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Parametrical Analysis for Symmetrical Loading of a Single-Span Composite String Steel Structure

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Abstract: The article analyzes the string and composite string bridge behavior and compositional parameters. The derived parameters are calculated and presented by selecting the appropriate limit parameters. The main parameters for suspended structures are the cross-sectional area of the tensile element and the initial sag of the structure. The selection of different component parameters and assigning different prestressing to the string leads to the analysis: which cross-sectional areas meet the defined conditions, what is the effect of prestressing, of the lower cable initial sag and the axial stiffness ratios of the string and the lower cable on the weight of the structure.

Keywords: Steel bridge, Symmetrical load, Suspended cable, String, Nonlinear analysis, Displacements, Strain, parametrical analysis

Introduction

Suspension bridges are among the most rational types of bridges in terms of their construction and amount of materials used (Gimsing, 1997, Strasky, 2005, Chen et al., 2014, Greco et al., 2014). The main advantage of these structures is the minimal impact on the environment and its flexible structure with its graceful appearance conditioned by the extremely small height of the deck and amount of steel. However, there are also some negative aspects related to the minimal consumption of materials. The more lightweight these suspended structures are, the more deformable they are. (Katchurin, 1969; Juozapaitis et al., 2006). The alternative for suspended structures – string structures – are none the less elegant and lightweight (Linkute., 2015). They are pre-stressed and have no initial sag, making them completely insensitive to displacements of kinematic origin. The main disadvantage of the string structures is reflected in the high shear forces. Moreover, analytical methods as well as design and composition recommendations have not been developed for the design of these kinds of structures.

In order to reduce the shear forces and general displacements, the string can be transformed into a combined structure (Sandovic & Juozapaitis, 2012, Yunitskiy, 2019.) It is additionally supported by a suspended single-span structure (Beivydas, 2019). This solves the problem of shear forces and reduces excessive displacements. Compared to a single-span structure, this solves the problem of kinematic displacements, and the string creates a straight structure shape adapted to the vehicle traffic (Beivydas, 2018).

However, the design and composition of such composite string structures is complex. The publications on this subject matter are scarce. Most of the developed calculation methodologies are either designed for cables (Chen et al., 2014; Juozapaitis & Norkus 2005) and suspension bridges (Chen et al. 2014) or they are adapted for the calculation of individual elements. However, some methodologies have also been developed for double-span bridges, and their parameters as well as behavioral properties have been defined (Sandovic et al., 2011). However, such structures do not meet the functionality requirements, i.e. they do not create a straight line for the traffic.

Since the main design criterion for suspended structures is their deformability and stiffness (Kulbach, 1999; Schlaich et al., 2011), the structure is analyzed by choosing different composite parameters.

For the analysis of the structure, the limit stiffness conditions of the structure are selected and rational parameters are calculated with the use of analytical and numerical methods. The string structure and the combined string structure, which are presented in sections 2 and 3, are analyzed separately. The stresses and displacements of the structures depending on the limit deflections are analyzed.

String Structure Analysis

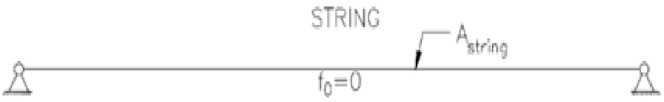


Figure 1. String structure

The well-known analytical expressions are used for the analysis of the string structure behaviour, their accuracy is confirmed by numerical methods (Linkute, 2015). The analysis is performed by applying the limits of the vertical displacements of the structure, and this condition is used for the calculation of the the required cross-sectional area of the string. The deflections of the analyzed structure are limited depending on the length of the span, i. e. three alternatives are investigated: $\Delta f_{lim} = (\frac{L}{400}, \frac{L}{250}, \frac{L}{100})$, where L is the span length, equal to 25 and 50 m.

By using the familiar string displacement equation (Linkute, 2015), we can calculate the required cross-sectional area:

$$\Delta f = \sqrt[3]{\frac{3}{64} \cdot \frac{(p+q)L^4}{EA}};$$

We express the required cross-sectional area, taking into account the above stiffness condition in the following way:

$$A = \frac{3}{64} \cdot \frac{(p+q)L^4}{E\Delta f_{lim}^3};$$

This expression is used for the required cross-sectional area of the string to be calculated. Since the analyzed string is given an additional prestress T, the required area is calculated as follows:

$$A = \frac{3}{64} \cdot \frac{(p+q)L^4(1-\beta)}{E\Delta f_{lim}^3};$$

$$\beta = \frac{T}{H_1};$$

$$H_1 = T + H;$$

$$H = \sqrt[3]{\frac{1}{24} \cdot \frac{EA \cdot (p+q)^2 L^2}{(1-\beta)}}.$$

where:

$\Delta f -$ displacement in the middle of the span;
$p + q -$ dead and live loads (2,5+7,5 kN/m);
$E -$ Elasticity module;
$A -$ cross-sectional area;
$H_1 -$ tension force, when the string is prestressed;
$H -$ tension force, when the string is not prestressed;
$T -$ prestressing force;
$\Delta f_{lim} -$ displacement limit.

We can calculate the stresses in such a string as follows:

$$\sigma = \frac{H}{A} = \frac{\sqrt[3]{\frac{1}{24} \cdot E \cdot (p+q)^2 L^2}}{(1-\beta) \cdot A^{\frac{2}{3}}} \leq \sigma_u;$$

where:

σ – stresses in the string;
σ_u – stress limit in the string.

In order to identify the advantages and disadvantages of the string and the possible uses, 2 options are considered: the span equal to 25 m and 50 m. All parameters are calculated based on the analytical method provided. In Tables 1-3 below we see the results where L = 25 m, in Tables 4-6 with L = 50 m.

The results show that the string must always be pre-tensioned, otherwise its use becomes irrational due to the extremely large cross-sectional area. We also see that the prestress reduces the vertical displacements, and at the same time it increases the stresses in the string. At the minimum limiting deflection of the string, the string has to be composed of a large axial stiffness cross section. As a result, with the increasing axial stiffness of the string and minimal change in tensile force, we will have lower stresses in the string when designing the structure according to the service limit state. In this case, it is generally irrational to apply the string, since steel as a material is not used for its purpose, and additional prestressing, due to high shear forces, will require extremely massive foundations.

If we provide the strings with a larger limit bend according to the design norms, we also have to follow the safety limit state. In Table 3 we see that when the ultimate deflection is L / 100 and the prestress is 20 MN, the stresses in the string reach as high as 2189 MPA. In this case, it would now be necessary to apply strong steels or spiral cables. In the case of such materials, the material behavior should also be evaluated. In order to use structural steel for the string (for example, steel strips), in the case of a marginal displacement of L / 100, we can tension the string to a maximum of 4-6 MN with a span of 25 m.

Table 1. Dependence of the required cross-sectional area of the string on the limit displacements and prestressing force at L = 25 m

Prestressing force T, kN	L/400	L/250	L/100
	String cross-sectional area A, m2		
0	3.75	0.92	0.06
200	3.69	0.89	0.06
600	3.58	0.85	0.05
1000	3.47	0.81	0.04
1200	3.42	0.79	0.04
4000	2.84	0.59	0.02
8000	2.29	0.41	0.01
10000	2.08	0.36	0.01
30000	1.10	0.14	0.00
50000	0.75	0.10	0.00

Table 2. Dependence of cross-sectional diameter on ultimate deflection and prestressing with L = 25 m

Prestressing force T, kN	L/400	L/250	L/100
	The cross-sectional diameter of the string, m		
0	2.19	1.08	0.28
200	2.17	1.06	0.28
600	2.14	1.04	0.25
1000	2.10	1.02	0.23
4000	1.90	0.87	0.16
6000	1.80	0.79	0.16
8000	1.71	0.72	0.11
10000	1.63	0.68	0.11
30000	1.18	0.42	0.00
50000	0.98	0.36	0.00

Table 3. Dependence of stress in the string on the ultimate deflection and prestress at L = 25 m

Prestressing force T, kN	L/400	L/250	L/100
	Stresses in the string, MPa		
0	3.33	16.98	52.08
200	3.41	17.86	54.98
600	3.57	19.32	72.95
1000	3.74	20.94	99.98
4000	5.10	35.90	334.68
6000	6.20	49.42	426.71
8000	7.43	66.86	1040.00
10000	8.87	85.36	1228.53
30000	32.34	480.18	-
50000	72.58	1057.99	-

Table 4. Dependence of string cross-section on ultimate deflection and prestress at L = 50 m

Prestressing force T, kN	L/400	L/250	L/100
	String cross-sectional area, m2		
0	7,5	1,831	0,117
200	7,44	1,808	0,11
600	7,324	1,763	0,107
1000	7,212	1,721	0,101
4000	6,466	1,458	0,071
6000	6,048	1,232	0,06
8000	5,682	1,211	0,051
10000	5,357	1,116	0,045
30000	3,409	0,627	0,02
50000	2,50	0,436	0,013

Table 5. Dependence of cross-section diameter when the cross-section is round, on the ultimate deflection and prestressing with L = 50 m

Prestressing force T, kN	L/400	L/250	L/100
	The cross-sectional diameter of the string, m		
0	3.09	1.53	0.39
200	3.08	1.52	0.37
600	3.05	1.50	0.37
1000	3.03	1.48	0.36
4000	2.87	1.36	0.30
6000	2.78	1.25	0.28
8000	2.69	1.24	0.25
10000	2.61	1.19	0.24
30000	2.08	0.89	0.16
50000	1.78	0.75	0.13

As we can see from Table 4, with a span of 50 meters and when limiting the displacement of the string to L/400, an extremely large cross-sectional area of the string (7.5 m^2) is required. This means that strings using a spiral cable require a cable with a diameter as thick as 3.1 m or 10 cables with 1 m in diameter. If we limit the boundary deflection of the string to L/100, we will need a 0.4 m diameter cable. After prestressing it with a force of 4000 kN, we will need a 0.3 m diameter cable. Since one of the main goals in designing and composition of a structure is to minimize the use of materials, it appears that the string should be used for structures with a smaller span where its ultimate deflection is limited to L/400 and more.

Graph 2 shows the results of the cross-sectional area of the string required to satisfy the limit displacement conditions. Graph 1 and Table 6 show the magnitude of the stresses occurring in the string. We can see that when the limit displacement is L/100, more attention should be paid to the stresses generated in the string as the cross-section may simply no longer satisfy the safety limit state.

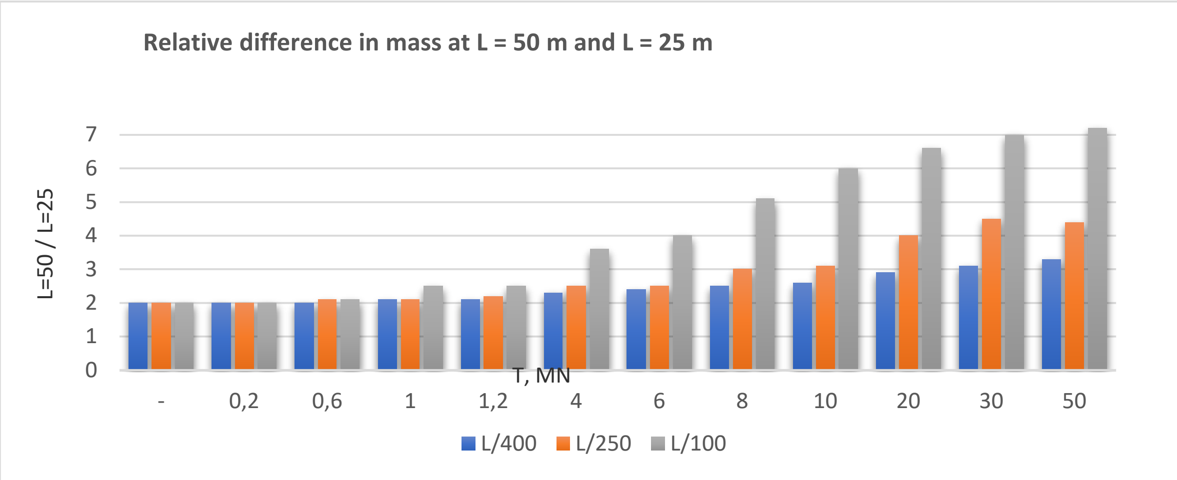
To show the differences more accurately, in Table 7 and Fig. 2 we can see how much the weight of the structure or the cross-section diameters will differ (in the case of a round shape cross-section) by comparing the spans of 25 and 50 meters. We can see that if the deflections of the structure should not exceed the limit values L/400, depending on the prestressing the masses differ from 2 to 3.3 times. At the same time according to Table 5 we can assume that the use of a string is highly irrational when the stiffness L/400 is required, and the use of a string is rational only at limiting deflections L/100. As a result, the weight of 25-meter span and 50-meter span structures can vary from 2 to 7 times, while increasing the span of the structure. This leads us to a conclusion that it is recommended to design a span of 50 meters only by tensioning the string to at least 1200 kN and limiting the stiffness to no more than L/100.

Table 6. Dependence of the stress in the string on the ultimate deflection and prestress at L = 50 m

Prestressing force T, kN	L/400	L/250	L/100
	Stresses in the string, MPa		
-	3,33	8,53	53,33
200	3,36	8,64	55,04
600	3,41	8,86	58,45
1000	3,47	9,08	61,88
4000	3,87	10,72	87,47
6000	4,13	11,81	104,53
8000	4,40	12,90	121,60
10000	4,67	14,00	138,67
30000	7,33	24,92	309,33
50000	10,00	35,84	480,00

Table 7. Relative difference in string cross-sections when the spans are 25 and 50 m, respectively. (L = 50 / L = 25)

Prestressing force T, kN	L/400	L/250	L/100
	The ratio of the cross-sectional areas of the string where L = 50 m and L = 25 m		
0	2.0	2.0	2.0
200	2.0	2.0	2.0
600	2.0	2.1	2.1
1000	2.1	2.1	2.5
4000	2.3	2.5	3.6
6000	2.4	2.5	4.0
8000	2.5	3.0	5.1
10000	2.6	3.1	6.0
30000	3.1	4.5	7.0
50000	3.3	4.4	7.2



In order to overlap the larger spans and keep the advantages of the string, the string needs to be combined with an additional support cable to limit vertical displacements. When combined with a supporting cable, most of the symmetrical load is taken over by the lower cable and as a result we have smaller displacements from the symmetrical load. The string, meanwhile, operates under an asymmetrical load when it takes over the kinematic displacements caused by the cable and reduces the overall displacements of the entire system. The parametric analysis of the combined structure is presented in section 3.

Figure 2. Relative difference in mass at L = 50 m and L = 25 m

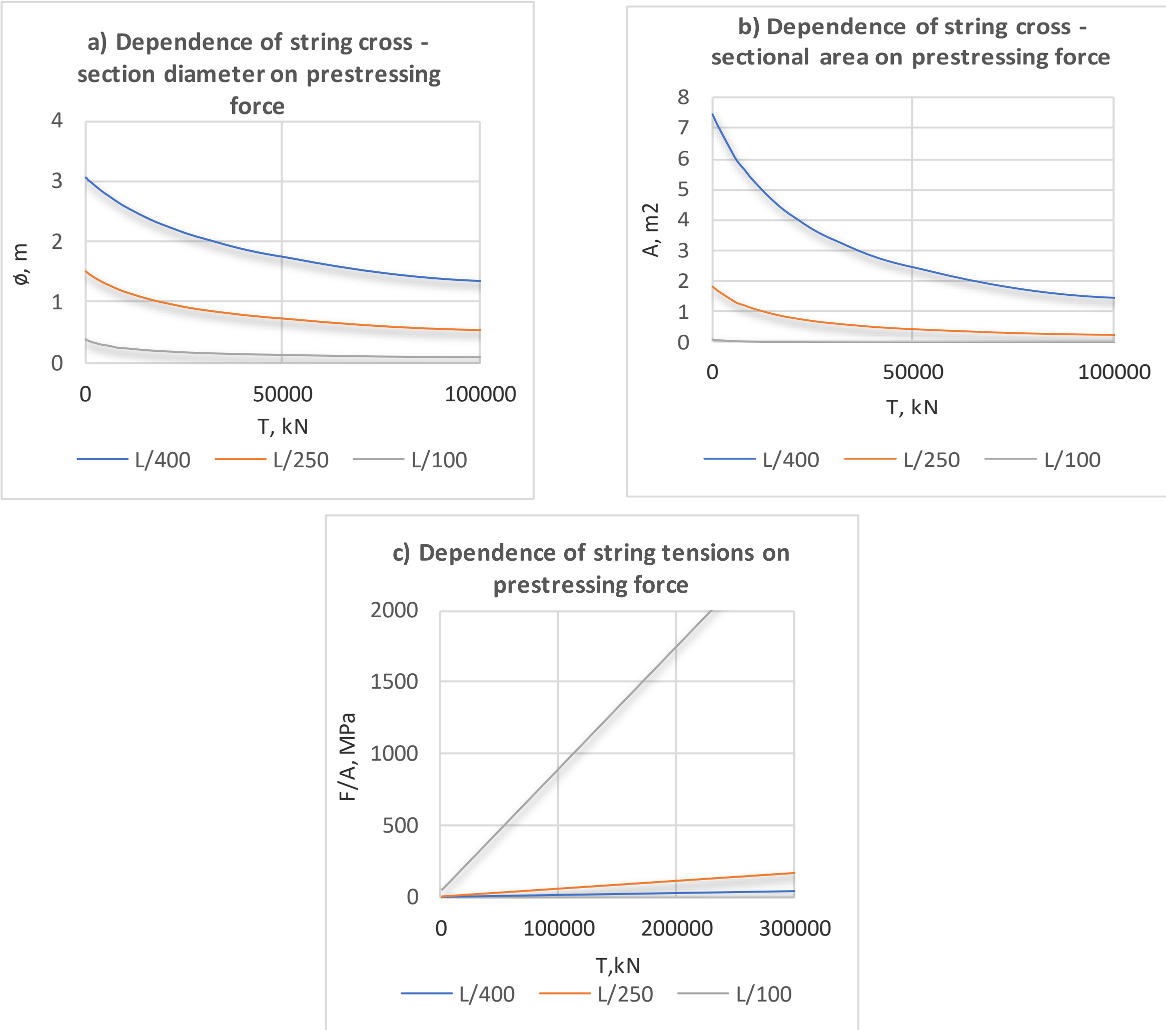


Figure 3. Dependence of string and lower cable parameters on limit deflections and axial stiffness

The Analysis of The Combined String Construction

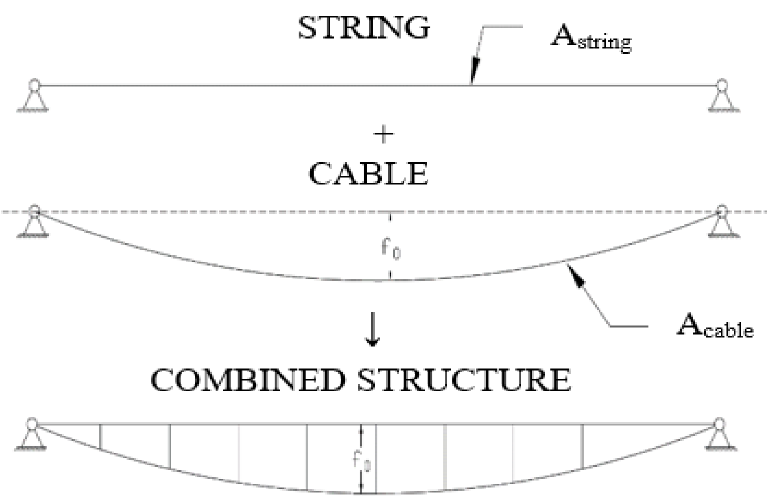


Figure 4. Combined string structure

The combined structure is a combination of a single-span and string structure. As seen in Figure 2, the string is supported by auxiliary cable using struts. This way the structure is combined into a joint operation. For the analysis of the combined structure, the familiar approximate calculation expressions are used (Beivydas, 2019).

$$\Delta f_{comb.} \cong \frac{3}{128} \cdot \frac{L^4}{E_{cable} \cdot A_{cable} \cdot f_0^2} \cdot (p+q)_{cable}; \quad (p+q)_{cable} = \sqrt[3]{\sqrt{\frac{1}{27} \cdot C^3 + \frac{1}{4} \cdot D^2} - \frac{1}{2} \cdot D} + \sqrt[3]{-\sqrt{\frac{1}{27} \cdot C^3 + \frac{1}{4} \cdot D^2} - \frac{1}{2} \cdot D};$$

Where:

$$C = \frac{32768}{9} \cdot \frac{E_{cable}^3 \cdot A_{cable}^3 \cdot f_0^6}{E_{string} \cdot A_{string} \cdot L^8};$$

$$D = (p+q) \cdot \frac{32768}{9} \cdot \frac{E_{cable}^3 \cdot A_{cable}^3 \cdot f_0^6}{E_{string} \cdot A_{string} \cdot L^8};$$

From these equations, we can notice what is required for the axial stiffness of the string and cable, depending on all parameters, i. e. the span length, the initial sag of the lower cable, the cross-sectional area of the string and the cross-sectional area of the lower cable.

$$A_{cable} \cong \frac{3}{128} \cdot \frac{L^4}{E_{cable} \cdot \Delta f_{Lim} \cdot f_0^2} \cdot \left[\sqrt[3]{\sqrt{\frac{1}{27} \cdot C^3 + \frac{1}{4} \cdot D^2} - \frac{1}{2} \cdot D} + \sqrt[3]{-\sqrt{\frac{1}{27} \cdot C^3 + \frac{1}{4} \cdot D^2} - \frac{1}{2} \cdot D} \right];$$

Table 8. Dependence of cross-sectional areas of combined structure on limit deflections.

Δf_{lim}	f_0	A, m^2 10^{-4}	n=3	n=1	n=0.5
L/100	L/10	A_s	22.53	11.38	8.55
		A_c	5.63	5.69	5.7
		A_{tot}	64.71	22.42	11.32
	L/20	A_s	86.28	44.84	33.96
		A_c	21.57	22.42	22.64
		A_{tot}	311.79	127.03	67.25
	L/50	A_s	415.72	254.06	201.75
		A_c	103.93	127.03	134.5
		A_{tot}	5.63	5.69	5.7
L/250	L/10	A_s	57	28.56	21.44
		A_c	14.25	14.28	14.29
		A_{tot}	169.86	56.98	28.54
	L/20	A_s	226.48	113.96	85.61
		A_c	56.62	56.98	57.07
		A_{tot}	1011.18	350.28	176.87
	L/50	A_s	1348.24	700.56	530.61
		A_c	337.06	350.28	353.74
		A_{tot}	16.9	5.69	2.851
L/400	L/10	A_s	68.49	22.86	11.43
		A_c	22.83	22.86	22.87
		A_{tot}	91.32	45.72	34.3
	L/20	A_s	273.36	91.35	45.71
		A_c	91.12	91.35	91.41
		A_{tot}	364.48	182.7	137.12
	L/50	A_s	1675.68	567.21	284.71
		A_c	558.56	567.21	569.42
		A_{tot}	2234.24	1134.42	854.13

Equations are used to calculate the cross-sectional areas of the string and the lower cable at the limit deflections at different axial stiffness ratios of the string and the lower cable. 3 options of the difference in axial stiffness are selected (the ratio of the cross-sectional areas of the string and the cable), i.e. when the axial stiffness of the string is 5, 1 and 0.5 times higher. In the same way 3 different limit deflections and 3 different lower cable displacements are selected. The axial stiffnesses of the cable, the axial stiffness of the string and the total axial stiffness are calculated separately to see the differences between the string and the lower cable. More details can be seen in fig. 5.

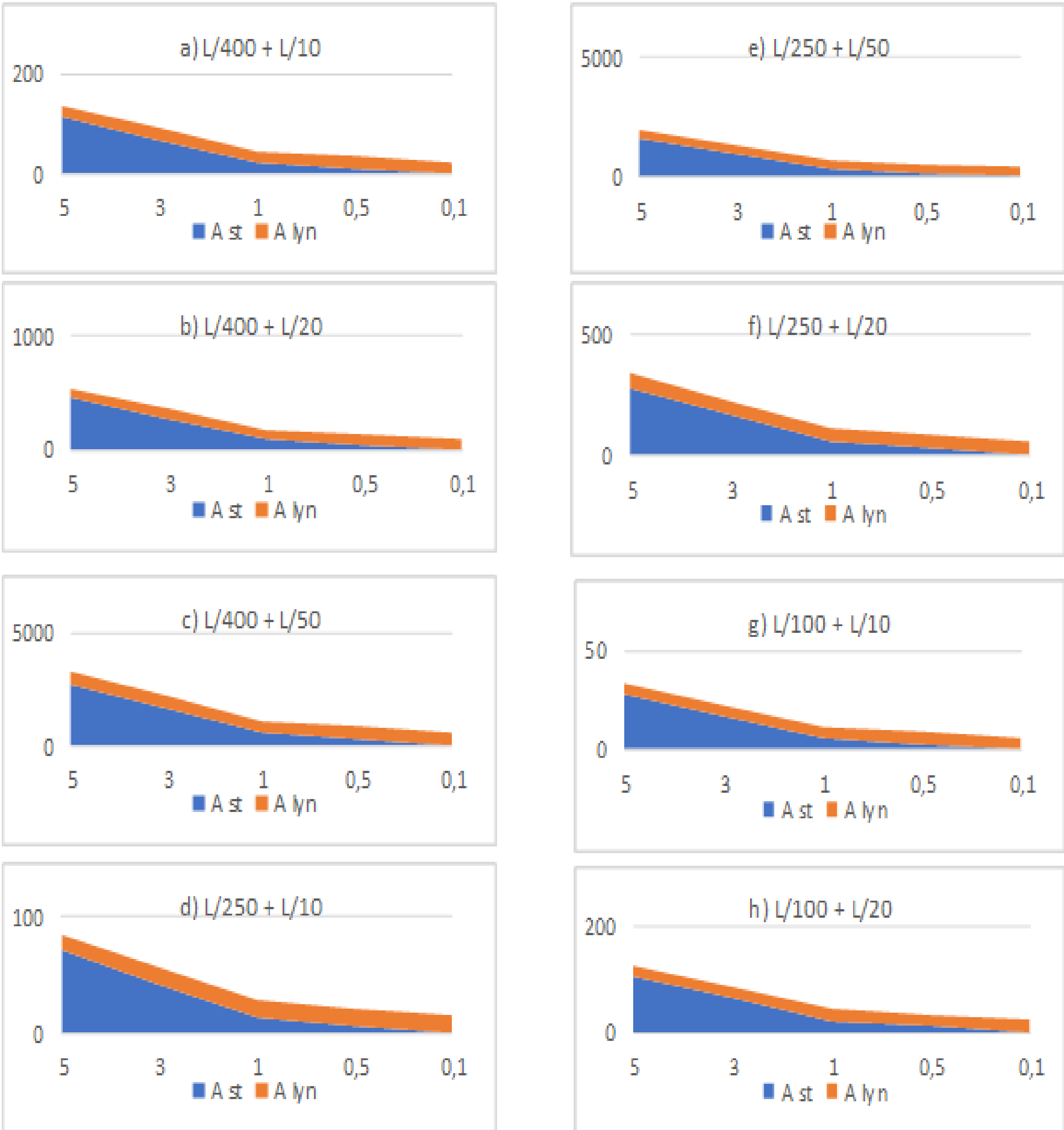


Figure 5. Dependence of the cross-sectional areas of the string and the lower cable on the ratio of the limit deflection and the axial stiffness. Where horizontal axis – String and lower cable cross-sectional area ratio (A_{st}/A_{cable}); Vertical axis – cross-sectional area; [L/x=1,2,3… + L/y=1,2,3…] – L/x=1,2,3… – limit of displacements, L/y=1,2,3… – initial sag ratio.

In Fig. 5, we see that almost in all the cases, only the strings and the total cross-sectional areas change as the axial stiffness ratio changes. Consequently, when the string is not pre-tensioned, almost the entire load is taken over by the lower cable, so the change in axial stiffness of the string is practically insignificant. Thus, if we have a non-tensioned string, it should be designed with the smallest possible cross-sectional area, transferring the entire load to the lower cable.

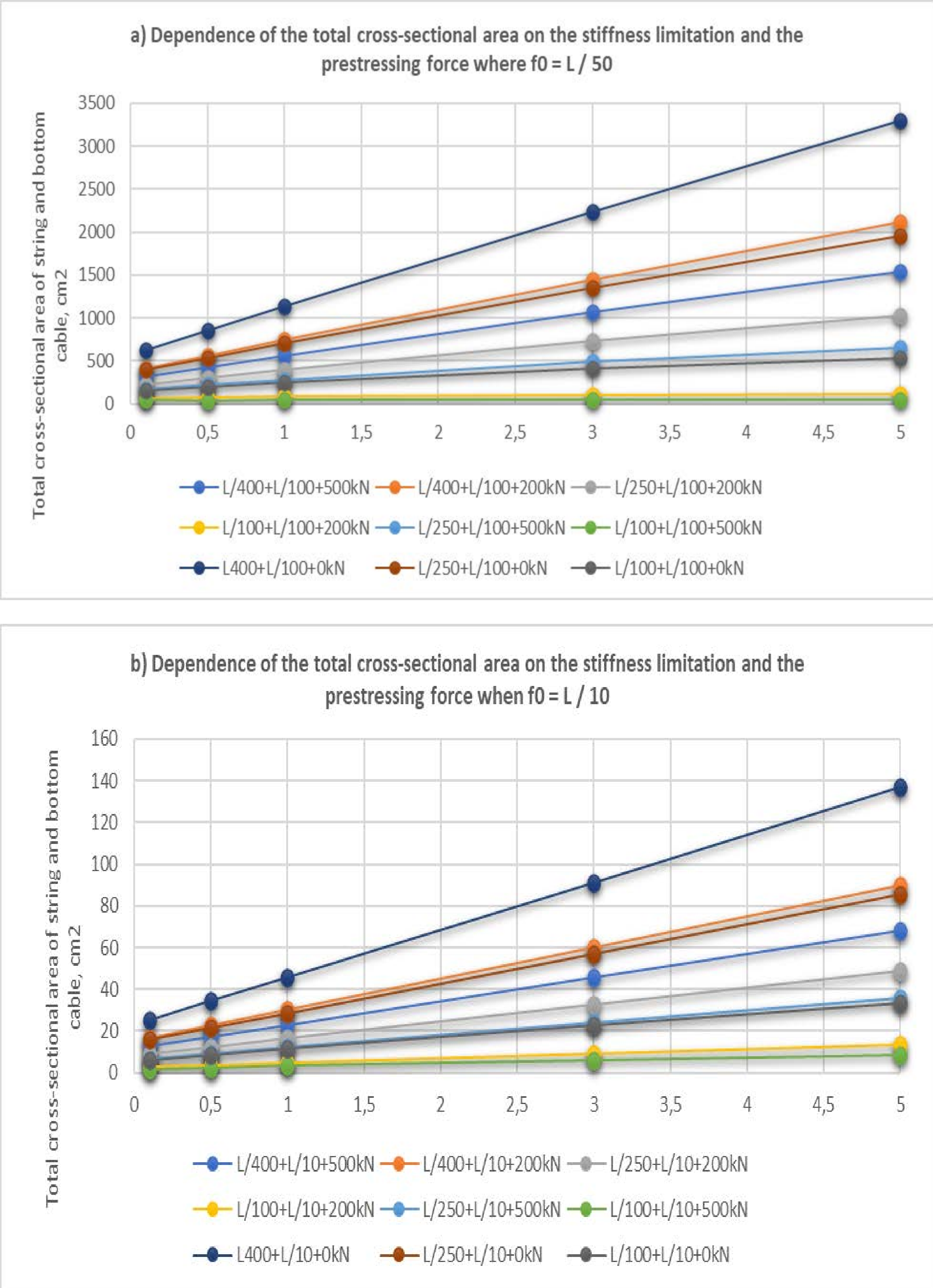


Figure 6. Dependence of the cross-sectional areas of the string and the lower cable on the ratio of the limit deflection and the axial stiffness. Where: [L/x=1,2,3… + L/y=1, 2, 3… + Z kN], L/x=1,2,3… + L/y=1,2,3…] – L/x=1,2,3… – limit of displacements, L/y=1,2,3… – initial sag ratio, Z – prestressing force.

The situation changes if the string is pre-tensioned. Very little additional prestressing force is required to express the advantages of the string. While comparing the option where the ultimate deflection is L/400 and the initial deflection of the lower cable is L/10, without prestressing with the option where the string is tensioned at 500 kN, when the ratio of axial stiffness is 5, the total cross-sectional area is reduced by 2 times; when the ratio of axial stiffness is 0.1, it decreases - 1.7 times. It is clear that regardless of the lower deflection of the lower cable, the pre-force gives the same result as the change in the mass of the structure.

Knowing that the prestress of a string has a significant effect on its axial stiffness when displacements is limited, the following are the results of the magnitudes of stresses in the string and the lower cable depending on the prestress of the string and the ratio of the axial stiffness of the string to the lower cable. The amount of the stresses indicates whether the main indicator is the safety limit state or the service limit state. Also, depending on the values of the forming stresses, it is possible to select the material used for both the string and the cable.
Tables 9 and 10 show that the string requires minimal stresses if it is not prestressed and how the stresses change after it is prestressed. Also, comparing the stresses and axial stiffnesses in the string and the lower cable, we see that the stresses are higher at a smaller cross-sectional area of the string and cable, which means that the element is used with higher efficiency.

Table 9. Dependence of stress in a string on limit deflection and prestressing (without pre-tension)

Δf_{lim}	f_0	σ, MPa	n=3	n=1	n=0.5
L/100	L/10	σ_s	0.41	0.27	0.18
		σ_c	95.30	277.52	550.88
	L/20	σ_s	0.41	0.27	0.18
		σ_c	546.70	546.61	546.65
	L/50	σ_s	0.41	0.27	0.18
		σ_c	218.67	218.67	218.67
L/250	L/10	σ_s	0.07	0.04	0.03
		σ_c	437.55	437.33	437.19
	L/20	σ_s	0.07	0.04	0.03
		σ_c	218.67	218.68	218.68
	L/50	σ_s	0.07	0.04	0.03
		σ_c	87.47	87.47	87.47
L/400	L/10	σ_s	0.03	0.03	0.03
		σ_c	273.51	273.32	273.24
	L/20	σ_s	0.03	0.03	0.03
		σ_c	136.67	136.67	136.66
	L/50	σ_s	0.03	0.03	0.03
		σ_c	54.67	54.67	54.67

Table 10. Dependence of stress in a string on limit deflection and prestressing (T=1000 kN).

Δf_{lim}	f_0	σ, MPa	n=3	n=1	n=0.5
L/100	L/10	σ_s	93.26	217.95	403.46
		σ_c	243.84	380.92	470.37
	L/20	σ_s	37.39	81.56	146.86
		σ_c	546.72	546.61	546.90
	L/50	σ_s	17.53	25.39	36.48
		σ_c	218.69	218.67	218.67
L/400	L/10	σ_s	36.65	109.55	218.85
		σ_c	273.35	273.37	273.29
	L/20	σ_s	9.31	27.54	54.87
		σ_c	136.66	136.67	136.66
	L/50	σ_s	1.66	4.58	8.95
		σ_c	54.67	54.67	54.67

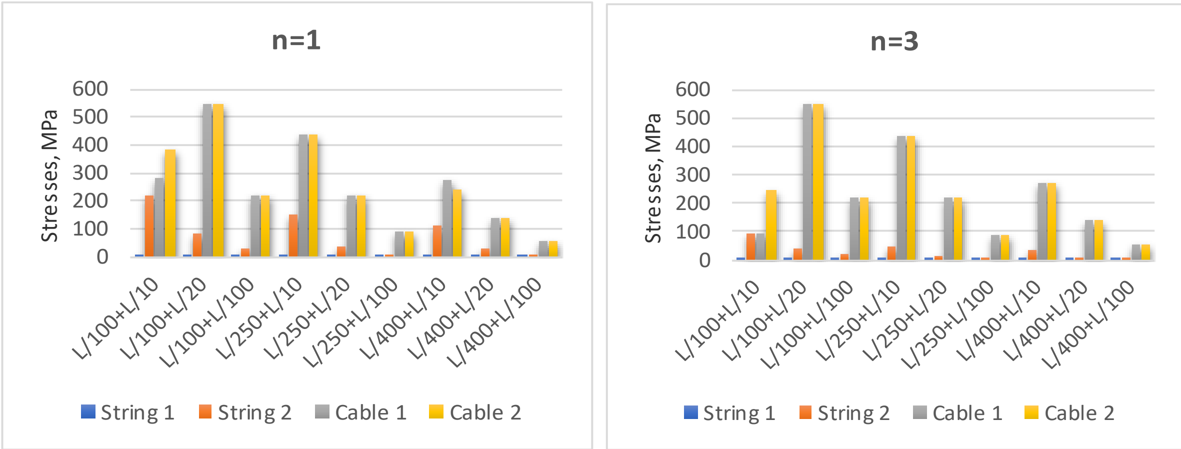


Figure 7. The dependence of the stresses in the string and the lower cable on the limit deflections of the structure when the string is additionally tensioned and non-tensioned. Where: [1] – string is not prestressed, [2] – string is bprestresssed, n – string ant lower cable cross-sectional ratio (A_{st}/A_{cable})

If we compare the differences between the string and the combined structure, we will see that the advantages of the combined structure are indisputable. However, it should be considered that the string fulfils its role in the functional way, and also all the advantages of the string are present with an asymmetrical load on the structure (Beivydas, 2018). Fig. 7 shows that regardless of whether the string is prestressed or not, in almost all the cases the stresses in the lower cable do not change, although the cross-sectional areas are reduced significantly.

Conclusions

The performed parametric analysis revealed the main advantages of the combined design compared to string and single-span constructions. When designing and composing a string structure, its main advantages are the definition of a straight line and the fact that it has only elastic displacements. The analysis of the parameters of the string through the ultimate stiffness shows that the string can be used only with small (up to 25 m) spans. When loading the string with a symmetrical load, the string must be pre-tensioned. Meanwhile, increasing the span of the string a problem appears where in order not to exceed the limit deflections, prestressing has to be increased immensely as well as the axial stiffness of the string. Although the stiffness of the string depends on the axial stiffness and the prestressing force, the actual problem is that by increasing the axial stiffness of the string, we increase the mass of the string, which consequently increases the load. This creates a dilemma in case of large spans. The more we increase the axial stiffness, the more the load will increase. The idea simply becomes irrational. In the case of single-span structures, in contrast to the string structures (depending on their initial sag) these absorb symmetrical loads perfectly and their elastic displacements are not large. However, in the case of asymmetric effects and taking into account that a single-span structure is not functional due to its shape definition, a single-span structure can be applied only to structures whose deformability is less limited and the shape of the structure is not particularly important functionally, i.e. in pedestrian bridges. Although in this case we can use larger spans (25-100 meters), the use of such a structure is strongly determined by functionality and usability. That is in the case of large spans, we will also have large initial sag, as a result of which such a structure will take up a considerable amount of space geometrically, thus, the field of application will be greatly reduced. Certainly small initial sag can be used, but this will cause the same problems as with the use of the string. By reducing the initial single-span sag, although we the kinematic displacements will be reduced, this will greatly increase the elastic displacements. When increasing the elastic displacements, we face the problem that the only way to increase the stiffness of a single span is to increase the cross-sectional area of the cable. The axial stiffness of the cable increases the mass of the structure, which becomes irrational. All these problems are solved by combining these two constructions into a joint operation. In order to limit the elastic displacements that are mainly taken over by the lower cable, we can increase the axial stiffness of the lower cable. In the case of asymmetrical effects, they are covered by the string. Also, not only in terms of deformations and stresses, such a structure can be used much more widely, due to its straight line.

Section 3 reveals that while using a non-prestressed string, almost all of the symmetrical loads are taken over by the lower cable, and when at least a little tension is applied, the string is also involved in the operation, immediately reducing the overall displacements of the structure. It can be concluded that when designing a structure, the axial stiffness of the string should be chosen to be the same as that of the lower cable or smaller, in order to take advantage of the prestressing of the string. The string can be pretensioned to its safety limit state because the tensions of the lower cable do not change or have minimal changes as a result. When comparing the string, the single-span and the combined structures with the same mass, one can achieve 2-3 times larger spans with a combined structure.

Scientific Ethics Declaration

The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

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