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Sources of Torsional Wind Loading on Tall Buildings: Lessons From the Wind Tunnel

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Introduction

Torsional wind loading on buildings is not as well understood as lateral or overturning loads, and is not as amenable to analytical treatment. Because of this, many designers—and indeed most codes of practice—ignore this aspect of the load, and simply apply the lateral load at the geometric or elastic center of the structure. Wind-tunnel tests on model buildings have revealed that torsional loads usually exist, and span a great range of significance. Several causes of the torsion can be identified, and this categorization aids the designer in providing methods to either reduce or manage the loading.

This paper identifies some common sources of torsional loading in terms of building shape, interfering effects of nearby buildings, and dynamic characteristics of the structural frame. In addition, it is shown that torsional loading is routinely larger than that provided for in most standards.

Shear and torsional loads on several building models are shown in Figure 1. All are real-life cases but represent somewhat elementary examples in terms of shape—all are essentially prismatic with the cross-section indicated; and exposure—all are essentially isolated buildings except where indicated. All were tested in a wind tunnel in turbulent shear flow. The loads are in coefficient form, with the coefficient of total shear defined as

$$C_V = \frac{V}{QDH} = \frac{\sqrt{V_x^2 + V_y^2}}{\rho U^2 DH / 2}$$

and the torsional moment M_z expressed as a normalized eccentricity,

$$\frac{e}{D} = \frac{M_z / V}{D}$$

where D = maximum building width, H = building height, U = a reference wind speed, and Q = a reference dynamic pressure. This normalized eccentricity gives a common and intuitive indication of the additive effect of torsion on the total building shear, at a given wind direction. Often the maximum eccentricity does not occur at the same wind direction as the maximum shear, as demonstrated by the graphs in Figure 1. In general the governing design case is not obvious and will depend on the torsion-resistance properties of the frame. For example, if torsion is resisted by shear walls placed near the ends of the building then a given torque may increase the shear stresses only slightly, and the wind direction of maximum overall building shear may well represent the design case. However, if the shear walls are concentrated near the core then the same torque will produce a much greater shear stress, and the design condition is more likely to occur at the direction of maximum eccentricity.

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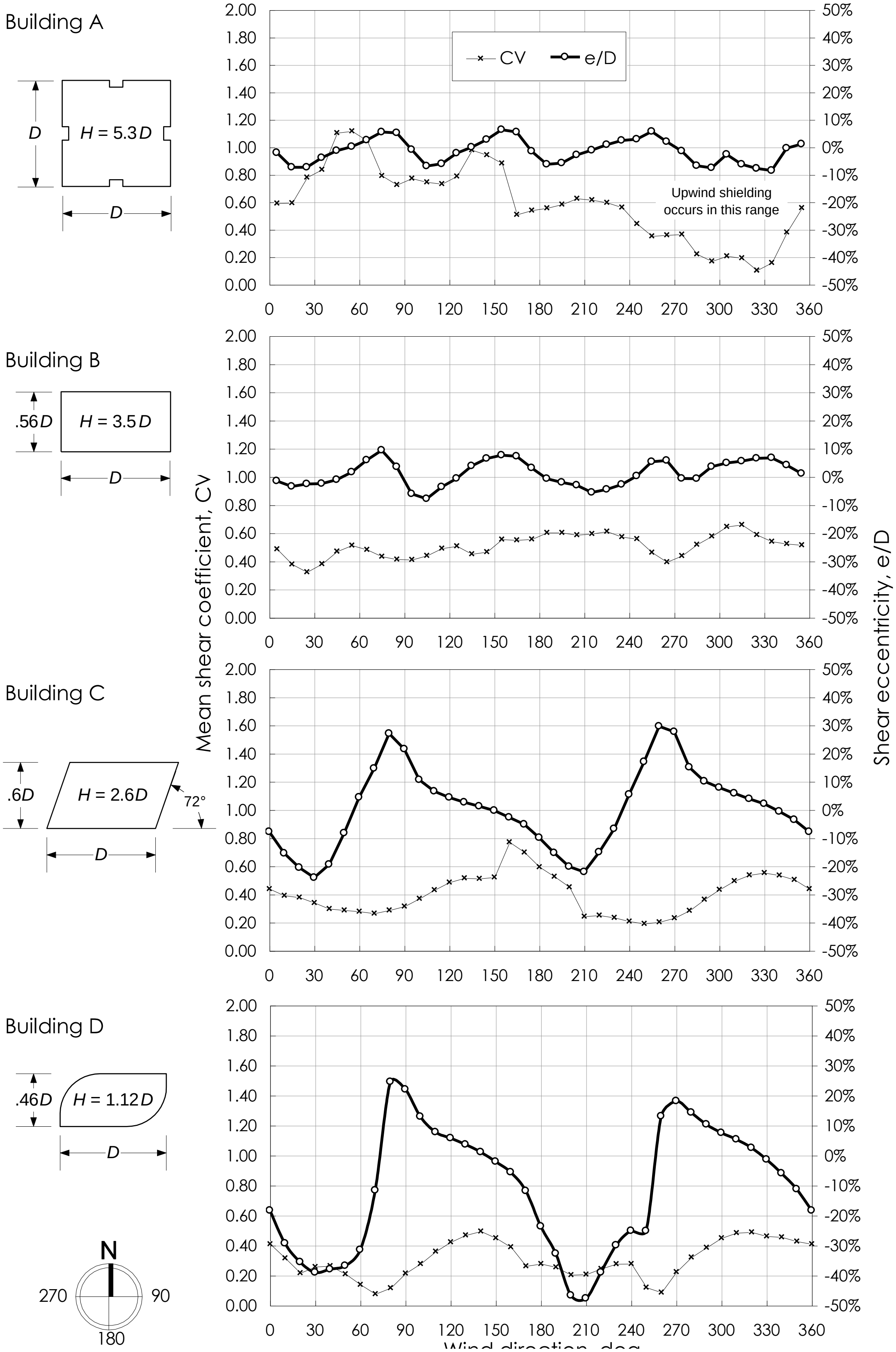
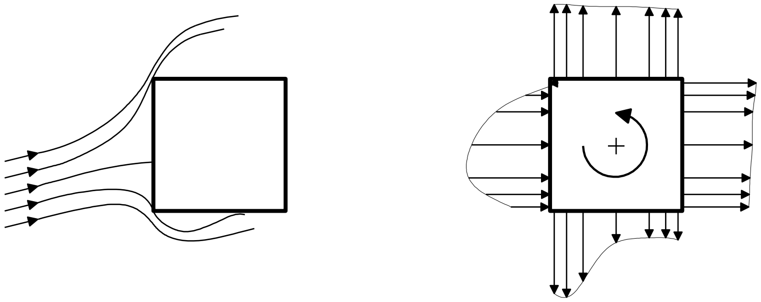


Figure 1 Measured shear and torque on a variety of elementary model shapes



STREAMLINES

PRESSURE DISTRIBUTION

Figure 2 Skewed flow about a symmetric object gives rise to a torque.

The Effect of Building Shape

Aerodynamic torsion occurs even on cylinders of elementary shape (other than round) whenever the angle of wind incidence is skewed to an axis of symmetry. This can be seen with the aid of Figure 2, which shows schematically the streamlines, separated areas, and pressure distribution on a square cylinder in steady uniform flow. The positive pressure distribution on the windward wall is slightly unsymmetric, resulting in a small anticlockwise torque. The leeward wall is in a separated zone, and the negative pressure acting on it is more nearly uniform. Perhaps less obvious and more important, however, is the pressure on the side walls. The flow is entirely separated from the upper wall, which therefore experiences moderately negative pressure, nearly uniformly distributed. Flow on the lower wall separates from the leading corner but eventually reattaches to the surface. Pressure within the separation bubble is more negative than in the reattached zone, and this nonuniform pressure results in an anticlockwise torque which reinforces the torque on the windward wall.

Thus a pattern of four cycles of alternating torque occurs within a period of 360 degrees of wind rotation. This pattern can clearly be seen in the eccentricity curves of Figure 1, buildings *A* and *B*. Building *A* is a square cylinder, and the maximum eccentricity is only about 6 to 8 percent. Building *B* is rectangular, and the maximum eccentricity approaches 10 percent. Also, note that the eccentricity (and also the torque, since the shear is nearly constant) is larger when the wind is nearly parallel to the long axis, than when it is nearly parallel to the short axis. This is reasonable in light of the above discussion of Figure 2, because the torque is effected more by the separated region on the bottom side wall than by the nonuniform pressure on the windward wall. In the former case this separated zone occurs at a greater distance from the building center.

The same effect occurs in Building *C*, but it is further accentuated by the skewed end walls. The maximum eccentricity is now 25 to 30 percent. In fact this parallelogram is a popular building shape, and it has become somewhat of a classic case for experiencing unusually high torsion.

An even more extreme case of shape-induced torque occurs in Building *D*, a rectangle with opposite corners rounded. For this case, when wind is *nearly* parallel to the long axis—say 80–90 degrees—separation occurs on one side but is essentially suppressed at the rounded opposite side. Thus, the negative pressure within the separation bubble has nearly nothing to counteract it on the opposite side, resulting in a very large torque, and eccentricity in the neighborhood of 20 percent. Even more interesting, however, is wind skirting the curved faces (i.e., roughly parallel to the long diagonal), say 30 or 210 degrees. A significant negative pressure develops on the curved walls, while the flat walls experience positive pressure on the windward side and slight negative pressure on the leeward side. All of these pressures contribute to a clockwise torque, and result in eccentricity of 40 to nearly 50 percent.

Although building shapes such as *C* and *D* are somewhat special in producing large eccentricities, it must be noted that the largest eccentricities coincide with a reduced shear of perhaps half the maximum shear. Conversely, the maximum shear tends to coincide with a relatively minor eccentricity. Critical design cases for such shapes will be highly dependent on the nature of the torsional resistance system: those with perimeter stiffness will tend towards governing by the maximum shear, and those with core stiffness will be more sensitive to the large eccentricities.

Interference Effects of Other Buildings

It is easily imagined that the torque on a high-aspect-ratio building would increase if wind on the broad face is partially shielded by an upwind building. Less obvious is the effect that occurs with an in-line upwind building, as illustrated on Building *E* in Figure 3*a*. This building was tested with and without the upwind interfering building at azimuths 220–290 degrees. Without this building, with winds from the neighborhood of 270 degrees, the maximum eccentricity is a modest 5 to 6 percent. When the building is added, the eccentricity increases to 8–10 percent. This increase occurs despite a slight reduction in the total shear force. Therefore, the effect of the interfering building is to provide some (slight) shielding regarding the total force on the subject building, but the torque is increased. It is conjectured that the interfering building, when slightly displaced from directly upwind, creates a sheared flow within its wake which engulfs the subject building. Thus the subject building is impacted by a mean flow which varies over its width, creating an unbalance.

Dynamic Effects

Figure 3*b* depicts the same Building *E*, but now the loads shown include the peak dynamic response (computed from the aerodynamic loading measured on a high-frequency base balance). At wind directions 0 and 180 degrees, where the maximum shear occurs, the dynamic load is about twice as great as the mean load indicated in 3*a*. This increase by a factor of about 2 is common, at least for buildings which are not excessively slender or dynamically active. The maximum eccentricity is hardly affected by the dynamic response, indicating that the dynamic torque increases in about the same proportion as the dynamic shear. However, at directions 90 and 270 degrees, where wind is parallel to the long axis and the total shear is minimal, the dynamic effect is more interesting. Here the peak shear exceeds the mean by a factor of 3 to 4. This happens because the total mean shear is essentially the alongwind component only while the total dynamic shear includes both alongwind and crosswind components. Similarly, the eccentricity curve is now "flatter," i.e., it has increased in the region of 90 and 270 degrees while remaining constant at 0 and 180 degrees. The end result of this behavior is that the large torsion now occurs concurrently with a significantly large shear, whereas the maximum mean torque in 3*a* tended to occur concurrently with a relatively small shear. In other words, the existence of dynamic response aggravated the torsion problem.

To some extent this dynamic problem is partially alleviated, because the load fluctuations in time may not be perfectly correlated; the peak torque may not occur at the same instant as the peak shear. This is not always the case and should not be assumed without special investigation, however, as demonstrated by the next example.

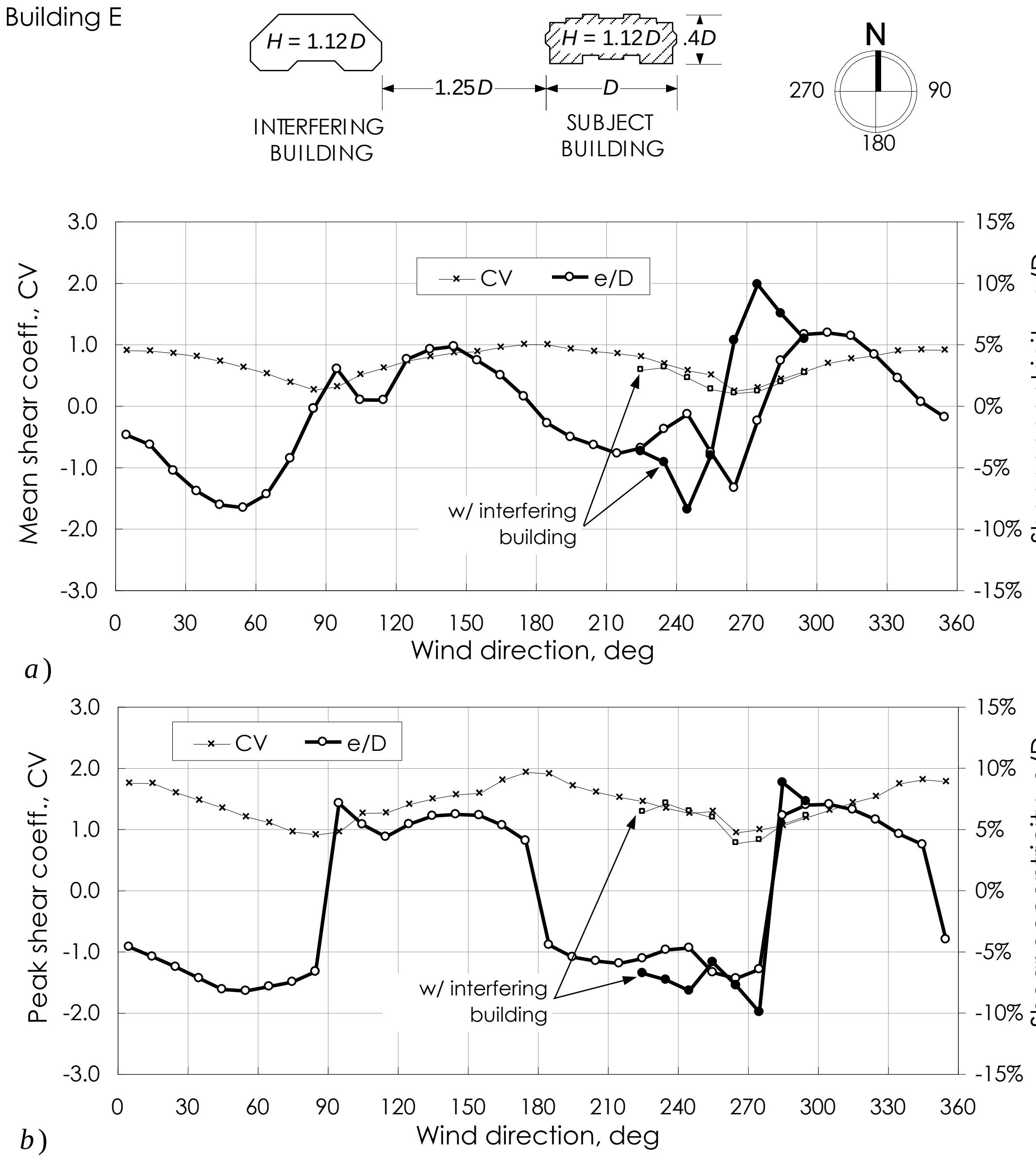


Figure 3 Effect of upwind interference. (*a*) mean loads; (*b*) peak dynamic loads.

Figure 4 shows the peak dynamic loads acting on Building *F*, which has a high-aspect-ratio shape in an environment which is mostly open except for two interfering buildings at an azimuth of about 150 degrees. Wind from 90 degrees produces a very high eccentricity of −30 percent, which is probably due to the inclined face on the north side vs. the flat south side which results in unsymmetric flow and unbalanced load, especially on the windward half of the building. The significance of this eccentricity is somewhat diminished, however, because it is accompanied by a shear which is only about half of the maximum value. Wind from 120 degrees is more interesting: the total shear is now near it maximum value, and the eccentricity is still 30 percent. Apparently, this can be attributed in part to the interfering buildings which are slightly off the upwind direction.

Examination of the structure's dynamic properties reveals another culprit, however. The shapes of the first three modes of vibration at the top floor are depicted in Figure 5. In the initial design, strong coupling exists between the *y* and torsional motions via the second and third modes. In other words, aerodynamic buffeting loads in the *y* direction, even if centered on the structure’s elastic axis, will induce twist along with the displacement. The torsional vibration in turn produces an equivalent-static torque, which adds to any aerodynamic torque which might also be present.

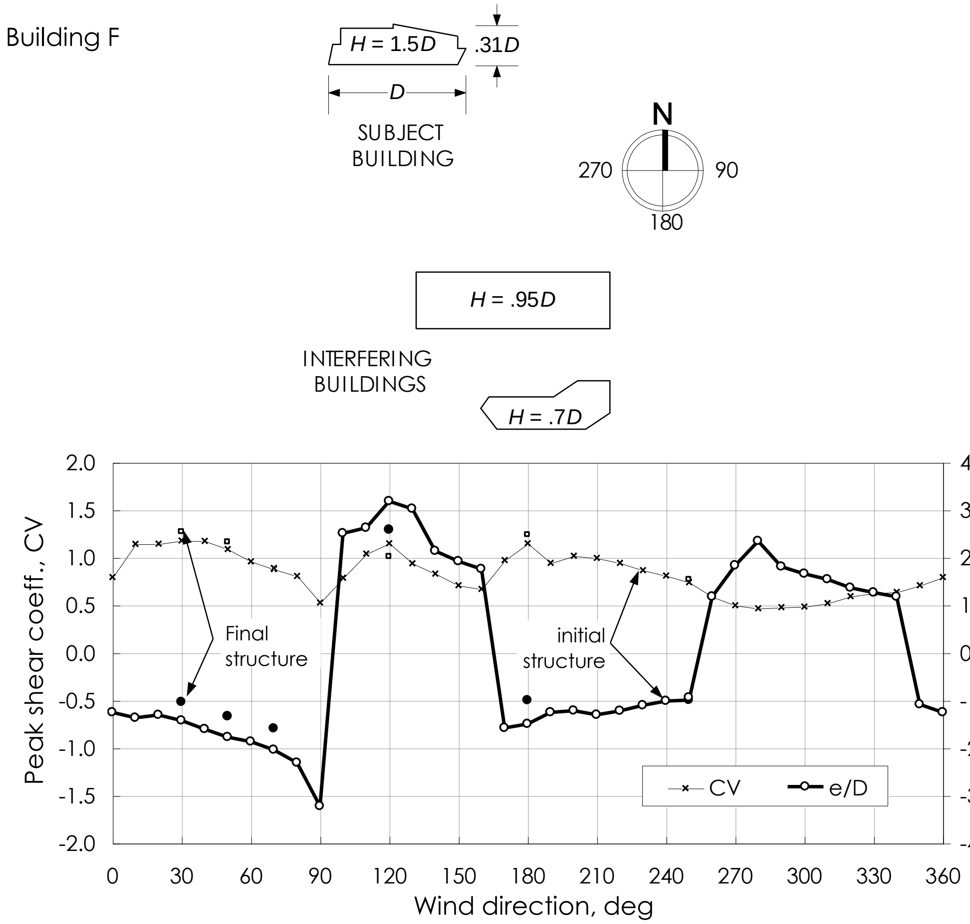


Figure 4 Effect of structural properties on shear and torque (see Fig. 5)

Analysis of the wind-tunnel data revealed that, at 120 degrees, most of the shear is in the *y* direction; further, most of this shear and virtually all of the torque were the result of dynamic resonance in mode 2. Because of this dynamic coupling, the shear and torque are highly correlated, as depicted in Figure 6*a*. Because of this, the wind-tunnel study specified one of the design load cases, indicated in Figure 6*a*, involving virtually the full torque simultaneously with the maximum *y* shear (*x* moment).

As a result of this wind-tunnel study, the engineer modified the structural properties by relocating and thickening selected shear wall areas. The natural frequencies of vibration were increased, which itself tends to reduce the dynamic loading. Even more important, most of the coupling between torsion and sway was eliminated as illustrated in Figure 5. The resulting loads at the most critical wind directions are noted in Figure 4. The effect was to reduce the eccentricity by about 5 percent of the building width. In addition the correlation between torque and the *y* shear (*x* moment) was much lower (Figure 6*b*), reducing the fraction of the peak torque which must be applied simultaneously with the peak shear. The following table describes the load combination specified for this building structure for a 120-

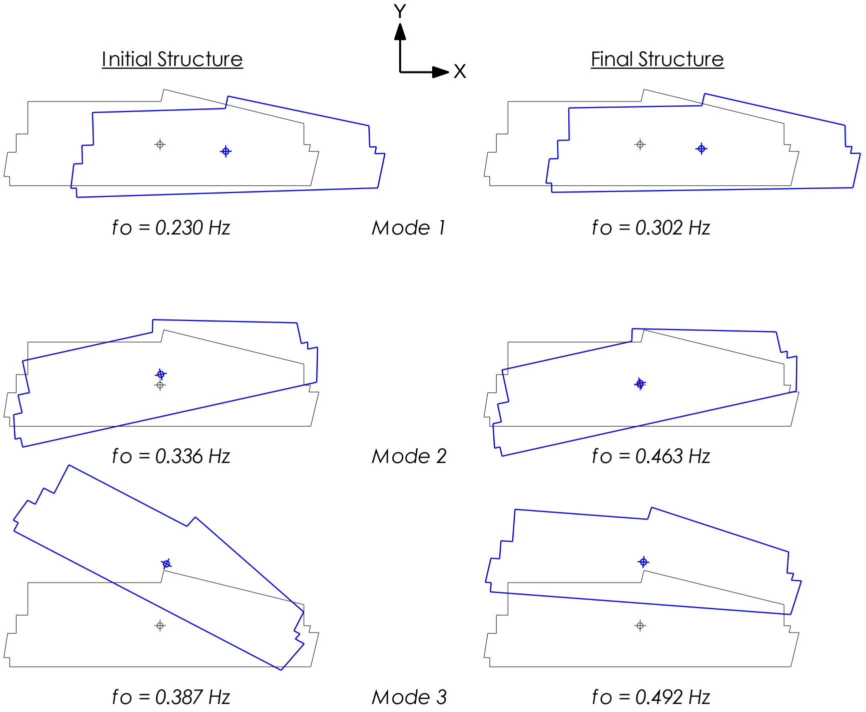
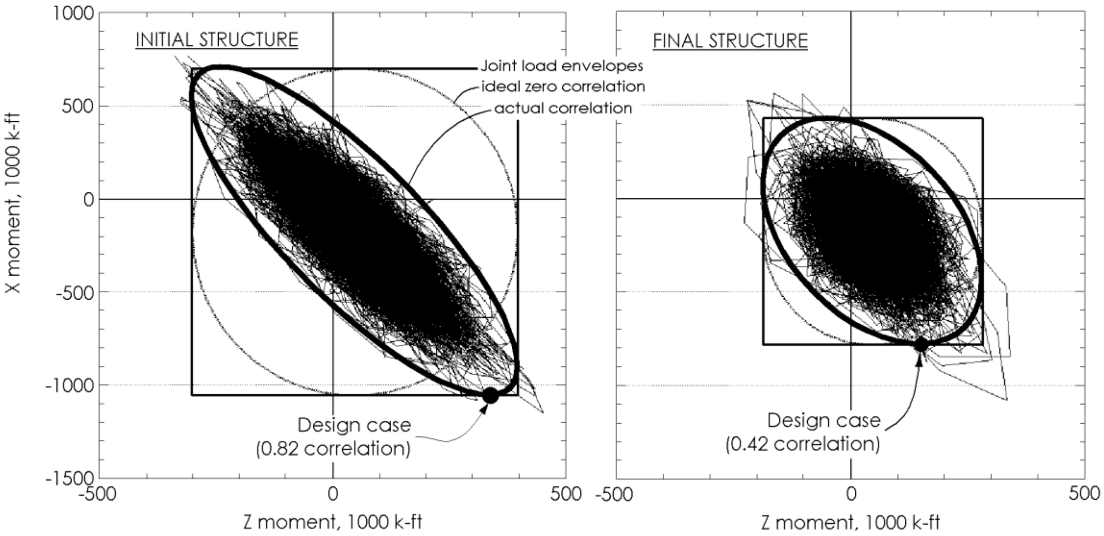


Figure 5 Mode shapes of initial and final schemes for the structure of Building F



a) *b*)

Figure 6 Calculated joint time series of sway and torsional moments on Building F (wind direction 120 degrees)

degree wind, where the maximum *y* shear occurs. The *x* moment and *y* shear have decreased somewhat, primarily because of the increase in natural frequency. The absolute peak torque (M_z) decreased a similar amount due to the natural frequency increase, but the *effective* peak torque which must be combined with the other loads decreased to 44 percent of its initial value. Because the total design shear decreased slightly, the reduction in effective eccentricity is slightly less at 50 percent.

Structure generation	M_x 1000 k-ft	M_y 1000 k-ft	M_z 1000 k-ft	V_x k	V_y k	V k	e/D
Initial	-1039	-46	335	-221	4635	4640	28%
Final	-830	-46	147	-221	4016	4023	14%
Final/Init.	0.80	1.00	0.44	1.00	0.87	0.87	0.50

Note: 1000 k-ft = 1.356 MN-m; 1 k = 4.448 kN

Because Building *F* is relatively tall, dynamic displacements in the form of acceleration are also important. The following table compares the acceleration at the northeast corner (the worst location) of the 28th (top occupied) floor, based on a mean recurrence interval of 10 years. The acceleration in the final structure has been reduced by more than half, primarily because of the reduced excitation of mode 2, which was coupled to *y*-direction forces in the initial design. The reduction was sufficient to change the building's occupant-comfort category from questionable to acceptable.

Structure generation	Mode 1 (rms milli-g)	Mode 2 (rms milli-g)	Mode 3 (rms milli-g)	Total (rms milli-g)	Total (peak milli-g)
Initial	1.40	7.30	0.50	7.45	29.0
Final	1.04	2.88	1.29	3.32	13.5
Final/Init.	0.74	0.39	2.57	0.45	0.46

Summary

Torsion arises from a number of causes: building shape, interference effects, and dynamic response. Engineers have slight influence on the first, none on the second, but much on third. Torsion cannot be eliminated but can possibly be minimized, or at least designed for if recognized. Wind tunnel studies have been the only way to identify torsion, but they also provide help in minimizing it or designing for it.

In contrast, building codes and standards have lagged behind the recognition of this important load type: most ignore torsion, ASCE 7 specifies an unbalanced load equivalent to an eccentricity of e/D = 3.5 percent, and Eurocode 1 specifies an eccentricity of 10 percent. But 10 percent is a typical value, and twice this much or more is not uncommon. For most cases these codes have been adequate because the lack of required torsion is compensated by conservative force specifications. It is hoped that future building codes will more accurately describe the real wind loads on a building, and that engineers will more widely recognize and effectively design for them.