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RÉSUMÉ

On a observé pendant plusieurs années les accélérations produites lors de vents modérés à forts au "Commerce Court Tower" de Toronto, au Canada, ainsi que l'effet de torsion aux étages supérieurs du bâtiment. Les observations sur place et sur modèle de la déviation normale de l'accélération correspondent pour la plupart des directions du vent. Les implications des résultats de cette étude pour la conception des structures au moyen d'essais en soufflerie ou d'une méthode de calcul basée sur le Code, sont examinées.

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COMPARISON OF MODEL AND FULL-SCALE ACCELERATIONS OF A HIGH-RISE BUILDING

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SUMMARY

Several years of observations of accelerations during moderate to high wind at the Commerce Court Tower in Toronto, Canada, are presented and the effect of torsion in the upper stories is shown. Model and full-scale observations of the standard deviation of acceleration correlate well for most wind directions. Implications for structural design using wind tunnel tests or a Code-based calculation method are discussed.

NOTATION

a	exponent for wind pressure profile (= 0.72 for city terrain)
a_D	standard deviation of along-wind acceleration, milli-g
a_W	standard deviation of across-wind acceleration, milli-g
C_e	exposure factor for wind pressure (= $0.0436H^{0.72}$ for city terrain)
D	along-wind building dimension, m
F	gust spectral energy ratio (= $x_o^2/[1 + x_o^2]^{4/3}$)
g	acceleration due to gravity (= 9.81 ms^{-2})
H	height of building, m
K	coefficient related to surface roughness (= 0.14 for city terrain)
n_i	fundamental translational frequencies of building, where i = D for along-wind, and W for across-wind directions, hz
s	size reduction factor (= $\frac{\pi}{3}/[1+8n_DH/3V_H]/[1+10n_DW/V_H]$)
V_H	wind speed at top of building, ms^{-1}
W	across-wind building dimension, m
x_o	reduced frequency for spectral calculations (= $1220n_D/V_H$)
β_i	fraction of critical damping corresponding to n_i
ρ_i	mass density, where i = A for air, B for building, kgm^{-3}

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1. INTRODUCTION

Wind engineers need assurance that design predictions of high-rise building accelerations are soundly based. Experience and preliminary calculations using analytical procedures guide the designer in deciding when to perform an aeroelastic model study, but the only way to calibrate experience, calculation methods and the aeroelastic modeling process itself, is through feedback from measurements on real buildings.

Commerce Court West, a 57-storey office tower designed with the aid of a wind tunnel study [ref.1], was instrumented to record various wind effects from 1974 until the fall of 1980. Model and full-scale comparisons of mean and peak surface pressures and displacements have been reported [ref.2-5]. Although acceleration measurements were started in March 1975 it was only after interesting discoveries about the role of torsion were made with a new multi-degree-of-freedom wind tunnel model [ref.6,7] that the full-scale records were re-examined for confirmation of this behaviour.

As accelerations are more closely related to occupant comfort criteria than deflections and are more sensitive to the effects of torsion, the designer faced with serviceability requirements needs to know what reliance can be placed on his principal sources of information. The object of this paper is to make such an assessment, both for an aeroelastic model with torsional degrees of freedom and for an analytical method supplied for use with the National Building Code of Canada [ref.8].

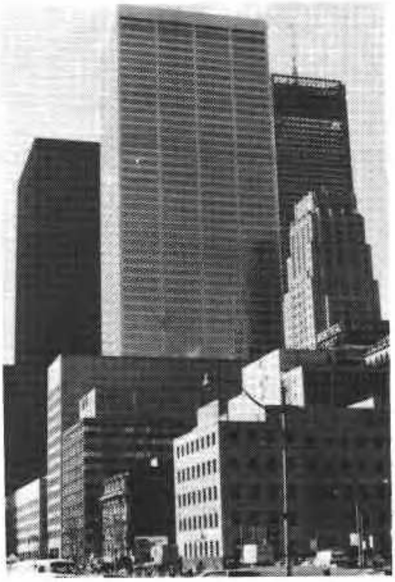
2. WIND ENGINEERING STUDY AT COMMERCE COURT WEST

2.1 The Building

Exposure. The steel frame structure, 36.5 m by 69.7 m in plan and 239 m tall, is sheltered from southwest to northwest by buildings from 175 m to 285 m tall (fig.1), and a half-kilometre wide strip of tall buildings stretches several kilometres to the north. Lake Ontario lies 1 km to the south, and the exposure is unobstructed "urban" terrain to the east.

Structure. Cladding and partitions were designed to allow movement with respect to the frame, which deflects mainly by shearing of adjacent floors (concrete) with little column shortening. The column layout is not symmetrical; consequently, although the centre of mass tends to be near the geometric centre, the elastic axis is generally about 5 m to the south, along the long axis of the building (fig.2).

The East-West (E-W) modes of the model building appear as closely spaced pairs due to inertial coupling between translation and torsion. The lower frequency member of each pair of E-W modes is mainly translation with a smaller, in-phase, torsional component and has almost the same frequency as



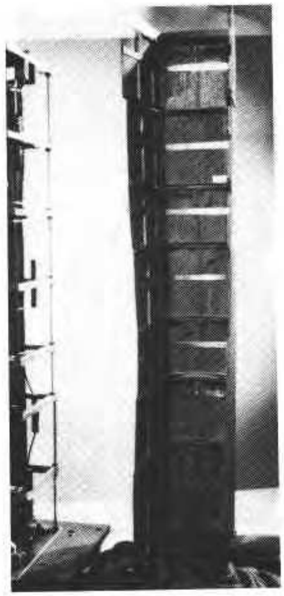


Fig. 1. Commerce Court West, viewed from E-S-E (about 200 degrees).

Fig. 3. Aeroelastic model of Commerce Court West with balsa-wood cover removed.

the equivalent first North-South (N-S) mode, which is uncoupled. The higher frequency member is primarily torsion with a smaller, out-of-phase translational component. The ratios of successive translational modes are approximately 1:3:5, indicating that the structure deforms primarily in shear.

The field study revealed that the natural frequencies of the building had a marked tendency to decrease as wind speed increased (Table 1), a behaviour not observed for the wind tunnel model.

TABLE 1

Variation of full-scale building frequencies with wind speed.

Wind speed (m/s)	Mode Identification, frequencies in hz $E\text{-}W_1$	$E\text{-}W_2$	$N\text{-}S_1$
7.0	.137	.184	.137
14.0	.133	.172	.131
15.0	.129	.172	.129
18.8	.129	.170	.129
26.1	.125	.164	.119
30.2	.125	.164	.121

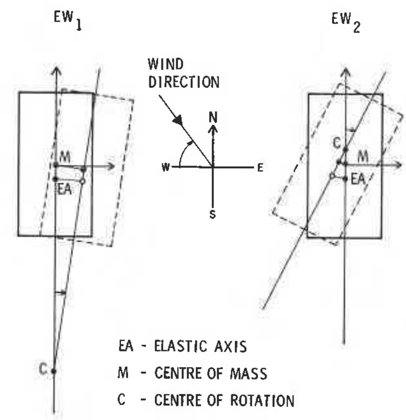


Fig. 2. Tip modal deflections for first two coupled modes (positive deflection east and north; positive rotation clockwise).

2.2 Field Data Acquisition

Reference speed. A three cup anemometer on a mast at 286 m above the street provides the reference speed. When the wind direction is 104 degrees (building west = 0) the cups are 9 pipe diameters downstream of the supporting 180 mm circular pipe, so a correction of the corresponding dynamic pressure was applied, varying from 0 to 40 per cent to 0 in the range 78 to 120 degrees.

Data collection. Two types of records were kept: summary data for either 5- or 10-minute averaging periods, and continuous time series whenever the reference wind speed exceeded 18 m/s mean value. Summary data consisted of the arithmetic mean, standard deviation, minimum and maximum for each sensor, computed on line from digitally sampled records. The sampling rate was 20 per second, and during high winds, time series consisting of every tenth data point were recorded as well.

When the field study began, summary data comprised two 5-minute periods from each hour of operation; the one with the highest reference wind speed (from the anemometer at the 286 m height) and the last one. Then in May 1979 a change was made to 10-minute averaging times and all six from each hour of operation were recorded. Most of the data reported herein were recorded from September 1978 to September 1980, when the field experiment was terminated. Some 70 per cent of the 4000 summary items having reference speeds over 12.5 m/s (corresponding to a dynamic pressure of 100 Pa) from that period were selected for discussion in this paper. They give reasonable coverage of 16 out of 36 10-degree wind direction segments. About 100 items were added from earlier, and in some cases less reliable, records either because they had exceptionally high winds or because the main data set had no information about a particular direction. The supplementary items also contain a few data points with averaging times of 35 minutes.

Each item consists of the dynamic reference pressure at 286 m and the standard deviations of three accelerations measured on the 50th floor, at a height of 202 m. Two are E-W accelerations, at the south end wall and the north end wall, and the third is the N-S acceleration, measured at the middle of the north end wall. All accelerations are reported as milli-g (m-g) or g x 10^{-3}, where g is the acceleration due to gravity.

2.3 The Model

The design and performance of the model is dealt with in ref. 5 and will only be briefly described here. Seven mass levels joined by corner columns provided 21 degrees of freedom and a segmented balsa-wood cover gave the aerodynamic shape of the 1:200 scale aeroelastic model (fig. 3). Fifteen sensors monitored three displacements, three strains, and nine accelerations. No attempt was made to represent the variation in natural frequencies with increasing wind speed. A velocity scaling ratio of 1:3.55, and a frequency scaling of 1:56 were used, based on full scale frequencies at 24 m/s. Structural damping in the model was 1 per cent of critical.

Model calibration. The model was designed using the structural properties provided by the building designers, adjusted to match the measured frequencies at 24 m/s. The accuracy of its simulation of the full-scale structure was determined through a detailed evaluation of the model's dynamic characteristics, including frequency, mode shape and damping [ref.6,7]. Examples are shown in Table 2.

TABLE 2

Comparison of model and full-scale frequencies and damping (model values converted to full-scale equivalent).

	$N\text{-}S_1$	$E\text{-}W_1$	$E\text{-}W_2$	$N\text{-}S_2$	$E\text{-}W_3$	$E\text{-}W_4$	Damping Ratio (wind "on")
Full Scale[a]	.119	.125	.170	.350	.391	.488	.03-.04
Model	.122	.124	.168	.347	.333	.453	.02-.03

[a]From a full-scale record with reference speed of 26 m/s.

3. CODE-BASED PREDICTIONS OF DYNAMIC BEHAVIOUR

The Supplement to the National Building Code of Canada [ref.8] gives as part of a detailed method for calculating gust effect factors for high-rise buildings, equations for predicting peak accelerations in the along-wind and across-wind directions. With the peak factor deleted, they predict standard deviation of acceleration. For wind direction normal to one face, the along-wind acceleration in milli-g is:

$$a_D = 10^3(0.5V_H^2/[gD])(\rho_A/\rho_B)(3.9/[2+a])\sqrt{KsF/[C_e\beta_D]} \quad (1)$$

The across-wind acceleration in milli-g is:

$$a_W = 6.2(V_H/[n_W\sqrt{WD}])^{3.3}(n_W^2\ WD/g)(\rho_A/\rho_B)/\sqrt{\beta_W} \quad (2)$$

Equations 1 and 2 are based on equations 22 (p. 154) and 11 (p. 153) of reference 8, but their components have been rearranged to form non-dimensional groups. Although they summarize experience gathered mainly in the wind tunnel, the present study provides at least one instance for comparison with field data. In the figures to follow, four different curves based on the above equations (across-wind and along-wind for E-W and N-S) are provided along with model and full-scale data. The building dimensions used in the calculations are: H, 239 m; W and D, 36.5 m and 69.7 m, interchanged as required by wind direction. The densities of air and building used are: ρ_A, 1.29 kgm^{-3} and ρ_B, 148 kgm^{-3}. The frequency was allowed to vary with V_H in accordance with Table 1, and the damping used was .03, approximately midway between model and full scale observations (Table 2).

4. COMPARISONS OF CODE AND MODEL WITH FULL-SCALE ACCELERATIONS

Field and model data are compared in 48 plots of acceleration vs reference pressure, 3 for each of 16 wind directions. Figures 4, 5 and 6 are mainly west, north and east; as there was little field data for south winds, figure 7 shows south-westerly directions. The three plots for each direction compare E-W accelerations at the south and north walls and the N-S acceleration.

The field and wind tunnel data show larger E-W accelerations at the north wall, a torsional effect not present in the code-based curves. Nevertheless, both the analytical model and the aeroelastic wind tunnel model agree surprisingly well with the field data considering the uncertainties in reference speed for northerly directions, the variation of full-scale frequency not accounted for in the wind tunnel model, and the difference in observed damping values.

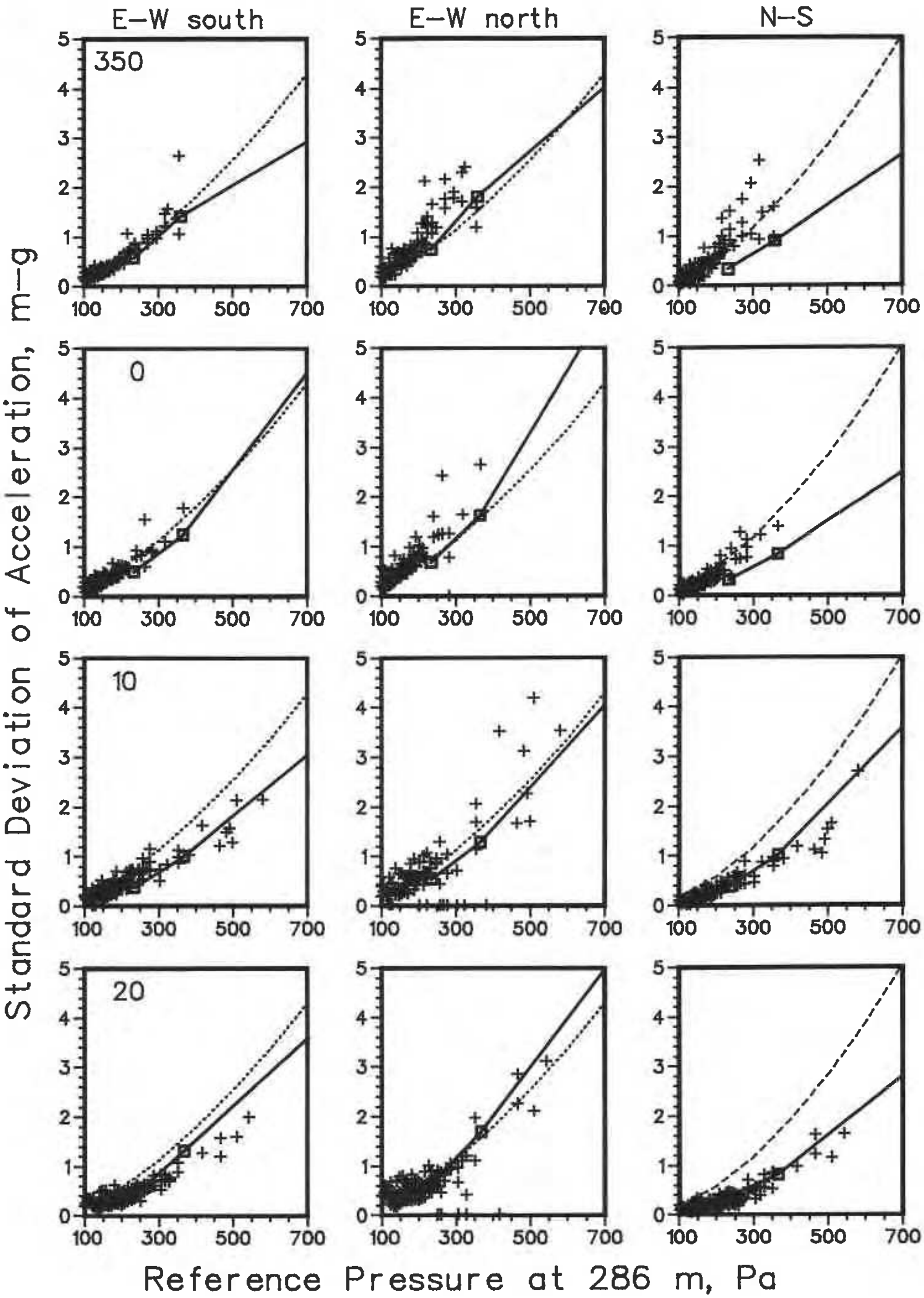


Fig. 4. Comparison of field data (+ main set, o supplementary data) with wind tunnel results (□) and calculations (‾...) for west to north-west winds.

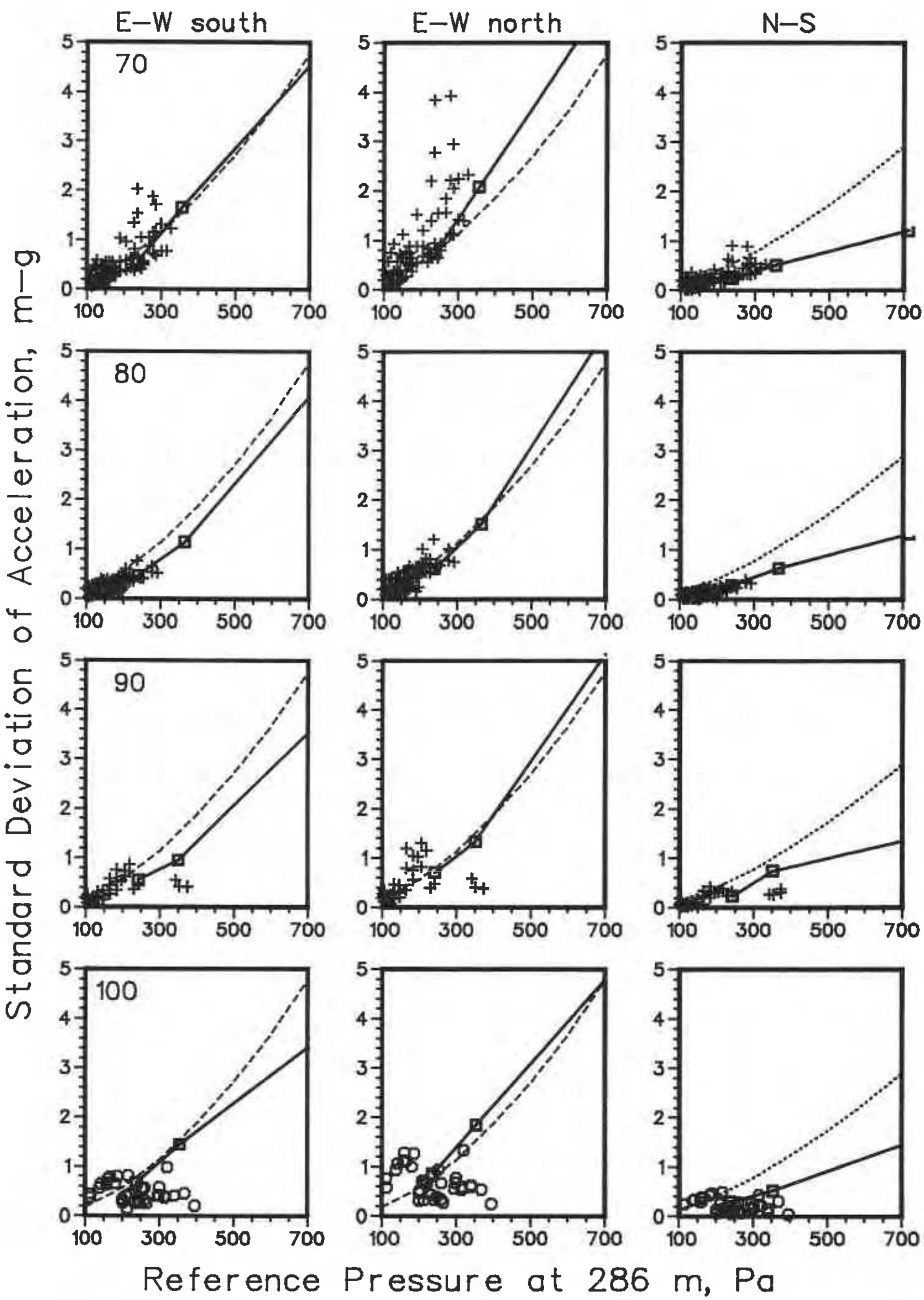


Fig. 5. Comparison of field data (+ main set, o supplementary data) with wind tunnel results (□) and calculations (⋯) for northerly winds.

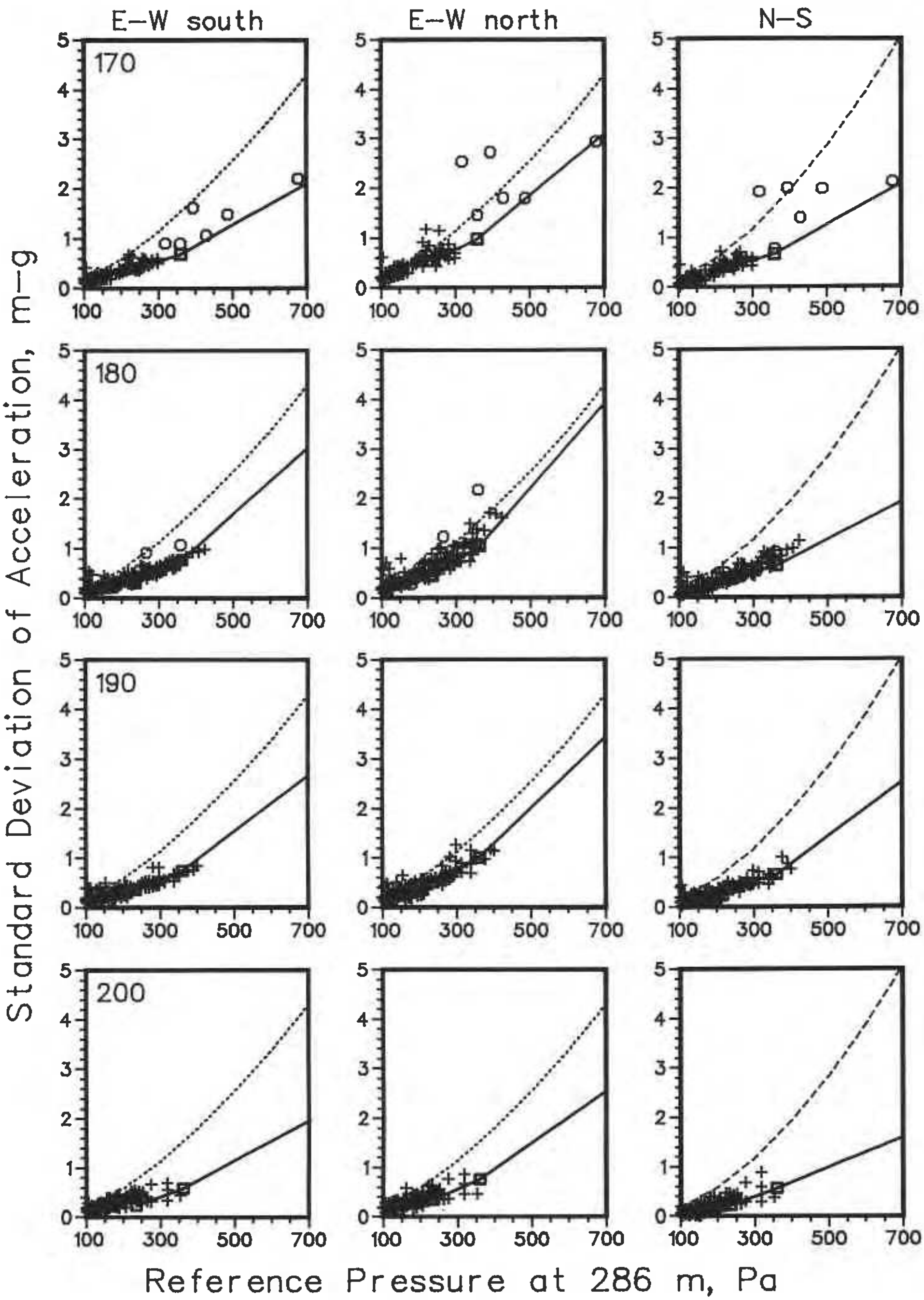


Fig. 6. Comparison of field data (+ main set, o supplementary data) with wind tunnel results (□) and calculations (...) for east winds.

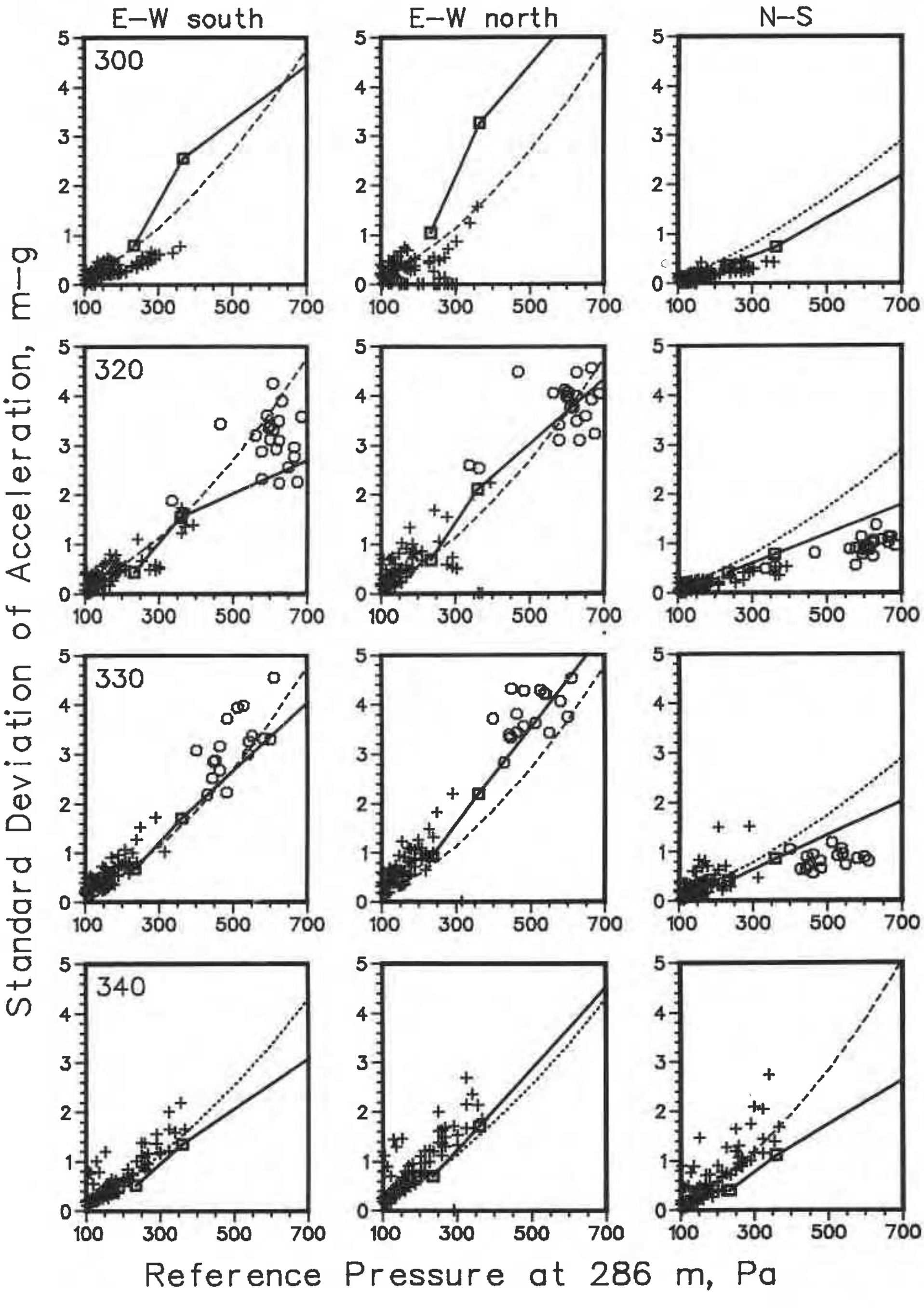


Fig. 7. Comparison of field data (+ main set, o supplementary data) with wind tunnel results (□) and calculations (‾‾‾) for south-west winds.

When the variation of frequency is taken into account, the analytical model predicts that across-wind and along-wind accelerations increase proportional to the 3.4 and the 3.2 powers of roof-height velocity respectively. Fitting power laws to the wind tunnel data gave an average exponent for all cases of 3.3, and the same was true for power law fits to field data sets so selected that the correlation coefficient for the fit was at least 0.5.

The largest deviation between field data and the models is shown for 70 degrees, not an unexpected result considering the large influence of a 285 m tall building to the north-west. Shown under construction in Fig. 1, it was completed before any of the data used in this study were gathered. There may be some effects of wake impingement from the taller building that were not correctly simulated in the wind tunnel.

Influence of torsion. On average, accelerations at the north end tend to be about 1.4 times those at the south end, for roof-height velocities of 20 to 30 m/s. This trend is clearly indicated by the results of the aeroelastic wind tunnel model and this example shows the value of, and necessity for considering torsion in design studies.

5. CONCLUSIONS

The Commerce Court experiments have provided a rare opportunity to examine the validity of analytical and wind tunnel predictions of building motion. The correlations found for accelerations are sufficient to build confidence in both as design tools; however, the inevitable scatter in field data sets practical limitations on the accuracy of such predictions. Two obvious sources of uncertainty are the selection of reference velocity and the specification of the dynamic characteristics of the building.

The importance of structural and aerodynamic asymmetries should be borne in mind while using the simpler analytical procedures. In practice, some allowance for such contingencies may be afforded by using recommended damping of only 1 per cent for steel frames. Such an allowance would be more than adequate for this particular building, for which the eccentricity is only about 7 per cent of the long dimension, but this would not always be the case. With continued work both in the laboratory and the field, one can look forward to a more consistent treatment of design predictions of tall building accelerations, and the development of checking equations able to deal explicitly with important effects such as torsion.

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