

Peak pressure effects on a high-rise building influenced by a mid-rise building

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ABSTRACT: Pressure measurements on the surfaces of a high-rise building model with height $h = 0.48$ m and width $b = 0.12$ m were performed in a boundary layer wind tunnel. Experiments were carried out for an isolated model and for three configurations with an interfering half-height building model. The effects of the interfering building to the minimum peak pressures on the reference model were determined. The influence of the separation distance and the shape of the interfering building (square and circular plan form) were investigated. For the smallest separation distance, $S = 0.5b$, the composition of the minimum peak pressures was studied in more detail by assessment of the mean and standard deviation pressure coefficient. This study shows that the magnitude of local minimum peak pressure increases with approximately 25-35% on two facades of the high-rise model. In the top corner of the façade on the side a reduction is observed of 20-40%, depending on the shape of the interfering model.

KEYWORDS: Wind interference, peak pressures, high-rise, mid-rise

1 INTRODUCTION

Wind loads on buildings can be influenced by the presence of nearby buildings. This influence can change the global loads on the interfering buildings, as well as the local loads on their building envelopes. Research on the influence of interference can be grouped in (1) studies on global loads and (2) studies on local loads. According to this categorization, Table 1 provides an overview of previously performed parametric wind tunnel studies on interference between high-rise buildings.

Studies on static global wind loads, performed by e.g. Taniike (1992) and Khanduri (1997), found that the influence of an interfering model with similar or larger height than the reference model can lead to an increase of 70-80%. Khanduri (1997) determined that the influence on the static wind load can be neglected if the interfering building is smaller than $\frac{3}{4}$ of the reference building height.

Even larger effects were found for dynamic global wind loads. Bailey and Kwok (1985) and Taniike and Inaoka (1988) found an increase in the dynamic base bending moment of respectively 440%, and 2000% for the case of a slender interfering model. Xie and Gu (2004, 2005 and 2007) performed an extensive wind tunnel study on two and three high-rise configurations. They derived a set of simplified guidelines and formulae to provide designers with tools to obtain an estimate for the influence of interference on the static and dynamic base-bending moment. According to these guidelines, an interfering building smaller than half the height of the reference building has no significant influence on the dynamic base-bending moment.

Table 1. Overview of previously performed parametric wind tunnel studies on wind load effects due to interference between high-rise buildings.

Literature source	Reference model dimensions	Flow properties at reference model height	Type of load	Type of statistic	Studied influence parameters
	$b \times d \times h$ [m]	I_u [-]	U_{ref} [m/s]	[-]	[-]
Bailey and Kwok (1985)	0.06x0.06x0.54	Not reported	Not reported	Global dynamic base moment	Std - Interfering model shape - Terrain roughness
Taniike and Inaoka (1988); Taniike (1991)	0.07x0.07x0.32	0, 0.12	1.6 – 10	Global dynamic base moment	Std - Interfering model width and depth - Terrain roughness
Xie and Gu (2004, 2005, 2007)	0.1x0.1x0.6	0.05, 0.08	Not reported	Global static & dynamic base moment	Std - Interfering model width, depth and height - Number of buildings - Terrain roughness
Taniike (1992)	0.07x0.07x0.32	0	6	Global static force	Mean/Std Interfering model width and depth
Khanduri (1997)	0.05x0.05x0.20	0.07, 0.13, 0.25	Not reported	Global static force	Mean/Std - Interfering model width and depth - Terrain roughness - Angle of incidence
Kim et al (2011)	0.07x0.07x0.28	0.2	8.2	Local static pressure	Peak - Interfering model height - Angle of incidence

Few comprehensive studies were performed on the interference effects between tall buildings with a focus on local loads. Kim et al (2011) did perform such an extensive parametric wind tunnel study. One of the configurations they tested was a high-rise reference model under influence of a half-height model. Kim et al (2011) concluded that, in urban terrain conditions ($z_0 \approx 1.4$ m), an interfering model with half the height of the reference model has limited influence on the peak pressure coefficients. Bronkhorst et al (2011) performed an analysis on the mean and standard deviation pressure distribution for the same case in suburban terrain conditions ($z_0 \approx 0.8$ m). Three pressure effects resulting from interference were determined:

1. An increase on the faces in the passage for wind parallel to the passage.
2. An increase on the side faces of the reference model at roof height of the half-height interfering model for wind parallel to the configuration.
3. A reduction in the top corner of both side faces for wind parallel to the configuration.

This study investigates the magnitude of these effects when minimum peak pressures are considered. The goals of the study presented in this paper are:

- To determine local peak pressure effects resulting from interference between a high-rise building model and a half-height interfering model.
- To investigate the influence of the separation distance, the shape of the interfering model and the angle of incidence on the peak pressure effects.
- To gain understanding on the composition of these peak pressure effects by assessment of the mean and standard deviation pressure coefficient.

2 MATERIALS AND METHODS

Wind tunnel experiments were carried out in the open circuit atmospheric boundary layer (ABL) wind tunnel of TNO in the Netherlands. Measurements were performed on the isolated configuration and on three tandem configurations as illustrated in Figure 1(a). A detailed description of the experimental set-up can be found in Bronkhorst et al (2011). Both the influence of an interfering half-height model with square and with a half-height model with circular ground plan were investigated. Measurements were performed for twenty-four angles of incidence in 15° increments, for each configuration. The reference model pressure taps were distributed as illustrated in Figure 1(b), with 38 pressure taps on each face. Taps are designated by face F (which can be A , B or C), row (i) and column (j). For example, the pressure tap on face A , in the second row and the fifth column is specified as $A25$; the minimum peak pressure coefficient determined at this position is specified as $C_{p,min}(A25, \theta)$.

The fluctuating pressures acting at the pressure taps were measured with a sampling rate of 400 Hz for a period of approximately 20.5 seconds. The undisturbed static and dynamic pressure were measured with a pitot-static tube positioned at model roof height ($h = 0.48$ m), 2.6 m in front of the model and 0.7 m to the side. The mean velocity at this height (U_{ref}) for all tests was approximately 14.1 m/s, which corresponds with a width-based Reynolds number of $Re_b = U_{ref}b/\nu \approx 1.1 \times 10^5$. The instantaneous static reference pressure, $p_{ref}(t)$, was measured at a pressure tap in the left side wall at 1.2 m height, at the same longitudinal position as the instrumented reference model.

The measured pressure time series were converted to pressure coefficients with:

$$C_p(t) = \frac{p_s(t) - p_{ref}(t)}{q_{ref}} = \frac{p_s(t) - p_{ref}(t)}{\frac{1}{2} \rho U_{ref}^2} \quad [1]$$

In which $p_s(t)$ is the instantaneous static pressure measured at the pressure taps, q_{ref} is the mean dynamic pressure measured at the pitot-static tube, and ρ is the air density.

The pressure coefficient time series were divided in thirty-two intervals of $t = 0.64$ s. For each interval, the mean, the standard deviation, and the minimum negative peak pressure coefficient were determined. The averages of each of these statistics over the thirty-two intervals are presented in the next paragraph.

Pressure coefficients have a magnitude and a sign. The magnitude (i.e. the absolute value) of the pressure coefficient is specified as large or small or showing an increase or decrease; the sign is negative or positive.

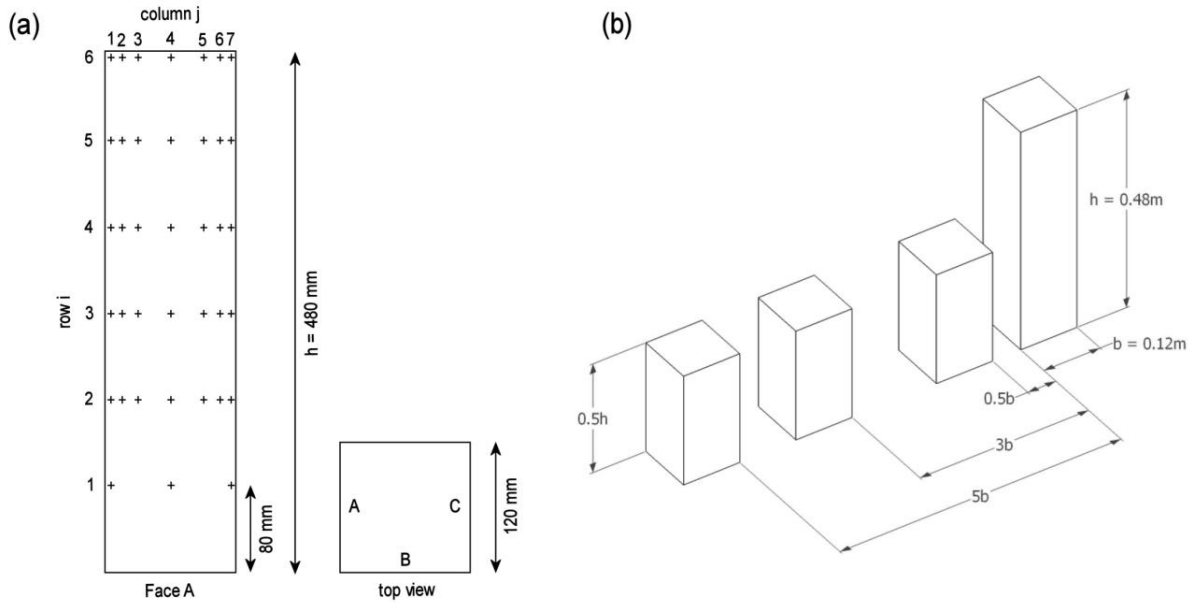


Figure 1. (a) Pressure tap distribution on the faces A , B and C of the instrumented building model, (b) the tandem configurations measured in the wind tunnel illustrated with the square half-height interfering model.

3 RESULTS AND DISCUSSION

This chapter gives results for the minimum peak pressure coefficient, and the mean and standard deviation pressure coefficient. First the overall effects are determined through investigation of the minimum peak pressure coefficients over all angles of incidence, the largest effects are investigated in more detail.

At each tap position, the minimum of the negative peak pressure coefficients over all angles of incidence $C_{p,min}(Fij,all)$ was determined. Figure 2 shows contour plots of the minimum peak pressure coefficient over all angles of incidence. The contour plots provide information on the location and the magnitude of the peak pressure effects which are a result of interference. The influence of the interfering half-height square cylinder is illustrated on the left-hand side; the influence of the circular cylinder is illustrated on the right. The pressure distributions on the model faces in the isolated case are plotted in the centre of the figure. The smallest minimum peak pressure coefficient for the isolated case, $C_{p,min}(F14,all) \approx -1.5$, is found in the middle of the model face, near the ground. The largest minimum peak pressure coefficients $C_{p,min}(F61,all) \approx C_{p,min}(F67,all) \approx -2.4$ are observed in the top corners.

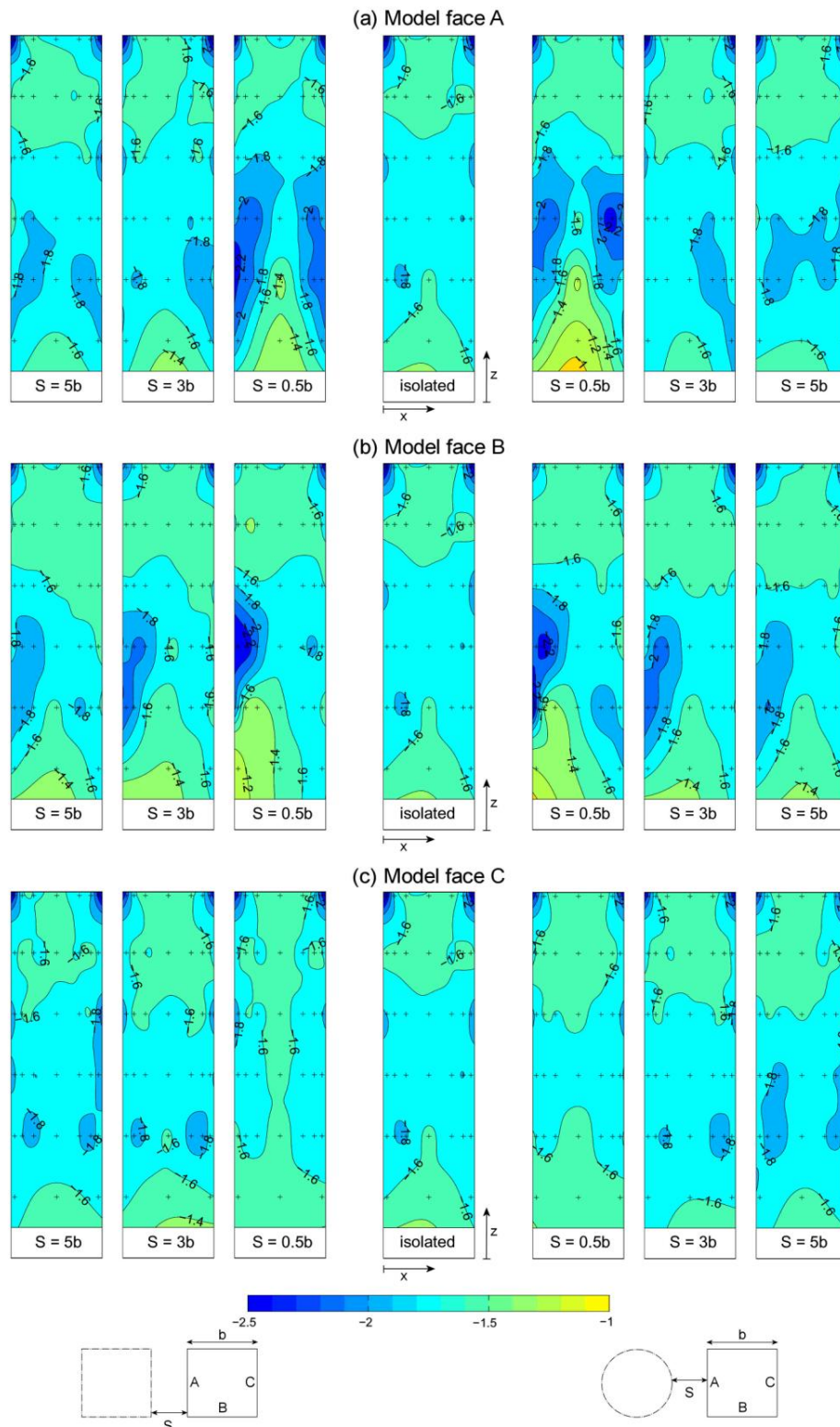


Figure 2. Contours of the minimum peak pressure coefficients over all angles of incidence, $C_{p,min}(F_{ij},all)$, on (a) face A, (b) face B and (c) face C of the reference model under influence of a square (left) and circular (right) mid-rise building. The contours of the isolated case are illustrated in the centre.

Table 2. Pressure coefficient values for the specified taps in Figure 2. For each position the minimum peak pressure coefficient over all wind directions are provided.

	<i>isolated</i>	<i>S = 0.5b</i>		<i>S = 3b</i>		<i>S = 5b</i>	
		<i>square</i>	<i>circle</i>	<i>square</i>	<i>circle</i>	<i>square</i>	<i>circle</i>
$C_{p,min}(A32,all)$	-1.7	-2.1	-2.1	-1.7	-1.8	-1.8	-1.8
$C_{p,min}(A21,all)$	-1.8	-2.2	-1.9	-1.7	-1.7	-1.8	-1.8
$C_{p,min}(B61,all)$	-2.4	-1.7	-2.0	-1.9	-2.1	-2.1	-2.2
$C_{p,min}(B32,all)$	-1.7	-2.3	-2.3	-2.0	-2.0	-1.9	-1.9

Figure 2(a) shows the influence of the half-height models on the minimum peak pressure distribution of face *A* with increasing separation distance (*S*). The largest interference effects on the minimum peak pressure are observed at taps *A32*, *A36*, *A21* and *A27*. At tap *A32* for a separation distance $S = 0.5b$, both square and circular interfering model increase the magnitude of the minimum peak pressure with approximately 25%. Table 2 shows that the square interfering model has a similar effect at tap *A21*. For $S = 3b$ and $5b$, these effects have disappeared, suggesting that the influence of the half-height interfering models on face *A* is only present for a separation distance smaller than at most three times the model width ($S < 3b$).

Figure 2(b) shows the influence of the interfering models on face *B*; the largest adverse effects are observed on the side of face *B* nearest to the interfering model (tap *B32*). At half the height of the reference model, the square and circular interfering models increase the minimum peak pressure coefficient with 25% and 35%. At a separation distance of $3b$ these effects have reduced to approximately 10%; at $S = 5b$ the influence has become negligible. Besides adverse pressure effects, the interfering models also have a positive effect on the local peak pressures. At the top corner near the front edge, tap *B61*, both square and circular interfering model increase the minimum peak pressure coefficient. The square interfering model increases the coefficient with 30%; the circular model results in a 15% increase.

The minimum peak pressure coefficient distributions on model face *C*, illustrated in figure 2(c), show little variation. Both square and circular interfering models have maximum effects which differ only 5% from the minimum peak pressures encountered in the isolated case. These effects are not nearly as large as the effects found on face *A* and *B*. Figure 2 and Table 2 show that the largest pressure effects are found at a separation distance $S = 0.5b$. Further discussion of the results focuses on the pressure effects observed on face *A* and *B* at $S = 0.5b$.

Figure 3 shows graphs of the mean (top graph), standard deviation (middle graph) and minimum peak pressure coefficient (bottom graph) versus angle of incidence for taps *A32*, *A21*, *B61* and *B32*. The graphs in Figure 3(a) show the influence of both a square and circular model ($S = 0.5b$) at pressure tap *A32*. For the isolated case, the largest value is -1.7, which is observed at $\theta = 75^\circ$ and $\theta = 90^\circ$. Both square and circular interfering models increase this minimum peak pressure coefficient to $C_{p,min}(A32,90^\circ) = -2.1$. At this angle of incidence ($\theta = 90^\circ$), the mean and standard deviation pressure coefficient show an increase of approximately 30% and 20%. Therefore, the amplification of the minimum peak pressure coefficient results from an increase in mean suction as well as an intensification of the fluctuations in the pressure signal. At pressure tap *A21*, illustrated in Figure 3(b), the square interfering model has a larger influence than the circular model over a large range of angle of incidence ($\theta = 45^\circ$ - 135°). The largest effect caused by the square interfering model is observed at $\theta = 90^\circ$ ($C_{p,min}(A21,90^\circ) = -2.2$). The circular interfering model has no large influence on the minimum peak pressure coefficient at this location, which indicates the square interfering model has a larger area of influence than the circular model on face *A* of the reference model.

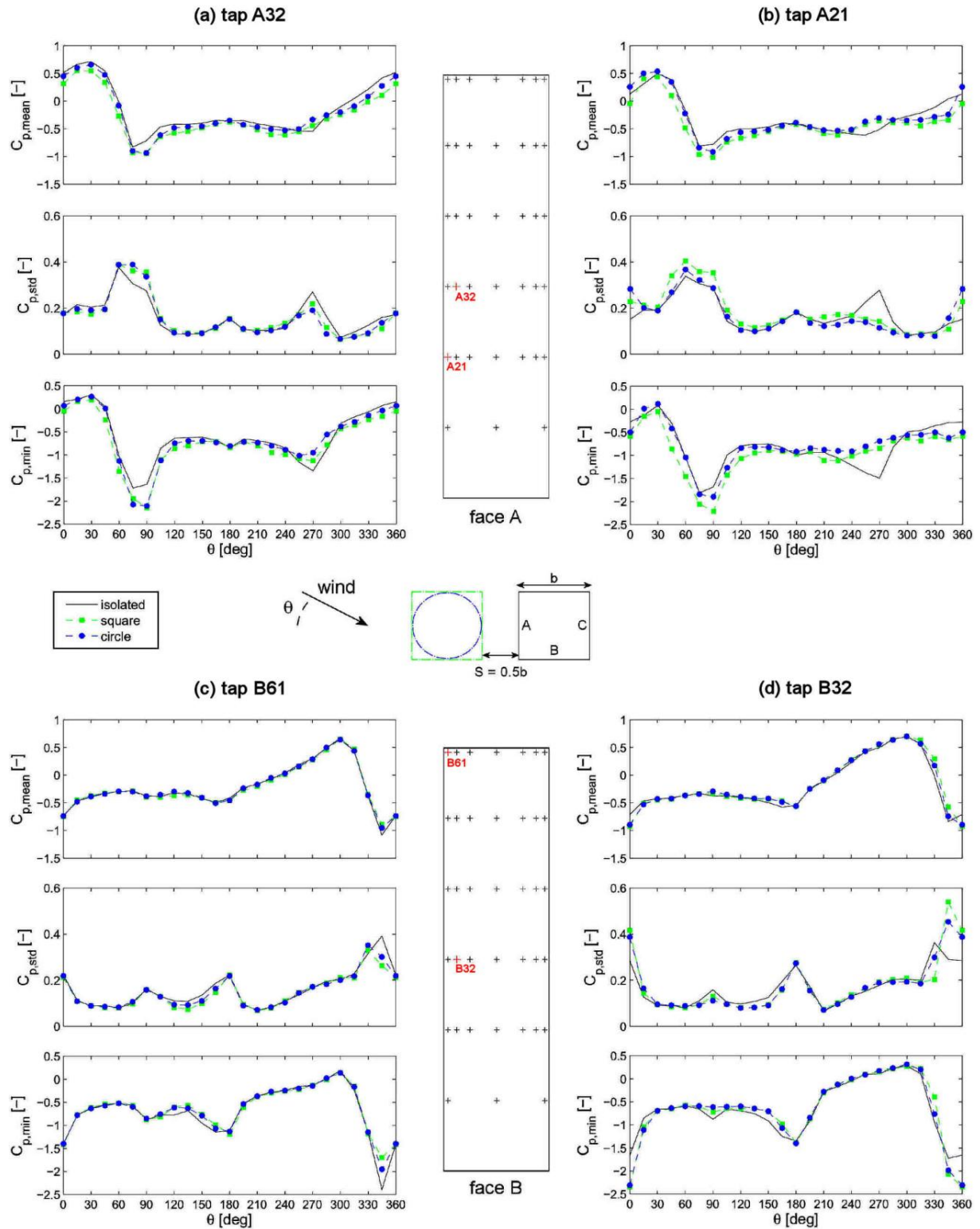


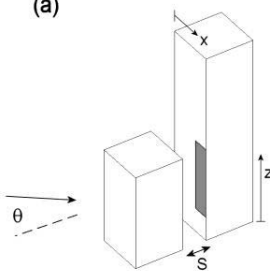
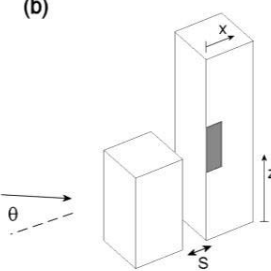
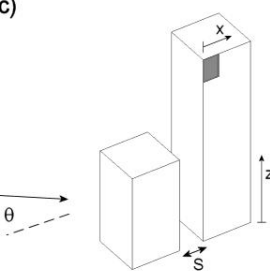
Figure 3. Variation of mean, standard deviation and minimum peak pressure coefficient with angle of incidence at the indicated taps on face A (a) tap A32 and (b) tap A21 and on face B (c) tap B61 and (d) tap B32.

The variation of the pressure coefficient with angle of incidence on face B at tap B61 and B32 is illustrated in Figure 3(c) and (d). Figure 3(c) shows that the decrease in minimum peak pressure observed in Figure 2(b) at tap B61 is found at $\theta = 345^\circ$. In the isolated case, the peak pressure coefficient at this angle of incidence is $C_{p,min}(B61, 345^\circ) = -2.4$. The interfering models reduce this coefficient with 15% (circular cylinder) or 30% (square cylinder). This alleviation effect is mainly caused by a reduction in pressure fluctuations; the interfering model reduces the standard deviation pressure coefficient with 30%, whereas the drop in mean coefficient is 10%.

The results determined for tap B32 are illustrated in Figure 3(d); they show an increase in minimum peak suction coefficient of 25% and 30% at an angle of incidence of 0° for the square and the circular interfering model. The largest intensities in pressure fluctuations are observed at an angle of incidence of 345° ; the square interfering model causes an increase of 90% ($C_{p,std}(B32, 345^\circ) = 0.55$) and the circular model an increase of 60% ($C_{p,std}(B32, 345^\circ) = 0.47$). The reduction in mean pressure coefficient is responsible for the smaller minimum peak pressure coefficient at this angle in comparison with the coefficient observed at 0° .

Table 3 gives a summary of the largest minimum peak pressure effects encountered on face A and B, and specifies in which ranges of the investigated influence parameters (S and θ) these effects are most severe. The grey areas specified in the figures are indicative for the region of influence. The pressure effect on face A, illustrated in Table 3(a), was also described by Kim et al (2011) and Lam et al (2008). According to these studies, this pressure effect is the result of an increase in velocity through the passage, which is known as channeling. The adverse pressure effect on face B, illustrated in Table 3(b), is most likely caused by the shear layer separating from the roof of the interfering model. Although the largest peak value is observed at $\theta = 0^\circ$, the largest intensity in pressure fluctuations is observed at $\theta = 345^\circ$. At the same angle of incidence, a reduction is observed in the top corner of face B, illustrated in Table 3(c). The pressure effects illustrated in Table 3(b) and (c) appear to be related. Future spectral analysis of the pressure signals and analysis of the velocity field can provide more support for this observation.

Table 3. Summary of the investigated influence parameters and the pressure effects described on face A and face B.

	(a)	(b)	(c)
			
Separation distance (S) ⁽¹⁾	$S < 3b$	$S < 5b$	$S < 5b$
Angle of incidence (θ) ⁽²⁾	75° - 90° and 270° - 285° ^(*)	0° - 15° and 345° - 0° ^(*)	15° and 345° ^(*)
Location largest peak effect			
Square cylinder	$(x, z) = (0.04b; 0.3h)$	$(x, z) = (0.12b; 0.5h)$	$(x, z) = (0.04b; h)$
Circular cylinder	$(x, z) = (0.12b; 0.5h)$	$(x, z) = (0.12b; 0.5h)$	$(x, z) = (0.04b; h)$
Largest minimum peak pressure			
Square cylinder (isolated)	-2.2 (-1.8)	-2.3 (-1.7)	-1.7 (-2.4)
Circular cylinder (isolated)	-2.1 (-1.7)	-2.3 (-1.7)	-2.0 (-2.4)

⁽¹⁾ The specified range in separation distance indicates a region of influence on the reference building in which the influence of the interfering model on the minimum peak pressure is larger than 10% when all angles of incidence are considered.

⁽²⁾ The specified value gives the angle of incidence at which the largest peak suction was determined.

^(*) The region of influence at this angle of incidence is illustrated; the same effect occurs on the opposite side or face at the other specified angle.

4 CONCLUSION

Wind tunnel experiments were performed to determine the interference effects of a half high model on the pressure distribution of a nearby high-rise building model. Mean, standard deviation and peak pressure coefficients were analysed. The main findings are the following:

- For a half high interfering model, local increases in the magnitude of the minimum peak pressure were found on face *A* and face *B* (for definitions, see figure 3).
- Both square and circular interfering model cause a maximum increase of the minimum peak pressure $C_{p,min}(Fij,all)$ (i.e. the minimum over all angles of incidence) of 25% on face *A* and 35% on face *B*, for the investigated configurations.
- The pressure effects on face *A* and face *B* were most pronounced for a separation distance $S = 0.5b$. For $S = 3b$, the interfering model has no significant influence on the pressure distribution of face *A*; the effects on face *B*, although less severe, are still significant for $S = 5b$.
- The effects on face *A* occurred at an angle of incidence of 75° and 90° , i.e. for a wind approximately parallel to the building passage. The interference effects observed in the pressure distribution of face *B* were encountered at an angle of incidence of 345° and 0° .

This work has analyzed the influence of a half high model on the wind-induced local pressures on a high-rise model in terms of three main interference effects and it has established two model configurations in which large adverse pressure effects occur.

The study presented in this paper did not yet define cause-effect relationships between flow phenomena and pressure effects. The definition of such relationships requires more detailed analysis of the measured pressures (e.g. spectral analysis) and further investigation of the flow surrounding the models. Future research will entail more detailed analysis of the measured pressures in the critical configurations; additional experimental and numerical work will be carried out.

5 UNITS

b	Width of the reference model (m)
$C_{p,mean}(Fij,\theta)$	Mean pressure coefficient on face F (<i>A</i> , <i>B</i> or <i>C</i>) at pressure tap <i>i, j</i> for angle of incidence θ (-)
$C_{p,std}(Fij,\theta)$	Standard deviation pressure coefficient on face F (<i>A</i> , <i>B</i> or <i>C</i>) at pressure tap <i>i, j</i> for angle of incidence θ (-)
$C_{p,min}(Fij,\theta)$	Minimum peak pressure coefficient on face F (<i>A</i> , <i>B</i> or <i>C</i>) at pressure tap <i>i, j</i> for angle of incidence θ (-)
h	Height of the reference model (m)
S	Separation distance between the wind tunnel models (m)
U_{ref}	Mean velocity at reference model height (m/s)
θ	Angle of incidence
ρ	Air density (kg/m^3)

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