Interpolation procedures for database-assisted design

Joseph A. Main

Building and Fire Research Laboratory, National Institute of Standards and Technology, 100 Bureau Drive, Stop 8611, Gaithersburg, MD, USA

ABSTRACT: Database-assisted design (DAD) is a methodology of designing structures for wind loads that makes direct use of pressure time series from wind tunnel tests. This paper presents interpolation procedures that enable application of the DAD approach for cases in which a wind tunnel model with matching dimensions is not available in the aerodynamic database. The procedures make use of pressures measured on models with differing dimensions by scaling the pressure tap coordinates to match the dimensions of the structure of interest. A fairly simple multi-dimensional interpolation scheme is presented to estimate peak responses for the structure of interest from peak responses computed using pressure measurements from several different building models. Several interpolation test cases are presented, which indicate that the proposed methodology can give quite accurate predictions of peak structural responses.

KEYWORDS: Database-assisted design, Wind loads, Interpolation; Low buildings.

1 INTRODUCTION

Database-assisted design (DAD) (e.g., [1], [2]) is a methodology of designing structures for wind loads that makes direct use of pressure time series from wind tunnel tests, rather than using simplified tabular representations of such measurements as in existing standards. This approach holds promise to enable the design of structures that are more risk-consistent and potentially more economical. To facilitate use of the DAD approach, an aerodynamic database is being assembled at the National Institute of Standards and Technology (NIST), containing measured pressure time series for a large number of building models with different dimensions. As part of this database, approximately 38 gable-roofed building model variations have been tested to date at the University of Western Ontario (UWO) [3], making the database considerably more comprehensive than the original data set on which current North American wind load standards are based. However, establishment of DAD as a broadly applicable methodology requires a reliable means of interpolation, to enable prediction of internal forces for cases in which the building dimensions to not precisely match the dimensions of an available wind tunnel model in the database.

Interpolation schemes proposed previously have aimed at interpolating pressure time series between those measured on different models [4], and artificial neural networks have been used in an effort to capture the complex nonlinear dependence of the measured pressure coefficients on building geometry, wind direction, and tap location [5]. This paper describes an alternative approach for interpolation, in which peak structural responses (e.g., bending moments and axial forces) are interpolated rather than wind pressures, thus eliminating the necessity of explicitly accounting for spatial and temporal correlations in the interpolation scheme. An overview of the proposed methodology is first presented, and then several interpolation test cases are presented, which indicate that the proposed methodology can give quite accurate predictions of peak structural responses.

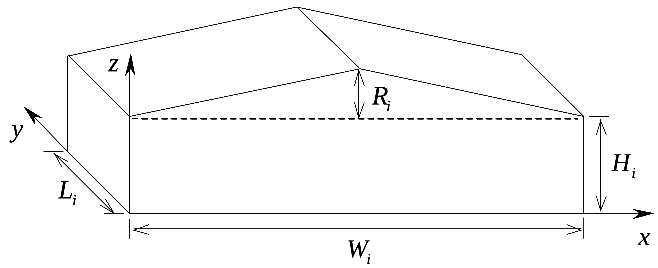

Figure 1. Schematic of gable-roofed building model with full-scale dimensions indicated.

2 OVERVIEW OF PROPOSED METHODOLOGY

The proposed methodology can be summarized as follows:

1. One or more building models are selected, whose dimensions most closely match the dimensions of the building of interest. A vector $\mathbf{d}_i$ is introduced to represent the geometry of the ith building model:

   $$\mathbf{d}_i = \begin{bmatrix} H_i / z_{0i} & L_i / W_i & H_i / W_i & \beta_i \end{bmatrix}^T \tag{1}$$

   where $\beta_i = \tan^{-1}(2R_i / W_i)$ is the roof slope (in degrees); W_i, L_i, H_i, and R_i are shown in Figure 1; and z_{0i} is the terrain roughness length. The index $i = 0$ is used to denote the dimensions of the building of interest, and a vector of deviations in the dimensions of the ith model can then be defined as

   $$\Delta\mathbf{d}_i = \mathbf{d}_i - \mathbf{d}_0 \tag{2}$$

   The components of $\Delta\mathbf{d}_i$ can be scaled by empirically determined factors that represent the sensitivity of building aerodynamics to changes in each component:

   $$\Delta\tilde{\mathbf{d}}_i = \mathbf{S}\Delta\mathbf{d}_i \quad \text{where} \quad \mathbf{S} = \mathrm{diag}(S_1, S_2, S_3, S_4) \tag{3}$$

   The scaled deviation vectors $\Delta\tilde{\mathbf{d}}_i$ are then used in selecting the building models whose dimensions match most closely, as well as in the interpolation of step 3.
2. For each of the selected building models, the archived pressure time series are loaded. The pressure time series are used in conjunction with influence coefficients for the structural responses of interest to estimate peak values of the structural responses for a unit wind speed from each direction at eave height. These peak responses are called Directional Influence Factors (DIFs) and can be represented as a matrix $\mathbf{X}_i^{peak}$, where the rows correspond to different responses, the columns correspond to different wind directions, and the subscript $i = 1, 2, \ldots, b$ denotes the number of the building model. In transforming the measured pressures to structural loads, the tap coordinates (illustrated in Fig. 2) are scaled to match the dimensions of the structure of interest and the pressures are distributed accordingly. With the coordinate system as shown in Figure 2, the scaled tap coordinates $(\tilde{x}, \tilde{y}, \tilde{z})$ are obtained from the original tap coordinates (x, y, z) as follows:

$$\tilde{x} = \frac{W_0}{W_i} x\,; \quad \tilde{y} = \frac{L_0}{L_i} y\,; \quad \tilde{z} = \begin{cases} (H_0 / H_i) z & , \; z \le H_i \\ H_0 + (R_0 / R_i)(z - H_i), & z > H_i \end{cases} \tag{4}$$

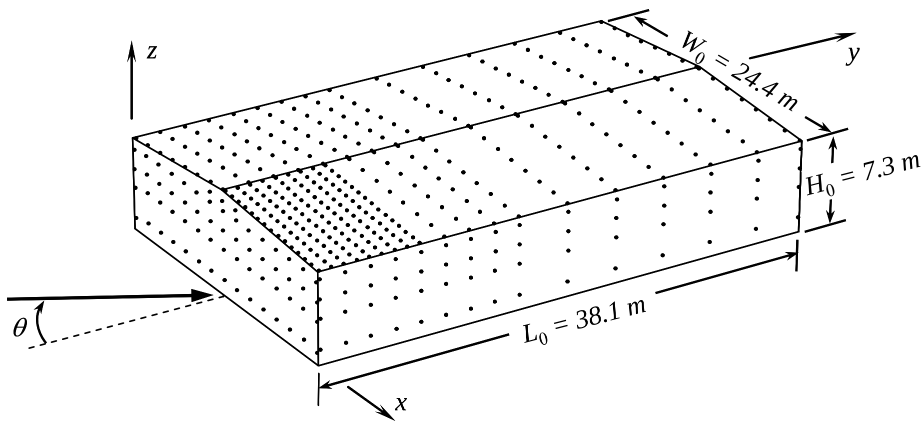

Figure 2. Perspective view of wind tunnel model showing tap locations, wind direction θ, and full-scale building dimensions (1:12 roof slope).

3. A best estimate of the DIF matrix for the building of interest is then obtained as a weighted average of the DIF matrices from the different building models as follows:

$$\tilde{\mathbf{X}}^{peak} = \sum_{i=1}^{b} \gamma_i \mathbf{X}_i^{peak} \quad \text{where} \quad \gamma_i = \left(\sum_{k=1}^{b} \frac{\left\| \Delta\tilde{\mathbf{d}}_i \right\|}{\left\| \Delta\tilde{\mathbf{d}}_k \right\|} \right)^{-1} \tag{5}$$

The interpolation scheme of Eq. (5) gives greater weight to models whose dimensions more closely match the building of interest, and it is noted that for one-dimensional interpolation with two building models ($b = 2$), Eq. (5) reduces to simple linear interpolation (see [2]).

3 INTERPOLATION TEST CASES

To evaluate the accuracy of the proposed interpolation methodology, pressure data are used from nine different building model variations tested at UWO, with dimensions listed in Table 1. Using these data, four interpolation test cases are considered, as listed in Table 2. In each test case, the goal is to predict peak structural responses for a building with the full-scale dimensions of model 0, given in the first row of Table 1, using pressure data from two models with different dimensions. Because these interpolation test cases consider differences in only one component of $\mathbf{d}_i$ at a time (or two components varied according to a fixed ratio in case D), the relative magnitude of the sensitivity factors in Eq. (3) has no influence on the interpolation of Eq. (5), and $\mathbf{S}$ can simply be set to the identity matrix in evaluating the scaled deviation vectors, so that $\Delta\tilde{\mathbf{d}}_i = \Delta\mathbf{d}_i$. These test cases can be used in assessing appropriate values of the sensitivity factors in $\mathbf{S}$ to be used for more complex cases of interpolation, and such efforts are currently in progress.

In evaluating structural responses, a structural system consisting of six frames equally spaced at 7.6 m (25 ft) intervals is considered, as shown in Figure 3. The structural response of interest is the bending moment at the left knee of the first interior frame, for which influence coefficients are shown in Figure 4. Figure 5 shows maximum values of this bending moment plotted against the wind direction θ, defined as shown in Figure 3. In each interpolation test case, errors can be assessed by comparing the interpolated value with the "true" value computed using pressure data from model 0. The maximum and root-mean-square (RMS) errors over all wind directions are presented in Table 2 for each case. Figure 5 and Table 2 show that the interpolated peak bending moments are quite accurate in general, being best in case D (models with different eave heights) and worst in case C (models with different roof slopes). In all cases the maximum errors are less than 15 %, and the RMS errors are less than 6 %.

Table 1. Full-scale dimensions of models used in interpolation test cases (1:200 scale).

Model number, i	Width, W_i	Length, L_i	Eave Height, H_i	Roof Slope, β_i
0	24.4 m (80 ft)	38.1 m (125 ft)	7.3 m (24 ft)	4.8° (1:12)
1	12.2 m (40 ft)	19.1 m (62.5 ft)	3.7 m (12 ft)	4.8° (1:12)
2	36.6 m (120 ft)	57.2 m (187.5 ft)	12.2 m (40 ft)	4.8° (1:12)
3	12.2 m (40 ft)	19.1 m (62.5 ft)	7.3 m (24 ft)	4.8° (1:12)
4	36.6 m (120 ft)	57.2 m (187.5 ft)	7.3 m (24 ft)	4.8° (1:12)
5	24.4 m (80 ft)	38.1 m (125 ft)	7.3 m (24 ft)	1.2° ($\frac{1}{4}$:12)
6	24.4 m (80 ft)	38.1 m (125 ft)	7.3 m (24 ft)	14° (3:12)
7	24.4 m (80 ft)	38.1 m (125 ft)	4.9 m (16 ft)	4.8° (1:12)
8	24.4 m (80 ft)	38.1 m (125 ft)	9.8 m (32 ft)	4.8° (1:12)

Table 2. Interpolation test cases and corresponding errors in interpolated bending moment. (Error percentages are referenced to the maximum bending moment computed using the "true" pressure data from model 0, which is 333 N·m.)

Interpolation test case	Selected models	Maximum error	RMS error
A	1, 2	28 N·m (8.3 %)	9.1 N·m (2.7 %)
B	3, 4	45 N·m (13 %)	16 N·m (4.7 %)
C	5, 6	47 N·m (14 %)	19 N·m (5.6 %)
D	7, 8	20 N·m (6.2 %)	6.1 N·m (1.8 %)

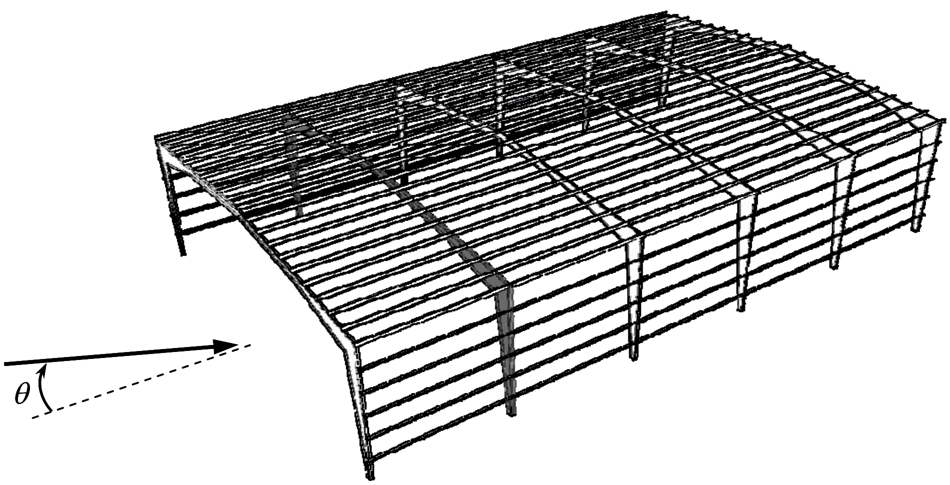

Figure 3. Perspective view of structural system showing frames, girts, and purlins (first interior frame highlighted).

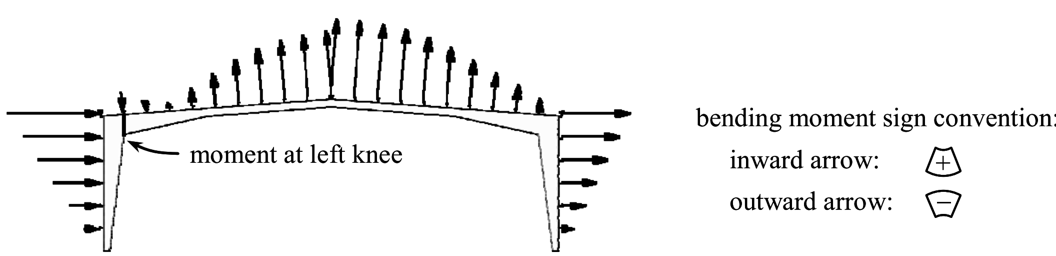

Figure 4. Influence coefficients associated with bending moment at left knee. Vectors show bending moments resulting from a unit force *inward* at each girt/purlin location.

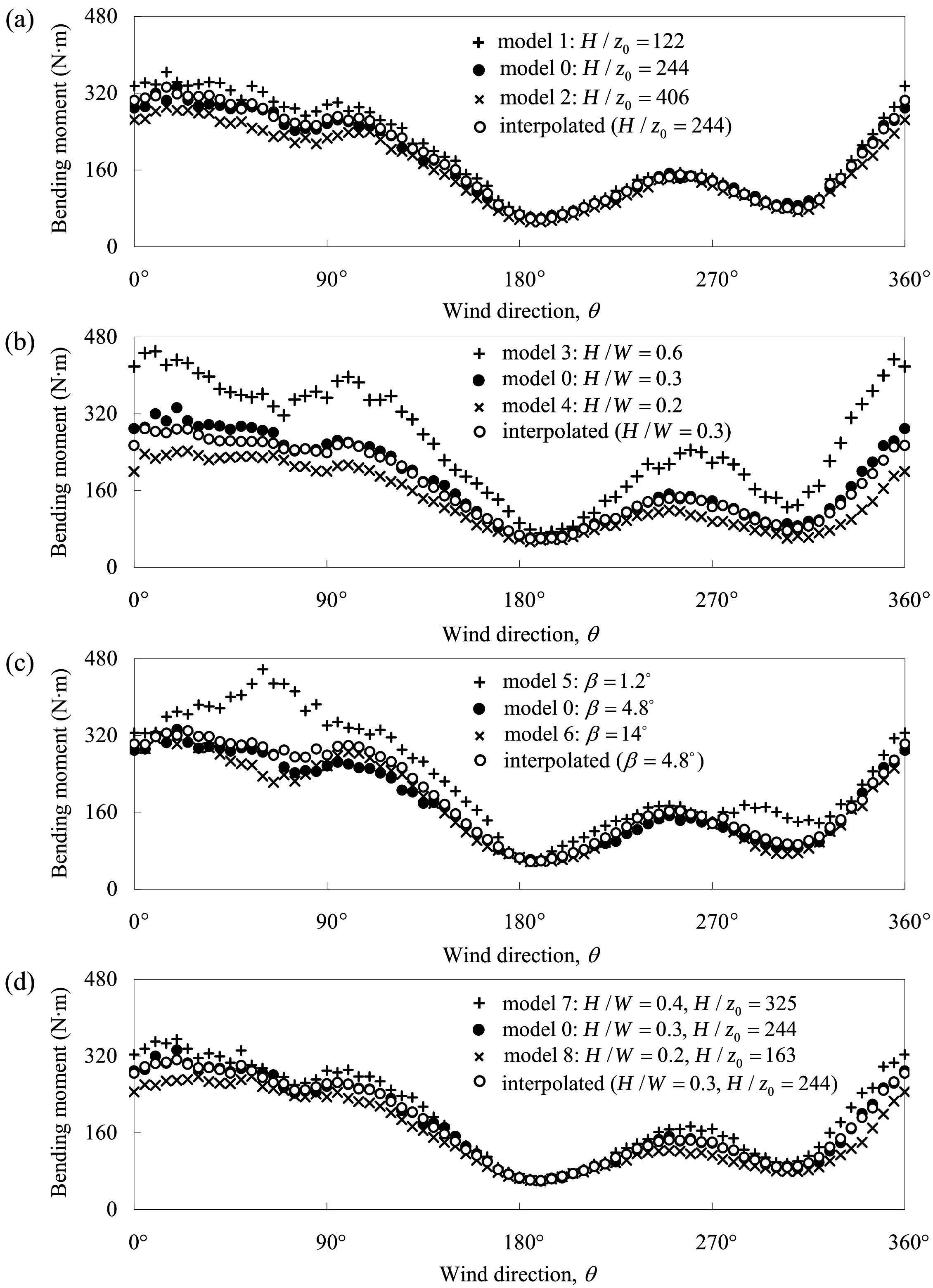

Figure 5. Maximum values of bending moment at the left knee of the first interior frame for the four interpolation test cases of Table 2: (a) case A; (b) case B; (c) case C; (d) case D. (Values correspond to an hourly averaged wind speed of 1 m/s at eave height.)

4 CONCLUDING REMARKS

Interpolation procedures have been presented that enable prediction of peak structural responses using pressure time series measured on several different wind tunnel models with dimensions that differ from those of the structure being designed. The peak structural responses are estimated as a weighted average of the peak responses computed using pressure data from each model, with greater weight being given to results from models with more closely matching dimensions. Four interpolation test cases were presented, which illustrated that the proposed approach can give quite accurate predictions. In all cases considered, the maximum errors were less than 15 %, and the RMS errors were less than 6 %. Efforts are currently underway to test the interpolation scheme for deviations in multiple building dimensions and to establish bounds its applicability.

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