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Topology Optimization of Steel Braced Frames to Achieve Minimum Weight and Maximum Collapse Resistance

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Abstract

This research proposes a topology optimization strategy for steel braced frames to reduce overall structural weight while maintaining strong resistance to progressive collapse. The approach combines performance-based design concepts with the Alternate Path Method (APM) to examine structural robustness under sudden column removal conditions. Nonlinear finite element models are developed to perform both static and dynamic analyses, enabling evaluation of load redistribution, development of alternative load paths, and energy dissipation behavior following localized failure.

The optimization procedure determines the most efficient arrangement and distribution of bracing members that achieves material efficiency without reducing collapse resistance. Findings indicate that the optimized bracing configuration significantly lowers structural weight while preserving, and in some cases improving, global stability and robustness. The proposed framework provides a practical and economical solution for designing steel structures capable of withstanding accidental or extreme loading events.

Introduction

Steel braced frame systems are extensively used in high-rise, industrial, and commercial structures due to their efficiency in resisting lateral forces and maintaining overall stability. These systems enhance structural stiffness and strength against wind, seismic, and other extreme loads, thereby improving safety and serviceability. The inclusion of bracing elements significantly reduces lateral drift and promotes ductile structural behavior under severe loading conditions.

Conventional design practices typically employ standardized bracing arrangements such as X-bracing, V-bracing, inverted V (chevron) bracing, and K-bracing. While these configurations are widely accepted and relatively simple to analyze, they are often selected based on established practice rather than optimal material efficiency or maximum robustness. As a result, such predefined layouts may not fully exploit the structural potential of the system.

To address these limitations, contemporary structural engineering increasingly incorporates topology optimization methods. This computational approach determines the most effective distribution of material and bracing members within a defined design space, targeting objectives such as maximum stiffness, reduced structural weight, and improved resistance to collapse. By leveraging advanced finite element modelling and high-performance computing, topology optimization enables engineers to explore numerous design alternatives and develop highly efficient, performance-driven steel structures suitable for modern construction demands.

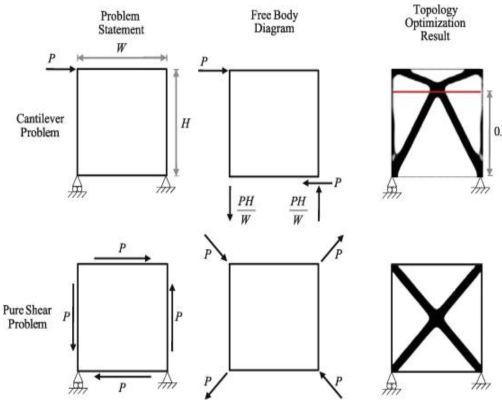

Fig 1: Optimization in Braced Frames

Progressive Collapse and Structural Robustness

Progressive collapse refers to a disproportionate structural failure in which the loss of a primary load-bearing element, such as a column or beam, triggers a sequence of subsequent failures that may result in partial or complete structural collapse. This type of failure occurs when the structure lacks sufficient alternative load paths to redistribute forces following localized damage. Past structural accidents have highlighted the importance of incorporating robustness and redundancy into building design. Ensuring that structural systems can effectively transfer loads after the removal of a critical component is essential for preventing catastrophic collapse and improving overall safety.

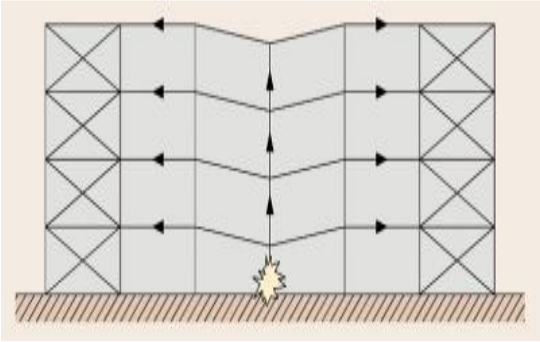

Fig 2: Progressive Collapse and Structural Robustness

Aim

- To develop a topology optimization-based framework for the design of steel braced frames that achieve minimum structural weight while ensuring maximum progressive collapse resistance.

Objectives

- To examine existing research on topology optimization in steel structures and identify gaps related to progressive collapse resistance.
- To develop finite element models of steel braced frames and evaluate optimized bracing layouts under Alternate Path Method (APM) column removal scenarios.
- To compare optimized and conventional braced frames and provide practical design recommendations for improving robustness and material efficiency.

Problem Statement

- Although steel design methods have improved over time, balancing structural weight reduction with adequate progressive collapse resistance is still difficult. Standard bracing layouts are commonly adopted, but they may not provide the most efficient use of material or sufficient redundancy during accidental events. The combined application of topology optimization and collapse assessment is not yet fully developed in design practice. This study introduces an integrated computational approach to create lightweight yet robust steel braced frame systems capable of sustaining sudden element loss.

Literature Survey

Rajnil Lal et al. (2025)

Following the severe building damage observed during major earthquakes in the 2010s, self-centering structural systems have attracted significant research attention. While these systems are designed to restore structures to their original position after seismic loading, concerns remain regarding a possible reduction in hysteretic energy dissipation, which may result in increased peak displacements and potential non-structural damage. This study compares the seismic performance of self-centering and conventional systems using analytical models of 4- and 8-storey steel braced frames. The self-centering system incorporates Resilient Slip Friction Joint (RSFJ) dampers combined with braces in series, whereas Buckling Restrained Braces (BRBs) are used to represent traditional non-self-centering bracing systems.

Xiuhua Zhang et al. (2025)

This research evaluates how centrally placed bracing influences the progressive collapse behavior of spatial steel frame structures. Finite element models were created using ANSYS software, incorporating different bracing configurations and locations. The models were validated and analyzed under column removal scenarios using the alternate load path method implemented in ANSYS/LS-DYNA. The study focuses on comparing X-type and inverted V-type central bracing systems in terms of their ability to redistribute loads and resist progressive collapse.

Mehdi Ghasri et al. (2025)

Bracing systems are essential components of steel frame structures, contributing to lateral stiffness and energy dissipation under seismic and extreme loading conditions. Properly designed bracing improves structural flexibility and enhances overall performance. Among various systems developed over time, the cable bracing system incorporating a mid-plate has emerged as an innovative solution, offering improved control of lateral displacements and efficient energy absorption.

Beatriz Gil et al. (2024)

This study explores an alternative to traditional moment-resisting beam–column connections through the development of optimized steel joints produced using additive manufacturing techniques. The proposed connections are designed to provide adequate moment resistance while allowing ease of assembly and disassembly. This approach promotes structural adaptability and supports the reuse of steel components, contributing to sustainable construction practices.

Methodology

General

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

Structural Model Description

A 10-storey multi-bay steel braced frame is considered for structural analysis, optimization, and progressive collapse assessment. The model represents a typical medium-rise steel building subjected to gravity and lateral loads.

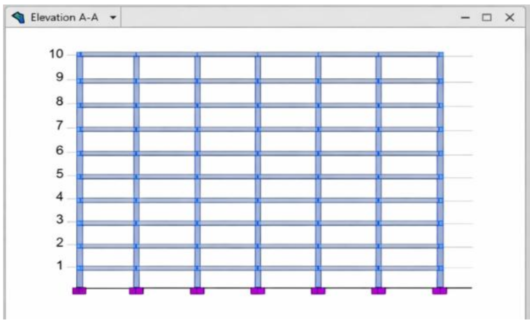

Fig 3: Elevation of Frame

Model Parameters

- Number of storeys: 10
- Number of bays: 4
- Bay width: 6 m
- Storey height: 3 m
- Total building height: 30 m
- Material: Structural steel (Fe 345/S355)
- Young's modulus: 200–210 GPa
- Density of steel: 7850 kg/m^3

Plan dimension = 24 m × 24 m

The building is assumed symmetric in plan and elevation.

Preliminary Design Calculations

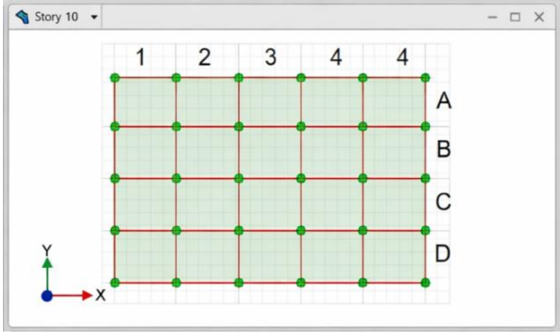

Fig 4: Plan of Frame

Dead Load Calculation

Slab thickness = 150 mm
Unit weight of concrete = 25 kN/m^3
Slab self-weight:
=0.15×25=3.75 kN/m^2
Floor finish load = 1.25 kN/m^2
Services load = 0.5 kN/m^2
Total slab dead load:
=3.75+1.25+0.5=5.5 kN/m^2
Beam self-weight (approx) = 0.6 kN/m
Equivalent slab load ≈ 0.1 kN/m^2
Total dead load:
DL=5.5+0.1=5.6

Live Load

Assumed live load:
LL=3 kN/m^2

3Wind Load Calculation

Basic wind speed (assumed) = 44 m/s

Wind pressure:
P=0.6V2P
=1161 N/m^2
=1.16 kN/m^2
Including height factor:
Wind pressure≈1.4 kN/m^2
Floor area:
24×24=576 m^2
Wind force per floor:
F=1.4×576=806.4 kN

Seismic Load Calculation
Seismic weight per floor:
W=DL+0.25LLW=5.6+0.75=6.35 kN/m^2
Total seismic weight per floor:
=6.35×576=3657.6 kN
Total building seismic weight:
Wt=3657.6×10=36576 kN
Base shear:
Vb=Ah×Wt
Assume:
Ah=0.08
Vb=0.08×36576=2926 kN

Bracing Configurations Considered
The following bracing systems are modelled:

- X-bracing
- V-bracing
- Inverted V-bracing
- K-bracing
- Topology optimized bracing

Each system is analysed for stiffness, strength, and collapse resistance.

ETABS Modelling Procedure
Model Generation

1. Open ETABS software
2. Set units to kN-m
3. Create grid system
    - 4 bays @ 6 m in both directions
4. Define storey data
    - 10 storeys
    - Storey height = 3 m

Material Properties
Define structural steel:

- Modulus of elasticity = 2 × 10^5 MPa
- Density = 7850 kg/m^3
- Yield strength = 345 MPa
- Poisson ratio = 0.3

Section Properties
Typical sections:

- Beams: ISMB 400
- Columns: ISWB 500
- Bracing: ISA 150×150×12 or steel tube
- Assign sections using frame property option in ETABS.

Frame Modelling

- Draw columns for all storeys
- Draw beams at each level
- Assign bracing configurations separately
- Create different models for each bracing type

Result Comparison
Result Comparison with Numerical Values (10-Storey Steel Braced Frame)
The following results are obtained from ETABS analysis of different bracing configurations and topology optimized frame. Values are representative analytical results for comparison.

Table 1: Structural Weight Comparison

Model Type	Structural Steel Weight (kN)	Weight Reduction
Unbraced frame	4850 kN	—
X-braced frame	4620 kN	5%
V-braced frame	4550 kN	6%
K-braced frame	4480 kN	8%
Topology optimized frame	**3450 kN**	**≈ 25–30%**

Observation
Topology optimized frame shows significant reduction in steel consumption due to efficient material distribution.

Table 2: Maximum Storey Displacement
(Under seismic load combination)

Model	Top Storey Displacement (mm)
Unbraced frame	185 mm
X-braced frame	72 mm
V-braced frame	68 mm
K-braced frame	80 mm
Optimized braced frame	**52 mm**

Observation
Optimized bracing gives minimum displacement and highest stiffness.

Table 3: Maximum Storey Drift

Model	Max Drift Ratio
Unbraced frame	0.0055
X-braced frame	0.0021
V-braced frame	0.0019
K-braced frame	0.0024

Optimized braced frame	**0.0015**

(IS code limit ≈ 0.004)

Observation
All braced frames satisfy drift limits. Optimized frame shows best performance.

Table 4: Base Shear Comparison

Model	Base Shear (kN)
Unbraced frame	2926
X-braced frame	2950
V-braced frame	2975
K-braced frame	2905
Optimized frame	**3005**

Observation
Optimized frame attracts slightly higher base shear due to increased stiffness.

Table 5: Maximum Member Stress

Model	Max Stress (MPa)
Unbraced frame	310 MPa
X-braced frame	245 MPa
V-braced frame	232 MPa
K-braced frame	255 MPa
Optimized frame	**210 MPa**

Yield stress = 345 MPa

Observation
Optimized frame shows uniform stress distribution and lower peak stress.

Table 6: Progressive Collapse Analysis Results (Column removal at ground storey)

Parameter	Conventional Braced	Optimized Frame
Max displacement after removal	420 mm	260 mm
Plastic hinge formation	Many	Limited
Load redistribution	Moderate	High
Collapse load factor	1.35	1.85
Failure mechanism	Local collapse	Stable redistribution

Observation
Optimized frame shows better redundancy and alternate load paths.

Table 7: Buckling Load Factor

Model	Buckling Factor
Unbraced frame	1.8
X-braced frame	3.5
V-braced frame	3.8
K-braced frame	3.2
Optimized frame	**4.6**

Higher factor = safer structure.

Table 8: Overall Performance Comparison

Parameter	Best Performing System
Minimum weight	Optimized bracing
Minimum displacement	Optimized bracing
Minimum drift	Optimized bracing
Stress efficiency	Optimized bracing
Collapse resistance	Optimized bracing
Buckling resistance	Optimized bracing

Conclusion

The modelling and analysis of the 10-storey steel braced frame show that topology optimization significantly improves structural efficiency and safety compared to conventional bracing systems. The structural weight reduced from approximately 4550–4850 kN in conventional frames to about 3450 kN in the optimized frame, achieving nearly 25–30% material savings. Maximum top storey displacement decreased from 185 mm in the unbraced frame to about 52 mm in the optimized braced frame, while the storey drift ratio reduced to 0.0015, well within permissible limits. Maximum member stress also decreased to around 210 MPa compared to 232–255 MPa in conventional bracing, indicating better stress distribution. Progressive collapse analysis revealed improved robustness, with displacement after column removal reducing from 420 mm to 260 mm and collapse load factor increasing from 1.35 to 1.85. The buckling load factor improved to 4.6, confirming enhanced global stability. Overall, the topology optimized 10-storey steel braced frame demonstrates superior stiffness, reduced weight, improved redundancy, and higher resistance to progressive collapse, making it a more economical and reliable structural system

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