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APPLICATION OF WIND ENGINEERING FOR BUILDING ENVELOPE DESIGNS

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Abstract : Professor Tanaka's contributions to bridge aerodynamics are well known to wind engineers world-wide. Also known are pioneering studies conducted at various international laboratories under his supervision for many of the world's milestone bridge structures. Tanaka also made significant contribution to the building envelope community through his novel ideas by blending wind engineering principals with building science theories. The objective of this presentation is to highlight these hidden secrets to the Canadian Civil Engineers.

At the Institute for Research in Construction (formerly known as Division of Building research) – National Research Council (NRC–IRC), researchers collaborated with Tanaka. In respecting the page limitation of this paper, author presents only three of them as follows:

1. Wind resistance evaluation of roof assemblies
2. Wind load determination for roof assemblies
3. Wind pressure interaction with building stack effect

These respectively summarize research collaboration in 2000's, 1990's and 1980's. Personally, author had the privilege of participating two of these research projects. Research findings resulted in the development of national standard by the Canadian Standards Association (CSA) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) design guidelines

1. Introduction

Canadian contribution to the wind engineering is not only well known to the Canadian Society of Civil Engineers (CSCE) but also to the international engineering community. So much so, given a wall of fame is created to wind engineers, Canadian research will dominate the wall. It is the CSCE members' pioneering developments offered solutions to some of the classical wind engineering problems. It is not hard to list to them as follows:

- Late Alan Davenport (University of Western Ontario): Statistical description of the complex wind and wind induced loadings on buildings and structures.
- Peter Irwin (formerly with NRC – RWDI Consulting Engineers): Practical applications of wind engineering theories to the design of international buildings and structures.
- Bob Wardlaw and Kevin Cooper (NRC): Application of low speed wind aerodynamics to the vortex shedding.
- Alan Dalglish and Don Taylor (NRC): Field measurement of the wind loads and development of glass standards.
- David Surry and Nick Isyumov (University of Western Ontario): Pneumatic averaging techniques and force balance techniques of wind interaction measurements in the boundary layer wind tunnel.
- Ted Stathopoulos (Concordia University): Codifications of wind loads for low rise buildings

It is hard to limit the above citation as many more are currently involved in advancing the state of the art. No doubt, the National Building Code of Canada (NBCC 2010) and its Part 4 Commentaries have benefited as these novel contributions translating into design guidelines and specifications. The global construction market recognized the leadership of Canadian Civil engineers through these knowledge acquisitions. Several international icon buildings and structures embraced Canadian engineering expertise in the design and construction process.

In this wall of fame, Hiroshi Tanaka takes a predominant place for his contributions to bridge aerodynamics and for his pioneering studies that were conducted under his supervision at various international laboratories. Equally, Tanaka made significant contribution to the building envelope community through his novel ideas by fusing wind engineering principals with building science theories. The objective of this presentation is to highlight these hidden secrets to the Canadian Civil Engineers. In respecting the page limitation of this paper, author presents only three of them as follows:

1. Wind resistance evaluation of roof assemblies
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These respectively summarize research collaboration in 2000's, 1990's and 1980's. Personally, author had the privilege of working with Tanaka in two of those research projects. Research findings resulted in the development of national standard by the Canadian standards associations and ASHRE design guidelines.

2. Wind Resistance Evaluation of Roof Assemblies

Wind uplift on Adhesive Applied Roofing System (AARS) induces both shear and tensile stresses on the roof components. Shear forces result in peeling failure, whereas tensile forces result in uplift failure. The shear and tensile force development is illustrated in Figure 1. Peeling failure is the single most common premature failure of AARS, and it leads to the loss of the watertight integrity of the AARS membrane (RICOWI 2006, 2007, 2010). Existing North American wind uplift standards [CSA A123.21 (2010), FM 4474 (2004) and UL 580 (2006)] mainly focus on mechanically-attached and fully-bonded roof assemblies. Little is known about the resistance of AARS against shear forces that are derived from the wind uplift, and there are currently no standards that can be used to evaluate the peel resistance of AARS.

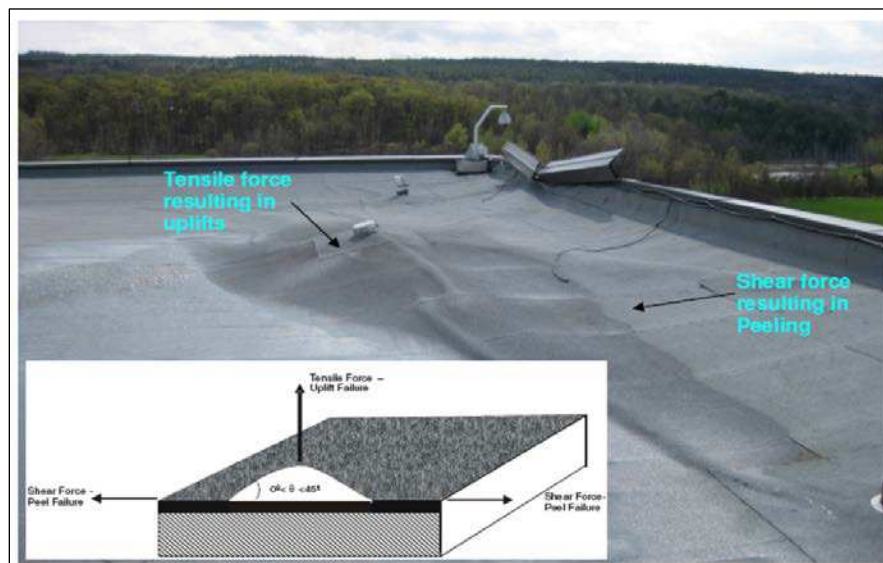


Figure 1: Force Development on a Adhesive Applied Roofing System (AARS)

Towards development of a national standard, Tanaka proposed a simplified engineering hypothesis that “Higher resistance against tensile and shear force will result in the same or higher wind uplift resistance”. Under his supervision, three Masters and a Doctorial student developed methods to validate this hypothesis. This approach offered alternates design options for the industries partners.

2.1 Small scale experiments simulating tensile forces

A detailed comparative analysis by Current (2009) concluded the most appropriate conditions for simulating tensile forces, in order of importance, are (figure 2a):

- Tensile loading rate = 0.25 in/min (6.35 mm/min)
- Specimen size = 12 in x 18 in (305 mm x 457 mm)
- Attachment condition = fixed end conditions

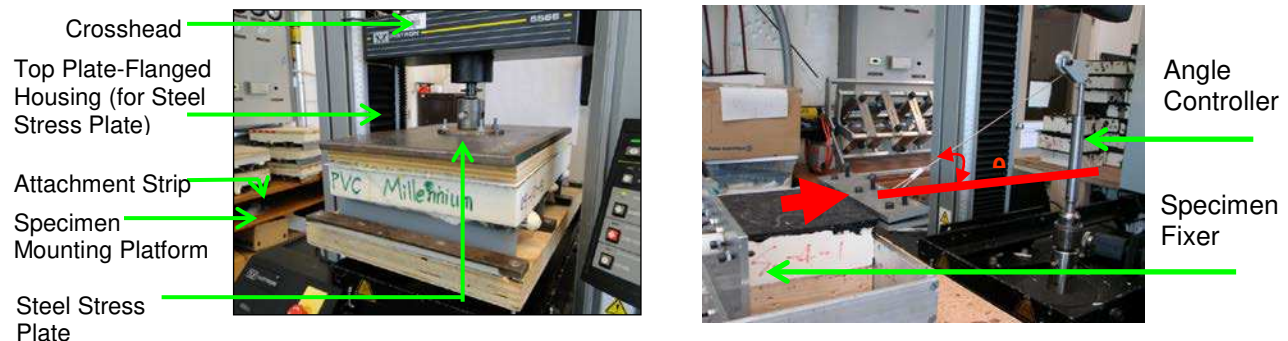
2.2 Small scale experiments simulating shear forces

To simulate shear forces, a peel test method was developed by Wu (2009) (figure 2b):

- Peeling rate = 1.0 in/min or 25.4 mm/min;
- Peeling angle = 15 degrees;
- The suggested sample curing time was 28 days after assembly.

2.3 Full-scale wind uplift test method

The full-scale test method simulates the wind uplift effects on AARS mock-ups. The full-scale experimental research on how to quantify the AARS wind uplift load resistance was carried out by Murty (2010). All experiments were carried out at the Dynamic Roofing Facility (DRF). Figure 2c displays the structure of the pressure chamber with a 16 ft x 32 ft (4.9 m x 9.8 m) table in which a 8 ft x 32 ft (2.5 m x 9.8 m) modified bitumen system was installed.



(a) Specimen ready for testing by simulating tensile forces

(b) Specimen ready for testing by simulating shear forces



(c) Specimen ready for testing by simulating wind uplift forces

Figure 2. Experimental Setup

2.4 Experimental Configuration

Li (2010) carried out a major experimental investigation towards validating Tanaka's hypothesis. This had been demonstrated using full-scale example in which the AARS had modified membrane as a waterproofing component. The roofing configuration includes a modified bitumen membrane (cap sheet and base sheet), a dense deck (DD) prime board and a steel deck. For Sample 1, the regular base sheet was integrated in the DD prime board with cold adhesive using the fully coated format. For Sample 2, the base sheet was self-adhered. A specific primer was rolled over the DD prime surface, then left to dry before laying the self-adhered base sheet. All other components were the same in both samples.

2.5 Validation of Hypothesis

As shown in figure 3, for Sample 1, the mean resistance values obtained from the nine uplift resistance and nine peel test specimens are 680 lbf (3025 N) and 136 lbf (605 N), respectively. For the wind uplift testing, a rating of 90 psf (4309 Pa) or resistance of 60 psf (2872 Pa) [Resistance = Rating / Factor of Safety = $90/1.5 = 60$ psf (CSA A123.21-10)] was obtained. For Sample 2, an increased mean value was obtained for the uplift resistance, peel and wind uplift resistance: 1108 lbf (4929 N), 197 lbf (876 N) and 80 psf (3830 Pa), respectively.

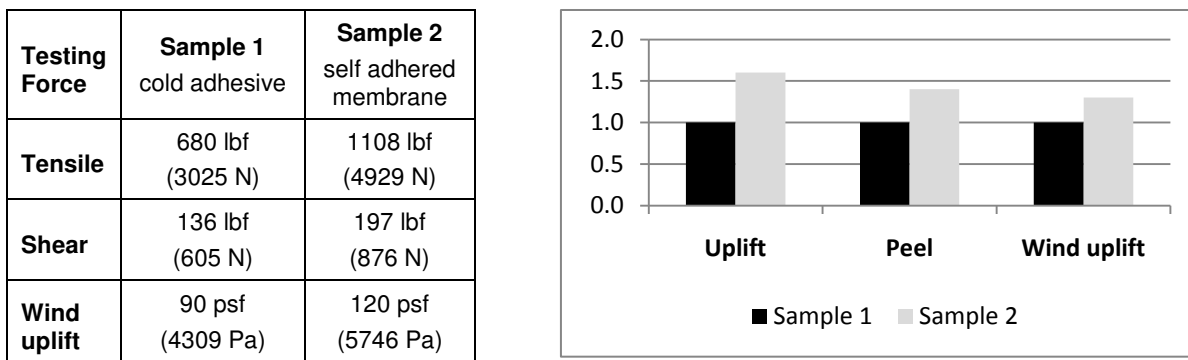


Figure 3: Resistance data tested by simulating tensile, shear and wind uplift forces

A resistance ratio of Sample 2 to Sample 1 for the quantitative comparison was developed and expressed by a column chart in figure 3. It normalizes the uplift resistance, peel and wind uplift resistances of Sample 1 to 1.0. The ratio of test results of Sample 2 is then calculated as the uplift resistance, peel and wind uplift resistance of Sample 2 divided by that of Sample 1. The trend can be clearly seen in figure 3: that the uplift resistance and peel resistances of Sample 2 are higher than that of Sample 1, when the self-adhered membrane is used instead of the cold adhesive bonded membrane.

The uplift resistance of Sample 2 was found 1.6 times higher than the uplift resistance of Sample 1; while its peel resistance was increased by 45% from 136 lbf (605 N) to 197 lbf (876 N). The dynamic wind uplift resistance of 80 psf (3830 Pa) for Sample 2 was 1.3 times higher than the original resistance of 60 psf (2872 Pa) for Sample 1.

This validates the hypothesis that “Higher resistance in both peel and uplift tests will result in the same or higher wind uplift resistance”.

3. Wind Load Determination for Roof Assemblies

NBCC (2010), international building codes and wind load specifications standards derived the design values (pressure coefficients) mainly from the wind tunnel studies. In a wind tunnel, buildings were modelled using appropriated linear scale and wind is generated by following boundary layer flow simulation. The scale model is instrumented with pressure tapes to quantify the wind induced pressures.

A flat roof surface is known to be subjected to unusually high suction induced by a pair of “horse shoe” vortices caused by the wind coming diagonally facing a corner of the building (Kind and Wardlaw, 1979).

This phenomenon can cause very serious damages to the roofing system such as dislocation of concrete “pavers” or insulation boards. It is also known that some architectural features of the building such as the existence of parapets and their height would have some influence on these phenomena (Baskaran, 1986). At the same time, wind tunnel testing of this situation is a challenging task because the extent of damages depends a lot on the structural details, which can hardly be modelled properly in a reduced scale.

Tanaka made a proposal to improve the situation of scaling by simulating only a half or even smaller portion of the building for wind tunnel tests, which in turn could be carried out in much larger scale, even at nearly full scale, provided that exceptionally large wind tunnel facilities are available. The idea is reasonable considering the fact that the “horse shoe” vortex pattern of wind flow over the roof for the most critical case is nearly symmetric with respect to the 45° diagonal line along the mean wind. An important question, of course, is whether or not a good simulation of flow pattern can be achieved when only a portion of the structure is modelled. If indeed it is confirmed that the similar flow and pressure pattern can be experimentally obtained with a half building configuration, it becomes possible to have a very large building model with the scale of 1/2 or even 1/1 in the NRCC 9m x 9m wind tunnel. Then it becomes also possible to examine the effectiveness of the structural details against the wind action.

What is presented here is a pilot study regarding this issue. A 1/10 scaled model of the building previously tested in the NRCC 9m x 9m wind tunnel (Kind, Savage & Wardlaw 1988) was constructed with a further reduction in scale to 1/100 in a smaller wind tunnel, the 0.9m x 0.9m wind tunnel which in fact is a 1/10 scaled model of the 9m x 9m tunnel, and was tested, first of all, to make sure that the same pressure pattern can be reproduced in this scale (figure 4). Then the same model was reduced from a whole building to a half of it (figure 5) to examine if the wind induced pressure pattern in the critical area of the roof would remain the same. Finally, two larger scales, 1/37.5 and 1/21, were introduced to examine the consistency of results in different linear scales. When the building model is constructed in larger scales, the building height becomes a new problem since the wind tunnel blockage becomes too excessive and a correction in one way or another would be required.

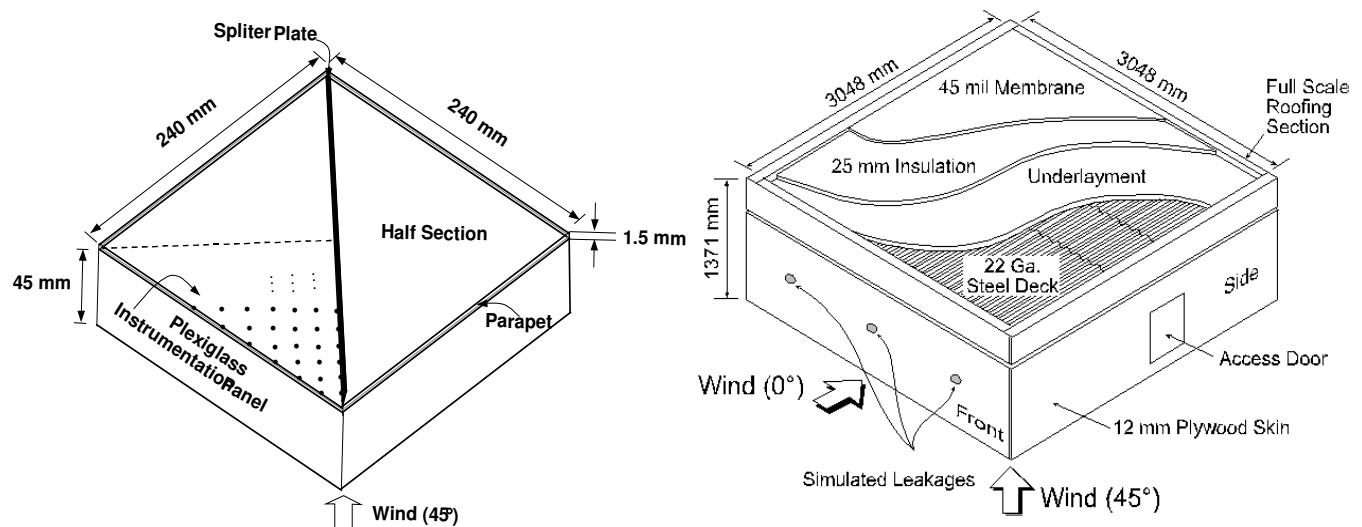
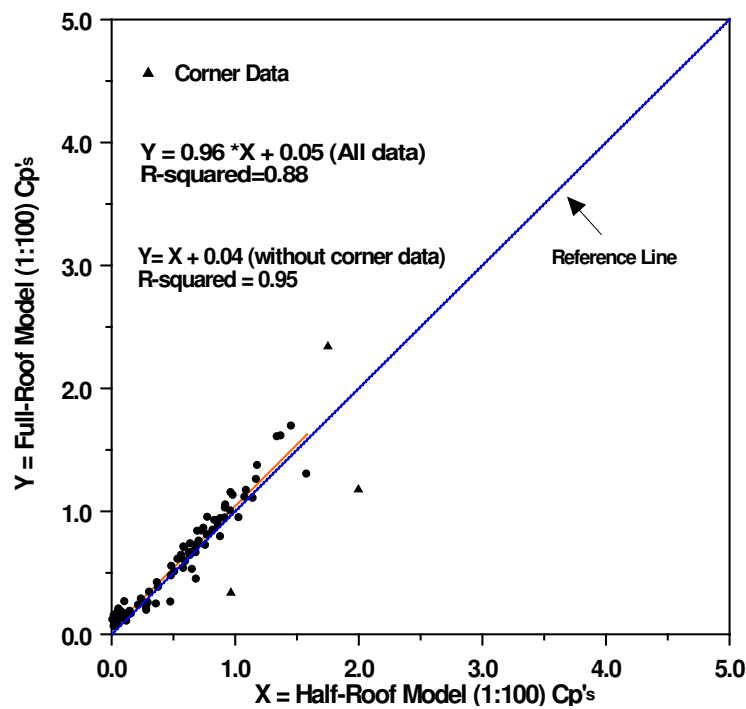


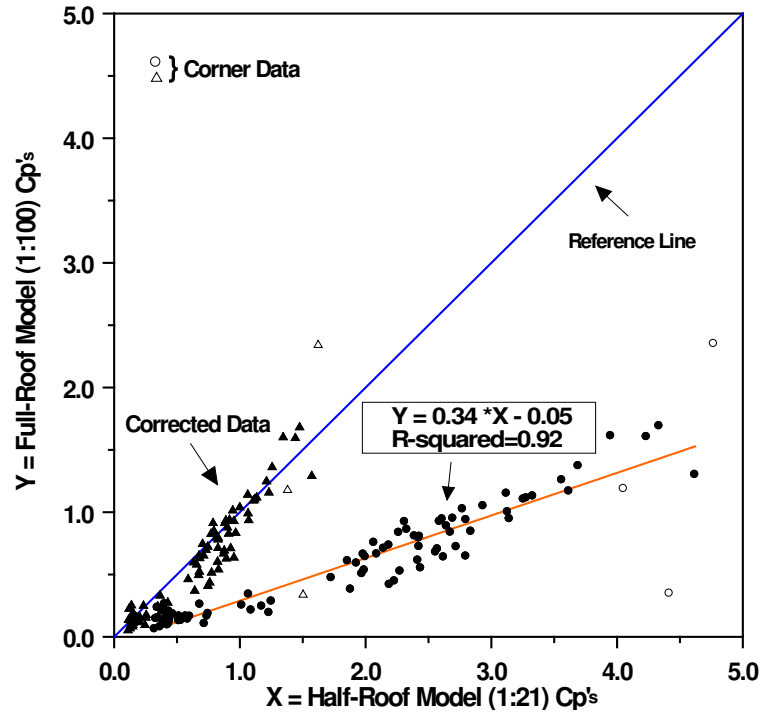
Figure 4. Full-roof and a half-roof of a full-scale model configurations

It is understood that testing full-scale roof components is an optimistic extension and it should be given some careful second thoughts. For example, when the building model is constructed in a very large scale such as 1/2 or 1/1, it may not be possible to simulate the building height with the same linear scale because the wind tunnel blockage would become too excessive. On the other hand, if the building height is reduced, the resulted roof pressure may not be the same. Another correction is needed to account for the building aspect ratio effect that can be treated separately or it may have to be combined with the blockage effect (Ghariani, 1991). Nevertheless, it still is useful to obtain data with 1/1 scale model for all

practical purposes. By taking Tanaka's novel idea, SIGDERS (Special Interest Group for Dynamic Evaluation of Roofing Systems) composed of roofing industries, manufacturers, associations and building owners, enhanced a wind load determination method on flat roofs (www.sigders.ca).



(a) Comparison of full- and half-roof models



(b) Comparison of 1/100 and 1/21 scale roof models

Figure 5: Effect of model scale on the measured roof pressure coefficients

4. Wind Induced Pressure Interaction with Building Stack Effect

Very few researchers quantified the contribution of various pressure differences across a building envelope. In 1980's, an extensive field measurements was completed by Tanaka's research group (Lee et al 1982). The measurements were made continuously for 5 months from November 1980 to March 1981 on a building located in the Ottawa downtown (figure 6). A difference between the internal and external pressures on a building can be caused by various factors. Three sources are considered here, namely: (i) Wind-induced external and internal pressures; ii) Natural ventilation caused by temperature differences, the so-called stack effect; and (iii) Forces or mechanical ventilation systems. The analysis of the data measured in this study is carried out on the assumption that the total pressure difference Δp is given by linear summation of the three kinds of pressure differences, i.e.:

$$[1] \quad \Delta p = (\Delta p)_w + (\Delta p)_s + (\Delta p)_v$$

where Δp is the total pressure difference across the wall, $(\Delta p)_w$ is the pressure difference caused by wind action, $(\Delta p)_s$ is the pressure difference caused by the stack effect, and $(\Delta p)_v$ is the pressure difference caused by mechanical ventilation.

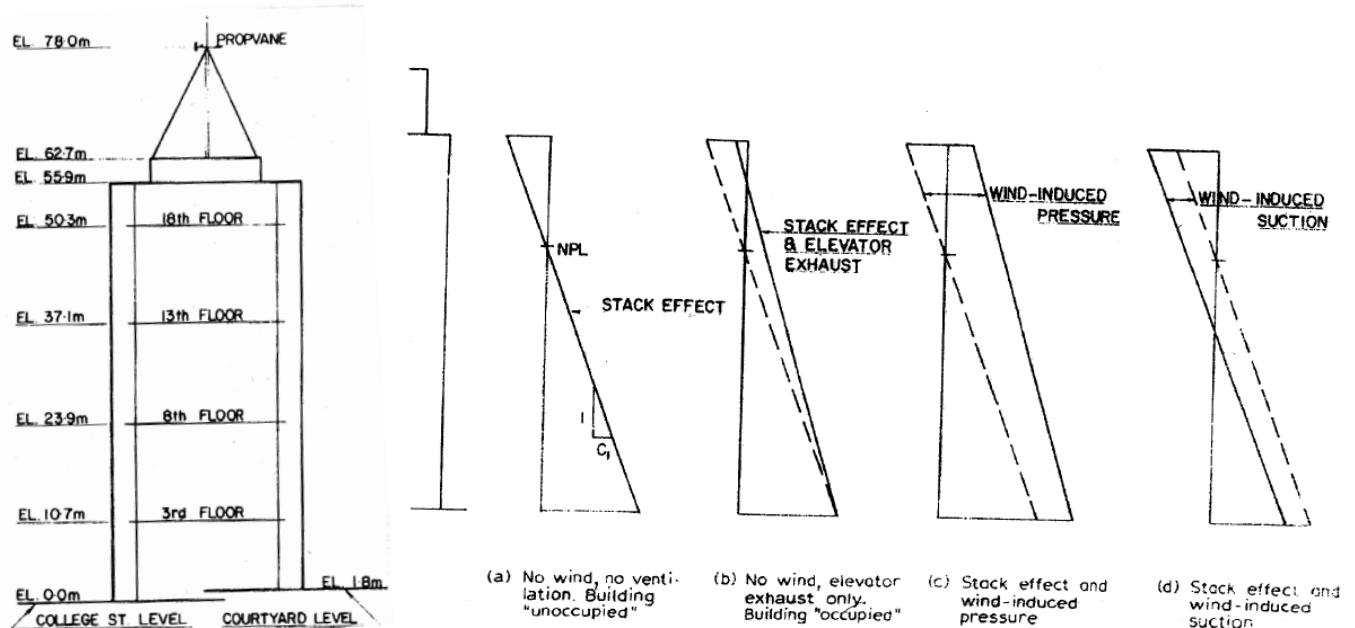


Figure 6. Various Pattern of pressure-difference profile across the building envelope.

The stack effect was found to be one of the major causative factors in the mean pressure difference across the building enclosure throughout the winter season. Its magnitude, in this particular set of measurements at the lower levels of the building was as high as 70-80Pa. This is comparable to the wind-induced positive pressure at a local mean wind-speed of $\sim 12 \text{ m s}^{-1}$.

5. Concluding Remarks

This paper highlighted Tanaka's major contributions to the building envelope design. These novel ideas exemplify how wind engineering principles can be fused with building science theories to provide a safer and economical building environment.

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