Engineering Structures 33 (2011) 674–684

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Database-assisted design methodology to predict wind-induced structural behavior of a light-framed wood building

Akwasi F. Mensah [a], Peter L. Datin [a], David O. Prevatt [a,*], Rakesh Gupta [b], John W. van de Lindt [c]

[a] Department of Civil and Coastal Engineering, 365 Weil Hall, University of Florida, Gainesville, FL 32611, United States

[b] Department of Wood Science and Engineering, Oregon State University, 114 Richardson Hall, Corvallis, OR 97331, United States

[c] Department of Civil, Construction and Environmental Engineering, University of Alabama, Tuscaloosa, AL 35487, United States

ARTICLE INFO

Article history:
Received 15 August 2010
Received in revised form
1 October 2010
Accepted 16 November 2010
Available online 16 December 2010

Keywords:
Wind engineering
Wind load
Database assisted design (DAD)
Light-framed wood structure
Influence functions
Wind tunnel
Structural load paths

ABSTRACT

This study investigates the applicability of the database-assisted design (DAD) methodology to predict structural reactions in a light-framed wood structure subjected to fluctuating wind pressures. Structural influence functions were determined on a 1/3-scale light-frame wood structure, which was then subjected to a wind flow, while the surface pressures and structural reactions at roof-to-wall and wall-to-foundation connections were simultaneously recorded. There was a good agreement between the DAD-predicted structural reactions and experimentally measured reactions, confirming that the DAD method is suitable for predicting the structural reactions in light-frame wood buildings. Subsequently structural reaction time histories at several connections within the building were generated using a 1:50 scale wind tunnel model of the structure and the peak structural reactions determined using the DAD method and previously obtained influence functions. When the DAD-estimated reactions were compared with reactions predicted by the ASCE 7-05 main wind force resisting system (MWFRS) method, they showed the ASCE 7 reactions were highly non-conservative(i.e. smaller than the DAD method predictions), by as much as 39% at the gable end truss. The components and cladding method showed reasonable agreement with the DAD method for the gable end and first interior truss reactions but it too underestimated the reaction loads at the second and third interior trusses by 30% and 12% respectively.

1. Introduction

Simiu and Stathopoulos [1] proposed the use of a database-assisted design (DAD) methodology to improve wind-resistant design of buildings. The approach differs from current wind load design codified provisions that use simplified aerodynamic models supplied in reductive tables, which the authors contend can result in risk-inconsistencies. The current wind design standards, such as the ASCE 7-05 [2], includes factors such as a gust effect factor, wind load factors for hurricane and non-hurricane regions, and aerodynamic and climatological wind directional effects which have been identified to contain significant inconsistencies with regards to risk [1].

Specifically, the ASCE 7-05 [2] standard contains wind loading provisions for main wind-force resisting systems (MWFRS) that represent fictitious loading conditions that, when applied to a building, envelopes the desired structural responses (e.g. bending moments, shear, thrust) independent of wind direction (see Commentary C6.5.11 in ASCE 7-05 [2]). These provisions were developed based on results from wind tunnel tests on low-rise industrial buildings, e.g. steel portal-framed buildings, in which the measured external pressures, used in conjunction with influence coefficients for rigid frames, were spatially and time averaged to develop the maximum applied forces needed for design. The provisions result in design values that are not risk consistent, particularly when applied to other structural systems [1]. Further, the wind load standards offer no information on wind loading so that influence-function-dependent wind effects can be calculated for structural systems that differ from that assumed in the original wind tunnel tests [1].

In its present form, the wind load standard does not allow explicit consideration of spatio-temporal wind load effects and local climatological data on structural behavior. However, including such flexibility within the wind design standard is impractical because the document would become bulky with overly complex provisions.

1.1. Database-assisted design methodology

The database-assisted design (DAD) methodology was developed for use on computers in structural design offices to

* Corresponding author.
E-mail address: dprev@ce.ufl.edu (D.O. Prevatt).

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doi:10.1016/j.engstruct.2010.11.028

simplify the manipulation of large databases of wind design information. The DAD methodology has three main components: (a) aerodynamic databases containing wind pressure time histories, (b) climatological databases containing historical wind speed and direction for a location, and (c) databases of structural influence coefficients to predict internal structural responses to wind loads. In the DAD framework, structural responses are numerically calculated in the following manner:

$$R_{\theta,j} = 1/2\rho V_H^2 \sum \left[N_{ij} A_i C_{p,\theta,i}\right] \quad (1)$$

where j is the reaction location; i is the pressure tap position; $R_{\theta,j}$ is the instantaneous structural response for a wind direction θ at the j-th reaction; ρ is the air density; V_H is design wind speed at building roof height; N_{ij} is the influence coefficient at the i-th pressure tap for j-th reaction; A_i is the tributary area of i-th pressure tap; and C_p is the instantaneous pressure coefficient for a wind direction θ at i-th pressure tap. With this simple approach, relying on wind-tunnel derived pressures over a building's surface and knowledge of structural load paths, reasonably accurate and risk-consistent structural reactions may be obtained.

The DAD method develops the time history of pertinent structural reactions from which the design values are determined. By knowing the influence coefficients (or influence surfaces) of specific load effects (i.e. bending moment, vertical reaction, torsion, etc.), the design wind structural responses can be determined for any component within the structure. The application of the DAD approach in practice requires software to facilitate its implementation. One example of a computer program to implement the DAD method, called *wind* PRESSURE [3], is a MATLAB-based software package for rigid, gable-roofed buildings which is in the public domain (see [4]). It uses pressure time series measured in a wind tunnel in conjunction with structural influence coefficients to compute peak values of the structural responses of interest (e.g., shear forces, bending moments, and displacements at various locations). In addition to the downloadable software from NIST, wind tunnel pressure databases for a few generic low-rise structures and influence coefficients for load effects in a steel portal framed building are also available.

A similar wind design approach, under development at the University of Notre Dame, will enable preliminary design of high-rise buildings subjected to wind loads, utilizing archives of experimental data from high frequency force balance measurements to predict overall building reactions [5].

1.2. Motivation for using DAD wind design approach

Coffman et al. [6] illustrated that simplifications in the wind design provisions of ASCE 7-05 [2] produces risk-inconsistent results for wind loading by comparing peak bending moments for steel portal framed industrial buildings calculated using the *wind* PRESSURE software and the ASCE 7-05 Analytical Method. In their study, the bending moments induced by incident winds from 36 wind directions were determined and the largest overall positive and negative moments at key locations (knee, pinch, and ridge of the portal frame) were identified. In the case of bending moment at the knee of the portal frame, Coffman et al. showed that the DAD technique yields moments that were generally 10%–40% larger than values obtained using ASCE 7-05, calculated per the main wind force resisting system. These non-conservative values provided by the ASCE 7-05 analysis occurred consistently in other locations, while the extent of under-estimation varied widely (from 15% to 70%). Despite the proposition that DAD predicts wind design loads on low rise buildings with better accuracy than current design standards, its application has been limited because wind pressure databases are not available for many building geometries and the influence functions, particularly for wood-framed buildings, are generally unknown.

There has been growing interest in understanding the structural load paths in light-frame wood structural systems. Several researchers have conducted full-scale experiments [7–9], scale model experiments, and analytical studies to understand wind load paths [10–12].

1.3. Objective of the study

The purpose of this study is to evaluate the applicability of the DAD approach for wind design of light-frame wood structures (LFWS). Structural influence coefficients (surfaces) were experimentally determined on a 1/3-scale wood-framed model of a gable-roof building. To validate the DAD approach for LFWS, the model building was subjected to a wind flow while simultaneously measuring pressures on the roof and wall and structural reactions at critical locations. Structural reactions were predicted using the measured wind pressures and the influence coefficients via a DAD-based MATLAB program and compared to the directly measured reactions. Furthermore, wind pressure time series on a 1/50-scale model of the prototype building were determined in an atmospheric boundary layer wind tunnel for five wind azimuths and used to predict structural reactions. DAD-based predictions were compared to structural reactions estimated based on ASCE 7-05 provisions. A flowchart of the components of the study is presented in Fig. 1. This research is part of a three-university collaborative study to better understand structural load paths in light-framed wood structural (LFWS) buildings, with the overarching goal to develop a performance-based design methodology for wind-loading on light-frame wood structural systems [13].

2. Experimental validation of DAD method for a LFWS system

2.1. Wood house/instrumentation

A 1/3 scale wood structure was built to represent a prototype structure with a rectangular floor plan of 12.2 m by 9.2 m (40 ft by 30 ft), ridge height of 4.2 m (13.8 ft), a 4 in 12 sloped-gable roof, and roof eaves extending 0.45 m (18 in.) beyond the exterior walls. The model framing member sizes were established using non-dimensional geometric scaling laws [14,15], with cross-sections of 12.7 mm by 29.7 mm (0.5 in. by 1.17 in.) representing a typical nominal 2 × 4 framing member. The structure was built using typical materials used in residential construction in the southeastern United States: southern yellow pine for roof trusses and spruce-pine-fir for wall studs. The roof and wall sheathing used on the model was 6.4 mm (0.25 in.) oriented strand board, scaled to represent the 12.7 mm (0.5 in.) thick OSB used at full scale. The walls have external sheathing only with no window or door openings. Typical spacing of the model scale roof trusses was 200 mm (8 in.) o.c. and the wall studs were spaced at 133 mm (5.3 in.) o.c. The building model (Fig. 2) has a rectangular floor plan measuring 3 m (10 ft) wide by 4.1 m (13.3 ft) long and a ridge height of 1.4 m (4.6 ft).

Twenty-one ±1300 N (300 lb) capacity uniaxial load cells were installed in the model house at critical locations: twelve at roof-to-wall connections and nine at the wall-to-foundation connections (Fig. 3(a)). Twenty-nine pressure taps were also installed: twenty-five distributed on the roof near the gable end and four installed in the walls — two in the side wall and two in the gable end wall (Fig. 3(b)). The pressure taps were connected to differential transducers (±6.9 kPa or ±1 psi) via 152.4 mm (6 in.) long, 4.8 mm (0.19 in.) inside diameter (ID) vinyl tubing. The load cells were connected to signal conditioners and signal amplifiers to increase the accuracy of the readings. After passing through the signal amplifiers, a data acquisition unit recorded the signals using a laptop connected via USB running a National Instruments LabVIEW data acquisition program.