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Suspension structure with cross-laminated timber deck panels

Подвесная конструкция с настилом из поперечно ламинированных деревянных панелей

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Key words: prestressed cable truss; cross-laminated timber deck panels; experimental verification; transformed section method; suspension bridge

Ключевые слова: предварительно напряженная вантовая ферма; поперечно ламинированные деревянные панели; экспериментальная проверка; метод трансформированного сечения; подвесной мост

Abstract. Innovative suspension structure with prestressed cable trusses as the main load-bearing members was developed. Cross-laminated timber panels of the deck are placed to the bottom chords of the prestressed cable trusses. The structure with the deck panels placed to the bottom chord with the clearances and behaves in bending in the transversal direction only, and the structure with the deck placed without clearances and behaves in bending in the transversal direction and in compression in longitudinal directions, are considered. The suspended pedestrian-bicycle bridge with the span and width equal to 60 and 5 m correspondingly and loaded by the imposed load 5 kN/m^2, was considered as an object of investigation. The optimization algorithm of the innovative suspension structure with cross-laminated timber deck panels was developed using the program ANSYS v12 optimization tools. Rational values of cross-section areas of suspenders, main load-bearing and stabilization cables were evaluated. It was shown, that placement of the deck panels without clearances, when the panels behave in compression in the longitudinal direction and in bending in transversal direction enables to decrease materials consumption by 25% in comparison with the case when the panels are placed with clearances and behave in bending in transversal direction only.

Аннотация. Предложена инновационная висячая конструкция с главными несущими элементами в виде предварительно напряженных вантовых ферм. Панели настила из склееных в двух перпендикулярных направлениях слоев досок размещены по нижнему поясу предварительно напряженных вантовых ферм. При этом рассмотрены варианты, когда панели настила размещены с зазорами и работают на изгиб только в поперечном направлении, а также вариант, когда панели размещены без зазоров и работают на сжатие в продольном направлении и на изгиб в поперечном. Подвесной пешеходно-велосипедный мост пролетом в 60 м и шириной в 5 м рассмотрен в качестве объекта исследования. Интенсивность полезной нагрузки принята равной 5 кН/м^2. Для рассмотренной конструкции разработан алгоритм оптимизации с использованием програмного комплекса ANSYS v12. С помощью разработанного алгоритма определены рациональные с точки зрения расхода материала вант сечения верхнего и нижнего поясов, а также подвесок. Показано, что размещение панелей настила по нижнему поясу без зазоров, когда панели работают на сжатие в продольном направлении и на изгиб в поперечном, позволяет уменьшить на 25 % расход

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материала вант по сравнению с вариантом, когда панели настила размещены с зазорами и работают на изгиб только в поперечном направлении.

1. Introduction

Replacement of non-renewable structural materials by the renewable ones and development of structures with rational from the point of view of materials consumption geometrical parameters, with decreased structural dead weight so as increased spans and durability are some of the modern tendencies, which enables to solve the problem of limited raw material and energy resources [1–3]. The structural efficiency can be increased by the using of renewable timber based structural materials for prestressed tensioned structures [4], which are characterized by the decreased materials consumption due to close to the uniform distribution of stresses by the area of cross-section [5, 6].

Possibilities of development of innovative suspension structure with timber deck panels were mentioned in the previous investigations [1, 5]. The prestressed cable trusses, consisting of the main load-carrying cables, stabilization cables and suspenders, were considered as the main load-carrying members of innovative suspension structure. The using of prestressed cable trusses is considered as an efficient way to decrease kinematic displacements of the innovative suspension structure [7–9]. Structural solutions of the prestressed cable trusses that are differed by the lattice configuration were considered [4, 10]. The cable truss with the vertical suspenders and chords joined in the middle of the span was considered as the most rational from the point of view of material consumption and maximum vertical displacements (Figure 1).

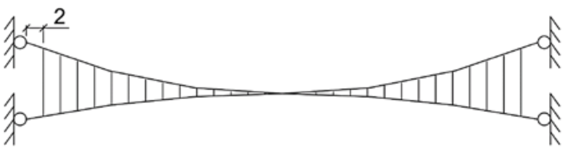


Figure 1. The cable truss with the vertical suspenders and chords joined in the middle of the span [4]

The determination of rational values of cross-sections of suspenders, main load-carrying and stabilization cables so as level of prestressing of stabilization cables probably enables to decrease materials consumption and increase the structural effectiveness of the prestressed cable truss. The rational values can be determined by the solution of optimization task.

Cross-laminated timber panels are considered as the deck material for the suspension structure. The cross-laminated timber panels are placed to the bottom chord of the cable truss without clearances and behave in the longitudinal direction in compression and in the transversal direction in bending. Such cross-laminated timber panel's placement enables to decrease cables materials consumption in comparison with the structure, when cross-laminated timber panels are placed with clearances and behaves in bending in transversal direction only [4, 11]. The optimization of the proposed cable structure with cross-laminated timber panel deck probably enables increasing structural effectiveness of the structure [1, 12].

Transformed section method was mentioned as a simple and enough precise one, which enables analysing load-carrying members from cross-laminated timber, subjected to flexure. This conclusion was obtained analytically and by the experiments conducted for the freely supported cross-laminated timber panels subjected to uniformly distributed load [13]. Other design schemes can take place for the cross-laminated timber panels subjected to flexure when the panel is suspended in four points. This case can take place in case of emergency when the deck can be disintegrated and stabilization cable excluded from the work. Therefore, the transformed section method application for the case should be also treated.

The optimization of the proposed suspension structure with prestressed cable trusses as the main load-bearing members and cross-laminated timber deck behaving in both directions is the target of the current investigation.

Possibility to decrease material consumption by the placing of CLT panels of the deck without clearances when they behave in both directions, and by evaluation of rational parameters of innovative suspension structure, should be checked.

Information regarding design procedure for analyse of timber deck panels from cross-laminated timber must be generalized and completed by the additional cases when the panel was suspended in four points.

Rational parameters of the developed structures are evaluated by the solution of optimization task. The optimization algorithm for innovative suspension structure was developed for the purpose.

2. Methods

2.1. Design methods for elements from cross-laminated timber

The most precise design method for elements from cross-laminated timber is an experimental once, but it is characterized by increased workability. Therefore, analytical methods, which are the most general and economical, are used. Nowadays, there are several analytical design procedures for elements from cross-laminated timber (CLT), including mechanically jointed beams theory (gamma method), composite theory (k-method), shear analogy method and transformed section method. No one from the above mentioned analytical design procedures has been universally accepted yet. The most widely used in practice design procedures for CLT elements and their major peculiarities are shown on Figure 2 [13–15].

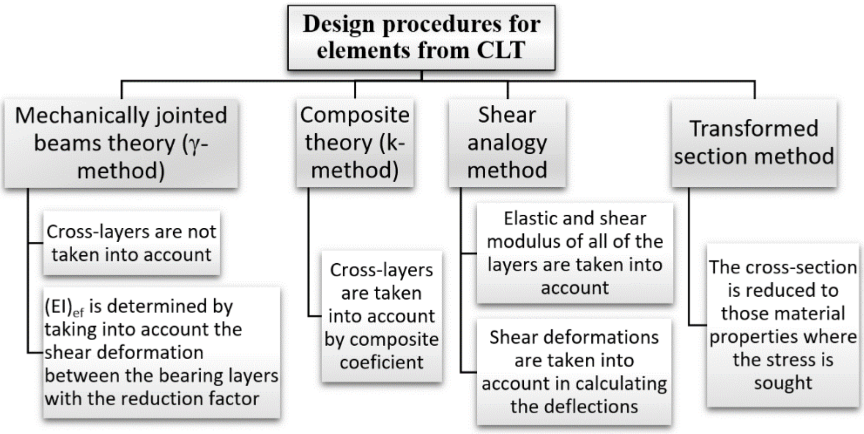


Figure 2. Design procedures for elements from cross-laminated timber

All mentioned above design procedures for CLT load-bearing members can be used for the design of out of plane loading panels subjected to flexure with span-to-depth ratio bigger or equal to 30, where shear deformation can be neglected.

The gamma method is based on Annex B of Eurocode EN 1995-1-1:2004. According to gamma method, transverse to the main load-bearing direction layers of CLT is not taken into account in the bending stiffness calculations. Shear deformation of the longitudinal layers is neglected, but the rolling shear stiffness of the transverse layers is taken into account by the reduction factor.

The composite method is based on theory used for plywood load-bearing members. All of the layers are taken into account in the bending stiffness calculations. The modulus of elasticity of the transverse layers is taken as a modulus of elasticity of external layers divided by thirty. The effective values of strength and stiffness are determined using a composition factor, which depends on loading scheme [13].

The modulus of elasticity and shear modulus of all layers in both directions are taken into account in the bending and shear stiffness calculations according to shear analogy method. The effect of shear deformation is considered in the calculations of deflection [14, 15].

The transformed section method is based on replacement of real cross-section by the equivalent transformed cross-section using the ratio of modulus of elasticity of the longitudinal and transverse layers.

$$n = \frac{E_{CR}}{E_t} \qquad (1)$$

where E_{CR} – modulus of elasticity of timber in transversal direction; E_L – modulus of elasticity of timber in longitudinal direction.

Material properties of the transformed cross-section depend on the determined ratio. For example, the cross-section of the 3-layer panel must be transformed to the outer layers properties, if maximal normal stresses are calculated and to the middle layer properties if maximal shear stresses are calculated. Transformed homogenous I-shape cross-section is obtained as a result. Further calculation is carried out according to the recommendations of the Eurocode 5. Serviceability limit state (SLS) is usually determinant check for CLT.

The CLT design procedures were verified by experiment and finite element method for options of the panels, which were differed by the schemes of loads applications and support conditions. Three-layer cross-laminated panels with the length, width and thickness equal to 2, 0.35 and 0.06 m, correspondingly, were experimentally tested in three-point and four-point bending [13, 16]. The additional experiments were done by suspending the panels in four points near it corners horizontally and under the angle equal to 16.8°. The distance between the points of suspensions was equal to 1.8 m. Suspended panels were loaded by the distributed in two zones vertical load (Figure3). The vertical load with total intensity till 9 kN was applied by pieces of steel with the approximate weight of 20 kg by the six stages with approximate intensity in 1.6 kN each to the horizontally suspended panel. The vertical load with total intensity till 5 kN was applied to the inclined panel.

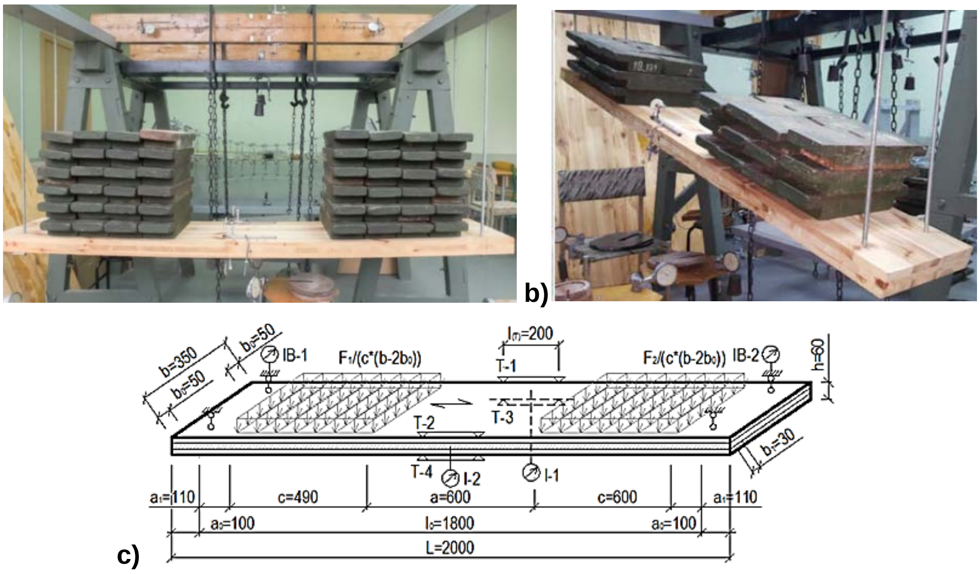
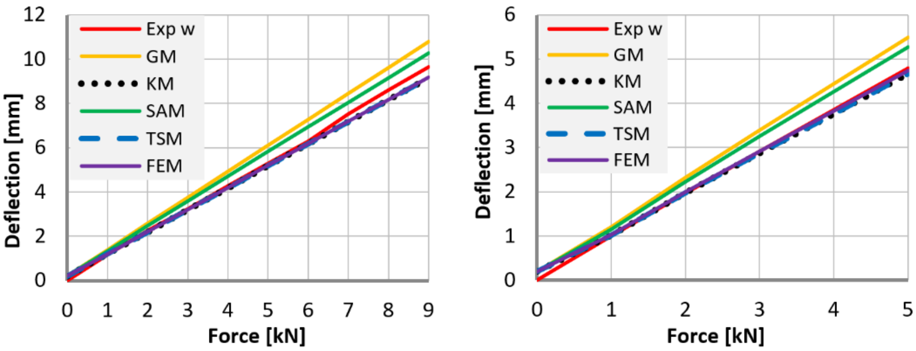


Figure 3. Design scheme and measuring devices placement for suspended CLT panel with four fixing points: a) CLT panel, which was suspended horizontally; b) CLT panel, which was suspended under the angle equal 16.8°; c) scheme of loading and measuring devices placement

Results of the three-point and four-point bending tests were summarized in [13] and show, that transformed section method enables to predict maximum vertical displacements and maximum normal stresses, acting in the edge fibres of the panels with precision from 3.3 to 20 %. Maximum vertical displacements in the middle of the span of the suspended panel with four fixing points (Figure 3), obtained by gamma method, composite method, shear analogy method and transformed section method, physical test and FEM as a function of the vertical load are shown in Figure 4. The differences between the maximum vertical displacements in the middle of the span of suspended in the four points CLT panel obtained by the gamma method, composite method, shear analogy method, transformed section method, FEM software and experimental displacement was equal to 12.5, 4.5, 7.2, 4.5 and 4.4 %, correspondingly.



a) b)

Figure 4. Maximal vertical displacements in the middle of the span as a function from the vertical load`s intensity: a) for CLT panel, which was suspended horizontally; b) for CLT panel, which was suspended under the angle equal 16.8°

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Based on the obtained results it can be concluded that the transformed section method enables to predict the behaviour of CLT panels in bending with span-to-depth ratio bigger or equal to 30 with the better accuracy than gamma method and shear analogy method. The results obtained by the transformed section method and composite method are the same, but design procedure of transformed section method is simpler. The transformed section method is chosen for analyse of cross-laminated timber deck panels in frames of the current investigation.

2.2. Structural solution for innovative suspension structure

2.2.1. Structural solution of suspension truss

The bicycle-pedestrian bridge with the prestressed main load-carrying members and a deck from CLT panels was considered as an example of the proposed suspension structure. Considered bicycle-pedestrian bridge has a span and width equal to 60 and 5m, correspondingly. Cambers of the main load-carrying and stabilization cables are equal to 6 and 3m, correspondingly. The sag to span and rise to span ratios were assumed as 1:20 and 1:10, for main load-carrying and stabilization cables. The characteristic value of imposed load was equal to 5 kN/m^2 [17]. According to Eurocodes, fire load is irrelevant for the bridge structure. The quasi-permanent representative value of the variable action is recommended by the Codes for the fire situation. The combination factor for the quasi-permanent value of the variable action on footbridge ψ_2 is equal to 0. This means that only dead load of the bridge and prestressing should be considered under fire. In case of fire, the external fire curve with the maximum gas temperature equal to 680°C should be applied. The residual strength of steel for this temperature is equal to 28%. The prestressing forces will disappear under thermal elongations caused by increased temperature reserving additional capacity of cables [18]. In addition, thermal expansions will cause an increase of the camber and decrease of internal forces. This means the cable structure will not collapse under fire. The 180 mm thick bridge deck ensure R180 fire resistance under fire design situation in case of one side burning. The dynamic approach is one of the regulated bridge design parts for this type of structure. According to the codes, the natural vibration frequency of the structure should not be within the limit of 1 to 3 Hz [17]. Different method could be used for determination of natural vibration frequencies of prestressed cable structures [19], like numerical methods or the simplified analytical method, proposed by Goremikins et al. [20]. The determination of the natural vibration frequencies of the structure is not within the scope of this research.

The prestressed cable truss with joined in the middle of the span load-carrying and stressing cables and vertical suspenders, which is characterized by the minimum structural materials consumption, was considered as the main load-carrying structure of the proposed structure. The distances between the vertical suspenders were equal to 2 m (Figure 1.). The steel cables with the design resistance in tension equal to 840 MPa were considered for load-bearing and stressing cables so as for elements of the lattice. Modulus of elasticity and poisons ratio for the considered cables were equal to 150000 MPa and 0.3, correspondingly [21].

Materials consumption of the structural solutions of prestressed cable trusses, which are differed by the system of the lattice and connection of the top and bottom chords, changes within the limits from 5.31 to 11.96 t for considered bicycle-pedestrian bridge [4]. Chosen option with joined in the middle of the span stressing cables and vertical suspenders is characterized by the materials consumption 4.59 t, maximum normal stresses acting in the members 692 MPa and maximum vertical displacements 0.2 m [4]. The values were obtained for the case when cross-laminated timber panels are placed with clearances and behave in bending in transversal direction only.

2.3. Structural solution of the deck

Cross-laminated timber panels were considered as the load-bearing elements of the deck for the proposed suspension structure [22, 23].

The transformed section method discussed in the second chapter was used for evaluation of the effective dimensions of the CLT panels for the deck of the bridge. The panel with length and span equal to 5 and 2 meters was analysed. The linear supports were assumed for the panel under consideration. Based on the calculation by the transformed section method the effective depth of the panel equal to 180 mm and thicknesses of the layers were obtained (Figure 5). Thicknesses of the layers with the fibers oriented in the longitudinal direction are equal to 40 mm. Thicknesses of the layers with the fibers oriented in the transversal direction are equal to 30 mm. The serviceability limit state was decisive for selection of the effective dimensions.

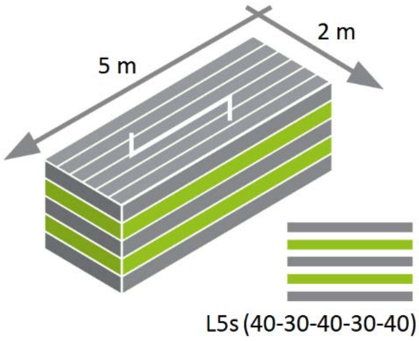

Figure 5. CLT panels for the deck of the innovative structure

The rational solution of the deck was chosen on the base of comparison of two probable options of decking panel's placement: by the top or the bottom chords of the prestressed cable trusses. Two prestressed cable trusses with joined load-bearing and stressing cables and vertical suspenders were considered as the main load-bearing structures of the pedestrian suspension bridge. Material consumption of the cable trusses was considered as a criterion for the options comparison. 2D model of the prestressed cable trusses for decking panel's placement by the top and bottom chords is shown in Figure 6.

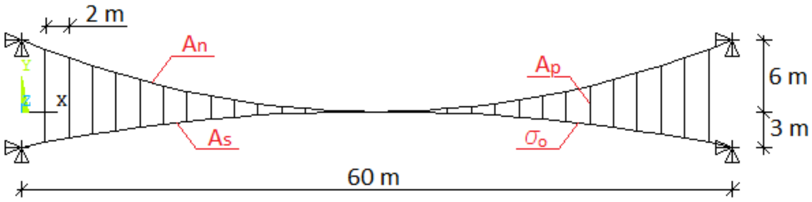

Figure 6. Numerical model of prestressed cable trusses of pedestrian suspension bridge

It was shown, that placement of the cross-laminated timber elements of the deck to the bottom chord enables decreasing by 16.7 % materials consumption of the cable trusses in comparison with the option when the elements of the deck are placed to the top chord of the cable truss. Therefore, placement of the cross-laminated timber panels to the bottom chord of prestressed cable truss is considered as the rational solution for the deck of the proposed cable structure [4]. The option of the structure with the CLT panels placed without mutual clearances enables developing the provisional longitudinal arch resisting part of the longitudinal internal forces. The combined behaviour of the prestressed cable trusses and cross-laminated timber panels in the longitudinal direction enables decreasing the materials consumption [1].

3. Results and Discussions

The optimization algorithm of the proposed cable structure with the cross-laminated timber deck was developed. The aim of the optimization is the obtaining of structural parameters which ensure minimum material consumption and maximum allowed stresses and displacements in the elements [24]. The optimization was performed using program ANSYS v12 optimization tool [25]. The 2D and 3D parametric numerical models of the prestressed bridge were developed. The first one (2D) was developed for the option of the structure with the CLT deck panels placed with mutual clearances and behaving in the transversal direction in bending only. The second one (3D) was developed for the option of the structure with CLT panels placed without clearances and behaving in both directions (figure 8).

The numerical models were developed in FEM software ANSYS 12. The 3D spar element LINK10 with tension only function was used for modelling the cable elements. The 3D layered shell element SHELL181 was used for modelling the deck. The deck and the cables were coupled in vertical and transversal direction, while in the longitudinal direction the cables and the deck were uncoupled. KILL/ALIVE commands were used for the modelling of the process of assembling the deck after prestressing. The prestressing was introduced into the stabilization cables. The prestressing of the cables was modelled by the temperature difference and thermal extension option.

The developed models with sufficient accuracy describe the behaviour of physical structures, which were experimentally tested with physical loading of prototypes of suspension bridges with a span of 2.17 m [4]. The developed optimization algorithm is shown in Figure 7.

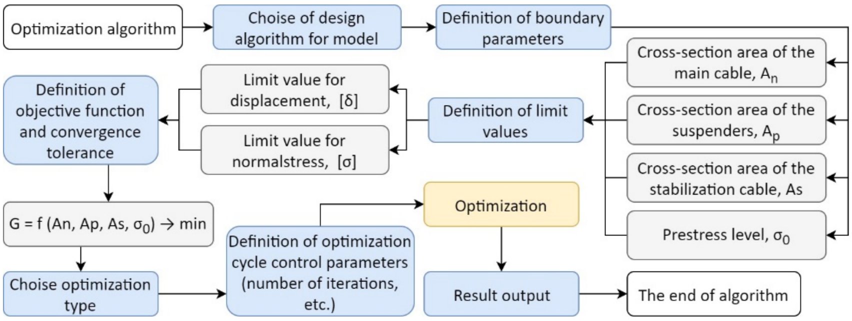

Figure 7. Optimization algorithm

The optimization of dimensions was used to get the rational parameters of the proposed structure. The size optimization is a type of structural optimization that found the optimal solution by changing the size of variables while maintaining topology. The optimization is carried out with the aim of identifying the values of the structural parameters that give the lowest consumption of the material maintaining the displacement and stress within the relevant limits.

The consumption of the material $G = f(A_n, A_p, A_s, \sigma_o)$ was taken as an objective function of the optimization task. In the equation above the variables are A_n, A_p, A_s – respectively, the cross-sectional areas of the bearing cable, the suspension and stabilization cables and σ_o – the prestressing level in the stabilization cable.

The first-order method based on the determination of the vector in each subiteration that points the direction of the greatest increase of function vectors, was used for the structural optimization.

This determines the direction of the search, and the search strategy is applied to the definition of the minimum of the objective function. The iterative process continues until convergence is achieved or the maximum number of iterations is reached.

It is assumed that the task is solved if by comparing the current iteration scheme (j) with the previous one (j-1) and the best (b) one the following conditions are fulfilled:

i) The change of the objective function in comparison with the best variant $f^{(b)}$ and the current $f^{(j)}$ is less than the accepted assumption τ:

$$f^{(j)} - f^{(b)} \leq \tau \qquad (2)$$

ii) The change of the objective function in comparison with the previous variant $f^{(j-1)}$ and the current $f^{(j)}$ is less than the accepted tolerance τ:

$$f^{(j)} - f^{(j-1)} \leq \tau \qquad (3)$$

The task estimation can be stopped before the approach if the maximum number of iterations is reached.

Consumption of steel material for both options of the bridge – with the CLT deck resisting and does not resisting the longitudinal direction forces of the bridge was compared by optimization of the numerical models of the suspension structure. 3D model of optimum suspension structure with CLT timber deck is shown in Figure 8.

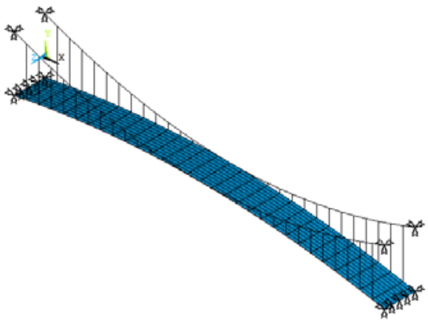

Figure 8. 3D model of optimum suspension structure with CLT timber deck which behaves in both directions

Results of optimization show that the option of the structure with the CLT deck panels placed without clearances and behaving in both directions is characterized by the decreased materials consumption and maximum vertical displacements in comparison with the option when cross-laminated timber panels are placed with clearances and behave in bending in the transversal direction only. Results of suspended bridge optimization are given in Table 1.

Table 1. Results of suspended bridge optimization

Rational parameters of the proposed suspension structure	Option of deck	
	Deck behaves in the transversal direction only	Deck behaves in two directions
Max displacements (load on span), m	-0.20174	-0.16029
Max displacements (load on ½ of span), m	-0.19946	-0.19940
Max stresses (load on span), MPa	824	743
Max stresses (load on ½ of span), MPa	768	692
Prestress level, MPa	651	532
Cross-sectional areas of the bearing cable, mm^2	5.75E+03	2.48E+03
Cross-sectional areas of the suspension cables, mm^2	71.5	89.2
Cross-sectional areas of the stabilization cable, mm^2	2.05E+03	3.35E+03
Material consumption, m^3	0.48366	0.36263
Material consumption, t	3.77	2.83

The material consumption of the cables of the structure with the span of 60 m loaded by 5 kN/m^2, when cross-laminated timber panels are placed with clearances and behave in bending in transversal direction only, is equal to 3.77 t. The material consumption for the cables of the structure when the CLT deck panels are placed without clearances and behave in both directions (Figure 8) is equal to 2.83 t. The evaluated rational parameters of the innovative suspension structure enable to decrease material consumption by 25 % by placing of CLT panels of the deck without clearances when they behave in both directions.

4. Conclusions

Innovative suspension structure with prestressed cable trusses as the main load-bearing members and cross-laminated timber panels which is characterized by the decreased materials consumption and improved behavior was proposed.

It was stated, that the transformed section method can be used to analyse of the cross-laminated timber deck panels due to its simplicity and reasonable precision for members subjected to flexure and compression with bending.

The developed optimization algorithm for the proposed prestressed suspension structure using program ANSYS v12 optimization tools enables computation of rational parameters of the structure. The optimized proposed suspension structure with CLT panels of the deck placed to the bottom cable without mutual clearances and behaving in both directions enables decreasing the material consumption by 25 % comparing to the option of the structure with the CLT deck behaving in transversal direction only.

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