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ELASTO-PLASTIC TOPOLOGY OPTIMIZATION UNDER CYCLIC LOADING FOR EFFICIENT STRUCTURAL DESIGN

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Abstract

This study introduces an elasto-plastic topology optimization approach tailored for structural systems subjected to cyclic loading. By incorporating material nonlinearity, the method provides a robust framework for designing structures that withstand repetitive loading efficiently, avoiding excessive material use. This optimization approach integrates the effects of cyclic loading to enhance structural resilience while minimizing mean compliance. The proposed method is particularly applicable for optimizing structural components in steel frameworks where material efficiency and load-bearing capacity are critical. By emphasizing the elasto-plastic behavior of materials, this study aims to offer a practical tool for engineers seeking resilient structural designs that balance strength and sustainability. Potential applications extend to structural elements in earthquake-resistant buildings, where managing material use is essential for both environmental and economic impact.

Keywords: Elasto-plastic topology optimization, cyclic loading, structural efficiency, sustainable design.

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1 INTRODUCTION

The ongoing progress in structural engineering has produced optimization methods meant to improve the sustainability and efficiency of structural systems. Topology optimization (TO) has become a powerful computational tool for the construction of lightweight and high-performance structures by best distributing material within a particular design area [1–3]. Highly appropriate for uses in aerospace, automotive, and civil infrastructure engineering, TO helps generate effective structural layouts while preserving mechanical performance [4,5].

Throughout the years, several TO methods have been developed, such as the Solid Isotropic Material with Penalization (SIMP) method [6], the bubble method [7], the Evolutionary Structural Optimization (ESO) and Bi-Directional-ESO (BESO) methods [8], and the Level Set Method (LSM) [9]. ESO and its improved version, BESO, iteratively remove and add material based on stress criteria, leading to robust and computationally efficient structural designs. BESO has attracted considerable interest owing to its capacity to handle nonlinear problems, making it particularly useful for applications involving plasticity, dynamic loading, and multi-material systems [10–12]. Pereira et al. [13] introduced a topology optimization approach using BESO for the design of porous and rigid materials. Zuo et al. [14] expanded the BESO approach to accommodate multiple constraints, including displacement, frequency, and material use.

Conventional topology optimization methods mostly depend on elastic material behavior, so their application to structures undergoing nonlinear effects like plastic deformation and cyclic loading is limited. In practical engineering, however, especially in steel constructions, materials can experience cyclic stress changes that cause plastic deformations and possible fatigue failure. This requires an elasto-plastic topology optimization (EPTO) framework considering the material nonlinearity and cyclic character of applied loads [15,16]. Ivarsson et al. [17] presented an EPTO framework that maximizes stiffness by restricting plastic work production using finite strain linear isotropic hardening plasticity. Bogomolny and Amir [17] proposed an EPTO framework for the design of reinforced concrete buildings.

Cyclic loading circumstances are often seen in several engineering domains, such as earthquake-resistant buildings, bridges, offshore platforms, and aerospace components. These structures undergo recurrent loading and unloading cycles, which may result in increasing plasticity, strain accumulation, and ultimately material failure if inadequately designed [18–20]. Traditional TO methods fail to capture these complexities, resulting in designs that may perform suboptimally or fail prematurely under repeated loading conditions. Consequently, recent studies have concentrated on integrating geometrically nonlinear, elasto-plastic behavior and fatigue effects into topology optimization frameworks to improve structural performance under cyclic loading situations [21–23]. Gao et al. [24] presented a defect-driven optimization method for topological fatigue to get optimal structures with maximum stiffness. Blachowski et al. [25] introduced an innovative approach for optimizing elasto-plastic materials subject to stress constraints. Moreover, Da Silva et al. [26] presented topology optimization equations for compliant systems that include geometric nonlinearity.

Despite these advancements, there remains a significant research gap in the systematic integration of elasto-plastic behavior with cyclic loading effects within a robust topology optimization framework. Existing studies focus on single-cycle plasticity modeling, neglecting the long-term degradation effects induced by repeated load cycles. Therefore, in this study, a novel elasto-plastic topology optimization framework is introduced, specifically tailored for structures subjected to cyclic loading. The BESO method is enhanced and refined to achieve this objective. The proposed approach effectively integrates material nonlinearity, cyclic plasticity, and optimized material distribution to develop highly resilient and resource-efficient structural designs. The novelty of this work lies in its explicit consideration of cyclic loading-induced plasticity within a topology optimization framework, bridging the gap between structural optimization and nonlinear material behavior.

2 CYCLIC ELASTO-PLASTIC TOPOLOGY OPTIMIZATION PROBLEM

This section presents an advanced framework that integrates elasto-plastic material modeling with cyclic loading considerations, enhancing traditional topology optimization methods. The developed framework extends the BESO approach, accommodating large deformations and geometric imperfections to ensure optimal structural performance under repeated loading conditions. Through the incorporation of sophisticated theoretical developments, this methodology redefines the capabilities of structural topology optimization.

2.1 Elasto-plastic formulation

To capture the elasto-plastic response of structures, incremental loading is applied. The load $\boldsymbol{F}_i$is defined as a product of the load multiplier m_s and the initial reference load $\boldsymbol{F}_0$.

To accurately model the elasto-plastic behavior of structures, an incremental loading strategy is employed. The applied load ($\boldsymbol{F}_i$) is expressed as the product of a load multiplier and an initial reference load ($\boldsymbol{F}_0$). As loading progresses, plastic zones expand until the structure reaches its ultimate plastic load, denoted as:

$$\boldsymbol{F}_p = m_p\,\boldsymbol{F}_0 \tag{1}$$

where m_p represents the load multiplier at which the structure transitions into the plastic case.

Emphasizing stepwise plasticity, a finite element-based formulation is devised for elasto-plastic analysis. This approach permits the exact monitoring of elastic-to-plastic transitions by assuming a piecewise linear stress-strain relationship within each load increment. An improved Lagrangian formulation is proposed to include nonlinear effects resulting from geometric and material features. This method increases the accuracy of big deformation and rotation modeling by repeatedly updating the reference configuration to reflect the distorted state from the previous increment. Often referred to as the modified updated Lagrangian or Eulerian approach [27], this formulation is essential for structural modeling dependability and stability.

2.2 Proposed Optimization Algorithm

The suggested topological optimization framework is developed to maximize structures under elasto-plastic conditions exposed to cyclic loads. Although the BESO method's fundamental ideas are widely known in literature [28,29], this work expands their application by including material attributes, geometric defects, and structural performance measures under cyclic loading scheme. Key constraints integrated into the formulation include buckling load factors, plastic limit multipliers, and material volume fractions. The optimization problem is structured as follows:

$$Minimize\colon C = \boldsymbol{u}^T\boldsymbol{K}\boldsymbol{u} \tag{2}$$

$$Subject\ to\colon\ V^* - \sum_{i=1}^{N} V_i x_i = 0 \tag{3}$$

$$\boldsymbol{K}\boldsymbol{u} = \boldsymbol{f} \tag{4}$$

$$x_i \in \{0,1\} \tag{5}$$

$$m_s - m_p \leq 0. \tag{6}$$

$$\lambda_j - \underline{\lambda} \geq 0 \tag{7}$$

where C represents the mean compliance of the structure, $\boldsymbol{u}$ denotes the displacement vector, and $\boldsymbol{K}$ is the global stiffness matrix. The volume of an individual element (V_i) must not exceed the total volume (V^*). N is the overall count of the elements in the design domain; the binary design variable $\boldsymbol{x_i}$ values 1 when an element is present and 0 otherwise. The plastic limit load multiplier m_p is constrained by a minimum threshold to ensure that the work resulted by applied forces always remain non-negative. while λ_j and $\underline{\lambda}$ correspond to the buckling load factor and its lower bound, respectively. The objective function is to minimize compliance while ensuring material efficiency and stability constraints are met.

3 SENSITIVITY ANALYSIS

The sensitivity number for a given element is computed as the variation in strain energy:

$$\alpha_i^e = \Delta C_i = \frac{1}{2}\{\boldsymbol{u}_i\}^T[\boldsymbol{K}_i]\{\boldsymbol{u}_i\} \tag{8}$$

where $\boldsymbol{K}_i$ represents the stiffness matrix of element i, and $\boldsymbol{u}_i$ denotes its nodal displacement vector.

A filtration scheme is implemented to resolve mesh dependency issues and checkerboard patterns [30]. The BESO method applies a sensitivity filter, ensuring a smooth material distribution. The enhanced sensitivity number for an element i is computed using neighboring nodes within a defined sub-domain:

$$\alpha_i = \frac{\sum_{j=1}^{k} w(r_{ij})\alpha_j^n}{\sum_{j=1}^{k} w(r_{ij})} \tag{9}$$

where $w(r_{ij})$ represents a weight factor, given by:

$$w(r_{ij}) = r_{min} - r_{ij} \tag{10}$$

where r_{ij} is the distance of node j from the center of element i, and r_{min} is a predefined filter radius is a predefined filter radius. To stabilize the optimization process, an iterative averaging scheme is applied:

$$\alpha_i = \frac{\alpha_i^k + \alpha_i^{k-1}}{2} \tag{11}$$

where k represents the current iteration's number. Afterward, it ensures that on the subsequent iteration, $\alpha_i^k = \alpha_i$.

The BESO method iteratively accomplishes optimization by constantly adding and deleting components until the convergence is attained. Convergence is assessed through the stabilization of the objective function:

$$\frac{\left| \sum_{i=1}^{N}(F_{k-i+1} - F_{k-N-i+1}) \right|}{\sum_{i=1}^{N} F_{k-i+1}} \leq \tau \tag{12}$$

F represents the objective function, τ denotes the permitted convergence tolerance, k indicates the current iteration, and N is an integer that produces a constant compliance for a specified number of successive iterations.

4 DEVELOPED ALGORITHM

The proposed methodology introduces a structured approach to solving the elasto-plastic cyclic loading topology optimization problem by utilizing an enhanced BESO technique. The framework systematically refines structural configurations while incorporating satisfying constraints and elasto-plastic material behaviour. The key procedural steps, as depicted in Figure 1, are outlined as follows:

- Determine the design domain.
- Perform elasto-plastic FEA to under cyclic loading configurations.
- Determine the sensitivity of each element.
- Determine the reliability of the next iteration by referencing the target volume.
- Iteratively modify the topology by removing or adding elements.
- Redo stages from 2 to 5 until all constraints are met.
- Confirm convergence.
- Produce the final topology that satisfies the specified constraints.

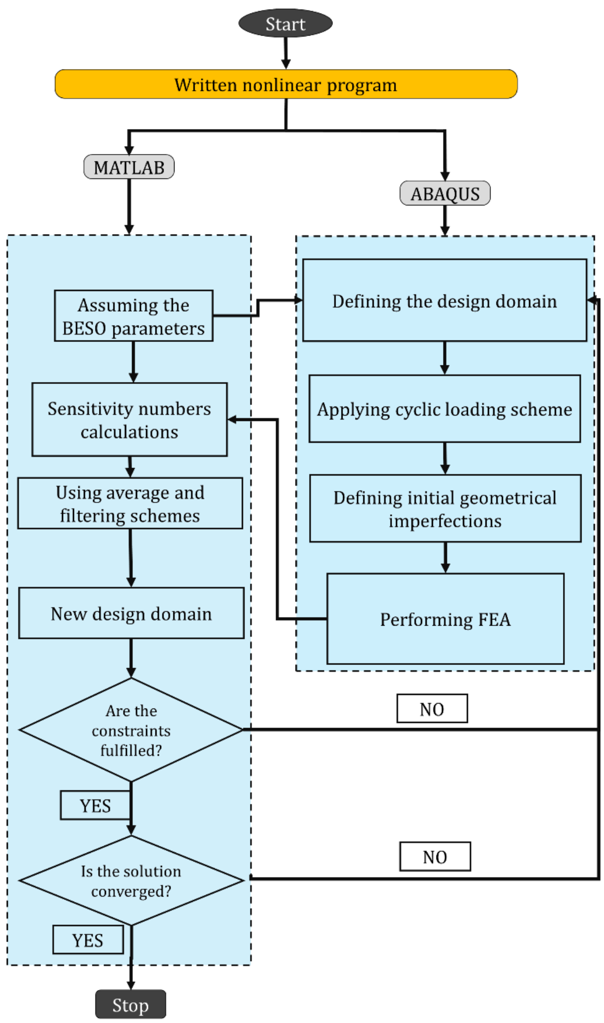
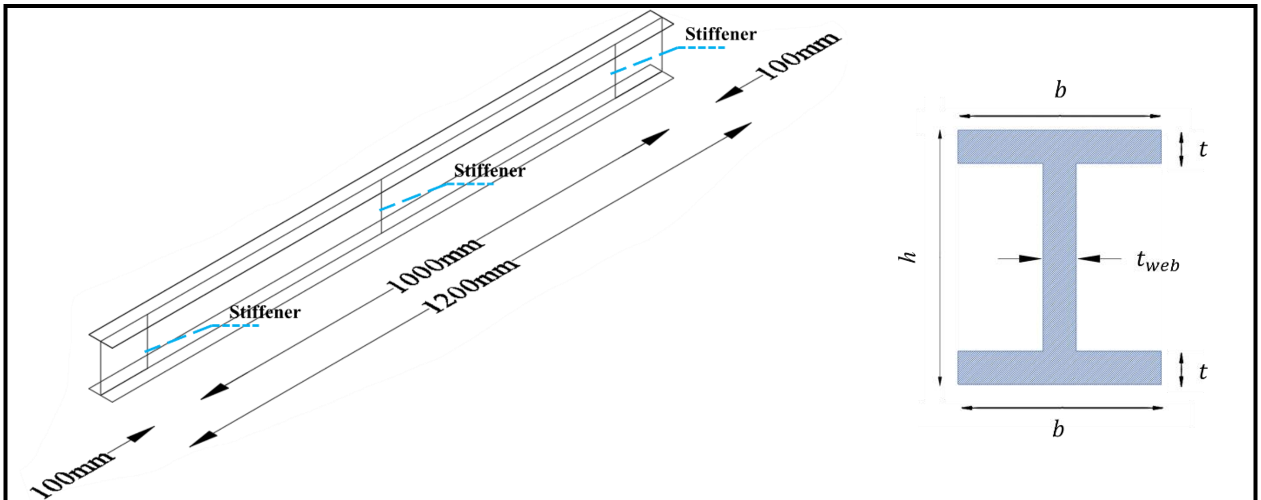


Figure 1 Flowchart illustrating the proposed methodology for cyclic elasto-plastic optimization

5 NUMERICAL EXAMPLES

This study explores EPTO problem considering cyclic loading scenario, and the impact of initial geometric imperfections. To address the complexities of such problems, an enhanced BESO algorithm is employed. A numerical example is used to illustrate the efficacy of the proposed approach featuring a steel I-section beam, following the validation methodology established by Habashneh and Rad [31].

The steel beam analyzed in this study is a plain-webbed I-section, chosen for its prevalent use in construction applications. Specifically, an ISMB 100 section was selected, with its geometric properties summarized in Table 1. The beam's flange width is 55 mm, and its total depth is 100 mm. 5 mm and 4.7 mm are considered as flange and web thicknesses, respectively. Additionally, flat transverse stiffeners are incorporated each with thickness of 5 mm. Table 1 also outlines the steel beam's geometrical specifications, applied loads, and boundary conditions considered in the analysis. To ensure an optimized material distribution while preserving structural integrity, the BESO parameters are meticulously chosen. The evolutionary rate (ER) is set at 1%, while the maximum allowable adjustment ratio (AR_{max}) is limited to 1%. A filter radius (r_{min}) of 138 mm is introduced to maintain a smooth material layout, and a convergence threshold (τ) of 0.1% is adopted. The volume fraction constraint (V_f), representing the ratio of the web opening volume to the overall web volume, is fixed at 0.60.



$t\ (mm)$	5
$t_w\ (mm)$	5
$b\ (mm)$	55
$h\ (mm)$	100

Table 1: Geometric properties and dimensions of the steel I-section beam.

The numerical model is constructed using nominal-sized shell elements to accurately represent the beam's structural characteristics. A geometrically nonlinear model with initial imperfections is employed, incorporating material properties such as a Young's modulus of $200\ GPa$, a Poisson's ratio of 0.3, and a yield stress of $355\ MPa$. An initial imperfection magnitude of $L/1000$ is assumed to account for real-world deviations in geometry. Boundary conditions are applied to reflect realistic constraints: all translational and rotational degrees of freedom are restricted at one end of the beam, whereas the opposite end allows movement along the z-axis while restricting displacement along the x and y axes. Concentrated loads are imposed at the upper mid-span point location along the beam's span, as illustrated in Figure 2. A detailed finite element model is developed to accurately capture the beam's structural response. The mesh consists of 10,890 quadrilateral S4 shell elements, each approximately 5 mm in size, striking a balance between computational efficiency and modeling precision. The S4 shell elements are particularly suitable for thin-walled structures, as they incorporate finite-membrane-strain formulations that enable the analysis of nonlinear effects stemming from both material behavior and geometric deformations.

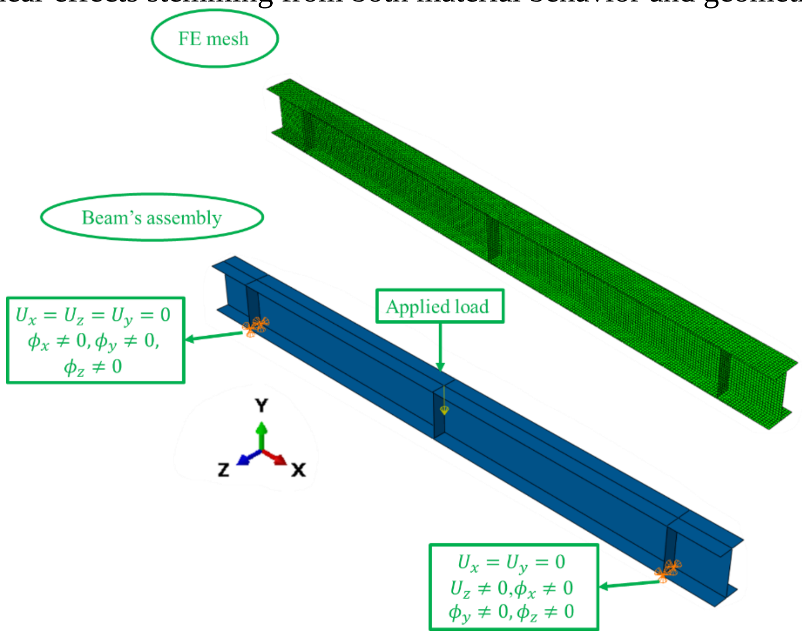


Figure 2: Beam numerical model

The cyclic loading scheme implemented in this study adheres to well-established methodologies for assessing elasto-plastic behavior under repeated stress reversals [32]. A reference force of 30 kN was selected, with its magnitude varying according to a time-dependent cyclic amplitude function. This approach, widely adopted in both experimental and numerical investigations, enables a realistic representation of structural loading conditions [33]. The applied loading function follows a sinusoidal pattern over a total duration of 40 seconds, with a time increment of 0.1 seconds, ensuring precise tracking of the material response within the plastic regime. By employing this cyclic loading history, the study effectively captures the accumulation of plastic strain and the redistribution of stresses, ensuring that the optimized structural configurations maintain their efficiency under repeated loading cycles. This methodology facilitates a comprehensive assessment of key elasto-plastic phenomena, including stress redistribution, plastic strain evolution, and failure mechanisms associated with cyclic hardening or softening.

To establish a benchmark for validation, an initial comparative analysis is conducted between the results obtained from this study and those reported by Habashneh and Rad [31]. The comparison is performed under identical loading conditions and volume fraction constraints to ensure consistency in the evaluation. The results of this comparison are presented in Table 2, where the second column illustrates the optimized topology obtained considering cyclic loading, while the third column corresponds to the previously developed topology optimization framework by Habashneh and Rad [31].

A key observation from this comparison is the presence of thicker structural regions in the optimized design under cyclic loading conditions. These reinforced areas, particularly in high-stress regions, emerge as a direct adaptation to cyclic loading effects. The increased material concentration in these zones serves to distribute stress more evenly, reduce localized damage, and enhance the overall durability of the structure. This finding underscore the critical role of incorporating cyclic loading effects in topology optimization to develop structurally efficient designs that not only enhance performance but also ensure long-term durability under real-world loading conditions.

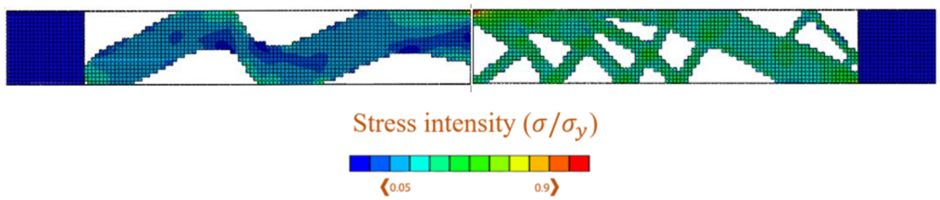
Beam	Considering cyclic loading	Habashneh and Rad [31]
$F = 31.5\ kN$ $V_f = 0.60$		

Table 2: Comparison of obtained topological layouts.

The second phase of this study is specifically designed to demonstrate the efficiency of the enhanced BESO algorithm in optimizing structural topology for increased load-bearing capacity. A key feature of this phase is the incorporation of the plastic ultimate load multiplier alongside cyclic loading, allowing for a more comprehensive assessment of how the optimized topology adapts to progressive plastic deformations and increasing load intensities. The initial applied load (F_0) is set at 10 kN, while the load multipliers (m_i), including the plastic ultimate load multiplier (m_p), are defined as $m_1 = 0.1, m_2 = 1.5, m_3 = 3.0, m_4 = 4.0$, and $m_p = 4.70$. Table 3 presents the results of the cyclic plastic-limit load optimization of the beam, illustrating the evolution of the optimized shape under increasing load multipliers. The applied load is scaled by different multipliers, and the corresponding optimized configurations are depicted alongside a stress intensity distribution ($\sigma/\sigma y$).

A progressive material redistribution is evident as the load factor increases. At $F_0 \times m_1$, the topology exhibits a relatively conservative material distribution, with substantial regions of high material density, particularly around the load application zones and boundary constraints. The stress intensity remains within a lower range (predominantly blue), indicating that plastic strain accumulation is minimal at this stage. At the highest load level, $F_0 \times m_4$, the topology optimization results in a stress distribution (indicated by the color gradient) shows higher concentrations of stress near mid-span and along the load paths, suggesting that the structure is approaching its plastic-limit capacity. The presence of thicker material regions in high-stress zones is a key observation, as these areas serve to enhance the load-bearing capacity, delay localized failure, and improve structural resilience under cyclic loading conditions. Furthermore, under this load condition, 161 out of 2,379 web elements (approximately 6.77%) have reached the yield stress. This percentage indicates that the structure is still within an acceptable performance range before significant plastic deformations or failure occur. The yielded elements appear to be concentrated near the regions of high stress, particularly along the diagonal struts and near the central opening, as seen in the stress distribution plot in Table 3.

Applied load	Optimized shape

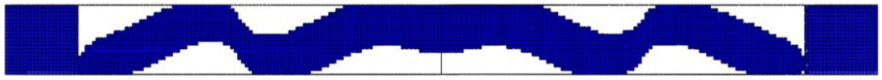
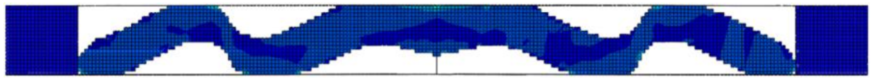
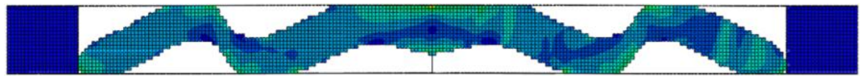
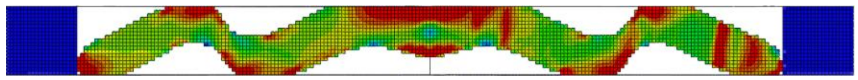
$F_0 \times m_1$	
$F_0 \times m_2$	
$F_0 \times m_3$	
$F_0 \times m_4$	
	Stress intensity (σ/σ_y) 

Table 3: Results of cyclic plastic-limit load optimization of the beam.

6 CONCLUSIONS

This study introduced an advanced elasto-plastic topology optimization framework specifically designed to enhance structural efficiency under cyclic loading. By refining the BESO method, the proposed approach effectively integrates material nonlinearity and cyclic plasticity into the topology optimization process. This integration enables the generation of resilient structural designs that balance load-bearing capacity with material efficiency, contributing to sustainable structural engineering practices. The numerical implementation and case study demonstrated the effectiveness of the framework in optimizing steel I-beam sections subjected to cyclic loading, showcasing significant improvements in stress distribution, plastic limit load multipliers, and overall structural resilience. The key findings of the study include:

- The incorporation of cyclic plasticity into topology optimization significantly enhances structural durability by redistributing material in high-stress regions.
- The optimized designs exhibit improved load-bearing efficiency while maintaining material sustainability, reducing unnecessary material use without compromising structural integrity.
- The enhanced BESO method effectively manages stress concentrations and minimizes plastic strain accumulation, ensuring prolonged structural performance under repeated loading cycles.
- Numerical results demonstrated that the proposed approach produces superior topological configurations compared to conventional optimization methods, particularly mitigating stress-induced failures and fatigue accumulation.
- The validation process, using a steel I-section beam, confirmed the reliability of the proposed methodology, highlighting its applicability in real-world engineering scenarios.

These findings establish a foundation for further expanding elasto-plastic topology optimization. Future advancements could explore multi-objective optimization strategies, integration with computationally efficient solvers, and real-world experimental validations.

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