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Application of High Strength Steels of Class S 60 to Long Span Highway and Railway Bridges

Application de l'acier à haute résistance, de classe 60, aux ponts-route et ponts de chemin de fer de grande portée

Anwendung hochfester Stähle S 60 in weitgespannten Strassen- und Eisenbahnbrücken

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1. General

There is a good number of theoretical, technological and constructive problems to be solved in connection with the application of high-strength steels in bridges. Special attention should be paid to the investigation of steels supplied by industry, to establishment of design specifications for them and development of technology of structures manufacture (including welding).

Consideration of analysis, design and practical application of high-strength steels in bridges are presented below.

The class of steel is being established according to a rated value of conditional yield stress $\sigma_{0,2}$ in kgf/mm^2. Thus, for example, yield stress of class S 60 steel is $\sigma_{0,2} \geqslant 60$ kgs/mm^2.

2. General Designing Specifications

The accepted in the USSR limit design method provides the satisfaction of the following inequality

$$S_{max} \leqslant \Phi_{min}$$

Here S_{max} - is maximum probable force in element; $S_{max} = \sum S_{i,2} n_i \xi$;
Φ_{min} - is minimum bearing capacity of element equal to $\frac{cm}{K_H}$ FR - when its strength is analysed; $\frac{\gamma cm}{K_H}$ RF - when fatigue strength is analysed; $\frac{\varphi m}{K_H}$ RF - when overall stability is analysed.

The values of design resistance R for steels of S 40, S 50 and S 60 classes are respectively equal to 3200, 3800 and 4350 kgf/cm^2.

a) Strength analyses are made on the basis of the criterion, proposed by the authors /1/, i.e. limited residual plastic strain $\varepsilon_{P_1 max} \leqslant 0{,}0025$.

The new methods, allowing estimation of strainstress state of complex systems, were developed by the authors on the basis of strain plasticity theory.

For example, the strength of bending element is calculated from the formula

$$M_{max} \leqslant \frac{cm}{K_H} W_{nt} R .$$

For box element with two axes of symmetry C is obtained from the formula

$$C = \frac{1-\theta}{K_\sigma} + \theta \frac{3+6\alpha - K_\sigma^2}{2+6\alpha},$$

where $K_\sigma = \frac{1}{1+\frac{E}{\theta\sigma_s}\varepsilon_{P_1 max}}$.

The corresponding formulas are derived for the case of compound bending when shearing stresses are taken into account.

The value of rasidual strain $\varepsilon_{P_1 i}$ for strength analysis of sections providing local stability of section elements is obtained from the formula (fig.1)

$$\varepsilon_{P_1 i} = \varepsilon_{cr,i} - \frac{\sigma_{cr,i}}{E}.$$

b) Fatigue strength analysis /2/ is made for rated service loads by the following formulas

- under tension and compression $N_r \leqslant \frac{\gamma m}{K_H} FR$;
- under bending in one of main planes $M_r \leqslant \frac{\gamma c'' m}{K_H} W_{nt}R$, etc.

The factors of design resistance reduction γ of elements base metal and of the metal o f their joints (welds, rivets, high-strength bolts) are derived from the formula

$$\gamma = \frac{1}{(a\beta+b)-(a\beta-b)\rho} \leqslant 1.$$

The values of parameters "a" and "b" for steels of different classes are: for S 40–a=0,74; b=0,18; for S 50–a=0,84; b=0,23; for S 60–a=1,00; b=0,24.

c)Overall stability analysis of axially compressed bars is made by the formula

$$N_{max} \leqslant \frac{\varphi m}{K_H} F_{Br}R.$$

The buckling factors φ for steel S 60 are calculated in respect with initial imperfections, and the factor φ^* – for welded and wide flange rolled elements of H-section and in respect with residual stresses (table 1).

Table 1

λ	φ	φ^*	λ	φ	φ^*	λ	φ	φ^*
0	0,93	0,93	70	0,49	0,46	140	0,14	0,13
10	0,92	0,92	80	0,40	0,36	150	0,12	0,12
20	0,89	0,89	90	0,32	0,28	160	0,11	0,11
30	0,86	0,86	100	0,25	0,22	170	0,09	0,09
40	0,76	0,75	110	0,21	0,19	180	0,08	0,08
50	0,67	0,65	120	0,18	0,17	190	0,08	0,08
60	0,58	0,56	130	0,16	0,15	200	0,07	0,07

The value of φ for steel of lower classes may be calculated on the basis of conventional flexibility

$$\lambda_1 = \lambda\sqrt{\frac{\sigma_{s,1}}{\sigma_{S,60}}} .$$

A method accounting for values of φ for axially compressed bars is proposed for bending and torsional analysis /3/.

d) Local stability analysis of plate elements is obtained from the formula

$$\sigma_{i_{max}} \leqslant \frac{1}{m^* K_H} \sigma_{cr},$$

where σ_{cr} for isotropic plates is derived by generally known methods, and for elastic plastic stage - by Ilyushin - Stowell theory.

The factor m^* is determined from the expression

$$m^* = \bar{\alpha} + \frac{\bar{\beta}}{(\sigma_S - \sigma_\pi)^2} (\sigma_{cr} - \sigma_\pi)^2,$$

where $\bar{\alpha}$ and $\bar{\beta}$ for welded structures from steel S 60 are equal to 1.1 and 0.28. For steels of other classes

$$\bar{\beta} = \frac{\sigma_s}{R} - 1.1 .$$

The safety factor K_H is equal to 1.0 for webs of girders being bent and to 1.1 for compression chord of a box girder.

Critical compressive stress in a box girder chord may be derived from the formula, developed by the author on the basis of anisotropic plates theory using Shenly's conception

$$\sigma_{cr} = \min \frac{\pi^2}{B^2 \delta_x'} \varphi_s \left(\gamma' \mathcal{D}_x \frac{1}{\lambda^2} + \mathcal{D}_y \lambda^2 + 2\mathcal{D}_{xy}\right),$$

where $\gamma' = \frac{3}{4}\frac{\varphi_t}{\varphi_s} + \frac{1}{4}$; $\lambda = \frac{A}{mB}$;

m - is a number of semi-waves which should be varied.

It is necessary that local stability of stiffeners and a plate in a compression chord and berides the stability of longitudinal stiffeners under bending and torsion should be determined.

The specifications of the USSR don't allow the performance of plate elements of bridges in a post critical stage.

The moment of inertia of a cross girder of compression chord of a box girder is determined proceeding from the equality between the free length of longitudinal ribs and the distance between cross girders by the value of critical stress of longitudinal ribs σ_{cr}.

This relationship may be written in the following form

$$J_{cr} = 2\left(\frac{\pi}{\alpha}\right)^4 \left(\frac{B}{A}\right)^3 \frac{\sigma_{cr}}{\sigma_{cr}^*} \cdot \frac{B}{b_0} \pi^2 J_{lng} \left(1 + \cos\frac{\pi}{K}\right),$$

where α - is factor of restraint of a cross girder ($\alpha = \pi$ in the case of hinged bearing);

b_0 - is distance between longitudinal ribs;

K - is a number of longitudinal ribs spans on the section of compression chord;

σ_{cr}^* - is critical stress of longitudinal ribs in the case of inlimited elasticity.

e) Linear and corner girders displacements in an elastic-plastic stage is obtained from the formula

$$W = \int \varkappa(x) M_i(x)\, dx,$$

where $\mathcal{X}(x)$ - is curvature of girder axis from prescribed load M;

M_1 - is bending moment from the corresponding single force.

Within the strain theory of plasticity and the method of analysis in elastic stage the general relationship between curvature and bending moment may be written as

$$\mathcal{X}(x) = \frac{M + \Delta M'}{EJ\psi_{\mu}'},$$

where

$$\psi_{\mu}' = \frac{1}{J}\int_F \frac{y^2}{1 + \frac{\omega\varepsilon_p}{\varepsilon_s}}\, dF; \Delta M' = \sigma_s(1-\omega)\int_F \frac{\varepsilon_p y}{\varepsilon_s + \omega\varepsilon_p}\, dF; \omega = \frac{\varepsilon_{p,1}}{\varepsilon_p};$$

$\varepsilon_{p,1}$ - is a part of residual plastic strain, changing elasticity parameters.

The given relationship reflects a combined method /4/ of plasticity theory for the case of validity of Prandtle diagram.

The method of additional loads by A.A.Ilyushin is valid when $\omega = 0$, while the method of variable parameters of elasticity by by I.A.Birger is valid when $\omega = 1$.

3. The Results of Trial Designing

Trial designing of three steel bridges was carried out to show up the effectiveness of the use of high-strength steels.

Bridge 1 - a railway continuous truss bridge with a composite action of the deck (spans are of 132 + 154 + 132 m size). Truss depth is 15 m, panel length is 11 m, the deck is analysed by the procedure /6/.

Bridge 2 - highway box-girder bridge with steel orthotropic deck (spans are of 90 + 3 x 148 + 90 m size). There are two boxes of 3.6 m depth in a cross section.

Bridge 3 - highway box girder bridge with concrete deck. There are two boxes of 3.6 m depth in a cross section.

The weight of metal for spans made of different steel classes is given in Table 2. Steels of class S 50 and S 60 were used for the most loaded elements.

Table 2

Bridge span	Steel class of the most loaded elements		
	S 40	S 50	S 60
N 1	100%	98%	94%
N 2	100%	95%	94%
N 3	100%	-	80%

The efficiency of high-strength steel used for spans of bridge 1 has been found to be lower than predicted because of the same sections sizez of box welded elements (depth, width). In this case however, available templates may be used in the process of manufacture.

Reduction of metal weight for spansof bridges 2 and 3 results from shortening of horizontal plates thickness. Here essential reduction of metal consumption is achieved in composite spans where high-strength steel should be used in the first place.

4. Constructed Bridges Examples

a) Highway stiffened bridge with flexible arch (fig.2). The arches (2) are of constant H-section along the whole length. Horizontal plates are of 530 x 32 mm size, while vertical oues are of 1120 x 50 mm. Arches are manufactured from steel of class S 50.

Continuous stiffening girder consist of four main web girders of 2,5 m depth. The bridge deck consist of a reinforced concrete slab (concrete - M400) with a composite action of beams. Beams are made from steel S 35.

Weldel structures were connected by high-strength bolts during the erection.

Metal consumption per 1 m^2 of the deck in a main spen is 365 kg/m^2, of approach spans - 201 kg/m^2; concrete consumption 0,16 m^3/m^2.

b) All-welded highway box-girder orthotropic tied bridge (fig.3). Steel of class S 60 is used for lower chords of box-girders. Other elements were manufactured from steel of class S 35. Steel consumption was 320 kg/m^2.

c) Composite steel welded deck with spans of 81 + 135 + 81 m (fig.4).

The span in its cross section has two boxes, connected by reinforced concrete slab (concrete M500). Steel members of the span were supposed to be manufactured from steel of class S 40, but practically a metalurgical plant delivered steel as strong as steel of class S 60. The thickness of webs varied from 14 to 32 mm, while the thickness of horizontal plates achieved 40 mm.

The consumption of rolled steel reached 285 kg/m^2, and reinforced concrete - 0,32 m^3/m^2.

Conclusion

The application of high-strength steels of classes higher than class S 40 in bridges may result in essential technical-economical effect provided the development of new design approaches to spans.

Though the considered above examples represent highly modern structures and progressive methods have been used for their analysis (including three - dimentional analysis method), the application of steels of classes S 50 and S 60 hasn't appeared to bring sufficient effect.

The use of high-strength steels has been found to be the most effective for tensile and compression members in the case of small values of flexibility.

These steels are not effective for members under vibration load, as the increase of fatigue limit falls behind strength growth.

High frost-resisting property of steels under review should be mentioned as positive.

Notation

S_{ir} - force in member from rated load i;
n_i - overload factor of load i;
ξ - factor of loads combination;
c - factor of conditional increase of design resistance as a result of plastic strains;

m - service factor of member;
R - design resistance;
F - design geometrical parameter of section;
K_H - factor ofsafety (equal to 1.1 when studying structure failure);
γ - fatigue ratio;
C'' - fatigue factor with regard to gradient of stresses (in the case of bending in one plane C'' = 1.05; skew bending C''_{max} = 1.25);
φ - factor of longitudinal bending;
W_{nt} - effective section resistance (netto);
E - Joung's modulus;
E' - modulus of strain hardening;
$\theta = 1 - \frac{E'}{E}$ - parameter of weakening (fig.1);
$\alpha = \frac{\Sigma F_p}{\Sigma F_w}$ (ΣF_p - total area of flanges; ΣF_w - total area of box webs);
σ_s - yield point;
ε_p - residual plastic strain;
ε_{cr} - critical value of strain;
σ_{cr} - critical stress;
F_{nt} - area of effective cross section (netto);
β - effective factor of stresses concentration;
$\rho = \frac{\sigma_{min}}{\sigma_{max}}$ - factor of asymmetry of variable stresses cycle;
λ - flexibility of bar;
σ_{pc} - limit of proportionality;
σ_i - intensity of stresses from design loads;
δ'_x - reduced depth of anisotropic plate;
B and A - width and length of anisotropic plate;
$\varphi_s = \frac{E_s}{E}$ - relative value of secant modules;
$\varphi_t = \frac{E_t}{E}$ - relative value of tangent modulus;
J_{lng} - moment of inertia of longitudinal rib;
J_{cr} - moment of inertia of cross rib.

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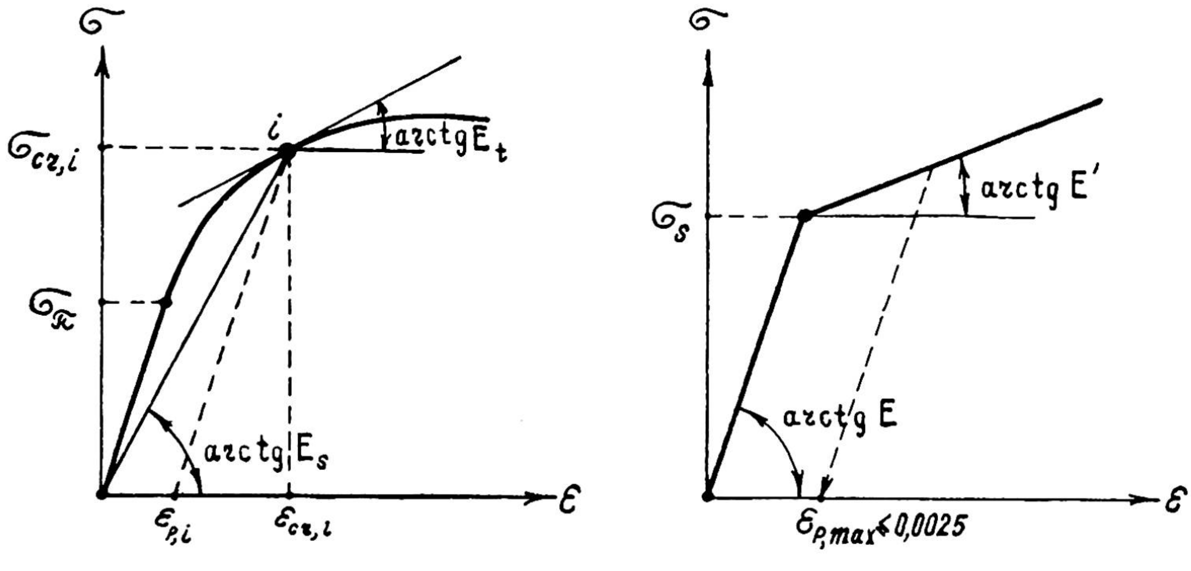

Fig. 1

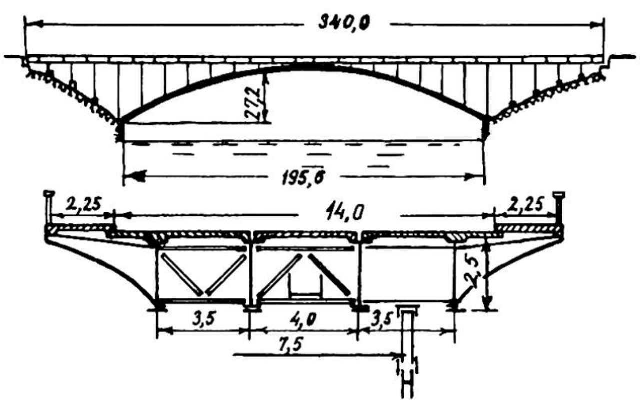

Fig. 2

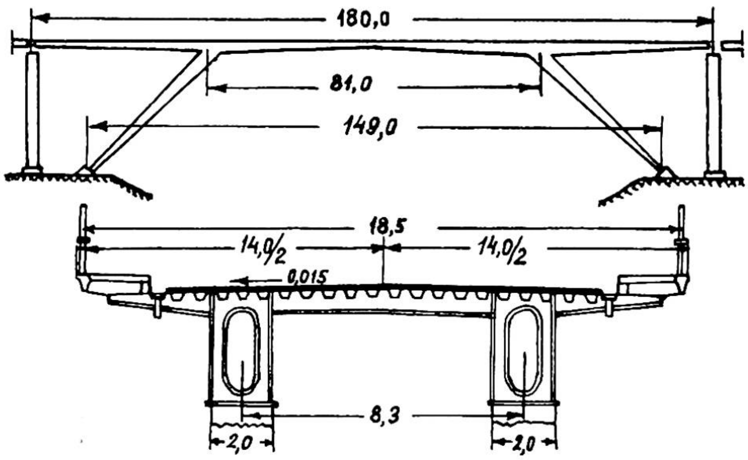

Fig. 3

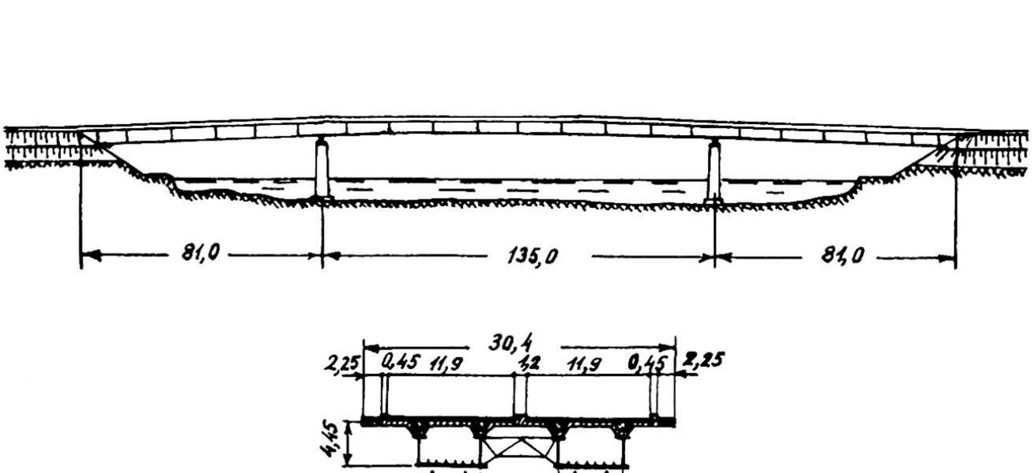

Fig. 4

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SUMMARY

The problems of effectiveness of high-strength steel application on bridges are analysed on the basis of specifications developed by the authors and used in the process of trial designing. The examples of constructed bridges are presented. The conclusion is drawn that research should be directed to development of new structural forms to make application of steels highly effective.

RESUME

On traite des questions de l'emploi efficace d'aciers à haute résistance pour les ponts sur la base de spécifications élaborées par les auteurs. Des exemples de ponts réalisés sont présentés. On conclut qu'il est nécessaire de rechercher de nouvelles formes de construction pour mieux utiliser les qualités des aciers à haute résistance.

ZUSAMMENFASSUNG

Die Probleme der wirkungsvollen Anwendung hochfester Stähle im Brückenbau werden aufgrund der vom Verfasser erarbeiteten Vorschriften und Berechnungsmethoden untersucht. Es werden Beispiele ausgeführter Brückenbauten vorgeführt. Man schliesst daraus, dass die wirkungsvolle Anwendung hochfester Stähle das Suchen nach neuen gestalterischen Formen im Brückenbau erfordert.