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ПРОГНОЗОВАНЕ ВИРІВНЮВАННЯ СТАЛЕВИХ КОНСТРУКЦІЙ ЗА ДОПОМОГОЮ ЗВАРЮВАННЯ

О. І. Голоднов [a,1], В. В. Псюк [a,2], Б. В. Іванов [b,3]
[a] *Донбаський держаний технічний університет,*
пр. Леніна, 16, м. Алчевськ, Луганська обл., Україна, 94204.
[b] *Луганський національний аграрний університет,*
Містечко ЛНАУ, м. Луганськ, Україна, 91008.
E-mail: [1] golodnow@ukr.net, [2] psuk@rambler.ru, [3] boris_work-stady@mail.ru

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Анотація. Тематику статті присвячено вирішенню актуального питання – можливості прогнозованого вирівнювання експлуатованих конструкцій за допомогою зварювання. Зміна залишкового напруженого стану конструкцій після наплавлення зварних швів прогнозується розрахунковим шляхом. При оцінці напружено-деформованого стану підсилених елементів приймаються загальноприйняті гіпотези – допущення про незначний вплив поперечних деформацій і гіпотеза плоских перерізів. Експериментальні дослідження роботи підсилених під навантаженням елементів дозволили встановити, що відхилення від лінійного закону розподілу деформацій мають місце в зонах, що безпосередньо примикають до зварних швів. Мала протяжність вказаних зон в порівнянні з розмірами перерізів дозволяють застосовувати гіпотези плоских перерізів в практичних розрахунках. Особливістю розрахунків підсилених елементів є необхідність моделювання технології підсилення, оскільки вона істотно впливає на роботу підсилених конструкцій. Чисельні розрахунки дозволяють отримувати розв'язок конкретних задач тільки при заданих параметрах системи, її початкових і граничних умовах і певній технології виконання робіт.

Ключові слова: експлуатація конструкцій, залишковий прогин, вирівнювання за допомогою зварювання, прогнозування залишкового напруженого стану, технологія.

ПРОГНОЗИРУЕМОЕ ВЫРАВНИВАНИЕ СТАЛЬНЫХ КОНСТРУКЦИЙ СВАРКОЙ

А. И. Голоднов [a,1], В. В. Псюк [a,2], Б. В. Иванов [b,3]
[a] *Донбасский государственный технический университет,*
пр. Ленина, 16, г. Алчевск, Луганской обл., Украина, 94204.
[b] *Луганский национальный аграрный университет,*
Городок ЛНАУ, г. Луганск, Украина, 91008.
E-mail: [1] golodnow@ukr.net, [2] psuk@rambler.ru, [3] boris_work-stady@mail.ru

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Аннотация. Тематика статьи посвящена решению актуального вопроса – возможности прогнозируемого выравнивания эксплуатируемых конструкций с помощью сварки. Изменение остаточного напряженного состояния конструкций после наплавки сварных швов прогнозируется расчетным путем. При оценке напряженно-деформированного состояния усиленных элементов принимаются общепринятые гипотезы – допущение о малости влияния поперечных деформаций и гипотеза плоских сечений. Экспериментальные исследования работы усиленных под нагрузкой элементов позволили

установить, что отклонения от линейного закона распределения деформаций имеют место в зонах, непосредственно примыкающих к сварным швам. Малая протяженность указанных зон по сравнению с размерами сечений позволяет применять гипотезы плоских сечений в практических расчетах. Особенностью расчетов усиленных элементов является необходимость моделирования технологии усиления, поскольку она оказывает существенное влияние на работу усиливаемых конструкций. Численные расчеты позволяют получать решения конкретных задач только при заданных параметрах системы, ее начальных и граничных условиях и определенной технологии выполнения работ.

Ключевые слова: эксплуатация конструкций, остаточный прогиб, выравнивание сваркой, прогнозирование остаточного напряженного состояния, технология.

PREDICTABLE ALIGNMENT OF STEEL STRUCTURES BY WELDING

Oleksander Golodnov [a, 1], Victor Psyuk [a, 2], Boris Ivanov [b, 3]
[a] Donbass State Technical University,
16, Lenina Av., Alchevsk, Luhansk Region, Ukraine, 94204.
[b] Lugansk National Agrarian University,
LNAU town, Lugansk, Ukraine, 91008.
E-mail: [1] golodnow@ukr.net, [2] psuk@rambler.ru, [3] boris_work-stady@mail.ru

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Abstract. Subject matter of article is solution of actual problem which is possibility of alignment of structures in operation by welding. Change of residual stress state of structure after overlaying of welding joints is predicted by calculations. In process of evaluation of reinforced elements deflected mode are accepted standard hypotheses such as smallness of lateral deformations influence assumption and flat sections hypothesis. Experimental research of work of elements reinforced under load helped to define that deviations from linear law of deformations distribution are found in zones which are directly adjacent to welding joints. Small length of mentioned zones in comparison with section dimensions allows usage of flat section hypotheses in practical calculations. Special feature of reinforced elements calculations is need for modeling reinforcement technology because it significantly influences on reinforced structures work. Numerical calculations help to receive solutions for particular tasks only by specified parameters of system, initial and limit conditions of system and particular work execution technology.

Keywords: operation of structures, residual deflection, alignment by welding, prediction of residual stress state, technology.

Introduction. Statement of problem

Work of reinforced structures is very complicated and depends on variety of constructional and technological factors. In process of development of reinforced structures calculation methods it stipulates necessity to neglect set of secondary factors and introduction of simplifying preconditions [1].

Choice of bar structures reinforcement scheme is multivariant task. Taking into account modern level of calculation methods and structures design development and also variety of possible schemes and reinforcement methods, development of general approach to optimization problems seems to be task of the future. Solution of optimization problems becomes complicated with the fact that main criteria of reinforcement optimality usually is not material saving or decrease of reinforcement work complex cost, but providing of its most significant manufacturability. Manufacturability means not ease of work execution, but possibility of work execution without production shutdown in minimal terms with aim of decrease of economic losses of enterprise in process of reconstruction [1].

Reinforcement by splicing of section is reasonable for relatively smooth elements. Ensuring of reinforced element firm adherence to structure which is being reinforced with further welding helps to provide further safe performance of composite section and, inversely, welding of

element to bent structure can reduce to zero whole reinforcement effect.

Considering all above mentioned it is assumed that we talk about structure reinforcement calculation according to specified scheme with parameters given in advance and with known effects on it. Particularly, presence of residual stress state provided by welding and other methods of local thermal effects (for example welding alignment) will enable increase or decrease of bearing ability and therefore also increase or decrease of structure service life (source).

Main part

Special features of calculation of reinforced bar systems are in the first place connected with disturbance of «natural» character of their deformation, especially at reinforcement under load. In connection with this, main attention in what follows will be paid to problems of definition of deflected mode (DM) of reinforced systems in process of reinforcement and further work [1].

In spite of simplification and idealisation of design schemes, problems of reinforced structures calculations remain difficult and in majority of cases can be realized only with help of computer. One of special features of such calculations is need for modeling of reinforcement technology in some cases because it significantly influences on reinforced systems work. Numerical calculations help to receive solutions for particular tasks only by given parameters of system, its initial and limit conditions and particular technology of work production. In this point numerical modeling is like full-scale experiment but with advantage of differential evaluation of influence of one or another factor (not group of factors) on work of reinforced structure and its elements.

Special attention should be paid to presence of residual stress state (RSS). Presence of welding joints and similar thermal effects causes occurrence of residual stresses (RS) in metal structure elements which influence on stability of separate elements as well as on bearing ability and deformability of structures in general. RS influence on stability of compression members is ambiguous. RS of tension on edges increase stability and stresses of compression decrease it. Degree of this influence depends on distribution of RS on section and on rigidness of the latter.

Existing design methods (in the first place DBN V.2.6-163:2010 [2] and DBN V.2.3-14:2006 [3] do not take into account possibility of increase or decrease of compression members bearing ability after overlaying of welding joints on belts edges.

Theoretical research of RSS in welding structures, history of their development and degree of influence on bearing ability of welding structures are considered in detail in works [4–8 et al.].

Methods of defining DM of compression reinforced members considering presence of RSS and its influence on stability are developed by following preconditions [1, 4–6 et al.].

1. Only longitudinal stresses σ_x are considered. Lateral stresses σ_y and tangential τ_{xy} are assumed as zero.
2. Deformations are defined by flat sections hypothesis.
3. Modulus of elasticity, modulus of shearing and Poisson ratio of steel are constant in all temperature range.
4. Dependence of steel yield point on temperature is schematized by type shown on fig. 1. On this fig.: T – heating temperature.
5. Material of elements (steel) is uniform elasto-plastic material (fig. 2). On this figure: $\varepsilon_{el}=R_y/E_s$ conventional maximal elastic deformation (R_y, E_s – correspondingly design resistance and elasticity modulus of steel).
6. Welded plates with thickness B are considered to be long enough, temperature on plate thickness is distributed uniformly [5, 6 et al.].
7. RS in consequence of rolling (in general case) are neglected because of their relative smallness, difficult and unpredictable orientation.
8. RSS (curves of residual stresses and deformations) are assumed as idealized. Element of double tee section is provisionally divided into strips [5, 6 et al.]. RSS is defined in strip welded butt-to-butt (beam belts at overlaying of welded joints), and in strip with overlaying welded roll on edges (web at overlaying of welding joints and belt at thermal effects on edges). RSS in belts and web at overlaying of welding joints or other types of thermal effects is shown on fig. 2.11, 2.12, 2.13 [6]. Strips are heated by part of heat which is diverted to belts and web in process of beam welding. Distribution of deformations after cooling-down is accepted as shown on fig. 7.8 [5].

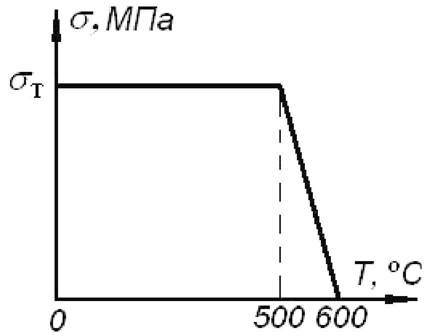

Figure 1. Dependence of steel yield point on temperature [4, 5, 6].

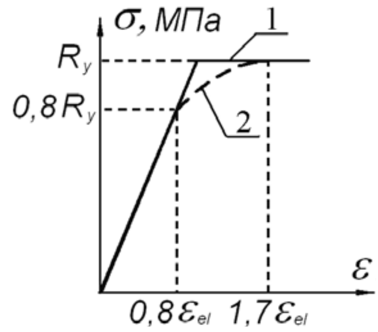

Figure 2. Diagrams «δ – ε» of steel [6]: 1 – idealized; 2 – unified.

9. Stability of II type is studied (deformations and buckling are growing from start of load application).
10. In case of non-repeated, alternating or cyclic load deformation initially occurs in coordinate system «$M_1 - \kappa_1$», unloading starts from point p_1 and curvature $\kappa_{p,1}$ ($\kappa_{p,2}$, ..., $\kappa_{p,i}$) and rigidity of design section in this point at unloading is $B_{red} = E_s \cdot I_{red}$, where $E_b \cdot I_{red}$ – is «elastic» rigidity of section. Deformation of element is performed in new coordinate system «$M_{2,1} - \kappa_{2,1}$» («$M_{2,2} - \kappa_{2,2}$», ..., «$M_{2,i} - \kappa_{2,i}$») on curve 2 (fig. 3); definition of sections rigidity at unloading is analogous to definition of sections rigidity at one-time loading [9, 10 et al.], i. e.

$$B_{2,i,j} = M_{2,i,j} / \kappa_{2,i,j} , \quad (1)$$

where $B_{2,i,j}$, $M_{2,i,j}$, $\kappa_{2,i,j}$ – correspondingly rigidity, bending moment and curving of i-th section in coordinate system «$M_{2,1} - \kappa_{2,1}$» («$M_{2,2} - \kappa_{2,2}$», ..., «$M_{2,i} - \kappa_{2,i}$»). Indexation in expression (1): 2 – unloading curve; i – unloading stage number; j – current values of parameters (rigidity, moments, curving) on i-th unloading stage. At further deformation unloading curve 2 corresponds to curve 3 of indirect loading.

Dependence «$M - \kappa$» in coordinate system «$M_{2,i} - \kappa_{2,i}$» with precision enough for calculations can be described by cubic equation or approximated by minimum quadrate method. Values of bending moments are defined by common rules of structural mechanics.

In case of non-repeated loading (fig. 3) after unloading (reaching of points $\kappa_{0,1}$, $\kappa_{0,2}$, ..., $\kappa_{0,i}$ on axis of abscissa, for which $M_0 = 0$), further loading takes place on curve 4, and initial rigidity of design section in this point at further loading is $B_{red} = E_s \cdot I_{red}$. Curve 4 in future corresponds to curve 1.

11. Fixation of element provides keeping of bending flat form (bending-torsion form of loss of stability is impossible). Possibility of bending-torsion form of stability loss is evaluated according to method recommended by norms {formula (1.6.5) DBN V.2.6-163:2010 [2]}.
12. Deformation takes place in plain of smaller or greater rigidity.
13. Deformations of longitudinal axis and approaching of element ends under loading are smaller in comparison with growth of bending.
14. Deformed state of sections is characterized by curvature κ.
15. Limit state of element is reached if:

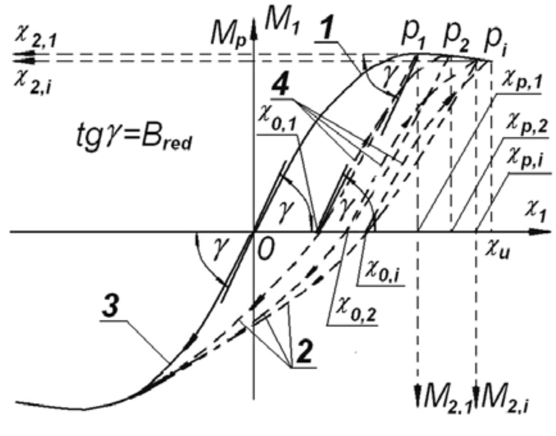

Figure 3. Diagrams «M – κ» at non-repeated, alternating or cyclic load modes.

– Maximum on state curve is reached (limit state of 1st group), i.e. criteria is executed (fig. 4)

$$\frac{dq_l}{df}=0, \qquad (2)$$

where q_l – force action vector modulus;
f – characteristic movement of structure;

– Element section is destroyed (stability loss of compression flange, web, or is reached maximal deformation value in compression flange – limit state of 1st group);
– Loss of form stability occurred which led to difficulties of normal maintenance (limit state of 2nd group).

16. Occurrence of residual bending after unloading is possible if element material passed into plastic state. Alignment is possible by overlaying of idle rolls on edges from side of convex facet (fig. 5). Zones of residual tension stresses (RTS) can be presented as external forces, values of which change in process of further loading (schemes of overlaying welding of rolls and distribution of RS after overlaying welding for some forms of sections are given on fig. 6).

Form of deflection curve after overlaying welding can be described by expression of method of initial parameters which were received on the basis of approximation of deflection curve expression by cubic spline ([6] et al.). For this purpose length of element L is divided into n zones and in each i-th point of division is defined curvature κ_i. Values of predicted curves y_i and turning angles φ_i are defined by formulas:

$$y_i = y_1 + \varphi_1 \cdot L \cdot \frac{i-1}{n} + \frac{L^2}{6 \cdot n^2} \cdot [(3 \cdot i - 4) \cdot k_1 + + 6 \cdot \sum_{j=2}^{i-1} (i-j) \cdot k_j + k_i] + q_d \cdot (\delta_1 - \delta_i); \qquad (3)$$

$$\varphi_i = \varphi_1 + \frac{L}{2 \cdot n} \cdot (k_1 + 2 \sum_{j=2}^{i-1} k_j + k_i). \qquad (4)$$

In general case is considered overlaying welding of idle rolls on length parts of aligned element. Curvature of section can be defined by formula (fig. 6):

$$\kappa_i = \frac{\sigma^{(f)}_{res,com} - \sigma^{(f)}_{res,ten}}{E \cdot h}, \qquad (5)$$

where h – distance between section points where values of RS equals zero $\sigma^{(f)}_{res,com}$, $\sigma^{(f)}_{res,ten}$.

Values of RS in section can be defined by known methods, for example [6], considering asymmetry of overlaying welding. Length of overlaying welding zone L_{weld}, parameters of idle roll and other technological parameters of process are established by trial-and-error method, gradually changing them for receiving predicted curve, value of which should be equal to residual curve of element after unloading.

Conclusion

1. Residual curve can occur in compression members of steel structures after unloading in consequence of passing of material into plastic state. It can be possible by overload of element, changing conditions of load application, decrease of lateral section area because of corrosion etc.
2. Calculation method for parameters of steel elements alignment by overlaying welding of idle rolls on convex facets is offered. Predictable alignment will help to exclude residual curve of structure and ensure elements work with smaller eccentricities of load application.
3. Predictable alignment can be used also for bendable elements except compression members with small eccentricities.

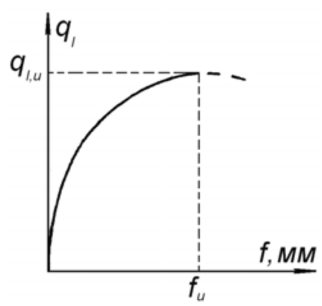

Figure 4. Diagram of system state.

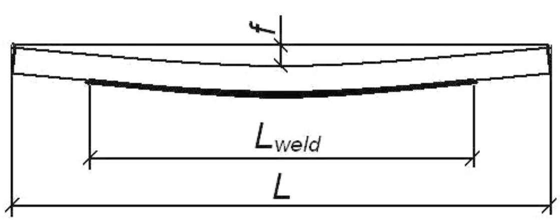

Figure 5. Scheme of overlaying welding of idle rolls in process of alignment of element by welding.

a) b) c)

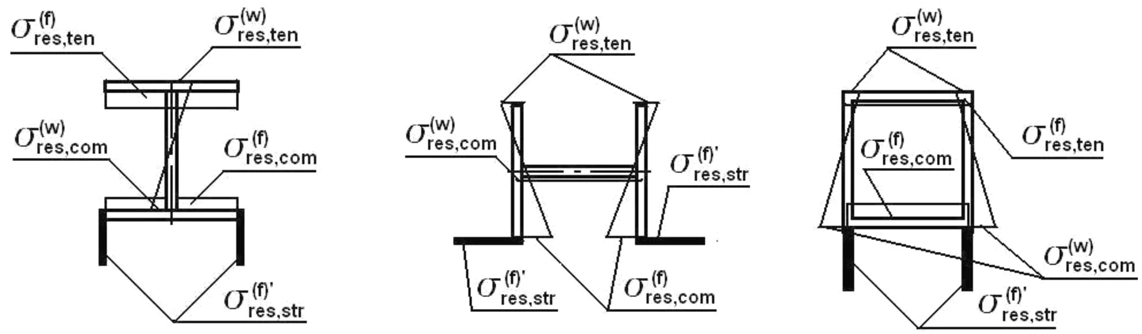

Figure 6. Schemes of overlaying welding of idle rolls and distribution of RS for different forms of sections: a) alignment of element of double tee section when bending in major rigidity plane occurs; b) alignment of element of double tee section when bending in smaller rigidity plane occurs; c) alignment of element of box section.

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Голоднов Олександр Іванович – доктор технічних наук, професор, професор кафедри будівельних конструкцій Донбаського державного технічного університету, дійсний член Академії будівництва України, член національного комітету з теоретичної та прикладної механіки. Наукові інтереси: нелінійна будівельна механіка стержнів і пластин, залишкові напруження та їхній вплив на стійкість сталевих конструкцій, надійність будівельних конструкцій при силових, деформаційних і високотемпературних впливах.

Псюк Віктор Васильович – кандидат технічних наук, доцент, доцент кафедри будівельних конструкцій Донбаського державного технічного університету, член-кореспондент Академії будівництва України. Наукові інтереси: залишкові напруження та їхній вплив на стійкість сталевих конструкцій, надійність будівельних конструкцій при силових, деформаційних і високотемпературних впливах.

Іванов Борис Валерійович – магістр будівництва, інженер-дослідник, аспірант кафедри будівельних конструкцій Луганського національного аграрного університету. Наукові інтереси: залишкові напруження та їхній вплив на стійкість сталевих конструкцій.

Голоднов Александр Иванович – доктор технических наук, профессор, профессор кафедры строительных конструкций Донбасского государственного технического университета, действительный член Академии строительства Украины, член национального комитета по теоретической и прикладной механике. Научные интересы: нелинейная строительная механика стержней и пластин, остаточные напряжения и их влияние на устойчивость стальных конструкций, надежность строительных конструкций при силовых, деформационных и высокотемпературных воздействиях.

Псюк Виктор Васильевич – кандидат технических наук, доцент, доцент кафедры строительных конструкций Донбасского государственного технического университета, член-корреспондент Академии строительства Украины. Научные интересы: остаточные напряжения и их влияние на устойчивость стальных конструкций, надежность строительных конструкций при силовых, деформационных и высокотемпературных воздействиях.

Иванов Борис Валериевич – магистр строительства, инженер-исследователь, аспирант кафедры строительных конструкций Луганского национального аграрного университета. Научные интересы: остаточные напряжения и их влияние на устойчивость стальных конструкций.

Golodnov Oleksandr – doctor of engineering sciences, professor, professor of department of building constructions of the Donbass State Technical University, actual member of Academy of building of Ukraine, member of national committee on theoretical and applied mechanics. Scientific interests: nonlinear structural mechanics of bars and plates, residual stresses and their influence on stability of steel constructions, reliability of build constructions at power, deformation and high temperature influences.

Psyuk Victor – candidate of engineering sciences, associate professor, associate professor of department of building constructions of the Donbass State Technical University, corresponding member of Academy of building of Ukraine, member of national committee on theoretical and applied mechanics. Scientific interests: residual stresses and their influence on stability of steel constructions, reliability of build constructions at power, deformation and high temperature influences.

Ivanov Boris – master's building degree, engineer-researcher, graduate student of department of building constructions of the Luhansk national agrarian university. Scientific interests: residual stresses and their influence on stability of steel constructions.