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CALCULATION OF THE IMPROVED STEEL BEAMS OF BUILDINGS AND STRUCTURES OF THE MINING AND METALLURGICAL COMPLEX

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Abstract. Load-bearing elements of buildings and structures of the mining and metallurgical complex in recent decades need to develop new more effective design solutions due to the intensification of technological processes, an increase in temperature loads and aggressiveness of the environment. The main direction of increasing the efficiency of such elements is their design from economically alloyed steel, which allows to increase the resource of structures and prevent accidents with a significant increase in temperature. Due to the fact that alloyed steels have higher mechanical characteristics at elevated temperatures, the question arises of creating lightweight beam structures from such steels, reducing their material consumption while maintaining the stability and fatigue strength of beams, the most promising is the use of welded beams with a perforated wall and composite beams.

The creation of the most effective cross-sectional shape of metal beams with a perforated wall and welded beams, as well as crane beams in transverse bending, considering strength, local stability, flat bending stability and fatigue strength is considered. It is shown that an effective shape of beams with a perforated wall is a box-shaped structure made of perforated channels. A calculation was carried out to select a rational design made of an assortment of hot-rolled channel profiles. It is shown that due to the use of the proposed sectional shape, significant savings in the weight of the structure can be achieved. Considering the three-dimensional stress-strain state, the fatigue strength of welded metal crane girders operating in severe conditions is estimated. The efficiency of using a hot-rolled I-beam as the upper chord of such welded beams is shown. The necessity of using a hot-rolled I-beam and to ensure the fatigue strength of the lower chord is demonstrated.

The use of the previously proposed combined method for calculating the structures of industrial buildings and structures and the use of economically alloyed steels allows us to create new designs of critical elements that reduce their material consumption and increase their resource. Further research can be carried out for real object designs in order to reduce their cost and increase reliability during operation in the conditions of mining and metallurgical production.

Key words: beam, perforated wall, weight saving, fatigue strength.

1. Introduction

Load-bearing elements of buildings and structures of the mining and metallurgical complex in recent decades need to develop new more effective design solutions due to the intensification of technological processes, an increase in temperature loads and aggressiveness of the environment [1, 2]. The main direction of increasing the efficiency of such elements is their design from economically alloyed steel, which allows to increase the resource of structures and prevent accidents with a significant increase in temperature [2, 3]. Due to the fact that alloyed steels have higher mechanical characteristics at elevated temperatures, the question arises of creating lightweight beam structures from such steels, reducing their material consumption while maintaining the stability and fatigue strength of beams, the most promising is the use of welded beams with a perforated wall and composite beams.

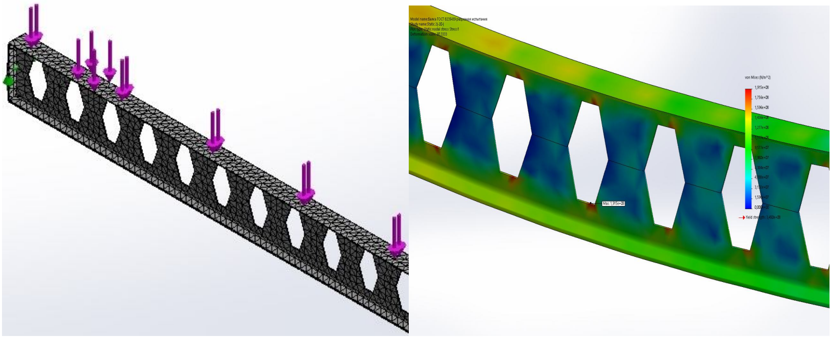
Traditionally, the most effective shape of the cross-section of beams is the I-section. A large number of studies have been devoted to the creation of various designs of perforated and composite I-beams [1, 4–7]. It is known that in the absence of lateral supports, I-beams bent in the plane of the wall may not be stable enough. If the loads, increasing, exceed certain limits, then such beams lose the stability of the flat form of bending, and they become unable to resist the load. Some modern articles take into account loading uncertainties in their calculations and estimation of stability and strength [9, 10] and it can be continuation of research in this field. This work uses traditional deterministic raw data.

Loss of stability of thin-walled elements of welded structures is also possible due to structural deviations arising during manufacture and operation [7–8]. At the same time, the shape determined by the section of hot-rolled I-profiles in accordance with GOST 8239-72 is difficult to improve and facilitate, since the achievement of the limiting conditions of strength and stability of flat bending occurs for such beams at very close loads. The creation of lightweight beams with a perforated web and composite beams from parts of such a profile, although it leads to an increase in the calculated permissible bending loads, requires the creation of constrained bending conditions to prevent buckling of the flat deformation form. Although many works [1, 4–7, 11–17] have been devoted to the issues of local stability of beams with cutouts, the problem of assessing the stability of perforated beams is still far from a final solution. Compared to experimental data, existing calculation methods in some cases give deviations reaching 70% [11, 12, 16]. The development of stable perforated web and polybeam structures is an important area of focus for more rational structural design.

There are three types of buckling of perforated beams: buckling of flat bending; loss of local stability of the beam wall, manifested in local bulging of the wall; loss of local stability of the beam chord [1, 12, 17]. In addition, beams with a perforated wall have a complex stress-strain state with a stress concentration in the notch zone [15]. All this necessitates a refined numerical simulation of the behavior of such beams without the use of simplifying hypotheses and design schemes. Such a calculation is possible on the basis of nonlinear modeling in the SolidWorks system [19], which we have successfully used earlier for calculating complex structures of the mining and metallurgical complex [2].

2. Calculation of effective perforated welded beams

To analyze the parameters of the bearing capacity of the beams, the design scheme of a three-dimensional elastic body under geometrically nonlinear deformation was used [2, 19].



(a) (b)

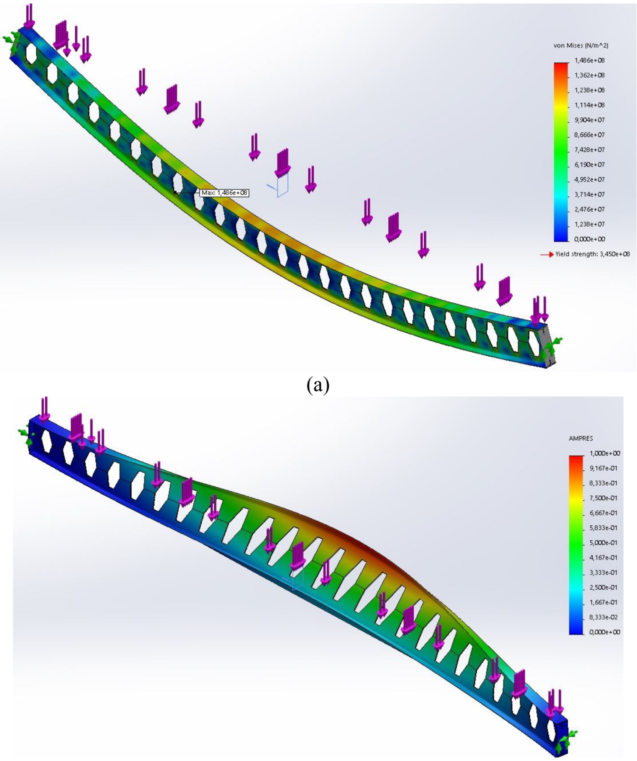
Fig. 1. Design scheme of a three-dimensional elastic body:
(a) - grid view, (b) - an example of calculating the stress state in the zone of concentrators

This makes it possible to simultaneously study the local and overall strength of the beam, the deformation stability of the walls and flanges, and the maximum deflection of the beam. Loads that did not lead to a loss of bearing capacity in terms of a set of parameters were considered acceptable. A multiple calculation was performed for beams of various sizes with the aim of selecting a beam of minimum weight, corresponding to the conditions of strength and stability at a given length and load.

The studies were carried out for a perforated I-beam made by cutting and subsequent welding of beams GOST 8239-72 according to a waste-free symmetric scheme [17] (Fig. 2).

A preliminary calculation carried out to find a rational design confirmed the low efficiency of reducing the weight of a perforated beam compared to a hot-rolled beam of the same bearing capacity due to a decrease in buckling loads for perforated beams.

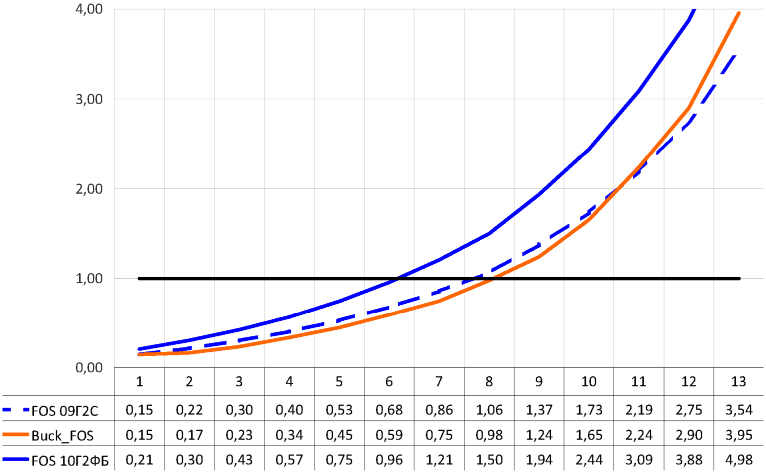
Comparison of the coefficient of stability of hot-rolled beams (the ratio of buckling load to the actual load, buckling factor of safety, Buckl_FOS) and the factor of safety (FOS) shows the practical coincidence of their permissible level for the same profile number for structural steel 09G2S. In fig. 3 is shown the dependences of the coefficients for beams with a length of 6 m with a uniformly distributed load with an intensity of 1.5 t/m and hinged fastening of the ends made of structural steel 09G2S and economically alloyed steel 10G2FB.



(a)

(b)

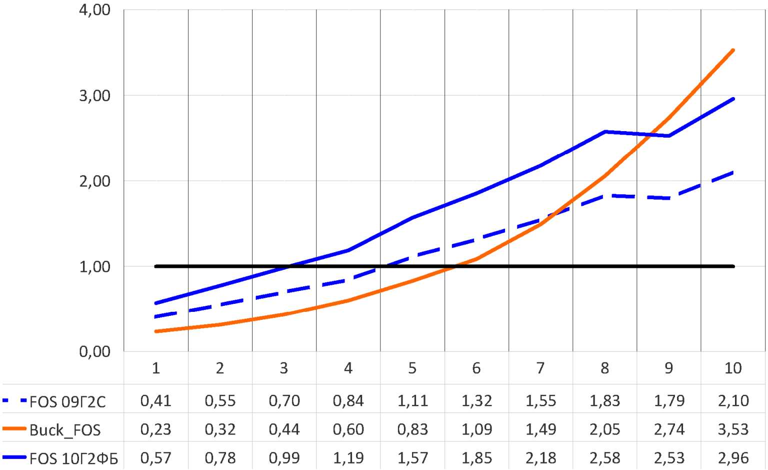
Fig. 2. Calculation of welded beams with a perforated wall:
(a) - stresses, (b) - displacements with loss of stability



	1	2	3	4	5	6	7	8	9	10	11	12	13
FOS 09Г2С	0,15	0,22	0,30	0,40	0,53	0,68	0,86	1,06	1,37	1,73	2,19	2,75	3,54
Buck_FOS	0,15	0,17	0,23	0,34	0,45	0,59	0,75	0,98	1,24	1,65	2,24	2,90	3,95
FOS 10Г2ФБ	0,21	0,30	0,43	0,57	0,75	0,96	1,21	1,50	1,94	2,44	3,09	3,88	4,98

Fig. 3. Dependence of the values of the stability and strength coefficients
on the serial number of the profile for hot-rolled beams GOST 8239-72

Fig. 4 shows the dependences of the stability and strength coefficients for perforated I-beams, made by cutting and subsequent welding of GOST 8239-72 beams according to a waste-free symmetric scheme, on the serial number of the profile corresponding to the workpiece from the hot-rolled beam. It is clearly seen that, despite a significant increase in the strength factor, there is a simultaneous decrease in the stability factor. This limits the possibility of using a lightweight beam: under the considered load, a beam with a perforated wall, equal in strength to a hot-rolled one, weighs only 9.2% less. Such weight savings do not always justify the additional technological costs of manufacturing a welded perforated beam.



	1	2	3	4	5	6	7	8	9	10
- - FOS 09Г2С	0,41	0,55	0,70	0,84	1,11	1,32	1,55	1,83	1,79	2,10
— Buck_FOS	0,23	0,32	0,44	0,60	0,83	1,09	1,49	2,05	2,74	3,53
— FOS 10Г2ФБ	0,57	0,78	0,99	1,19	1,57	1,85	2,18	2,58	2,53	2,96

Fig. 4. Dependence of the values of the stability and strength coefficients on the serial number of the profile for welded I-beams with a perforated wall

As an alternative to the design of an I-beam, we propose to use box-shaped welded beams made of hot-rolled channel according to 8240-89 using waste-free technology (Fig. 5). Such a structure is in fact a welded I-beam with a perforated wall cut along the wall and butt-welded along the edges of the flanges. Calculation of box-shaped welded beams with a perforated wall (Fig. 6) showed their significant advantages over those previously investigated.

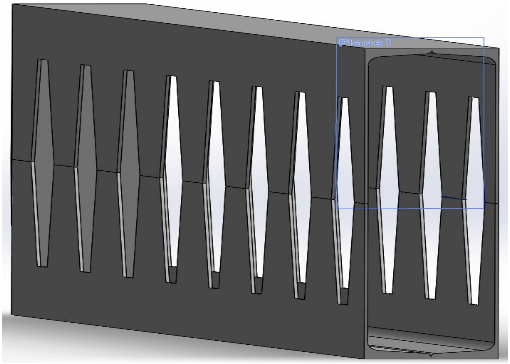
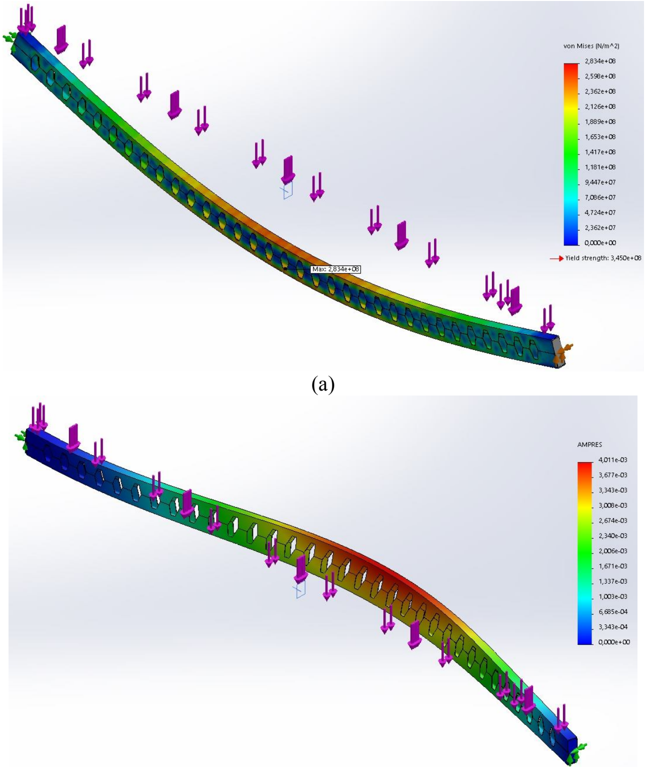


Fig. 5. Scheme of a box-shaped welded beam



(a)

(b)

Fig. 6. Calculation of welded box beams with a perforated wall:
(a) - stresses, (b) - displacements with loss of stability

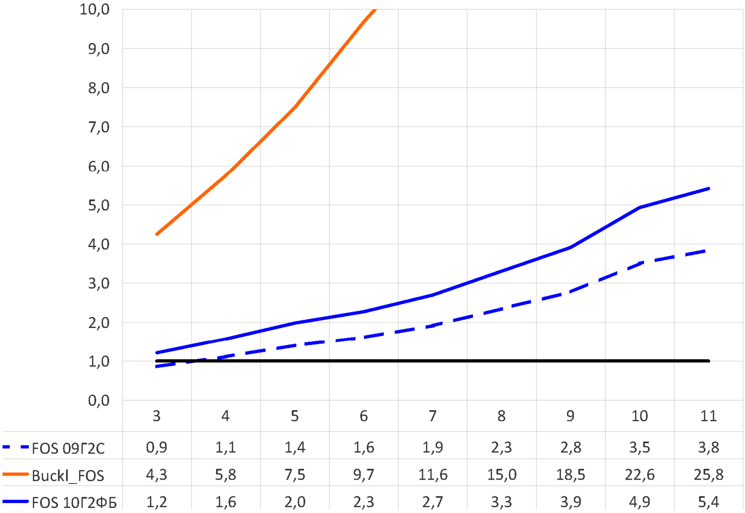
The stability coefficient for such beams significantly exceeds unity for all considered cases, which indicates the impossibility of losing the bearing capacity of such beams due to the loss of stability (Fig. 7).

Under these conditions, the use of beams with perforated walls provides significant advantages over hot-rolled ones, especially when using economically alloyed steels. Table 1 shows the comparative parameters of beams with a minimum weight of 6 m in length at a load of 1 t/m, made of economically alloyed steel 10G2FB. It can be seen that the weight loss is more than 31%, which makes it possible to recommend beams of this design for use in the construction of modern buildings and structures.

Table 1

Comparison of hot rolled and welded box girders

Beam type	Profile No.	Strength factor	Stability factor	Weight, kg
Hot rolled	22	1,8	1,12	148
Welded box-shaped	16	1,2	4,2	102



	3	4	5	6	7	8	9	10	11
FOS 09Г2С	0,9	1,1	1,4	1,6	1,9	2,3	2,8	3,5	3,8
Buckl_FOS	4,3	5,8	7,5	9,7	11,6	15,0	18,5	22,6	25,8
FOS 10Г2ФБ	1,2	1,6	2,0	2,3	2,7	3,3	3,9	4,9	5,4

Fig. 7. Dependence of the values of the stability and strength coefficients on the serial number of the profile for box-shaped welded beams with a perforated wall 6 m long at a uniformly distributed load of 1.5 t/m and hinged ends

An additional advantage of beams with a perforated wall is the ability to lay communications in them and provide access to them for preventive and repair work. This, in turn, allows you to reduce the height of the interfloor spaces.

3. Calculation of effective welded crane girders considering fatigue strength

It is known that in welded crane girders operating under severe operating conditions, the most vulnerable point is the longitudinal weld seam connecting the upper flange with the wall [20, 21]. The location of the welded seam in the most stressed sub-rail zone is one of the main disadvantages of welded crane beams, since in this zone the amplitudes of shear stress oscillations are greatest. The authors of the monograph [21] propose the removal of welds from the under-rail zone of the beams at a distance where the shear stress fluctuations attenuate so significantly that they are not able to cause the initiation and development of cracks. The results of the tests given in [21] confirm the high endurance of beams with belts made of rolled tees. In beams with T-belts, the weld seam is removed downward at a considerable distance from the contact zone of the rail with the beam belt. Therefore, the amplitudes of fluctuations of local stresses in the weld are significantly reduced, which minimizes the risk of fatigue cracks in the weld.

Beam designs proposed by the authors [21] that increase the fatigue strength of longitudinal seams are difficult to manufacture and operate. The calculations performed in [21] were carried out using the beam scheme and did not consider the complex stress-strain state of the structure near the load transfer zone, which requires the use of the design scheme of a three-dimensional body.

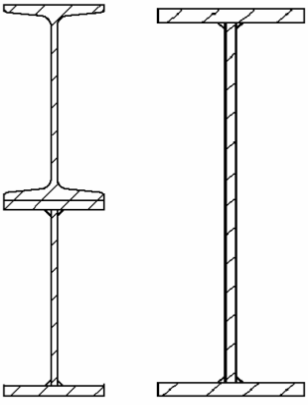


Fig. 8. Shape of sections of welded beams

In order to create a rational design of a crane girder and a method for refined calculation of such beams, we used a module for calculating fatigue of welded seams of the SolidWorks complex and a scheme of geometrically nonlinear deformation of a three-dimensional elastic body. Welded beams of two types were considered - a composite beam from a hot-rolled I-profile No. 20 and a corresponding welded profile of the same height (Fig. 8 (a)), and a welded I-beam of the same height, corresponding in width to a hot-rolled profile No. 30 (Fig. 8 (b)).

A 6 m long beam with rigidly clamped ends was considered, which corresponds to the operating conditions of the middle part of a continuous crane girder loaded with 4 t forces on each of two 15 mm long sections located at a distance of 1 m in the middle part of the span (Fig. 9).

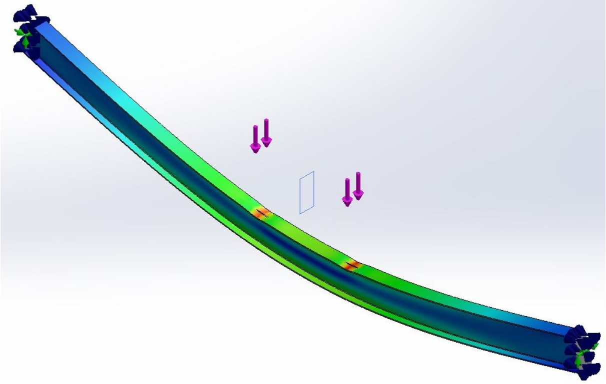


Fig. 9. Design diagram of the crane girder

Initially, the calculation of the static stress-strain state of the beam under working loads was carried out, confirming the bearing capacity of the beam (Fig. 9). For the beam under consideration, the maximum stresses close to the steel plasticity limit were achieved locally in the load zone. Such operating conditions for the crane girder are difficult.

The change in the load was taken according to a zero cycle according to the quasi-static load scheme, i.e., the load changed from the level of its absence to the maximum value, and possible dynamic processes were not taken into account. Only the fatigue of the welded seams was considered, since the fatigue of the upper most loaded flange strongly depends on the conditions of contact with the rail, which was not adequately described under the conditions of this model.

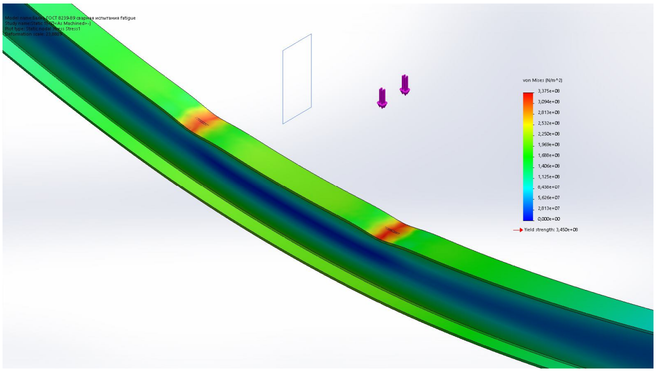


Fig. 10. The stress-strain state of the crane girder

Calculation of weld fatigue for a solid welded beam (Fig. 11) confirms the conclusions [21]. The zone of minimum fatigue strength extends over the entire thickness of the upper flange of the beam and sections of the welded seam in the load zone. Under the given conditions, corresponding to the conditions of static strength, the welded seam is able to withstand only about 32 thousand cycles, which is significantly lower than the standard resource. This confirms the need to calculate the material and welded seams of crane girders for fatigue strength in the design of industrial facilities.

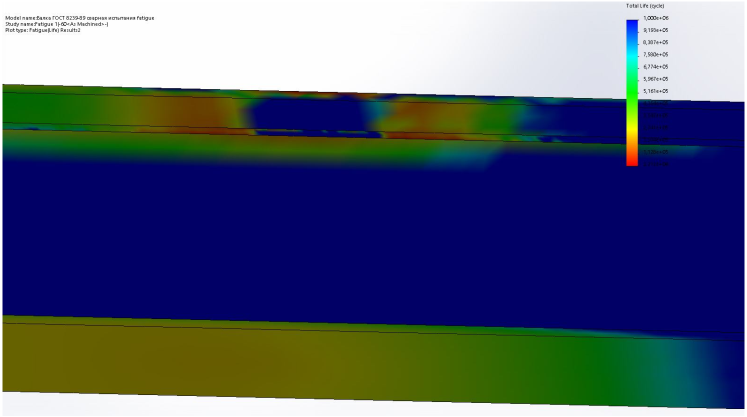


Fig. 11. Distribution of fatigue strength zones of a welded beam

The stress-strain state of a composite beam practically does not differ from the state of an I-beam welded beam (Fig. 12).

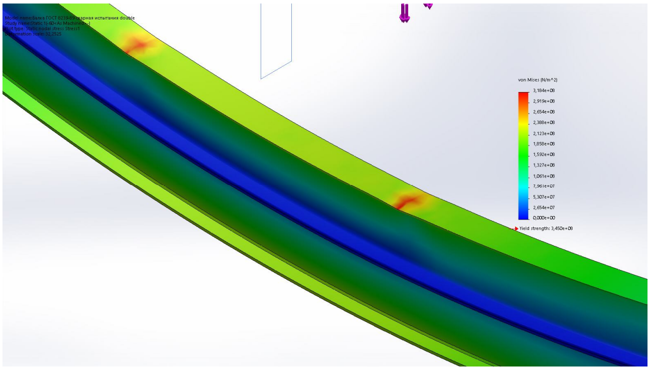


Fig. 12. Stress-strain state of the composite welded crane girder

It is clearly seen that the welds between the beams are in the zone of minimum deformations and do not determine the fatigue strength of the structure. This is confirmed by the calculation of fatigue (Fig. 13): these seams withstand in such a structure more than 1 million cycles, which is close to the design standard.

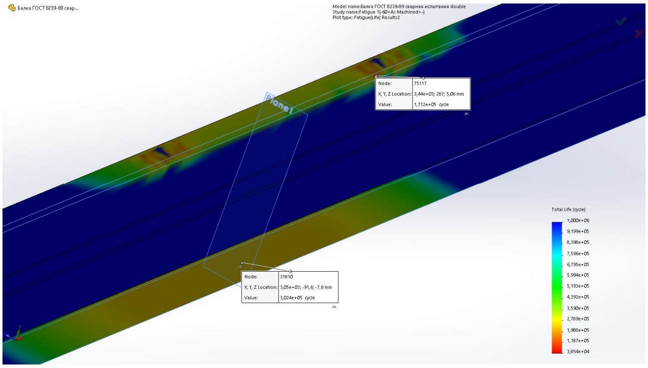


Fig. 13. Distribution of fatigue strength zones of a composite beam

Maximum displacements are now in the weld zone of the bottom flange of the welded beam. Their resource is about 300 thousand cycles, which determines the resource of the whole structure. This resource is significantly lower than standard, but an order of magnitude higher than the resource of the welded I-beam.

Thus, a detailed calculation based on a three-dimensional model shows that not only the elements of the upper, but also the lower chord of the crane girder are subject to replacement with hot-rolled elements. In addition, in order to ensure the standard fatigue life, it is necessary that the maximum stresses in the beam be slightly lower than the calculated ultimate stresses in the static calculation, which should certainly lead to an increase in the mass of the crane girder.

4. Conclusions

The use of the previously proposed combined method for calculating the structures of industrial buildings and structures and the use of economically alloyed steels allows us to create new designs of critical elements that reduce their material consumption and increase their resource. Further research can be carried out for real object designs in order to reduce their cost and increase reliability during operation in the conditions of mining and metallurgical production.

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РОЗРАХУНОК ВДОСКОНАЛЕНИХ СТАЛЕВИХ БАЛОК БУДІВЕЛЬ І СПОРУД ГІРНИЧО-МЕТАЛУРГІЙНОГО КОМПЛЕКСУ

В останні десятиліття несучі елементи будівель і споруд гірничо-металургійного комплексу потребують розробки нових більш ефективних конструкторських рішень в зв'язку з інтенсифікацією технологічних процесів, збільшенням температурних навантажень і агресивності середовища. Основним напрямком підвищення ефективності таких елементів є їх конструювання з економно легованої сталі, що дозволяє збільшити ресурс споруд і запобігти аварійність при значному підвищенні температури. У зв'язку з тим, що леговані сталі мають більш високі механічні характеристики при підвищених температурах, виникає питання про створення полегшених балкових конструкцій з таких сталей, зниження їх матеріаломісткості при збереженні стійкості і втомної міцності балок, найбільш перспективним представляється використання зварних балок з перфорованою стінкою і складових балок.

Розглядається питання створення найбільш ефективної форми поперечного перерізу металевих балок з перфорованою стінкою і підкранових зварних балок, а також підкранових балок при поперечному вигині з урахуванням міцності, місцевої стійкості, стійкості плоскої форми вигину і втомної міцності. Показано, що ефективною формою балок з перфорованою стінкою є коробчата конструкція з перфорованих швелерів. Проведено розрахунок для вибору раціональної конструкції, виготовленої з сортаменту гарячекатаних профілів швелерів. Показано, що за рахунок застосування запропонованої форми перерізу може бути досягнута значна економія ваги конструкції. З урахуванням тривимірного напружено-деформованого стану оцінена втомна міцність зварних металевих підкранових балок, що працюють у важких умовах. Показана ефективність використання гарячекатаної двотаврової балки в якості верхнього пояса таких зварних балок. Продемонстровано необхідність застосування двотаврової гарячекатаної балки і для забезпечення втомної міцності нижнього пояса.

Застосування запропонованого нами раніше комбінованого методу розрахунку конструкцій промислових будівель і споруд та використання економно легованих сталей дозволяє створити нові конструкції відповідальних елементів, що дозволяють знизити їх матеріаломісткість і підвищити ресурс. Подальші дослідження можуть бути проведені для реально проектованих об'єктів з метою їх здешевлення і підвищення надійності при експлуатації в умовах гірничо-металургійного виробництва.

Ключові слова: балка, перфорована стінка, економія ваги, втомна міцність.

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РАСЧЕТ УСОВЕРШЕНСТВОВАННЫХ СТАЛЬНЫХ БАЛОК ЗДАНИЙ И СООРУЖЕНИЙ ГОРНО-МЕТАЛЛУРГИЧЕСКОГО КОМПЛЕКСА

В последние десятилетия несущие элементы зданий и сооружений горно-металлургического комплекса нуждаются в разработке новых более эффективных конструкторских решений в связи с интенсификацией технологических процессов, увеличением температурных нагрузок и агрессивности среды. Основным направлением повышения эффективности таких элементов является их конструирование из экономно легированной стали, что позволяет увеличить ресурс сооружений и предотвратить аварийность при значительном повышении температуры. В связи с тем, что легированные стали имеют более высокие механические характеристики при повышенных температурах, возникает вопрос о создании облегченных балочных конструкций из таких сталей, снижения их материалоемкости при сохранении устойчивости и усталостной прочности балок, наиболее перспективным представляется использование сварных балок с перфорированной стенкой и составных балок.

Рассматривается вопрос создания наиболее эффективной формы поперечного сечения металлических балок с перфорированной стенкой и подкрановых сварных балок, а также подкрановых балок при поперечном изгибе с учетом прочности, местной устойчивости, устойчивости плоской формы изгиба и усталостной прочности. Показано, что эффективной формой балок с перфорированной стенкой является коробчатая конструкция из перфорированных швеллеров. Проведен расчет для выбора рациональной конструкции, изготовленной из сортамента горячекатаных профилей швеллеров. Показано, что за счет применения предложенной формы сечения может быть достигнута значительная экономия веса конструкции. С учетом трехмерного напряженно-деформированного состояния оценена усталостная прочность сварных металлических подкрановых балок, работающих в тяжелых условиях. Показана эффективность использования горячекатаной двутавровой балки в качестве верхнего пояса таких сварных балок. Продемонстрирована необходимость применения двутавровой горячекатаной балки и для обеспечения усталостной прочности нижнего пояса.

Применение предложенного нами ранее комбинированного метода расчета конструкций промышленных зданий и сооружений и использование экономно легированных сталей позволяет создать новые конструкции ответственных элементов, позволяющие снизить их материалоемкость и повысить ресурс. Дальнейшие исследования могут быть проведены для реально проектируемых объектов с целью их удешевления и повышения надежности при эксплуатации в условиях горно-металлургического производства.

Ключевые слова: балка, перфорированная стенка, снижение веса, усталостная прочность.

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Гезенцвей Ю.І., Олевський В.І., Волчок Д.Л. Олевський О.В. **Розрахунок вдосконалених сталевих балок будівель і споруд гірничо-металургійного комплексу** // // Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА. 2021. – Вип. 106. – С. 54-67.

Створення раціональної конструкції підкранової балки і методики уточненого розрахунку з використанням модуля розрахунку на втому зварних швів комплексу SolidWorks і схеми геометрично нелінійного деформування тривимірного пружного тіла.

Табл. 1. Іл. 13. Бібліогр. 21 назв.

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Gezentsvey E.I., Olevskyi V.I., Volchok D.L., Olevskyi O.V. **Calculation of the improved steel beams of buildings and structures of the mining and metallurgical complex** // Strength of Materials and Theory of Structures: Scientific-and-technical collected articles. – K.: KNUBA. 2021. – Issue 106. – P. 54-67.

Creation of a rational design of a crane beam and a refined calculation method using the module for fatigue calculation of welded joints of the SolidWorks software and a scheme of geometrically nonlinear deformation of a three-dimensional elastic body.

Tabl. 1. Fig. 13. Ref. 21.

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Гезенцвей Ю. И., Олевский В.И., Волчок Д.Л., Олевский А.В. **Расчет усовершенствованных стальных балок зданий и сооружений горно-металлургического комплекса** // Сопротивление материалов и теория сооружений. – 2021. – Вып. 106. – С. 54-67.

Создание рациональной конструкции подкрановой балки и методики уточненного расчета с использованием модуля расчета на усталость сварных швов комплекса SolidWorks и схемы геометрически нелинейного деформирования трехмерного упругого тела.

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