDUSTRIAL WIND TUNNEL PROJECT

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Le Viaduc de Millau (France) (Courtesy of Le Viaduc de Millau)

Notation

C_p	dimensionless pressure coefficient defined as: $C_p = \frac{P - P_{ref}}{\frac{1}{2} \times \rho \times V_{ref}^2}$;
P	pressure (Pa);
P_{atm}	barometric pressure (Pa);
P_{eaves}	pressure at eaves (Pa);
P_{ref}	time-averaged reference pressure (Pa) measured at the reference Pitot tube;
Re	Reynolds number;
T	temperature (Kelvin);
Tu	turbulence intensity defined as: Tu = u'/V;
u'	root mean square of longitudinal component of turbulent velocity (m/s);
V	velocity (m/s);
V_{ref}	time-averaged reference velocity (m/s) (i.e. reference Pitot tube velocity);
V_o	free-stream velocity (m/s);
x	longitudinal coordinate (m); positive in the downstream flow direction with x = 0 at the building model centreline;
y	transverse coordinate (m); with y = 0 at the wall supporting the reference Pitot tube;
z	vertical coordinate (m) positive upwards;

Greek symbols

δ	boundary layer thickness (m);
μ	fluid dynamic viscosity ($N.s/m^2$);
α	angle of incidence;
ρ	fluid density (kg/m^3);

Subscript

ref	reference flow conditions: i.e., measured at the reference Pitot tube.

1. Presentation

1.1 Project description

The purpose of the experimental work is to introduce undergraduate students to the complexity of turbulent flow studies, the complex interactions between fluid and structures particularly in civil engineering, and the difficulties associated with experimental works in a large-size wind tunnel (e.g. App. I, III and IV). The students will investigate the flow field around a building in an atmospheric boundary layer. For one inflow velocity but several wind directions, they will conduct detailed turbulent velocity measurements as well as the pressure forces on the building, and the lift and drag forces for the selected flow conditions.

The students will process and analyse their data, and compare these with the ideal-fluid flow theory and real fluid flow theory (CIVL2131, CIVL4160). They will also conduct a bibliographic search for similar studies around the world.

In addition, the students will investigate a simple developing boundary layer on a flat rough plate in absence of pressure gradient. The data will be analysed and a comparison with the atmospheric boundary layer data will be developed.

The assignment will show practical details which must be considered during the study of a system : e.g., fluid structure interactions, wake region (App. III). Model tests will take place in the University of Queensland Industrial Boundary Layer Wind Tunnel in the AEB Hydraulics Laboratory of the School of Civil Engineering. Additional experiments will also take place in the Hydraulics Laboratory: e.g., Hele-Shaw cell flow visualisation.

This design work will be a group work to emphasise **team work, collaborative efforts and communication**, complemented by individual works. A building model will be investigated in a large wind tunnel (App. I). The model will be experimentally studied by a group of 5 students on 9 April 2015. The students will compare their data with theoretical calculations (e.g. flow net, 2DFlow+) and the bibliography. The project will be concluded by a report submission and an oral presentation (Table 1-1). The latter will be assessed by both lecturers and peers.

Table 1-1 - Time table

Week	Date	Description	Remarks
1	2 March	Course profile and project time table.	Draft project details
5	2 April	Complete instructions, timetable and deadlines. Group composition for wind tunnel testing.	
	7 April	Final instructions. Last minute instructions and practical matters.	
	9 April	Wind tunnel study incl. (1) Wind loads on buildings, (2) Boundary layer experiment and (3) Hele-Shaw cell analogy study	AEB Hydraulics Laboratory. Full day wind tunnel study per group of 3-5 (4) students. Time: 07:30-15:30. Every student must attend.
6		Assistance from lecturers & tutors.	
9	4 May	Oral presentations for each student (from 14:00).	Every student must attend.
10	11 May	Report submission.	Deadline: 2:00 pm in Prof Chanson's hands.

1.2 Project background

Many civil engineering structures are affected by wind aerodynamics. In some cases, the fluid structure interactions may lead to failures. Appendix IV details real-case studies.

On 18 March 1998, several transmission towers were damaged in the Brisbane valley. Most damage occurred near Harlin, Colinton and Kangaroo Creek. It is believed that the towers collapsed during gusty, tornado-like winds with wind gusts in excess of 200 km/h (Fig. 1-1). The replacement towers were designed to withstand winds up to 210 km/h.

Another example of failure is La Grande Arche in La Défense, a western suburb of Paris (France). Completed in 1989, the building is 110.9 m high, 112 m long and 106.9 m wide. Shortly after completion, very strong winds were felt at the bottom of the Arch. This was caused by natural strong winds experienced at La Défense associated by a Venturi effect induced by the arch shape (Fig. 1-2). As a result, a 2,300 m^2 surface area membrane (PTFE-coated glass fiber fabric) was installed at the foot of the arch to reduce the wind speed at pedestrian level. The membrane is clearly seen in Figure 1-2.

The third example is not a failure. Completed in 1995, the Pont de Normandie is a suspension bridge on the Seine river (Fig. 1-3). The total length is 2,141 m and the central span is 856 m long. The estuary of the Seine river is well-known for strong Westerly winds and the bridge was designed to sustain wind speeds of up to 300 km/h. The bridge deck was streamlined to reduce the wind drag and its design was tested in wind tunnel.

A fourth example is the Millau suspension bridge (or Millau viaduct) in Southern France (Fig. 1-4). Completed in 2004, the bridge is 342 m tall and 2,460 m long. It was designed to sustain storm wind speeds up to 250 km/h. The final design was tested in both wind tunnel and water tunnel. In the water tunnel, the physical model was built at a 1:3,000 scale.

Fig. 1-1 - Damaged transmission tower (275 kV double circuit electricity transmission tower) in the Brisbane valley in March 1998 (Courtesy of Prof C. LETCHFORD)

Fig. 1-2 - La Grande Arche, La Défense (France) (Courtesy of VF Communication, La Grande Arche) - Looking West

Fig. 1-3 - Le Pont de Normandie (France) in May 2003- North pier, driving South (Courtesy of Mr and Mrs CHANSON)

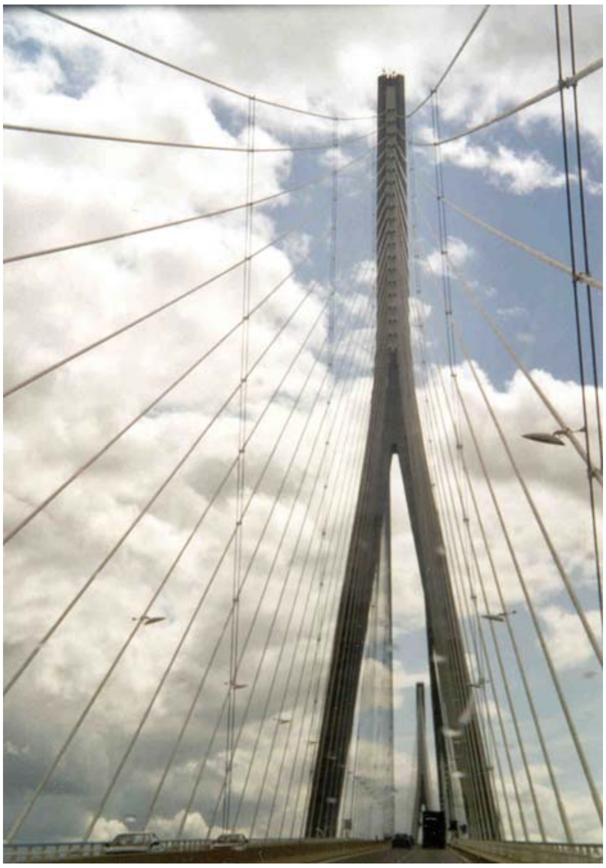


Fig. 1-4 - Airbus A380 flying over Le Pont de Millau (France) (Courtesy of Le Viaduc de Millau)

2. Wind tunnel study

2.1 Wind tunnel experiments

The physical modelling experiments will take place on 9 April 2015 (2015/1). The wind tunnel tests shall be conducted in the University of Queensland AEB Hydraulics laboratory located in building 49, level 1. The cross-section of the wind tunnel test section is 0.7 m by 0.7 m and ithe wind tunnel specifications are listed in Table 2-1..

Each group will have a fully-instrumented perspex model with pressure tappings (App. I and III). The fully-instrumented perspex model will be used to measure the pressures and pressure fluctuations at the surface of the model as functions of the angle of incidence (Table 2-2). The model will be centred on the wind tunnel and the angle of attack α (0 degree = building walls horizontals in wind tunnel and aligned with main stream direction) will be changed by rotating the model. Pressure measurements will be conducted with a Scanivalve™ system connected to a data acquisition computer scanning the data at 600 Hz.

Velocity and turbulent velocity fluctuation measurements will be performed with a single wire 55P11 straight hot-wire controlled by a Constant Temperature Anemometer (Dantec™ Streamline). Both upstream and downstream velocity distributions will be recorded. The former will be used to assess the inflow conditions. The latter measurements (downstream velocity profiles) will be performed in the near-wake region to characterise the recirculation region and hydrodynamic instabilities.

The wind tunnel experiments will be complemented by a series of flow visualisation in a Hele-Shaw cell experiment with suitable boundary shapes. The resulting two-dimensional flow patterns are analogous to the ideal-fluid flow calculations.

Further some turbulent velocity measurements will be conducted in a developing boundary layer above a flat plate (smooth or rough). These will be conducted immediately upstream of the plate and at several locations downstream of the plate leading edge.

Prof Hubert CHANSON and a number of Civil Engineering School staff will be available on 9 April 2015 **between 7:30am and 3:30pm** to assist the students. The Hydraulics Laboratory Manager, Mr Jason VAN DER GEVEL, will be in the laboratory all the days, and Prof. CHANSON will be contactable.

The start time of the groupwork is 7:30am in the Wind tunnel area of the AEB building Hydraulics laboratory (49, level 1) (UQ St Lucia).

The experimental equipments are provided by the UQ Civil Engineering Hydraulics Laboratory and they are commonly used for industrial/consulting testing activities. ALL the equipments must be returned un-damaged at end of the experiment. (Lateness in returning any equipment and damage to any equipment shall be heavily penalised.)

PLEASE clean up all equipment and the wind tunnel office before returning all the gears undamaged.

Inflow conditions

For this project, the inflow conditions will be identical for all designs but for the angle of incidence (Table 2-2). That is, a free-stream velocity of about 15 m/s (i.e. V_o = 15 m/s). The wind tunnel intake, screens and convergent were selected to provide the suitable shapes of velocity and turbulent velocity profiles in the approaching flow.

The study is focused on the wind loads on the building models as functions of the angle of incidence for one set of inflow conditions.

Table 2-1 - AEB Hydraulics laboratory wind tunnel specifications

Specification	Description
Screenbox	• Bellmouth Inlet • Side door Access for Easy Screen Removal/Installation • 4 Turbulence Reduction Screen Slots • Steel Construction
Contraction	• 6:1 Contraction Ratio • Settling Chamber = 14.8 inches • Removable Leg Extensions • Durable Casters for Ease of Transport • Steel Construction
Test Section	• Quantity = 3 • W x H x L = 30"x30"x47" • Acrylic Side and Ceiling Windows • Gas Shocks and Rubber Clamps for Quick Model Access • Custom Aluminum Corner Fillets • Black Macropoxy Paint • Aluminum Frame Construction
Diffuser	• 2:1 Diffuser Ratio • Square to Round Transition • Equivavlent Cone Angle = 6° • Durable Casters for Ease of Transport • Steel Construction
Fan	• Airfoil Type Vane-axial Fan • Number of Blades = 9 • Propeller Diameter = 48 in • Blade Angle = 32 deg
Motor	• 75 HP • 3-Phase 230/460 Vac • RPM = 1800 • Nominal Current = 170.2/85.1 • Service Factor = 1.15
Variable Frequency Drive (VFD)	• Model ACS550-CC-125A-4 • 100 HP • 3-Phase 480 Vac

Fig. 2-1 - Photographs of wind tunnel experiment
(A) Sideview with flow direction from left to right

(B) Wind flow direction from foreground right to background left

(C) Details of intake system

2.2 Wind tunnel measurements

Each group will conduct a series of measurements within a full working day (i.e. from 7:30am to 3:30pm). In each case, the wind tunnel will operate, at design flow conditions, for a reference velocity of 15 m/s, where the reference velocity V_{ref} is measured in the intake contraction and using the reference Pitot tube installed at the upstream end of the test section. For that reference velocity and the upstream screen setup, the free-stream velocity and the upstream boundary layer characteristics shall be deduced from velocity measurements.

The wind tunnel setup is shown in Figure 2-1. The boundary layer experiment is presented in Figure 2-2. Figure 2-3 illustrates a Hele-Shaw cell flow visualisation.

[0] Hot-wire probe calibration

Measurements of velocity and turbulent velocity fluctuations will be conducted with a hot-wire probe controlled by a Constant Temperature Anemometer (CTA). Basically the probe wire is heated at a constant temperature. The voltage delivered to the wire is a function of the wind velocity.
First the hot-wire probe must be calibrated by placing it next to the reference Pitot tube. Then the wind tunnel is operated for a range of velocities from V = 0 to a maximum (reference) wind speed of 20 m/s.
At least eight velocity measurements must be performed with at least 5 data points between 0 and 20 m/s, but more might be required depending upon a statistical error analysis.

During the measurements, study the oscilloscope display to observe the general nature of the flow.

[1] Inflow conditions

The upstream velocity and turbulent velocity profiles will be measured at the upstream reference location, corresponding to x = - 0.25 m with the building model in position at zero angle of incidence. Measurements will be conducted with a 1-D hot-wire probe Dantec connected to a StreamLine Constant Temperature Anemometer system, managed by the software Streamware. The hot wire probe readings will be scanned at 400 Hz for 5 seconds. **The reference velocity V_{ref} shall be 15 m/s**.

The inflow conditions shall be analysed to estimate the free-stream velocity, the upstream velocity profile, and the upstream turbulence intensity distribution. This analysis is important to characterise the inflow conditions.

[1B] Boundary layer experiment

Measurements of velocity and turbulent velocity fluctuations will be conducted with a hot-wire probe controlled by a Constant Temperature Anemometer (CTA) in the developing boundary layer above a flat plate. The plate is 0.335 m wide and 0.8 m long, and it set with a slight upward slope ($\tan\theta \approx 0.01$). A smooth plate will be used. (Note the trip wire at the upstream end.). Vertical turbulent velocity profiles will be measured upstream of and above the flat plate. The hot wire probe readings will be scanned at 400 Hz for 20 seconds at each sampling location. **The reference velocity V_{ref} shall be 15 m/s**.
First the vertical velocity profile will be measured at x' = -0.10 m where x' is the downstream distance from the plate leading edge.
Then the vertical turbulent velocity distributions will be measured at several cross-sections x' (Table 2-3, column 3). For each vertical profile, **at least twenty-five velocity measurements** must be performed, with a very close spacing in the vicinity of the plate. At least 15 data points must be sampled in the developing boundary layer and another 2 points at least must be in the free-stream.

During the measurements, study the oscilloscope display to observe the general nature of the flow in the boundary layer next to the rough plate and in the free-stream.

[2] Pressure measurements

With the fully-instrumented perspex model installed on the turning table, the students will record pressures and pressure fluctuations at each pressure tapping by scanning at 600 Hz for 60 seconds each point. That is, each pressure tapping will be scanned for 60 seconds. A total of 32 pressure tappings are installed: 8 tappings on each side of the building model. The channels 1 and 2 are respectively the static and dynamic pressures of the reference Pitot tube.
Experiments will be repeated for several angles of incidence a (Table 2-3, column 3). Here the angle of incidence is zero when the building walls are aligned with the free-stream velocity.

The pressure measurements will provide dimensionless pressure coefficients C_p : mean values, standard deviations, maximum values and minimum values. The results shall be integrated along the building surface to calculate the **drag force** and **lift force** acting on the building.

The dimensionless pressure coefficient is defined as :

$$C_p = \frac{P - P_{ref}}{\frac{1}{2} \times \rho \times V_{ref}^2}$$

where ρ is the fluid density, P_{ref} is the reference pressure (i.e. time-averaged static pressure at reference Pitot tube) and V_{ref} is the time-averaged reference velocity.

NB: The pressure measurement system is a newly installed system. If a problem arise on the day of the experiment (based upon the technical advice of Jason VAN DER GEVEL), you would conduct **additional** velocity measurements in the wake of the building. These additional data sets would allow a more accurate estimate the total drag force on the building using the momentum integral method. Additional downstream velocity measurements would be conducted at x = +0.45 m and +0.60 m.

[3] Downstream velocity measurements
With the fully-instrumented perspex model installed on the 'turning table', vertical profiles of velocities and turbulent velocity fluctuations will be recorded at a distance x = +0.0675 m, and 0.30 m measured from the model centreline (That is, at the turning table centreline location.) In addition an upstream velocity profile will be performed at x = -0.15 m. All measurements will be performed on the test section centreline. Measurements will be conducted with a 1-D hot-wire probe Dantec connected to a StreamLine Constant Temperature Anemometer system, managed by the software Streamware. The hot wire probe readings will be scanned at 400 Hz for 20 seconds at each sampling location. **The reference velocity V_{ref} shall be 15 m/s**.
The measurements will be focused on the wake region, flow separation and vortex shedding. They will extend across the entire wind tunnel (App. V). It is expected that at least 35 points will be required per horizontal profile. Details of the separation region and vortex shedding shall be obtained using fine horizontal displacements in the separation regions. At least 20 points shall be recorded in the separation region and vortex shedding zone.
The **raw probe outputs** shall be recorded and saved for *at least 5 data points* in the vortex shedding region. The data will be subsequently analysed to document the vortex shedding behind the building model.
Experiments will be performed for a number of angles of incidence (Table 2-2, column 4).

Table 2-2 - Experimental flow conditions for cyclonic wind loads on building (atmospheric wind tunnel experiments)

Model (1)	Aspect ratio (2)	Angle of incidence (°) Pressure measurements (3)	Angle of incidence (°) Wake flow measurements (4)	Comments (5)
M1	1:1			Square shape. Size: 0.045 m.
		0, +5, +10, +15, +30, +35, +40, +45	0 +30	Group 1

Table 2-3 - Boundary layer investigations above a flat plate

Group	Plate	Measurement locations
1	Flat plate	x' = -0.10, +0.10, +0.20, +0.40 m, +0.60 m, +0.75 m

Note: x' : downstream distance from the plate leading edge

Practical considerations
ALL THE DATA shall be recorded in writing. These data will constitute a key component of the final report and of the group work assessment. Students are very strongly encouraged to think beforehand how they will record the data and to prepare relevant books and notepads. Any loss of data is not acceptable. Use carbon copies (e.g. accounting books) to backup your data regularly.

Wind tunnel observations will include some fluid mechanics and fluid-structure interaction measurements : e.g., velocity, turbulent velocity measurements, pressure, pressure fluctuations.

Air temperature and barometric pressure.
Check the barometric pressure at least 3 times during the day.
Air temperature in the wind tunnel must be recorded every 20 to 30 minutes.

During experiments, **check the reference velocity V_{ref} to be 15 m/s** using the projection manometer. (Adjust gently the wind tunnel motor speed if needed.)

In operating the traverse mechanism, the person standing in the wind tunnel must: (1) be downstream of the probe and (2) next the wall during data acquisition to reduce blockage effects.

2.2 Boundary layer experiment and analysis

As indicated above [1B], some turbulent velocity measurements will be conducted in the developing boundary layer above a flat plate. The aim of that section it to characterise a turbulent developing boundary layer above an uniformly-distributed surface with one type of plate roughness (smooth or rough). This does include :

- to plot the boundary layer development : i.e., boundary layer thickness, displacement thickness, momentum thickness and energy thickness as functions of the downstream distance from the plate leading edge (take the free-stream velocity at z' = 100 mm),
- to compare the results with a developing boundary layer above a smooth plate,
- to plot the velocity profiles at each cross-sections in a dimensionless form (V_x/V_o vs y/δ), to compare the data with a power law and a log-law
- to plot the turbulent intensity profiles at each cross-section in a dimensionless form (Tu vs y/δ), and to compare the results with well-known results,
- to deduce the shear velocity V_* and boundary shear stress τ_o at each location x',
- to discuss and compare the developing boundary layer characteristics with a developing boundary layer corresponding to a Category 2 storm/cyclone in a semi-urban area (Australian Standards 1983),
- to estimate the skin friction force on the entire plate (upward side only). (Use at least two techniques: e.g., (a) the application of the momentum integral equation to estimate the mean bed shear stress between two or more measurement locations on the flat plate (choice dependent on best data), and (b) best fit of the velocity distribution with the law of wall.)

> + Each group of students should make measurements at the location x' given in Table 2-3. They could exchange their data with the other groups to enlarge their data set and their analysis, with proper acknowledgments.
> + Take the free-stream velocity of the developing boundary layer at z' = 100 mm where z' is the vertical elevation above the plate.

2.3 Wind loads on building under severe wind conditions

Each group will perform a series of pressure and velocity measurements on the building model for a wind speed of 15 m/s and several angle of incidence (Fig. 2-3). The data analysis will provide a range of informations, including the drag and lift forces on the building model. The drag force will be calculated by two methods:
(a) integration of pressure distributions, and
(b) application of the momentum principle.
The lift force will be deduced from the pressure data.

Further the fluctuating wind load and its characteristic frequency(ies) will be deduced from the analysis of the velocity and pressure data. The velocity measurements in the building model wake will provide information on the characteristic fluctuating frequencies in the wake, while the instantaneous pressure data analysis will give some details on the characteristic fluctuating loads on the building faces.

The study will be performed for several angles of incidences.

Fig. 2-2 - Photograph of the boundary layer experiment: smooth plate - Wind flow from left to right, with the reference Pitot tubes on the left of the photograph

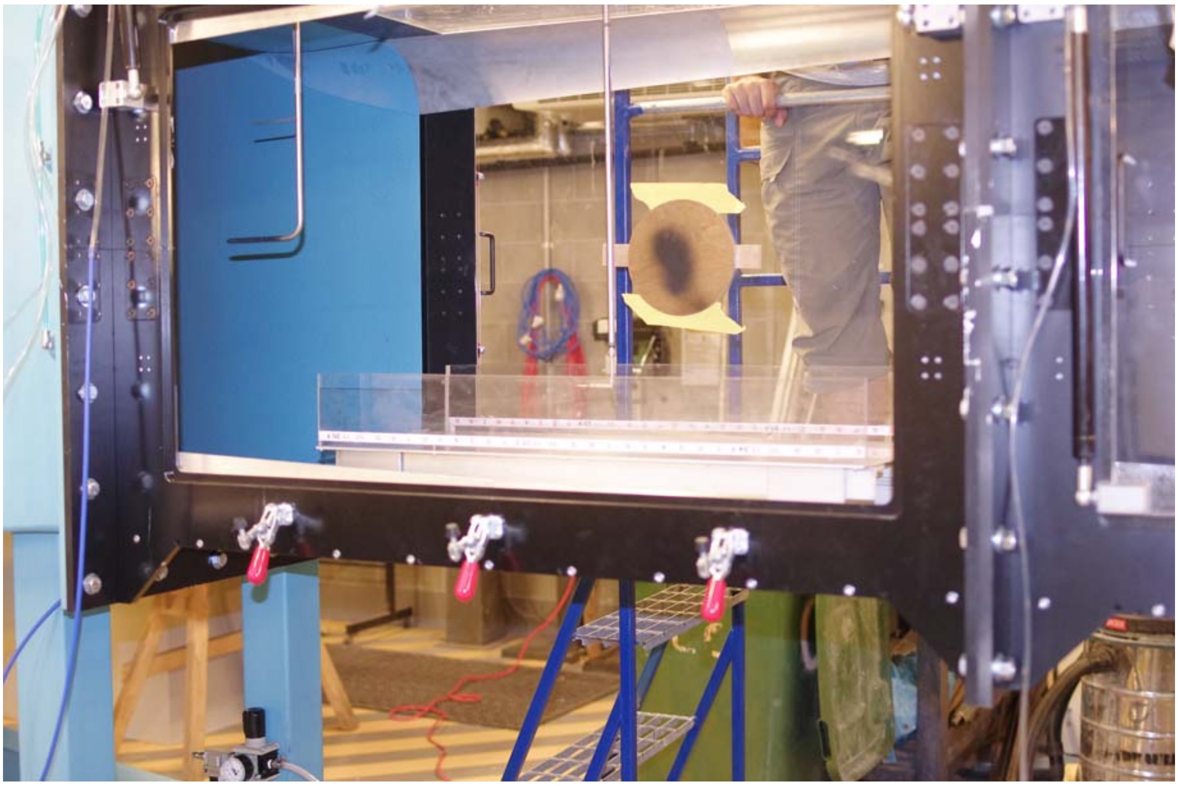
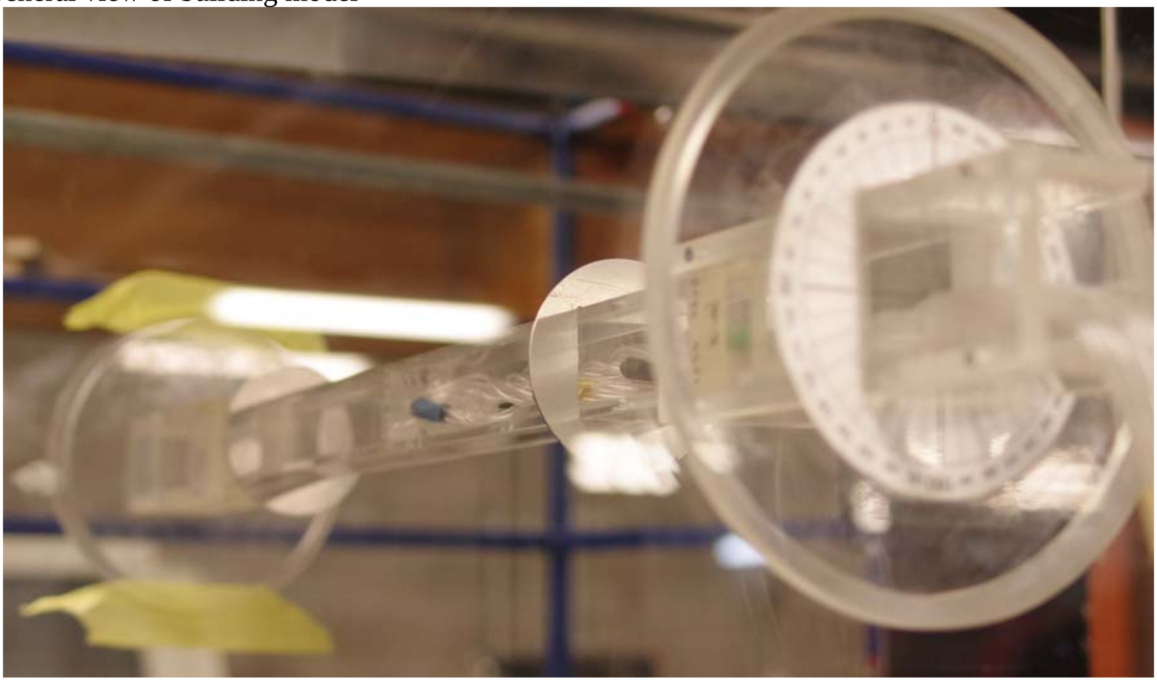
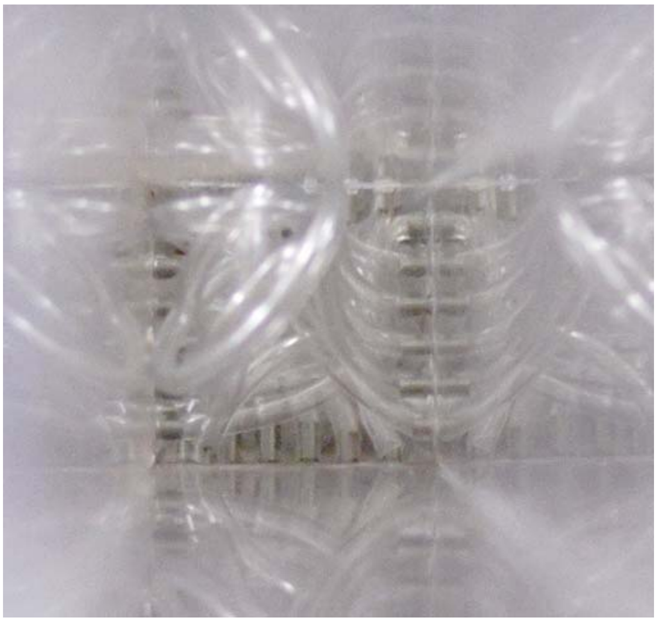


Fig. 2-3 - Photographs of the building model
(A) General view of building model



(B) Details of building model in the test section, with wind flow direction from left to right - Note smoke flowing around the building model

(C) Details of the pressure tapping tubes inside the building model - Note the tapping connection with the plastic tubes



<u>2.4 Hele-Shaw cell experiment</u>

Each group may study visually the flow past a 2-D building in a Hele-Shaw cell experiment. (Bring a camera.) Flow visualisations with dye injection will provide the complete streamlines.

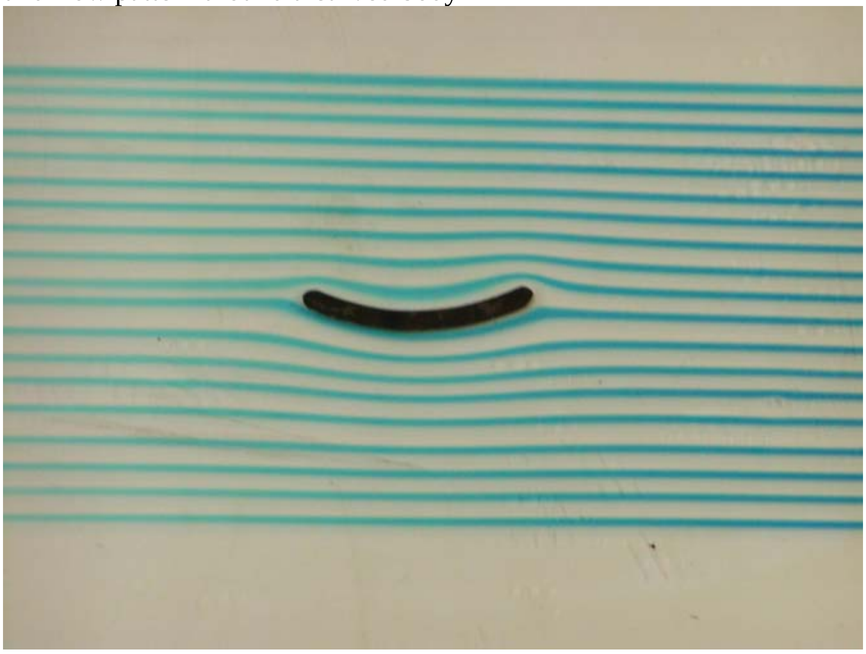
Students are strongly encourage to bring cameras and video cameras. (Digital photographs and movies should form part of the digital material supporting the report.)

Study the streamline pattern for at least two angle of incidence. Record/measure the angle of incidence and the distance between streamlines.

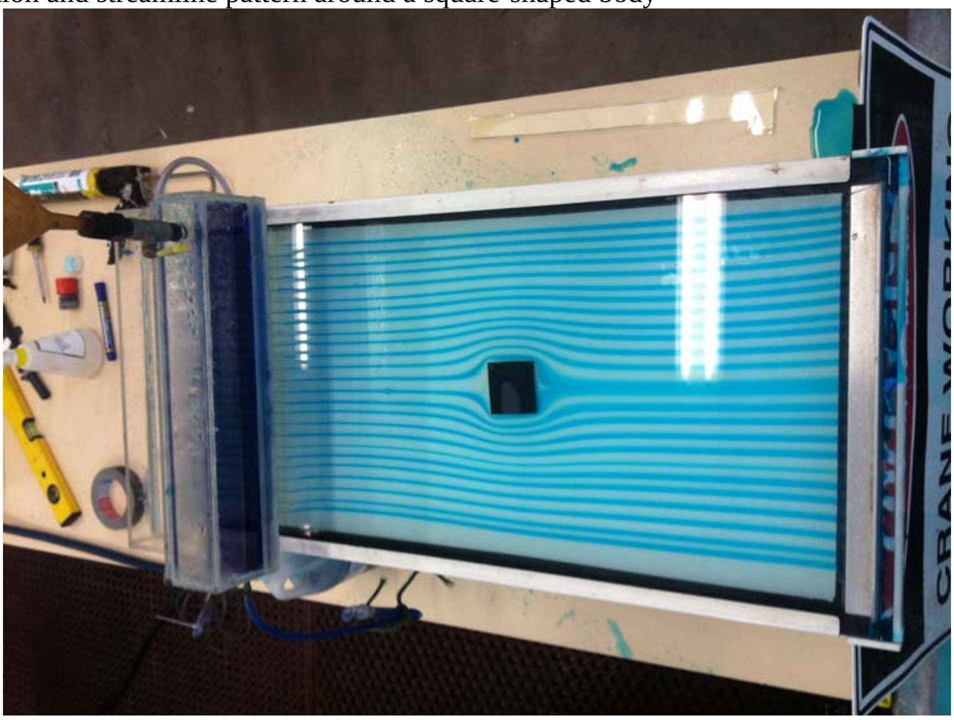
NOTES

- The Hele-Shaw experiments will be run by Jason VAN DER GEVEL in the AEB Hydraulics Laboratory.
- Students have the responsibility to alert Jason VAN DER GEVEL about 20-30 minutes before the Hele-Shaw cell visualisation experiment, to allow time to start up the experiment.

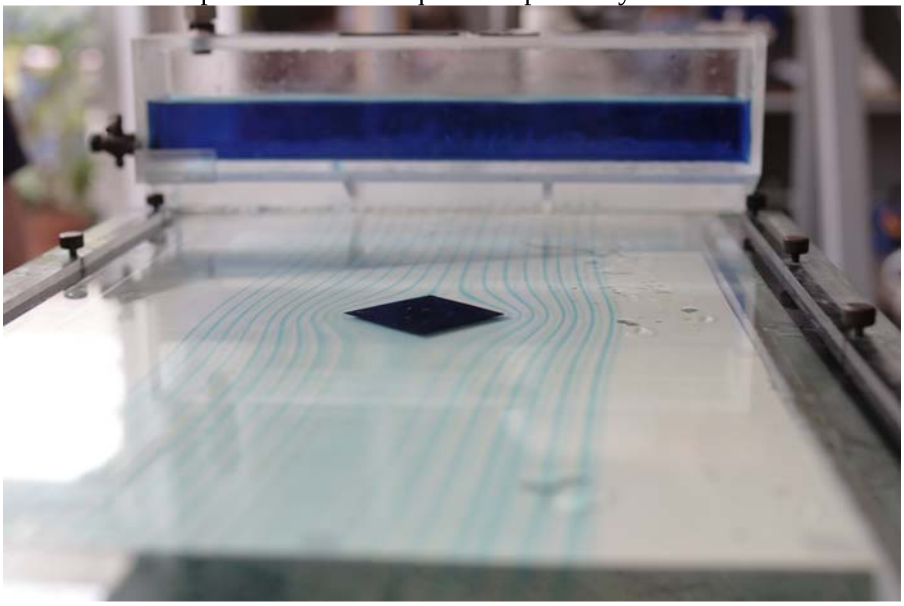
Fig. 2-4 - Photograph of the Hele-Shaw cell apparatus
(A) Dye injection and flow pattern around a curved body



(B) Dye injection and streamline pattern around a square-shaped body



(C) Dye injection and streamline pattern around a square-shaped body



2.5 Preparation

Students are advised to inspect the wind tunnel and the building models at least a couple of days before the experimental work and to plan all practicalities associated with a full-day long study.

It cannot be stressed enough that experimental works require a very thorough preparation.

The time schedule is limited and no further opportunity will be available outside of the outside scheduled times.

Measure precisely the dimensions of both models (full-instrumented and "dummy").

This should be done beforehand.

Bring pen disks and hard disks (in good condition, spam-free and **virus-free**) to backup your data.

You may choose to bring a personal notebook computer to start processing some data on the day.

Bring a stopwatch.

Bring a calculator.

You may bring your own computer to start processing the data.

Bring cameras, films, tapes and memory cards.

Photographic evidence may be useful to support your report and presentation. Video evidences (e.g. MPEG or Quicklime format) may also be used and placed with the digital material.

Bring permanent marker pens for relevant marking.

Make up clear log-in sheets for all the data recordings for all the day. Have a backup system.
Remember that the data set will constitute a substantial part of the report and assessment.

Bring sturdy clothing.

Bring any relevant equipment that may be needed. (For example, a thermometer, a calculator, some blank virus-free memory stick.)

In Addition

Include photographs of the experimental works and of the models in your documentation.

Include dimensioned drawings of the model in your report (e.g. in Appendix).

Beforehand, do a bibliographic search for any past relevant studies. The building model shapes were commonly studies during the 19th, 20th and 21st centuries, both analytically and experimentally.

Find relevant wind tunnel studies of your model.

Photographs of relevant buildings in Australia and around the world ...

Each student is expected to keep both printed and digital forms of the boundary layer experiment data. These will be used in classes and during tutorials.

2.6 Access

The experimental works will take place in the AEB Hydraulics Laboratory of the School of Civil Engineering of the University of Queensland (building 49, St Lucia campus).

2.7 Safety

Safety is uppermost important during any experimental works.

+ **Students will be working in groups of no less than 2 people at any time on site.**

+ Follow the instructions of the lecturers and technical staff.

+ **Good common sense is recommended to avoid any injury: e.g., do not jump from stairs, watch your head**.

+ When you enter the wind tunnel test section, **do watch for the reference Pitot tube, the traverse mechanisms, the models, the hot-wire probe**.

+ It is strongly advised to wear adequate shoes or boots. Strong clothing is recommended, incl. shorts and trousers, hat (for winds).

+ If the weather is hot and sticky, bring mosquito repellent.

+ During or immediately before the experimental works, DO NOT consume alcohol or other intoxicating substances.

Emergency

A safety officer (Jason VAN DER GEVEL) will be on site There is also a First Aid Kit in the Mechanical Engineering building.

Technical staff will be on duty during the days of the wind tunnel tests.

3. Assignment

For fluids of low viscosity the effects of viscosity are appreciable only in a narrow region surroundings the fluid boundaries. For incompressible flow where the boundary layer remain thin, non-viscous fluid results may be applied to real fluid to a satisfactory degree of approximation. An ideal fluid is defined as a non-viscous and incompressible fluid and it must satisfy : (1) the continuity equation, (2) the equations of motion at every point at every instant and (3) neither penetration of fluid into nor gaps between fluid and boundary at any solid boundary. Converging or accelerating flow situations generally have thin boundary layers but decelerating flows may have flow separation and development of large wake that is difficult to predict with non-viscous fluid equations.

Although no ideal fluid actually exists, many real fluids have small viscosity and the effects of compressibility may be small. Applications include the motion of a solid through an ideal fluid which is applicable with slight modification to the motion of an aircraft through the air, of a submarine through the oceans, flow through the passages of a pump or compressor, or over the crest of a dam.

In the present study, students will investigate the aerodynamics of an idealised building (App. I & III) and the associated fluid structure interactions. A major outcome will be the estimate of the drag and lift forces acting on the building as functions of the angle of incidence. Another outcome will be detailed information on the flow turbulence in the separation and wake regions.

A professional study of building aerodynamics does include typically some physical modelling, some analytical calculations (e.g. ideal fluid flow), numerical calculations, a study of relevant past works and a comparison with existing building designs. In each group, the students will perform these tasks.

For each design, the students will conduct :
- some physical modelling in a large Wind Tunnel,
- some Hele-Shaw cell flow visualisation,
- some ideal fluid flow calculations (incl. flow net analysis, 2DFlow+),
- some real-fluid flow calculations, and
- a comparison with existing works.

The inflow conditions will be fixed and identical for each project. For each design, several angles of incidence will be investigated (Table 3-1).

The project is not just on wind tunnel measurements and physical modelling. It is a complete design project that shall include detailed flow calculations, including flow net analyses, flow computations, pressure force analyses and comparative analysis of the results with pertinent relevant studies,

Table 3-1 - Investigations of flow around a building model (minimum required)

Student	Angle of incidence				
	Graphical analysis (flow net)	Software 2DFlow+	Hele-Shaw cell experiment	Ideal fluid flow calculations	Wind tunnel experiments
JWB	0, +5	0, +5, +30	2 angles	at least 2 angles	See Table 2-1
WIC	+10, +25	+3, +10, +25	2 angles	at least 2 angles	See Table 2-1
GD	+7.5, +32.5	+7.5, +15, +32.5	2 angles	at least 2 angles	See Table 2-1
DJK	+20, +37.5	+15, +20, +37.5	2 angles	at least 2 angles	See Table 2-1
CW	+15, +45	+2.5, +15, +45	2 angles	at least 2 angles	See Table 2-1

Keywords

1. Experimental study (Real-fluid flow)

Wind load on building under severe wind conditions

- Upstream flow conditions
  - Free-stream velocity V_o, turbulence levels ...
- Pressure measurements
  - Lift force based upon integration of pressure distributions
  - Drag force based upon integration of pressure distributions
- Vortex shedding in building wake
  - Instantaneous velocity data analysis for characteristic fluctuating frequencies in the wake
  - Instantaneous pressure data analysis for characteristic fluctuating loads on the building
- Velocity distribution measurements
  - Turbulence characteristics in the separation and wake regions
  - Flow field outside of the wake region
  - Drag force based upon the application of the momentum principle
- For several angles of attacks (Table 3-1)

Developing boundary layer study

- Boundary layer characteristics (V_o, δ, displacement thickness, momentum thickness, ...)
- Turbulent velocity distributions in the developing boundary layer (V_x, $Tu = v_x'/V_x$)
- Skin friction

Hele-Shaw cell study

- flow visualisation
- with 2 angles of attacks at least
- photographs, movies

2. Ideal fluid flow analysis (assuming two-dimensional flows)

Graphical flow net analysis

- for several angles of attacks (Table 3-1)
- Velocity field
- Lift force
- Drag force

Numerical analysis (Software 2DFlow+)

- for several angles of attack (Table 3-1)
- Velocity field
- Lift force
- Drag force

Analytical calculations (ideal fluid flows)

- for several angles of incidence (Table 3-1)
- Velocity field
- Lift force
- Drag force

3. Bibliographic research

Past relevant studies

- Building/Architecture
- Aerodynamics/Fluid dynamics
- Hydraulics
- Fluid mechanics

Comparison with existing building designs

- Known problems
- Operational & constructions issues

4. Comparative analysis

Comparison between all studies

Lift force versus angle of incidence

Ideal fluid flow calculations (flow net, 2D Flow+, theoretical calculations)

Real-fluid flow (aero-dynamic textbooks)

Wind tunnel tests (pressure measurements)

...

Drag force versus angle of incidence

Ideal fluid flow calculations (flow net, 2D Flow+, theoretical calculations)

Real-fluid flow (aero-dynamic textbooks)

Wind tunnel tests (pressure measurements)

...

Comparison with bibliographic references

5. Discussion

The study may provide further information on :

- the maximum and minimum instantaneous pressures on the building,
- the maximum instantaneous wind velocity next to the building,
- vortex shedding in the wake of the building,
- the characteristics wind flow directions around the building,
- the flow field (pressure/velocity) in the wake of the building,
- the effects of the inflow conditions,
- the wind velocity at the leading and trailing edges of the building,

...

These results must be discussed in a professional context. Recommendations for optimum design and environmental management may be derived. (See Appendix IV for applications.)

4. Assessment

4.1 Presentation

The assessment of the project will take place as :

- a project work during the semester (**35% of CIVL4160 subject**), and
- some individual examination at the end of semester examination.

During the semester, students will work in groups of **5 people** for the experiments, with individual report and presentation. The group will be formed on Thursday 2 April. A building model will be investigated (App. I). the group will be able to give some preferences for the date of the experiments.

Each student has the responsibility to read the project instructions, participate in person to the wind tunnel experiments and contribute to the project. The experiments will be conducted in group. If any problem arises during the group work, student(s) are asked to contact the lecturer immediately and, in any case, prior to the final submission of the report.

4.2 Assessment

The project will be assessed as a combination of report submission and oral presentation. The individual reports will be assessed by the lecturers. The individual oral presentation will be assessed by the lecturers and by the other groups.

Individual report	65% (Note the penalty for lateness below)
Individual presentation (lecturers' assessment)	20%
individual presentation (peers' assessment)	15%

4.3 Instructions for report submission

Each report will be assessed upon :

the wind tunnel data of the group (35%), incl. quality and presentation,
the data analysis (15%), incl. ideal fluid flow calculations and flow net analysis
the technical contents, accuracy and soundness (35%)
the presentation style (15%)

4.3.1 Report submission and instructions

For each students, three copies of the report must be submitted to Prof CHANSON before Mon. 11 May 2:00pm. The report will be reviewed by the lecturers.

Note that the report submission deadline is after the oral presentation. This will give opportunity for each student to revise its report after the oral presentation based upon advice and comments received during the presentation. It is expected that each student will honestly acknowledge any advice received during the presentations and discussions.

+ Page Limits

Each report must be complete within a limit of 20 pages including front page, table of contents, main text, figures and references (but excluding appendices and drawings attachments). Reports that exceed this limit will be penalised by **5% penalty per extra page**. Shorter reports of significance will be given preferences. Each report will be single-sided. Each page must be numbered. The text is to be **single-spaced, 12 pt** Times Roman or similar. The paper is to be printed on plain A4 size paper. The manuscripts must be typed within the area of 255 mm by 170 mm. With a normal A4 size paper, the distances between the edge of the sheet and the text become as follows:

top: 2.0 cm
bottom: 2.0 cm
sides: 2.0 cm

+ Layout of Text

The front page must follow the template given in Appendix II.

The report should contain as a minimum :

- the front page (see Appendix II), followed by
- a table of contents,
- an introduction followed by the text,
- conclusions,
- list of references (bibliography),
- the Appendix I containing all the group data.
- the Appendix II containing all the measurement handwritten data sheets.

+ Figures and tables

Figures and tables must be placed in the text next to the first reference. These figures and tables would be referred to as "Figure 1" and "Table 1". Titles of figures and tables are to be in 12pt Times Roman.

+ Format for references

Reference should be listed at the end of the paper and should include the following information: Author's family name, Initials. : Paper title, Journal's title, Volume No., (year), pages.

For example :

APELT, C.J. (1983). "Hydraulics of Minimum Energy Culverts and Bridge Waterways." *Australian Civil Engrg Trans.*, I.E.Aust., Vol. CE25, No. 2, pp. 89-95.

CHANSON, H. (1999). "The Hydraulics of Open Channel Flows: An Introduction." *Butterworth-Heinemann*, Oxford, UK, 512 pages. (Reprinted in 2001)

+ **Digital data**

Each group is asked to submit at least one CD containing all their data set in a digital form. Students should consider either or both digital formats CD-R and DVD+/-R (single- or dual-layer). (Only these formats shall be assessed.)

The CD-ROM/DVD-ROM will also include relevant photographs (JPEG format), video movies (MPEG or Quicktime format), some data analysis, the numerical modelling and a copy of the group report (e.g. PDF format).

The digital data must be properly presented. The material may be sub-divided into sub-directories while a text file, acting as map of the CD/DVD-ROM contents, must be placed of the top of the directory tree.

Note : Each group will record a lot of information, (1) during the wind tunnel study, (2) during the Hele-Shaw cell visualisation, and (3) with the data analyses . All the information needs to be recorded, including relevant handwritten comments, ... (The CD-ROM/DVD-ROM may include a scanned version of the handwritten log-in sheets, relevant photographs, tabulated data sheets, a copy of the report, ...)

The digital informations constitute an integral part of the report supporting material. They will be carefully scrutinised and assessed.

4.3.2 Deadlines

The group reports are due on Mon. 11 May before 2:00pm. **The reports must be submitted directly and physically to Prof Hubert CHANSON** who will write down, on the cover page, the submission date and time. (It is the responsibility of each group to find the lecturer and to hand him the report.)

Penalty for lateness are 10% per hour of lateness on Mon. 11 May after 2:00pm and zero marks for submission after the submission day.

4.4 Instruction for oral presentation

Presentations will take place on Monday 4 May between 14:00 and 15:50 in the classroom. Each student will be given **15 minutes for presentation followed by up to 4 minutes for discussion**. Lecturers and fellow students will contribute to the discussion.

The (maximum) presentation duration will be enforced to ensure that each group can present its work within the 1 hour 50 minute time slot.

Students may use Powerpoint presentations, overhead projector transparencies and/or slides. (The Powerpoint files and slides must be provided on a CD-ROM/DVD-ROM to Prof CHANSON no later than Monday 4 May 9:00am.) **No Powerpoint files shall be accepted during the presentations** ([1]).

Each presentation will be judged upon :

the quality of the data set (15%),
the technical content (30%),
the presentation style (20%),
the expertise and ability to answer questions during the discussion (35%).
(See penalty for presentation over-length.)

4.5 Attendance

The attendance to the whole presentation duration is compulsory.

Each presentation will be assessed as a combination of assessment by lecturers and by the other students. Each student will be requested to submit its assessment of the other students' work on Monday 4 May 3:45 pm.

4.6 Assistance and Discussion

Prof CHANSON and the tutors will be available during weeks 6 for some advice, assistance and feedback on the data analysis, fluid dynamics calculations, report preparation and oral presentation.

4.7 Deadlines

11 May before 2:00pm (in Prof CHANSON's hands)	Complete design report Penalty for lateness : - 10% per hour of lateness on 11 May - zero marks for submission after the submission day.
4 May between 14:00 and 15:45 CIVL4160 classroom	Group presentation Penalty for lateness : - Presentation time and marks reduced accordingly (e.g. 5 minutes lateness = only 14 minutes for presentation & discussion = 26% penalty) - Presentation cancelled and zero marks for any group not ready 10 minutes after the official start time. Penalty for overlong presentation and reduced discussion : - Discussion marks reduced accordingly (e.g. 17 minutes presentation = only 2 minutes for discussion = 50% penalty on discussion marks).

[1]These requirements are typical of many international scientific conferences where the presentation files must be submitted and checked at least one day prior to the presentation day.

5. References

Australian Standards (1983). "Minimum Design Loads on Structures known as the SAA Loading Code. Part 2 - Wind Forces." *Standards Association of Australia*, AS 1170, Part 2,-1983, Sydney NSW, Australia.

Australian Wind Engineering Society (1994). "Cladding Pressure and Environmental Studies." *Quality Assurance Manual AWES-QAM-1-1994*, Australia, 19 pages.

CHANSON, H. (2009). "Applied Hydrodynamics: An Introduction to Ideal and Real Fluid Flows." *CRC Press*, Taylor & Francis Group, Leiden, The Netherlands, 478.

LIGGETT, J.A. (1994). "Fluid Mechanics." *McGraw-Hill*, New York, USA.

SCHLICHTING, H. (1979). "Boundary Layer Theory." *McGraw-Hill*, New York, USA, 7th edition.

SCHLICHTING, H., and GERSTEN, K. (2000). "Boundary Layer Theory." *Springer Verlag*, Berlin, Germany, 8th edition., 707 pages.

STREETER, V.L. (1948). "Fluid Dynamics." *McGraw-Hill Publications in Aeronautical Science*, New York, USA.

VALLENTINE, H.R. (1969). "Applied Hydrodynamics." *Butterworths*, London, UK, SI edition.

Internet resources

CHANSON, H. (2005). "CIVL4160 Advanced Fluid Mechanics" *Internet resource*.
(Internet address : http://www.uq.edu.au/~e2hchans/civ4160.html)

CHANSON, H. (2005). "Gallery of Photographs" *Internet resource*.
(Internet address : http://www.uq.edu.au/~e2hchans/photo.html#Civil_eng_structures)

Softwares

Software	Company	Applications
2DFlow+	Dynaflow Inc., USA	2D Irrotational flow motion CFD
DPlot	Hydesoft Computing, USA	Graphical data analyses

Appendix I - Sketch of the building model

Fig. I-1 - Building model - Overall view

Fig. I-2 - Building model - Inside details of the pressure tappings

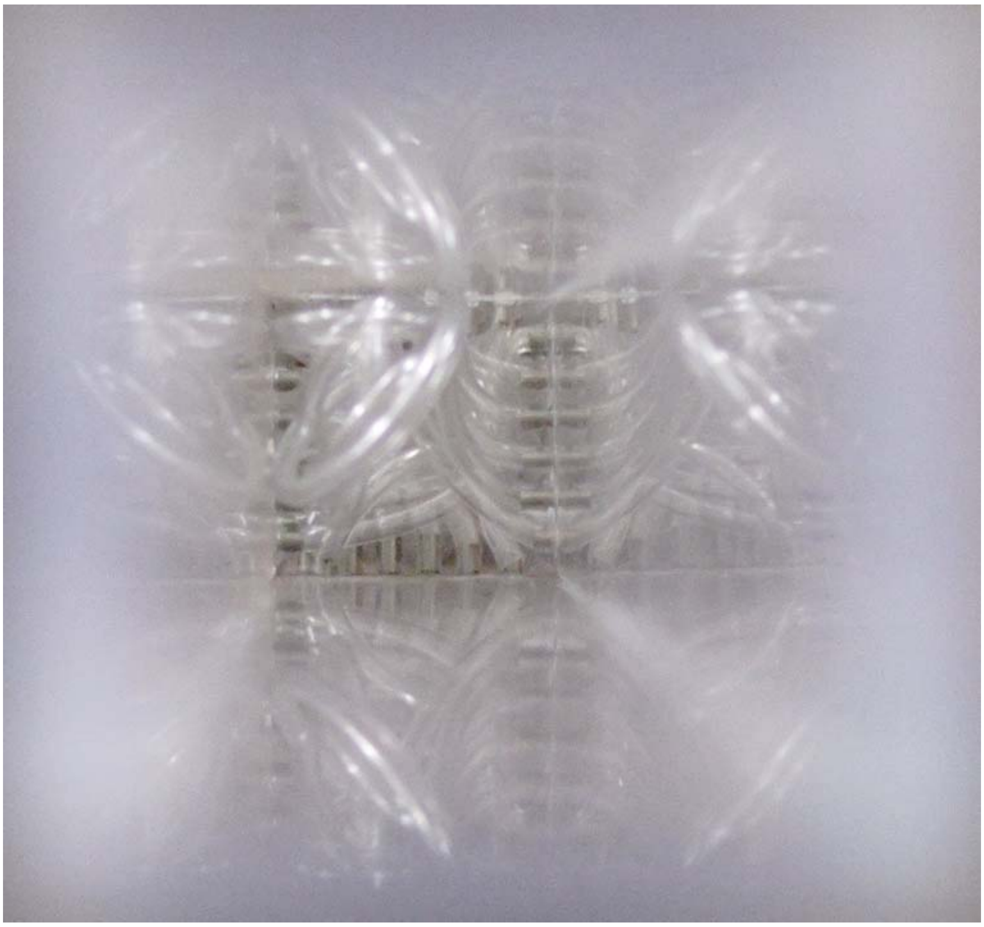


Fig. I-3 - Building model - Details of the pressure tappings

Appendix II - Template of the report front page

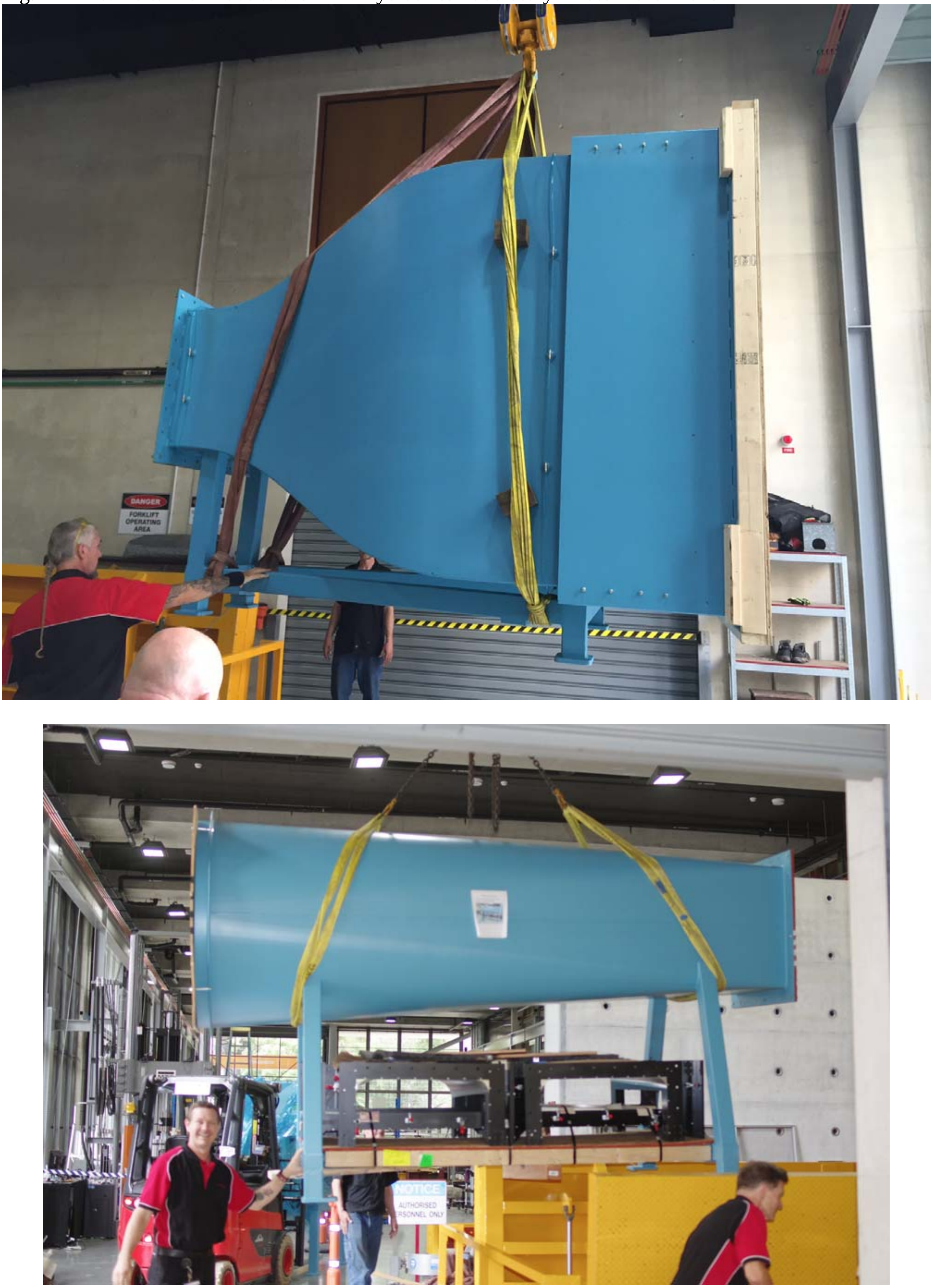
Wind loads on a building model in an University of Queensland Wind Tunnel

Model	Student ID	Student name	Signature
Square tower			

Submission date	Time	H. CHANSON's initials

Appendix III - Photographs of wind tunnel model

Fig. III-1 - Wind tunnel move to the AEB Hydraulics Laboratory in late March 2015



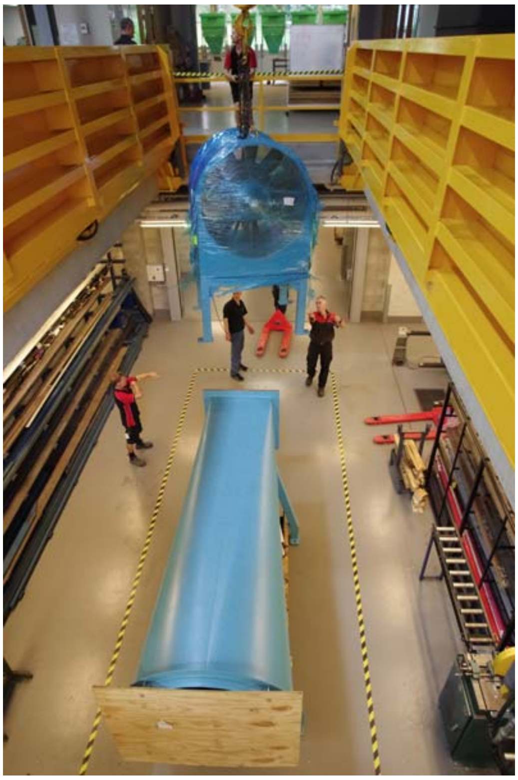


Fig. III-2 - Assembly of the wind tunnel in April 2015

Fig. III-3 - Divergent section

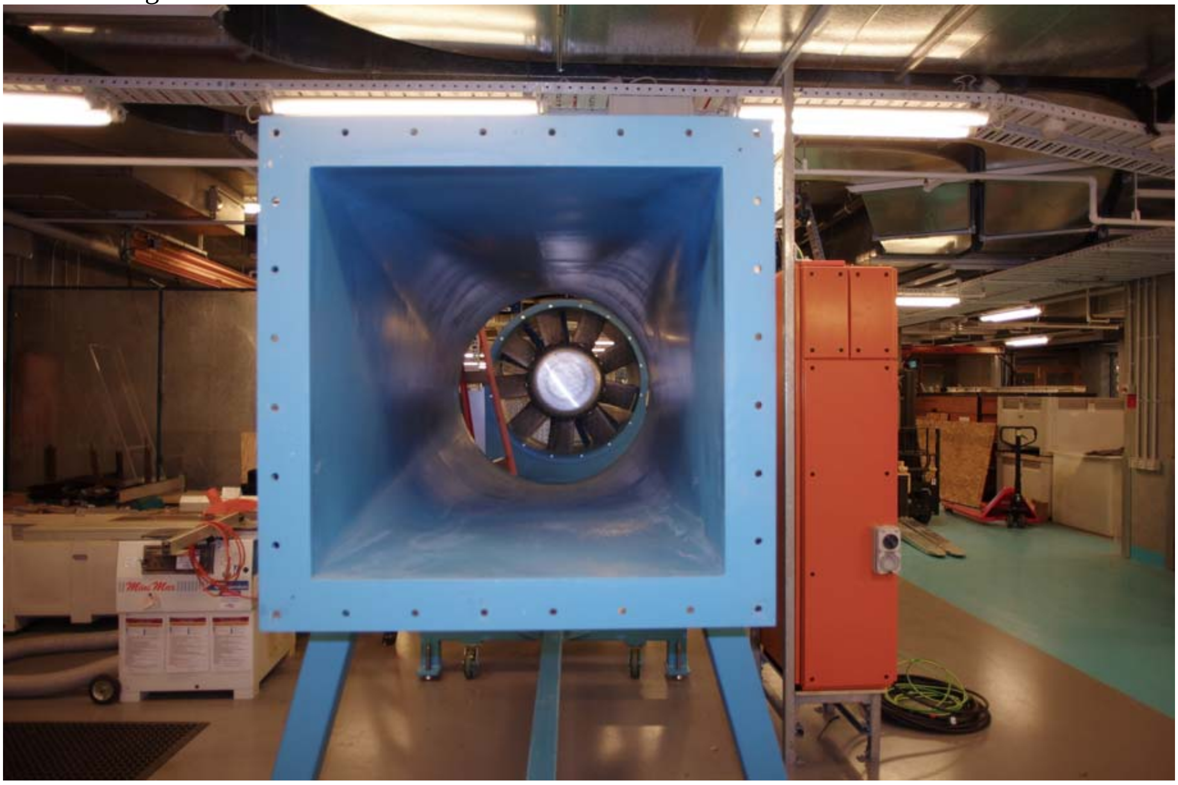


Fig. III-4 - Test section assembly

Fig. III-5 - Wind tunnel shortly prior to commissioning

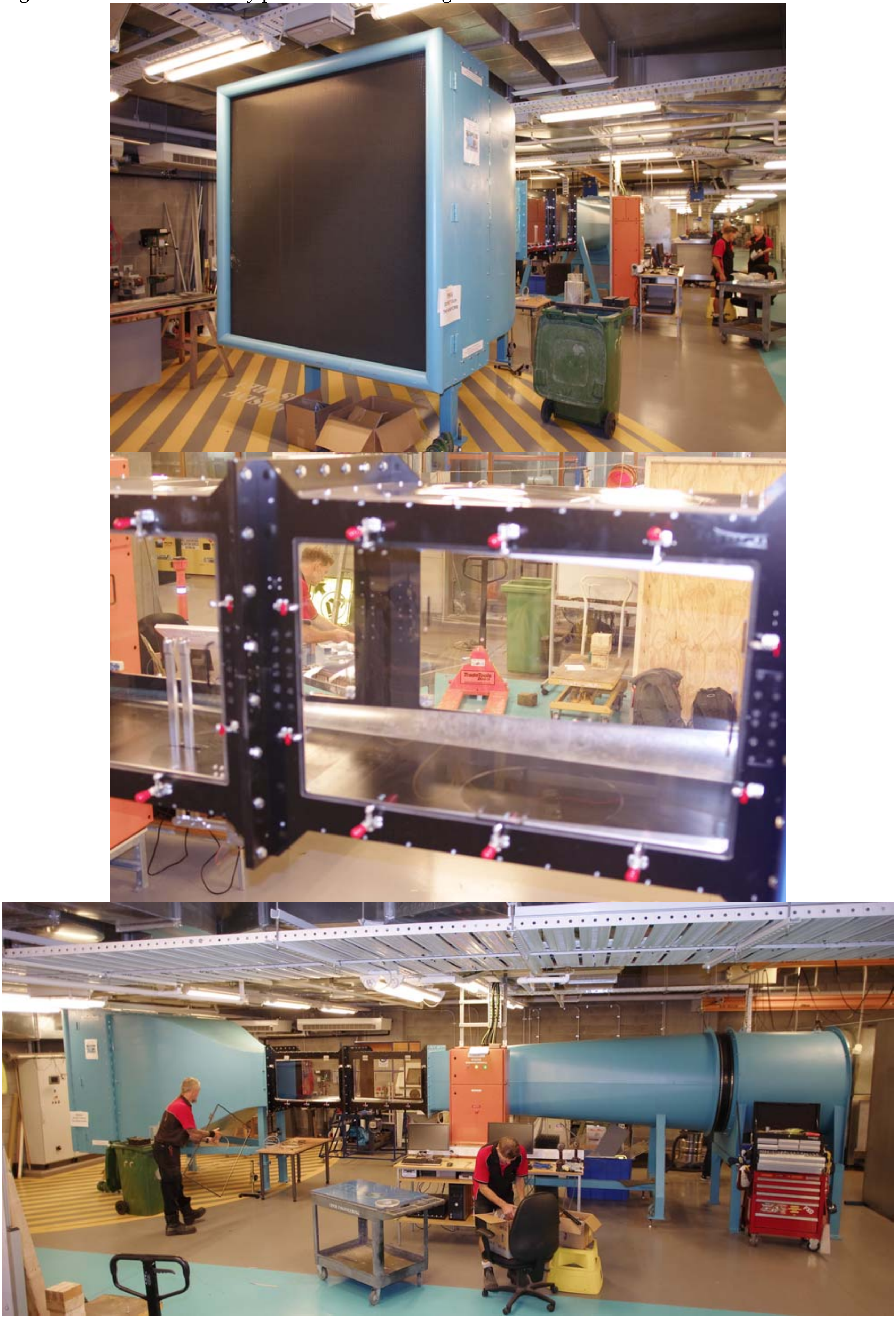
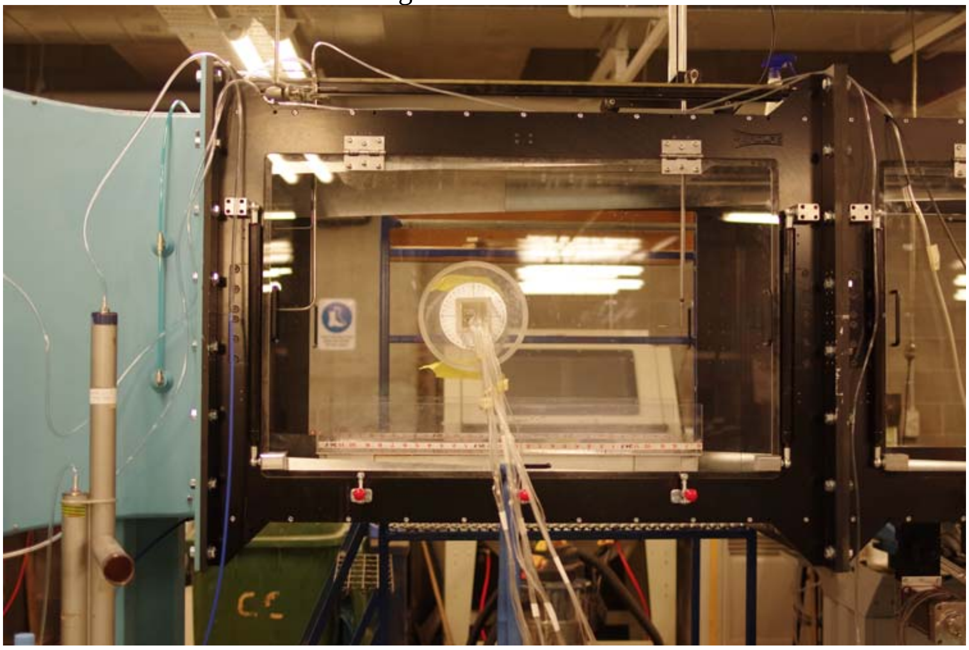
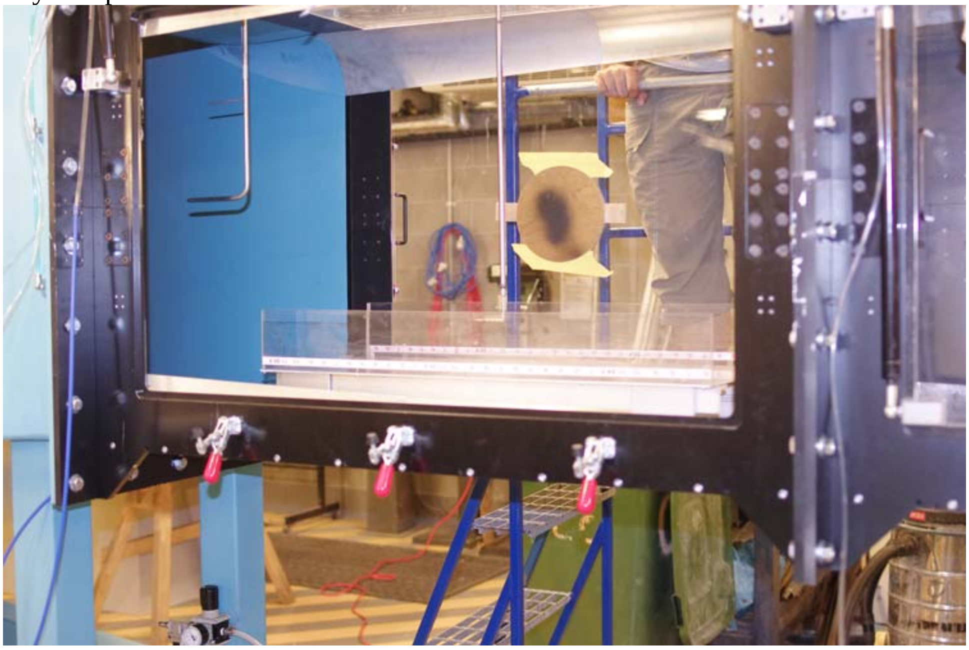


Fig. III-6 - Wind tunnel in operation

(A) Test section - Wind direction from left to right



(B) Boundary layer experiment



(C) Building model

(D) Reference Pitot tubes

Appendix IV - Real-life examples of wind aerodynamic problems in Civil Engineering

IV-1 Transmission towers damaged in the Brisbane valley in March 1998

The Harlin Transmission Line is part of the Tarong-Mt England 275 kV Transmission line. Five towers (275 kV double circuit electricity tower, designed to withstand winds up to 180 km/h) collapsed on 18 March 1998 in the Brisbane valley, 80 km NorthWest of Brisbane. (Near the intersection of the Brisbane valley highway and D'Aguilar highway. Around 152.36 E & 26.96 S). The most damaged area was Harlin, Colinton & Kangaroo Creek. It is believed that the towers collapsed during gusty, tornado-like winds (Fig. IV-1).
The replacement towers were designed to withstand winds up to 210 km/h. (The transmission authority was Powerlink.)

Fig. IV-1 - Wind damage in the Brisbane valley in March 1998 (Courtesy of Prof C. LETCHFORD)
Wind gusts in excess of 200 km/h were experienced in the valley, causing extensive damage
(A) Fallen tree

(B) Damaged transmission tower (275 kV double circuit electricity transmission tower)

(C) Another damaged transmission tower (275 kV double circuit electricity transmission tower)

IV-2 La Grande Arche, La Défense (France)

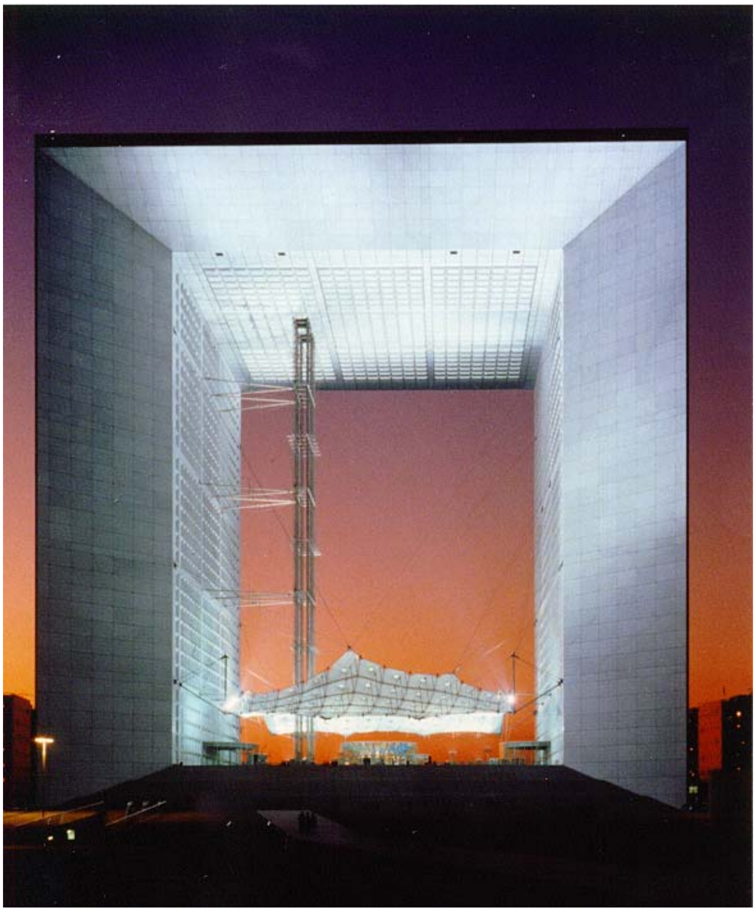
La Grande Arche is located in La Défense, a western suburb of Paris. Completed in 1989, the building is 110.9 m high, 112 m long and 106.9 m wide. The arch is inclined with a 6.33º towards the "Grand Axe" of Le Louvre museum, The Obélisque, the Champs Elysées, the Arc de Triomphe and the Avenue de la Grande Armée (Fig. IV-2). (The primary reason for the angle is related to foundation problems.)

Shortly after completion, very strong winds were felt at the bottom of the Arch. This was caused by the natural strong winds experienced at La Défense associated by a Venturi effect induced by the arch shape. As a result, a 2,300 m^2 surface area membrane (PTFE-coated glass fiber fabric) was installed at the foot of the arch. The membrane is called Les Nuages ("The Clouds") (Fig. IV-2).

Fig. IV-2 - La Grande Arche, La Défense (France) (Courtesy of VF communication, La Grande Arche)
(A) The Grande Arche, looking East toward Paris

(B) Looking West

(C) Looking West at sunset - Note the "Clouds" (Les Nuages)



Internet references
{http://www.structurae.de/en/index.php}   Structurae database

{http://www.structurae.de/en/structures/data/str00133.php}
{http://www.structurae.de/en/structures/data/str00134.php}
{http://www.uq.edu.au/~e2hchans/photo.html#Civil_eng_structures} section ce8

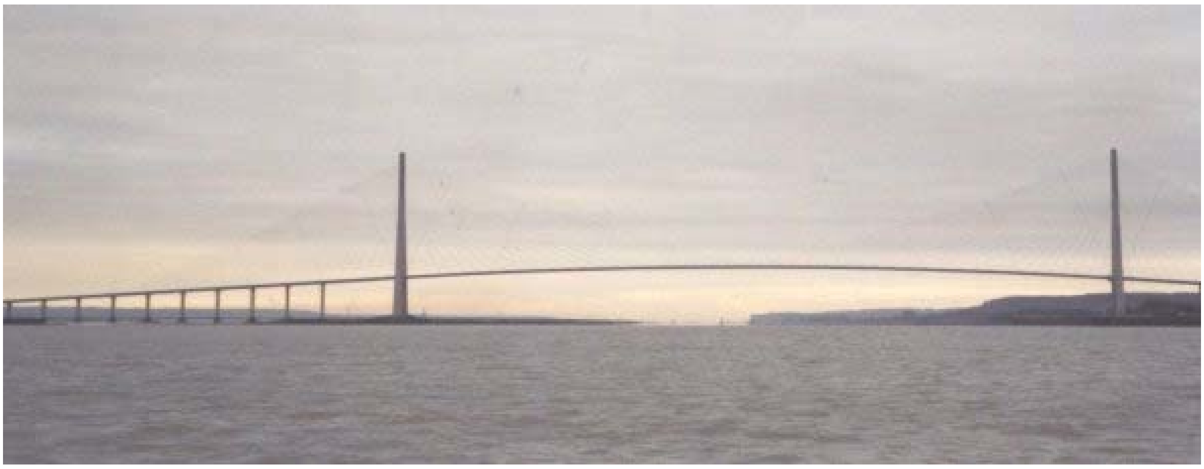
IV-3 Le Pont de Normandie, France

Completed in 1995, the Pont de Normandie is located next to the Seine river mouth (Fig. IV-3). It is a suspension bridge. The total length is 2141 m and the central span is 856 m long. The main deck is 52 m above the highest water levels while the pylon height is 214.77 m. There are a total of 184 suspension cables. Cable lengths range from 95 to 450 m. Part of the deck cantilevering out from the pylons was built as a hollow box made of prestressed concrete, but about two thirds of the deck were made of a steel.
The estuary of the Seine river is well-known for strong Westerly winds and the bridge was designed to sustain wind speeds of up to 300 km/h. The bridge deck was streamlined to reduce the wind drag and its design was tested in wind tunnel.

Technical details

The wind reference velocities were an average velocity of 35.3 m/s at 10 m/s above ground, 44 m/s at deck level and 49 m/s at the top of pylon (210 m above water).
The bridge deck is a box-girder to increase the torsional rigidity of the bridge and to limit the first torsional period to less than half of the first vertical flexion period. The deck was streamlined to reduce wind forces, with the box-girder height of less than 3.0 m. The design was aimed to reduce vortex shedding by increasing the width to height ratio of the deck. The pylon shape was selected to limit second order effects and to increase its structural capacity to resist wind loads.
Although the vibration periods of the cables would have been about 4 seconds, four damping ropes were installed to interconnect the cables and to reduce the first period to about 1.25 seconds.

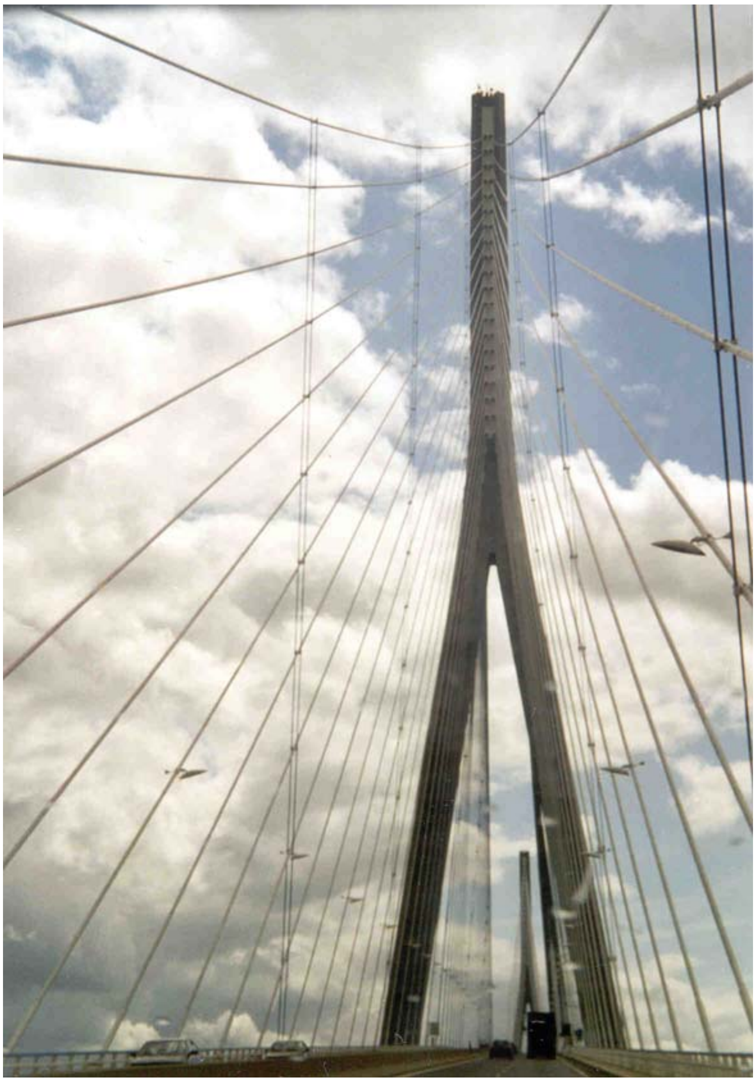
Fig. IV-3 - Le Pont de Normandie (France)
(A) View from a sailing boat looking upstream (Courtesy of Sequana-Normandie)



(B) View from the South in May 2003 (Courtesy of Mr and Mrs CHANSON)

(C) View from the North in May 2003 (Courtesy of Mr and Mrs CHANSON)

(D) North pier, driving South (Courtesy of Mr and Mrs CHANSON)



Reference

VIRLOGEUX, M. (1993). "Wind Design and Analysis for the Normandy Bridge." Structural Engineering in Natural Hazards Mitigation, Proc. Structures Congress, Irvine CAL, USA, Vol. 1, pp. 478-483.

Internet references

{http://www.sequana-normandie.com/} Go to "BACS et PONTS" (on Left Top)
{http://www.structurae.de/en/index.php} Structurae database
{http://www.structurae.de/en/structures/data/str00048.php}
{http://www.structurae.de/en/refs/subjects/sub0107.php}

{http://www.uq.edu.au/~e2hchans/photo.html#Civil_eng_structures} section ce9

<u>IV-4 Le Viaduc de Millau, France</u>

The Millau suspension bridge (or Millau viaduct) is located in Southern France. The architect was Lord Norman FOSTER and the engineering designer was Michel VIRLOGEUX. Completed in 2004, the bridge is 342 m tall and 2,460 m long. It was designed to sustain storm wind speeds up to 250 km/h. The final design was tested in both wind tunnel and water tunnel. In the water tunnel, the physical model was built at a 1:3,000 scale.

Technical details

Length: 2,460 m
Width: 32 m
Height of tallest pier: 245 m

Height of pylons: 87 m
Number of piers: 7
Length of spans: 2 en spans of 204 m and 6 central spans of 342 m
Number of stay: 154 (11 pairs per pylon)
Tension of stays: 900 t to 1,200 t
Structural guarantee: 120 years

Fig. IV-4 - Le Viaduc de Millau (France)
(A) Construction of the viaduct (Courtesy of Le Viaduc de Millau)

(B) Construction details (Courtesy of Le Viaduc de Millau)

(C) Viaduc de Millau on 1 May 2009 (Courtesy of Mr and Mrs J. CHANSON)

Internet references

{http://www.leviaducdemillau.com/en_index.php}	Official website
{http://en.wikipedia.org/wiki/Millau_Viaduct}	Millau viaduct
{http://www.structurae.de/en/index.php}	Structurae database

Appendix V - Wind tunnel measurements - Example of past project workflow

[0] Hot-wire probe calibration

Velocity at the reference Pitot tube is measured with a T.E.M.™ projection manometer. The reading is mm of H_2O with an accuracy of about 0.2 mm of H_2O. (Zero properly the manometer. Level must be horizontal.) Install the hot-wire next to the Pitot tube.

For safety, watch the Pitot tube that is about eye level.

Measure the temperature in the wind tunnel.
Record the barometric pressure.

Switch on the Dantec streamline CTA.
Switch on the data acquisition computer.
Start the Streamware software.
Select : (1) data acquisition card National Instrument PCI-6024E, (2) single wire 55P11 straight (general purpose) probe, (3) straight probe support, (4) 4-m cable, (5) data acquisition channel = 7, (6) scan at 40 Hz for 5 sec. (2000 samples), (7) single-ended reference (0-10 V).
Define experiment.
Calibration setup

At least 5 points (incl. V = 0). Check the error analysis and add further calibration points if required.
It is advised to select wind speeds in arithmetic progression : e.g., 0, 3, 6, 9, 12, 15, 18 m/s.

For each point, (1) measure the pressure difference across the projection manometer, (2) calculate the reference velocity, (3) read the hot-wire probe voltage.
Later, (1) save the calibration curve, (2) create a data reduction setup and (3) set data conversion setup as default.

At end, DISABLE the probe (with the Streamware software) before moving the probe to the traverse mechanism.

The result of a calibration curve is shown below.

ΔP mm of H_2O (1)	V m/s (2)	Voltage V (3)	Remarks (4)
0	0	1.535	Wind tunnel stopped
0.8	3.6	1.891	
6.7	10.4	2.101	
10.2	12.8	2.144	
21	18.3	12.246	

[1] Inflow conditions

The upstream velocity and turbulent velocity profiles will be measured at the upstream reference location, corresponding to the upstream end of the turning table (x = - 0.9 m) with the building in position at zero angle of incidence. The reference velocity V_{ref} shall be 15 m/s (AC motor + DC motors).

Measure the temperature in the wind tunnel.

Calculate the air density - Note that the air velocity will vary with the temperature

$$P = \rho \times R \times T$$

where P is the absolute pressure in Pascal, T is the air temperature in Kelvin, R is gas constant (R = 287 J/kg.K for air) and ρ is the air density (kg/m^3).

Calculate the inflow velocity

(a) Based upon the pressure difference in the intake contraction (contraction ratio: 5.526:1)

$$V = \sqrt{2 \times \frac{\Delta P}{\rho} \times \frac{5.526}{4.526}}$$

where ΔP is the pressure difference (Pa).

(b) Based upon the Pitot tube reading:

$$V = \sqrt{2 \times g \times \frac{\rho_{water}}{\rho} \times H}$$

where ρ_{water} is the water density, g is the gravity acceleration and H is the manometer reading (m).

Note: The Pitot tube reading is deemed more accurate.

Set the probe on the tunnel centreline next to the reference Pitot tube..
Check the reference velocity V_{ref} to be 15 m/s using the projection manometer. (Adjust gently the wind tunnel DC motor speed if needed.)
Start at z = 150 mm.
Run Experimental setup (Run Experiment).
Perform velocity measurements for the location shown in the table below.
Later (1) run Data reduction, (2) export the reduced data.

At end, DISABLE the probe (with the Streamware software) before moving the probe to the traverse mechanism.

x m (1)	y m (2)	z m (3)	V m/s (4)	u' m/s (5)	Remarks (4)
-1.30	1.50	0.025			
		0.050			
		0.100			
		0.200			
		0.300			
		0.40			
		0.600			
		0.800			
		1.000			
		1.200			

Notes :
- Between each data point, and if the wind tunnel door is opened, wait for the reference velocity to settle down to 15 m/s.

[2] Boundary layer experiment

Measurements of velocity and turbulent velocity fluctuations will be conducted with a hot-wire probe controlled by a Constant Temperature Anemometer (CTA) in the developing boundary layer above a flat plate. The plate is 0.335 m wide and 0.8 m long, and it set with a slight upward slope ($\tan\theta$ = 0.01). A smooth plate will be used. Vertical turbulent velocity profiles will be measured upstream of and above the flat plate. The hot wire probe readings will be scanned at 400 Hz for 20 seconds at each sampling location. **The reference velocity V_{ref} shall be 15 m/s**.

First the vertical velocity profile will be measured at x' = -0.10 m where x' is the downstream distance from the plate leading edge.
Then the vertical turbulent velocity distributions will be measured at several cross-sections x' (Table 2-2, column 3). For each vertical profile, **at least twenty-five velocity measurements** must be performed, with a

very close spacing in the vicinity of the plate. At least 15 data points must be sampled in the developing boundary layer and another 2 points at least must be in the free-stream.

During the measurements, study the oscilloscope display to observe the general nature of the flow in the boundary layer next to the rough plate and in the free-stream.

[3] Pressure measurements

With the fully-instrumented perspex model installed on the turning table, the students will record pressures and pressure fluctuations at each pressure tapping by scanning at 600 Hz for 60 sec. each point. That is, each pressure tapping will be scanned for 60 sec.. A total of 32 pressure tappings are installed: 8 tappings on each side (App. I). The channels 1 and 2 are respectively the static and dynamic pressures of the reference Pitot tube.

Experiments will be repeated for three angles of incidence (Table 2-1, column 3).

Beforehand, check carefully the location of the pressure tappings.

Measure the temperature in the wind tunnel.

Check the reference velocity V_{ref} to be 15 m/s using the projection manometer. (Adjust gently the wind tunnel DC motor speed if needed.)

Ensure that the compressed air pipe is connected to the laboratory compressor.
At the start, switch one the Scanivalve computer. Then switch on the Lab view computer.
With the wind tunnel switched off and the door fully-open, Zero the Scanivalve system. (Press the ZERO button and wait until the dark blue light become light blue.)

Sequence / Start tasks

Enter the basic information on the 'Test information' window.
$P_{ref}/P_{eaves} = 1$
Length scale: 1:400
Sampling frequency = 600 Hz
Sampling time = 60 s
1 sample to average (i.e. no averaging; all data are instantaneous data)
Then SCAN.
At end, enter the relevant filename including the .txt postfix.

Remark : Using a ratio $P_{ref}/P_{eaves} = 1$, the data outputs are expressed in terms of dimensionless pressure coefficients defined as function of the reference static pressure and reference dynamic pressure :

$$C_p = \frac{P - P_{ref}}{\frac{1}{2} * \rho * V_{ref}^2}$$

That is, the data outputs are the measured data.
For some applications, it may be more suitable to define dimensionless pressure coefficients in terms of the velocity at the building eaves :

$$C_p = \frac{P - P_{ref}}{\frac{1}{2} * \rho * V_{eaves}^2}$$

In such a case, the ratio P_{ref}/P_{eaves} is the value based upon the measured reference velocity the upstream velocity profile. (The ratio P_{ref}/P_{eaves} is a correction factor.). It is the ratio of the reference static pressure to the static pressure at the eaves of the building with zero angle of incidence :

$$\frac{P_{ref}}{P_{eaves}} = \frac{V_{ref}^2}{V_{eaves}^2}$$

where V_{ref} is the measured reference velocity, and V_{eaves} is the upstream velocity at the building model eaves.

For a new angle of incidence, redo the sequence

Notes :

+ The pressure data are presented in terms of dimensionless pressure coefficients C_p defined as :

$$C_p = \frac{P - P_{ref}}{\frac{1}{2} * \rho * V_{ref}^2}$$

+ During experiments, check the air temperature and the wind tunnel ambient pressure.

+ During experiments, check the reference velocity V_{ref} to be 15 m/s using the projection manometer. (Adjust gently the wind tunnel DC motor speed if needed.)

+ The reference velocity measured by the Pitot tube and calculated using the air density corresponding to the wind tunnel temperature and absolute pressure.

[4] Downstream velocity measurements

Profiles of velocities and turbulent velocity fluctuations will be recorded in the wake of the model . That is, at one body length immediately downstream of the model trailing edge.

At that streamwise location, velocity profiles will be conducted at several cross-sections. The measurements will be focused on the wake region. It is expected that about 35 points will be required per horizontal profile. At least 20 points shall be recorded in the separation region and vortex shedding zone.

The **raw probe outputs** shall be recorded and saved for *at least 5 data points* in the vortex shedding region. The data will be subsequently analysed to document the vortex shedding behind the building model.

Experiments will be performed for several angle of incidence.

Run Streamware

Run Experiment

x m (1)	y mm (2)	z m (3)	V m/s (4)	u' m/s (5)	Remarks (4)
		0.10			
		0.30			
		0.50			
		0.70			
	400				Towards the reference Pitot tube.
					Centreline

2600

At end, DISABLE the probe (with the Streamware software) before moving the probe to the traverse mechanism.

Notes :
+ During experiments, check the air temperature.
+ During experiments, check the reference velocity V_{ref} to be 15 m/s using the projection manometer. (Adjust gently the wind tunnel DC motor speed if needed.)
+ During experiment, any person in the wind tunnel must be standing (1) downstream of the probe, (2) next to the wall during data acquisition, and (3) must be wearing safety clothing (e.g. glasses).