

Mechanical Performance of Box Section Steel Beams under Damaged Conditions based on Finite Element Analysis

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Abstract

This study systematically investigates the degradation patterns of mechanical performance in box-section steel beams under damaged conditions using finite element analysis. A refined finite element model was developed on the ABAQUS platform, incorporating material nonlinearity, geometric nonlinearity, initial imperfections, and residual strains. Damage scenarios were simulated through a material reassignment approach. Particular emphasis was placed on examining the influence of flange width, section height, and beam span on the load-bearing capacity of the steel beams. The results indicate that structural damage leads to stress redistribution, reduces the ultimate load-carrying capacity, and may trigger local instability or brittle fracture. Increasing the flange width or section height enhances the ultimate load-bearing capacity of damaged box-section steel beams, whereas an increase in beam span results in a decline in their load-carrying capacity. These findings provide a theoretical basis for the safety evaluation and retrofit design of existing steel structures.

Keywords

Box Section Steel Beam; Damage; Finite Element; Mechanical Properties; Safety Assessment.

1. Introduction

During the long-term service of steel structures, various factors can lead to a certain degree of damage and deformation [1]. For box-section members that have already sustained localized damage, completely dismantling and replacing them would result in significant waste of financial and material resources. Conversely, if these components continue to bear loads that exceed their current residual load-carrying capacity, it is highly likely to cause localized failure or even overall structural safety incidents of the box-section steel beams. Such failures not only threaten human life but also result in substantial social and economic losses [2]. Whether damaged steel structures can still meet normal usage requirements involves critical concerns regarding life and property safety, making it a focal point of public attention [3].

2. Current Status of Damage Analysis Research

2.1 Current Status of Research on the Flexural Behavior of Bending Members

In recent years, there has been a growing body of research both domestically and internationally focusing on the flexural performance of structural members, particularly steel members. Given the diverse types of member configurations, their impacts on the overall performance of structures vary significantly.

Beg [4] et al. conducted four-point bending tests and finite element analyses on welded H-section flexural members to investigate local stability issues. The results indicated that the interaction between the flange and the web has a significant influence on the load-carrying capacity of the flexural members. Based on their findings, an analytical formula for calculating the limiting width-to-thickness ratio was proposed.

Sause [5] conducted experimental studies on H-section flexural members, demonstrating that high-strength steel members exhibit significantly enhanced flexural performance compared to ordinary steel members. The experimental results were compared with the provisions of steel structural codes, validating the reliability of the experimental conclusions.

Zhou Xuhong [6] et al. conducted experimental research on the flexural behavior of cold-formed thin-walled channel steel beams. The study investigated the effects of height-to-width ratio, width-to-thickness ratio, and span-to-height ratio on their failure modes and ultimate load-carrying capacity. The results indicated that the width-to-thickness ratio and the height-to-width ratio have a significant impact on the load-carrying capacity.

Ye Liming [7] conducted bending reinforcement experiments on H-shaped steel beams using various sizes of reinforcement materials. The study employed the section equivalent substitution method to analyze the reinforced steel beams and provided theoretical derivations, thereby offering a theoretical calculation method for the analysis of reinforced steel beams.

2.2 Current Status of Research on the Flexural Performance of Damaged Steel Beams

As the application of steel structures becomes increasingly widespread, numerous studies have been conducted both domestically and internationally to better understand and utilize their performance by investigating the effects of various factors that cause damage to steel beams.

Nakai [8] et al. artificially introduced holes to simulate pitting corrosion in steel. The experimental results showed that the greater the depth and density of the pits, the more rapidly the strength and ductility of the corroded steel deteriorated. Compared to uniform corrosion, non-uniform corrosion has a more significant impact on both the tensile strength and yield strength of steel.

Wang Zhihan [9] et al. designed three H-shaped steel beams to investigate the effects of static strain aging on the mechanical properties of damaged steel beams. An experimental study was conducted using a two-stage loading protocol to examine how strain aging influences the behavior of damaged beams. The results indicated that the load-carrying capacity of damaged steel beams is jointly governed by residual deformation and variations in material mechanical properties. When the damage is mild, the changes in mechanical performance are not significant. However, when the damage leads to strains exceeding 4.5%, the beams are deemed unsuitable for reuse even after repair.

Yin Chao [10] focused on steel box girders, analyzing the mechanical properties of steel beams under various degrees of corrosion. Through experimental loading tests, the study investigated the influence of corrosion location and severity on the ultimate load-bearing capacity and failure modes of steel beams. The research demonstrated that the mass loss ratio of specimens is a critical factor affecting the load-carrying capacity of steel beams, whereas the depth of corrosion is the key factor influencing the load-bearing capacity of pitted steel beams.

Xiang Yuxuan [11] conducted four-point bending tests on H-shaped steel beams to investigate the changes in mechanical properties under varying degrees of damage. The experimental results showed that minor damage within a certain range has no significant effect on the ultimate load-carrying capacity of the steel beams. However, once the damage exceeds a critical threshold, the ultimate load capacity decreases progressively with increasing damage severity.

2.3 Current Status of Finite Element Analysis Research

Gorl [12] utilized finite element technology to conduct a study on the identification of damage location and severity in a double-layer steel frame structure. In the course of the research, an initial finite element model was first established using the vibration test responses from the undamaged

structure. Subsequently, based on the stiffness changes before and after the damage, and by integrating experimental modal data from the damaged structure, the study successfully identified the extent of structural damage.

Shen Zuyan [13] et al. applied an optimized numerical integration technique for finite element simulation analysis based on the mechanical model of damage accumulation and the fracture criterion under cyclic loading conditions for steel. They developed a component restoring force model that takes into account both damage accumulation and fracture effects.

Zhou Taiquan [14] integrated the fully coupled fatigue damage analysis procedure based on continuum damage mechanics into the user-defined interface of the commercial finite element software ABAQUS. Using this fully coupled fatigue damage analysis method, the key welded components of the Qingma Bridge were analyzed in terms of fatigue damage accumulation. The results demonstrated that this analytical approach is both reasonable and feasible.

Zhao Yuan [15] et al., in their research on structural damage detection, investigated the limitations of the flexibility difference method in identifying multiple damage locations and introduced the concept of flexibility curvature. Through finite element simulation experiments, they verified that this method can accurately identify damage at multiple locations in the structure.

3. Finite Element Analysis of Damaged Box Section Steel Beams

Compared to traditional physical model testing, finite element simulation offers significant advantages in enhancing the accuracy and refinement of product design, while substantially accelerating the research and development cycle. Moreover, it provides highly efficient analysis, cost savings, and access to more comprehensive datasets. In other words, finite element simulation plays an irreplaceable role in optimizing problem-solving strategies, reducing research costs, and improving overall work efficiency.

3.1 Establishment of a Finite Element Model for Damaged Box-Section Steel Beams

In this study, shell elements were used to establish the finite element model of the box-section steel beam. When creating individual components, only the cross-sectional dimensions of the box section need to be input, and then extruded in the specified direction to generate the geometric model, as shown in Fig. 1. To facilitate the subsequent application of residual stresses, the cross-section was further divided according to the calculated residual stress distribution. The resulting cross-sectional partitioning is illustrated in Fig. 2.

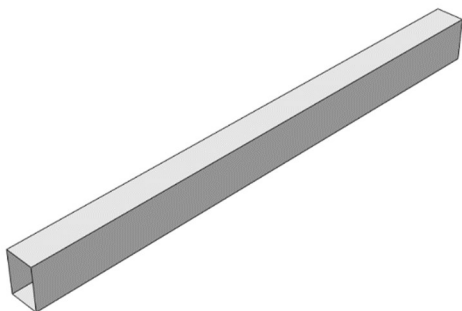


Fig.1 Geometric model of shell elements

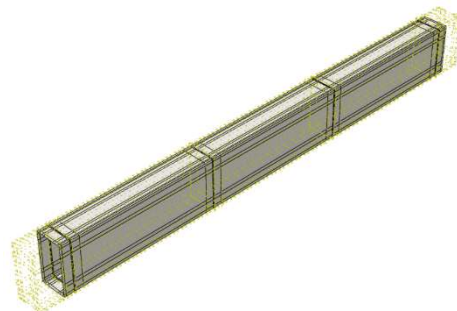


Fig.2 Diagram of cross-sectional segmentation

For the convenience of input into the finite element model, the residual stress distribution model was simplified, resulting in the residual stress distribution shown in Fig. 3. The finite element residual stress contour plot is illustrated in Fig. 4.

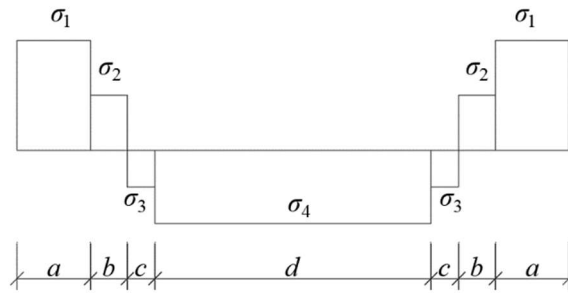


Fig.3 Finite element residual stress model

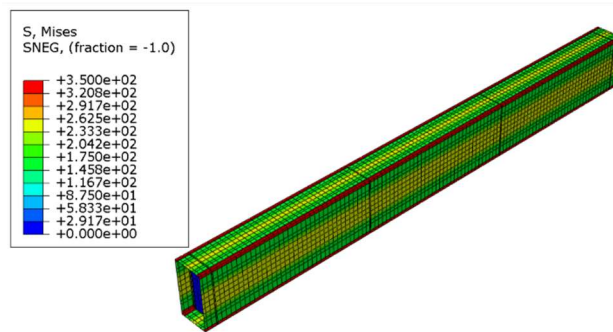


Fig.4 Finite element residual stress contour map

3.2 Influence of Different Parameters on the Performance of Damaged Steel Box Girders

3.2.1 Influence of Flange Width on the Performance of Damaged Steel Box Girders

To investigate the influence of flange width on damaged box-section steel beams, parametric analyses were conducted by varying the flange width while keeping the section height constant. The comparison of simulation results is presented in Table 1 and Fig. 5.

Table 1. Load-carrying capacity of damaged steel beams with different flange widths

Serial number	Flange width /mm	Ultimate load P_{max} /kN	Rate of change R^* /%
A	100	246.76	0
B	125	273.86	10.98
C	150	314.37	27.40
D	175	341.03	38.20
E	200	367.17	48.80

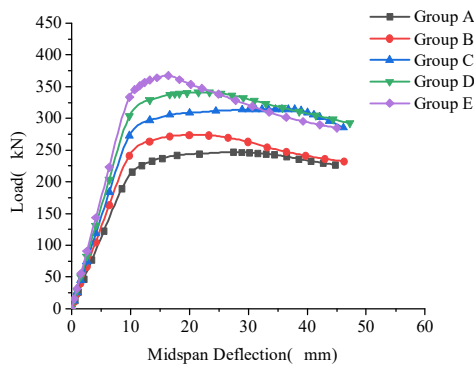


Fig.5 Load-midspan deflection curves of box section steel beams with different flange widths

3.2.2 Influence of Section Height on the Performance of Damaged Box-Section Steel Beams

To investigate the influence of section height on damaged box-section steel beams, parametric analyses were conducted by varying the web height while keeping the flange width constant. The comparison of simulation results is presented in Table 2 and Fig. 6.

Table 2. Load-carrying capacity of damaged steel beams with different flange widths

Serial number	Flange width /mm	Ultimate load P_{max} /kN	Rate of change R^* /%
A	100	246.76	0
B	125	273.86	10.98
C	150	314.37	27.40
D	175	341.03	38.20
E	200	367.17	48.80

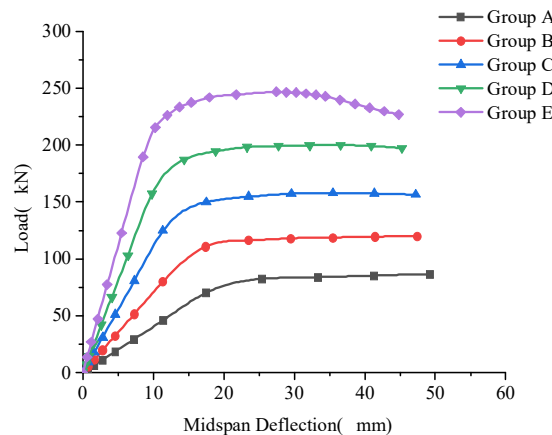


Fig.6 Load-midspan deflection curves of box section steel beams with different section heights

4. Conclusion

In this study, a finite element model of a box-section steel beam was established using ABAQUS. The modeling process and methodology are introduced, and the results are analyzed in detail. The finite element analysis revealed the following findings:

When the section height is constant, increasing the flange width of the box-section steel beam is beneficial for enhancing its load-carrying capacity. However, the improvement is relatively small. For instance, doubling the flange width results in an increase of nearly 50% in the ultimate load-carrying capacity. Conversely, when the flange width is held constant, increasing the section height of the box-section steel beam significantly enhances its load-carrying capacity. In particular, doubling the web height leads to a doubling of the ultimate load-carrying capacity.

Therefore, in structural design, when conditions permit, the load-carrying capacity of steel beams can be effectively improved by increasing the flange width and section height.

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