Numerical Study of the Influence of the Distance between Stiffeners on the Loss of Stability of the Web of an I-Section Steel Beam

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Abstract. When designing welded I-elements, it is necessary to ensure the reliability of positional web resistance and system stability. The arrangement of transverse stiffeners allows you to break the web into separate compartments. The distance between stiffeners is assigned by the engineer. It is important to assign the distance between transverse stiffeners satisfying the requirement of positional web stability without increasing the web thickness. The article studies the effect of the distance between stiffeners on positional stability. Four test models of steel I-beams with a span of 15 m, with different distances (steps) of double-sided transverse stiffeners are considered. The web of the four models is divided by transverse stiffening ribs into 9, 11, 13, and 15 compartments, respectively. The calculations were performed numerically using SCAD Office software package. For modeling beams, a rectangular shell finite element, type No. 41 is assigned. The left supports of beams are hinged and fixed, right hinged and mobile. The load is collected for floor beams with a step of 6 m and is applied to the upper girdle, as evenly distributed along the axis of the web. From the plane of the beams, in the level of the upper girdle of the welded I-beam, the constraint linear displacements are assigned. The first forms of loss of positional web stability for four models are graphically shown and described. The reliability coefficients for stability for the first three forms of each model are obtained. Conclusions on the effect of the distance between double-sided transverse stiffeners on the positional resistance of the steel I-beam web are given.

1. Introduction

Metal structures in the Russian Federation and a number of other countries are projected in two stages. The first stage of design documentation for metal structures is carried out by the project organization and includes: collecting loads, forming a design scheme, static calculation, selection of sections, development of wiring diagrams, construction of main components (GOST 21.502-2016). Further working documentation of the metal structure comes to the factory. The manufacturer prepares the next set of working documentation - metal construction details. At the metal construction details stage, all elements are dimensioned, broken up into separate parts for manufacturing and transportation to the
construction site, welds are assigned, secondary nodes are developed, a detailed specification of rolled metal is prepared.

Design in two stages allows reducing the number of errors in the final documentation and taking into account the technological features of the manufacturer. The placement of stiffeners is usually performed at the stage of metal construction details. The distance between stiffeners in welded elements is appointed by the designer in accordance with the provisions of building codes (SP 16.13330.2017). As a rule, depending on the value of the conditional flexibility of the web, the distance between stiffeners is assigned in the range of values: \( h_w \ldots 2.5h_w \), where \( h_w \) is the height of the beam web.

In this article, it will be shown that distance between stiffeners significantly affects the positional stability of the thin web of the beam and, as a result of this, the overall stability of the entire system as a whole [1-3]. Changing the distance between stiffeners, you can change the shape of the loss of positional web stability. Studying the form of loss of positional stability allows identifying weak areas of the system. By changing the distance between the transverse stiffeners, you can increase or decrease the reliability of the stability of the system [4, 5]. To study the effect of distance between stiffeners on the stability of a thin web, we will use numerical methods. The calculation for stability is performed using SCAD Office software [6, 7]. The program performs the calculation by the finite element method (FEM). The basis of the FEM is to partition the system into small sublimities or elements and find the basis function on each small element [8, 9]. Such small areas and elements are mated at common points called nodes. Each node and element has its own numbering. The increase in the number of small areas increases the accuracy of the calculation, but also complicates the calculation itself and the preparation of the initial data of the calculation model.

2. Statement of the problem and assessment methodology

The effect of the distance between double-sided transverse stiffeners on the stability of the web and the system has been studied using the example of four test models of a steel beam of an I-beam cross section with a span of 15 m. Distance between beams is 6 m. The construction material is С255 steel. The web of the beam with a thickness of 7 mm of each of the four models is divided into compartments with double-sided stiffeners with a thickness of 8 mm, in increments of 1660 mm, 1360 mm, 1150 mm and 1000 mm, respectively ‘Figure 1’. The calculation was performed using SCAD Office software package (Version 21.1.1.1) based on the FEM.

Elements of computational models ‘Figure 2’: web, girdle, stiffeners, support stiffeners, are represented as rectangular finite shell elements; the type of element in program is No. 41. The following finite element thickness was assigned: web - 7 mm, shelves - 20 mm, support stiffeners - 16 mm, stiffeners - 8 mm. All elements of the models have a total number of finite element plates: “Model No. 1” - 4572, “Model No. 2” - 5088, “Model No. 3” - 4856, and “Model No. 4” - 4932.

Connections in the form of restrictions on linear displacements are established in such a way that it corresponds to a constructive solution to the junction of beam elements (along the axes of the bolts): the left hinged fixed bearing, the right hinged movable right support [10]. To prevent loss of overall stability and limit the bending deformation from the plane in the level of the upper girdle, constraint linear displacements along the Y axis are laid in the compressed zone ‘Figure 1’ [11, 12]. These links symmetrically fasten the upper girdle of the beam from the plane (along the Y axis) into four sections with a pitch of 3340 mm and 4150 mm.
2.1. Load on design scheme

The following vertical loads were applied to the beam: Dead load (constant loads): 4.605 kN/m$^2$; Live load: 2.66 kN/m$^2$.

Total design load: $q = 7.265 \text{kN/m}^2 \times 6\text{m} = 43.59 \text{kN/m}.$

2.2. Assessment method

To assess changes in the stability of the web and the system, quantitative and qualitative criteria are applied. The quantitative criteria are: the amplitude values - displacements of the FE nodes of the web, in the places of curvilinear sections of convexities, in the region of instability. An important
quantitative criterion for assessing positional web stability is the value of the coefficient of reliability for stability - “k”. The reliability coefficient for stability numerically describes how many times it is necessary to increase the calculated load in relation to the critical one in order for a loss of stability to occur. With “k = 1” the load value becomes critical. Critical means the load at which the web bulges [13–16].

When the critical load is reached, the system in question cannot remain in the initial position, since it becomes unstable and any, even very small disturbances will lead to instability. In this case, the system passes the limiting points of the original form of equilibrium of the system and then, the original stable form of equilibrium is replaced by another stable (sometimes unstable) new form of equilibrium. Further, with increasing load, the emergence of new forms of equilibrium is possible. If the value of “k” is greater than one, then the system is stable and has a margin of stability.

In this article, the values of the coefficients “k” are given in table 1, for the first three equilibrium forms of the system of each calculated model. The qualitative criterion is the graphic display and description of the new forms of equilibrium of the system. This paper describes the first form of buckling for the four models ‘Figure 3’.

It is important to change the nature of the deformation of the web, taking into account the spacing of the stiffeners. Changes can occur both along the beam axis in different compartments, and along the web height inside one compartment. The description of the change in the shape of the equilibrium helps to identify the weakest areas of the web and determine the spacing of the transverse stiffeners, providing the required stability of the web, the reliability of the steel beam. Rational arrangement of stiffener spacing allows thinner webs to be used, which saves metal [17–20].

3. Analysis of the results of numerical calculation

When reducing the spacing between stiffeners in the three models, the first form of loss of web stability is observed in the extreme, supporting compartments: “5L”, “6L”, “7L” ‘Figure 3’. Loss of stability for the first three models occurs on a half-wave of the sinusoid in the longitudinal direction of the beam. Sine waveform for the calculation results “Model No. 1” in the compartment “5L” on the opposite side of the web forms a new half-wave. But the second half-wave of the sinusoid in the longitudinal direction of the beams has much smaller amplitude with respect to the first half-wave, which is closer to the support. The size of the second half-wave decreases with decreasing length of the compartment. With the length of the compartment approaching in size to the height of the web, the second half-wave of the sinusoid almost disappears. It can be noted that an increase in the length of the compartment does not significantly affect the first longitudinal half-wave located near the support stiffeners of the beam, but contributes to the formation of a new half-wave sinusoid of the loss of positional stability of the web between the stiffeners. New half-wave sinusoids are formed in the section of the compartment closer to the mid-span of the beam ‘Figure 3’. The maximum amplitude of the half-wave is about 240 mm for the first three models.

In the fourth model “Model No. 4” loss of web stability is observed in the middle five compartments: “3R”, “2R”, “1”, “2L”, “3L”. The form of web buckling in “Model No. 4” fits into a sinusoid having two formed half-waves in each of the five middle compartments. The maximum amplitude of 118 mm is obtained in the middle compartment “1” ‘Figure 3’. In “Model No. 4” as it moves away from the middle compartment “1”, the sine wave fades away.

The height of the cross section in the extreme compartment ‘Figure 4’, for the first three models, the sinusoid is located close and skew-symmetrical to the beam section axis. In “Model No. 4” the sinusoidal buckling pattern is located in the upper part of the cross section in the compressed zone of the web in the compartments ‘Figure 5’: “3R”, “2R”, “1”, “2L”, “3L”.

Table 1 shows the values of the safety factors for stability. The coefficients “k” has similar values for the three forms of buckling, for all four models and increase with decreasing stiffener spacing of the beam.
Table 1. The values of reliability coefficients for the stability of four models of beams, taking into account the three forms of buckling.

| Model No. | 1st form | 2nd form | 3rd form |
|-----------|----------|----------|----------|
| Model No. 1 | 2.17     | 2.24     | 2.25     |
| Model No. 2 | 2.27     | 2.35     | 2.38     |
| Model No. 3 | 2.36     | 2.42     | 2.47     |
| Model No. 4 | 2.47     | 2.50     | 2.52     |

Figure 3. Geometric schemes of the first form of loss of stability of the web along the longitudinal axis of the beam (4 variants of stiffener spacing).
Figure 4. Geometric scheme of the first form of buckling, “Model No. 1”, the compartment “5L”.

Figure 5. Geometric scheme of the first form of buckling, “Model No. 4”, the compartments “2R” - “1” - “2L”.

4. Conclusions
Based on the results of research performed in this work, we can draw the following conclusions:

4.1. Reducing the spacing of transverse stiffeners in steel I-beams increases: the reliability of positional web stability and the overall stability of the system.

4.2. In steel I-beams with transverse stiffeners, the most sensitive for loss of positional stability of the webs are the extreme and middle sections.

4.3. A constructive, solution should be studied with a decrease in the spacing of the stiffeners in the extreme and middle sections of steel I-beams, and in the other compartments to use large distances between the stiffeners.
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