Choice of rational structural solution for smart innovative suspension structure

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Abstract. Choice of the rational structural solution for smart innovative suspension structure was carried out. The prestressed cable trusses and cross-laminated timber panels were considered as the main load bearing members for the smart innovative suspension structure. The FEM model, which enables to predict behaviours of the structure, was developed in the programme ANSYS v12. Structural solutions that are differed by the lattice configuration of the cable truss and placement of cross-laminated timber panels were considered. The variant of the cable truss with the vertical suspenders and chords joined in the middle of the span was chosen as the best one. It was shown, that placement of cross-laminated timber panels by the bottom chord of the prestressed cable truss enables to decrease materials consumption by 16.7% in comparison with the variant, where the panels are placed by the top chord. It was stated, that the materials consumption decrease by 17.3% in the case, when common work of the prestressed cable trusses and cross-laminated timber panels is taken into account. The cross-laminated timber panels are working in the both directions. Physical model of the structure with the span equal to 2 m was developed for checking of numerically obtained results.

1. Introduction
The problem of limited raw material and energy resources can be solved by decreasing the structural dead weight, increase of span and durability of load carrying structures. The structural efficiency can be increased by the using of renewable structural materials for prestressed tensioned structures, which are characterized by the close to uniform stresses distribution of the tensioned members’ cross-sections. The using of prestressed cable trusses as the main load carrying structures enables to solve the problem of increased deformability of suspension structures, which is conditioned by the appearance of kinematic displacements [1, 2]. The prestressed cable trusses were considered as the main load carrying members of smart innovative suspension structure, which can be used for roofs and bridges.

Cross-laminated timber is a structural material which is used for several load-bearing elements during the last years. Cross-laminated timber is environmentally renewable material which is used for load-bearing walls and plates in multi-storey timber buildings and for span structures of pedestrian and road bridges [3]. Therefore, cross-laminated timber panels were considered as the structures, which are based on the prestressed cable trusses. The durability of CLT decking should be ensured by the constructive solution like replaceable cover and by improvement of timber durability properties by impregnation.

The suspension structures, where prestressed cable trusses were used together with the cross-laminated timber panels, are differed dependently from the placement of the panels by the top or bottom chords of the cable trusses. When cross-laminated timber panels are placed to the bottom chord of the
prestressed cable trusses, arch-type structure could be created, which take up part of the design vertical load and, probably, improve behaviour of the prestressed cable trusses [4]. Cross-laminated timber panels will work in bending in transversal direction and in compression in longitudinal direction [5]. Smart innovative suspension structure will be developed in this case.

The developed smart innovative suspension structure is characterized by the replacement of non-renewable structural materials by the renewable ones so as by the improved behaviour, which must be provided by the choice of rational structural solution.

Therefore, choice of rational solution for smart innovative suspension structure must be carried out in the current paper. The rational solutions for prestressed cable trusses and cross-laminated timber deck must be evaluated. Interaction between cross-laminated timber panels and prestressed cable trusses must be investigated. Physical models of the structure should be created for the purpose.

2. Choice of rational solution of cable truss

2.1. Approach to the solution of the problem

Some types of prestressed cable trusses, which are differed by the system of lattice and joining of the top and bottom chords, are shown in the figure 1. The types of prestressed cable trusses could be used as the main load carrying structures of suspension pedestrian and motor bridges so as cable roofs [6, 7].

![Figure 1. Variants of prestressed cable trusses: a) and b) with parallel suspenders; c) – f) with triangular lattice.](image)

The main differences between considered variants of prestressed cable trusses are configuration of elements of the lattice and connection of top and bottom chords of the cable trusses. Variants a) and b) are characterized by the parallel suspenders. Variants c) – f) are characterized by the triangular lattice. The top and bottom chords of variants b), d) and f) are joined together in the central point of the span. The top and bottom chords of variants a), c) and e) are not joined together and joining is provided by the elements of the lattice only. All the variants have the same chambers of the load bearing and stressing cables (top and bottom chords).

Comparison of variants of the cable trusses, which are shown on the figure 1 was conducted on the base of the numerical experiment. The numerical experiment was carried out by the program ANSYS v12. The cable trusses were modelled by the LINK 10 finite element type, which works at tension only [8]. Cable structures are characterized by large cinematic displacements, when the behavior of structure is characterized by the large nodes cinematic displacements at relatively small elastic deformations. Stepped analyze, when the load is divided into small load increments, is used to solve geometrically nonlinear problem. The large-deflection effects should be turned on (NLGOEM,ON) to update stiffness matrix based on the incremental nodal displacements at each equilibrium iteration. The prestressing of stabilization cable was defined by the temperature change as the most stable way from
the point of view of solution convergence. Cable trusses materials consumption was considered as a criterion of rationality of the variant of prestressed cable truss. Cable trusses materials consumption was determined for the cases when design value of imposed load was applied to the whole span and to half span. Permanent load of the structure was not taken into account. The variant of prestressed cable truss, which is characterized by the minimum structural materials consumption, was considered as a rational one.

2.2. Numerical results

Six variants of prestressed cable trusses with spans equal to 60 m were considered. Cambers of load bearing and stressing cables were equal to 6 and 3 m, correspondingly. The distances between the vertical suspenders were equal to 2 m. The horizontal distances between the nodes of the prestressed cable trusses with triangular lattices were equal to 2 and 4 m. 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 [9]. The prestressed cable trusses were considered as the main load-bearing structures of pedestrian bridge with the span and width equal to 60 and 5 m, correspondingly. The characteristic value of imposed load was equal to 5 kN/m² [10]. Numerical models of prestressed cable trusses for the cases when the imposed load is applied at the whole span and half span are shown on the figure 2 a) and b), correspondingly.

![Figure 2. Numerical models of prestressed cable trusses: a) imposed load is applied at the whole span of the prestressed cable truss; b) imposed load is applied at the half of the span of the cable truss.](image)

Material consumption of load-bearing and stressing cables so as for elements of the lattice was determined by the program ANSYS v12 with the using of parametric programming language APDL. The using of parametric programming language APDL enables to decrease a time, which is necessary for determination of prestressed cable truss materials consumption due to the automatization of the model developing process. The process of materials consumption evaluation for the certain variant of prestressed cable truss consists from the following stages: formation of numerical model; analyse of the model; analyse of obtained results and determination of materials consumption. The materials consumption was obtained as a target function from the level of prestressing of stressing cables, areas of cross-sections of all groups of cables. The maximum available vertical displacements and maximum available strain, which were used for prestressing of the trusses, were limited by 0.2 m and 0.014, correspondingly. The six considered variants of the prestressed cable trusses are characterized by the equal maximum vertical displacements in the cases when the load is applied by the whole span and it half. The value of maximum vertical displacement was equal to 0.2 m. The maximum vertical displacements were determined as a difference between the stage, when cable truss is subjected to prestressing only and stage, when the structure was loaded by the imposed load [11]. The stresses acting in the members of prestressed cable trusses also were carried out under the control and did not exceed 840 MPa.
The values of maximum stresses acting in the members of the six variants of the prestressed cable trusses, which are shown on the figure 1, are shown on the figure 3 for the cases when imposed load was applied by the whole span and it half.

![Graph 1: Maximum stresses in members of prestressed cable trusses](image1)

![Graph 2: Materials consumption for prestressed cable trusses](image2)

**Figure 3.** Maximum stresses in the members of prestressed cable trusses for the cases when imposed load was applied by the whole span and it half: 1) – 6) variants of the prestressed cable trusses are explained on the figure 1.

**Figure 4.** Materials consumption for prestressed cable trusses for the cases when imposed load was applied by the whole span and it half: 1) – 6) variants of the prestressed cable trusses are explained on the figure 1.

The values of materials consumption were analysed for the six variants of the prestressed cable trusses. The values of materials consumption for the cases when imposed load was applied by the whole span of prestressed cable trusses and it half are shown on figure 4.

Materials consumptions for considered variants of prestressed cable trusses are equal to 0.671, 0.596, 0.650, 0.771, 0.631 and 0.705 m³ for variants a), b), c), d), e) and f), correspondingly, when the imposed load is applied by the whole span of prestressed cable trusses. Materials consumptions for considered variants of prestressed cable trusses are equal to 0.778, 0.503, 0.573, 0.529, 0.656 and 0.535 m³ for variants a), b), c), d), e) and f), correspondingly, when the imposed load is applied by the half of the span of prestressed cable trusses. So, variant b) with joined load-bearing and stressing cables and vertical suspenders was considered as the rational solution for the prestressed cable truss of smart innovative suspension structure. The considered variant of prestressed cable truss is characterized by the following rational parameters: materials consumption 0.596 m³, maximum normal stresses acting in the members 698 MPa, maximum vertical displacements 0.2 m.

3. **Choice of rational solution for deck**

Cross-laminated timber panels were considered as load-bearing elements of deck for smart innovative structure of suspension bridge. The choice of rational solution for deck is joined with comparison of two probable variants of decking panel’s placement: by the top or bottom chords of prestressed cable trusses. The span and width of the considered pedestrian suspension bridge were equal to 60 and 5 m, correspondingly. Two prestressed cable trusses with joined load-bearing and stressing cables and vertical suspenders were considered as the main load-bearing structures of pedestrian suspension bridge. The behaviour of prestressed cable trusses were evaluated by the numerical model, which was explained in the chapter 2 of the current paper. Design value of the vertical imposed load was applied as the system of concentrated forces to the nodes of top or bottom chords of prestressed cable truss. Consumption of cable trusses material was considered as a criterion for variants comparison.

It was shown, that placement of cross-laminated timber elements of the deck to the bottom chord enables to decrease by 16.7% materials consumption of cable trusses in comparison with the case, when the elements of the deck are placed by the top chord of the cable truss. So, placement of the cross-
laminated timber panels by the bottom chord of prestressed cable truss is considered as the rational solution for deck of for smart innovative structure of suspension bridge.

![Figure 5. Numerical models of prestressed cable trusses of pedestrian suspension bridge: a) cross-laminated timber panels are placed by the top chord; b) cross-laminated timber panels are placed by the bottom chord.](image)

Usually, the deck of the prestressed suspension structure is transmitting applied load to the cables and is working only in transversal direction. CLT panels, used as a deck of suspension bridge, could resist load in both transversal and longitudinal direction. In transversal direction CLT deck is working as a beam. In longitudinal direction CLT deck is working as an arch, which couldn’t lose stability due to the connection to stabilization cable.

3D numerical model was developed to describe the behaviour of the CLT deck working in both directions using FEM software ANSYS 12. The cable elements were modelled using 3D spar element LINK10. The deck was modelled by 3D layered shell element SHELL181. The deck was connected to the cables only in vertical and transversal direction. The deck and cable are not connected in longitudinal direction. The deck is not resisting any moment in longitudinal direction as it’s build from separate panels.

The deck should be assembled to the cable truss after prestressing. This process was modelled by KILL/ALIVE commands in ANSYS [8].

Results obtained using 3D numerical model which included the longitudinal arch work of the deck were compared with results obtained from 2D model of cable truss only. It was determined, that the structure with CLT deck working in transversal and longitudinal direction allowing to reduce material consumption of the cables by 17.3% comparing with the model of cable truss only. The dimensions of the deck assumed to be the same in both cases.

4. Validation of numerical models by experiment

4.1. Description of physical models

To validate the performance of the numerical models, a set of experiment was carried out. Two physical models were constructed. The deck of the first model (called further as the model without arch) is able to resist loads in transversal direction only, the deck of the second model (called further as the model with arch) is able to resist loads in both transversal and longitudinal direction.

![Figure 6. Physical model, where plywood boards are placed: a) with the clearances and the deck is working in bending in transversal direction only; b) without the clearances and the deck is working in both directions.](image)

The deck is modelled by the plywood boards with thickness equal to 6.5 mm and length equal to 600 mm. The width of boards was specially selected to achieve perfect contact in case of the model with arch and distance between boards in case of the model without arch. The plywood boards are placed
with the clearances in the first case, when the decking is working in bending in transversal direction only. The first physical model, where plywood boards are placed with the clearances, is shown on the figure 6 a). The material properties of the plywood deck boards were assumed according to the manufacturer declaration of conformity. Therefore, characteristic values of moduli of elasticity in bending parallel and perpendicular to the fibres of outer layers were equal to 13101 and 4899 MPa, correspondingly.

The plywood boards are placed without the clearances in the second case, when the deck form arch-type structure in the direction of the span of prestressed cable trusses. The deck is working in bending in transversal direction and in compression with the bending in the direction of the span of cable trusses. The second physical model, where plywood boards are placed without the clearances, is shown on the figure 6 b).

The span of the physical models of prestressed suspension bridge is equal to 2.17 m. Main and stabilisation cable camber is equal to 0.217 and 0.109 m, correspondingly. The width of the model is equal to 0.5 m. The structure is divided to 14 parts by suspenders. Only vertical coupling is provided between stabilization cables and decking panels and free sliding of the deck panels by cables is possible. The diameters of top and bottom chords so as suspenders are equal to 6, 5.5 and 1.5 mm, correspondingly. The modulus of elasticity of the cables was obtained using calibration of the model of structure without arch and is equal to 105 GPa.

4.2. Physical models testing
The both physical models were subjected to the action of static vertical loading and prestressing. The prestressing is organized in stabilization cable. The model was prestressed by load 905 kg for each side. The deck was assembled after prestressing. Two types of loading were applied to the model: symmetrical and non-symmetrical. The load was applied to the deck by placing of steel peaces which weight changes within the limits from 17 to 20 kg each. The physical models were loaded up to the load equal to 793 kg with step 264 kg in symmetrical loading case and up to the load 396 kg with step 132 kg in non-symmetrical loading case.

![Figure 7. Symmetrical (a) and non-symmetrical (b) load applied to the physical model of prestressed suspension bridge, where plywood panels are placed with clearances.](image)

The vertical displacements in quarters and in the middle of the span were fixed by three couples of mechanical deflectometers. Prestressing in cables was measured by dynamometers connected to the stabilization cables.
4.3. Results of experimental model testing

The models were tested by symmetrical and non-symmetrical loads. Loaded part moves downwards, but non-loaded part moves upwards in case of non-symmetrical loading.

The horizontal support reaction of stabilisation cable was measured during all load steps. The measured support reaction in case of symmetrical load is equal to 800 and 832 kg in case of models with and without arch, respectively. The measured support reaction in case of unsymmetrical load is equal to 765 and 804 kg in case of models with and without arch, correspondingly. It could be seen from the results that the support reaction was decreased less in case of arch, that’s means the main cable was loaded less, while the applied load is the same.

The maximum displacements in case of symmetrical load were measured in the centre points of the model. The maximum displacements of the model in case of unsymmetrical load were calculated as a sum of measured displacements of points placed in the quarters of the span from the opposite sides of the structure. In case of unsymmetrical load non-loaded part is moving up and loaded part is moving down. The experimentally obtained and numerically calculated results of displacements are depicted in figure 8.

![Figure 8. Maximum vertical displacements under different loading cases.](image)

The maximum displacement in case of symmetrical load is equal to 10.47 mm and 10.74 mm for the models without the arch and with arch, respectively. The maximum displacement in case of unsymmetrical load is equal to 8.60 mm and 9.36 mm for the models without the arch and with arch, respectively. It could be noticed, that displacements in case of symmetrical load are larger than in case of unsymmetrical load. In previous researches [4] opposite effect was observed when the main and stabilization cables were not connected in centre.

It was stated, that taking into account interaction between the prestressed cable trusses and cross-laminated timber deck enables to decrease materials consumption for prestressed cable trusses. It means that variant when cross-laminated timber panels are placed without clearances to develop arch-type structure in the direction of the span of prestressed cable trusses is considered as preferable for smart innovative suspension structure.
5. Conclusions
Rational structural solution for smart innovative suspension structure was chosen and treated on the example of suspension pedestrian bridge with the span and width equal to 60 and 5 m, correspondingly. It was shown, that prestressed cable truss with joined in the middle of the span load-bearing and stressing cables and vertical suspenders is the rational structural solution for prestressed cable truss of smart innovative suspension structure.

It was stated, that placement of cross-laminated timber panels of the deck by the bottom chord of the prestressed cable truss enables to decrease by 16.7% materials consumption of cable trusses in comparison with the case, when the elements of the decking are placed by the top chord of the cable truss.

It was shown, that taking in to account interaction between the prestressed cable trusses and cross-laminated timber deck enables to decrease by 17.3% materials consumption for prestressed cable trusses. It means that variant when cross-laminated timber panels are placed without clearances to develop arch-type structure in the direction of the span of prestressed cable trusses should be considered as preferable for smart innovative suspension structure.

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