Wind and Structures, Vol. 14, No. 1 (2011) 55-70
DOI: http://dx.doi.org/10.12989/was.2011.14.1.055

Design criteria of wind barriers for traffic. Part 1: wind barrier performance

Soon-Duck Kwon*[1], Dong Hyawn Kim[2], Seung Ho Lee[1] and Ho Sung Song[1]

[1]KOCED Wind Tunnel Center, Department of Civil Engineering, Chonbuk National University, Chonju, Chonbuk, 561-756, Korea
[2]Department of Coastal Construction Engineering, Kunsan National University, Kunsan, Chonbuk, 573-701, Korea

(Received August 8, 2009, Accepted September 7, 2010)

Abstract. This study investigates the design criteria required for wind barriers to protect vehicles running on an expressway under a high side wind. At the first stage of this study, the lateral deviations of vehicles in crosswinds were computed from the commercial software, CarSim and TruckSim, and the critical wind speeds for a car accident were then evaluated from a predefined car accident index. The critical wind speeds for driving stability were found to be 35 m/s for a small passenger car, yet 30 m/s for a truck and a bus. From the wind tunnel tests, the minimum height of a wind barrier required to reduce the wind speed by 50% was found to be 12.5% of the road width. In the case of parallel bridges, the placement of two edge wind barriers plus one wind barrier at center was recommended for a separation distance larger than 20 m (four lanes) and 10 m (six lanes) respectively, otherwise two wind barriers were recommended.

Keywords: wind barrier; shelter effect; driving stability; parallel bridge; vehicle protection; wind tunnel test.

1. Introduction

Vehicles in coastal regions or in a valley area sometimes deviate from their desired path because of the strong crosswind accelerated by the concentration of flow over the bridges or valleys. Continual compensation of the steering wheel against the crosswind causes stress for the driver, leading to an increase of accident risk. There has been considerable research into the effects of wind loads on moving vehicles. However, it is still claimed that as many as 2% of accidents could be due to windy conditions (Smith and Barker 1998). Considering that 88%, 10% and 2% of traffic accidents have been caused by driver distractions, road conditions and automobile problems respectively, 2% of accident probability is large amount. To reduce accidents, criteria for an appropriate driving speed limit and proper countermeasures such as providing wind barriers has been demanded.

The investigation of the crosswind sensitivity of vehicles is essential for developing safety criteria.

* Corresponding Author, Associate Professor, E-mail: sdkwon@chonbuk.ac.kr

A large amount of research has been carried out in this field. Baker (1986), Baker and Reynolds (1992) have made extensive studies on the performance of high-sided vehicles in cross winds on roads. Baker proposed fundamental equations for wind actions on vehicles. Xu and Guo (2003), and Chen and Cai (2004) made a dynamic model for a three dimensional vehicle combined with quasi static wind forces. The aerodynamic design of motor vehicles in combination with crosswind sensitivity has also been intensively studied by automobile manufacturers and their researchers (Sorgats 1976, Emmelman 1981, MacAdam *et al*. 1990 and Gawthorpe 1994). Especially, Emmelman (1981) provided a comprehensive summary of driving stability in a crosswind. Recently Maruyama and Yamazaki (2006) used the driving simulator to evaluate the lateral deviation of a vehicle under a strong crosswind.

Concerning the safety criteria, only a very limited number of research articles are available. Wyatt (1992) introduced speed limits at the Severn Bridge and the Forth Road Bridge. Smith and Barker (1998) have summarized a typical action plan for a cross wind imposed on major bridges in the U.K. Each bridge has a different reaction, and wind speeds that would cause a closure of the bridge ranged from 16 m/s to 22 m/s. Kwon and Jeong (2004) proposed an action plan for speed limits and restriction at an expressway. Their speed limit scenario currently used in Korea consisted of three steps for wind speeds from 15 m/s to 25 m/s. Dellwik *et al*. (2005) have calculated a total percentage of time for bridge restriction for the Fehmarn Belt Bridge, the Oresund Bridge and the Great Belt Bridge in Denmark according to the criterion that a bridge closes when the wind speed is over 21 m/s or 17 m/s for perpendicular winds. Wang *et al*. (2005) presented wind speed criteria for the Sutong Bridge in China.

A wind barrier, often referred to as a wind screen, wind fence or wind shield, is a countermeasure to ensure driving stability of ground transportations in crosswinds. A large amount of literature on this field can be found. Counihan *et al*. (1974), and Bradly and Mulhearn (1983) studied the mean velocity reduction along the downstream direction behind the barrier. Borrelli *et al*. (1987), Ranga Raju *et al*. (1988) and Papesch (1992) performed wind tunnel tests of wind barriers to reduce wind speed for agricultural purposes. They measured the mean and turbulent wind speeds behind a wind barrier for different geometric porosities. Wyatt (1992), and Smith and Barker (1998) have introduced wind barriers used in British bridges. Lee and Kim (1999), Lee and Park (2000) have intensively studied flow structures behind porous fences to investigate the environmental problems occurring at an open coal storage yard. Kwon and Jeong (2004) tested wind barriers made of expanded metal with various porosities in small scale wind tunnel tests. Charuvisita *et al*. (2004) investigated the effects of a wind barrier on a vehicle passing in the wake of a bridge tower. Recently, Saito *et al*. (2006) studied the effects of wind barriers on railway vehicles in cross winds.

The safety criteria and the decision making process are mostly based on intuition or subjective experience (Chen and Cai 2004). Moreover, the above mentioned results are not systematically linked to each other. Therefore, integrated criteria for the design of wind barriers and decision making for installation of wind barrier are very desirable. In order to develop a reasonable vehicle protection plan to reduce car accident risk, the quantitative relations between crosswind speed and driving safety first need to be defined. The first objective of this study is to establish the safety criteria for a vehicle under a crosswind. The numerical approach was used to evaluate the lateral deviation under wind for various vehicles. The second purpose of this study is to obtain design parameters for wind barriers. Wind tunnel tests were performed, and the appropriate height of the wind barrier was then proposed from the results. Moreover, the installation method of wind barriers was investigated for separated parallel bridges.

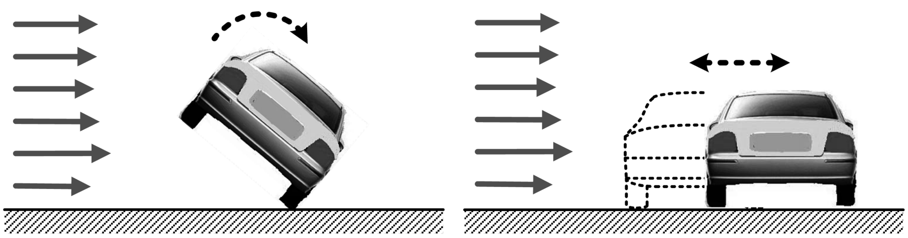
2. Vehicle accidents in crosswind

Overturning and sideslip can be represented as typical vehicle accident types when winds blow perpendicular to the road (see Fig. 1). The overturning can be clearly defined from the equilibrium of forces acting on the vehicle. The overturning crosswind speed can be simply computed from the following equation (Carr *et al*. 1993).

$$V_{over} = \sqrt{\frac{2mg}{\rho A(C_L + 2C_{RM}l/t)}} \tag{1}$$

where l is the wheel base, t is the mean wheel tread, ρ is air density, A is the frontal projected area, m is vehicle mass, g is gravity acceleration, C_L is the lift coefficient, C_{RM} is the rolling moment coefficient.

MIRA has carried out studies to identify vehicles which are particularly at risk to overturning in cross-winds (Carr *et al*. 1993). Fig. 2 shows the relationship between vehicle speed and cross wind speed required to cause overturning of high side vehicles which are relatively sensitive to overturning compared with small passenger cars. As can be seen in the figure, the overturning wind



(a) Overturning (b) Sideslip

Fig. 1 Vehicle accidents in crosswind

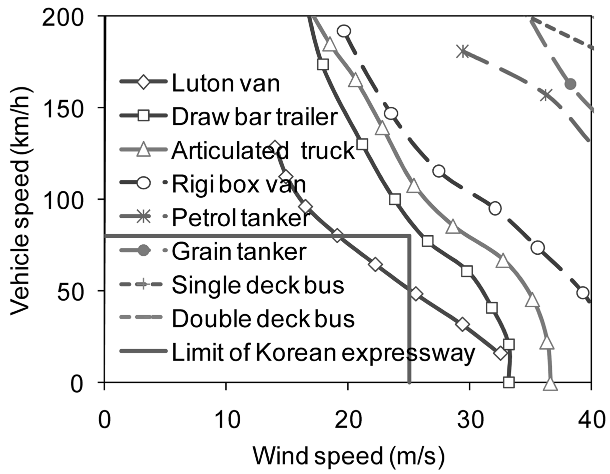


Fig. 2 Crosswind speed required to cause vehicle overturning (Carr *et al*. 1993)

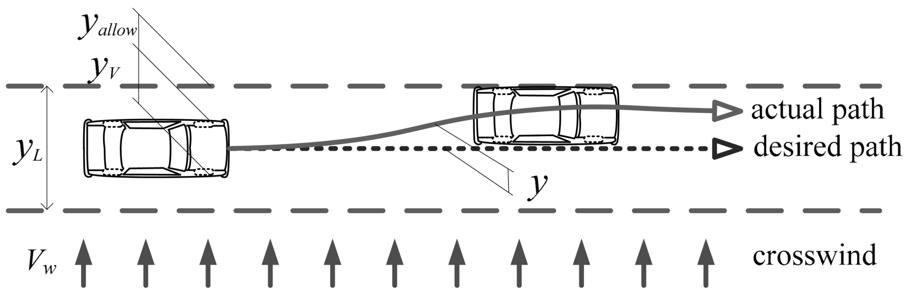


Fig. 3 Vehicle path under crosswind

speed for high side vehicles, with the exception of the Luton van, are over 25 m/s at a vehicle speed of 90 km/h, which is the speed limit of trucks on Korean expressways.

The sideslip accident is a collision with another vehicle or a safety barrier, and is not easy to define. The issue related to sideslip is how to mathematically define the accident from the computed lateral deviation of vehicles in a crosswind. In present study, the car accidents due to side wind are defined in the case where (1) the yawed angular deviation of the vehicle reaches 10 degree, and (2) the vehicle deviates to the next lane. To define a critical wind speed for lateral deviation, we consider a running vehicle on an expressway as shown in Fig. 3. Vehicle velocity of acceleration components is not considered here. The level of approach to next lane can be expressed by the following car accident index (Emmelman 1981)

$$C_F = \sqrt{\frac{1}{1-(2y_{t=0.8}/y_{allow})}} - 1 \tag{2}$$

where $y_{t=0.8}$ is the lateral deviation of the vehicle under a crosswind after a time lapse of 0.8 seconds, y_L is the width of the traffic lane, y_V is the width of the car, and y_{allow} (= $\{y_L - y_V\}/2$) is the lane margin. The car accident index increases slowly as the vehicle deviates from the desired path, and becomes infinite when the vehicle reaches to next lane.

Approximately 0.8 seconds is required for a vehicle to start to recover its path after wind action because of the steering play and dynamics of the steering system (Emmelman 1981, Baker 1986). Until today, the yaw rate and resultant lateral deviation have been similar regardless of the driver's steering methods. Therefore, the lateral deviation at 0.8 seconds after wind action is used to compute the car accident index. A vehicle is considered to have lost its driving stability when the car accident index exceeds 3 where the index increases rapidly. Fig. 7(a) shows an example of the car accident index evaluated from the lateral deviation of a sedan.

3. Critical wind speeds for driving stability

3.1 Methodology

Key elements that affect crosswind sensitivity are aerodynamic properties, vehicle dynamic properties, steering system characteristics and driver closed-loop steering preferences (MacAdam *et*

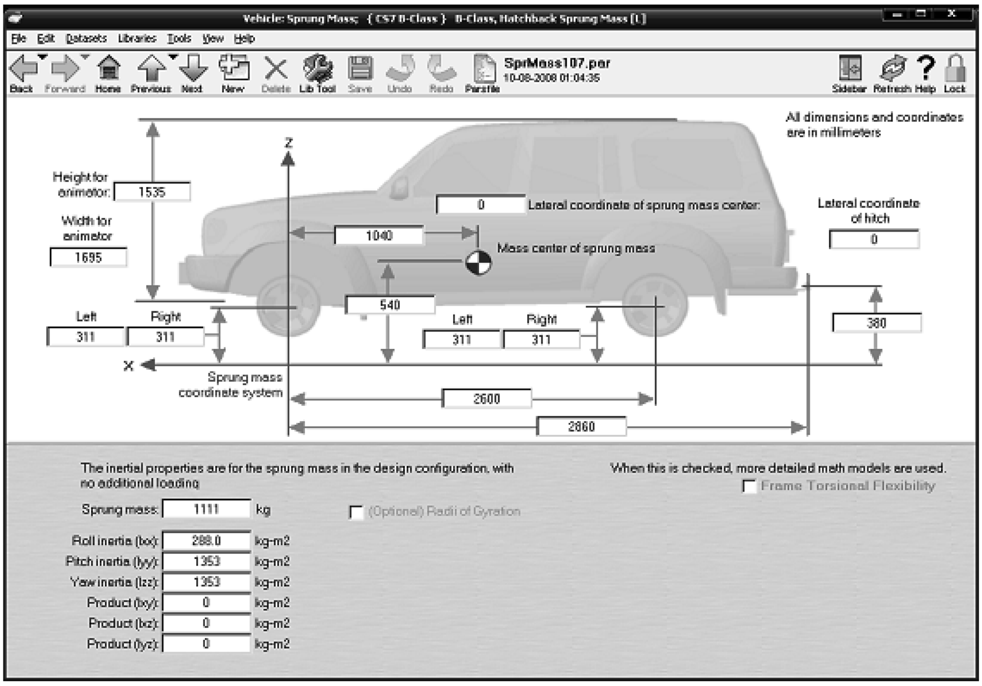


Fig. 4 Simulation of vehicle motion under crosswind by CarSim

al. 1990). The above mentioned data are required for accurately computing the lateral deviation of vehicles under crosswind. However, some data, especially vehicle dynamic properties, are confidential and may not be available.

To overcome this problem, the CarSim (v7.1a) and the TruckSim (v7.1) developed by Mechanical Simulation Corporation (2007) were used to compute the lateral deviation and the overturning wind speed of vehicles in the present study (see Fig. 4). The CarSim and the TruckSim are commercial vehicle dynamics simulation software which have been widely used in the automotive industry (Kinjawadekar *et al*. 2009), and originated from the Transportation Research Institute at the University of Michigan. A total of twelve typical vehicle models including three sedans, three hatchbacks, one minivan, two SUV's and three trucks provided with CarSim and the TruckSim have been used for analysis. Fig. 5 shows detail information for the vehicle models used in the analysis.

In the dynamic analysis, the vehicle speeds, wind speeds, surface friction coefficients and driver models were adjusted to simulate actual road conditions. The small passenger cars were driven at a fixed control, yet the truck was lead by a driver. Friction coefficients of road surface were assumed to be 0.85 for a dry condition and 0.4 for wet a condition (Gillespie 1992). Vehicle speeds, constant at a certain event, were changed from 20 km/h to 160 km/h. It was assumed that wind speed was constant during simulation and wind direction was perpendicular to the expressway. Wind speeds were set from 10 m/s to 40 m/s at every 5 m/s. Fig. 4 shows simulation of vehicle behavior under crosswind obtained by CarSim.

(a) Sedan

(b) Hatchback

(c) Minivan and SUV

(d) Truck

Fig. 5 Vehicle models used in analysis

3.2 Results

The effects of some parameters were investigated to clarify the simulation conditions before detail analysis. The first one was the effect of friction coefficients of road surface on lateral deviation of vehicle. Fig. 6 shows the lateral deviations from its desired path under a crosswind after a time lapse of 0.8 seconds. It was found from the simulations that the road conditions, 0.85 and 0.4 for dry and wet respectively, had a minor effect to the lateral deviation due to crosswind.

The second one was wind off and wind on conditions. Considering the case where the vehicle runs on a tunnel and a consecutive bridge, a cross wind can be suddenly applied to a vehicle. Fig. 7 reveals the effects of sudden and gradual increment of wind velocity on vehicle responses. Sudden wind was assumed to be blown from 0 to 30 m/s at instant, yet gradual wind was linearly increased from 0 to 30 m/s at a time lapse of 3 seconds. There were some time shift in the curves for car accident indices and yaw angles in two wind conditions but the slope of curves were almost similar. These represent that side slip accident may happen in both cases but those in gradual wind may delay just a little because of gradual wind increment. The effect of the wind off and the wind on conditions was found to be insignificant.

Fig. 8 shows the lateral deviations from its desired path after 0.8 second and their corresponding car accident indices of a truck computed from CarSim and TruckSim. The car accident index was evaluated by inserting the lateral deviation into Eq. (2). The car accident indices shown in Fig. 8(b)

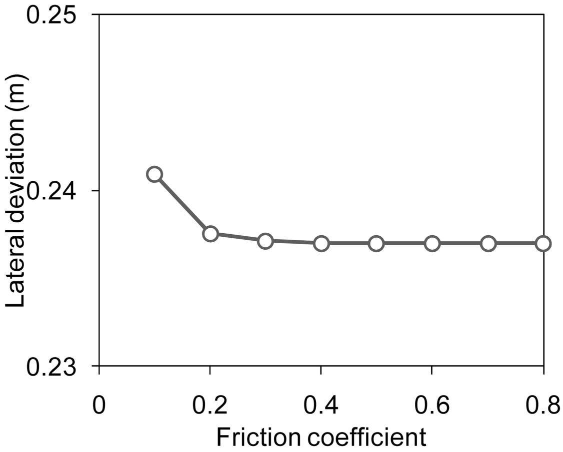
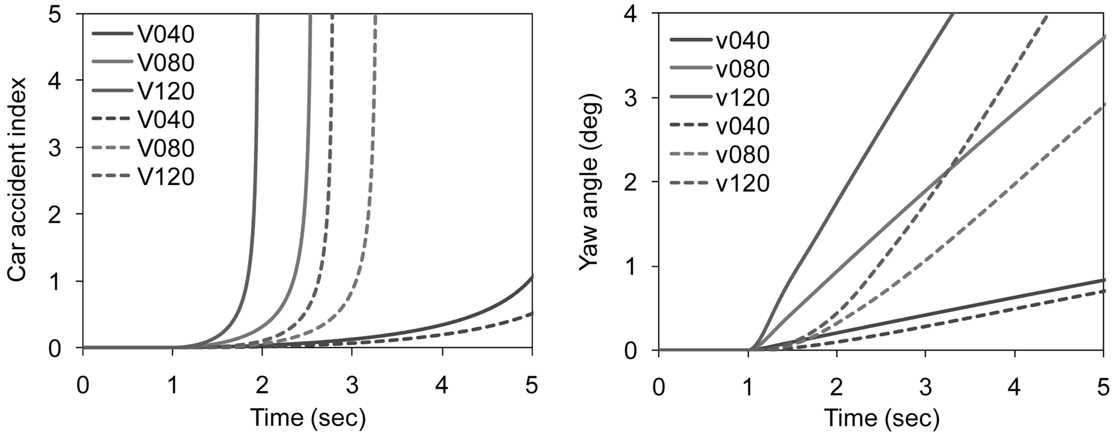


Fig. 6 Lateral deviations of a sedan under various friction coefficients of road surface



(a) Car accident indices

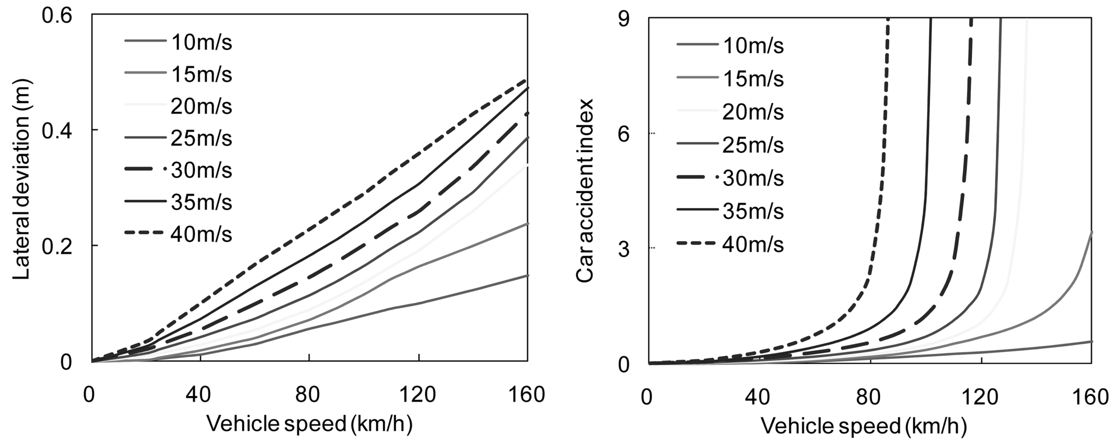
(b) Yaw angles

Fig. 7 Car accident indices and yaw angles of a sedan under wind action. Solid line: wind suddenly increased from 0 to 30 m/s, dotted line: wind linearly increased from 0 to 30 m/s for 3 seconds

were evaluated for every 12 vehicle models from the dynamic simulations. From Fig. 8(b), the vehicle speed corresponding to a car accident index of 3 is around 81 m/s when the wind speed is 40 m/s.

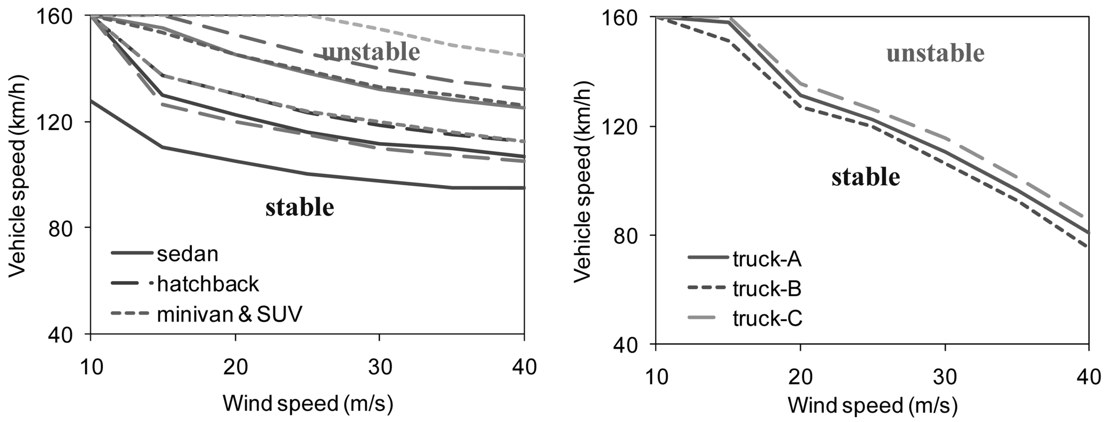
Fig. 9 shows the crosswind speed necessary to cause a sideslip accident as defined in the previous section. The upper and lower areas divided by the line for a certain vehicle in Fig. 9 denote the safe zone and the unsafe zone under wind, respectively. For instance, it is a risky condition, as shown in Fig. 8(b), if a 40 m/s wind attacks truck-A running at 120 km/h. If the wind speed is under a 20 m/s wind, however, it is safe.

In order to determine the general safety criteria for driving stability, the vehicles were categorized into two groups. The first group is small passenger cars which includes a sedan, a hatchback, a minivan and an SUV. The second group is a truck and a bus. The stability diagrams for the first group are given in Fig. 9(a), and those for the second group are in Fig 9(b). From Fig. 8(a), the



(a) Lateral deviations (b) Car accident indices

Fig. 8 Lateral deviations and their corresponding car accident indices of a truck according to wind speeds (dry condition)



(a) Small passenger cars (b) Truck

Fig. 9 Safety limits for driving stability of road vehicles

minimum critical wind speed of a truck is found to be 35 m/s when the vehicle speed is limited to 110 km/h. A truck with a speed limit on the expressway of 90 km/h has a critical wind speed over 30 m/s, as shown in Fig. 9(b). Those wind speeds are three seconds average value. The criterion for the bus was immediately adopted from that for the truck because the dynamic behavior of bus seems to be similar to that of a high side truck without verification.

4. Shelter effect of wind barriers

To provide a consistent driving stability for vehicles in a crosswind, the wind speed at the road needs to be kept within the critical wind speed as defined in the previous section. If speed limitation of the vehicle according to wind speed is not allowed at the expressway, the wind barrier is the only solution to reduce the wind speed applied to the running vehicle. Wind tunnel tests were performed to obtain the design data for wind barriers and the results are given in this and the following chapters.

4.1 Experimental setup

The experiments were performed in a wind tunnel at Chonbuk National University. This closed-return type vertical returning wind tunnel has two test sections. The tests were carried out at the low speed test section of 12 m (W) × 2.5 m (H) × 40 m (L). The wind tunnel has five fans and motors with 215 KW each. The free stream velocity of this low speed test section ranges from 0.3 m/s to 13 m/s.

The mean velocity of the free stream flow was made by using three pitot tubes and pressure transducers (Setra 239). Two temperature and humidity sensors (Vinotech GHP-20R) were used to evaluate air density. DANTEC CTA-90C10 constant temperature anemometer incorporated with DANTEC 55P11 hotwire sensors was used to measure the turbulent wind velocity behind the wind barriers. At each measurement, 15,000 velocity data were acquired at a 5 kHz sampling rate. The measurements were repeated five times at each point.

The natural atmospheric boundary layer flow has a different mean wind speed and turbulent intensity according to height from the surface. However, the velocity profile may be considered as a constant value within the barrier height because the height of the target barriers in this study is less than 6 m. Therefore, a smooth flow instead of a boundary layer flow was used in this study to clearly find the shielding effects of wind barriers.

Two types of wind barriers were used. One was made by expanded metal with a porosity ratio of 53.7% and the other was a folded porous plate with a porosity ratio of 50%. Kwon and Jeong (2004) provided test results for wind barriers with various porosities ranged from 50% to 80%. Among them, the above mentioned two wind barriers were select considering the shielding performance and the driver's visibility. The mesh size of the expanded metal and the diameter of the small holes at the folded porous plate were kept the same as those of the actual barriers in order to prevent possible scale effects.

A schematic diagram of wind barrier arrangements is shown in Fig. 10. In this study, the model scale was 1/10. The height of the wind barrier was 60 cm, including a safety barrier of 10 cm. The width of the road was 600 cm, corresponding to 10 times the barrier height. The tests were carried

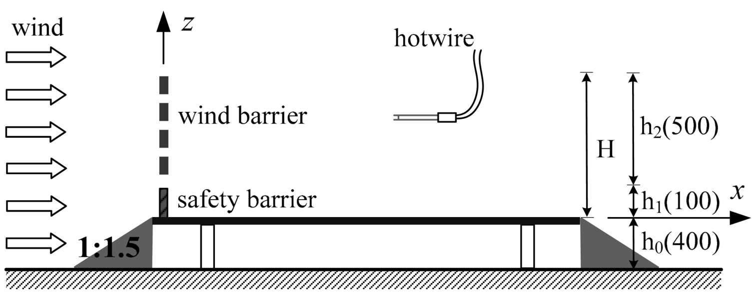


Fig. 10 Schematic diagram of wind barrier arrangements at elevated bridge and embankment

out for two cases, e.g., wind barriers installed at an elevated bridge and at an embankment. To simulate the elevated bridge, the bridge deck was uplifted 40 cm from the wind tunnel floor and the wind flow could pass beneath the deck. Triangles with a slope ratio of 1:1.5 were added at both sides of the road to simulate the embankment.

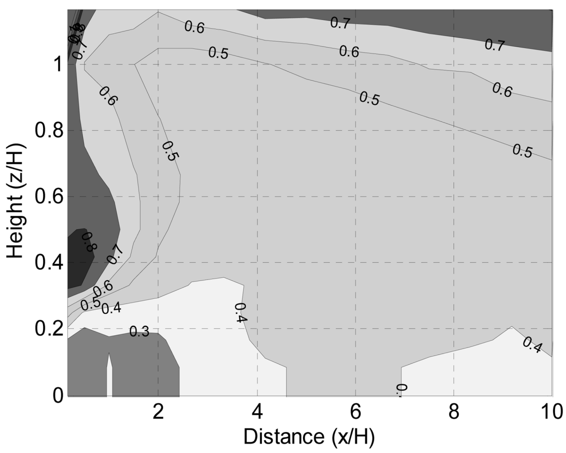
The measurements of the turbulent flow were taken along the downstream distance behind the wind barrier for 10 locations and 8 different heights in the same straight line along wind direction for each location. Thus the measurements were carried out for a total of 80 points. All of the measured data have been expressed by the normalized horizontal distance (x/H) and the normalized vertical height (z/H). Here, x is the downstream distance from the wind barrier; H is the height of the wind barrier; and z is the vertical distance from the road. Wind direction was not considered in this study.

4.2 Experimental results

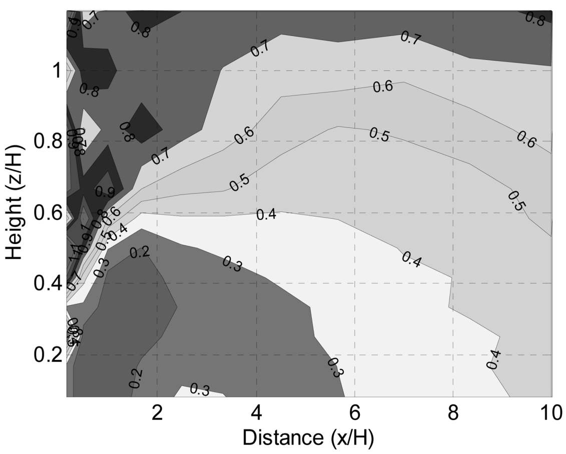
The shelter effect is determined by the flow reduction which is expressed as the normalized wind velocity (V/V_∞). The normalized wind velocity is the ratio of the mean wind velocity (V) at each downstream station of the wind barrier to the free stream velocity (V_∞). Figs. 11 and 12 show the contour for the normalized wind velocities behind the wind barriers installed at the elevated bridge and the embankment. As can be seen from the figure, a significant decrease in the oncoming wind speed after it passes through the barrier can be obtained. In particular, the wind velocities within $x \le 10$ H and $z \le 0.8$ H are less than 50% of the free stream velocity.

The normalized wind velocities just behind the wind barriers, $x \le 2$ H, have not significantly decreased compared with other stations further away from the wind barrier. This is because of the mesh size of the screen. As was mentioned in the previous section, the mesh size of expanded metal was not scaled down to prevent possible scale effects. The wind velocity immediately behind the wind barrier was not reduced because of the relatively large space between meshes. The diameter of the holes at the porous plate also plays a similar role as that of mesh size.

The reduction of wind velocities behind the wind barriers made by both expanded metal and

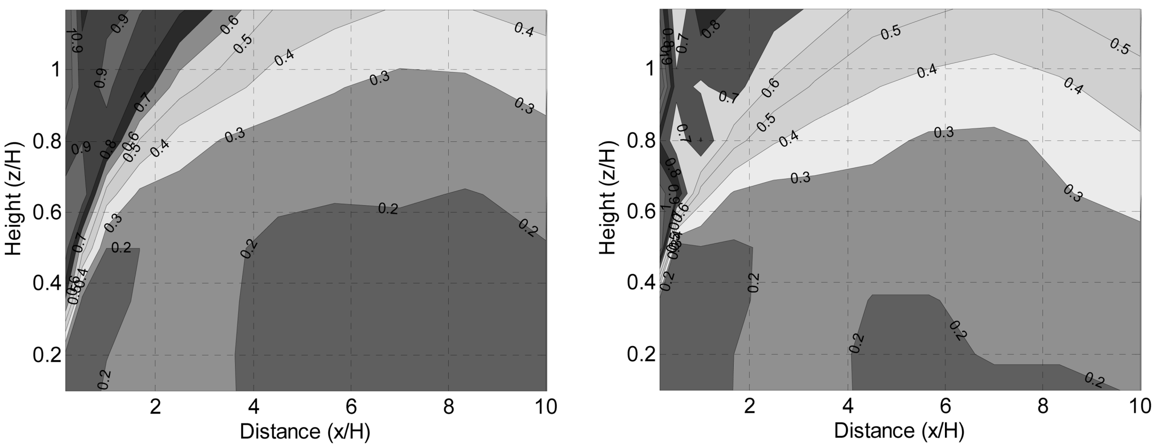


(a) Expanded metal barrier



(b) Folded porous plate barrier

Fig. 11 Normalized wind velocities (V/V_∞) behind the wind barrier installed at elevated bridge



(a) Expanded metal barrier (b) Folded porous plate barrier

Fig. 12 Normalized wind velocities (V/V_∞) behind the wind barrier installed at embankment

folded porous plate definitely decrease within $x \le 10$ H. The shelter effect is valid for the wind barriers installed at the elevated bridge as well as at the embankment. Summarizing the shelter effects again from the Figs. 11 and 12, a 50% reduction of wind velocity can be expected within $x \le 10$ H and $z \le 0.8$ H. From the results, the minimum height required for the wind barrier to reduce the wind velocity within the road by 50% can be proposed as follows by combining these two conditions, 0.8 H $\ge x/10$.

$$H_{min} \ \geq \ \text{(road width)} \ / \ 8 \tag{3}$$

The standard width of an expressway with six traffic lanes in Korea is 30.6 m. Inserting this width into Eq. (3), the minimum height of wind barrier is computed as 3.83 m, which includes the 1 m height of the standard safety barrier.

4.3 Design wind pressure

The wind force acting on wind barriers was measured from the wind tunnel tests. Fig. 13 shows the test model for wind barrier installed at the embankment. The measurement part, a 100 cm wide and 50 cm high piece of the wind barrier, was inserted between two dummy barriers to prevent the three-dimensional mixture of flow at the edges. Since the wind barrier was a porous plate, wind force was measured and then converted to wind pressure. The wind force was measured using a pair of force transducers that was connected to the measurement part separated from the dummy parts. The force measurements were performed at wind speeds of 8 m/s and 12 m/s in the wind tunnel, and repeated twice independently. The measured mean wind force, *P*, was non-dimensionalized by the free stream velocity, V_∞ , air density, ρ, and the measurement part area, *A*. The pressure coefficient, C_p, is expressed as follows

$$C_p = \frac{P}{\frac{1}{2}\rho V_\infty^2 A} \tag{4}$$

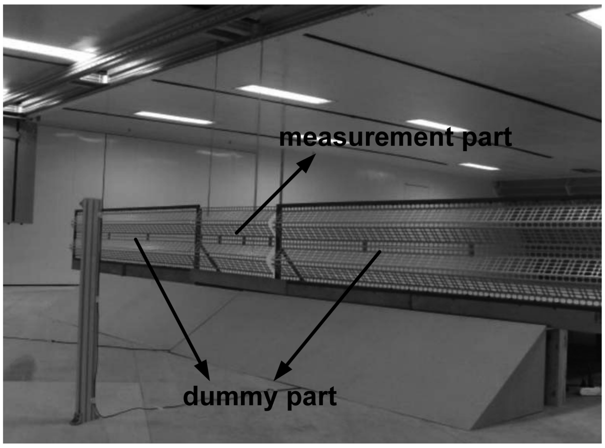


Fig. 13 Measurement of wind force acting on wind barrier

Table 1 Pressure coefficients of wind barriers

Location	Type	C_p
Elevated bridge	Expanded metal	0.81
	Folded porous plate	0.82
Embankment	Expanded metal	0.69
	Folded porous plate	0.83

The measured pressure coefficients of wind barriers are listed in Table 1. When the wind forces were measured, a solid safety barrier of 1 m high was included in the measurement part. Because the pressure coefficient of sold plate is generally higher than that of porous plate, the actual pressure coefficient for the wind barrier excluding safety barrier seems to be slightly less than the value in Table 1. Though there is little difference in material type and placing location, the design pressure coefficients used for wind barriers can be 0.8.

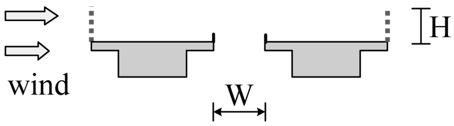
5. Case study for parallel bridges

5.1 Wind barriers for parallel bridges

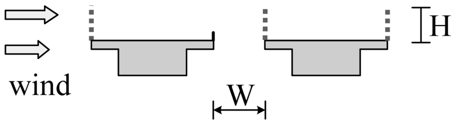
The shelter effects of the wind barriers at parallel bridges may depend on the distance between two bridges. The best way to decrease the wind velocity inside the road is to install the wind barriers at both sides of each bridge. However, this is not economical and a proper guideline for the positioning of wind barriers is required in the case of parallel bridges.

Fig. 14 shows wind tunnel tests of wind barriers at parallel bridges. The scale of model was 1/10. Most of the expressway in Korea consists of four traffic lanes or six traffic lanes where widths are 23.4 m and 30.6 m respectively. For parallel bridges, half of those lanes are carried by each bridge respectively. In the experiments, the shelter effects were measured for the two cases shown in Fig. 15. In the first case (C1), two wind barriers were placed at the windward and leeward sides of the

Fig. 14 Wind tunnel test of wind barriers at parallel bridges



(a) Two wind barriers at windward and leeward (C1)



(b) Two wind barriers at windward and leeward plus one at center (C2)

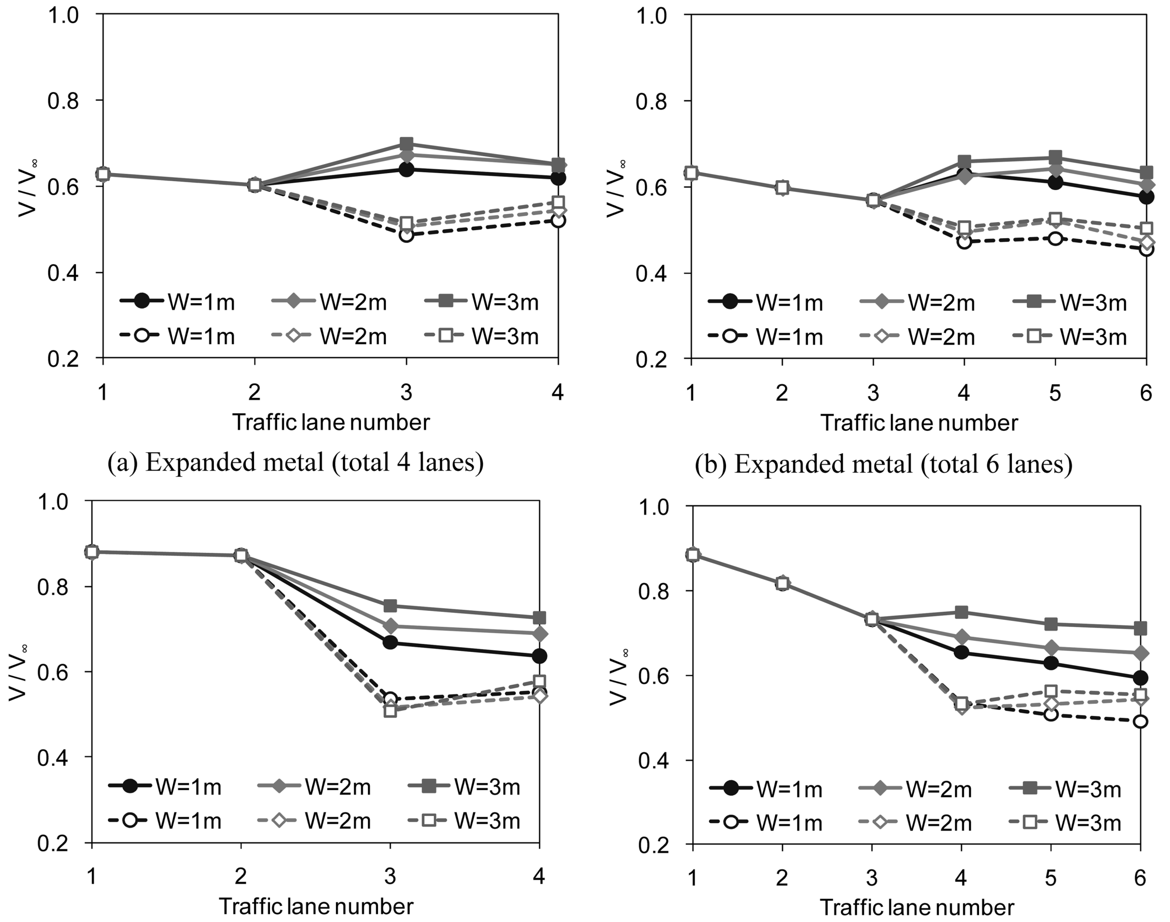
Fig. 15 Placement of wind barriers at parallel bridges

bridges. One barrier was added at the center in the second case (C2). The gap (W) between parallel bridges was 1 m, 2 m and 3 m in the tests because the gap for most parallel bridges on the Korean expressway were found to be less than 30 m, which corresponds to 3 m in the model downscaled to 1/10. Mean wind velocities were measured at 0.1 m, 0.2 m, 0.3 m and 0.4 m above the road surface at the center of each traffic lane.

5.2 Effect of gap width

The normalized wind velocities at 0.4 m above the road are given in Fig. 16. The traffic lanes were numbered from windward in the figure. It is clear from the figure that the reduction ratios of wind velocity under with and without wind barrier are dependent on the gap size regardless of the total number of traffic lanes and barrier placements. The reduction ratio of the wind velocity is inversely proportional to the gap size.

When only two wind barriers were placed (C1), the shelter effect in the lanes at the leeward bridge did not decrease much in the bridges with a total of four lanes, yet the shelter effect deteriorated in bridges with a total of six lanes compared with case of four lanes. However, the



(a) Expanded metal (total 4 lanes)

(b) Expanded metal (total 6 lanes)

(c) Folded porous plate (total 4 lanes)

(d) Folded porous plate (total 6 lanes)

Fig. 16 Normalized wind velocities at 0.4 m above road at center of traffic lanes numbered from windward; solid line: C1, dotted line: C2

shelter effect improved when one wind barrier was added at the center (C2). This demonstrates that one additional wind barrier is required to reduce the wind velocity for parallel bridges with wider gaps.

A general rule for the placement of wind barriers at parallel bridges can be made from the results. Table 2 summarizes the guideline. Two wind barriers can be placed at windward and leeward sides of the bridges for the cases where parallel bridges have a gap size less than 20 m for four lanes and 10 m for six lanes. Otherwise, the placement of 2 edge wind barriers plus 1 wind barrier at center is

Table 2 Placement of wind barriers for parallel bridges according to gap size

Lanes	W≤10 m	10 m<W≤20 m	20 m<W
4(2+2)	C1	C1	C2
6(3+3)	C1	C2	C2

required. When the wind direction for a certain parallel bridge is consistent, only one barrier can be added in front of the leeward side of the bridge.

6. Conclusions

The design criteria required for wind barriers to protect vehicles running on an expressway under a crosswind were investigated in this study. The sideslip caused by crosswind was computed using vehicle dynamics simulation software, CarSim and TruckSim, and the critical wind speeds for a car accident were then evaluated from the predefined car accident index. It was found from numerical simulation that critical wind speeds for driving stability were 35 m/s for a small passenger car and 30 m/s for a truck and a bus. Wind tunnel tests were performed to investigate the shielding performance of wind barriers made by expanded metal and folded porous plate with a porosity ratio of 53.7% and 50% respectively. From the wind tunnel tests, the minimum height required for a wind barrier to reduce the wind speed by 50% was found to be 12.5% of the road width. The wind pressure coefficient for the wind barriers was found to be 0.8. In the case of parallel bridges, the placement of two edge wind barriers plus one wind barrier at center was recommended for a separation distance larger than 20 m for four lanes and 10 m for six lanes respectively, otherwise it is recommended to place two wind barriers at the windward and leeward sides of the road.

Acknowledgements

This research was partially supported by the grant (09CCTI-A052531) from the Ministry of Land, Transport and Maritime of Korean government through the Super Long Span Bridge R&D Center. The authors also gratefully acknowledge the support of the Korea Expressway Corporation.

References

Baker, C.J. (1986), "A simplified analysis of various types of wind induced road vehicle accidents", *J. Wind Eng. Ind. Aerod.*, **22**(1), 69-85.

Baker, C.J. and Reynolds, S. (1992), "Wind-induced accidents of road vehicles", *Acc. Anal. Prev.*, **24**(6), 559-575.

Borrelli, J., Gregory, J.M. and Abtew, W. (1987), "Wind Barrier : A reevaluation of height, spacing, and porosity", *Proceedings of the Summer Meeting of the American Society of Agricultural Engineers*, Baltimore, MD, USA, June-July.

Bradly, E.F. and Mulhearn, P.J. (1983), "Development of velocity and shear stress distribution in the wake of porous shelter fence", *J. Wind Eng. Ind. Aerod.*, **15**, 145-156.

Carr, G.W., Ing, E. and Rose, M.J. (1993) "Cross-wind stability of vehicles on bridges", *Proceedings of the Safety and the Automobile AUTOTECH93*, Birmingham, UK, November.

Charuvisita, S., Kimura, K. and Fujino, Y. (2004), "Effects of wind barrier on a vehicle passing in the wake of a bridge tower in cross wind and its response", *J. Wind Eng. Ind. Aerod.*, **92**(7-8), 609-639.

Chen, S.R. and Cai, C.S. (2004), "Accident assessment of vehicles on long-span bridges in windy environments", *J. Wind Eng. Ind. Aerod.*, **92**(12), 991-1024.

Counihan, J., Hunt, J.C.R. and Jackson, P.S. (1974), "Wake behind two-dimensional surface obstacles in turbulent boundary layer", *J. Fluid Mech.*, **64**(3), 529-563.

Dellwik, E., Mann, J. and Rosenhagen, G. (2005), *Traffic restrictions due to wind on the Fehmarn Belt bridge*, Risø National Laboratory, Risø-R-1521.

Emmelman, H.J. (1981), *Driving stability in side winds, Aerodynamics of Road Vehicles*, (Ed. W.H. Hucho), Vargel Verlag.

Gawthorpe, R.G. (1994), "Wind effects on ground transportation", *J. Wind Eng. Ind. Aerod.*, **52**, 73-92.

Gillespie, T.D. (1992), *Fundamentals of Vehicle Dynamics*, SAE International.

Kim, D.H., Kwon, S.D., Lee, I.K. and Jo, B.W. (2011), "Design criteria of wind barriers for traffic. Part 2: decision making process", *Wind Struct*., **14**(1), 71-80.

Kinjawadekar, T., Dixit, N., Heydinger, G.J., Guenther, D.A. and Salaani, M.K. (2009), "Vehicle dynamics modeling and validation of the 2003 Ford Expedition with ESC using CarSim", *Proceedings of the SAE World Congress & Exhibition*, Detroit, MI, USA, April.

Kwon, S.D. and Jeong, U.Y. (2004), "Vehicle protection program against high winds in Korea", *Proceedings of the Bluff Body Aerodynamics & Applcations (BBAA5)*, Ottawa, Canada, July.

Lee, S.J and Kim, B.H. (1999), "Laboratory measurements of velocity and turbulence field behind porous fences", *J. Wind Eng. Ind. Aerod.*, **80**(3), 311-326.

Lee, S.J and Park, C.W. (2000), "The shelter effect of porous wind fences on coal piles in POSCO open storage yard", *J. Wind Eng. Ind. Aerod.*, **84**(1), 101-118.

MacAdam, C.C., Sayer, M.W., Pinterm, J.D. and Gleanson, M. (1990), "Crosswind sensitivity of passenger cars and the influence of chassis and aerodynamic properties on driver preferences", *Vehicle Syst. Dyn.*, **19**(4), 202-236.

Maruyama, Y. and Yamazaki, F. (2006), "Driving simulator experiment on the moving stability of an automobile under strong crosswind", *J. Wind Eng. Ind. Aerod.*, **94**(4), 191-205.

Mechanical Simulation Corporation (2007), *CarSim User manual*.

Papesch, A.J.G. (1992), "Wind tunnel tests to optimize barrier spacing and porosity to reduce wind damage in horticultural shelter systems", *J. Wind Eng. Ind. Aerod.*, **44**(1-3), 2631-2642.

Ranga Raju, K.G., Garde, R.J., Singh, S.K. and Singh, N. (1988), "Experimental study on characteristics of flow past porous fences", *J.Wind Eng. Ind. Aerod.*, **29**(1-3), 155-163.

Saito, H., Suzuki, M. and Tanemoto, M. (2006), "Effects of wind fences on aerodynamic characteristics of train/vehicles in cross winds", *Proceedings of the APCWE6*, Seoul, Korea, September.

Smith, B.W. and Barker, C.P. (1998), "Design of wind screens to bridges, experience and application on major bridges", *Proceedings of the International Symposium on Advances in Bridge Aerodynamics*, Copenhagen, Denmark, May.

Sorgats, U. (1976), "Simulation of directional behavior of road vehicles", *Vehicle Syst. Dyn.*, **5**(1-2), 47-66.

Wang, D.L., Chen, A.R. and Pang, J.B. (2005), "Wind speed criteria of driving safety of vehicles on cablestayed bridges", *Proceedings of the Sixth Asia-Pacific Conference on Wind Engineering*, Seoul, Korea, September.

Wyatt, T.A. (1992), "Recent British developments: Wind shielding of bridges for traffic", *Proceedings of the First International Symposium*, Copenhagen, Denmark, February.

Xu, Y.L. and Guo, W.H. (2003), "Dynamic behavior of high-sided road vehicles subject to a sudden crosswind gust", *Wind Struct*., **6**(5), 325-346.

CC