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**The Graphical Method of Design for Flexural Members
Using the SP 16.13330.2017 Standard****Vera V. Galishnikova¹**, **Tesfaldet H. Gebre^{1,2}**¹RUDN University, Moscow, Russian Federation²Moscow State University of Civil Engineering (National Research University), Moscow, Russian Federation

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Abstract. The objective of this paper is to propose the graphical design method for doubly symmetric steel beam section under flexural load compliant to the latest draft of the SP 16.13330.2017 standard. There are different design approaches for steel structures, including manual calculation, computer programs and hybrid methods which are used in different design standards for calculating allowable strength of flexural members. The graphical approach is commonly used in American Institute of Steel Construction as an alternative method and aims in improving the design efficiency for elastic and inelastic flexural members. The current method is intended to design flexural members according to the Russian design standards of the steel construction (SP 16.13330.2017) for steel sections commonly used, and available in the Russian Federation. The results consist of graphical demonstration of the relationships between the nominal flexural strength and the effective member length for various cross-sectional sizes. Using this graphical method to design flexural members can help the designer to select the optimum steel sections, furthermore it will be more helpful to the steel manufacturer to recommend more new Russian steel sections to narrow the gaps between the consecutive section dimensions. With the increasing demands of slender members, the graphical approach is a quick method of design for engineers and researchers to select an optimum steel beam section. In addition, this paper provides a practical example which confirms the efficiency and simplicity of designing a flexural member using this method.

Keywords: Flexural member, lateral torsional buckling, steel design, lightest section, Russian steel sections, graphical method

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Графический метод проектирования изгибаемых элементов с использованием стандарта СП 16.13330.2017

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Аннотация. Цель исследования — предложить метод графического проектирования двусимметричного сечения стальной балки при изгибе в соответствии с последним проектом СП 16.13330.2017. Существуют различные подходы к проектированию стальных конструкций, включая ручной расчет, компьютерные программы и гибридные методы, которые используются в разных нормах проектирования для расчета допустимой прочности элемента на изгиб. Графический подход широко используется в Американском институте стальных конструкций в качестве альтернативного метода и направлен на повышение эффективности проектирования упругих и неупругих изгибаемых элементов. Настоящий метод предназначен для проектирования изгибаемых элементов в соответствии с российскими нормами проектирования стальных конструкций (СП 16.13330.2017) для стальных профилей, широко используемых и доступных в Российской Федерации. Результаты работы представляют собой графическую демонстрацию соотношения между номинальной прочностью на изгиб и эффективной длиной элемента для различных размеров поперечного сечения. Использование этого графического метода для проектирования изгибаемых элементов может помочь проектировщику в дальнейшем подборе оптимальных стальных профилей, а производителю стали будет полезен для рекомендации большего количества новых российских стальных профилей для уменьшения зазоров между последовательными размерами профиля. В связи с растущими требованиями к гибким элементам графический подход является быстрым методом проектирования, позволяющим инженерам и исследователям выбрать оптимальное сечение стальной балки. Кроме того, в данной статье приводится практический пример, подтверждающий эффективность и простоту проектирования гибких элементов.

Ключевые слова: изгибаемый элемент, продольный изгиб с кручением, проектирование стальных конструкций, наименьшее сечение, российские стальные профили, графический метод

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1. Introduction

Due to the use of various steel sections that provide greater architectural flexibility than conventional reinforced concrete structures, steel or composite structures have grown in popularity worldwide. Architects and design engineers are increasingly shifting their attention to steel structures considering that they are much more quickly to construct than reinforced concrete constructions. Using high grade steel structural

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faster to construct than reinforced concrete ones. Using high grade steel structural elements has been attracting interest in Russian construction projects because it yields a more slender structure and the stability analysis dominates the design procedure [1]. Recommendations faster to construct than reinforced concrete ones. Using high grade steel structural elements has been attracting interest in Russian construction projects because it yields a more slender structure and the stability analysis dominates the design procedure [1]. Recommendations from different authors for the steel construction standards of the Russian Federation have improved and updated the design standards for steel structures to align with international standards including AISC and Eurocode [2–4]. The graphical approach, which aims to increase the design efficiency for both elastic and inelastic flexural components, is only utilized as an alternative method in the American Institute of Steel Construction standard [5–7]. The proposal of graphical design method using Russian steel sections will provide efficient steel beam design tools for structural designers. Using those methods, it becomes possible to identify the optimum section considering the moment and unbraced length of the flexural member. The graphical method is commonly used by AISC (American Institute of Steel Construction), it is not implemented in other national standards [1–5]. Lateral torsional buckling (LTB) analysis approaches for hot rolled doubly symmetrical sections using different standards are diverse in the consideration of the geometric imperfection, residual stress, and also in the consideration of the inelastic and elastic LTB approaches [6; 7]. AISC used a design calculation method in which the LTB curve is divided into three different parts: the yield (plastic) region, inelastic buckling and elastic buckling [8]. The design calculation and construction procedures of different international standards might differ from country to country and also may result in noticeable variations in the weight of steel considered. The AISC standard is prepared with detailed and simplified approaches and is considered by researchers are considered as a benchmark for comparison with other standards for traditional design aid [8–9]. Because of the presumptions and algorithms employed in commercial software, there are still valid reasons to consider design charts as a crucial practical tool even though the demand for traditional design, which depends on tables and charts, has decreased slightly. In addition, the trial and error method is based on an approximate moment and selecting trial shape, then finally checking the compliance of the section with the requirements of the specification [10–13]. This will lead to the waste of raw materials and energy, as well as the failure to account for effects on the environment [15]. Similarly, the Russian standard follows the same traditional approach for designing flexural members [16]. To overcome this limitation chart-based approach is an alternative and economical approach. The recommended graphical design approach for steel beams under flexural load which adheres with the most recent draft of SP 16.13330.2017 can be used as a quick, error-proof design tool for a variety of steel sections and as a validating tool. While it is a quick design aid, it can be used for educational purposes because it can improve students' engineering perspective and judgment through visual representation. As part of the steel design procedure for flexural members, considering the lateral torsional buckling analysis is a part of the limit state that must be checked for steel beams [17]. Hot-rolled doubly symmetric I-beams are designed for lateral torsion buckling in various stages by taking into account a wide range of scenarios like support conditions, web openings and corrugated webs [15; 18–21]. AISC, Eurocode 3, AS4100, and other common design standards were taken into consideration when evaluating the research utilizing various design guidelines according to their geographic location. Based on the Russian standard (SP) for flexural steel member design, the analysis is carried out using plastic moment resistance, forming plastic hinges, and section element proportions to avoid local buckling [22; 23]. The Russian standard does not use the elastic critical moment and the non-dimensional slenderness like in the American Institute of Steel Construction (AISC) and Eurocode 3 (EC-03) for steel design, but it has a coefficient that accounts for the plasticity and imperfection [24–29]. The lack of the elastic critical moment for LTB capacity of wide flange sections and the modification factor leads the Russian standard to be uneconomical and limited to a specific unbraced length. Generally, the advantages of the elastic design for lateral torsional buckling are to consider in long span beams with a focus on the efficiency and optimization of the member. The elastic critical moments for LTB capacity were studied in different stages which was proposed by [30], and later on studied by different authors for the classical solution for the critical LTB in

different loading types and modification factors [31–36]. Lateral torsional buckling (LTB) is of concern in long-span flexural members, particularly in the negative bending moment regions of continuous-span, steel I-shaped members and during construction. While the elastic critical LTB capacity of a simply supported I-shaped member subjected to uniform moment has a closed-form solution, most LTB modification factors for beams subjected to moment gradients in the literature are empirical and work well only for specific loading and boundary conditions [37]. Through comparisons with analytical solutions using the Rayleigh — Ritz method and numerical solutions from finite element analyses, the stability of the various LTB modification factors in literature and design specifications for various loading and boundary conditions was investigated. The analytical LTB modification factors are derived for doubly symmetric I-shaped members with different combinations of ideal flexural and torsional boundary conditions (simply supported and fixed) and subjected to different loading scenarios. The validity of the LTB modification factors determined using the Rayleigh — Ritz method and other formulae in the literature are also assessed for realistic intermediate restraint conditions, which are neither fully pinned nor fixed, by examining laterally continuous beams. Demonstrating that current design specifications for elastic critical LTB modifications are overly conservative for beams with complete or partial warping fixity, the authors recommend practical and simple alternatives to design such beams. The Russian standard for steel structures has limitations in calculating the stability of flexural members and different methods are recommended by different authors to overcome the limitations [38].

The current paper deals with the proposal of a chart-based method of design for LTB for hot-rolled symmetric I-beam steel using Russian standards. In the presented charts, the flexural member design approach for LTB was considered. The analysis considered three different sections as plastic or yielding, inelastic LTB and elastic LTB based on the unbraced length of the beam. The proposed graph-based design for Russian standard steel sections makes it simple to determine the optimum steel section while taking the available moment and unbraced length of the beam section into account. The graphs are formulated in such a way that the solid lines of the graphs indicate the optimum section for the definite unbraced length with available moment, being stronger than the steel section denoted with a dashed line [3; 39]. The most common graphical method is prepared for AISC steel sections with imperial units which are not commonly available in the Russian steel markets [39]. The current proposal for the design curve method will facilitate the selection of lightweight steel sections, thereby reducing construction costs. Additionally, it may serve as an opportunity for steel manufacturers to propose new steel section sizes based on the gaps among existing sizes.

2. Methods

In this study, the static schematic adapted is a cantilever beam with doubly symmetric I-section which is restrained against warping and rotation at the support in its bending plane as shown in Figure 1.

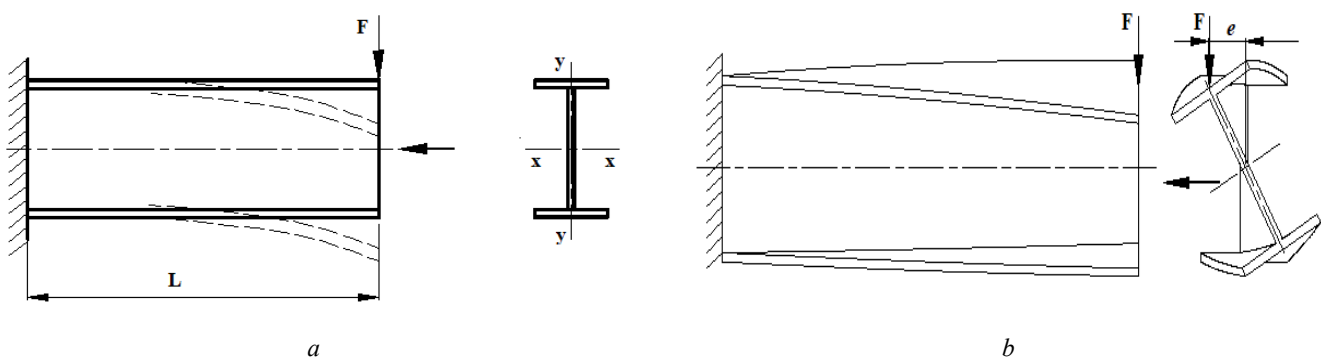


Figure 1. Static schematic of a beam:
a — without loss of stability; *b* — with buckling of a beam
 Source: made by T.H. Gebre.

The graphical method of design for flexural members using the SP 16.13330.2017 standard requires moment capacity graphs from a wide range of steel sections available on the Russian steel markets. This method is used in AISC manual with a variety of graphs, but for the USA steel sections only, therefore it is inapplicable to the Russian steel sections. Developing the graphical method of steel design using the Russian manual and steel sections is performed for an alternative option for designers and researchers. The current study used the Russian code and steel sections to develop the graphical method of design for flexural members [40]. As this approach is a common method in AISC and it is known by design engineers, therefore, it can be assumed that any further actions will not lead to a violation of the integrity of the document's philosophy. For the plastic design under the action of the moment in one of the principal planes for Class 1 members, if the member is loaded with moment in the major principal plane only, the ratio is given by [40]:

$$\frac{M_x}{\phi_b W_{cx} R_y \gamma_c} \leq 1, \quad (1)$$

where M_x is the factored moment about the major principal axis, x , W_{cx} is the section modulus of cross section about the principal axis, x , computed for the compression flange, W_{cx} is the minimum section modulus of cross section about the principal axis, x , R_y is the design yield strength, γ_c is the service factor for structural members and connections, and ϕ_b is the stability factor in bending.

The design buckling moment resistance (nominal moment capacity) for lateral torsional buckling should be computed by eq. (2) for elastic and inelastic designs with limited bracing lengths and loaded exclusively on the major plane:

$$M_x = c_x \beta W_{xn, \min} R_y \gamma_c, \quad (2)$$

where $W_{xn, \min}$ is the minimum section modulus of cross section about the principal axis, x , R_y is the design yield strength for tension, compression, and bending, c_x is the coefficient for the calculation of structural elements taking into account the development of plastic deformations for Class 2 and Class 3 sections, β is the coefficient that takes into account the effect of average shear stress on the moment capacity.

3. Results and Discussion

Flexural members are dominated by bending deformation when subjected to different types of loadings. The available steel sections for flexural members on the Russian market are considered in the current study. Based on the Russian steel manufacturing companies, the most common beam section are designated as Б and III section types [40]. The Б section are doubly symmetric section beams with small flange width to height ratio and III section is a wide flange section with high performance in stability and it has better performance in bending and compression compared to the Б sections [16]. In the current study we tried to consider the III beam section as a case study. The analysis of the nominal bending moment and the development of the design charts for the current study are considered based on the Russian standard (SP 294.1325800.2017) [10]. When we consider the buckling curves for SP 294.1325800.2017, it does not classify sections, but the noticeable part is for the compact section as we considered a limit of the unbraced length for each section. The nominal bending moments are considered for the moderate and slender beams as it gives as a high buckling resistance. The nominal bending moments decrease to a relatively small magnitude and remain constant when we consider a slender beam section. The graphical method of design for flexural members using the SP 16.13330.2017 standard is considered based on M_x vs L_b graphs for each section type and a combined chart is developed. The combined graphical formation of M_x vs L_b chart for 26III2 & 23III1 sections is shown in Figure 2. The graphical method to select the lightest steel section between 26III2 & 23III1 steel sections is given in Figure 2. The combined moment capacity vs lateral

unbraced length graph reflects that 26III2 is heavier than 23III1 section which turns into the dashed line after an intersection between the two graphs. We can consider different options in selecting the lightest section from 26III2 & 23III1 by referring to Figure 2 and I-option, both 26III2 & 23III1 can be selected, but relatively the 23III1 is the lightest one. II-option, as it is above the two curves and the moment capacity of the two sections is small so there is no sufficient section. For III-option, similarly, as it is outside the two curves, in the current graph both 26III2 & 23III1 are not applicable. Special case can be considered as VI-option as shown in Figure 2, 23III1 is the optimal section which is considered as lightest and strong steel section.

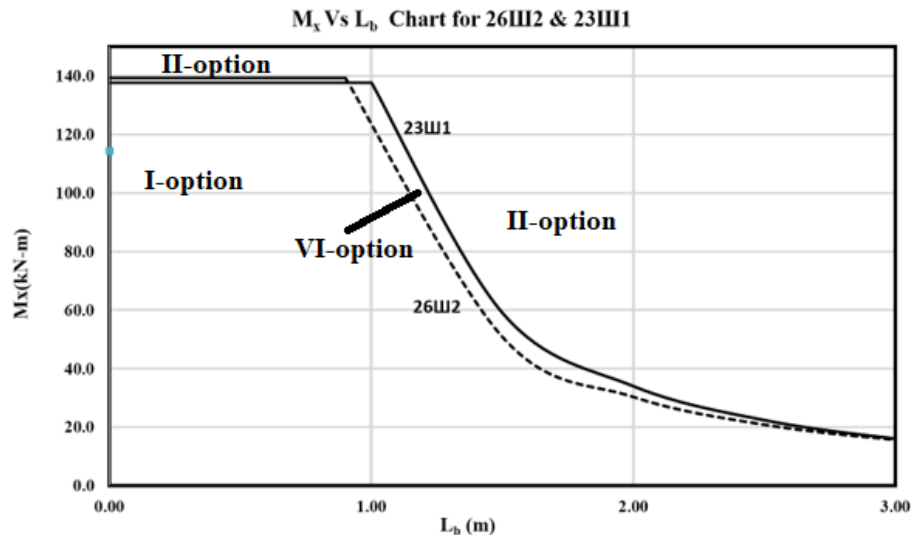


Figure 2. The graphical representation of (M_x) vs L_b Charts for 26III2 & 23III1 sections

Source: made by T.H. Gebre.

By considering the Russian steel sections, the graphical method may be applied in the actual practical design process. First, we must determine the unbraced length and total bending moment of the beam member. For example, let us consider the unbraced length of 2.5 m and the required moment of 300kN-m. Referring to Figure 3, the horizontal and vertical lines corresponding the required moments and unbraced length respectively have to be formed and intersect at a specific point. The intersection point is considered as a bench mark for the selection of the lightest section and 40III1 section is the lightest and adequate section. By projecting the horizontal line backward, the moment capacity is 302 kN-m and it is greater than the required moment which is 300 kN-m as shown in Figure 3.

The graphical method moment (M_x) vs unbraced length (L_b) design curves for moments ranging from 0 to 800 kN-m are shown in Figure 3.

The chart for the flexural member is a plot of moment vs unbraced length and the graph is considered as a strength curve for each specific beam section. The two axes for each graph characterize available moment and unbraced length respectively. Referring to Figure 3 for each steel section designated as per the SP standard, the solid lines represent the lightest and most economic section whereas the dashed lines represent the weaker sections to be considered at first. The continuity or termination of the lines within the graphs indicate the slenderness behavior of the beam section and when the beam is inadequate to resist the load. Generally, the graphs for lateral torsional buckling based on the AISC are classified in to three different types: plastic, inelastic and elastic stages. Plastic moment indicates that the beam is fully braced and reaches its plastic moment capacity before buckling. The moment capacity starts to drop with yielding behavior and it is considered as inelastic lateral torsional buckling. The third stage is elastic lateral torsional buckling as the beam drops below the yielding point and it is considered as a slender member. In the current

study, the chart based flexural member design is prepared based on the Russian standard. This method will overcome the limitation of the traditional method of design of flexural members which follows the tubulated data and iterative methods for selecting the lighter section. common wide flange sections are considered and the graphs are compiled together as shown in Figures 3, 4 and 5. The graphical method moment (M_x) vs unbraced length (L_b) design curves for moments ranging from 800 to 2500 kN-m are shown in Figure 4.

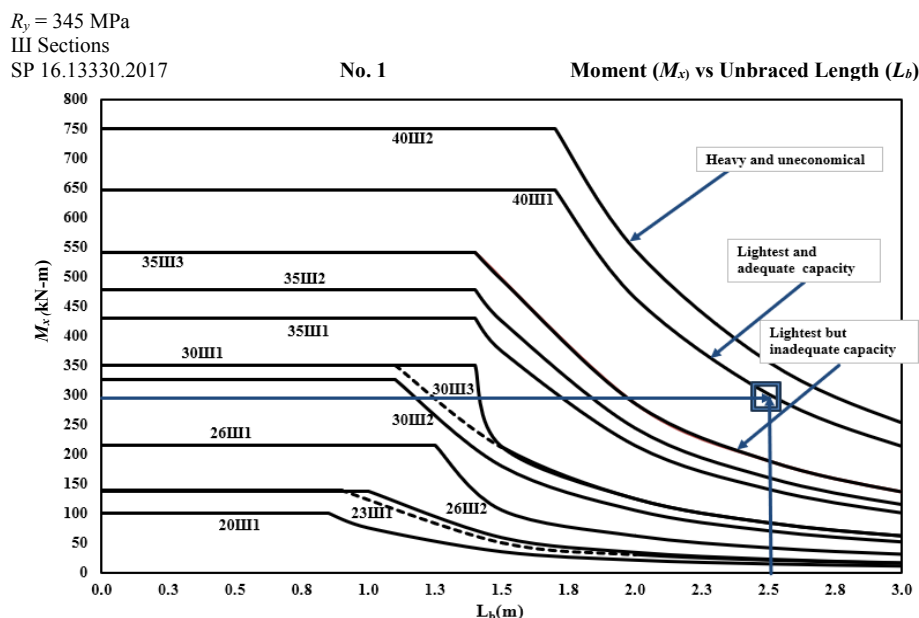


Figure 3. The graphical method moment M_x vs unbraced length L_b design curves for moments from 0 to 800 kN-m

Source: made by T.H. Gebre.

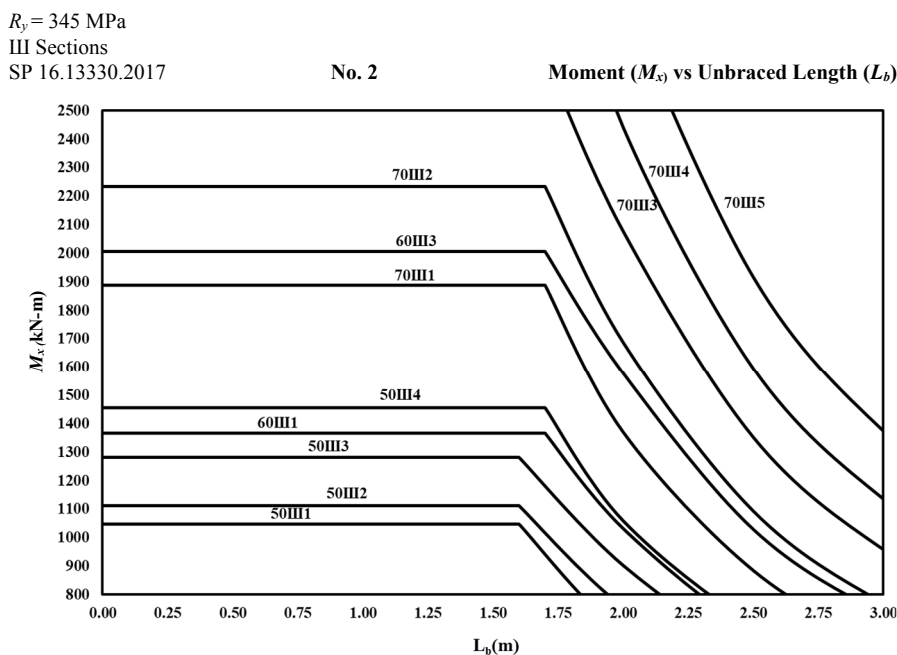
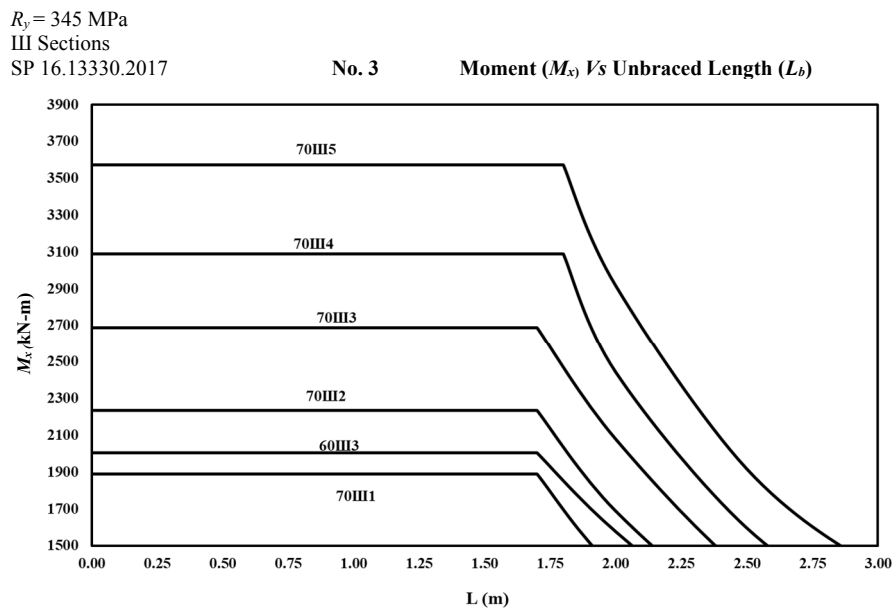


Figure 4. The graphical method moment M_x vs unbraced length L_b design curves for moments ranging from 800 to 2500 kN-m

Source: made by T.H. Gebre.

Similarly, the moment capacity for the ranges between 1500 to 3900 kN-m can be computed for different values of unbraced length using the graphs shown in Figure 5.

The above results are considered for charts of plastic moments and inelastic lateral torsional buckling as the Russian standard is recommended for limited unbraced length. The Russian standard (SP 16.13330.2017) provides buckling factors and limited optimum unbraced length of every beam section based on the section properties. In order to consider the stability of the flange or local buckling, the characteristic nominal slenderness is less than the ultimate slenderness value which can be calculated from ultimate nominal slenderness [10; 14]. The overall stability of the beam is checked and considered to be ensured if a solid rigid flooring is supported on the upper belt and securely fixed to it. According to SP 16.13330.2017 [10; 15] the nominal slenderness and stable unbraced length for the lateral — torsional buckling strength and for doubly symmetric I — section may be calculated by Eqns. (3)–(9).



$$\frac{\ell_{ef}}{b'_f} \leq \left[0,35 + 0,0032 \frac{b'_f}{t_f} + \left(0,76 - 0,02 \frac{b'_f}{t_f} \right) \right] \frac{b'_f}{h_f} \sqrt{\frac{E}{R_y}}, \quad (3)$$

where ℓ_{ef} is the effective length, b_f and t_f are the width and thickness of the compression flange; h_f is distance (height) between the axes of the flanges. If the limit slenderness, which is flange stability, is $b/l < 15$, the value of $b/l = 15$ needs to be taken. If the stability condition is not met, then it is necessary to check the overall stability, taking into account the coefficient of reduction of the design resistance (ϕ_b) according to the formula:

$$\sigma = \frac{M}{W_x \phi_b} \leq R_y \gamma_c. \quad (4)$$

To determine ϕ_b , ϕ_1 needs to be found using the following equation:

$$\phi_1 = \psi \frac{I_y}{I_x} \frac{h}{\ell_{ef}} \frac{E}{R_y}. \quad (5)$$

The ψ coefficient is taken according to Table 73 of the SP 16.13330.2017 standard and depending on the parameter shown below:

$$\alpha = 8 \left(\frac{l_f}{h_f} \frac{t_f}{b_f} \right) \left(1 + \frac{a t_w^3}{b_f t_f^3} \right), \quad (6)$$

where $a = 0.5h_f$, φ_b is determined from Table 74 of SP 16.13330.2017, and when checking the local stability of the wall, the following conditions must be met:

$$\bar{\lambda}_w = \frac{h}{t_w} \sqrt{\frac{R_y}{E}} \leq 2.5, \quad (7)$$

in the presence of local stresses, and

$$\bar{\lambda}_w = \frac{h}{t_w} \sqrt{\frac{R_y}{E}} \leq 3.5, \quad (8)$$

in the absence of local stresses. If these conditions are not met, the beam web must be strengthened with transverse stiffeners, the maximum distance between which should not fall outside

$$a_{\max} \leq 2h_w \rightarrow \bar{\lambda} > 2.5, \quad a_{\min} < 2h_w \rightarrow \bar{\lambda} > 3.2, \quad (9)$$

if the we tried to consider for the elastic design (slender member) based on the Russian standards, which is more conservative in comparing with AISC-LRFD [39] and Eurocode 3 [28; 29], then its flexural capacity is considered minimum. Therefore, the chart method for larger unbraced length is considered to account for the elastic design or for slender steel beam sections. The graphical design method for optimal flexural member using the SP 16.13330.2017 standard with the Russian version of steel sections has been presented. These visual representations can be easily implemented for the designs of steel beams at the technical office because they generate the same optimal sections as the standard computer programs. Additionally, other nations that employ Russian steel with doubly symmetric sections various for support conditions and thin members can use the graphical method used in this work as a design guide.

4. Conclusion

The paper presented the graphical scheme of design using the Russian design procedure and steel sections as an alternative to the existing technique. Doubly symmetrical wide flange sections identified as III sections were considered and the graphical results are presented. The graphical method of design can be used by engineers as an alternative and quick method of design for flexural members based on the moment capacity and unbraced length as an input data. For manual or computer design procedure, the design curves for the method are considered as a validation tool and it increasing the accuracy of the design procedure for steel members. From the current study of graphical method of design, three different sections as plastic or yielding, inelastic LTB and elastic LTB based on the unbraced length of the beam, were considered. The proposed graph-based design for Russian standard steel sections makes it simple to determine the optimum steel section while taking the available moment and unbraced length of the beam section into account. The graphs are formulated in such a way that the solid lines of the graphs indicate the optimum section some definite unbraced length with available moment, being stronger than the steel section denoted with a dashed line. The current proposal for the design curve method will facilitate the selection of lightweight steel sections, thereby reducing construction costs. Additionally, it may serve as an opportunity for steel manufacturers to propose new steel section sizes based on the gaps among existing sizes.

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