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Strengthening of the cross-section of steel i-beams in the tension zone: a review of scientific research

The article reviews scientific research on methods and means of strengthening steel beam structural elements by increasing (building up) cross-sections using additional elements made of steel rolled profiles, plates, reinforcing bars and plates made of polymeric materials. The main conclusions and directions of further scientific research on effective methods and means of strengthening steel beam structural elements by increasing (building up) their cross-sections, which have the potential for widespread use in the repair and reconstruction of buildings and structures, are substantiated.

Keywords: steel beam structural elements, repair and strengthening, cross-section increase, a review, scientific researchs

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Introduction

Currently, the long-term operation of construction facilities and the development of industrial production are inextricably linked with repair, reconstruction, expansion, and technical re-equipment of enterprises. Strengthening existing steel beam structures is a common approach to prevent failure due to significant physical deterioration, changes in functional purpose, or construction errors during design and manufacturing. Moreover, any reconstruction of an operational facility is typically accompanied by changes in the loads acting on building structures, and sometimes even by alterations to their original structural schemes. This necessitates an assessment of the technical condition of structural elements and an increase in their load-bearing capacity through rational strengthening.

Clause 8.3 of the national building code DBN B V.3.1-2:2016 [1] outlines the main methods and techniques for strengthening steel structures, one of which is the method of partially increasing the cross-sectional area. Reinforcing the cross-sections of steel beams by enlarging the tension zone with additional elements such as steel rolled profiles, plates, reinforcing bars, or polymer composite plates is one of the most commonly used methods. This is due to its practicality during installation, the homogeneous (isotropic) properties and ease of processing of the materials used, high tensile ductility, and excellent fatigue resistance. This method allows for the strengthening of steel beam structures in existing buildings and facilities either under load or with temporary unloading.

When choosing a method for strengthening steel beams, according to the requirements of clause 8.4.2 of DBN B V.3.1-2:2016 [1], the following factors must be considered: the support conditions of the floor or roof elements on the beam (whether on the upper or lower flanges); the possibility of increasing the constructional height of the beam and the availability of space to accommodate strengthening elements; the feasibility of performing the work without interrupting production or during natural technological pauses; and the technological capabilities for manufacturing and installing the strengthening components. To select the most effective method for strengthening steel beams by enlarging the cross-section in the tension zone, a comprehensive analysis of the full range of prior scientific research conducted to date must be carried out.

Problem statement

The **aim of the work** is to conduct a review of scientific research devoted to theoretical developments and experimental testing of steel beam elements with symmetrical cross-sections, which are strengthened in the tension zone additional longitudinal elements made of steel rolled profiles, plates, reinforcing bars and plates made of polymeric materials.

Review and analysis of research sources and publications

The analysis of scientific research has shown that there is a wide range of methods for strengthening the bending strength of metal beams by increasing (augmenting) their cross-sections along the length. In recent years, in addition to traditional methods of reinforcing metal beams by augmenting their cross-sections with additional elements made of shaped and sheet rolled sections or reinforcement bars. Methods of reinforcement through cross-sectional increase using adaptive wire manufacturing have also been introduced (WAAM) and the installation (fixing, bonding) of additional elements made of carbon fiber (CFRP) to the lower tension zone of metal beams. In the studies [2], [3], researchers J. Yang, M.A. Wadee, and L. Gardner conducted experimental investigations to evaluate the bending strength of hot-rolled steel beams, which were reinforced along their length by increasing the I-shaped cross-section through arc-based additive wire manufacturing (WAAM). The beams were tested under four-point or three-point bending conditions. The results showed that as the mass of the specimens' cross-sections increased from 2,63% to 12,26%, the bending strength of the beams increased by 11,5%–33,2%.

In the work [4], researchers Ghafoori E. and Motavalli M. experimentally and numerically investigated the transverse-torsional bending of steel beams reinforced with a layered carbon fiber reinforced polymer (CFRP) material of normal modulus of elasticity (NM). The test results showed that reinforcing steel beams with layered carbon fiber materials almost equally increases the elastic stiffness of the specimens, both for bonded and unbonded systems, compared to the reference beam. Specimens reinforced with unbonded carbon fiber reinforced polymer (CFRP) laminates have higher strength than those reinforced with bonded carbon fiber reinforced polymer laminates. Pre-stressing of the carbon fiber reinforced polymer layered materials does not affect the elastic stiffness of the reinforced beams, but it significantly influences their bending strength. Higher levels of prestressing do not necessarily lead to an increase in bending strength in the retrofitted beams. [4]. The article by Omnia R. AbouEl-Hamd [5] presents the results of experimental and numerical studies on steel beams, which were reinforced along their length with hybrid fiber-reinforced polymers (HFRP) using steel bolts. Tests on 22 steel beams demonstrated their plastic behavior upon failure, with an increase in yield and ultimate bending strength by 15,1% and 22,2%, respectively [5]. The study of a structural solution for strengthening steel beams using adhesive strips made of shape memory alloy steel (also known as iron-based shape memory alloy, Fe-SMA) was conducted by Sizhe Wang and other researchers in work [6].

In the study [7], researchers Linghoff D., Al-Emrani M., and Kliger R. tested five beams under static four-point bending. The beams were fabricated from standard HEA180 steel profiles with a nominal span length of $L_u = 1.8$ m. The length of the carbon fiber-reinforced polymer (CFRP) laminate used to strengthen the beams at the level of the lower flange was 1600 mm, leaving an unreinforced gap of 100 mm between the ends of the CFRP laminate and the supports. Parametric studies were carried out to investigate how different parameters, such as the variation in thickness and elastic modulus of the laminates and the adhesive layer of different epoxy resins, would affect the strength and behavior of the strengthened beams. The CFRP laminate strips were bonded to the steel beam using epoxy resin over the entire surface with the help of a hard roller. To ensure a uniform thickness of epoxy resin along the bonding length, thin wooden strips were glued to the bottom flange of the beam. These strips, having a thickness of 2 mm plus the thickness of the CFRP laminate, served as supports during the placement of the laminate strips. Based on the test results, the ultimate loads of the strengthened beams were compared with that of the reference beam. The ultimate load for the reference beam was defined as the applied load level that resulted in a strain of 2% in the extreme tensile fiber of the beam, corresponding to a deflection of $f = 50$ mm. The ultimate load for the strengthened beams was defined as the load that caused rupture or delamination of the CFRP laminate. According to the data presented in Table 3 [7], the increase in ultimate load ΔP for the strengthened steel beams compared to the reference beam, depending on the strength characteristics of the CFRP laminate material used, ranged from 2% to 18%.

In research [8] Liu, Y. and Gannon, L. conducted experimental investigations on steel I-beams with cross-section W 310×100×28.3 and effective lengths of L_u=2.4 m and L_u=1.2 m. The beams were strengthened using conventional methods:

- by welding under load steel vertical cover plates with dimensions $t \times h$=9.5×320 mm along the length of the specimens symmetrically to the top and bottom flanges;
- by welding a horizontal cover plate with dimensions $t \times b$=9,5×137 mm along the length of the tensioned bottom flange of the I-section beam.

The experimental results [8] indicated that the degree of preloading influences the strength of the reinforced beams, which fail as a result of torsional bending of the vertical plane. Specifically, when the beams were strengthened under a preload level of 50–53% of the ultimate strength of the unstrengthen beam, the ultimate strength of the reinforced beam under torsional buckling decreased by 13–14.2%.

In the study [9], Ridha, S., Abbood, A., and Atshan, A. conducted experimental investigations on three steel I-beams with IPE 100 cross-sections and a nominal span length of L_u=1.0 m. The beams were strengthened at mid-span by welding under load with inclined steel plates of dimensions $t\times b\times l$ = 3×12.5×250 mm or $t\times b\times l$ = 3×25×250 mm. Horizontal plates with dimensions $t\times b\times l$ = 3×12.5×500 mm or $t\times b\times l$ = 3×25×500 mm were also used for strengthening, symmetrically to the upper and lower flanges. As a result, the strength of the beam reinforced with 12.5 mm wide plates increased by 21.15% compared to the reference specimen under an ultimate load of F = 157.5 kN, while the beam reinforced with 25 mm wide plates increased its strength by 37.69% at F = 179 kN. Strengthening with additional plates and inclined stiffeners altered the failure mode from "lateral buckling" (as observed in the control specimen) to a "plastic hinge" formation at the point of concentrated load (mid-span). Additionally, reinforcing the beams with extra plates significantly reduced both vertical and horizontal deformations, as well as deflection and lateral bending, compared to the reference specimen.

In research [10], Yossef, N. conducted experimental tests on six steel I-beams with IPE 200 cross-sections and a nominal span of L_u = 1.8 m. The beams were strengthened at mid-span by welding, under load, by steel plates to the bottom flange with dimensions $t\times b$ = 6×80 mm and lengths of l = 650 mm or l = 900 mm. Additionally, horizontal plates of dimensions $t\times b\times l$ = 6×80×900 mm and $t\times b\times l$ = 6×80×450 mm were welded symmetrically to the bottom and top flanges, respectively. The test results indicated that the ultimate strength of the beams depends on the length of the welded reinforcement plate and the welding technology used under different load levels. Increasing the reinforcement plate length from 36% to 50% of the span led to an increase in beam strength ranging from 1% to 5%.

In the study [11], A. Al-Balhawi et al. carried out experimental tests on two steel I-beams with IPE 100 cross-sections and a nominal span length of L_u = 1.4 m. Beam B1 was strengthened at mid-span by welding a plate of dimensions $t\times b$ = 6×65 mm and length l = 1250 mm to the top flange. Beam B2 was reinforced by welding horizontal plates symmetrically to the top and bottom flanges with dimensions $t\times b\times l$ = 6×65×1250 mm and $t\times b\times l$ = 3×65×1250 mm, respectively. The additional bottom plate in beam B2 increased its flexural strength in the elastic stage twofold compared to beam B1.

In the study [12], Yu. Kushnir conducted experimental research on five steel I-beams fabricated from rolled I-section No. 16 with a nominal span length of L_u = 1.7 m. The beams were reinforced in the tensile zone by installing two additional reinforcing bars made of A500-grade steel with diameters of 10 mm, 16 mm, 20 mm, and 32 mm. The distance from the bottom flange to the longitudinal axis of the reinforcing bars was set at a = 25 mm for 10, 16, and 20 mm bars, and a = 30 mm for 32 mm bars. Experimental data on relative strains in the fibers of the I-section and comparisons with limiting stress values confirm the elastic-plastic behavior of the strengthened beams at the failure section. As the plastic zone at the failure section increased from 5% to 20%, the load-bearing capacity of the specimens also increased compared to the reference beam. The load-bearing capacity of beams reinforced with 10, 16, and 20 mm bars increased by 5–10%, while the beam reinforced with 32 mm bars showed a 51% increase in comparison to the reference specimen [12].

For the specimens that predominantly failed due to flexural bending about the horizontal plane, the level of preloading showed a negligible effect on the ultimate strength of the strengthened specimens. In article [13] and research work [14], researchers Mohammadzadeh, M. and Bhowmick, A. conducted finite element (FE) analyses to investigate the stress–strain behavior and flexural strength of steel I-beams with cross-sections strengthened under load by additional steel cover plates. A series of simply supported steel I-beams, reinforced with cover plates welded to the bottom tension flanges, was thoroughly analyzed. The finite element analysis shows that as the level of preloading increases, the load-bearing capacity of the I-beam strengthened under load decreases when the failure mode is lateral-torsional buckling (loss of stability from the vertical plane). On the other hand, variations in the level of preloading have a minimal effect on the behavior and ultimate strength of the strengthened beam when failure occurs in pure bending. In studies [15] and [16], Assaad Taoum, together with Jiao, H. and Holloway, D., investigated the effectiveness of the Local Prestressing Technique (LPT) for improving the repair of damaged steel beams. The studies demonstrated that the level of prestressing, the type of LPT method (internal or external), and the diameter of the reinforcing bars used had a significant impact on the stiffness of the beams and their ultimate load-bearing capacity [14], [15].

In article [17] Piotr Szewczyk and Maciej Szumigała presented the results of experimental investigations and numerical analysis on the strengthening of steel–concrete composite beams. The steel section of the IPE200 I-beam profile was strengthened along its length by welding additional steel plates with a thickness ranging from 6 to 22 mm to its bottom flange. One of the objectives was to find an optimal solution that minimizes costs while maximizing bending strength. To achieve this objective, the energy parameters available in numerical simulations were reviewed and analyzed. The proposed numerical models were experimentally validated using three specimens. The maximum deviation between the experimental and the average numerical bending strength of the reinforced composite beams is approximately 2,5%.

The strengthening of composite steel–concrete beams using externally prestressed reinforcement bars has been the focus of studies by researchers such as El-Zohairy A. and Salim H. [18], M.Yu. Izbash [19], R.M. Shemet [20], as well as T.A. Halinska, V.F. Pentz, and Yu.O. Kushnir [21]. In article [18] El-Zohairy A. and Salim H. presented a numerical model for investigating the nonlinear behavior of composite beams reinforced with externally prestressed reinforcement bars (tie rods). The reliability of the developed numerical model was confirmed by comparing its results with available experimental data. Study [18] investigated the influence of various strengthening parameters, including inclined (triangular and trapezoidal profiles) and straight bars (tie elements); the length of the bars (ties); the effect of additional prestressing on restoring the bending performance of an overloaded beam; the eccentricity of stress application; and the degree of shear connection. A good agreement was obtained between the proposed model and the experimental data. The results indicate that, at the same stress application eccentricity, the trapezoidal profile demonstrates superior load-bearing capacity for reinforced beams compared to the horizontal strengthening element. In article [21], the authors present a classification of steel–concrete composite beams strengthened with prestressed horizontal elements (tie rods), based on the composite properties of their components and the cases of the ultimate stress–strain state.

Identification of unresolved issues

The analysis of research conducted by various scholars has demonstrated that the method of strengthening steel beams by partially increasing the cross-sectional area, particularly in the lower tension zone, can significantly enhance the load-bearing capacity (strength and stiffness) of the reinforced steel beams. In recent years, in addition to traditional strengthening or repair methods using welded or bolted plates and reinforcement bars, an alternative method involving the application of carbon fiber reinforced polymer (CFRP) laminate strips has been introduced and increasingly implemented in repair practice. These strips are either bonded or mechanically fastened to the flange sections of steel beams.

Experimental studies conducted by researchers have shown that the use of various strengthening systems enables partial or full restoration (or enhancement) of the load-carrying capacity of deteriorated beams. The increase in ultimate load capacity (ΔP) of the strengthened steel beams compared to the reference beam depends on numerous influencing factors. When strengthening the tension zone of steel beams using additional elements applied locally at mid-span, without extending to the support areas, several problems arise due to the altered cross-section. These include the non-uniform stress distribution, characterized by a stress intensity factor that varies at different stages of the stress-strain state of the strengthened beam, as well as the necessity of developing a constructive solution for anchoring the ends of the added strengthening element. The types and combinations of such connections present a wide range of possible configurations.

Conclusions

Thus, the conducted analysis of scientific studies has shown that an unresolved aspect of the broader issue concerning the development and improvement of strength calculation methods for strengthened structural elements is the lack of a clear (engineering) methodology for calculating the bending strength of metal beam structures (elements) strengthened by the addition of supplementary components in the tensile zone of their cross-section such a methodology should take into account the loading history, the strength characteristics of the materials, and the stages of their stress–strain state at the moment of failure.

The overall aim of the research is to develop an analytical method for calculating the bending strength of metal beams with symmetrical cross-sections that are strengthened under load by installing additional longitudinal reinforcement bars or other elements in their tensile zone, without prior prestressing.

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Підсилення поперечних перерізів сталевих двотаврових балок в зоні розтягу: огляд наукових досліджень

В результаті довготривалої експлуатації сталеві балкові конструкції в існуючих будівлях і спорудах зазнають фізичного зношення, часткового чи повного руйнування під впливом агресивного середовища, статичних і динамічних навантажень вибухового типу. Під впливом агресивного середовища з підвищеною вологістю і перепадом температур, який характеризується циклічним заморожуванням та відтаюванням, наявністю хімічно активних сполук в рідині і повітрі, які безпосередньо контактують з конструкцією, в стальних балкових елементах виникають пошкодження у вигляді: появи і розвитку поверхневої корозії різної глибини на визначених ділянках чи по всій їх поверхні. Випадкова або непередбачена дія позапроектного статичного чи динамічного навантаження вибухового типу, також можуть призвести до перевантаження і появи ознак значного фізичного зносу і зрілої форми видимого руйнування сталевих балкових конструктивних елементів, таких як: залишкові деформації у вигляді прогинів, величина яких перевищує гранично допустиме значення; поява і розвиток тріщин різної орієнтації в полицях і стінці перерізу балки у зонах її згину і зрізу, особливо у місцях поблизу зварних швів чи місць зміни площі перерізу, де виникають локальні зміни структури матеріалу чи додаткові внутрішні напруження різної інтенсивності; наявність загального вигину поздовжньої осі балкового елементу із вертикальної площини, величина якого перевищує гранично допустиме значення; точкові чи локальні вминання полиці в стиснутій зоні чи вертикальної стінки, ребер жорсткості в перерізі балки на величину, що перевищує гранично допустиме значення.
В статті проведено огляд наукових досліджень, які присвячені методам і способам підсилення сталевих балкових конструктивних елементів шляхом збільшення (нарощування) поперечних перерізів за допомогою додаткових елементів із сталевих прокатних профілів, пластин, арматурних стержнів та пластин із полімерних матеріалів. Обгрунтовані основні висновки і напрямки подальших наукових досліджень ефективних методів і способів підсилення сталевих балкових конструктивних елементів, що здійснюються шляхом збільшення (нарощування) їх поперечних перерізів, які маємо можливість застосувати при ремонті та реконструкції будівель і споруд.

Ключові слова: сталеві балкові конструктивні елементи, ремонт та підсилення, збільшення поперечного перерізу, огляд, наукові дослідження

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