Human Response to Wind-Induced Motion of Buildings

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Some tall buildings sustain motions and other effects in intense wind storms which cause discomfort to the occupants. The results of surveys conducted of occupants of two buildings after several wind storms are given in detail. The writers propose a methodology and criterion format for rationally analyzing the wind-motion-discomfort problem for tall buildings. Finally, tentative motion criterion values, based primarily on the two occupant surveys presented, are proposed.

WIND-MOTION-DISCOMFORT PROBLEM

Motivation for Concern—For several decades the problem of wind-induced motions of tall buildings and the effect of such motions on building occupants has been recognized as a problem. In fact, an early reference to the concern for human comfort was made by the Structural Division ASCE Subcommittee No. 31 in 1931, when it stated in a list of recommendations:[5] "That structural frames be so designed as to ensure that deflections will be kept within such limits as to render buildings comfortably habitable." Even recently, Committee 442 of the American Concrete Institute stated:[10] "The reduction of such perceptible motion to acceptable levels thus becomes an important criterion in the design of any tall building."

However, there is almost no reference in the literature to specific buildings which cause discomfort to occupants. Chang, in a 1967 article, states that an estimated acceleration of 0.005 g in the Empire State Building is:[2] "somewhere between not perceptible and on the threshold of perceptibility; this conclusion is in line with the practical experiences of the occupants of the building." But this quote is relative to motion perceptibility. Jacob Feld lists the more significant issue in referring to a problem with one 55-story

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tower in New York City, stating that:[6] ". . .the building itself takes on some disturbing oscillations during northeast storms, enough to make it impossible to write at a desk located in the top few floors, so that employees are regularly excused during such storm period."

Additional evidence that some buildings exhibit motions so intense during wind storms that occupants are disturbed is offered by the writers.

The paramount issue to the building designer is the level of motion tolerance which building occupants will accept. In this context, it is important to distinguish between "threshold of perception" and "level of tolerance." Recently several studies,[3,7,8] using laboratory conditions, have been conducted to determine thresholds of perception. Although the results of these studies are important in gaining insight into the aspects of the problem, the results do not define *tolerance* levels.

It is difficult also to extrapolate from other moving environments. A person either working or living in a tall building views his environment relative to the "normal" situation; it is the "out of the ordinary" motion cues perceived on a stormy day that are important. Therefore, a moving building is different from a ship, an airplane, or other moving vehicle. The primary difference is that a building is not supposed to move.

TALL BUILDING HUMAN RESPONSE SURVEY

The writers are aware of a number of buildings in the United States that have motion characteristics which may be undesirable. They were fortunate enough to have the opportunity to study two of these buildings shortly after each had been subjected to separate wind storms. In each case the wind-induced motions, and other cues which disturb human beings, were of such intensity that a significant portion of the occupants of the upper floors of each building were disturbed.

Each building studied was of recent steel construction, each approximately 40 stories high—one constructed with a moment-resistant frame, the other with a tube-type structural system. Table 1 presents the other relevant data. Both buildings were designed by engineers of competence. Both buildings were responsive to the building codes of the cities in which they are located.

Table 1. Summary of Building Information

Statistic (1)	Building A (2)	Building B (3)
Height	~550 ft	~550 ft
Periods of vibration (1st mode)	EW 5.25 sec NS 5.90 sec Twist 5.35 sec	4.2 sec 4.2 sec 2.7 sec
1st mode damping (percentage critical)	EW ~ 0.9 NS ~1.8 Twist ~ 0.8	~1.5 ~2.0 —
Building density	9 lb/cu ft- 10 lb/cu ft	9 lb/cu ft- 10 lb/cu ft
Environment	Urban Near ocean	Urban Near coast
Building occupancy	Office	Office
Average number of occupants	2,800	2,800

Fig. 1. Example acceleration record

During the winter of 1971, two wind storms, with peak wind velocities in a range of 40 mph to 60 mph buffeted the two buildings in their respective cities. Prior to the onset of the wind storm on Building A, it had been instrumented by the writers and others with four accelerometers mounted on the 34th floor in such a manner that both translations and the twist of the building could be detected. Building B, on the other hand, was not instrumented; however, in the design of the building an extensive wind-tunnel study of an aeroelastic model of the building had been made. In addition to this study, one of the writers measured the fundamental periods and damping coefficients of Building B, during a later visit to the building.

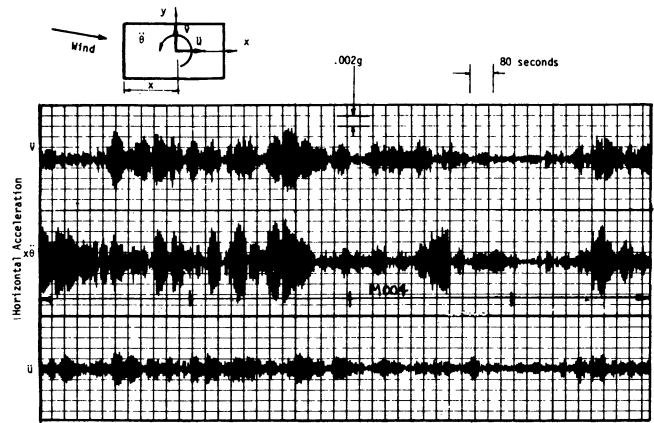Table 2 presents information on the storm characteristics and motion of the two buildings.

Both storms lasted almost all day, and occurred during normal working hours. Figure 1 also presents an example of acceleration records for Building A during its storm. The twist acceleration is of considerable interest.

Immediately after each storm, one of the writers interviewed a number of the occupants of each building,[9] being introduced to the interviewee by a representative of the building's owner. Each interview took about 10 min to complete, the interviewer following a set of questions previously prepared, and described in detail in Ref. 9.

The survey questionnaires were carefully studied, reduced, and are summarized in Tables 3 through 8. Shown in Tables 3 and 4 are general survey statistics given in numbers of people. From these tables, distributions of the subjects interviewed can be deduced.

Tables 5 through 8 show reduced results reported as the percentage of subjects interviewed in each building. All subjects in Building A, but only subjects on floors above T-20 in Building B, are included in the results of Tables 6 through 8. It is recognized that those below floor T-20

Table 2. Motion Intensity and Duration

Statistic (1)	Building A (2)	Building B (3)
Length of perceptible motion during work day	6 hr	5 hr
Length of storm peak	30 min	20 min
Average rms motion level during entire perceptible period (averaged over top building floor)	0.001g (rms)[a]	0.002g (rms)[b]
Average rms motion level during storm peak (averaged over top building floor)	0.002g (rms)[a]	0.005g (rms)[b]

[a] Measured.
[b] Estimated.

Table 3. General Survey Statistics, Building A

Statistic (1)	Men (number) Age 40 and under (2)	Men (number) Age over 40 (3)	Women (number) Age 40 and under (4)	Women (number) Age over 40 (5)	Total (number) (6)
Floor location[a]					
T-2	2		3		5
T-3		2	5		7
T-4	5	3	2		10
T-5	5	1	5	1	12
T-6	11	3	12	4	30
Total	23	9	27	5	64
Room location					
With windows	22	9	7	2	40
Without windows	1		20	3	24
Total	23	9	27	5	64
Observed previous year's storm	15	8	20	2	45

[a] Floors measured from top down; T-0 is top floor.

did not represent the workers in the top one-third of the building. Table 5 includes all subjects and indicates that the interviewees who did not know that Building B was moving all worked on floor T-26. These tables are analyzed and the implications of their results are presented in the following.

After an interviewee indicated that the building was moving the day of the storm, he was asked what motion signs led him to believe that the building, in fact, was moving. The worker would give several cues and then pause, after which the investigator asked about the un-mentioned cues on the questionnaire. Then the interviewee was asked which cue was the most noticeable, second most, etc. If the subject was uncertain, the first two cues mentioned by him were recorded as the most and second most noticeable in their order given, unless the subject said specifically that he had no preference. Only the first two ordered cues were considered significant.

These results are reported in Table 5. Column 1 of the table indicates for each building whether the cue was sensed at all—without regard to the order of noticeability. The row labeled "other" refers to such cues, as: elevator noise, wind whistling, looking through a telescope at the moving horizon, differential movement of cracks in the core, etc. (Strangely enough, one of the occupants of Building A reported this activity. But then he had experienced a some-what similar storm 1 year earlier.)

The most important cues in Building A are creaking noise followed by feeling movement, and seeing movement of objects. In contrast, Building B workers said that feeling motion was most noticeable, followed by noise and co-worker comments. It is the belief of the writers that the noise level in Building A was higher than in B.

It is interesting to note the percentages shown for the "looking out of window and sensing building moving" category. This phenomenon can be observed only if a

Table 4. General Survey Statistics, Building B

Statistic (1)	Men (number) Age 40 and under (2)	Age over 40 (3)	Women (number) Age 40 and under (4)	Age over 40 (5)	Total (number) (6)
Floor location[a]					
T-3,4		3	5	2	10
T-5,6,7	2	3	4	2	11
T-8,9	3	1	2		6
T-11,12,14	1	5	3	3	12
T-18,19		1	1	2	4
T-24,25,26	2		6	1	9
T-42	1				1
Total	9	13	21	10	53
Room location					
With windows	7	13	12	6	38
Without windows	2		9	4	15
Total	9	13	21	10	53

[a] Floors measured from top down; T-0 is top floor.

building twists. Building A had twisting motions which were perceptible to anyone who tried to look out the window during the peak of the storm. Still, it is remarkable that 62.5% observed this phenomenon. Building B has a type of construction which is torsionally relatively stiff and should not have twisted perceptibly. Strangely, 11.3% claimed to have observed this cue.

The "feeling self-moving" category includes both motion sensation and symptoms of motion sickness. Both of these are presented in more detail in Table 6. The fact that these "feeling" motion cues ranked so high is significant, considering the low levels of motion. The other cues have the effect of drawing people's attention to the fact that the building is moving, and this tends to lower their threshold of perception. Comments from co-workers appear to have

Table 5. Noticeability of Motion Cues

Motion Cues (1)	Building A Total percent-age, if noticed at all (2)	Most notice-able, as a per-centage (3)	Next most notice-able, as a per-centage (4)	Building B Total percent-age, if noticed at all (5)	Most notice-able, as a per-centage (6)	Next most notice-able, as a per-centage (7)
Movement of doors, fixtures, etc.	56.2	18.8	9.4	64.1	9.4	37.7
Creaking sounds	92.1	28.1	34.4	64.1	20.8	26.4
Feeling self-moving (includes motion sickness symptoms)	62.5	28.1	17.2	69.9	51.0	15.1
Looking out window and sensing building moving	62.5	4.7	10.9	11.3	1.9	3.8
Comments from co-workers	37.5	12.5	7.8	17.0	11.3	
Other	46.9	4.7	12.5	34.0		1.9
No preference		3.1	7.8		5.6	15.1
Not knowing building was moving				5.6[a]		
Total		100.0	100.0		100.0	100.0

[a] Subjects worked on floor T-26.

Table 6. Summary of Motion Feeling Response

Feeling (1)	Men, as a percentage		Women, as a percentage		Total, as a percent-age (6)
	Age 40 and under (2)	Age over 40 (3)	Age 40 and under (4)	Age over 40 (5)	
(a) Building A					
Primarily motion sensation	14.1		10.9	1.6	26.6
Primarily motion sickness symptoms	15.6	4.7	12.5	3.1	35.9
Total	29.7	4.7	23.4	4.7	62.5
(b) Building B (Above Floor T-20)					
Primarily motion sensation	7.0	16.3	9.3	2.3	34.9
Primarily motion sickness symptoms	7.0	4.7	16.3	18.6	46.6
Total	14.0	21.0	25.6	20.9	81.5

the same effect. This confirms the experimental result of Chen and Robertson,[3] that the threshold of motion perception tends to decrease significantly when motion is anticipated.

It was found that the workers usually lumped all motion cues as being either a nuisance or not. Therefore, no attempt is made to separate the individual factors in terms of a nuisance rating. The exceptions are the comments concerning elevators, which will be analyzed subsequently.

Each occupant interviewed was asked to project his like or dislike for motion to the future. In reference to the storm and motion experience, the interviewee was asked how many times a year would a similar experience occur before it became objectionable. He was asked to classify his opinion as: once a day, several times a year, once a year, or once every 5 years. An additional category, "No objection ever," was indicated by many and accordingly recorded. The summary of this response is shown in Table 7. This group division proved to be adequate. Any attempt to subdivide the "several times a year" group was unworkable. A few people were asked the alternate question: "How many times a year would you consider it objectionable if

a similar motion experience occurred?" The replies were usually puzzled looks and required a restatement of the question, i.e., "How about several times a year?" Most people did not object to several times a year, but strongly opposed the motion occurring every day. The intent of the categories was to include two to five storms per year in the "several times a year" group, and to place six to 365 storms a year in the "once a day" category. The latter assumption is conservative, but as will be shown, this is not critical.

Because a large number felt the motion both as mechanical sensations and as sickness symptoms, it is worthwhile to look closely at this response. Shown in Table 6 is a detailed breakdown of the motion feeling response. Motion sickness symptoms, as used herein, refer to the full range of response—including headaches, dizziness, queasiness, and nausea. It is significant that motion sickness symptoms rated so high. It was the people with sickness symptoms that usually indicated that the experience was a nuisance, and that they were uncomfortable. It was also these people who most often objected to the motion occurring more than "once a year" or "several times a year."

The reason that the total percentage for Building B (81.5%) does not equal the corresponding percentage (69.9%) in Table 5 is that only people above floor T-20 are considered in the Table 6 statistics.

All people were asked what time of day the motion was most noticeable. More than 70% were accurate to within

Table 7. Motion Objection Rating

Occurrence rate (would object if rate occurs) (1)	Building A, as a percentage (2)	Building B, as a percentage[a] (3)
No objection ever	21.8	27.9
Once a day	68.8	46.5
Several times a year	7.8	14.0
Once a year	1.6	11.6
Once every 5 yr		
Total	100.0	100.0

[a] People at and below T-20 not included.

Table 8. Percentage Objection Versus Number Storms

Number of storms occurring per year (1)	People objecting, as a percentage	
	Building A (2)	Building B (3)
1	1.6	11.6
2–5	9.4	25.6
6–365	78.2	72.1

1 hr of the peak motion periods. This helps show that people can discriminate consistently in indicating their perception of motion.

Twenty-five people in Building A and four people in Building B voluntarily stated that they heard non-normal scraping or slapping noises while riding in the elevators. (The writers listened to the elevator noises in Building A with somewhat mixed feelings. They are not included in the statistics cited.) Of those, 13 in Building A and three in B considered this cue a nuisance. This feeling was independent of nuisance consideration of the other motion signs.

The people in Building A were asked additional questions concerning an intense storm which occurred the previous year. Eighty-two percent of the people present in both storms felt that the first storm-induced motion was worse. (The writers unfortunately were not able to measure the building motions in the earlier storm.) Ninety-two percent of these people felt that they had learned from the previous experience and were better prepared to cope with the most recent storm event. Note that after the first storm, the building owners had issued a memorandum which explained that the motion of the building was normal, and assured the occupants that the structure was sound. This indicates a possible learning mechanism and ability for people to adapt, somewhat, to the motion situation. More data are needed to pursue this idea further.

As suggested by the responses of people experiencing actual building motions, there is more to the problem than just "feeling" a building move. Other cues, including noise, seeing movement of fixtures, and sensing visually that the building is twisting, are also important. In reality, it is the *total* effect of all perceived cues that determines the response of an individual to building motion. In general, the type of cues which are sensed, their magnitude, and the duration of perceptibility are all important.

MEASURE OF HUMAN OBJECTION TO BUILDING MOTION

From the motion response surveys and answers the people gave to the question as to how frequently the motion would have to occur before it became objectionable, a quantitative measure between motion and human response is developed. Only the subjects working in the top third of a building are considered, since the response survey relates to this group. It is assumed that the motion intensity, averaged over a reasonable period during the storm peak, is the significant variable to consider. It is further assumed that all storms have a similar character, i.e., lasting a major part of the day with a gradual increase in velocity to a peak, and then slowly tapering off. The building motion also parallels this pattern. This may not be applicable to parts of Southern United States, where both tropical and nontropical storms occur, the tropical storms being of shorter duration.

The argument leading to a measure of human dislike for building motion must be statistically based. One uncertain component which must be considered is the number of large storms occurring in any year. Intense storms occur relatively infrequently and can be treated statistically as rare events, so that an approximate model for the probability distribution of the annual number of severe storms is the Poisson distribution[1]

$$p(i) = \frac{\nu^i e^{-\nu}}{i!} \qquad (1)$$

in which $p(i)$ = probability that the annual number of storms equals i; i = the annual number of storms; and ν = the mean annual number of storms having (or exceeding) a given intensity level. Note that the entire distribution depends on a single parameter, ν, the mean arrival of storms having (or exceeding) a given intensity level.

The occupants in Buildings A and B projected their desires on the basis of the motion level they experienced. The levels are different for Buildings A and B as shown in Table 2. In general, of course, actual storm histories will show a mix of intensity values and, from a design point of view, it is necessary to combine data on human discomfort gathered during storms with different intensity levels. In the following probabilistic analysis, however, principally due to a lack of information, the two data sets are handled separately. In each case, it is assumed that all storms will cause motion levels similar to the survey storm data.

Table 7 gives the percentage of people who will object for several ranges of storm frequency. Table 8 is derived directly from Table 7 and shows the percentage of people objecting as a function of the number of storms per year. Note again that all people who indicated objections to storms occurring every day are placed in the "6–365" category in Table 8. The *expected* percentage, $E[P]$, of people objecting can be determined from the data in Table 8 and the Poisson distribution. It involves combining the outcomes for each possible storm-number combination and the probabilities that the combinations will occur. Percentage $E[P]$ is expressed by the following equation, which can be evaluated for each mean storm arrival rate, ν:

$$E[P] = P_1 p(1) + P_{2-5} \sum_{i=2}^{5} p(i) + P_{6-365} \sum_{i=6}^{365} p(i) \qquad (2)$$

in which $E[P]$ = expected percentage who will object; $p(i)$ = Poisson probability mass function (see Eq. 1); and P_i = percentage who will object if i storms occur during year.

A probability tree, shown in Fig. 2, represents Eq. (2) for Building A when the annual mean storm arrival rate equals ν = 1 per year. This example shows that if one storm per year occurs "on the average," then 3.11% of the people are expected to object.

The expectation calculations for Buildings A and B are summarized in Fig. 3, where the average percentage of people objecting is plotted against the mean storm arrival rate. Two different curves are obtained, one which characterizes Building A occupants who based their objection
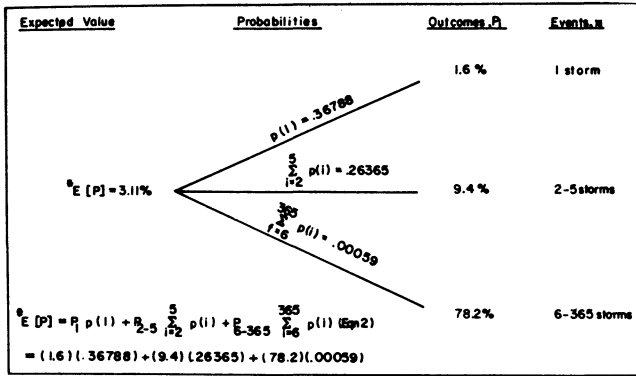
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Fig. 2. Example expectation computation for Building A
(1 storm per yr mean arrival rate)

on a storm of root mean square (rms) intensity equal to 0.002 g; the second, Building B occupants who experienced motion with 0.005 g rms intensity. Again, implicit in the derivation of each curve is that all future storms will be similar to the one on which the survey was based.

As shown in Fig. 2, the contribution to the expected percentage from the "6–365" group is very small. The contribution from this group never exceeds one-fifth of the total expected value and usually much less. Therefore, the decision to place the response group "objection to a storm occurring once a day" in the "6–365" storms per year event is not critical.
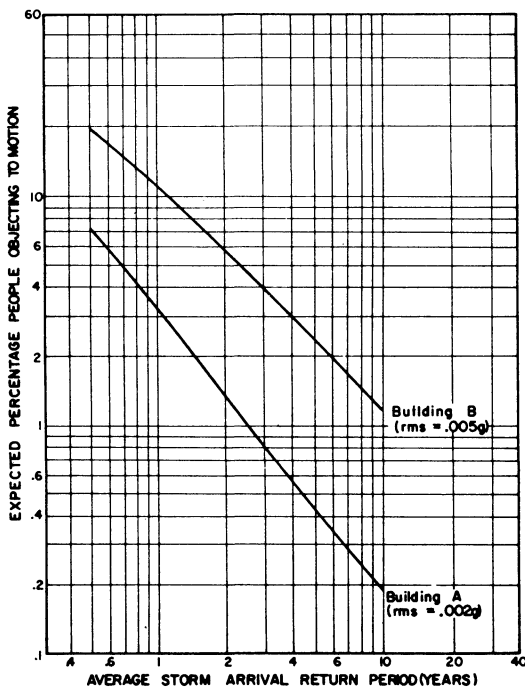
Fig. 3. Percentage occupant objections versus return period of storms

This approach leading to a measure of displeasure with building motion is superior to limits taken from laboratory experiments. From the observations of Steele,[12] who expressed the view that motion sickness is the combined result of *all* factors, this approach automatically accounts for environmental and psychological factors peculiar to tall buildings. Admittedly, more survey data from many buildings are needed to add confidence to the results shown in Fig. 3.

Also, whether people will act in reality according to their objections is debatable. However, the latter problem can be resolved only by obtaining long-term motion-response histories. Projecting from the responses of people who have had motion experiences in tall buildings is better than extrapolating from laboratory experiments, which are difficult to perform properly.

PROPOSED METHODOLOGY FOR EVALUATING BUILDING MOTION

The proposed methodology for evaluating building motion is based on considering the number of perceptible storms which occur per year. This is in contrast to lumping together all motion occurring during a year. The latter technique has been used by Robertson and Chen.[11] For design constraints, such as strength and fatigue, the average total time above a motion threshold is meaningful. However, human memory of building motion tends to record the storm experience as a single entity. It is reasonable that a person remembers better the number of storms in a year which cause discomfort, rather than the total time spent perceiving motion. Therefore, 40 hr of motion above a particular perception threshold in 1 yr is not as meaningful as whether this time is divided among two, three, or four storm events.

Using the number of perceptible storms occurring per year as a basis, the following criterion form for limiting tall building motion is proposed:

"The return period, for storms causing an rms horizontal acceleration at the building top, which exceeds $\bar{\sigma}^*$, shall not be less than R^* years. The rms acceleration shall represent a 20-minute average at the storm peak and shall represent a spatial average over the top building floor."

The rms acceleration obtained at the storm peak and averaged over the top floor area appears to best characterize the storm's severity in relation to human discomfort. It is closely related to the average peak acceleration, but the latter statistic is considerably more difficult to deal with during the process of temporal and spatial averaging.

A 20-min averaging period is selected, since it represents a time interval over which the mean wind velocity fluctuates very little. This is best explained by the "spectral gap" which occurs in the wind velocity power spectrum between about 5 min and 4 hr-5 hr.[4] The 20-min period is recommended, since it is in the spectral gap and should give a reasonably stable estimate.
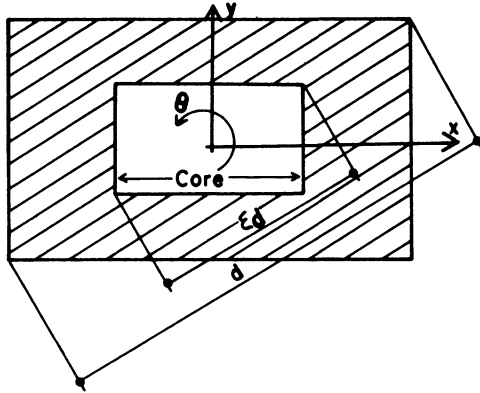
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Fig. 4. Building plan view

NS (V,ϕ) is the mean number of storms/year density distribution $(No./mph/\theta)$

Fig. 6. Storm number distribution

Since it has been observed that buildings both translate in two directions and may twist,[9] an average rms acceleration over the top building floor is appropriate. The spatial averaging should consist of computing the *peak* rms acceleration of each floor point (excluding the building core) and then averaging these values. In the most general sense the spatially averaged rms, $\bar{\sigma}$, would include the two translational rms values, the rotational rms, and the correlations between all three rms values. For the special case where the building is symmetric, as shown in Fig. 4, the following *approximate* expression for the spatially averaged (peak) rms, $\bar{\sigma}$, when plan aspect ratio of the building is less than 3:1, is suggested:

$$\bar{\sigma} = \sigma_{\mathrm{peak}}(0,0)\,\frac{1}{1-\epsilon^2}\left[\left(1+\frac{\gamma^2}{3}\right)^{1/2}\right.$$
$$\left.-\epsilon^2\left(1+\epsilon^2\frac{\gamma^2}{3}\right)^{1/2}\right] \quad (3)$$

$$\sigma_{\mathrm{peak}}(0,0) = \left\{\frac{\sigma_{\ddot{x}}{}^2 + \sigma_{\ddot{y}}{}^2}{2} + \left[\left(\frac{\sigma_{\ddot{x}}{}^2 - \sigma_{\ddot{y}}{}^2}{2}\right)^2\right.\right.$$
$$\left.\left.+ (\rho_{xy}\sigma_{\ddot{x}}\sigma_{\ddot{y}})^2\right]^{1/2}\right\}^{1/2} \quad (4)$$

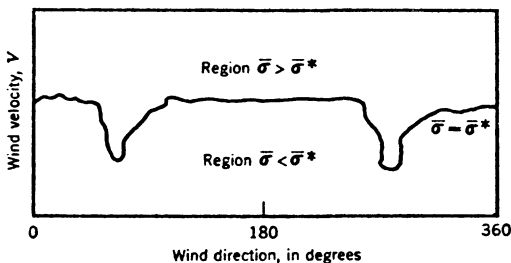$$\gamma = \frac{\dfrac{d}{2}\sigma_{\ddot{\theta}}}{\sigma_{peak}(0,0)} \quad (5)$$
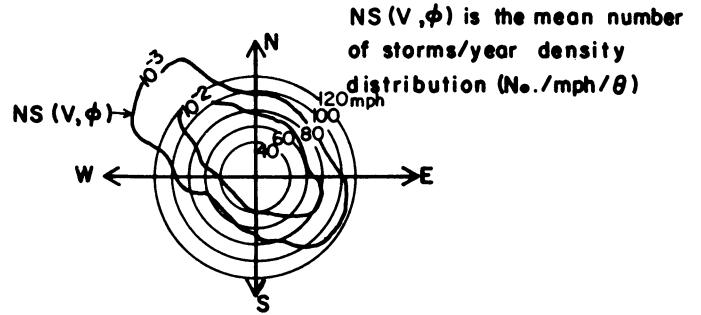

Fig. 5. Plot of motion data

in which $\sigma_{\mathrm{peak}}(0,0)$ = the peak rms horizontal acceleration at the center of the building; $\sigma_{\ddot{x}}$ = rms horizontal acceleration in the x direction at the building center; $\sigma_{\ddot{y}}$ = rms horizontal acceleration in the y direction at the building center; $\sigma_{\ddot{\theta}}$ = rotational acceleration about the vertical building axis; ρ_{xy} = the correlation coefficient between the x and y motions; and d and ϵ are as defined in Fig. 4. Note that the direction of the x-axis is selected parallel to a building side and such that $\sigma_{\ddot{x}} > \sigma_{\ddot{y}}$.

Comparing this approximate formula with an exact solution, which assumes the floor does not distort in the horizontal plane, a maximum error of 20% is found. As can be seen from Eqs. (3), (4), and (5), the effect of twist and a larger building core is to increase the average peak rms. The correlation effect between translation and twist motions tends to cancel out in the averaging process and, therefore, does not appear in the approximate Eq. (1).

To implement the proposed methodology, information on building motion as a function of wind velocity and direction is required. An example plot of the data form which might be obtained from an aeroelastic wind tunnel test is shown in Fig. 5. The rms value, $\bar{\sigma}*$, is the target value described in the foregoing.

In addition, a statistical description of the wind environment is needed. Figure 6 gives an example plot of the distribution of the number of storms, $NS(V,\phi)$, which denotes the average number of storms per year as a function of the wind velocity (20 min average) and the wind direction. Although this form of distribution is not directly provided by the U.S. Weather Bureau, it can be constructed for any city from a review of the daily weather sheets recorded at a nearby weather station.

Note that the wind velocity in both Figs. 5 and 6 are referenced to the same datum.

The implementation of the recommended criterion requires the computation of the average annual number, $NA(> \bar{\sigma}*)$, of storms with motion greater than $\bar{\sigma}*$:

$$NA(> \bar{\sigma}*) = \int\int NS(V,\phi)d\phi dV; \text{ region, rms} > \bar{\sigma}* \quad (6)$$

This integration amounts to computing the volume under the $NS(V,\phi)$ distribution (Fig. 6) in the region where $\bar{\sigma} >$

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Table 9. Allowable Percentage of People Objecting to Motion (from interviews)

Interviewee (1)	Percentage (2)
Owner/developer	2–5
Owner/developer	2
Owner/developer[a]	2
Engineer	2–5

[a] Also said that a perceptible motion should be allowed only once in 5 yr.

$\bar{\sigma}^*$ (as given by Fig. 5). The return period, R, for storms causing motion greater than $\bar{\sigma}^*$ is

$$R = \frac{1}{NA(> \bar{\sigma}^*)} \qquad (7)$$

Finally the criterion check becomes:

$$R > R^* \qquad (8)$$

in which R^* is a prescribed allowable value.

PROPOSED TENTATIVE CRITERION

Several prominent building owner/developers and one competent structural engineer were interviewed and asked the following question:

"Assuming you are going to build a new office building and you are concerned about human discomfort from building sway, but you do not want to spend any extra

Fig. 7. Criteria selection

money for this factor: What percentage of the people in the top one-third of the building can object to the sway motion each year and not seriously affect your renting program?"

The question responses are summarized in Table 9. The names have been withheld by request. From these results it appears that a reasonable limit is about 2%. This represents a "status quo" value. If a larger percentage occurs, the owner may lose money through lease terminations, the building's bad reputation, etc. If a lower value is desired, the owner may expect to pay a higher construction price.

Based on the results of interviewing people in Buildings A and B (as expressed in Fig. 3) and limiting to 2% the average number of people in the top one-third of a building who object to the building sway, the writers tentatively propose that $\bar{\sigma}^*$ be chosen at 0.005 g when R^* is set at 6 yr. Figure 3 is repeated as Fig. 7, whereon the criteria selection is superimposed. Because the arguments relating probabilities and return periods for low return periods tend to break down, it is more appropriate to define the comfort standard using the Building B curve. It is shown in Ref. 9 that the results of the Building A survey are consistent. The writers have observed that for four buildings recently constructed, analyzed by wind-tunnel methods, two satisfied the preceding criterion and two failed.

An assumption made in proposing the preceding criterion values is that *all* storms which cause motion above the 0.005 g level will, in fact, produce motions very near that level. Because of the rapid exponential decay of the wind velocity probability mass distribution, this is a reasonable assumption. A development of this argument is shown in Ref. 9.

The writers propose these as tentative criterion values, since they are based on very limited information. It is hoped that in the future similar surveys will be conducted, and the results used to add confidence to these values or to propose new ones.

CONCLUSIONS

The responses of people to wind-induced tall building motion depends on many motion cues, including: motion, noise, visual observations, and co-worker comments. A principal objective in design is to provide an environment which will be tolerated by the building's occupants. Because motion tolerance is a subjective value, which varies from person to person, the amount of building sway permitted may differ between owner and occupant.

People react to individual storms as single events, each of which can be identified by an average rms acceleration, with the average taken in time, during the most intense part (20 min) of the storm, and in space, over the top floor area of the building. This rms acceleration can in turn be linked to a distribution of human response. The format of the proposed criterion is to set a lower limit to the value of the return period of storms during which an average of 2% or more of the people object to the motion. This corresponds
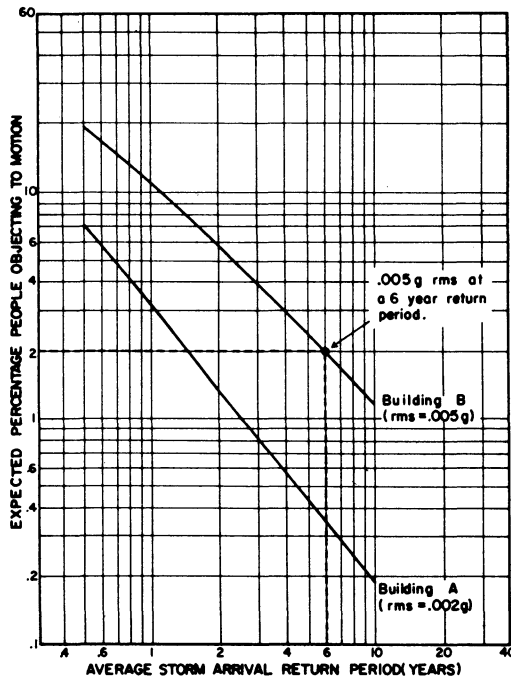
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roughly to imposing a lower limit of 6 years to the return period of storms with rms acceleration levels in excess of 0.005 g. The criterion values presented were obtained primarily from an owner's perspective. Different values can be inserted into the proposed criterion format as dictated by differing viewpoints of the users.

NOMENCLATURE

d = diagonal building plan dimension

$E[P]$ = expected percentage of people who will object to building motion

i = annual number of storms

$NA(> \bar{\sigma}^*)$ = average number of storms per year with motion greater than $\bar{\sigma}^*$

$NS(V,\phi)$ = average number of storms per year density distribution as function of wind velocity V and direction ϕ

P_i = percentage of people who will object if i storms occur per year

$p(i)$ = probability that annual number of storms equals i

R = return period, in years

R^* = criterion value of R

V = 20 min mean wind velocity at storm peak

$\gamma = d/(2\sigma_{\ddot{\theta}})/[\sigma_{peak}(0,0)]$

ϵ = diagonal building core plan dimension— expressed as fraction of d

ν = mean annual number of storms having (or exceeding) given intensity level

ρ_{xy} = correlation coefficient between x and y motions

$\bar{\sigma}$ = spatial and temporal averaged peak rms horizontal acceleration—averaged over top building floor

$\bar{\sigma}^*$ = criterion value of $\bar{\sigma}$

$\sigma_{peak}(0,0)$ = peak value of rms horizontal acceleration at center of top building floor

$\sigma_{\ddot{x}}$ = rms horizontal acceleration in x direction at center of top building floor

$\sigma_{\ddot{y}}$ = rms horizontal acceleration in y direction at center of top building floor

$\sigma_{\ddot{\theta}}$ = rotational acceleration about vertical building axis—evaluated at top building floor

ϕ = wind direction angle

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