***NADOLSKI V.V.* Analysis of settlement models of resistance to local loading of steel elements**

The article highlights the current state of the issue of calculation of steel structures to the action of local transverse forces. The basic theoretical assumptions underlying the Eurocode 3 are shows. The theoretical assumptions laid in resistance models of local buckling under transverse forces are compared. Future directions of further development of models of resistance to local loads are marked.

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LIMIT STATE DESIGN OF SLENDER STEEL WEBS ASSOCIATED WITH THE SHEAR BUCKLING

1 Introduction. The determination of shear resistance of slender steel web in modern normative documents is based on post - buckling stage. It is assumed that the principal behavior of the web change from a stable state to a post - buckling stage during the process of increasing load. In this formulation, shear resistance is determined by adding resistance to the loss of local stability and by additional resistance provided by the process of post – buckling stage.

Shear resistance models which take into account the post - buckling stage get the reasonable value of ultimate shear resistance of steel elements (the term ultimate shear resistance means the value of shear force after which the element can not resist the load). These models are suitable for the ultimate limit states (ULS), but one of following situations is possible under common conditions:

a) loss of local stability of the web which can cause a discomfort to people;

b) multiple loss of local stability which can cause fatigue failure of the material;

c) decrease of a member stiffness due to the loss of local stability of the web after which requirements of the serviceability limit states (SLS) on deformability are not satisfied.

The situations mentioned above are not associated with collapse or with other similar forms of structural failure and therefore they can be well covered by (classified as) serviceability limit states (SLS). Models of shear resistance which are based on the elastic critical plate buckling stress should be used to check these states.

Verification formulas for SLS related to the local buckling of web from the action of shear stresses are offered in the first part of the paper. An analysis of reasonability of the use of SLS criteria for determination of shear resistance is given in the second part.

2 Verification formulas based on the SLS criteria

a) Avoiding single web buckling at ordinary conditions (or at common circumstances). This verification should be carried out in cases when the web buckling can cause discomfort to people by sound or by visual effect. A moment of local stability loss of the web is considered as limit state. In order to prevent this state, it is necessary to assure that the level of actual stress does not exceed the critical stress for a shear buckling mode. Actual stress must be determined using a SLS load combination. It is reasonable to use the characteristic load combination according to EN1990 [1] to avoid this state.

Verification formula can be written as follows:

$$V_{Ed,SLS} \le V_{Rd,SLS}. \tag{1}$$

Where $V_{Ed,SLS}$ is a design value of a *load effect for SLS verifications* which is calculated using the load combination according to [1]:

$V_{Rd,SLS}$ is a *shear resistance for SLS verifications* at the moment of web buckling.

b) Avoiding the multiple (frequent) web buckling (excessive "web breathing"). Multiple buckling (breathing) of the web can cause fatigue of the material in the bent area and can lead to a fatigue (brittle) fracture. This fracture can appear in tension areas of the web-flange interface and in tension areas of web-stiffener connection for crane and bridge girders. It is related to a large variability of loading for these constructions. Verification of this situation is published in EN 1993-2 [2] and EN 1993-6 [3]. In addition, application of this verification is possible, for example, if the staff is well informed about possibility of local buckling of web and knows that it is acceptable state. This verification can be used for more general cases.

This verification is given in the section SLS and named "Limitation of web breathing" [2, 3]. This condition is written as follows:

$$\sqrt{\left(\frac{\sigma_{x,Ed,ser}}{k_{\sigma}\sigma_E}\right)^2 + \left(\frac{1.1\,\tau_{x,Ed,ser}}{k_{\tau}\sigma_E}\right)^2} \le 1.1. \tag{2}$$

Where $\sigma_{x,Ed,ser}$ and $\tau_{x,Ed,ser}$ are normal and shear stress from the frequent load combination respectively.

Considering only the shear stress this verification can be written as follows:

$$V_{Ed,SLS} \le V_{Rd,SLS}. \tag{3}$$

The frequent load combination permits a local buckling but limits its number.

c) Avoiding element stiffness decrease. This verification is relevant in cases when the stiffness verification is decisive for element design, so the additional stiffness reduction is not acceptable. As a result, it is necessary to consider a value of a resistance at the moment of a web buckling. This type of verification is analogical to the previous one, but it is necessary to use the same load combination as at the verification of deflections to determination of a design value of a load effect for SLS.

3 Procedure of reasonability of use of SLS criteria for shear resistance verification

3.1 General case. It is necessary to analyze whether it makes sense to carry out verifications mentioned above or it is enough to perfom verifications for ULS (according to EN 1993-1-5[4]) and above mentioned states will not occur. Procedure that gives an answer to this question is described further.

It is possible to calculate a value of a *shear resistance for ULS* for given characteristics of an element according to chapter 5 [4]:

$$V_{Rd,ULS} = V_{bw,Rd} + V_{bf,Rd}, \tag{4}$$

Next, the design value of a *load effect for ULS verifications* can be defined according to the full usage of element resistance:

$$V_{Ed,ULS} = V_{Rd,ULS}. \tag{5}$$

It is possible to define characteristic values of action components from the design value of a resulting load by following formulas [5]:

$$G_k = \frac{V_{Ed,ULS}}{\{\xi\}\gamma_G + \dfrac{(\{\psi_Q\}\gamma_Q + k\{\psi_W\}\gamma_W)\chi}{(1+k)(1-\chi)}}; \tag{6}$$

$$Q_k = \frac{\chi\, G_k}{(1+k)(1-\chi)}; \tag{7}$$

$$Wk = k\, Qk. \tag{8}$$

Here the parameter χ denotes the ratio of variable actions

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$Q_{k,1}+Q_{k,2}$ to the total load $G_k+Q_{k,1}+Q_{k,2}$ given as:

$$\chi = (Q_{k,1} + Q_{k,2})/(G_k + Q_{k,1} + Q_{k,2}). \qquad (9)$$

Loading parameters $k = Q_{k,2}/Q_{k,1}$ characterizes the relationship between the leading and the accompanying variable action.

Next, it is necessary to calculate a design value of *load effect for SLS verifications.* Rules of load combination depend on the examined verification. Rules of load combination for SLS are given in EN 1990[1]:

- characteristic load combination

$$V_{Ed,SLS} = \sum_{j\geq 1} G_{k,j} \text{"+"} Q_{k,1} \text{"+"} \sum_{i>1} \psi_{0,i}\, Q_{k,i}\ ; \qquad (10)$$

- frequent load combination

$$V_{Ed,SLS} = \sum_{j\geq 1} G_{k,j} \text{"+"} \psi_{1,1}\, Q_{k,1} \text{"+"} \sum_{i>1} \psi_{2,i}\, Q_{k,i}\ . \qquad (11)$$

Resistance based on critical stresses can be used to determine the value of *shear resistance for SLS verifications*

$$V_{Rd,SLS} = \tau_{cr}\, h_w\, t_w, \text{ but no more than } f_{yw}\, h_w\, t_w \big/ \sqrt{3}\ . \qquad (12)$$

Where τ_{cr} is a critical shear stress [4].

Now it is possible to make a conclusion about the necessity of the SLS verification. If the ratio of *load effect* $V_{Ed,SLS}$ to *shear resistance* $V_{Rd,SLS}$ is greater than 1, then the verification for SLS is more important than for ULS.

3.2 Particular case. For particular cases, it is possible to get analytical expression for an answer on this question. Let us have a look at one of the cases.

Flanges contribution is neglected when to determining shear resistance for ULS verifications:

$$V_{Rd,ULS} = V_{bw,Rd} = \chi_w \cdot f_{yw} \cdot h_w \cdot t_w \big/ \sqrt{3}\ . \qquad (13)$$

Partial factor γ_{M1} is assumed to be 1.

Let us consider a non-rigid end post to determine the parameter χ_w and then the values χ_w can be calculated by a following formula:

$$\chi_w = 0{,}83 \big/ \bar{\lambda}_w\ , \qquad (14)$$

Following expression for the shear resistance is obtained:

$$V_{Rd,ULS} = V_{bw,Rd} = 0{,}83 \cdot f_{yw} \cdot h_w \cdot t_w \big/ \left(\bar{\lambda}_w \sqrt{3}\right). \qquad (15)$$

Only a permanent and a variable load are taken into account. Using a load combination (6.10) [1] to determine the design value of *load effect for ULS verifications* and values of the partial factors for action γ_G = 1.35, γ_Q = 1.5 an expression for the characteristic values of loads can be obtained:

$$G_k = V_{bw,Rd} / (1{,}35 + 1{,}5\,\chi / (1 - \chi)); \qquad (16)$$

$$Q_k = \chi\, G_k / (1 - \chi). \qquad (17)$$

A design value of *load effect for ULS verifications* using characteristic load combination can be determined as follows:

$$V_{Ed,SLS} = G_k + Q_k = V_{bw,Rd}\,(1 + \chi / (1 - \chi)) / / (1{,}35 + 1{,}5\,\chi / (1 - \chi)). \qquad (18)$$

For determination of a *shear resistance for SLS verifications* a critical stress, expressed through a slenderness parameter is used:

$$V_{Rd,SLS} = \tau_{cr} \cdot h_w \cdot t_w = 0.762 \cdot f_{yw} \cdot h_w \cdot t_w \big/ \bar{\lambda}_w^{2}\ . \qquad (19)$$

Expressions for the limiting (border) slenderness can be achieved by equating the shear resistance and the design value of load effect:

$$\bar{\lambda}_{w.\lim} = 0{,}180\,\chi + 1{,}627. \qquad (20)$$

When the web slenderness $\bar{\lambda}_w$ is higher than $\bar{\lambda}_{w.\lim}$ the verification in SLS is decisive.

4 Analysis. As can be seen from the above shown procedure the result of analysis depends on a large number of parameters. These parameters can be divided into several groups:

- parameters of the resistance model for ULS verifications (shear resistance of the web $V_{bw,Rd}$ and the shear resistance of flanges $V_{bf,Rd}$, type of end supports for girders and other);
- parameters of the load combination for ULS verifications (type of the load combination, partial factors, number of loads, ratio of variable loads to the total load);
- parameters of the resistance model for SLS verifications;
- parameters of the load combination for SLS verifications (type of the load combination, partial factors, number of loads).

The analysis of SLS verification for the exception of the single web buckling is presented on Fig.1. The analysis of SLS verification for exclusion of multiple web buckling (excessive "breathing" webs) are presented on Fig. 2. Both figures show limiting slenderness when the web slenderness $\bar{\lambda}_w$ is higher than $\bar{\lambda}_{w.\lim}$ the SLS verification is dominant. The effect of the type of end supports is considered for every verification.

The value of the slenderness parameter decreases when accounting flanges shear resistance contribution.

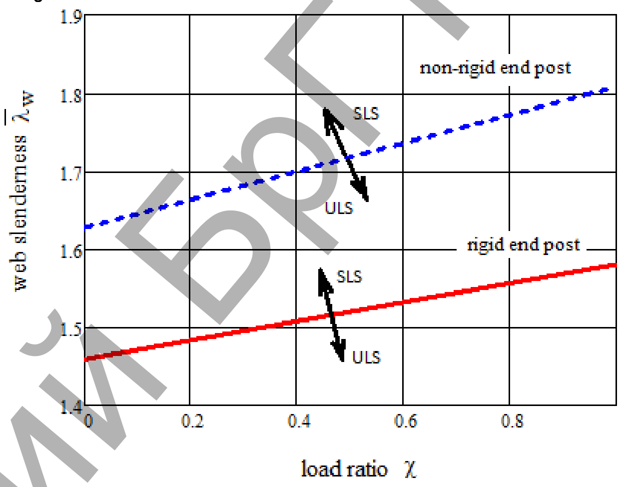

Figure 1. The limiting (border) slenderness for exclusion of single web buckling at ordinary conditions

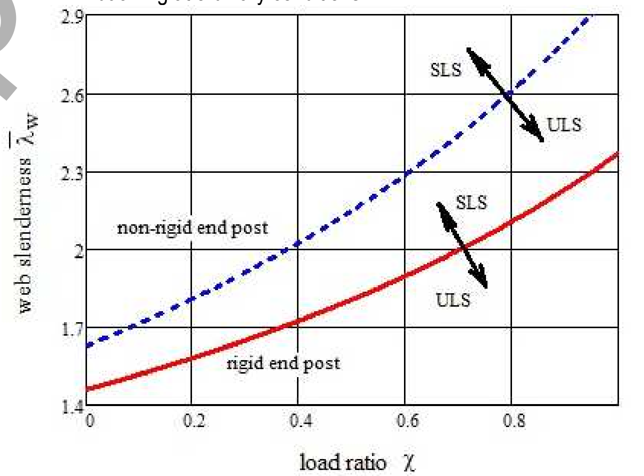

Figure 2. The limiting (border) slenderness for exclusion of multiple web buckling

Similar results have been obtained by varying other parameters. The analysis showed that a type of end supports and the partial factors included in the combination of actions for the SLS verification have the biggest influence on the results of calculations. Otherwise, it was shown that the check of SLS verification taking into account the web buckling may be decisive.

5 Conclusions. This work revealed that SLS verifications for the slenderness above 1.5 approximately are decisive. It is recommended to consider the loss of a local stability (single or multiple shear buckling) as a serviceability limit states.

It is necessary to clarify following issues to use the proposed method of calculation:

- to determine basic load combinations for each verification;

- to specify a value of the critical stress taking into account the features of an element behavior for each verification. For example, when a single web buckling is verified, it can be considered a restraining effect of web in flanges, since a level of stress is elastic;
- to determine values of partial factors.

Only shear resistance models (loss of local stability of the action of shear stresses) are analyzed in this issue, there is a need to extend this technique with the other components (other forms of loss of local stability).

References

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The interaction of some cases ultimate limit state with the serviceability limit states is established. Thereby the single and multiple local buckling of the web are considered as serviceability limit state for checking shear resistance according to Euro code 3 «Design of steel structures». The method for checking shear resistance with the aforementioned serviceability limit state is developed and the sphere of application of these checking is proved. A general procedure for determining the necessity of the serviceability limit states associated with the loss of local stability is described. The necessity of the serviceability limit states in determining the shear resistance of steel elements is analyzed. It is shown that the limit state of serviceability, the corresponding local buckling of the web due to shear stresses can be reached before the ultimate limit state. The conclusions of the necessity of the further researching into the improvement of the engineering design method of shear resistance.