Rational cross-sectional design and behavioural analysis of the low-sag stressed ribbon pedestrian bridges

V. Kleinas

1 Introduction

Stress ribbon bridges represent one of the most elegant redundant bridge constructions used in modern lightweight pedestrian bridges [1], [2], [3], [4], [7]. These structures are environmentally friendly in their construction techniques and very rational under favourable geological conditions [1], [4]. Geometrically nonlinear behaviour of stressed ribbon structures greatly influenced by initial inclinations, cross-sectional stiffness and structural weight [1], [2], [4], [9].

In the recent years different mechanical and hydraulic dampers have been used for flexible and lightweight stress ribbon designs to prevent the unwanted oscillations and vibrations [17], [18], [19], [20], [21], [22], [23].

Bending stiffness can be effectively used to stabilise lightweight steel suspension bridges [5], [6], [10], [11], [12], [13], [14], [15].

The cross-sectional structure and construction technology of stress ribbon structures are very appropriate for using the new composite materials [24], [25], [26], [27].

The practical use of structures is directly related to the walking part longitudinal incline limitations, which are usually defined by normative technical documentation and the requirements for people with disabilities. The longitudinal slope to the bridge (i) is limited by 3-12.5% incline in different design conditions [4]. In urban areas with mixed traffic, the pedestrian bridge longitudinal slope (i) usually limited by 4% incline.

It is essential to choose a rational geometric shape, and the load-bearing element's cross-section composing a digital computational scheme for geometrically nonlinear behaviour stressed ribbon structures. The article presents methodology for selecting the low-sag bearing element's rational cross-section and geometry parameters, taking into account the suspension bridge's required rigidity k. The paper defines the approximate limits of application of stressed ribbon bridges of various weights and stiffness. The structure's behaviour in asymmetrical loads is discussed, and recommendations for selecting the saddle-support geometry are given. The reinforced concrete deck's stiffness was not evaluated in the studies (only the mass of concrete deck and rigidity of load-bearing elements).

2 Geometry and physical parameters

The geometric scheme of the stress ribbon bridge bearing component in Figure 1:

- $L_s$ – length of the span;
- $L_b$ – length of the saddle;
- $L_{anch.1}$ – anchorage length;
- $L_1$ – length of the edge of the saddle;
- $R_b$ – radius of the edge of the saddle;
- $T$ – axial force of the load-bearing element;
- $h_s$ – height difference between supports;
- $f_s$ – sag under permanent load;
- $\alpha_v, \beta, \beta_b$ – angles of structural geometry;
- $\sigma_{max}, \sigma_N$ – normal stresses in the saddle and span zones;
- $B, b_v, b_2$ – geometrical parameters of the deck;
- $B_t, b_t, t_1$ – geometrical parameters of load-bearing sheets;
- $A_t$ – cross-sectional area of the bearing cables or sheets;
- $t_c$ – thickness of the concrete slab;
- $\gamma$ – ratio of variable and constant loads ($v_k/g_k$).
The stress ribbon bridges' behaviour greatly influenced by the structure's dead weight (permanent load). Bridges with more massive decks are more resistant to asymmetrical loads but have significantly higher axial forces in the load-bearing elements. The article analyses the cross-sections of lightweight (a) and classical-ly structured (b, c) stress ribbon bridges. Variable and constant load ratio values \( \beta \) from 0.43 to 2.26. The effect of the live human load in the calculations estimated by the load of 5 kPa.

Bridge cross-sectional parameters and loads are shown in Table 1 – the bearing element materials' physical characteristics provided in Table 2.

- \( i \) – the most extensive longitudinal slope of the bridge deck (\( \beta \), %);
- 1 – steel sheet;
- 2 – sheets of steel or composite material;
- 3 – steel cables;
- 4 – reinforced concrete deck slab.

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Bridge cross-sectional parameters and loads are shown in Table 1 – the bearing element materials' physical characteristics provided in Table 2.

Before calculating the cross-sectional area of the load-bearing element, a permanent deck load must be selected, which is characterized by \( t_0 \). This load also includes the weight of the bearing element. After the required area of the bearing element selected (Equ. 11) the actual deck's plate thickness \( t_C \) can be calculated by subtracting the load-bearing element's weight (Equ. 12).

### Table 1. Bridge cross-sectional parameters and loads

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>( (B, B) / 2, m )</th>
<th>( b_2 / 2, m )</th>
<th>( t_r ), mm</th>
<th>( t_C ), mm</th>
<th>( g_k ), kN/m</th>
<th>( v_k ), kN/m</th>
<th>( \gamma = v_k / g_k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2.3</td>
<td>2.0</td>
<td>20</td>
<td>-</td>
<td>3,539</td>
<td>10</td>
<td>2.83</td>
</tr>
<tr>
<td>b, c</td>
<td></td>
<td></td>
<td>20</td>
<td>50</td>
<td>3,539</td>
<td>10</td>
<td>2.83</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>200</td>
<td>8,847</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>300</td>
<td>11.50</td>
<td>0.58</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>400</td>
<td>17.25</td>
<td>0.43</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2. Types of load-bearing elements and physical parameters of materials

<table>
<thead>
<tr>
<th>Cross-section</th>
<th>Load-bearing element type</th>
<th>Modulus of elasticity ( E ), GPa</th>
<th>Material density ( \rho ), kN/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Steel sheet</td>
<td>210</td>
<td>76.93</td>
</tr>
<tr>
<td>b, c</td>
<td>Steel sheet</td>
<td>210</td>
<td>76.93</td>
</tr>
<tr>
<td></td>
<td>Carbon fibre sheet</td>
<td>250</td>
<td>76.93</td>
</tr>
<tr>
<td></td>
<td>Steel cable</td>
<td>195</td>
<td>76.93</td>
</tr>
<tr>
<td></td>
<td>Reinforced concrete deck</td>
<td>-</td>
<td>25.00</td>
</tr>
</tbody>
</table>

The rational cross-sectional area of the load-bearing element

The axial forces in the load-bearing suspension element should be calculated based on the installation technology, the load-bearing element’s material (steel cables or sheets, composite materials), the deck structure's cross-section, etc. It is essential to know the load-bearing element's displacements at each construction stage, assessing the construction and installation work technology and temperature effects.

The behaviour of the suspension structure is geometrically nonlinear. It is necessary to calculate the geometry's definition under permanent load and determine the cross-sectional area to model a numerical model of a computational scheme that would ensure an element's design definition and displacements. By selecting the bearing element’s cross-sectional area, the computatio-
The digital model’s calculation scheme’s geometric parameters are commended by selecting the digital model’s calculation scheme.

The support height difference (1):

\[ h_s = \frac{\tan(\beta_0) \cdot f_v}{2} \]

The sag under constant characteristic load (4):

\[ f_{vk} = \frac{\tan(\beta_0) \cdot f_v}{d} \]

The axial force of the element under constant characteristic load (5):

\[ T_{vk} = \frac{E \cdot S_g \cdot \cos(\beta_0)}{8} \cdot L_v \cdot \frac{\sin(\beta_0)}{\cos(\beta_0)} + \frac{f_v}{f_v} \]

The geometric length of the suspension element under constant characteristic load (6):

\[ S_g = L_v \cdot \left[ \frac{1}{\cos(\beta_0)} \right] \]

The displacement under characteristic variable load (7):

\[ \Delta f_0 = \frac{L_n}{10} \]

Where: \( k \) – the sag coefficient is selected based on the required rigidity of the structure.

The sag under constant and variable characteristic loads (8):

\[ f_{v0k} = f_{vk} + \Delta f_0 \]

The axial force of the suspension element under constant and variable characteristic loads (9):

\[ T_{v0} = \frac{E \cdot S_g \cdot \cos(\beta_0)}{8} \cdot f_{v0k} \]

The geometric length of the element under constant and variable characteristic load (10):

\[ S_{v0} = L_v \cdot \left[ \frac{1}{\cos(\beta_0)} \right] \]

The cross-sectional area of the load-bearing element (11):

\[ A_{c,load} = \frac{1}{E} \cdot \frac{\tau_{v0}}{\beta_0} \cdot \left( \frac{\tau_{v0} \cdot \tau_{v0}}{\beta_0} \right) \cdot \frac{S_{v0}}{S_{v0}} \]

Where: \( E \) – the modulus of elasticity.

The actual thickness of the deck slab based on the assessment of the weight of the load-bearing element (12):

\[ t_0 = \frac{2 \cdot \rho_{v0} \cdot A_{c,load} \cdot \rho_s}{B \cdot \beta_0} \]

Where: \( \rho_{v0} \), \( \rho_s \) – the load-bearing element and the deck plate material densities.

The average axial stresses of the suspension element cross-section under constant and full (permanent and live) loads (13):
The calculated strength of the load-bearing element material can be calculated as follows (14):

\[
f_{w,d} = \frac{f_k}{\gamma_f}
\]

where:
- \(f_{w,d}\) – the characteristic value of the strength of the material according to the yield strength or relative yield point;  
- \(\gamma_f\) – load reliability coefficient, recommended value 1.35; 

The structure displacements depend directly on the cross-sectional area. The cross-sectional area of the suspension element must be selected according to the characteristic loads. The load reliability coefficient must increase the characteristic stresses \(\gamma_f\) to ensure the ultimate limit state.

The cross-sectional area selected according to the required stiffness \(k\) and modulus of elasticity of the structure. The material's strength should be chosen according to the minimum radius of the saddle's edge. The minimal radius of the saddle's edge of the rectangular load-bearing element can be calculated according to the following formula (15):

\[
r_{k,min} = \frac{E \cdot \gamma_f}{\left(\frac{f_{w,d}}{f_k} - \sigma_{y,c}\right)}
\]

The stresses of the load-bearing element subject to the calculation can be calculated according to the following formula (16):

\[
\sigma_{y,c} = \gamma_s \cdot \sigma_{y,c} + \gamma_s \cdot \sigma_{y,c} + \gamma_k \cdot \sigma_{y,c} + \left|\sigma_{y,c}\right|
\]

Where:
- \(f_k\) – the characteristic normative strength of the material according to the yield strength or relative yield point;  
- \(\gamma_s\) – load reliability coefficient, recommended value 1.35;  
- \(\gamma_k = 1 - \frac{\sigma_{y,c}}{\sigma_{y,c}}\) \(\sigma_{y,c}\) = 0.1 ... 0.25 – coefficient estimating the effects of bending during asymmetrical longitudinal loading, depending on the sag coefficient \(k\) (Table 4);  
- \(\sigma_{y,c}\) – combined stresses of the load-bearing cross-section caused by axial and bending effects;  
- \(\sigma_{y,c}\) – design stresses of the load-bearing cross-section caused by the effect of negative temperature.

Fatigue processes should be considered in the selection of the material and strength of the load-bearing element, taking into account the effects of temperature and humidity in case of reinforcement with CFRP [30].

The methodology can be applied in the case of various longitudinal slopes (Table 3). The results obtained using methodology and geometric nonlinear numerical analysis [28] (applied the Newton – Raphson iteration method) practically coincide (Table 5).

The minimal saddle's edge radius depends directly on the thickness of the load-bearing element. A rational solution is to apply thin elements or to have a sufficient calculated margin of load-bearing stresses – use high strength materials.

## 3 Lightweight deck cross-sectional analysis

Chapters describe the approximate application limits of a single span lightweight stress ribbon structure (Fig. 1a)). The calculation scheme of the research presented in Figure 2. The research performed using the methodology presented in Chapter 2. The cross-section of the structure is shown in Figure 1a).

The cross-section of the load-bearing steel sheet deck without additional permanent loads applied during the analysis. The calculations made by limiting the load-bearing sheet's thickness under the condition: 20 mm < \(t_f\) < 50 mm.

The lightweight deck will always require a relatively large cross-sectional area for the load-bearing element, primarily to ensure greater rigidity of the structure. Due to the large cross-sec-

### Table 4. Dependence of bending stresses by varying stiffness of structure in case of longitudinal asymmetric loading

<table>
<thead>
<tr>
<th>k</th>
<th>250</th>
<th>365</th>
<th>485</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\gamma_f)</td>
<td>0.19</td>
<td>0.13</td>
<td>0.11</td>
</tr>
</tbody>
</table>

### Table 5. Comparison of methodology and numerical analysis results

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Geometrically nonlinear numerical analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Symmetric</td>
</tr>
<tr>
<td></td>
<td>L_v</td>
</tr>
<tr>
<td></td>
<td>m</td>
</tr>
<tr>
<td>k = 250, (\gamma = 0.87 ) (t_f = 200) mm</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td>k = 365, (\gamma = 0.58 ) (t_f = 300) mm</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td>k = 485, (\gamma = 0.43 ) (t_f = 400) mm</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
</tbody>
</table>
on area, the lightweight deck’s load-bearing elements are subject to low stresses that make the standard construction steel suitable for this construction type (Figure 7).

4 Medium-size and heavy deck cross-sectional analysis

Chapters describe the approximate application limits of a single span stress ribbon structure (Fig. 1b)). The calculation scheme of the research presented in Figure 2. The research performed using the methodology presented in Chapter 2. A steel sheet was bearing element chosen for the research.

The calculations were made by limiting the decks’ geometry under the condition:

$t_\text{L} < 60 \text{ mm}, \ b_\text{L} < 1 \ 200 \text{ mm}; \ t_\text{C} > 100 \text{ mm}.$

The permanent load growth can effectively increase the rigidity of the structure. Heavier decking (Fig. 1b), (c)) reduces the effect of the variable load. Chapter 2 presents the methodology based on the structural stiffness condition. The stiffness $k$ of the methodology’s structure is a constant value, which does not depend on the materials’ properties. As the bearing element change’s material properties (E), the cross-section geometry is changing, but the stresses and displacements remain the same.

Therefore, a rational cross-sectional area of the load-bearing elements can be selected by increasing the permanent load based on the strength of bearing element’s material (Figure 12) and its rigidity (Figure 11). In case of the application of the medium-size and heavy deck cross-section of low-sag stressed steel ribbon constructions could be applied to large spans (Figure 8, Figure 9, Figure 10).

Fig. 12 shows that the design stiffness $k$ can determine the load-bearing element material has required strength for the selected constant load. Figure 11, 12 shows that for each case of the permanent load, the load-bearing element’s material strength should be maximised to reduce the stress difference between the full and permanent loads, thereby reducing the elastic deformations of the structure under variable loads. The load-bearing elements of the medium-size and heavy decking are subject to high stresses which make the high-strength cables or composite materials suitable for this type of constructions.

Fig. 13 presents the dependence of the axial forces of the load-bearing elements on the span by applying different sag coefficients $k$, and at the same time using different values of the constant load. The figure shows that the axial forces of low deformability cross-sections (heavy deck) are approximately 50% higher...
than in lightweight and medium-weight structures. It is necessary to define the conditions of the ultimate and serviceability limit state of structure for each design situation to design rational load-bearing structures.

5 The behavioural analysis of the load-bearing elements

The bearing elements' geometric definition and the cross-sectional parameters are selected according to formulas (1)–(14). The geometrically nonlinear analysis performed for 30 and 50 m long spans. The Midas Civil finite element program used for numerical analysis using the Newton-Raphson iteration method [28] – concrete deck’s rigidity not assessed in the model.

A simplified spatial cross-section model of type (b) used in the calculations (Fig. 1). The model loads are given in Table 1 – the calculation scheme of the research presented in Figure 2. Rectangular cross-sections with a thickness of 60 mm and modulus of elasticity of 195 GPa for the load-bearing elements were applied. The load-bearing elements connected by the „elastic link“ rigid joints (Fig. 13).

Where:
- \( L_v \) – span; ~ cross-section area according to (11);
- \( \sigma_x, \sigma_y \) – cross-section axial stresses according to (13);
- \( \Delta f \) – the displacement under characteristic variable load;
– Load 01 – full asymmetric load distributed on one side of the span \( L_s \);
– Load 02 – full asymmetric load distributed on one side of the cross-sectional width \( b_1 \) (Fig. 1) along the span.
– \( \sigma_{g1}, \sigma_{g2} \) – normal cross-sectional stresses under Load 02 on load-bearing elements which are on different sides of the bridge cross-section (Figure 18, Figure 19);
– \( \sigma_{b} \) – normal stress resulting from moment \( M_y \) about the element’s local y-axis;
– \( \sigma_{\text{comb}} \) – combined stress \( (\sigma_{ax} \pm \sigma_{by} \pm \sigma_{by} \pm \sigma_{ax}(\text{warping})) \).

Fig. 12. The effect of constant load on the stresses of the cross-section
Source: V. Kleinas
Bild 12. Auswirkung einer konstanten Belastung auf die Spannungen des Querschnitts Abb.: V. Kleinas

Fig. 13. The effect of constant load on the axial force of the cross-section
Source: V. Kleinas
Bild 13. Auswirkung einer konstanten Belastung auf die Axialkraft des Querschnitts Abb.: V. Kleinas

Figure 14, Figure 15, Figure 16, Figure 17 and Figure 18 show a 30 m length span bridge’s behaviour when \( k = 250, \gamma = 0.87 \). It is evident that the cross-sectional area of the load-bearing element makes the axial stiffness sufficient to manage asymmetric loads (Load 01) – the element displacements do not exceed \( \Delta_f \). Also, under asymmetrical load (Load 1) the cross-sections of the load-bearing elements are not deformed more than in the case of symmetrical loads. Low-sag structures are not sensitive to this effect.

The asymmetrical load (Load 02) is the most dangerous one. Under such load, the bridge’s cross-section will twist and may not meet the requirements set forth for the serviceability limit state. Non-identical displacements of two load-bearing elements result in bending moments in cross-sections (Fig. 15). As the number of joints between the load-bearing elements increases, the bending effects decrease, so it is rational to evaluate these effects based on the number of joints of the deck elements and the support conditions.

The bending and torsional effects on the main load-bearing elements can be reduced by incorporating the deck’s stiffness into the overall load-bearing cross-section. It can be done by securing the deck elements to support and stress them by tensioning the technological cables. In this case, it will be necessary to assess the bending and rotating effects on the rigid deck [1], [2].

The cross-sectional twists in the central part of the span given in Figure 19 and Figure 20. In the presented graphs, the effect of the bridge deck weight on the cross-sectional displacements is visible \( (g/g_v \gamma) \). The appropriate deck’s stiffness should be designed to minimise the cross-sectional twists in the bridge’s central part.

6 Recommendations

Stressed ribbon bridges are very durable. The structure does not have support bearings or expansion joints, which often require constant maintenance during operation, and if not maintained – damages the structures. The appropriate materials should be selected, and the construction of assemblies should ensure conditions resistant to adverse effects to design durable structures.

At the beginning of the bridge’s geometry and cross-sectional composition, the suspension part’s desired stiffness \( k \) must be selected. The stiffness coefficient \( k \) defines the maximum incline of the suspension part under the variable vertical load. The higher this factor, the more rigid the suspension structure. Low-sag suspension elements applied to bridges are not sensitive to asymme-
tric loads distributed on one side of the span \( L_v \). The suspension elements’ displacements in the quarters of the span never exceed the limits defined by the stiffness coefficient \( k \).

The structures of the lightweight deck are susceptible to longitudinal asymmetric variable loads. Various structural cross-sectional solutions can increase the stiffness of the suspension part of the bridge:

- providing additional tension force to the bearing element;
- using additional technological cables (Figure 21 e.1);
- giving stiffness to the bearing element (Fig. 21 e.2, e.3);
- applying high modulus of elasticity, strength and low sensitivity to temperature composite materials and designing cross-section of the deck with required stiffness from lightweight reinforced concrete. It is rational to compress the deck’s cross-section with external technological cables protected from weather effects. These cables can always be maintained and replaced during bridge repairs (Fig. 21 e.4).

The various calculation methods of post-stressing the reinforced concrete deck, taking into account the effects of installation and the environment, are described in detail in [1],[2].
Modern technologies allow the production of steel, concrete and composite materials of various strengths. The construction is very favourable for applying high-strength composite materials. Sleek shapes, open surfaces of supports saddles allow for high-quality fastening, gluing and protecting bearing sheets made of composite materials.

The cross-sectional area of high-strength steel cables or composite material sheets can be calculated as follows (Fig. 1b), c)): 1. Freely selectable stiffness coefficient $k$, according to Figure 11. schedule.

2. Freely selectable constant concrete load thickness $t_0$. The larger this thickness, the smaller the area of the load-bearing element can be selected.

3. Knowing the constant load, calculate $A_{L,\text{min}}$ according to formula (11). Knowing the cross-sectional area, select the required sheet or cross-sectional cable parameters.

4. Calculate the concrete slab's actual thickness by estimating the load-bearing element's weight, according to formula (12).

5. The load-bearing element material's strength is selected by evaluating the bending stresses in the saddle zone (Formula 17).

Fig. 17. The diagram of the axial forces. Asymmetric load Load 02. $N_{\text{min}} = 8700 \text{ kN}$, $N_{\text{max}} = 8906 \text{ kN}$ Source: V. Kleinas

Bild 17.Diagramm der Axialkräfte. Asymmetrische Last Last 02. $N_{\text{min}} = 8700 \text{ kN}$, $N_{\text{max}} = 8906 \text{ kN}$ Abb.: V. Kleinas

Fig. 18. The diagram of the transverse forces. Asymmetric load Load 02: a) $F_y$, b) $F_z$ Source: V. Kleinas

Bild 18. Diagramm der Querkräfte. Asymmetrische Last Last 02: a) $F_y$, b) $F_z$ Abb.: V. Kleinas

Fig. 19. Cross-section twists in the centre of a 30 m long bridge. Asymmetric load, Load 02 Source: V. Kleinas

Bild 19. Querschnittsverdrehungen in der Mitte einer 30 m langen Brücke. Asymmetrische Last, Last 02 Abb.: V. Kleinas

Fig. 20. Cross-section twists in the centre of a 50 m long bridge. Asymmetric load, Load 02 Source: V. Kleinas

Bild 20. Querschnittsverdrehungen in der Mitte einer 50 m langen Brücke. Asymmetrische Last, Last 02 Abb.: V. Kleinas
The thick steel sheet construction is a very durable and low maintenance construction. Extremely high-strength steel grades are not required. The sheet’s steel grade can be changed by adjusting the radius of the saddle edges. As the radius increases, the total stresses in the support element decrease.

The cross-section of a single load-bearing steel sheet is calculated differently from that of cables or sheets (Figure 1a):

1. Freely selectable steel sheet thickness \( t \).
2. The stiffness coefficient \( k \) of a load-bearing element is determined when the cross-sectional area calculated according to formula (11) satisfies the condition:
   \[
   A_{L, \text{min}} = A_L = b_L \cdot t_L.
   \]
   Where: \( b_L \) – the width of the support sheet (Fig. 1a).
3. The load-bearing element material’s strength is selected by evaluating the bending stresses in the saddle zone (Formula 17).

The stressed ribbon construction (Fig. 1a) represents the behaviour of lightweight decking structures. Light decks are sensitive to asymmetric loading. The standard load of 5 kPa caused by the pedestrian crowd is a high value of this thin structure’s variable load. Studies have shown that with a lower value of the variable load, the structural displacements caused by the sheet’s asymmetrical longitudinal, transverse loading are significantly smaller. Thin, cable-stabilised structures can be adapted to the combined structures or pedestrian bridges of local, recreational significance (Fig. 21 e.1). Rigid wooden decking can be used effectively in lightweight constructions. The constructions are favourable for the bearing-deck printing using the composite materials.

The axial force of the suspension element under constant load can be expressed by the effect of temperature (18):

\[
\Delta T_{PA} = \frac{T_{ph}}{E_r \cdot A_{L, \text{min}} \cdot \alpha T}
\]

where:
- \( \alpha T \) – the coefficient of thermal expansion of the material of the load-bearing element;
- \( T_{ph}, A_{L, \text{min}} \) are calculated according to formulas (5) and (11).

The effects of temperature are significant for the behaviour of the suspension structure.

Effect of negative temperature: \(- T_{T1}\)
Effect of positive temperature: \(+ T_{T2}\)

The maximum approximate deflection of the suspension structure under the effect of positive temperature can be calculated as follows (19):

\[
\varepsilon_{P,T2} \approx \left( T_{ph} \cdot \left( \Delta T_{PA} + \Delta T_{T2} \right) \right) \cdot 1.02
\]

Then the maximum angle of inclination of the suspension structure (20):

\[
\beta_{P,T2} = \frac{4 \cdot \varepsilon_{P,T2}}{L}
\]

It is crucial to choose the saddle edge parameters so that the suspended structure does not reach the saddle edge during construction and operation. The approximate minimum geometrical parameters of the saddle edge can be calculated as follows (21):

\[
L_{\text{CM}} = 2 \cdot R_k \cdot \sin(\beta_{P,T2} - \beta_A); L_1 = L_{\text{CM}} \cdot \sin(90^\circ - \beta - \beta_{P,T2} - \beta_A)
\]

where: \( R_k \) – the radius of the edge of the saddle (\( \geq R_{\text{min}} \) according to formula 15).
The curve OA (Fig. 21) is always more significant than the length of the suspension structure's overlap in the saddle's edge zone.

The radius of the central part of the saddle (22):

$$ R_c = \frac{AB}{\cos(\alpha)} \cdot \frac{L_0}{2} \; ; \; AB = \frac{L_0}{2} \cdot \cos(\beta) \; ; \; R_c \geq R_{c, min} $$

Length of the central part of a saddle (23):

$$ L_c = R_c \cdot \beta - R \; \text{mm} $$

The height of the central part of a saddle (24):

$$ h_c = R_c - \sqrt{R_c^2 - (0.5 \cdot L_0)^2} $$

**Literatur**


