

## IMPROVING BRIDGE AERODYNAMICS

By Gordon Dunn, Principal

When we think of a wind-induced structural failure, our minds conjure up images of debris laden hurricane force winds, uprooted trees and people running for cover. However, for the designers of long-span bridges, a disaster can occur on a routine windy day.

The failure of the Tacoma Narrows Bridge in 1940 brought to the foreground the importance of wind in the design of long-span bridges. The bridge collapsed in 40 mph winds from an aerodynamic instability known as flutter. Wind tunnel testing formed an important part of the investigation into that failure and has since become an integral component of long-span bridge design.

### Baffle plates on model of steel bridge

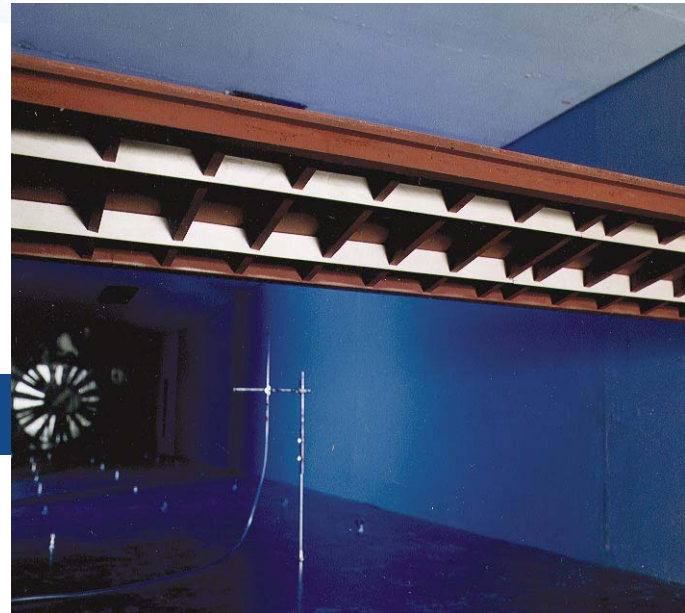
As wind separates and flows around a bridge deck, vortices are formed at the windward edge of the bridge. These vortices then roll in an alternating pattern along the top and bottom of the bridge deck. When the frequency of the vortex shedding approaches the natural frequency of the bridge, the bridge deck will move in tune with the vortices.

Vortex shedding is considered a problem when the accelerations caused by the motions disturb or startle motorists. A second concern is long-term fatigue if the deflections and their frequency of occurrence are excessive.



Tacoma Narrows Bridge Failure

As both vortex-induced motions and flutter are sensitive to the deck's height to width ratio, reducing the profile of the deck edge is the easiest way to improve the bridge's aerodynamic performance. However, there are practical limits on how much the profile of the deck can be reduced. If further improvement is required, special aerodynamic modifications can be developed through wind tunnel testing. Edge treatments, such as fairings and deck extensions, have been successfully used. However, changes to the outside of the edge girder are not readily accepted by bridge designers due to their negative impact on aesthetics, structural inspection requirements, and construction cost.



Because of the catastrophic consequences, the flutter characteristics of a long-span bridge, are without question, the most critical wind engineering issue. Flutter occurs when the wind forces and the dynamic characteristics of the bridge combine in such a way that the wind feeds energy into the oscillations. The bigger the oscillations, the more energy is fed into them. As there are no limits to these motions, the cycle continues until the structure ultimately fails.

Many of today's lightweight steel designs use plate edge girders. These designs tend to be more vulnerable to instability and often aerodynamic modifications are required. With the trend towards pricing both steel and concrete design alternates, any modifications made in the name of aerodynamics have to be simple and cost effective to keep the steel alternates competitive.



The addition of baffle plates along the underside of the deck has become a preferred modification. Typically, two rows of baffles running along the main span at the quarter chord location, is most effective in terms of improved stability versus cost. Where we have recommended baffles, their construction costs have been in the \$100,000 to \$200,000 range, depending on the length of the main span.

However, more baffles have been used in some cases such as the existing Quincy Bridge over the Mississippi River (Illinois) where five baffles were used.

The adjacent table summarizes the aerodynamic improvements achieved on four bridge sections recently tested at our wind tunnel facilities.

In each case the addition of the baffle plates provided substantial improvement in flutter speed. The improvements in the vortex induced motions were more modest, but the resultant accelerations were acceptable. This consistent aerodynamic performance combined with very low impact on bridge aesthetics and serviceability and the baffle's relative low cost, makes it easy to understand why the baffle plate has been readily accepted by today's bridge designers.

	Flutter speed (mph)		Vertical Displacement (feet)		Torsional Displacement (degrees)	
	Without Baffles	With Baffles	Without Baffles	With Baffles	Without Baffles	With Baffles
Bridge A	69	90	0.90	0.10	0.70	0.50
Bridge B	99	124	1.10	1.00	1.60	1.00
Bridge C	61	91	0.85	0.60	0.55	0.25
Bridge D	154	193	0.80	0.53	0.40	0.40

## HIGH RISE BUILDINGS IN HURRICANE AREAS

### A Case Study

by Michael Soligo, Principal

In our last newsletter, the advantages of wind tunnel studies for high rise buildings in hurricane areas were discussed. In this article, a case study is being presented of two residential developments in Miami. The study compares wind tunnel loads to the ASCE 7-93 analytical code requirements.

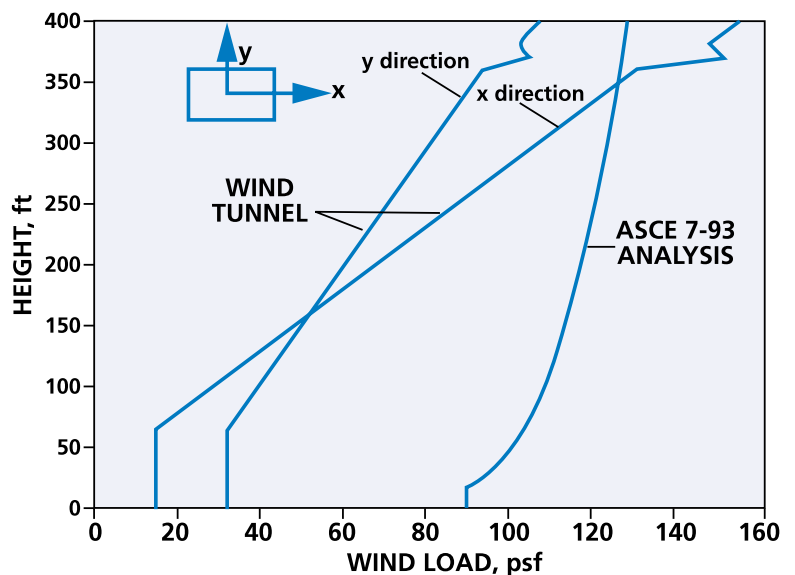
	ASCE 7-93 Method Range of Results	Wind Tunnel Method Range of Results
Building 1	108 - 260	80 - 170
Building 2	100 - 242	80 - 125

Negative Pressures, psf

Wind loading patterns on buildings are very complex and variable. However, to remain practical, building codes must simplify the treatment of wind loads, and they often produce conservative results. This conservatism can translate into extremely high loads in hurricane areas.

Project-specific wind tunnel studies can be used where the benefits to the design outweigh the extra cost of the study. Wind tunnel testing is recognized by the ASCE 7-93 Standard and the other major building codes as an appropriate method for determining wind loads.

The table below summarizes the comparison of wind tunnel results with those of the analytical procedure of ASCE 7-93 Standard for two typical high rise residential buildings. The ASCE 7-93 method produces very high wind suction on corners, well in excess of 200psf. The wind tunnel results are considerably lower than the analytical results, the highest suction being 170psf. Lower loads are obtained from the wind tunnel tests mainly because better account is taken of the building shape and details such as balconies and parapets. As well, the results often identify high loads in specific area that are not picked up by the code method, thereby ensuring greater safety in design.



Structural Wind Loads



The figure below compares the wind tunnel loads on the main structural system of Building 1 with the loads from the ASCE 7-93 method. As shown, the wind tunnel loads are less than the code loads for the majority of the building. The wind tunnel method has also improved design safety by identifying higher loading for the upper levels of the structure. The code method would have produced insufficient loads in this area.

For many of today's unique tower designs, the torsional loading can be critical. While ASCE 7-93 does not account for torsional effects, wind tunnel testing ensures that this type of loading is properly considered. In addition, the

greater understanding of the torsional loading provided by the wind tunnel testing allows optimization of the building design (e.g., placement of shear walls).

The **benefits of wind tunnel studies** can be summarized as follows:

- \* **Increased accuracy,**
- **Building and site specific,**
- **Reduced construction cost by minimizing conservatism (cost savings of \$500,000 or more have resulted),**
- **Increased safety, and**
- **Increased knowledge of torsional effects.**

## MOTION CRITERIA

by Peter A. Irwin, Principal

Oscillation of a structure in wind can rapidly lead to structural failure if the oscillations grow to a large amplitude. However, certain types of oscillation, while they are not large enough to cause structural problems, may cause problems of human discomfort in tall buildings and on long-span bridges.

### Horizontal Motions in Buildings

Building motions under the action of commonly occurring winds need to be kept within comfortable limits for the building occupants. For lightweight modern structures, keeping the building motions within acceptable limits can be more of a challenge than ensuring that they have sufficient structural strength.

Acceleration has emerged as the most common index of motion effects. The horizontal force felt on the human body is directly proportional to the horizontal acceleration. An acceleration of one thousandth of gravity is called a milli-g. People are sensitive to accelerations as small as a few milli-g.

It is unrealistic to demand that no perceptible motions ever occur. Therefore, how much horizontal acceleration is acceptable and how often can it take place? The International Standards Organization (ISO) has published guidelines (see adjacent graph) in terms of the root-mean-square (RMS) value of the acceleration on the top floor that should not be exceeded more than once in five years on average. For example, for a building with a five second period, the five year acceleration should not exceed 18 milli-g. For a building with an eight second period, a higher five year acceleration not exceeding 22 milli-g is acceptable. These accelerations will be perceived, but if they only occur once every five to ten years, the functioning and commercial viability of the building will not be adversely affected.

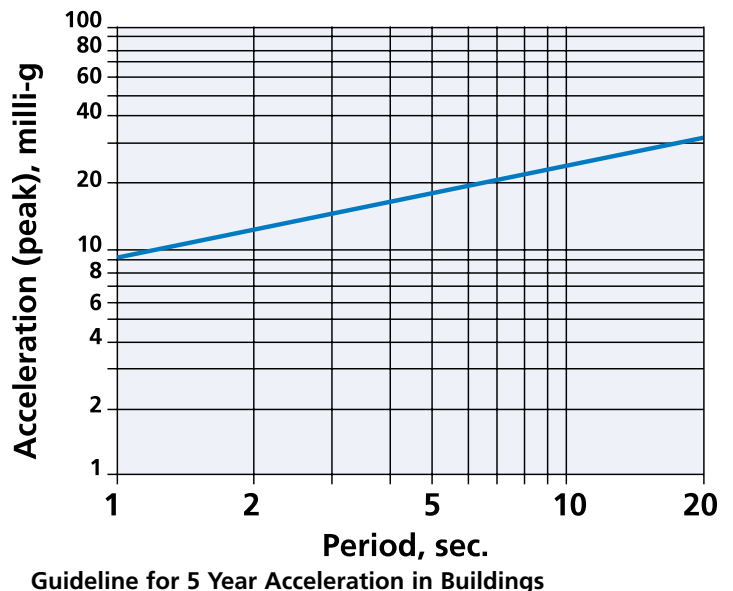
More recently there has been a trend towards setting the criteria at a shorter return period of one year with values of acceptable acceleration set about 30% lower. This has been prompted by the increasing number of buildings being constructed in hurricane and typhoon areas. Typically, in these areas, there is ample warning of the five or ten year winds caused by these storms. Buildings are usually evacuated before the storm hits, and occupants who stay are not expecting normal comfortable conditions. Therefore, in such areas, it is more meaningful to consider the one year wind event.

The criteria discussed above apply primarily to office buildings since the most data are available for that situation. Target accelerations for residential buildings are often set 20% to 30% lower.

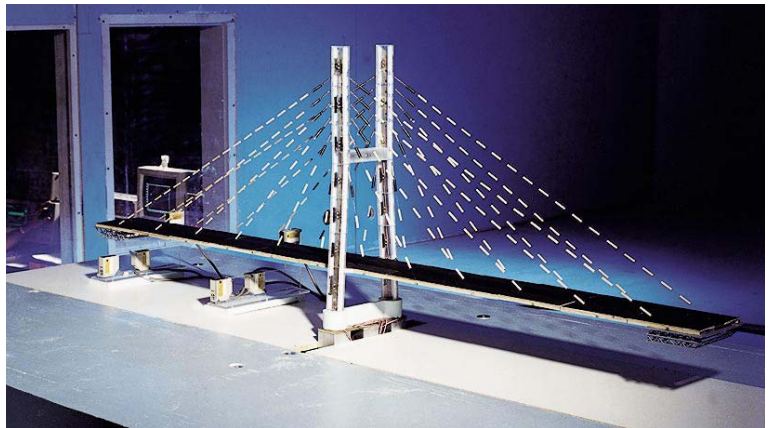
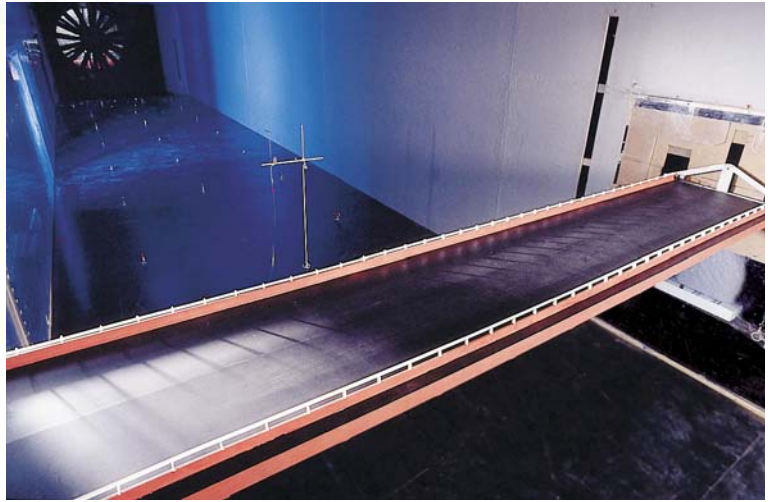
### Long-Span Bridges

Long-span bridges can also move enough in wind to disturb people. Some bridges have experienced severe oscillations due to vortex shedding, where the motion is in the vertical direction. A guideline frequently used in North America is that the peak acceleration not exceed 5% of gravity, i.e. 50 milli-g, for wind speeds below 30 mph (13 m/s) and not above 10% of gravity, i.e. 100 milli-g for winds higher than 30 mph. The British use a criterion of 40 milli-g for wind below 20 m/s (45 mph) with no limit for higher winds.

These criteria are clearly much higher than those for horizontal motions in buildings. This difference is because of several factors including; the direction of motion; the outdoor environment: people on bridges are typically moving in vehicles and notice bridge motions less: at the higher wind speeds the buffeting action of wind on the vehicle will be more noticeable than the bridge motions; and at very high wind speeds the bridge will probably be closed to traffic.



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CONSULTING ENGINEERS  
& SCIENTISTS

**Rowan Williams Davies & Irwin Inc.**  
(519) 823-1311 [www.rwdi.com](http://www.rwdi.com)

**RWDI Anemos Ltd.**  
01582 470250 [www.rwdi-anemos.com](http://www.rwdi-anemos.com)

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