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AI-driven topology optimization framework for tall buildings subjected to dynamic wind excitation

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SUMMARY:
The structural design procedure of buildings goes through time-consuming iterations, especially at the preliminary design stage, where a structural layout is predefined based on the designers' experience and architectural considerations, which might not yield an optimal design. This procedure becomes more complicated for tall buildings where an adequate Main Wind Force Resisting System (MWFRS) layout needs to be designed. MWFRS design includes both layout (e.g., cores or peripheral shear walls) and structural element sizes (e.g., shear wall length). This paper presents a multiobjective AI-driven topology optimization framework for tall buildings subjected to dynamic wind loads to find an optimal shear wall layout based on the required objective functions (e.g., MWFRS weight). An automated time history analysis for a wind-excited building is conducted to prepare a database for surrogate model training. An Artificial Neural Network (ANN)-based surrogate model is created using a prepared database of structural responses. This model is coupled with a genetic algorithm to identify the optimal layout of shear walls within the predefined architectural and structural constraints. The developed framework managed to reduce the weight of the required shear wall elements with an adequate distribution of straining actions and minimum eccentricity.

Keywords: Topology optimization, Wind load, Tall building.

1. INTRODUCTION

Tall buildings are increasingly becoming taller and more slender, necessitating more efficient structural systems. In 2019, a new record was set with the construction of 126 tall buildings exceeding 200 meters, as reported by (CTBUH, 2019). The design process of tall buildings typically goes through a time-consuming iterative procedure to ensure the cost efficiency of the proposed structural system. Therefore, structural optimization frameworks have been developed to minimize the cost of proposed structural systems. Structural designers follow two main optimization philosophies when designing tall buildings to withstand such loads (Lee et al., 2012). The first approach involves reducing wind loads through changes in the building's shape (i.e., outer shape optimization), as studied by (i.e., outer shape optimization) (Bernardini et al., 2015; Elshaer and Bitsuamlak, 2018; Kareem et al., 2013). The second approach, which is the focus of this study, is optimizing the Main Wind-Force Resisting System (MWFRS) through structural optimization. This approach aims to determine the optimal system and layout configuration (e.g., shear walls, cores, bracing systems) to achieve the desired performance of the building at the least cost and/or to improve structural performance. For instance, (Bobby et al., 2014) employed Monte Carlo simulations to develop a performance-based topology optimization framework for tall buildings, utilizing an approximate static subproblem for the vertical layout of the bracing system. (Luo et al., 2017) extended this framework to consider 3D performance-based topology optimization problems with dynamic wind loads obtained from boundary layer wind tunnel tests. Meanwhile, most of this research focused on the vertical layout of the MWFRS. However, a limited contribution was found to consider the dynamic wind load for the horizontal layout of the MWFRS, noting that some layouts' dynamic loads show lower responses than the correlated static loads (Alanani and Elshaer, 2022).

This paper provides a multiobjective Main Wind-Force Resisting System (MWFRS) (i.e., shear walls) layout optimization framework for dynamically sensitive tall buildings subjected to dynamic wind load. An experimentally validated CFD model is adopted to generate the required wind load time history that will be used to prepare a FEM database for developing a surrogate model that can capture the structural response of a time history analysis. The developed framework relies on an ANN-surrogate model through a non-gradient optimization algorithm for objective functions and constraints evaluation due to the discontinuity and complexity of modelling the governing equations for such structures.

2. STRUCTURAL-WIND OPTIMIZATION FRAMEWORK (SWOF)

The developed Structural Wind Optimization Framework (SWOF) has been previously used for optimizing tall buildings subjected to static wind load (Alanani and Elshaer, 2023). In this study, SWOF is expanded to include multiple objective functions to enhance the quality of the produced optimal layout and provide varieties for structural designers to choose from. In addition, the dynamic behaviour of wind loads is also included within SWOF to capture more accurate structural behaviour that could not be achieved using static wind loads. Although this study will focus on the shear wall layout, SWOF is developed generically to incorporate different materials and structural systems. As shown in Figure 1, a flowchart represents the procedure of structural wind optimization. The procedure starts with defining the optimization problem, which includes identifying the objective functions (i.e., fitness functions). The optimization algorithm adopts six objective functions in SWOF for evaluating generated random samples defined in Table 1.

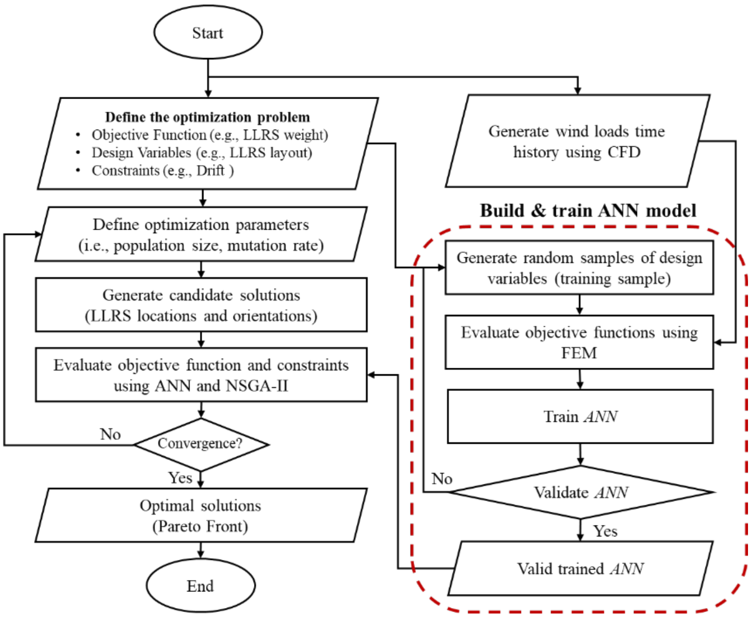

Figure 1. Structure wind optimization framework (SWOF) flowchart

Table 1. Objective functions definition

Objective Functions	Notation
Total number of shear wall segments	$\sum_{i=1}^{N} S_i$
Total number of piers	N_P

Torsional effect (Eccentricity)	$e_{C_M C_R} = \sqrt{(X_{C_R} - X_{C_M})^2 + (Y_{C_R} - Y_{C_M})^2}$
The minimum demand-to-capacity ratio	D/C_{min}

The last part of problem definitions is the constraints, where design code limitations are also included as constraints in addition to architectural constraints and any supplementary parameters required by the designer. In this paper, interstorey drift is considered a constraint in both X-direction (δ_x) and Y-direction (δ_y) with a limit of 0.2% based on (NBCC, 2020). In addition to the maximum demand-to-capacity ratio (D/C_{max}) that should not exceed a value of 1.

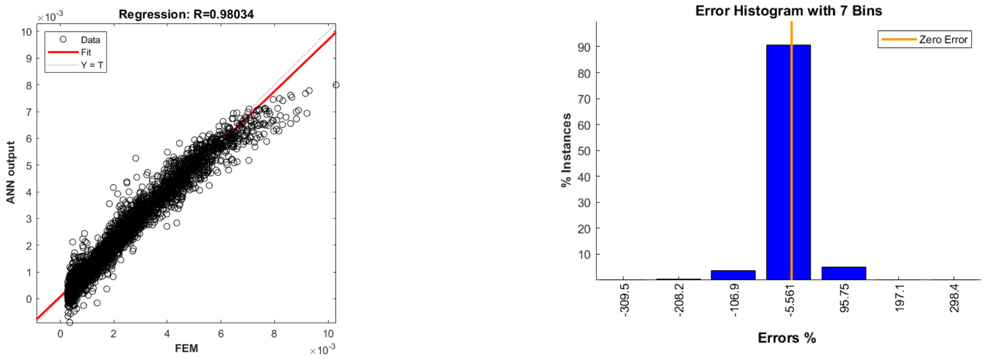

Figure 2 Regression coefficient and error histogram for intersorey drift in Y-direction

In this study, a forward-propagation neural network is utilized to determine the functions used as objective functions and constraints. The Bayesian regularization backpropagation algorithm is adopted to update the weight and bias values based on Levenberg-Marquardt optimization. The neural network minimizes a combination of squared errors and weights to produce a generalized network. The input layer consists of 170 neurons that accept binary values representing possible locations of shear wall segments, while the output layer consists of one neuron representing the structural response value. The number of hidden layers and their sizes are determined based on the complexity of each function. Sensitivity analysis is carried out to determine the training sample size, and the regression coefficient (R) is used as an indicator of the ANN's performance. For example, the correlation coefficient between the FEM database and the ANN model of insterstorey drift in the Y-direction, δ_y, is found to be 0.98, as shown in Figure 2. While the error distribution in the testing samples is analyzed, and the results show that ~90% of the samples have an error of less than a 6%. Overall, the developed ANN models show promising performance in predicting the output of various functions.

3. RESULTS AND DISCUSSION

An evolutionary algorithm called nondominated sorting genetic algorithm II (NSGA-II) is chosen to tackle the presented multiobjective problem. NSGA-II relies on numerous objective function evaluations by altering design variables systematically using mutation and crossover operators until a group of optimal solutions are found called the "Pareto Front". This Pareto Front is found through sorting procedures based on non-dominated ranking and crowd distance sorting, as shown in Figure 3. SWOF's powerful approach is in tackling various parameters that affect the layout. For instance, the demand-to-capacity ratio (D/C) where SWOF maximize the D/C_{min} of generated shear wall layout, while at the same time maintaining the maximum value of the $\boldsymbol{D/C}$ to their limit (i.e., 1) to assure that the majority of the capacity of the generated shear walls is efficiently used. As shown in Figure 4, one of the optimal solutions found on the Pareto Front is presented where only 15 piers are formulated. It also shows how the SWOF is capable of recognizing the moment of inertia concept without explicitly defining it through the developed code Moreover, using ANN as a surrogate model proved its efficiency in capturing complex variations in objective functions and constraints with a correlation coefficient that ranges between 90% to 98% and make it possible to explore numerous layouts in an affordable computational time.

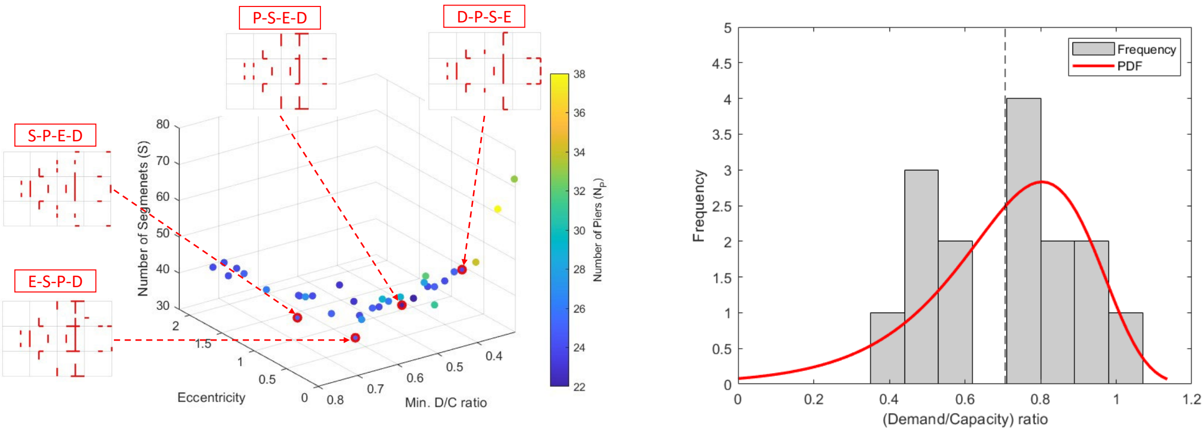

Figure 3 Pareto Front optimal layouts and corresponding objective function values, and Histogram of the demand-to-capacity ratio of all piers of the optimal solution

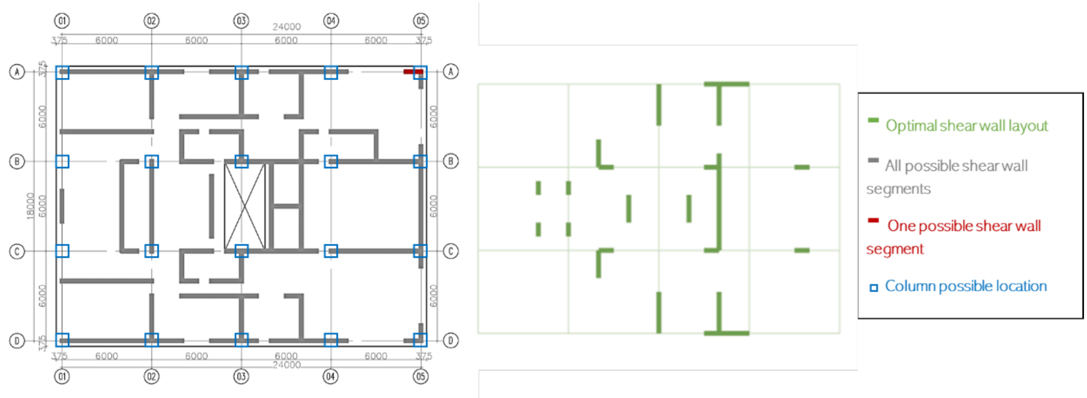

Figure 4. SWOF optimal shear wall layout result

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