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BEHAVIOR OF PRE-STRESSED INTERSECTING CABLE STEEL BRIDGE

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Abstract. Cable-stayed bridges are known as one of the most effective and graceful forms of bridges. The main problem in the design of cable-stayed steel bridges is their deformability, especially under asymmetrical loads. Stabilization of the initial form of cable-stayed bridges can be achieved by selecting the appropriate cross-sectional area of the cables and their pre-stressing, as well as by increasing the cross-sectional height of the stiffness beam. However, a greater effect can be achieved by applying new forms of such bridges. Solutions for such bridges with an atypical arrangement of cables and additional pylons are already applied in practice. The article discusses an innovative pre-tensioned intersecting cable steel bridge structure system. The behavior of this bridge system under permanent and temporary loads is analyzed. Based on the performed numerical experiment, the efficiency of the innovative cable-stayed steel bridge system was determined. This newly designed bridge system is more effective in terms of stress and displacement distribution than a classic cable-stayed bridge system.

Keywords: cable-stayed bridge, steel bridge, intersecting cables, non-linear analysis, stresses, displacements, pre-stressing.

Introduction

Due to their efficiency and architectural appearance, cable-stayed bridges take a special place among other bridge construction systems (Gimsing & Georgakis, 2012; Svensson, 2012). Cable systems are also successfully used in pedestrian bridges with lower spans (Strasky, 2005; Song et al., 2018; Pearce & Jobson, 2002). However, these bridges also have several drawbacks. First, they are deformable under asymmetrical loads and have relatively heavy stiffening girders and pylons (Martins et al., 2020; Ferreira & Simoes, 2019; Reis & Oliveira Pedro, 2019). To “control” the behavior of cable-stayed bridges under different loading variants, certain design solutions are applied: additional cables, “branching” cables, pylon joints, etc. (Walther et al., 1999; Lee et al., 2008; Malinowski et al., 2018). Secondly, the minimum angle of inclination of the cable limits their application possibilities. If the cable is tilted at an angle of fewer than 30 degrees, it becomes inefficient (Straupe & Paeglitis, 2012). This leads to the need for a high pylon, especially to overlap large spans. Unfortunately, urban or economic conditions can limit the height of the pylon, thus reducing the adaptability of the system (Cid et al., 2018).

A successful means of stabilizing the initial shape of the bridge could be the use of crossbows and additional intermediate pylons (Beivydas, 2019). This allows to reduce the height of the main pylons and at the same time successfully control the displacements of the bridge. The following examples of this kind of cable-stayed pedestrian bridges have been implemented in: Royal Victoria Dock Bridge in the United Kingdom (Pearce & Jobson, 2002), Passerelle du Grand Large Bridge in Dunkirk (Robin et al., 2014), and Taiping North Road Pedestrian Bridge (Brownie et al., 2008). The system of intersecting cables in these bridges allows the use of relatively light girder beams.

The article discusses an innovative cable-stayed steel bridge system consisting of intersecting cables and additional intermediate pylons. The behavior of this new structural system under symmetrical and asymmetrical loads is analyzed using a numerical experiment (Evans, 2009). The article evaluates the efficiency of the load-bearing structural system of this cable-stayed steel bridge.

1. Intersecting cables and equal pylons bridge variant

As already mentioned, the system of intersecting cables cable-stayed bridge structures has not only two main pylons arranged at the bridge supports, but also intermediate

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*Corresponding author. E-mail: *povilas.dabrila@vilniustech.lt* pylons mounted on the stiffness beam along the length of the bridge span at the points of attachment of conventional bridge cables. The pylons are arranged in a uniform step of 20 m along the entire length of the bridge to form a truss-like grid. These intermediate pylons can be rigidly or flexibly connected to the stiffness beam. Pre-tensioned cables are laid from the top of the intermediate pylons to the points of attachment of the adjacent pylons to the stiffness beam (Figure 1). Such a system of pylons and intersecting cable-stays not only reduces (compared to the classic cable-stayed bridge) the height of the pylons, but also allows to control the displacements of the stiffness girder not only in the case of symmetrical, but also in the case of asymmetrical loading. In order to determine the influence of intermediate pylon heights on the stresses and displacements of the cable-stayed bridge, the variants of the same and different intermediate pylon heights were chosen.

In the first variant, the heights of all pylons are chosen to be the same 20 m (see Figure 1). The distance between the pilons would be constructed in such a way that the angle of inclination of the cross shrouds is 45°.

For the numerical analysis of the behavior of cable-stayed bridges, bridge constructions with the length of the main span of 100 meters were selected. The applied loads are evenly distributed on the longitudinal beams. The constant load is 12.5 kN/m. The variable (traffic) load (12.5 kN/m) is divided into two variants: symmetrically over the entire length of the bridge and asymmetrically over half of its length. The cross sections of the structural elements are given in Table 1. The main load-bearing elements of the bridge (beam and pylons) are designed from structural steel S355. Cables are heavy steel (HSS) round cross-section elements of group A (European Committee for Standardization, 2006).

The analysis of the considered bridge structure systems (numerical modeling) was performed using the BEM program and using a geometrically nonlinear calculation procedure. The summary results of the behavioral analysis of this bridge variant are presented in Table 2. Figures 2–4 show the diagrams of stress distribution (axial forces and bending moments) and displacements in the structural elements of the bridge under symmetrical and asymmetrical loads. The presented data show that the values of bending

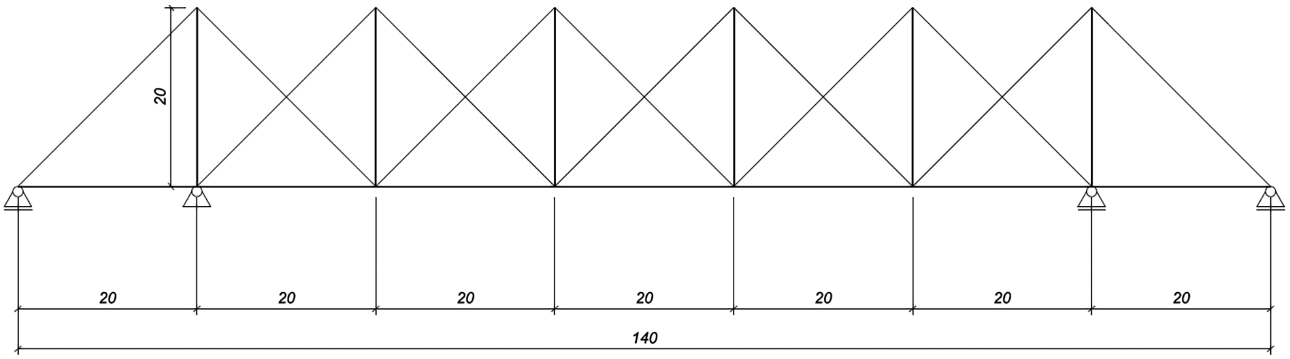

Figure 1. Equal pylons bridge

Table 1. Sections of structural elements

Element	Steel type	Shape type	Parameters
Cables	S960	●	d = 0,05 m
Pylons	S355	○	d = 0,508, t = 0,03 m
Girder	S355	▯	610×305, t = 0,019 m

Table 2. Equal pylons bridge elements stresses

Equal pylons bridge							
Girder							Cable
	Maximum bending moment [kNm]		Minimum bending moment [kNm]		Axial forces [kN]	Deflection [mm]	Axial forces [kN]
	M+	M-	M+	M-			
Symmetrical loading	894	728	639	244	–2463	754	2604
Asymmetrical loading	874	657	438	134	–2102	528	2260

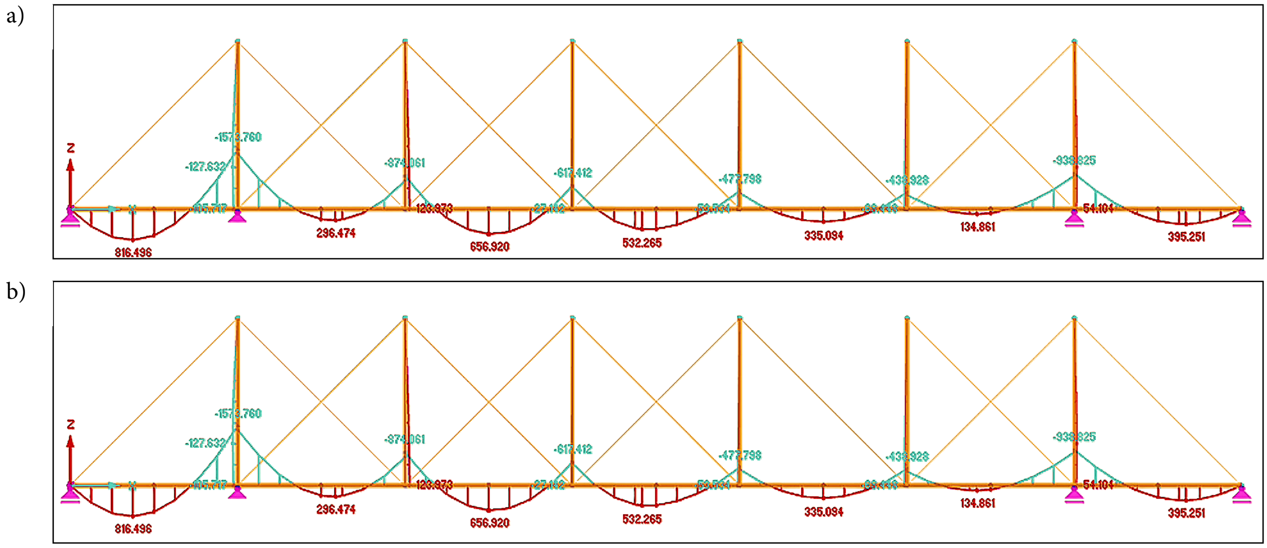

Figure 2. Equal pylons bridge. Bending moments: a) under symmetrical loading; b) under asymmetrical loading

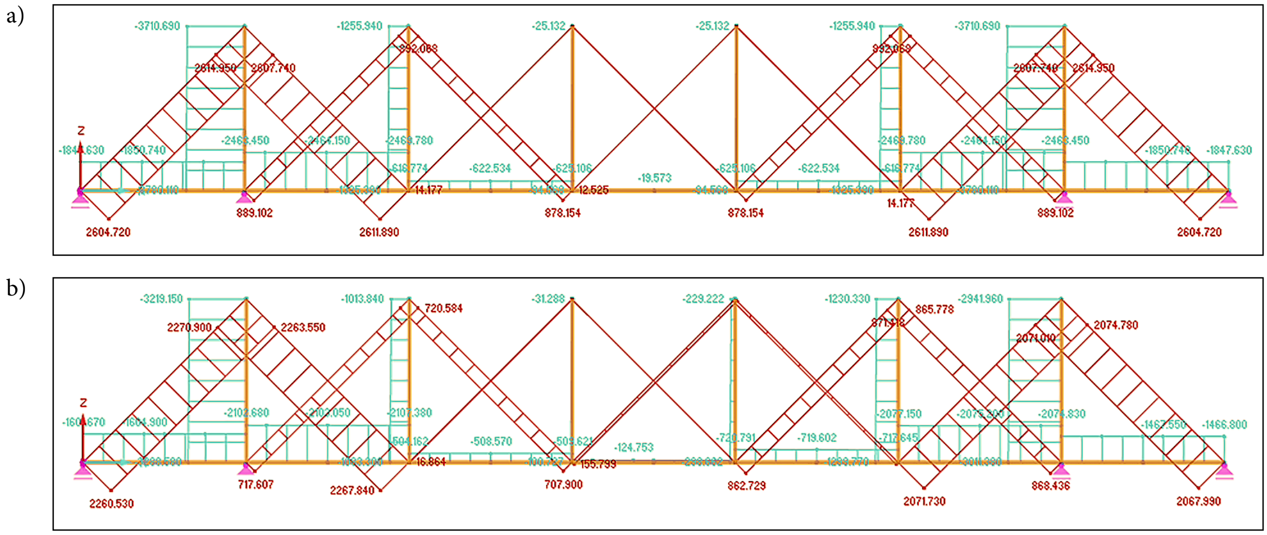

Figure 3. Equal pylons bridge. Axial forces: a) under symmetrical loading; b) under asymmetrical loading

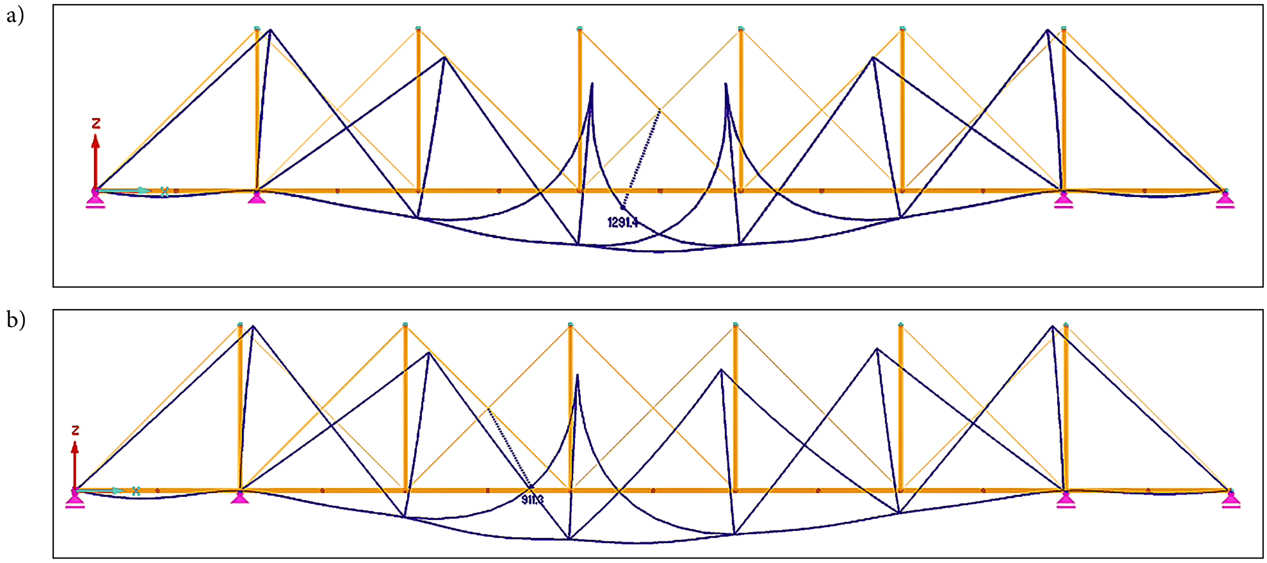

Figure 4. Equal pylons bridge. Deflections: a) under symmetrical loading; b) under asymmetrical loading

moments in the stiffness girder in the case of asymmetrical loading are close to the values of the moments caused by symmetrical loading. The same could be said for the distribution of axial forces in the cables and the stiffness girder under different load variants. These results demonstrate the behavioral advantages of the new design system because in classic cable-stayed bridges, asymmetrical loading often results in significant asymmetries in the stress distribution: higher bending moments in the main span of the stiffness beam and lower axial forces in the sheds and the stiffness beam. It was found that the maximum value of bending moment in the stiffness beam is formed under symmetrical loading and is equal to 1640 kNm at the main pylon, and the lowest (244 kNm) in the beam span. This difference between the maximum and minimum values of bending moments in the stiffness girder is due to the accepted element scheme of the stiffness girder.

When analyzing the displacements of the bridge stiffness girder, it can be seen that in the case of asymmetric loading the displacements are distributed practically symmetrically with respect to the middle of the span and their values are smaller (about 30%) than in the case of symmetrical loading.

2. Intersecting cables and varying pylons bridge variant

As already mentioned, the "challenges" of the behavior of cable-stayed bridges can be reduced by changing the standard (conventional) cable-staying scheme to the so-called cross-crossing (see Figure 2). It is proposed to improve the cross-hinge system by installing different pylon heights and vary them according to the parabolic curve (see Figure 5). The bridge of this structure is sometimes called the inverted truss of Fink (Robin et al., 2014). Such an innovative bridge construction has another peculiarity – the point of the highest pylon with cables and the stiffness beam of its bridge can be, as is usual in cable-stayed bridges, sliding in a horizontal direction.

A visualization of the obtained analysis results is provided in Figures 6–8, and the summarized results are presented in Table 3.

The displacements and stresses of this bridge variant in the case of symmetrical and asymmetrical loading differ relatively little, on average about 7 percent. This testifies to the ability of this cross-shaft construction system to successfully "resist" asymmetrical loading.

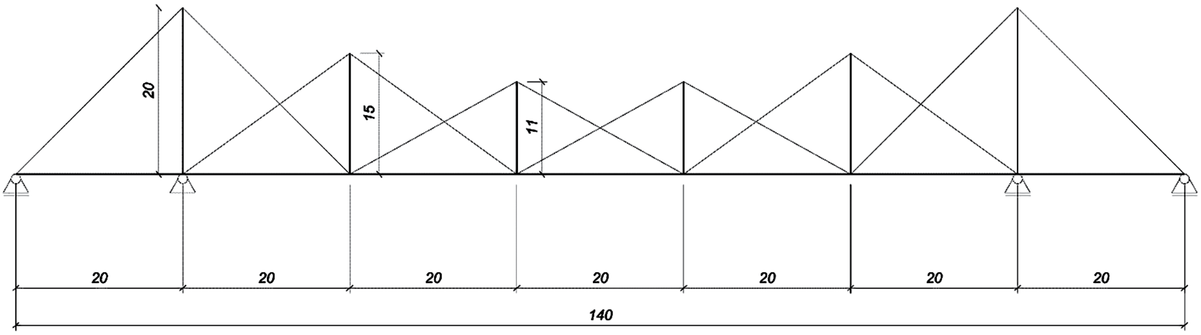

Figure 5. Varying pylons bridge

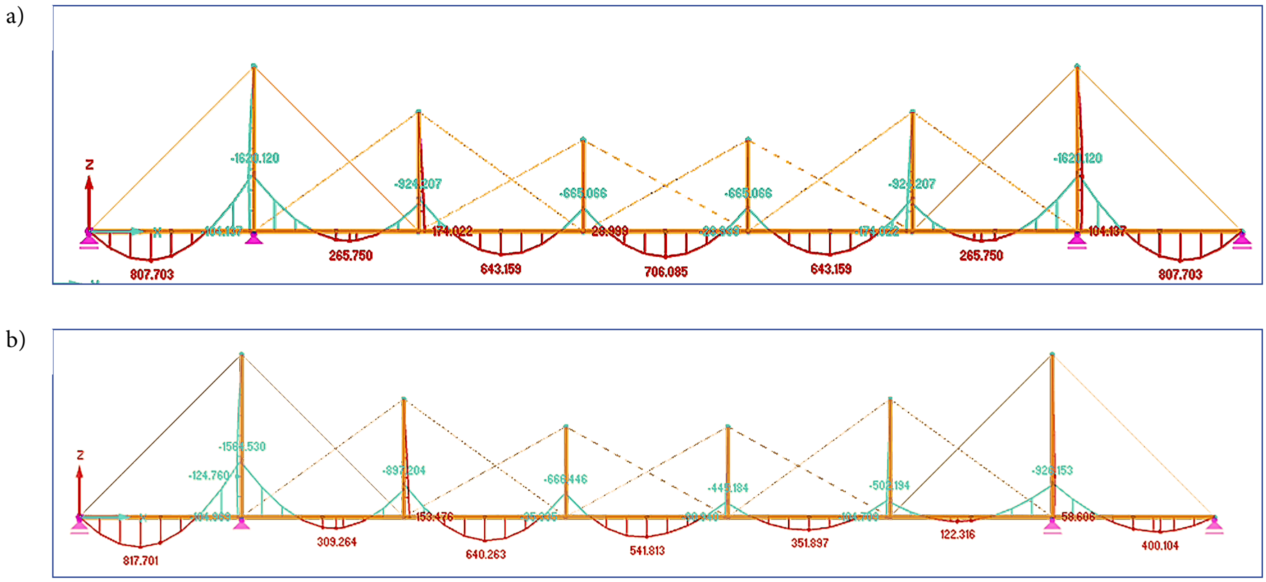

Figure 6. Varying pylons bridge. Bending moments: a) under symmetrical loading; b) under asymmetrical loading

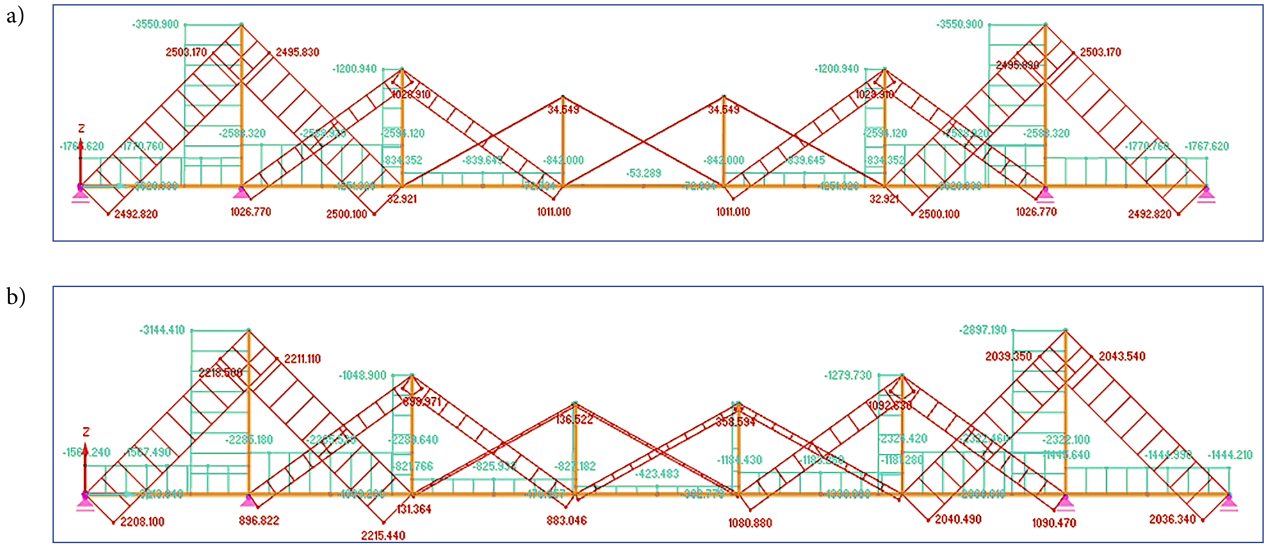

Figure 7. Varying pylons bridge. Bending moments: a) under symmetrical loading; b) under asymmetrical loading

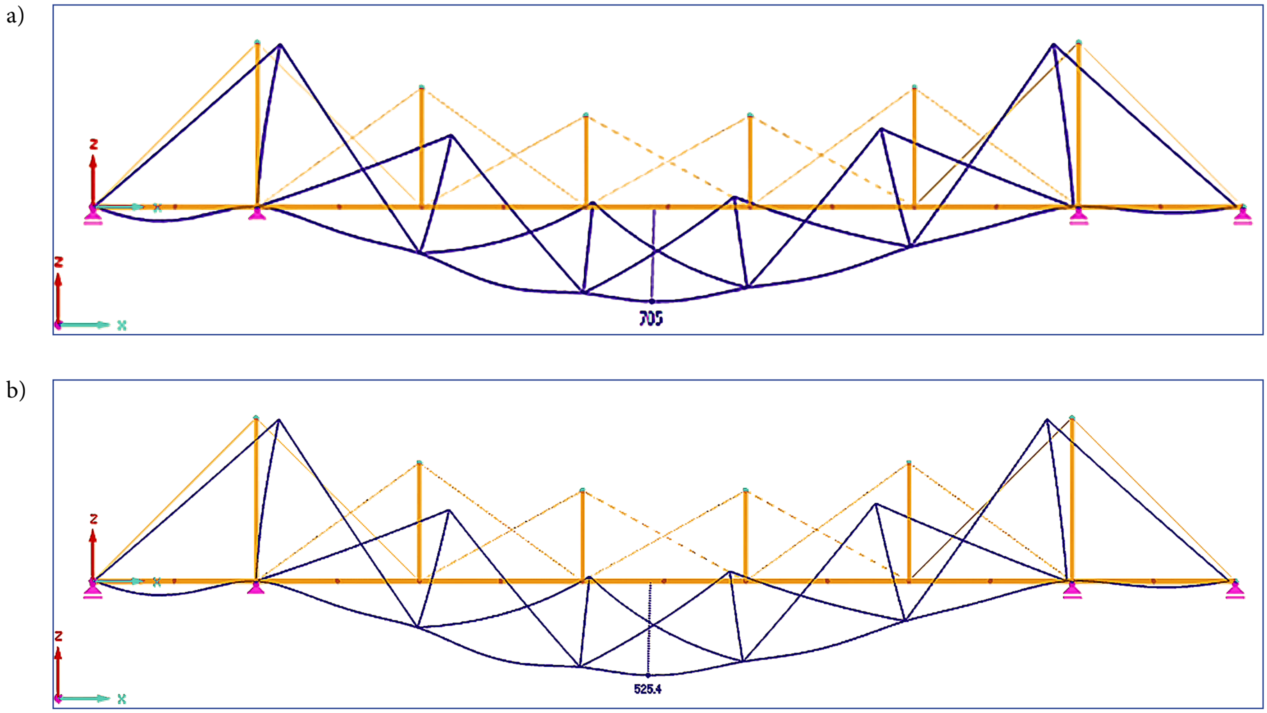

Figure 8. Varying pylons bridge. Deflections: a) under symmetrical loading; b) under asymmetrical loading

It can be seen in Figure 6 that the maximum bending moments in the stiffness girder in the case of asymmetrical loading are lower than the moments caused by the symmetrical loading in it. Maximum axial forces in the cables and pylons under asymmetrical loads are also lower than under symmetrical loads.

When comparing the two intersecting cable bridge variants it should be noted that the bending moments in the stiffness beam are about 4 percent lower than in the equal pylon height bridge variant for both symmetrical and asymmetrical loading (Tables 2 and 3).

The analysis of the previously discussed bridges is performed by comparing them with a standard cable-stayed bridge (Table 4, Figure 9). The most pronounced difference in bending moments between standard and intersecting cable systems can be observed by examining the relationship between asymmetrical and symmetrical loading results. In both cases, the asymmetrical loading on the stiffness beam caused higher stresses than the symmetrical ones. However, in a cross-type bridge, asymmetrical loading at the central span at no point generates greater bending stresses than symmetrical loading. When the bridge is operated under different load combinations, the moments are not higher that discussed outline, so we can predict the behavior of this system.

Table 3. Varying pylons bridge elements stresses

Varying pylons bridge							
Girder							Cable
	Maximum bending moment [kNm]		Minimum bending moment [kNm]		Axial forces [kN]	Deflection [mm]	Axial forces [kN]
	M+	M-	M+	M-			
Symmetrical loading	924	–706	665	265	–2285	705	2500
Asymmetrical loading	897	–640	445	122	–2588	525	2215

Table 4. Standard cable-stayed bridge elements stresses

Standard cable-stayed bridge							
Girder							Cable
	Maximum bending moment [kNm]		Minimum bending moment [kNm]		Axial forces [kN]	Deflection [mm]	Axial forces [kN]
	M+	M-	M+	M-			
Symmetrical loading	732	825	675	192	–1601	970	1477
Asymmetrical loading	742	967	237	172	–1508	826	1393

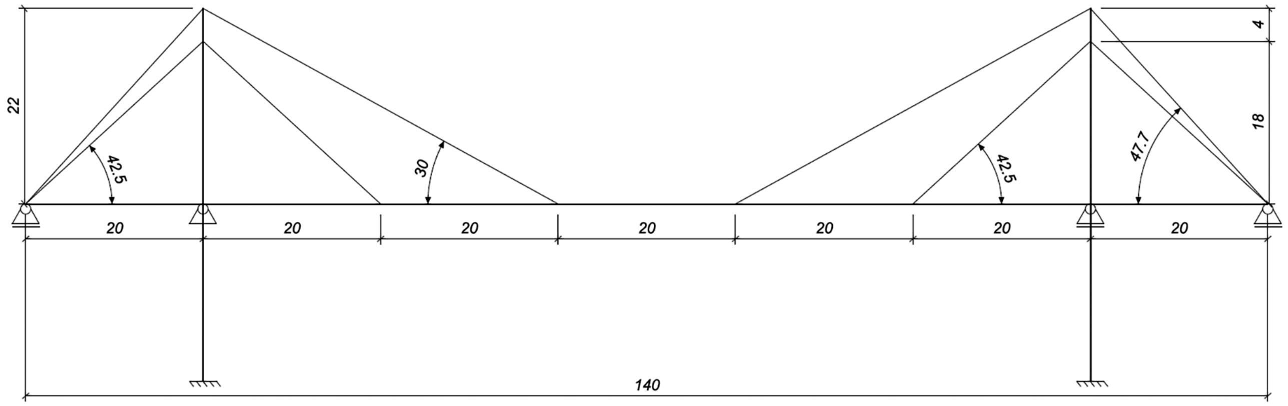

Figure 9. Standard cable-stayed bridge

It should be noted that under axial loads, the axial force in the stiffness beam of the crushing bridge is significantly increased (as much as 53% compared to the classic bridge). The cross system has more shrouds that transmit their horizontal component of tensile force to the stiffness beam.

It should be noted that the design of a cross-beam bridge requires higher prestressing values in the cables than in a standard bridge. This necessitates larger cross-section elements or higher grade steel. However, it is worth noting that the extreme values of moments in the stiffness beam are reduced by 14% compared to the standard version of a cable-stayed bridge.

Conclusions

1. In intersecting cable bridge systems, it is possible to effectively stabilize the initial shape of this structural system under different loading with proper prestressing of its elements (strings and cross-cables). It should be noted that in the case of asymmetrical loading, the moments in the stiffness beam do not exceed the values of the symmetrical loading moments.
2. In the bridge system under consideration, due to the effect of intersecting cables, a larger part of the acting external load is transmitted to the stiffness beam as an axial force (compared to standard cable-stayed bridges) thus reducing bending moments in it.
3. In an innovative bridge with variable height pylons arranged in a parabolic definition, there are vanishingly small bending moments in the intermediate pylons. In such a construction system, the only bendable-compressible element remains the stiffness beam.
4. At relatively high/high levels of cable stresses, it is recommended to use high-strength steel HSS (S690, S960). This allows a significant reduction in the total mass of these elements.

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