Choice of rational parameters of combined structure

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Abstract

Combined stayed roof with the span equal to 60 m is considered as an object of investigation. The roofs framework is formed by two groups of structural members, which are placed in longitudinal and transversal directions. The frames, which are formed by the trusses and columns, are placed in transversal direction. Structural steel S355 is considered as a materials of all rigid members – pylons, columns and girders. Three variants of materials for suspenders were considered. The dependences of materials consumption and main geometrical parameters of combined stayed roof were obtained for three above mentioned variants of suspender materials were obtained on the base of numerical experiment. The numerical experiment was carried out by the program LYRA 9.4. It was stated, that the rational values of suspenders amount, transversal frames bay and height of pylon are equal to 8, 6 m and 18 m, correspondingly.

Keywords: Tensioned element; hybrid composite suspender; long span steel structure; static loading

1. Introduction

Large span structures are widely used for such types of residential and industrial buildings as exhibition and trade hales so as supermarkets, airports, stations and hangars roofings etc. Possibility to use internal space rationally due to the decreased amount of intermediate supports, expressiveness of architectural shapes so as decreased, in comparison with the short span structures, materials expenditure, are some from the main reasons, why large span

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structures cause interest of engineers and architects. The investigation, which must be carried out in this study, is
joined with choice of proper structural solution of large span exhibition hall and evaluation of it rational parameters.
The main objective of this study is to choose based structural solution for the exhibition hale with the span equal to
60 m. Choice of structural materials and main geometrical parameters of considered structure must be based also.
The large span structures can be divided into several groups depending from the type of used load bearing members.
The first group includes large span structures, consisting from the compliant members, mainly. Pneumatic domes
and shells, cable roofs are some of examples of such large span structures [1, 2, 3, 4]. Load bearing members, which
can take up longitudinal tension forces only, are mentioned here as the compliant members. The flexural rigidity of
such members is marginal and can be neglected during it analyses [5]. Steel, composite and hybrid composite
cables are the examples of such compliant members [6]. Decreased materials consumption and increased
compliance are the main peculiarities of this group of large span structures [7].

The second group includes large span structures, consisting from the rigid members, such as beams, trusses, and
columns, slabs etc., which can take up bending moment and compression force also. Beams, truss, arches systems,
large span roofs, so as domes and shells are some examples of such large span structures. Decreased compliance and
increased materials consumption are the main peculiarities of this group of large span structures.

The third group includes large span structures, consisting from the rigid members and compliant once. The main
targets of compliant members adding are improvement of structural schemes of rigid members and taking up of
design loads, acting on the structure. Combined cable roofs are main examples of such group of large span structures
[8, 9, 10, 11]. Combined cable roofs are characterized by the decreased, in comparison with the cable roofs,
compliance and decreased, in comparison with the beams, truss and arch systems large span roofs, materials
consumption. So, combined structures took an intermediate position between the first and second groups of large
span structures, mentioned above. So, combined structure will be considered.

Combined structures also can be divided in to several groups depending on it structure. But the combined stayed
roofs take a special position among the combined structures due to it decreased compliance and possibility to
provide stability of shape [12]. In this connection, combined stayed roof is considered as a structural scheme of for
the exhibition hale with the span equal to 60 m, which is considered as an object of investigation (Fig. 1).

![Fig.1. Scheme of combined stayed roof: 1 – pylon; 2 - main girder; 3 – girder of transversal frame; 4 – column of transversal frame; 5 – suspenders.]

The combined stayed roof of sporting hall, which was created in Brunswig, German [3], was considered as a
prototype of roof of exhibition hall, which was considered as an object of investigation.

Pylons, main girder and suspenders are the main load bearing members placed in the longitudinal direction. The
main girder is placed horizontally without two slopes unlike the considered prototype (Fig. 2).
Transversal frames with the pinned girder to column connections and restrained in foundation columns are the main load bearing members placed in the transversal direction. The girders are two slope trusses with parallel chords and triangular web (Fig. 2).

2. Choice of structural materials

Steel of grade S355 was chosen as a structural material for main girder, pylons, girders of transversal frames and columns. Increased grade of steel is based on the requirement to use structural material with the increased specific strength. Using of steel grade S355 enables to decrease materials expenditure from one hand and did not use steel of higher grade S460, from other. Yielding and tensile strength so as modulus of elasticity for steel of grade S355 are equal to 355, 510 and $2.10^{105}$ MPa, correspondingly.

Three variants of materials for suspenders were considered. Steel cables with modulus of elasticity in $1.70 \cdot 10^5$ MPa and tensile strength of steel wire in 1960 MP was the first variant. Carbon fiber reinforced plastic (CFRP) with the modulus of elasticity in $1.65 \cdot 10^5$ MPa, tensile strength in 2800 MP and ultimate strain in tension in 1.8 % was the second variant. Hybrid composite element, consisting from steel, CFRP and Kevlar components with the volume fractions in 0.6, 0.2 and 0.2, correspondingly, was the last variant of suspenders [12, 13]. The modulus of elasticity and tensile strength of hybrid composite element were evaluated as $1.14 \cdot 10^5$ MPa and 2152 MPa, correspondingly. Approach for evaluation of mechanical properties of tensioned hybrid composite element [14, 15], which is based on the method of proportional summing, was used. Approach for evaluation of mechanical properties of tensioned hybrid composite element was tested experimentally. Three specimens, consisting from four steel and one CFRP bands were tested. CFRP band Sika CarboDur S-512 and cold rolled steel of grade DC01 (EN 10130-06) were used. All bands were joined together by the epoxy glue Sika Dur-30 and have cross-sections 50X1.2 mm. Breaking forces and load-strain curves were obtained as results of experiment. Difference between the analytical and experimental results does not exceed 20%. It enables to consider the adopted approach as corresponding.

3. Method of analyse

Evaluation of main geometrical parameters of combined stayed roof was formulated as one of the main targets of this paper. The angle of transversal frames girder inclination ($\alpha$), suspenders amount (n), transversal frames bay (b) and height of top part of pylon ($H_p$) are considered as the main geometrical parameters of combined stayed roof (Fig. 3).
The dependences of materials consumption and main geometrical parameters of combined stayed roof were obtained for three above mentioned variants of suspender materials. Each from the mentioned above main geometrical parameters has three values (maximum, minimum and mean). It means, that total amount of treated variants was equal to 81 for each from three above mentioned variants of suspender materials. The dependences were obtained as a second power polynomial equation on the base of numerical experiment, which was carried out by the program LYRA 9.4.

\[ G = b_0 + b_1 \cdot \alpha + b_2 \cdot n + b_3 \cdot b + b_4 \cdot H_p + b_{13} \cdot \alpha \cdot n + b_{14} \cdot \alpha \cdot b + b_{14} \cdot \alpha \cdot H_p + \\
+ b_{23} \cdot n \cdot b + b_{24} \cdot n \cdot H_p + b_{34} \cdot b \cdot H_p + b_{31} \cdot \alpha^2 + b_{22} \cdot n^2 + b_{33} \cdot b^2 + b_{44} \cdot H_p^2, \]

(1)

Spacious model of the combined stayed roofs framework was analyzed on the action of design load combination, which involves dead weight, snow and wind. The snow load uniformly distributed by the surface of the roof, was considered. Internal forces acting in the load-bearing members than were used for determination of cross-sections parameters. Dimensioning of the members cross-sections was carried out by the Eurocode 3. Design schemes of transversal frame and main girder are shown on Figure 4. Deformations of pylon and corresponding displacements of supporting points of main girder were neglected.

The main girder has welded double-T cross-section with two webs. Column of transversal frame has hot-rolled double-T cross-section (EN 10025). The girders of transversal frames are two slope trusses with parallel chords and triangular web with hollow rectangular cross-sections (EN 10219).
The coefficients of dependences of materials consumption and main geometrical parameters of combined stayed roof were obtained by the less squares method.

Rational from the point of view of materials consumption values of transversal frames girder inclination (α), suspenders amount (n), transversal frames bay (B) and height of top part of pylon (Hp) were determined by the system of equations (2).

\[
\begin{align*}
\frac{\partial G}{\partial \alpha} &= b_1 + b_{12} \cdot n + b_{13} \cdot b + b_{14} \cdot H_p + 2 \cdot b_{14} \cdot \alpha = 0, \\
\frac{\partial G}{\partial n} &= b_2 + b_{12} \cdot \alpha + b_{23} \cdot b + b_{24} \cdot H_p + 2 \cdot b_{22} \cdot n = 0, \\
\frac{\partial G}{\partial b} &= b_3 + b_{13} \cdot \alpha + b_{23} \cdot n + b_{34} \cdot H_p + 2 \cdot b_{33} \cdot b = 0, \\
\frac{\partial G}{\partial H_p} &= b_4 + b_{14} \cdot \alpha + b_{24} \cdot n + b_{34} \cdot b + 2 \cdot b_{44} \cdot H_p = 0.
\end{align*}
\]

(2)

The obtained results then were corrected by the inspection.

4. Evaluation of rational parameters of combined stayed roof

The angle of transversal frames girders inclination changes within the limits from 9° to 18°. Suspenders amount, transversal frames bay and height of pylon changes within the limits from 4 till 8, from 4.5 till 7.5 m and from 12 till 18 m, correspondingly.

Snow and wind loads were determined for Riga climatical conditions. Maximum intensities of dead weight, snow and wind loads are equal to 1.252, 1.500 and 0.315kPa, correspondingly. The roofing consists from the profiled steel sheets, heat insulation and protective layers.

The dependences of materials consumption and angle of transversal frames girder inclination (α), suspenders amount (n), transversal frames bay (b) and height of top part of pylon (Hp) were obtained for cases, when suspenders were made from steel, CFRP and hybride composite on the base of steel, CFRP and Kevlar. The materials consumption was obtained as a total dead weight of suspenders, main girders and transversal frames. Dead weight of pylons was not taken in to account.

The dependence, which was obtained for steel suspenders, is shown in Fig. 5.
Fig. 5. Total material consumption as a function of suspenders amount and height of top part of pylon for variant with the steel suspenders. The angle of transversal frames girder inclination and transversal frames bay are constant and equal to $1.50^\circ$ and 5 m, correspondingly.

The dependence, which was obtained for CFRP suspenders, is shown in Fig. 6.

Fig. 6. Total material consumption as a function of the angle of transversal frames girder inclination and height of top part of pylon for variant with the CFRP suspenders. The suspenders amount and bay of transversal frames are constant and equal to 5 and 6 m, correspondingly.

The dependence, which was obtained for hybrid composite suspenders, is shown in Fig. 7.
The dependences presented on the Fig. 5 – 7 have the similar characters. Total materials consumption for all three variants of suspenders materials practically changes within the limits from 79.59 to 173.23 tons. The maximum difference of total minimum materials consumption was equal to 5.00% and took place between the variants with steel and CFRP suspenders.

The coefficients of second power polynomial equations for the variants of structure with steel, hybrid composite and CFRP suspenders are given in Table 1. The coefficients were determined by the less squares method. The obtained second power polynomial equations allow to describe the results obtained in the course of numerical experiment with precision till 15 % in general.

Table 1. Coefficients of second power polynomial equations for the variants of structure with steel, hybrid composite and CFRP suspenders.

<table>
<thead>
<tr>
<th>Coefficients of second power polynomial equations</th>
<th>Variant with steel suspenders</th>
<th>Variant with hybrid composite suspenders</th>
<th>Variant with composite suspenders</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_0$</td>
<td>68699.10</td>
<td>62170.00</td>
<td>60417.00</td>
</tr>
<tr>
<td>$b_1$</td>
<td>9931.65</td>
<td>9597.84</td>
<td>9451.50</td>
</tr>
<tr>
<td>$b_2$</td>
<td>4167.54</td>
<td>4057.64</td>
<td>3369.88</td>
</tr>
<tr>
<td>$b_3$</td>
<td>14886.00</td>
<td>16884.20</td>
<td>17479.80</td>
</tr>
<tr>
<td>$b_4$</td>
<td>-1507.24</td>
<td>-1065.75</td>
<td>-1119.34</td>
</tr>
<tr>
<td>$b_{11}$</td>
<td>-384.05</td>
<td>-395.67</td>
<td>-383.25</td>
</tr>
<tr>
<td>$b_{12}$</td>
<td>24.51</td>
<td>53.15</td>
<td>56.24</td>
</tr>
<tr>
<td>$b_{13}$</td>
<td>-998.03</td>
<td>-965.47</td>
<td>-973.56</td>
</tr>
<tr>
<td>$b_{14}$</td>
<td>6.46</td>
<td>19.83</td>
<td>7.35</td>
</tr>
<tr>
<td>$b_{22}$</td>
<td>832.69</td>
<td>743.39</td>
<td>689.89</td>
</tr>
<tr>
<td>$b_{23}$</td>
<td>-2678.71</td>
<td>-2521.56</td>
<td>-2376.25</td>
</tr>
<tr>
<td>$b_{24}$</td>
<td>0.70</td>
<td>-10.86</td>
<td>4.27</td>
</tr>
</tbody>
</table>
The values of obtained coefficients allow to analyze level of importance of each from four above mentioned main geometrical parameters of combined stayed roof. The bay of transversal frames and number of suspenders are the parameters which most significantly influence on the total materials consumption.

Rational from the point of view of total materials consumption values of transversal frames girder inclination angle, suspenders amount, transversal frames bay and height of top part of pylon were determined (see Table 2). The results were completed by the additional dependences, which were obtained separately for the main girder and suspenders.

Table 2. Rational values of transversal frames girder inclination, suspenders amount, transversal frames bay and height of top part of pylon (The values in denominator are obtained on the base of dependences obtained for the main girder only).

<table>
<thead>
<tr>
<th>Main geometrical parameters of combined stayed roof</th>
<th>Variant with steel suspenders</th>
<th>Variant with hybrid composite suspenders</th>
<th>Variant with composite suspenders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle of transversal frames girder inclination $\alpha$, °</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Suspenders amount $n$</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Transversal frames bay $b$, m</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Height of top part of pylon $H_p$, m</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
</tbody>
</table>

So, the combined stayed roof with the angle of transversal frames girder inclination, suspenders amount, transversal frames bay and height of top part of pylon equal to $9^\circ$, 8, 6 m and 18 m, respectively, was considered as a rational solution. Corresponding total material consumptions were equal to 84.00, 83.18 and 79.59 tons for the variants with steel, hybrid composite and CFRP suspenders, respectively. Materials consumptions of main girder, girders of transversal frames, columns of transversal frames and suspenders were equal to 15, 52, 35 and 4%, correspondingly. So, using of CFRP suspenders instead of steel enables decrease total material consumption at 5% only. Cable material consumption decreases 7.57 times, correspondingly. We can conclude also, that type of suspenders structural material does not have a big influence on total materials consumption.

The dependences of suspenders material consumption on the angle of transversal frames girder inclination, suspenders amount, transversal frames bay and height of top part of pylon, were obtained for three variants of suspenders materials. The obtained dependences have nonlinear character and are similar to the dependences, which are shown on Fig.5-7.

5. Conclusions

Combined stayed roof was considered as a preferable structural solution for the exhibition hale with the span equal to 60 m. Choice of structural materials and main geometrical parameters of considered structure were based also.

It was stated, that the rational from the point of view of materials consumption angle of transversal frames girder inclination, suspenders amount, transversal frames bay and height of top part of pylon are equal to $9^\circ$, 8, 6 m and 18 m, respectively. Corresponding total material consumptions were equal to 84.00, 83.18 and 79.59 tons for the variants with steel, hybrid composite and CFRP suspenders, respectively.
It was shown that using of CFRP suspenders instead of steel enables a decrease total material consumption at 5% only. Cable material consumption decreases 7.57 times, correspondingly.

References