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Review paper on Topology optimization of steel braced frames to achieve minimum weight and maximum collapse resistance

[1]Prof. G. S. Supekar [2]Niranjan Pansare

[1 2] Civil Department, Jaihind College of Engineering, Kuran Junnar

Email: supekar01@gmail.com[1] pansareniranjan@gmail.com[2]

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Abstract

This study presents a topology optimization approach for steel braced frames aimed at achieving minimum structural weight while ensuring maximum resistance against progressive collapse. The optimization process integrates performance-based design principles with the Alternate Path Method (APM) to evaluate structural robustness under sudden column removal scenarios. Finite Element Models (FEM) of steel braced frames are developed using nonlinear static and dynamic analyses to assess the redistribution of loads, formation of alternate load paths, and energy dissipation mechanisms. The topology optimization algorithm identifies the optimal configuration and placement of braces that minimize material usage without compromising collapse resistance. Results demonstrate that the optimized bracing layout effectively reduces structural weight while maintaining or enhancing global robustness, offering a reliable and efficient design framework for modern steel structures subjected to accidental or extreme events.

INTRODUCTION

Steel braced frames are one of the most efficient and reliable structural systems widely used in high-rise, industrial, and commercial buildings. These systems provide the necessary lateral stiffness and strength to resist wind, seismic, and accidental loads, ensuring overall structural stability and safety. The incorporation of bracing members helps reduce lateral displacements and improves the ductile behavior of the structure under extreme loading conditions. Traditionally, engineers have employed standard bracing configurations such as X-braces, V-braces, inverted V-braces (chevron), and K-braces, which are selected based on past experience and simplified analysis models. However, these predefined configurations do not always lead to the most efficient material utilization or maximum structural robustness. To overcome these challenges, modern structural design has adopted topology optimization techniques, which enable the determination of the optimal material distribution and bracing pattern within a given design domain. Topology optimization bridges the gap between computational design and structural performance by exploring multiple configurations that achieve maximum stiffness, minimum weight, and enhanced collapse resistance. With the advent of high-performance computing and advanced finite element software, topology optimization has become a powerful design strategy for developing next-generation, high-efficiency steel structures.

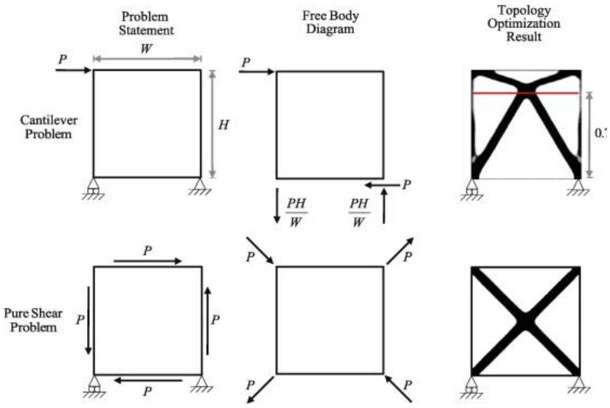

Fig. 1 Optimization in Braced Frames

Need for Topology Optimization in Braced Frames:

The conventional design of steel braced frames often focuses on meeting code requirements related to strength and serviceability without explicitly optimizing the material layout or load path redundancy. As a result, such designs may be heavier, less sustainable, and sometimes less robust under accidental loading conditions. In contrast, topology optimization provides a rational and systematic approach for improving performance by identifying where material is truly needed to resist applied loads effectively.

In practical terms, topology optimization of braced frames enables:

- Reduction in overall structural weight, leading to lower construction and fabrication costs.
- Enhanced stiffness and stability, improving the structure's response to lateral and dynamic loads.
- Improved robustness against sudden local failures through the creation of multiple alternate load paths.
- Sustainable design practices, aligning with the global trend toward resource-efficient and environmentally conscious engineering.

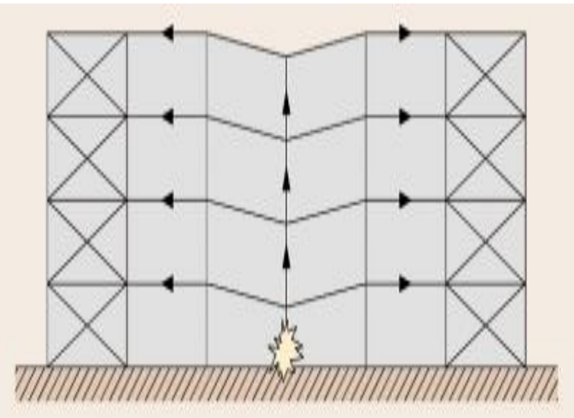

Fig. 2 Progressive Collapse and Structural Robustness

LITERATURE REVIEW

Rajnil Laletal (2025)

Self-centering systems are increasingly studied after devastating earthquakes in the 2010s that caused irreparable damage to buildings. Currently, there is conflicting evidence as to whether the re-centering (restoring) capabilities are gained at the expense of hysteretic damping, potentially leading to larger peak displacements and damage to non-structural elements. This study examines the earthquake response of self-centering and non-self-centering systems through analyses of 4-storey and 8-storey steel-braced frames. The Resilient Slip Friction Joint (RSFJ) dampers, combined with steel braces in series, represent the self-centering bracing system, whereas the Buckling Restrained Braces (BRBs) represent the non-self-centering bracing system. Results suggest that peak displacements, base shears, and floor accelerations were comparable between the two systems. A possible explanation is that the peak response occurs on the first major excursion; similar peaks result from similar backbone curves in the run-up to the peak. Conversely, the amount of hysteretic damping only begins to affect the post-peak behavior. For instance, the RSFJ system reintroduces seismic energy into the structure post-peak (rather than dissipating it like the BRB). Subsequently, it leads to larger vibration amplitudes about the central position, increasing the risk of secondary peaks. This contrasts with the BRB system, which exhibits smaller vibration amplitudes about an increasingly deformed position due to seismic ratcheting. Unsurprisingly, residual deformations were high for the BRBs (1.7 % on average) and negligible for the RSFJ. However, RSFJ produced smaller peak inter-storey drifts between 13 %–18 % but higher peak accelerations by 4 %–5 %. The results suggest that multi-storey braced frames could be designed with similar or smaller forces when self-centering systems are used.

Xiuhua Zhangetal (2025)

This study investigates the impact of central bracing on the progressive collapse resistance of spatial steel frame structures. Finite element models incorporating various central bracing types and positions were developed using ANSYS software. The validated models employed the alternate load path method within ANSYS/LS-DYNA to analyze the progressive collapse behavior of spatial steel frames with X-type and inverted V-type central bracing subjected to column removal scenarios. The analysis reveals that X-type bracing significantly enhances the overall stability and load-bearing capacity of the frame structures. A comprehensive parametric study was subsequently conducted on frames equipped with X-type central bracing, evaluating the effects of bracing arrangement position, transverse span length, floor slab presence, and column removal location. A formula was derived for estimating the catenary action capacity of the central bracing-steel frame system. The influence of the studied parameters on progressive collapse resistance was quantitatively analyzed by comparing plastic energy dissipation ratios across different configurations. Results indicate optimal design parameters include a story height of 3.3 m, a longitudinal span length of 6.6 m, and a transverse span length between 6.6 m and 7.2 m. For a 5-span steel frame, the most effective bracing arrangement positions are the side spans and both sides of the middle span. The most critical column removal locations are the transverse edge column and the internal middle column. Following column loss, the flexural action of the floor slab effectively enhances the vertical stiffness of the structure, thereby improving the structure's progressive collapse resistance and effectively reducing the dynamic response of the remaining structure.

Mehdi Ghasrietal (2025)

Steel frame bracing systems play a critical role in enhancing structural flexibility, enabling buildings to absorb and dissipate energy during seismic events or other extreme conditions. This underscores the importance of designing effective bracing systems to control lateral movement and improve structural performance. Over the years, various bracing systems have been developed to address these challenges, with the cable bracing system featuring a mid-plate emerging as a promising solution. This system utilizes cables and a mid-plate to delay the activation of the cables until higher lateral displacements occur, thereby compensating for ductility limitations and improving energy absorption. Recent studies have highlighted the significance of the mid-plate's topological shape, as it directly influences the system's plasticity, energy dissipation, and cable activation timing. This study examines the best mid-plate topology for optimal performance. It also investigates a deep learning program to simulate system behavior virtually, providing insights into performance and revealing that optimized mid-plate topology withstands greater forces with less displacement. Additionally, deep learning improves analysis speed, aiding in understanding system responses and design parameter interdependencies, allowing rapid exploration of designs to optimize steel frame systems.

Research Gap

Current studies on steel braced frames mainly focus on minimizing weight or maximizing stiffness but rarely address both objectives simultaneously. The integration of topology optimization with progressive collapse evaluation methods, such as the Alternate Path Method (APM), is still limited. Research on self-centering bracing systems emphasizes seismic performance but overlooks their role in enhancing collapse resistance. Comparative studies between conventional and topology-optimized bracing layouts are also scarce, leaving uncertainty about their effectiveness in load redistribution and robustness. Therefore, a research gap exists in developing a multi-objective topology-optimized bracing system that achieves both minimum weight and maximum collapse resistance for improved structural resilience.

METHODOLOGY

Develop bracing layouts for a steel multi-storey frame that simultaneously minimizes mass (M) and maximizes progressive-collapse resistance measured by a Collapse Load Factor (CLF) via the Alternate Path Method (APM).

Formulate a multi-objective optimization problem: Minimize [f1(x) = M(x), f2(x) = -CLF(x)] subject to equilibrium, code limits (drift, stresses), buckling, and constructability constraints

Choice of Parametrization

A ground-structure-based approach is recommended for realistic steel layouts and easier mapping to standard members.

Nodes are defined at potential brace connection points, with candidate members representing possible bracing links.

Design variables are the cross-sectional areas Ai ≥ 0 of members, promoting sparsity for optimal bracing layouts.

Design Domain and Baseline Model

Example Frame Geometry:

- 4 bays (6 m each) × 6 storeys, storey height = 3.0 m
- Columns: rolled I-sections
- Material: Steel grade S355, E = 210 GPa, ρ = 7850 kg/m^3, fy = 355 MPa

Baseline bracing patterns: X, V, K, chevron, concentric bracing, and unbraced cases for comparison.

Structural Analysis Levels

1. Fast fidelity: 2D/3D beam-element frame

model (linear-elastic or elastic–plastic). Used for quick evaluations during optimization.

2. High fidelity: Nonlinear static analysis (P–Δ, plasticity) for detailed APM simulation using OpenSees or Abaqus.

CONCLUDING REMARK

- A literature survey has been carried out to understand the existing research and identify knowledge gaps.
- The aim and objectives of the study have been clearly defined.
- The problem statement has been formulated based on the findings from the literature review.
- The research methodology has been outlined to guide the investigation effectively.
- A detailed research plan has been prepared to structure the overall study process.

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