Engineering Structures 140 (2017) 225–240

Contents lists available at ScienceDirect

Engineering Structures

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

Shear wall layout optimization for conceptual design of tall buildings

Yu Zhang *, Caitlin Mueller

Massachusetts Institute of Technology, Department of Civil and Environmental Engineering, 77 Massachusetts Ave, Cambridge, MA 02139, United States

A R T I C L E I N F O

Article history:
Received 7 December 2016
Revised 13 February 2017
Accepted 22 February 2017

Keywords:
Conceptual structural design
Structural optimization
Topology optimization
Shear wall design
Reinforced concrete

A B S T R A C T

In the design of tall buildings, the lateral system that resists wind and seismic loading usually dominates the structural engineering effort; therefore, optimal lateral system design is important for material efficiency. In a shear-wall-based building, the conventional design process starts with an architect generating a floor plan, which is then passed to a structural engineer, who, based on knowledge and prior experience, tries to place shear walls to balance conflicting requirements: minimum structural weight, satisfactory structural strength and serviceability, conformity to architectural layout. This design process can be slow and inefficient, requiring a trial-and-error approach that is unlikely to lead to the best solution. The work presented in this paper intends to accelerate the process with an optimization system involving a ground structure program formulation, a modified evolutionary algorithm, and innovative computational techniques. Unlike existing work that focuses either exclusively on structural performance or architectural layout, this research integrates both. An efficient computational design methodology for shear wall layout in plan is introduced. The method minimizes structural weight with constraints on torsion, flexural strength, shear strength, drift, and openings and accessibility. It can be applied from the very beginning of floor plan design or after generating an architectural floor plan. This paper demonstrates the potential of this approach through a variety of case studies. Key contributions include a novel application of the ground structure method, a fast and robust modified evolutionary algorithm, and a simplified auto-calculation system for reinforced concrete design.

1. Introduction

1.1. Background

In the design of tall buildings, the lateral system that resists wind and earthquake loads often dominates. Reinforced concrete shear walls, a common type of the lateral system often arranged around elevators and other vertically continuous building elements as shear cores, require special consideration both structurally and architecturally because of their impact on spatial arrangement in plan. The requirements from architects, engineers and clients are usually conflicting and highly interconnected: for example, architects may focus on the spatial interaction and arrangement, natural lighting, and accessibility; structural engineers would like to place a sufficient amount of shear walls to satisfy the structural strength and serviceability; clients, however, would prefer the cost of material and labor to be as low as possible. A highly symmetric floor plan can address this issue, appearing organized to the architect and efficient to the structural engineer. However, for buildings with irregularity (irregular shape in plan, or with atriums or spacious wall-free area), which are very common contemporarily, the process becomes considerably more complex and interdisciplinary. Traditionally, to design a floor plan with an asymmetrical layout, architects and structural engineers, working separately, rely on a wide range of inputs, including intuition, experience, rules of thumb, analytical modeling, and simulation, all combined in an iterative design-and-test process. Although a valid layout might be obtained consequently, there is no way to guarantee it is optimized in terms of any particular goal.

1.2. Related work

Currently, there is limited research directly on this topic. Most existing literature focuses on related topics either from an exclusively structural or architectural perspective. In the structural engineering field, most research looks at the optimization of lateral systems in 2D elevation view, rather than the layout in plan. For example, Chan and Wong used hybrid OC-GA method to generate both sizes and topologies at the same time for braced frame structures [1]. Liang et al. used performance-based design method to generate optimal structural design by removing inefficient

* Corresponding author.
E-mail address: yu1031@mit.edu (Y. Zhang).

http://dx.doi.org/10.1016/j.engstruct.2017.02.059

materials from a continuum design domain [2]. While this type of research is important and useful, it does not address the organization of the lateral system in plan and its inherent interactions with architectural decision-making.

In the architectural field, floor plan layout topology has been studied: Peng et al. proposed an integer programming-based approach to model corridors in a floor plan, where they defined a set of room templates and generated a subset of all possible potential room placements such that no two overlap and together cover the area [3]. Lai used graph theory for floor plan design where the rectangular dualization problem was reduced to a matching problem on bipartite graphs [4]. Terzidis developed software called autoPLAN that generates architectural floor plans with the boundary and adjacency matrix of a given site [5]. Stiny proposed the formulation of floor plans using a shape grammar, which is a rule-based procedure for generating different geometric shapes [6]. Shekhawat developed an algorithm which takes connectivity into consideration [7]. Nevertheless, these floor plan optimizations are more relevant to architectural design than structural engineering. The lateral system is not adequately considered, which would affect the structural performance of high-rise buildings and lead to laborious iterations due to the separation between architectural and structural approaches during the design process.

Aminnia et al. looked for the optimal patterns by locating the components of shear wall lateral systems, but the configuration of shear walls was constrained to be T-shaped, Z-shaped, U-shaped or L-shaped beforehand [8]. The broader general topology optimization problem remains unaddressed and is thus one of the main focuses of this paper.

1.3. Organization of paper

The research presented in this paper aims to develop a computational method for producing architecture-compatible shear wall layouts with minimized structural weight under basic structural analysis. A simple example of the desired result is shown in Fig. 1. Section 2 gives a detailed description of the general methodology: Section 2.2.2 introduces a novel ground structure method which discretizes a given building footprint into a quadrilateral mesh with each edge modeled as a potential location of a shear wall member. By activating and deactivating shear walls on these edges of the mesh, different possible layouts can be generated. Section 2.2.3 proposes a simplified method for reinforced concrete design regarding irregularly configured shear walls. Due to the large number of possible layouts and a complex objective function containing both linear and nonlinear constraints, a modified evolutionary algorithm is introduced in Section 2.3. Since the optimal set of optimization parameters varies with different buildings, effectively selecting parameters is essential and the method is described in Section 2.4. Section 3 illustrates the results and evaluation of a simple case study. In Section 4, this paper introduces more complex case studies with different combinations of irregular contour and void spaces, or with fixed floor plans. This illustrates applications in two design phases: (1) during the floor plan design phase, which brings more flexibility and inspiration to architects and simultaneously allows more usability (Section 4.1), and (2) after floor plan design phase, when architects have already arranged the space and thus yielded a fixed floor plan to the structural engineers who would like to know the optimal shear wall layout for this specific case (Section 4.2). Finally, Section 5 summarizes the contributions of the paper and suggests areas for further research.

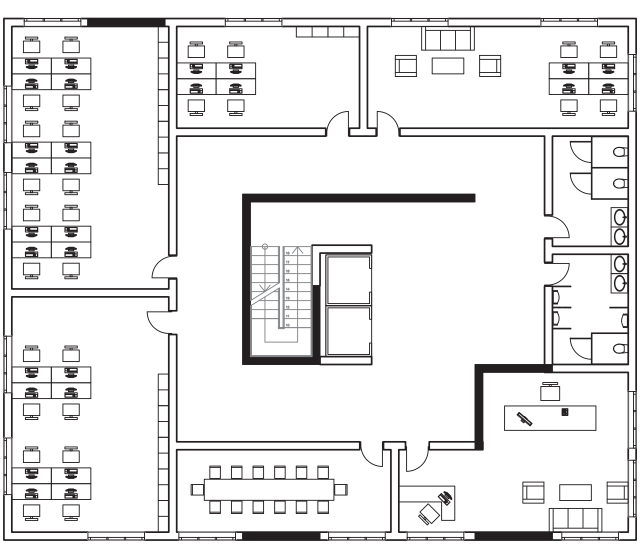

Fig. 1. Example of a desired final layout result. The solid lines represent locations chosen for the shear walls.

2. General methodology

2.1. Conceptual overview

This research develops a system to optimize the layout of shear walls in terms of structural weight, under structural and architectural constraints. To illustrate the methodology simply and clearly, this paper assumes that the default input problem domain is a 2D rectangular building footprint (more variations are discussed in Section 4). The footprint is firstly discretized into a quadrilateral mesh with each edge representing a potential shear wall location. This mesh is modeled as an unconventional ground structure, such as those seen in the topology optimization of truss structures [9], allowing the shear wall on each edge to be either activated or deactivated. For the purpose of optimization, a modified evolutionary algorithm is introduced. The goal is to minimize structural weight with penalties on structural requirements (torsion, flexural, shear, and drift) and on basic architectural requirements (accessibility and openings) to be detailed in later sections. With algorithmic parameters defined by users, this evolutionary algorithm mimics biological evolution by iterating through several cycles of reproduction and selection. However, to accelerate the evolving speed, biased and directional pairing and mutation is applied in the reproduction process. The subset of best-performing individual layouts in the last generation is considered the result of this optimization.

In this paper, a twenty-story residential building in Boston, with dimensions of 80ft × 60ft × 240ft tall (24m × 18m × 70m tall), is set as a simple example to illustrate the method. With each shear wall element being 10ft (3m) long, the footprint of this building is meshed into a 6 by 8 grid.

2.2. Setup

2.2.1. Parameters

Defined at the model initialization step and remaining unchanged during optimization process, a parameter set consists of algorithmic parameters and structural parameters. Algorithmic parameters include evolutionary parameters determining the optimization speed and diversity (such as mutation rate, generation size, and number of generations), and objective function parameters adjusting the evaluation standard. While algorithmic parameters are subjective and affect the general optimization capacity of the model, structural parameters (including building geometry parameters, shear wall property parameters, and loading and