Time-dependent wind effects: database-assisted design and estimation of ultimate limit states for rigid and flexible structures

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ABSTRACT: We describe the database-assisted design approach for wind loading, and its application for estimating limit states – including ultimate limit states -- for low-rise buildings and tall buildings experiencing along-wind, across-wind, and torsional dynamic effects. Database-assisted designs account for the temporal and spatial variation of wind effects and can result in far more risk-consistent, safe, and economical structures than those based on conventional standard provisions. Structural reliability methods are currently applied to database-assisted designs with a view to developing improved estimates of probabilities of failure under wind loads.

INTRODUCTION

Current building codes and standards typically include simplified static descriptions of wind loading originally developed to allow slide-rule calculations. Because wind loads depend in a complex manner on space and time those simplified descriptions result in estimates of wind effects that are generally crude and inconsistent with respect to risk.

The database-assisted design (DAD) approach can improve significantly upon those estimates, resulting in structures that can be *both* safer and more economical (Whalen et al., 1998).

2. DESCRIPTION OF BASIC DAD APPROACH

The basic DAD approach utilizes simultaneous time histories of pressures measured in the wind tunnel at hundreds of points on the building envelope. Summations of pressures weighted by appropriate tributary areas and influence coefficients yield time histories of bending moments, shear forces, and axial forces at any cross-section of any member of the wind-load-resisting system. For any cross-section, these time histories have peak values that govern its design. Estimators of those peaks can be the observed peak values, but routine procedures are available for estimating statistics of the peak values for time histories with Gaussian or non-Gaussian marginal distributions (Sadek and Simiu, 2002). Allowable stress design or conventional limit state design of the type used in U.S. practice can be based on the basic DAD approach, which is currently permitted under the provisions of the ASCE 7 Standard provisons.

3. ESTIMATION OF ULTIMATE LIMIT STATES

In this approach the effects of gravity loads, multiplied by appropriate load factors, are added to the effects of the wind loading. The spatial distribution of the wind loading whose peak governs the design of the cross-section of concern generally differs markedly from the distribution specified in standards. Incrementally increasing the wind load -- with spatial distribution based on the actual aerodynamic data -- until that cross-section fails by local buckling or in another failure mode yields the wind speed associated with failure (Jang et al, 2001). The corresponding annual probability of failure of the component or structural system of concern can then be estimated by using standard structural reliability procedures. This estimation corresponds to the observed realization of the stochastic pressure field. Simulations of pressure fields based on that realization and estimates of the corresponding failure probabilities make it possible to estimate conditional confidence bounds for the failure probability. Figure 1 shows an example of the difference between the spatial distribution of the wind loads specified in the ASCE 7-93 Standard and the wind loads as measured in the wind tunnel. Fig-

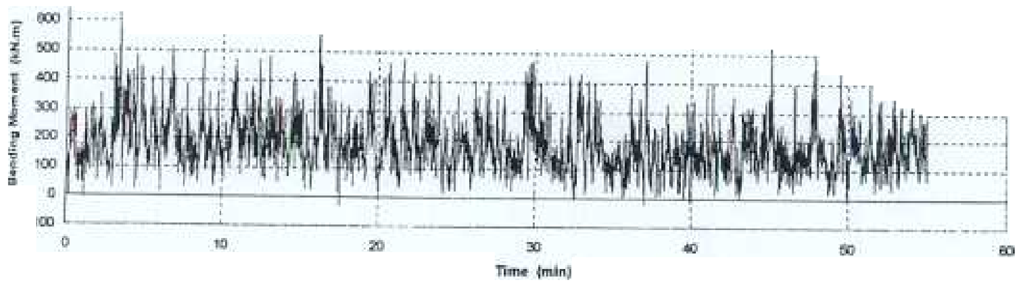
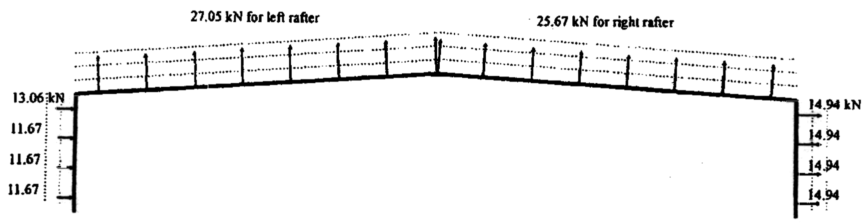
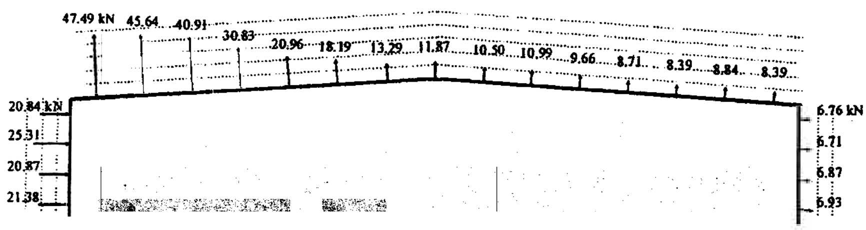


Fig. 1. Typical time history of bending moment at frame knee for a low-rise industrial building. Wind load of Fig. 2b is calculated at the time *t*.3.5 s at which the bending moment reaches its peak.



(a)



(b)

Figure 2. (a) Wind forces specified by ASCE 7-93 Standard; (b) wind forces obtained from aerodynamic database for a frame subjected to wind normal to ridge.

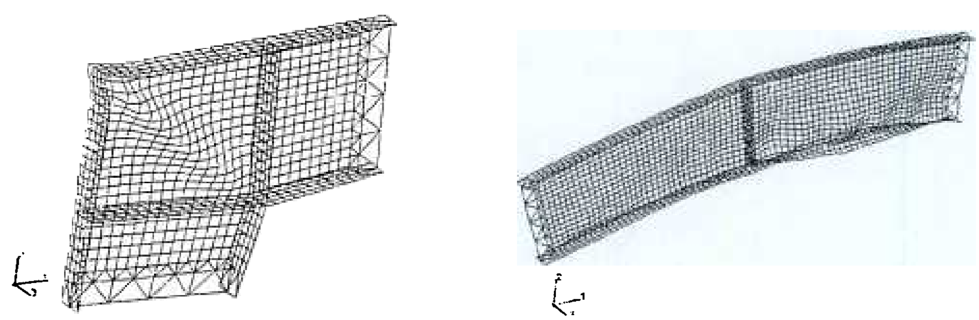


Figure 3. Typical failure modes.

ure 2 show examples of local buckling induced by superposed gravity loads and wind loads with the spatial distribution pattern of Fig. 1.

3. AERODYJNAMIC AND CLIMATOLOGICAL DATABASES

The application of the DAD approach requires the development of comprehensive aerodynamic databases. A collaborative effort with this objective currently involves the University of Western Ontario, Texas Tech University, and the National Institute of Standards and Technology. Efficient, user-friendly software has been developed that uses as input the aerodynamic data, extreme wind climatological information, and the requisite properties of the structure. The climatological databases may include, especially for hurricane winds, sets of extreme wind speeds for a sufficient number of azimuth directions (Rigato, Chang, and Simiu, 2001). The output consists of the wind effects being sought (Whalen, Shah, and Yang, 2000). The output is affected by errors and uncertainties inherent in the physical, probabilistic, and statistical models being used. When used in conjunction with DAD, structural reliability methods that account for these errors and uncertainties yield far more dependable structural reliability estimates than those based on code-based wind load representations (Minciarelli et al., 2001).

4. APPLICATION OF DAD TO TALL STRUCTURES

DAD can similarly be used for flexible structures exhibiting dynamic effects, for example tall buildings. Aerodynamic data can be measured in the wind tunnel (or, in principle, obtained by CFD methods) on a rigid model. The data can then be used in the time domain to develop time histories of the dynamic response. Fluctuating wind loads are considered simultaneously for the along- and across-wind directions as well as for torsion. As is the case for low-rise structures, the input includes the aerodynamic databases, information on the wind environment, and the requisite structural characteristics. The output includes time histories of deflections (displacements, velocities, and accelerations) and internal forces (axial forces, shear forces, and bending moments), and can account explicitly for wind directionality effects. This approach makes it possible to estimate the time histories' spectral densities and their Gaussian or non-Gaussian marginal distributions, and hence the peak wind effects. In addition, this approach allows the improved estimation of sampling errors, ultimate capacities and failure probabilities under wind loading. The application of DAD to tall structures has to be consistent with the limitations imposed on conventional dynamic calculations by the possibility that the structure will be significantly affected by aeroelastic forces, which
are normally appreciable only if the structure is more slender than typical tall or very tall buildings. DAD calculations for tall buildings have the added advantage of allowing designers to perform studies on the effectiveness of structural control devices, such as viscous or viscoelastic dampers, tuned mass dampers, and tuned liquid dampers, and their optimal design, location, and distribution. Software development for performing DAD of tall structures is currently in progress at NIST.

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