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Time-domain wind-induced damage estimates for building structures

Mihail Iancovici [1], George Bogdan Nica [2], Radu Văcăreanu [3], Georgiana Ionică [4]

[1] *Technical University of Civil Engineering Bucharest, Romania, mihail.iancovici@utcb.ro*
[2] *Technical University of Civil Engineering Bucharest, Romania, george.nica@utcb.ro*
[3] *Technical University of Civil Engineering Bucharest, Romania, radu.vacareanu@utcb.ro*
[4] *Technical University of Civil Engineering Bucharest, Romania, georgiana.ionica@utcb.ro*

SUMMARY:
Higher-level damage, fragility, and loss estimates analysis modules for building structures are under development thanks to efficient Nonlinear Dynamic Analysis (NDA) solvers. The Force Analogy Method (FAM)- based computational package handles long duration records from wind tunnel measurements and provides the inelastic response and the associated structural damage states. These are straightforward provided in time-domain with reasonable required analyses accuracy and duration. A probabilistic fragility analysis for wind loads based on the Incremental Dynamic Analysis (IDA) approach is performed for an 80 metres tall, flexible RC building.

Keywords: wind speed, damage, fragility

1. INTRODUCTION

Significant economic losses and societal disruptions due to extreme wind-induced damage to civil infrastructure, generates a strong social demand to turn the current design practice into a resilience-based design one. The analysis end-product will provide in a not-too-distant future, loss estimations and associated repairing cost, as well as functional recovery duration estimates.

The Database-Assisted Design (DAD) for tall, flexible, linear-elastic behavior building structures developed in early 2000 (Diniz et al., 2004; Simiu et al., 2008), provides accompanying softwares (Main and Fritz, 2006; Yeo and Simiu, 2011; Iancovici, 2019). For nonlinear problems however, most of the numerical solvers fail to handle long-duration time-histories of wind loads. An efficient numerical algorithm based on Force Analogy Method (FAM; Lin, 1968; Hart and Wong, 1999) incorporated in a MATLAB-based computational platform, efficiently captures the inelastic structural behavior of building structures (Iancovici et al., 2022a&b). This opens new frontiers for structural wind-induced damage evaluation and loss estimation, as key-components for a resilience-based design, in a further unified seismic- and wind- Performance-Based Design (PBD) framework (ASCE, 2019).

In this paper, the integrated analysis platform consisting of linked-in modules like wind tunnel aerodynamic test data and nonlinear dynamic response analyses, that efficiently generate damage estimations at section, member, story, and structural level, is presented. The Incremental Dynamic Analysis (IDA) approach (Vamvatsikos and Cornell, 2002) is used then to perform probabilistic structural fragility analyses for an 80 m height typical building structure.

2. WIND LOADS FROM WIND TUNNEL MEASUREMENTS

Simultaneous wind pressures time-histories corresponding to eleven wind blowing directions ($\theta_w = 0^o$ to 50^o), recorded in the wind tunnel (Wind Engineering Research Center from Tokyo Polytechnic University work highly acknowledged) are used in the analyses. A total number of 200 pressure taps (50 taps for each side) are placed on a 1/400 scale rigid model façades. The prototype building has a square plan shape of $40\,m$ total span and $80\,m$ height (Figure 1). Typical mean wind pressure coefficients distribution is given in the Figure 1 for $\theta_w = 0^o$ wind blowing direction (*y*- direction), corresponding to 80 minutes duration for the prototype building.

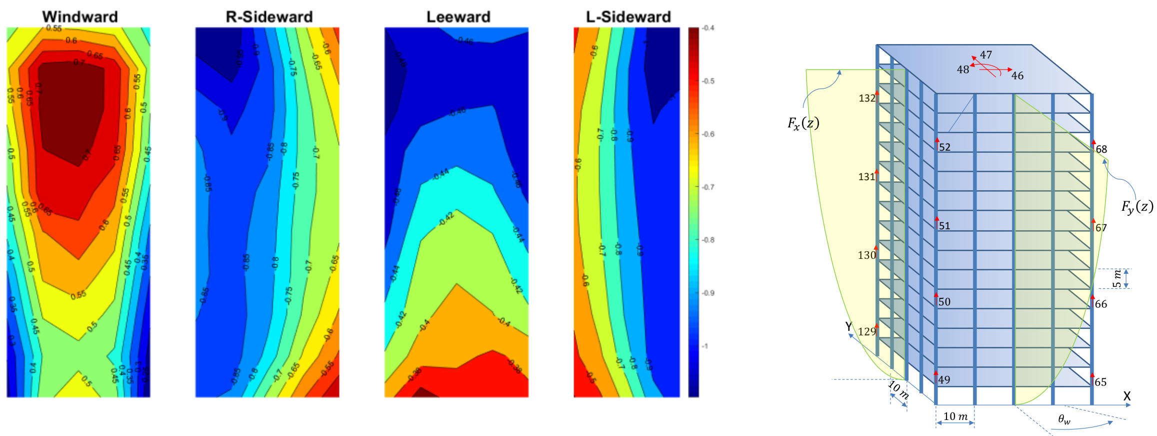

Figure 1. Mean wind pressure coefficients distribution $(\theta_w = 0^o)$ and the prototype structural model

3. DYNAMIC RESPONSE ANALYSIS

Force Analogy Method- FAM (Lin, 1968; Hart and Wong, 1999) is used to efficiently solve the nonlinear equations of motion and to further provide the whole range of engineering response parameters for the higher-level analysis modules. The technical background and the features of 3D-FAM package developed by the Structural Dynamics Group at UTCB are given in Iancovici et al. (2022a).

The principle of FAM is to update the displacement vector at any integration time-step, rather than the stiffness matrix. The total displacement vector $\boldsymbol{u}$ of the structure is expressed as a sum of two components i.e., the pseudo-elastic displacements vector- $\tilde{\boldsymbol{u}}$ and the inelastic displacements vector- $\boldsymbol{u}''$ (Hart and Wong, 1999),

$$\boldsymbol{u} = \tilde{\boldsymbol{u}} + \boldsymbol{u}'' \tag{1}$$

The inelastic displacement component is transferred to the right-hand side of the system's equation of motion, and viewed as a force correction vector at any integration time-step i.e.,

$$\boldsymbol{M}\ddot{\boldsymbol{u}}(t) + \boldsymbol{C}\dot{\boldsymbol{u}}(t) + \boldsymbol{K_0}\boldsymbol{u}(t) = \boldsymbol{F}(t) + \boldsymbol{K_0}\boldsymbol{u}''(t) \tag{2}$$

where, $\boldsymbol{K_0}$ is the elastic stiffness matrix of structure and $\boldsymbol{F}(t)$ is the wind load vector.

3.1. Case study

The prototype building is a typical 16 stories RC flexible frame structure (Figure 1). The structural plan layout consists of four regular spans of $10\,m$ and a story height of $5\,m$. The cross-section of columns is $1.8\,x\,1.8\,m$, and the beams are of $0.9\,x\,0.5\,m$ cross section. The plasticity model is concentrated at the members ends, the plastic hinges are modelled with bilinear $M - \theta$ relationship (2% post-yield stiffness degrading ratio) and associated interaction surface. The natural vibration periods for the fundamental modes yield $T_{1x} = T_{1y} = 2.91\ s$ (sway) and $T_{1\theta} = 2.49\ s$ (torque). For each wind blowing direction and load increment with respect to the mean hourly wind speed at the top of the prototype building- ranging from $\overline{U}_{H,p} = 50\ m/s$ to $80\ m/s$, NDA provides the most unfavourable loading conditions and the dynamic pushover curves to further developing the fragility analysis (Figure 2, 3 and 4).

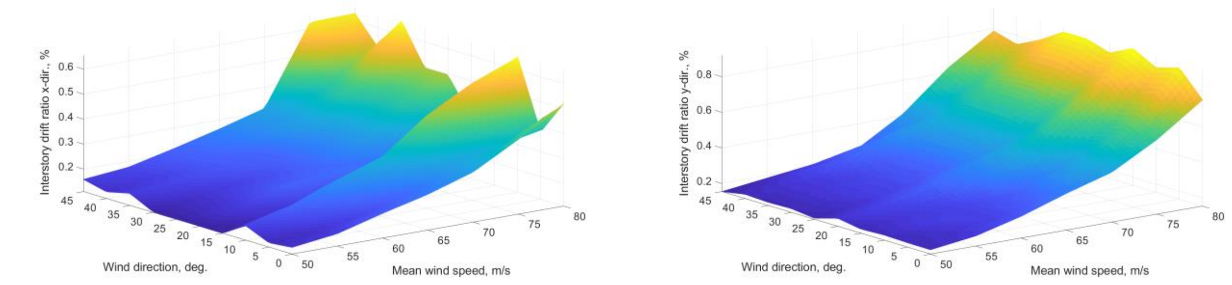

Figure 2. Wind directionality and load intensity effects on the peak interstory drifts

4. DAMAGE EVALUATION AND PROBABILISTIC FRAGILITY ANALYSIS

The damage index proposed by Park and Ang (1985) is motly used in seismic applications. The member, story and structural damage index is computed from the sectional response and inelastic properties (Park et al., 1987). Typical time-domain structural damage accumulation, as well as the wind directionality and load intensity effects on the associated damage level are represented in the Figure 3.

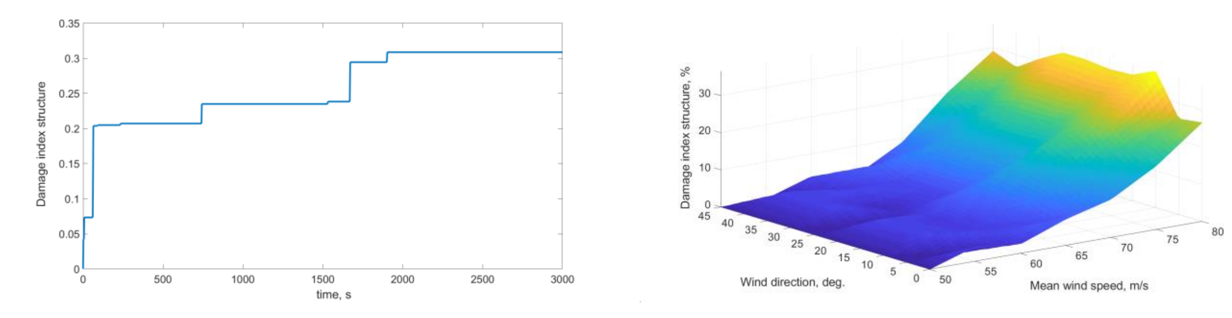

Figure 3. Time-domain structural damage accumulation ($\overline{U}_{H,p} = 80\ m/s$ and $\theta_w = 15^o$; left figure), and wind directionality and intensity effects on the peak structural damage index (right figure)

The probabilistic fragility analysis of structures is currently based on HAZUS methodology. Thus, the story fragility functions are modelled as cumulative log-normal distributions given the median and log-standard deviation of mean wind speed at the top of the building. The intra- and inter-event variability are directly accounted for.

Damage states are identified in this paper, based on IDA approach, by correlating the maximum interstory drift ratio and associated damage indices. Thus, Immediate Occupancy-IO (0.2%), Life Safety-LS (1%) and Collapse Prevention-CP (2.5%) limit states associated values are proposed for the current building. Typical story fragility functions and the structural fragility function are represented for the Immediate Occupancy damage state in the Figure 4.

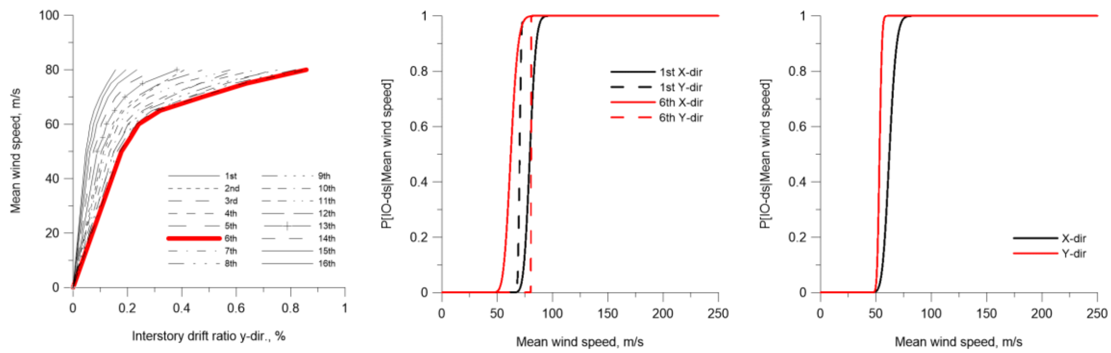

Figure 4. Story median IDA curves, story and structural fragility functions corresponding to Immediate Occupancy (IO) damage state

Once available, the fragility functions are further used to estimate the wind-induced losses, associated repair costs and duration for function recovery, for various wind scenarios.

4. CONCLUSIONS

FAM-3D nonlinear dynamic analysis-based software package provides fast and accurate results for buildings subjected to wind loads as a major step towards creating a resilience-based structural design framework.

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