Comparing optimization approaches in the direct displacement-based design of tall mass timber lateral systems

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ABSTRACT

Numerical analyses can aid design exploration, but there are several computational approaches available to consider design options. These range from "brute-force" search to optimization. However, the implementation of optimization can be challenging for the complex, time-intensive analyses required to assess seismic performance. In response to this challenge, this study tests several optimization strategies for the direct displacement-based design of a lateral force-resisting system (LFRS) using mass timber panels with U-shaped flexural plates (UFPs) and post-tensioning high-strength steel rods. The study compares two approaches: (1) a brute-force sampling of designs and data filtering to determine acceptable solutions, and (2) various automated optimization algorithms. The differential evolution algorithm was found to be the most efficient and robust approach, saving 90% of computational cost compared to brute-force sampling while producing comparable solutions. However, every optimization formulation did not return best range of design options, often requiring reformulation or hyperparameter tuning to ensure effectiveness.

INTRODUCTION

The design of mass timber lateral systems involves navigating an interconnected web of constraints and objectives, especially when performing seismic design. Assessing the seismic design performance of lateral force-resisting systems can thus require significant computation, even if aspects of full three-dimensional behavior are simplified for design. Using numerical analyses, design exploration can be achieved manually, through optimization, or a brute-force search that generates many candidates. Optimization can in theory lead to acceptable answers most efficiently, but its implementation with certain structural analysis algorithms can be challenging. Many optimization-based structural analysis models behave as black boxes that only produce data at certain steps, requiring careful problem formulation, algorithm selection, and a strategy for monitoring extracted data to achieve quality results.

This research focuses on testing various optimization approaches for the direct displacement-based design of lateral force-resisting systems (LFRS) that combine mass timber panels with U-shaped flexural plates (UFPs) for energy dissipation and post-tensioning high-strength steel rods for self-centering. First, a brute-force sampling approach is coupled with the OpenSeesPy analysis framework (McKenna et al., 2010) to analyze thousands of models with different design inputs, such as the number and characteristics of UFPs. Additional design variables used to generate these samples include the diameter of post-tensioning steel rods, their post-tensioning force, UFP width and thickness, and a moment distribution factor which indicates the load percentage that must be carried by the mass timber panel plus the high-strength steel rods. The difference must be carried by the energy dissipators (the UFPs). For each design iteration, the initial multi-degree-of-freedom (MDOF) model is substituted with an equivalent single-degree-of-freedom (SDOF) oscillator to estimate the design forces associated with the target drift, which was defined for Service Level Earthquake (SLE), Design Earthquake (DE), and risk-targeted Maximum Considered Earthquake (MCER) levels. Once the sampled simulations were generated, data filtering was used to determine acceptable solutions based on the demand-over-capacity ratio and validate the initial moment distribution factor. Next, several optimization algorithms were tested with varying arrangements of objectives and constraints to solve this design problem automatically and return qualified solutions. The results were then compared to determine how much benefit the optimization provides in terms of fewer simulations, which translates to less computation time, while still finding a similar number of qualified solutions for further evaluation by the designer.

BACKGROUND REVIEW

Structural Optimization for Seismic Loads. Optimization has been widely used in other engineering fields but has recently gained attention in the design of building systems (Gerber & Lin, 2014; Wortmann, 2019). However, the complex and multi-disciplinary nature of early building design and the need for custom solutions for specific sites have limited the use of optimization in practice to only a few prominent examples (Cichocka et al., 2017). In traditional engineering, designers will typically simulate a limited number of options. If the design options can be encoded parametrically, designers can potentially improve the outcome by considering many more possibilities. This is commonly done using a brute-force method, which involves creating many designs and then filtering through the data to identify a few acceptable design solutions (Brown & Mueller, 2017). If the problem can be formulated well, structural optimization can provide a more efficient design approach. Optimization has been applied to the design of lateral force-resisting systems and has shown promise in seismic design. Recent examples include large-scale building and bridge designs, as well as the structural component optimization of seismic dampers (Apostolakis et al., 2023; Velasco et al., 2022; Xiang & Zhu, 2022). To further consider lateral force-resisting systems, researchers have coupled OpenSees with various optimization algorithms (Arroyo & Gutiérrez, 2017; Moradi & Burton, 2018). However, the optimization routines are usually controlled by another software and full integration of OpenSees models with optimization remains challenging (Xu et al., 2021).

Direct Displacement-based Design. OpenSees (Open System for Earthquake Engineering Simulation) is an open-source software framework that allows for the simulation of complex structural behavior, particularly in the context of earthquake engineering (McKenna, 2011). Direct displacement-based design (DDBD) is a seismic design approach that focuses on designing structures based on their expected displacement demands rather than their force demands (Powell, 2008). DDBD allows engineers to simulate the behavior of structures under various seismic loads (e.g., using OpenSeesPy) and to directly design them based on the resulting displacements, ensuring that they will perform well during earthquakes (Abdi et al., 2022). This approach offers several advantages over traditional design methods, including better performance and reduced construction costs. By utilizing DDBD, engineers can achieve more efficient and effective design solutions that prioritize structural safety and resilience in seismic events (Segovia & Ruiz, 2017). Using open-source analysis tools like OpenSeesPy aids in designing structural systems and components that are not currently listed or developed in codes and standards.

Converging Design. Coupling different structural seismic design criteria with multi-objective optimization would enable a novel design approach for optimizing functional recovery that incorporates sustainable building design principles. Efforts to develop such a Converging Design (CD) Methodology for functional recovery and sustainability are ongoing (TallWood Design Institute, 2023). As part of this larger project, a full-scale six-story mass timber structure will be subjected to multiple earthquakes on the shake-table at the NSF-NHERI Experimental Facility (EF) San Diego Large High Performance Outdoor Shake Table (UC San Diego, 2023), a shared use experimental facility. The testing will assess three different LFRS: (1) mass timber panels with UFPs and high-strength post-tensioned rods in both directions of the building; (2) replacement of the mass timber wall panels in one direction with new walls using buckling-restrained braces (BRB) and high-strength post-tensioned rods; and (3) replacement of the same walls as in phase 2 with a BRB truss system; the other direction will use the previous setup style. The case study used in this paper simulates the setup of Phase 1. Both the brute-force method and optimization approaches are used herein to demonstrate direct displacement-based design of tall timber lateral systems using OpenSeesPy.

METHODOLOGY

As shown in Figure 1, the design exploration phase for structural systems can involve evaluating different combinations of design variables and filtering data to identify the best outcomes. However, this process can be time-consuming, and the range of acceptable answers may not be clear. To address these issues, architects and engineers can utilize optimization to monitor the computational process and gradually move towards increasingly optimized design alternatives. This paper seeks to evaluate the efficiency of optimization in extracting suitable solutions.

Figure 1. An overview of different methodologies for finding efficient structural designs

Figure 2 provides an illustration of the potential advantages of an optimization approach. Although defining the initial problem for optimization requires more careful attention to parameters, variables, and objectives, this approach can significantly reduce the time-consuming simulation process by ignoring poor-performance solutions. By gradually directing the optimization process towards the best possible answers, given defined objectives and constraints, architects and engineers can save time and resources while achieving more effective designs. However, these benefits are only realized if algorithms can actually solve the problem. Depending on problem structure, there may be both mathematical and practical reasons why this is not the case. This research tests whether a seismic design problem, based on direct displacement-based design using OpenSeesPy, is amenable to solving through optimization.

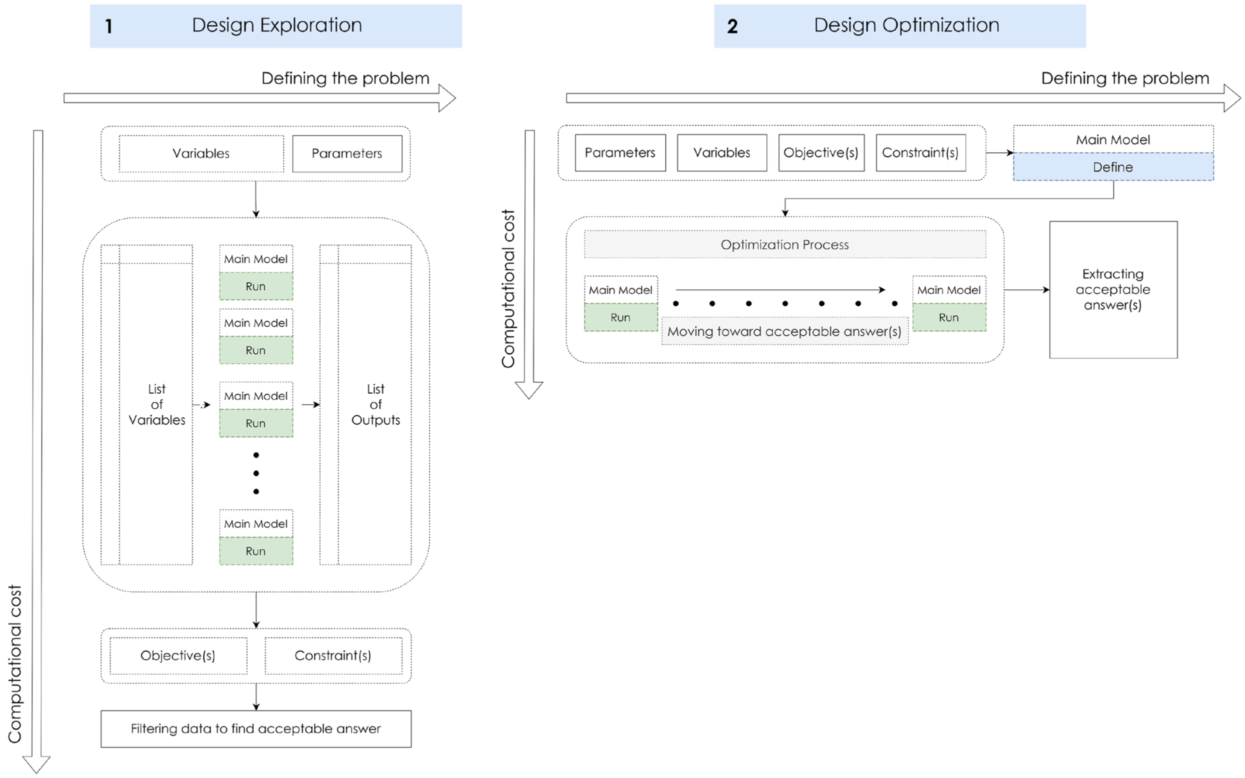


Figure 2. Comparing brute force sampling and multi-objective optimization in terms of problem definition and computational cost

Strategy 1: Brute-force Sampling. An initial design space is first created by defining a 2D model of the 6-story mass timber structure. The prototype, from the CD research project, focuses on commercial mass timber spine systems using steel energy dissipators. The design is defined based on several modifiable variables (Figure 3). In the E-W direction, the walls of the structural system are composed of mass ply panels (MPP), while the N-S direction are cross laminated timber (CLT) panels. In both directions, UFPs are placed to connect the walls with the end-columns. The UFPs work as the main energy dissipation source of the system, while the high-strength post-tensioned steel rods provide recentering capabilities. The analysis model was created using OpenSeesPy, and direct displacement-based design was used to extract necessary data regarding simulated performance. To explore different design alternatives, a for-loop was implemented into the model to go through variables and store simulation results in a CSV file. The desirable answers were then extracted for further investigation by the designers by filtering the data to meet specific criteria. These acceptable or qualified solutions meet the specific requirements with the minimum number of UFPs and efficient cross sections. However, it should be noted that in a real building, the list of acceptable solutions would require further attention in terms of nonlinear analysis than what is presented here. This simulation is thus an initial step in the design process.

Strategy 2: Optimization. The optimization approach is built on several steps from the brute-force method. Although optimization requires extra time and attention for the problem definition, it has the potential to provide acceptable answers at each generation or step of computing, which could save simulation time overall. As shown in Figure 4, the optimization focuses on minimizing the number of UFPs and sometimes other characteristics while meeting pre-defined constraints. This problem is local to just the energy dissipation elements—when optimization is done more globally, engineers focus on optimizing structural systems, cross sections, or material usage across the entire building. All these variables could be incorporated into the framework in the future. However, the current approach minimizes material usage for the UFPs towards a more efficient design within a defined scope, for a specific section of the mass timber building. The number of UFPs is considered as the main objective, and the constraints include criteria such beta comparison (error) or demand over capacity (DC) ratio. Five different optimization algorithms are implemented with the Pymoo python library (Blank & Deb, 2020) on the defined structural model: NSGA2, NSGA2_MOO, NSGA3, SRES, and Differential Evolution. The range of algorithms allowed for a combination of objectives and constraints to be tested, sometimes replacing one another depending on the attempted problem definition.

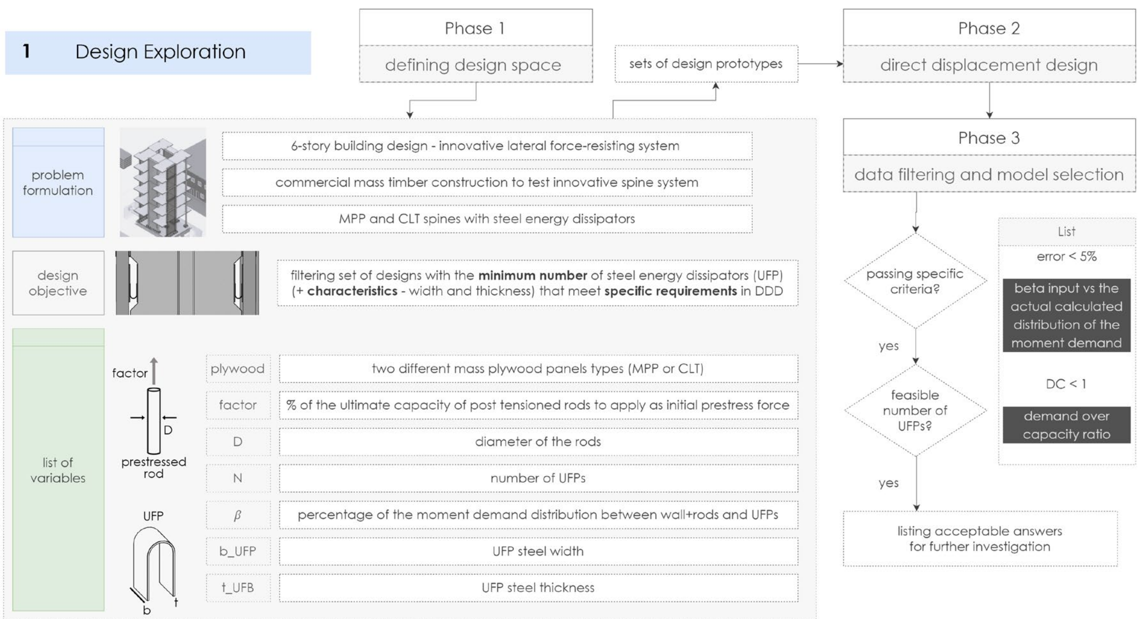


Figure 3. The design space, brute force sampling, and data filtering

There is one key difference in the optimization strategy compared to traditional structural optimization. Most applications of structural optimization intend to return a single best design. In this problem, many solutions exist with the same number of UFPs that possess secondary characteristics, both quantitative and qualitative, that require further consideration by engineers. Thus, in this project, the optimization algorithms are used to extract any acceptable solutions while they run that achieve the filtering criteria from the brute force approach. This strategy has some conceptual similarities to an isoperformance design methodology (de Weck & Jones, 2006), although the implementation is different. It should also be noted that while number of UFPs is the main objective in the optimization process, it is also part of initial variables that define the OpenSeesPy model in first place. However, since it is affected by other variables such as width and thickness of UPFs, the automated process can find solutions that navigate the tradeoffs between all variables to find designs that meet all constraints.

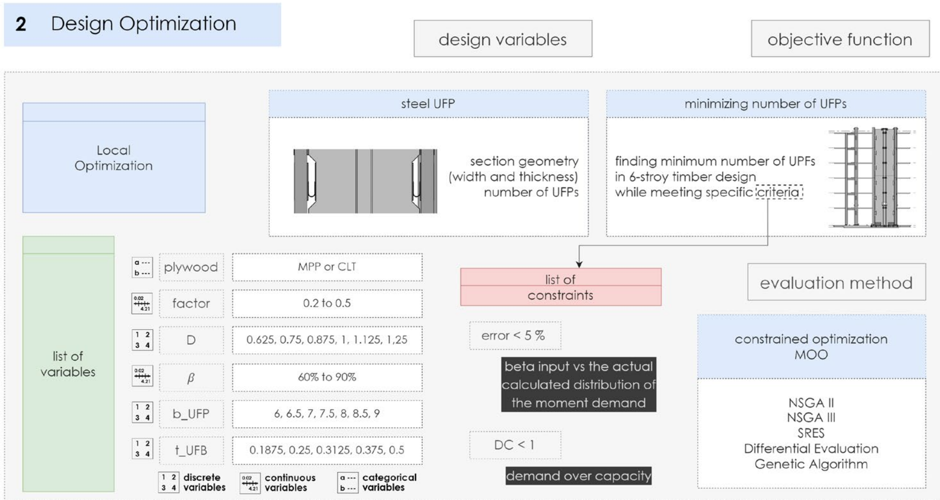


Figure 4. Design variables, constraints, and objectives for the optimization approaches

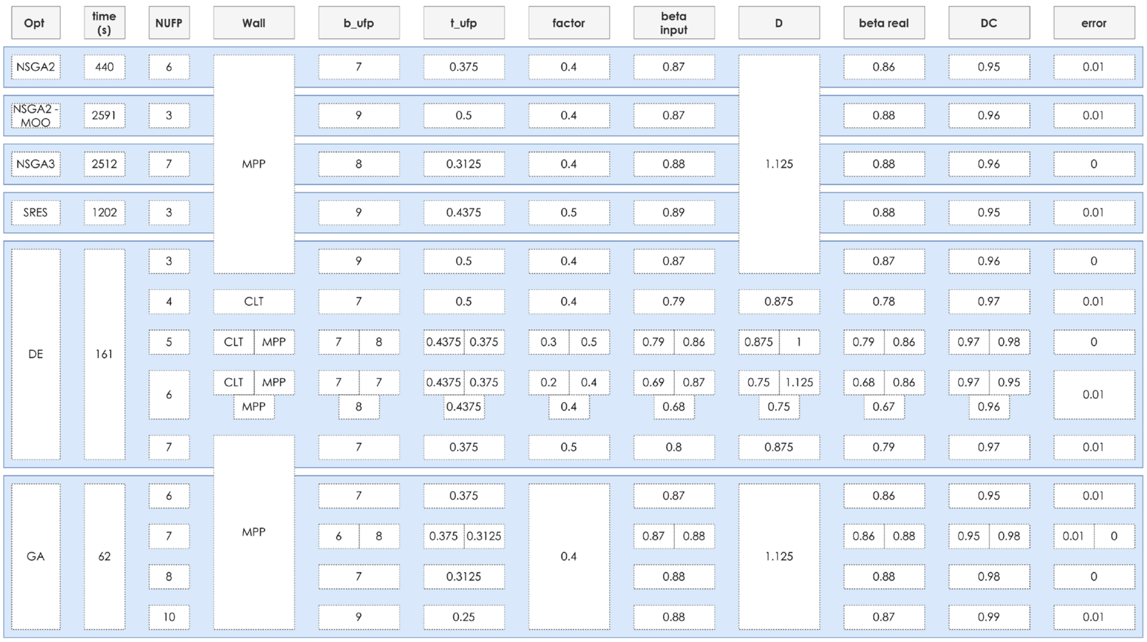
RESULT AND DISCUSSION

Data Filtering and Qualified Designs. For brute-force sampling, the simulations were first completed for the MPP walls, and then CLT was added to expand the range of design inputs. More than 400,000 models (200,000 each) were simulated in Python in consecutive order. The data was then filtered to make sure the difference between the initial moment distribution factor and calculated one after the analysis was less than 5%, and to check if the DC ratio is less than 1. The designs with 9 or fewer UFPs, which is a physical restriction on the 6-story specimen, that meet the above criteria were extracted for further design investigation. Figure 5 is a sample result of filtered data for MPP, highlighting 18 eligible designs—results for CLT were similar. The DDBD thus produced qualified designs for further qualitative evaluation and nonlinear analysis.

NUFP	b_ufp		t_ufp	factor	beta input	D		beta real		DC		error	
4	7.5	8	0.5	0.2	0.75	1	1	0.77	0.76	0.98	0.96	0.03	0.01
	8.5	8.5				1	1.125	0.75	0.78	0.96	0.96	0.01	0.05
	9	9				1	1.125	0.74	0.77	0.96	0.96	0.02	0.03
5	6	6.5	0.5			1	1	0.77	0.76	0.98	0.96	0.03	0.01
	7	7				1	1.125	0.74	0.78	0.96	0.96	0.01	0.04
7	8	8.5	0.375			1	1	0.77	0.76	0.99	0.97	0.03	0.01
	9	9				1	1.125	0.75	0.78	0.96	0.95	0.01	0.04
8	7	7.5	0.375			1		0.77	0.76	0.99	0.97	0.03	0.01
9	6.5	9	0.375 0.3125			1		0.76	0.77	0.98	1	0.02	0.03

Figure 5. Qualified MPP design prototypes extracted by brute-forcing different design alternatives and filtering the data based on specific criteria.

Optimization. To begin, several evolutionary optimization algorithms were tested on the model for two different scenarios: constraints plus single objective (all five algorithms) and multi-objective considering constraints as objectives (NSGA-II). Monitoring the optimization process, the constrained optimization procedure was the most effective at extracting qualified solutions based on DDBD. However, a few of the algorithms (NSGA-II, NSGA3, SRES) generated a single output that best managed the tradeoffs. Genetic Algorithm and Differential Evolution were able to extract several qualified designs meeting all criteria (Figure 6). The setup was defined so that the optimization process stopped either based on the algorithm's stopping criteria or once it had extracted 18 qualified designs, to make the comparison between optimization and brute-force.



Opt	time (s)	NUFP	Wall	b_ufp	t_ufp	factor	beta input	D	beta real	DC	error
NSGA2	440	6	MPP	7	0.375	0.4	0.87	1.125	0.86	0.95	0.01
NSGA2 - MOO	2591	3		9	0.5	0.4	0.87		0.88	0.96	0.01
NSGA3	2512	7		8	0.3125	0.4	0.88		0.88	0.96	0
SRES	1202	3		9	0.4375	0.5	0.89		0.88	0.95	0.01
DE	161	3		9	0.5	0.4	0.87		0.87	0.96	0
		4	CLT	7	0.5	0.4	0.79	0.875	0.78	0.97	0.01
		5	CLT, MPP	7, 8	0.4375, 0.375	0.3, 0.5	0.79, 0.86	0.875, 1	0.79, 0.86	0.97, 0.98	0
		6	CLT, MPP, MPP	7, 7, 8	0.4375, 0.375, 0.4375	0.2, 0.4, 0.4	0.69, 0.87, 0.68	0.75, 1.125, 0.75	0.68, 0.86, 0.67	0.97, 0.95, 0.96	0.01
		7	MPP	7	0.375	0.5	0.8	0.875	0.79	0.97	0.01
GA	62	6		7	0.375	0.4	0.87	1.125	0.86	0.95	0.01
		7		6, 8	0.375, 0.3125		0.87, 0.88		0.86, 0.88	0.95, 0.98	0.01, 0
		8		7	0.3125		0.88		0.88	0.98	0
		10		9	0.25		0.88		0.87	0.99	0.01

Figure 6. Qualified design prototypes extracted from optimization process; the wall material (CLT or MPP) considered as one of the variables in optimization.

Discussion: brute-force versus optimization. The brute-force approach can eventually provide satisfactory results, but optimization generally ran with less computational cost. The best optimization algorithm (differential evolution) yielded the same number of acceptable answers using 15% of the iterations (Table 1). The ~23,000 iterations for differential evolution optimization took ~3 minutes on a professional-grade desktop computer to generate same number of results (18) as brute-force. Cutting the number of evaluations by ~90% would save significant time on a full building analysis. However, the optimization process needed to be monitored and occasionally modified to achieve diverse, qualified solutions, as not every algorithm produced desirable results. For example, the Genetic Algorithm produced limited results and required adjustments to the hyperparameter population size. In summary, optimization can reduce computational costs, but some experimentation with different algorithms and hyperparameter settings may be necessary.

Table 1. Brute-force sampling and optimization approach results

Algorithm		Number of evaluations	Number of feasible designs generated
Brute-force Search		201,810	18
Optimization	Genetic Algorithm	22,800 **(11%)**	6
	Differential Evolution	31,800 **(15%)**	18

CONCLUSION

Numerical analyses and optimization can facilitate design exploration, but optimization can be challenging to implement even for simplified direct displacement-based design. This paper presents a comparison of optimization approaches for designing mass timber lateral force resisting systems and found the differential evolution algorithm to be the most efficient and robust approach, saving a significant amount of computational cost compared to brute-force sampling. Overall, this study demonstrates the importance of carefully formulating the problem, selecting the appropriate algorithm, and monitoring extracted data to achieve quality optimization results in the local optimization of structural components for the design of mass timber lateral force-resisting systems. Future work, more optimization algorithms can be tested, and the analysis can be expanded to the full building scale, where computational savings are likely even more important.

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