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BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

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ASSESSMENT OF THE IMPACT OF MATERIAL DEFECTS ON THE PERFORMANCE OF STEEL STRUCTURAL ELEMENTS

The purpose of this study is to investigate the influence of rolled metal defects of various origins on the stress–strain state and load-bearing capacity of steel structural elements, as well as to assess the extent of their impact depending on the type and volume of defects. **Methodology.** The study was carried out using the finite element method, employing a computational model in the form of a cantilever beam with a rectangular cross-section. Several beam lengths and different operating scenarios were considered: a solid material without defects, as well as models with internal voids and surface damage. Internal defects were modeled as localized volumetric voids, while external defects were represented as geometric surface irregularities. For each case, stresses and displacements were determined and subsequently compared. **Findings.** The results showed that the presence of defects leads to changes in the stress distribution and increases displacements compared to defect-free models. It was established that as the volume of defects increases, the equivalent stresses and deflections of the structural element also increase. Internal defects were found to have a more pronounced effect, as they contribute to the formation of local stress concentrations within the material. External defects also affect the performance of the element, but their influence is less significant. Furthermore, a relationship between the geometric parameters of the beam and sensitivity to defects was identified: as the element length increases, the impact of defects becomes more pronounced. **Originality**. The study provides generalized quantitative assessments of the influence of internal and external defects on the stress-strain state of steel structural elements. Differences in the impact of various types of defects were demonstrated, and the dependence of this impact on the geometric parameters of the elements was established. **Practical value.** The results of this study can be applied to assess the technical condition and residual load-bearing capacity of steel structures with defects. The proposed modeling approach allows for consideration of the actual material defectiveness in engineering calculations. The obtained relationships are recommended for use in determining permissible defect levels and refining safety factors.

Keywords: steel structural elements; modeling; rolled metal; internal defects; external defects; load-bearing capacity; stress-strain state; finite element method; building structures

Introduction

The reliability and durability of structural steel constructions are largely determined by the material quality and the presence of defects that arise during the manufacturing, installation, or operation of structural elements. Under real production conditions, it is practically impossible to completely eliminate metal defects, as they may form both at the stage of metallurgical production and during processing, welding, or long-term service of structures. The presence of such imperfections can alter the stress-strain state of elements, cause local stress concentrations, and reduce their load-bearing capacity (Вабіщевич, Нестор, Фесун, & Бурківський, 2024; Ivanova, Radkevych, Olishevska, & Ma, 2025; Zhang, Liu, et al., 2025; Du, Liu, Li, et al., 2023).

Modern studies are focused on numerical modeling, monitoring, and assessment of the technical condition of steel structures, taking into account local damage or material defects. In particular, it has been shown that even minor defects can lead to redistribution of internal forces within a structural system and affect its overall reliability (León-Henao, Morales-Galeano, Santa-Marín, et al., 2024).

Some studies confirm that the presence of initial defects or non-metallic inclusions significantly reduces the fatigue strength of metal and promotes crack initiation (Yonezawa, Mori, & Tsutsumi,

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2024). The analysis of fatigue behavior of welded joints indicates that welding defects are among the main causes of fatigue crack development in steel structures (Zhang, Liu, et al., 2024; Karuskevych, M., Maslak, Karuskevych, O., & Vlasenko, 2025). In addition, recent studies emphasize the importance of accounting for defects when assessing the durability and reliability of structures throughout their entire life cycle (Zembrzuski, Sobczyk, Miśkiewicz, et al., 2025).

At the same time, most studies are still focused on general reliability issues or material characteristics, whereas the influence of specific metal defects on the performance of individual structural elements remains insufficiently investigated. This necessitates detailed studies aimed at determining the permissible level of material defectiveness and evaluating its impact on the load-bearing capacity of structural elements.

Thus, the study of the influence of metal defects on the performance of structural elements is an actual scientific task aimed at improving the reliability and safety of buildings and structures, as well as substantiating the safety factors adopted in design practice.

A new stage in the development of materials science necessitates the improvement of approaches to assessing metal quality and defectiveness. Despite the wide variety of steel grades and advances in production technologies, it is impossible to completely eliminate material defects. They are formed at different stages of the life cycle of structures-from smelting to operation.

Metal structures always contain defects of various origins-metallurgical, technological, and operational-which, under certain conditions, may lead to crack initiation and structural failure. The rate of their initiation and propagation depends on the material structure, design parameters, loading conditions, and environmental influences (Ivanova, Radkevych, Olishevska, & Ma, 2025; Xue, 2025).

Thus, material defectiveness is an inherent factor that determines the reliability and durability of steel structures and must be taken into account in their analysis and technical condition assessment.

The most dangerous failure modes of steel structures are associated with the initiation and propagation of defects in critical zones under the influence of operational and manufacturing-related factors. In recent years, the relevance of improving the durability of steel structures has increased due to rising stress levels and the growing corrosive aggressiveness of the environment.

Previously, steel was considered to have a homogeneous and maximum dense structure; however, during smelting, rolling, and transportation, numerous defects may arise that reduce the performance characteristics of structures. The study (Fedoriachenko, Ziborov, Laukhin, et al., 2025) examines the formation and development of microdefects in cast metal alloys, in particular microporosity and microcracks, which determine the durability and reliability of structures. It is shown that microvoids of approximately 10 μm are difficult to detect using conventional inspection methods; however, they significantly reduce fatigue resistance, ductility, as well as tensile strength and yield strength.

Purpose

The purpose of this study is to investigate the influence of rolled metal defects (internal voids and external surface damage) on the stress-strain state and load-bearing capacity of steel structural elements based on finite element modeling of a rectangular beam.

Methodology

During the manufacturing and processing of structural steel elements, defects may occur, i.e., certain deviations of products from regulatory requirements. The classification of metal defects is carried out according to their location and manifestation into internal (volumetric) and external (surface) defects (Власенко, 2019).

Internal defects (Figure 1) include pores (internal voids formed due to gas entrapment or shrinkage during solidification), shrinkage cavities (resulting from volumetric contraction of metal during solidification), and non-metallic inclusions (oxides, sulfides, nitrides formed or introduced into the metal during melting). External (surface) defects (Figure 2) include cracks, scratches, laps, and other surface imperfections.

The following processes can be identified as common sources of defect formation:

- Defects arising from solid deformation. The formation of defects during small deformations is not intensive. After the removal of the applied stress, the material may return to its original shape. However, if the level of deformation exceeds a threshold value, the number of defects increases

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rapidly, leading to irreversible plastic deformation of the material. Plastic deformation is conditioned by the density and magnitude of the defects formed, which prevent the specimen from returning to its original shape.

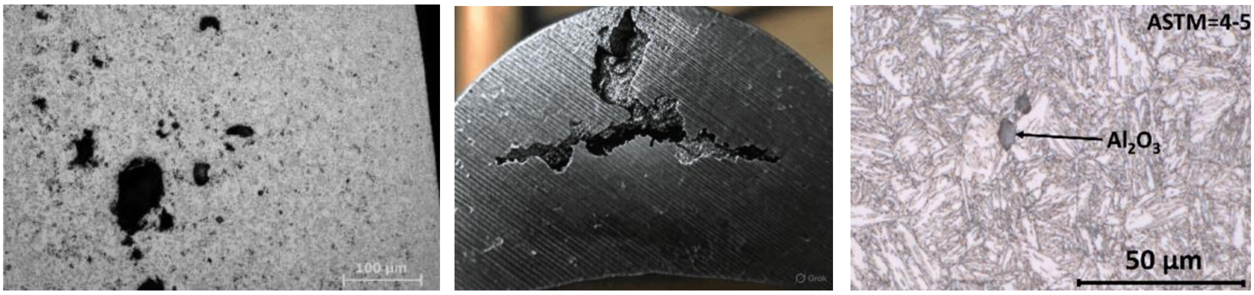

Figure 1. Examples of internal defects

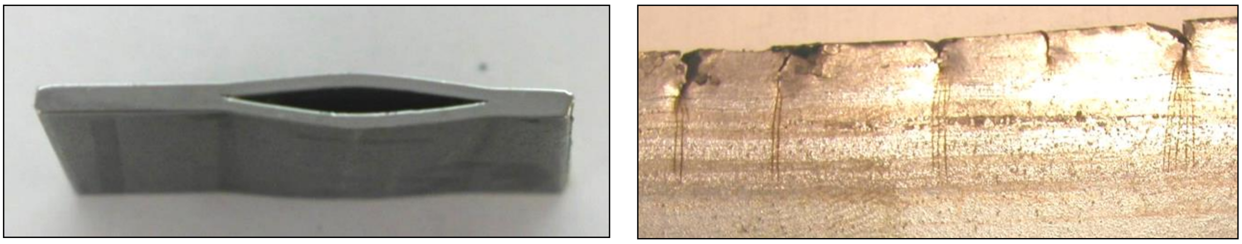

Figure 2. Examples of external defects

- Surface processing defects. During machining or grinding, microcracks inevitably form on the surface of the material.
- Casting defects. When molten alloy is poured into molds and begins to cool, uneven cooling causes some parts of the casting to solidify earlier than others, leading to layer displacement. In addition, small air bubbles may become trapped in the alloy, resulting in porosity.
- Rolling process defects. Rolling defects occur due to violations of rolling technology or improper preheating of the billet. An incorrect reduction ratio or insufficient heating prior to rolling may result in surface defects such as laps, seams, flakes, cracks, chips, deformed ends, and other imperfections.
- Heat treatment defects. Heat treatment defects arise from incorrect selection or violation of the thermal regime. The most common defects at this stage include overheating (which can be corrected by reheating), burning, thermal cracking, and others. Defects may also occur during storage, transportation, and handling.
- Storage defects. During transportation or storage, metal may be deformed (bent or dented). Additionally, prolonged storage may lead to aging of the material, resulting in a reduction in its strength and ductility properties.

Data on the accidental destruction of metal structures are given in Table 1.

Table 1

Data on the accidental destruction of metal structures

Influence of operating conditions, %	60
The influence of the human factor, %	19
Destruction of individual structural elements, %	10
Sudden impacts, %	8
The cause is unknown, %	3

The accumulation of damage, the appearance and development of defects reduces the load-bearing capacity of structures, therefore, for large-sized and multi-element systems, the probability of loss of load-bearing capacity and reduction of service life increases.

The defectiveness in the control element is determined by the following formula:

$$q=\frac{\sum \Delta S}{S_p},$$

where q – defectiveness in the controlled element; ΔS – total area of defects; S_p – design area of the control cross-section.

An increase in the size and number of elements

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in structural systems leads to a higher probability of defect occurrence and the manifestation of a scale effect, which affects the overall serviceability of the system (Ivanova, Hapieiev, Shapoval, Zhabchyk, & Zhylinska, 2021). The emergence of additional forces and displacements in such systems can significantly alter their stress state (Ivanova, Zhabchyk, Khoziaikina, & Hryhoriev, 2023).

Findings

To study the influence of defects on the strength of a structural element, a model of a rectangular steel beam with a cross-section of 20×100 mm was developed and analyzed. The calculations were performed using the LIRA-SAPR software package.

During the modeling process, internal defects-represented by voids located in separate groups or chains within the metal-and external defects located on its surface were considered. Internal defects may arise during primary crystallization, while external defects can be caused by various factors. A cantilever beam with a fixed support at one end was analyzed, with a concentrated load of 3000 N applied at the free end (Figure 3). The material of the model was structural steel grade – construction steel three beam lengths were considered: 0.5 m, 1.0 m, and 1.5 m. The maximum size of the finite element was 4 mm (Figure 4).

The modeling was carried out for three cases:

1. Analysis of a model with a homogeneous solid medium.
2. Analysis of a model with internal defects.
3. Analysis of a model with external defects (dents, corrosion damage, etc.).

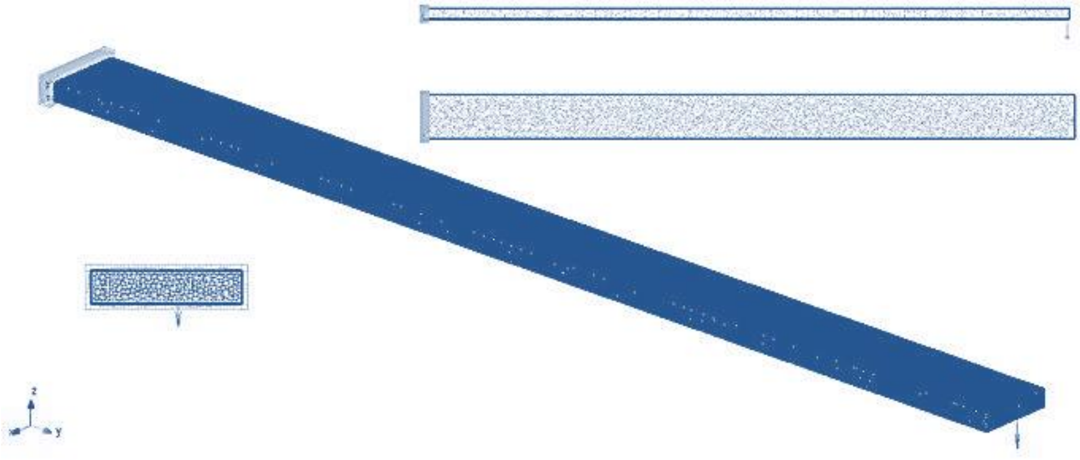

Figure 3. Beam model

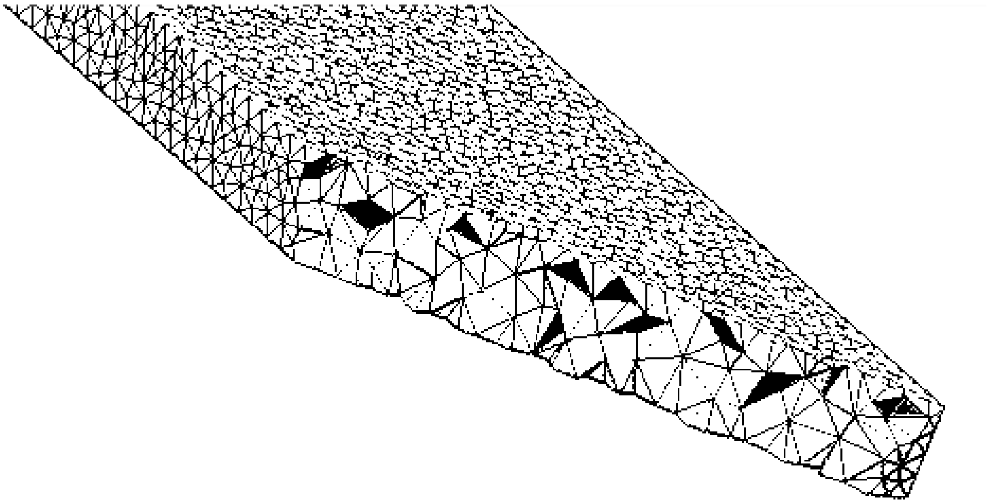

Figure 4. Finite element mesh for the model with internal defects

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Initially, simulations were performed for both the solid model and the model with defects. The volume of defects was varied arbitrarily (Table 2).

The results showed that the reduction of metal volume due to defects leads to a decrease in the load-bearing capacity of the element. For the 1.5-meter model, the increase in stresses reached 38.6%, while the deflection increased by 5.3 %.

The calculation results for the 0.5 m model shown in Figure 5.

Table 2

Input data for modeling

Model length, m	Volume of the solid model, cm^3	Volume of voids or external defects, cm^3
0.5	1000	9
1	2000	17
1.5	3000	26

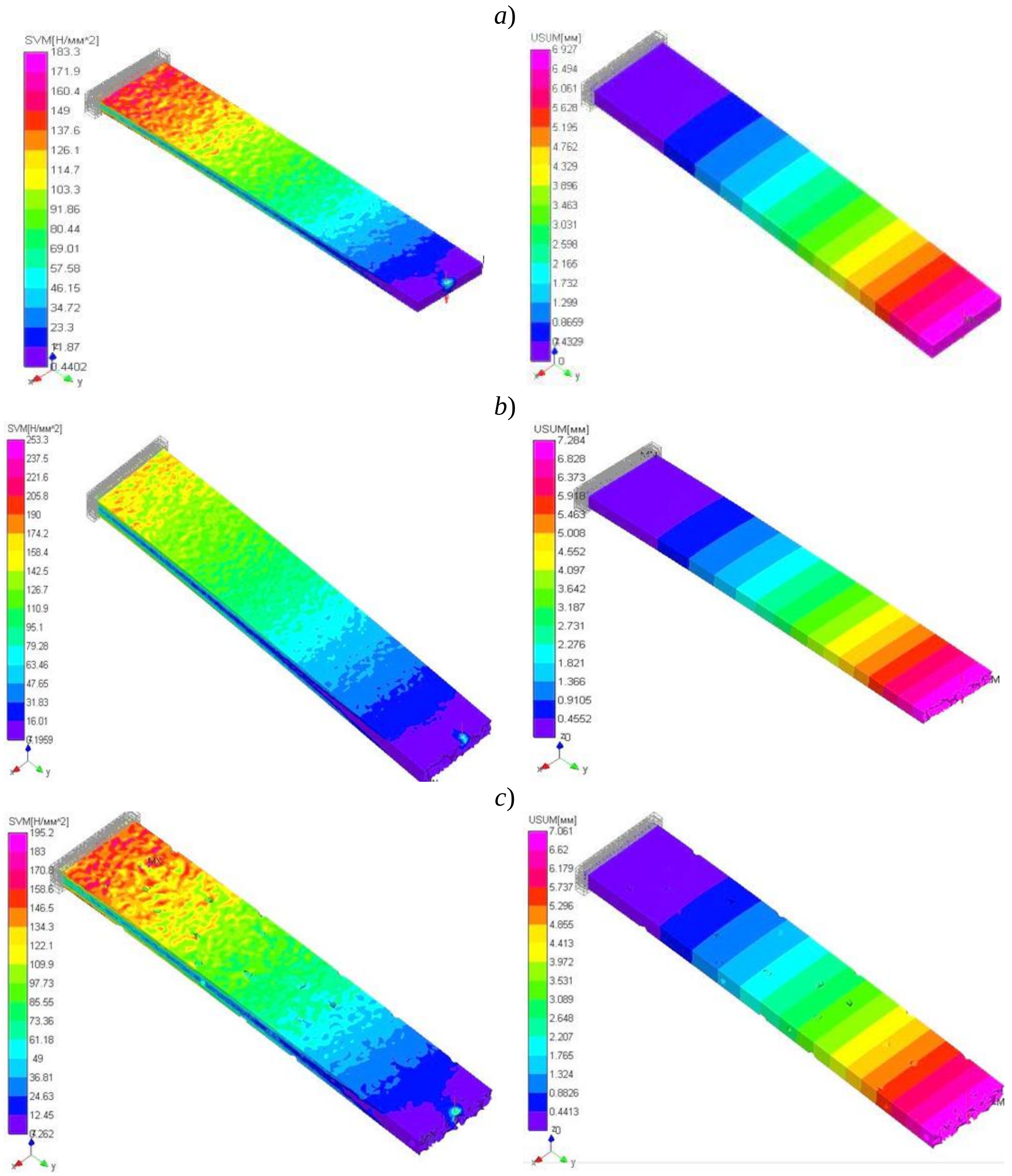

Figure 5. Stress and displacement contours for the 0.5 m long model:
a) solid model; *b*) internal defects; *c*) external defects

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Similar stress and displacement contours were obtained from the analysis of the 1 m and 1.5 m long models. The calculation results presented in Table 3.

Table 3

Calculation results for the three cases

Length of the model, m	Stress in the model, N/mm^2			Deflections of the model, mm		
	Solid	Internal defects	External defects	Solid	Internal defects	External defects
0.5	183.3	253.3	195.2	6.92	7.284	7.061
1	386.8	519	445	11.74	15.02	14.64
1.5	579.2	795	762.8	18.9	21.9	20.4

Based on the calculation results, it can be concluded that internal defects are more critical than external ones.

A graphical interpretation of the calculation results presented in Figures 6 and 7.

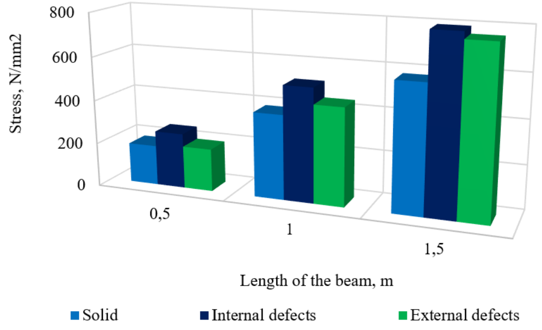

Figure 6. Dependence of stress
on the defectiveness of the model

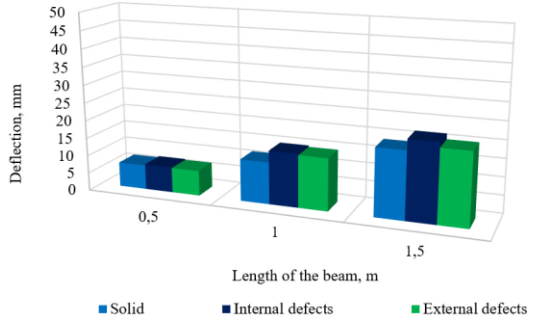

Figure 7. Dependence of deflection
on the defectiveness of the model

Originality and practical value

This study investigated the influence of internal and external defects in rolled metal on the stress-strain state of steel structural elements. Quantitative estimates of stress and displacement variations were obtained depending on the volume and type of defects. It was shown that internal defects cause a more significant increase in stresses compared to surface damage. A dependence of defect impact on the geometric parameters of the element was established, indicating that the sensitivity of the structure to defects increases with its size.

The practical significance of this work lies in the possibility of using the proposed approach to assess the technical condition of steel structures, as well as to justify the permissible level of material defectiveness during the operation and reconstruction of buildings and structures.

Conclusions

The numerical modeling carried out in this study has shown that the presence of defects in rolled metal significantly affects the stress-strain state and load-bearing capacity of steel structural elements. The reduction of the effective cross-section due to defects leads to an increase in stresses and displacements compared to solid elements. It was determined that internal defects are more critical than external surface damage, as they cause significant local stress concentrations and are more difficult to detect using non-destructive testing methods. According to the calculations, the increase in equivalent stresses for models with internal defects reaches up to 20 %.

A dependence of defect impact on the geometric parameters of the element was established: as the length of the beam and the volume of defects increase, stresses and deflections also increase, indicating a scale effect and a higher sensitivity of the structure to material defects.

It was shown that even relatively minor material defects could lead to a redistribution of internal forces within the structure, which aligns with current understanding of reduced reliability and service life of building systems in the presence of local damage. The results obtained confirm the necessity of accounting for material defects when designing and analyzing structures, particularly when determining safety factors and assessing the residual load-bearing capacity of elements.

Further research should focus on the consideration of defect development over time (fatigue, corrosion, crack formation), as well as the analysis of spatial structural systems, taking into account the stochastic nature of defect occurrence.

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ОЦІНКА ВПЛИВУ ДЕФЕКТІВ МАТЕРІАЛУ НА РОБОТУ ЕЛЕМЕНТІВ СТАЛЕВИХ КОНСТРУКЦІЙ

Мета. Метою роботи є дослідження впливу дефектів металопрокату різного походження на напружено-деформований стан і несучу здатність елементів металевих конструкцій, а також оцінювання ступеня їх впливу залежно від типу та об’єму дефектності. **Методика.** Дослідження виконано із застосуванням методу скінченних елементів із використанням розрахункової моделі у вигляді консольної балки прямокутного поперечного перерізу. Розглянуто декілька варіантів довжини елемента та різні сценарії його роботи: для однорідного матеріалу без дефектів, а також для моделей із внутрішніми порожнинами та поверхневими пошкодженнями. Внутрішні дефекти моделювалися у вигляді локальних об’ємних порожнин, тоді як зовнішні – у вигляді геометричних нерівностей поверхні. Для кожного випадку визначалися напруження та переміщення з подальшим порівнянням результатів. **Результати.** Отримані результати показали, що наявність дефектів призводить до зміни характеру розподілу напружень і збільшення переміщень у порівнянні з моделями

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без дефектів. Встановлено, що зі збільшенням об’єму дефектів відбувається зростання еквівалентних напружень і прогинів конструктивного елемента. При цьому внутрішні дефекти виявляють більш суттєвий вплив, оскільки сприяють утворенню локальних концентрацій напружень у матеріалі. Зовнішні дефекти також впливають на роботу елемента, проте їх дія є менш вираженою. Крім того, виявлено залежність між геометричними параметрами балки та чутливістю до дефектності: зі збільшенням довжини елемента вплив дефектів посилюється. **Наукова новизна.** У роботі отримано узагальнені кількісні оцінки впливу внутрішніх і зовнішніх дефектів на напружено-деформований стан елементів металевих конструкцій. Показано відмінності у впливі різних типів дефектів та встановлено залежність цього впливу від геометричних параметрів елементів. **Практична значимість.** Результати дослідження можуть бути використані при оцінюванні технічного стану та залишкової несучої здатності металевих конструкцій із дефектами. Запропонований підхід до моделювання дозволяє враховувати реальну дефектність матеріалу при виконанні інженерних розрахунків. Отримані залежності доцільно застосовувати при визначенні допустимого рівня дефектів і уточненні коефіцієнтів запасу міцності.

Ключові слова: елементи металевих конструкцій; моделювання; металопрокат; внутрішні дефекти; зовнішні дефекти; несуча здатність; напружено-деформований стан; метод скінченних елементів; будівельні конструкції

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