Lateral Stability of Network Arch Bridges

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Abstract. Network arch bridges are arch bridges where hangers intersect each other at least twice. Although these innovative bridges present several advantages in terms of cost and structural performance with respect to the conventional tied-arch bridges, they remain vulnerable under certain loading condition. Indeed, due to the large compressive force that may arise in steel arches of the bridge under service, they are prone to deflect out of his plane resulting in the degradation of the aesthetic aspect often praised of bridges of this type and later its service disablement. For this reason, the lateral behaviour of such kind of bridges should be investigated carefully. In this study, lateral structural response of network arch bridges against traffic loads has been analyzed through extensive non-linear analyses. Firstly, a calibration is useful to validate the numerical model. Then, initial geometric imperfections are assigned to the arch member before the analysis in order to take into consideration defects from the manufacturing process. Finally, non-linear analyses are performed on a full 3D numerical model to capture the behaviour of the arch bridge. The results showed that the lateral displacement of the arch member increase with the increase of the traffic loads up to a certain value. In addition, it is observed that the lateral arch's bracing changes the development of plastic hinges in the arch.

Keywords: Out of plane buckling · Finite element analysis · Vertical loads

1 Introduction

In bridges' industry, tied-arch bridges represent types of bridges where hangers are used to transfer vertical loads from deck to arches. In this condition, the arches are substantially subjected to compression axial force instead of in the deck or tie beam there is a tensile axial force and reduced bending moment due to hangers. Network arch bridges are widely spread around the world due to several advantages from the aesthetical aspect to the cost-performance ratio. This new typology of arch bridges has been introduced for the first time by Per Tveit during his Ph.D. with the aim to present innovative tied-arch bridges having a better structural performance [1]. According to Per Tveit [2], network arch bridges are defined as tied arch bridges where inclined hangers intersect each other at least twice. These bridges are often mistaken to Nielsen bridges, which provide also inclined hangers, which intersect each other but only once [3]. Figure 1 provides the common cable distribution in arch bridges from the vertical arrangement to network arrangement.

A. Arêde and C. Costa (Eds.): ARCH 2019, SI 11, pp. 358–365, 2020.
https://doi.org/10.1007/978-3-030-29227-0_37

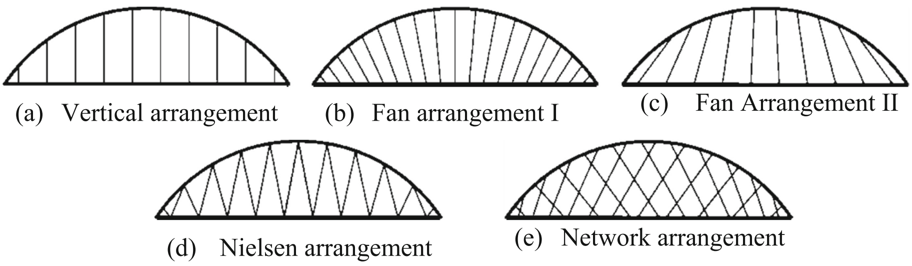


Fig. 1. Hanger arrangement for existing tied-arch bridges

Due to excessive axial force developed in the arches, they are sensitive to undergo instability phenomenon, either in plane or out-of-plane or both. For this reason, it is usually necessary to provide an optimum cable arrangement, which gives a minimum stress distribution into structural elements. Several authors [4–6] focused their researches to deliver an optimal cable distribution within the arch.

In regards to the arch's instability phenomenon, three different behaviors are often observed (see Fig. 2). Amongst them, out-of-plane buckling has captured great attention recently. Sakimoto et al. [7] conducted experimental tests on arches with square hollow sections to study the out-of-plane buckling of the arch. New column curves for the out-of-plane verification have been derived as the outcome. La poutré et al. [8] investigated the elasto-plastic out of plane buckling response of roller bent circular steel arches under a vertical force located at the crown. Several tests were performed and the presence of plastic zones in the arch rib featured the arches failure. Spoorenberg et al. [9] performed sensitivity numerical analyses to evaluate the influence of initial imperfections on the out-of-plane buckling response of steel arches. The authors proposed a design rule to check the response of freestanding circular roller bent steel arches under symmetric loads. When dealing with the analysis of lateral displacement of the arch, it is important to consider the existing imperfections of the element developed during the manufacturing process of the structural steel. Lonetti et al. [10], through non-linear analyses, showed the influence of considering geometrical imperfections in the analysis while the influence of geometrical out-of-plane imperfections on the lateral buckling behavior using a highly detailed finite element model has been investigated by Backer et al. [11].

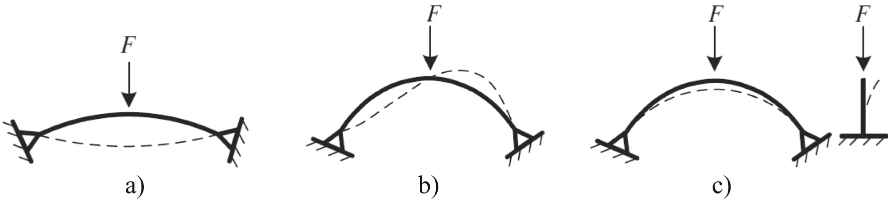
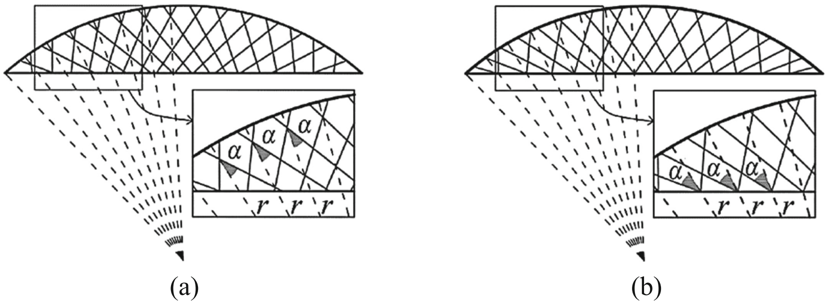


Fig. 2. Global instability behaviour of free standing arch; (a) snap-through; (b) in-plane buckling; (c) out-of-Plane buckling extracted from Spoorenberg et al. [9]

In this study, the global lateral behavior of network arch bridges under traffic loads has been studied throughout extensive nonlinear finite element analyses. Initial geometric imperfections equivalent to the first buckling mode of the free arch have been assigned in arch elements. Finally, the influence of the lateral bracing typologies and its position to the lateral displacement have been developed. One of the principal outcomes from performed analyses showed that the lateral displacement of the arch in network arch bridges subjected to vertical loads increase with an increase of live loads up to the critical load.

2 Description of the Bridge

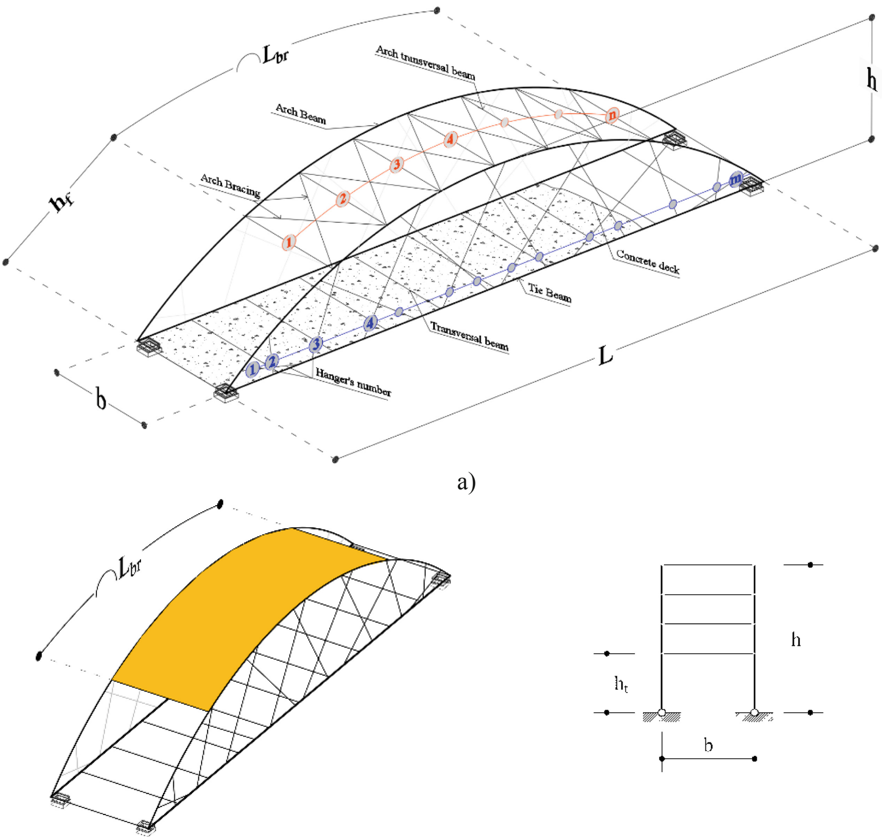
The bridge considered in this study is a 100 m span simply supported steel bridge. The height of the arch has been chosen to have a desired span/height ratio equal to 0.20. The bridge consists of two arch layouts with network arrangement of hangers. The two arches are welded directly to two lateral girder beams inter-connected throughout 10 m equally spaced transversal beams, which represent the width of the bridge. Each arch plane has 26 inclined cables to distribute the loads throughout structural elements. In particular, the hanger's arrangement in this study follows an equal radial distribution on arch rib (see Fig. 3a). The structural response of an arch plane can be compared to an IPE section element where both arch and girder play the same role than the upper and lower flange and hangers are considered as the web.



(a) (b)

Fig. 3. Radial hanger arrangement: (a) equal distribution on the arch; (b) equal distribution on the tie beam

The deck will be composed of 8 m width traffic lane with two footways of 1 m width each. IPE lateral beams are used to connect altogether the two arches. To study the influence of lateral bracing, hollow circular elements have been used to connect the existing transversal arch beam. A global view of the arch bridge geometry is presented in Fig. 4 while the information regarding the dimension of the structural elements considered is presented in both Tables 1 and 2.



a)

b)

c)

Fig. 4. Generic network arch bridge considered in the study: (a) 3D view of the network arch bridge with structural elements; (b) braced zone of the arch; (c) Front view of the arch

Table 1. Structural elements cross-section: (1) tie beam; (2) arch; (3) secondary and arch transversal beams; (4) lateral bracing; (5) cable

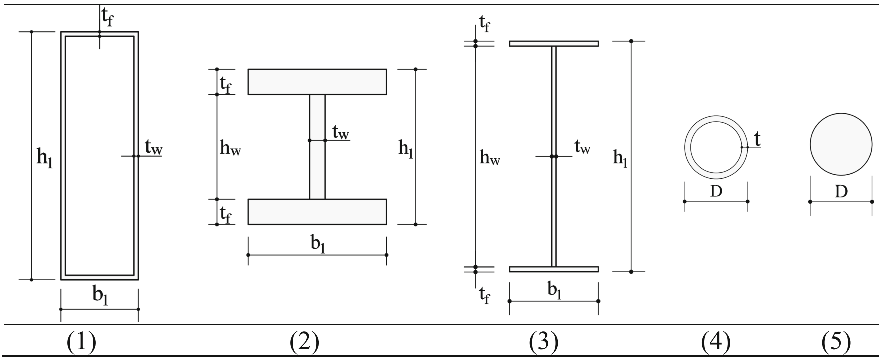


Table 2. Section dimensions of the structural elements considered in the analysis

Structural elements	h_1 [mm]	b_1 [mm]	t_w [mm]	t_f [mm]	D [mm]	t [mm]
Tie Beam	1600	500	80	80		
Arch	474.6	424	47.6	77		
Secondary beam	650	250	12	14		
Arch transversal beam	398	141.8	6.4	8.6		
Cable					12	
Lateral bracing					250	5

3 Description of the Finite Element Model

FEM analysis has been performed in this study considering 1D element for all structural elements unless cable and deck. The latter has been modelled as 2D shell elements with eight nodes quad8 and six degrees of freedom. Hanger's arrangement follows the radial distribution along the arches. Imperfections equal to first buckling mode of the arch has been applied to the arch before the buckling analysis of the whole model. To perform the GMNIA, a perfect elasto-plastic steel material behavior has been considered. S420 and S355 steel classes were considered in the analysis while cables were modelled as tension only material to avoid any risk of buckling of slender cable section. An overview of the 3D FEM model is presented in Fig. 5.

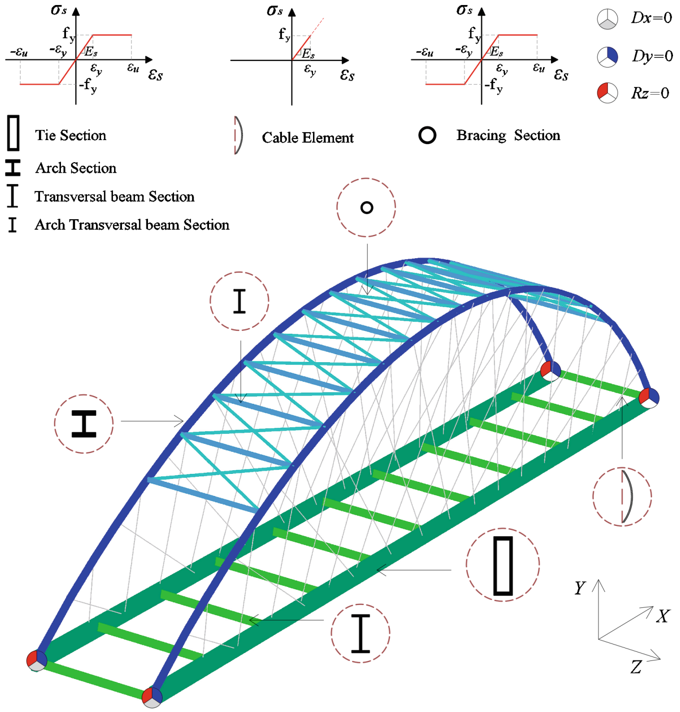
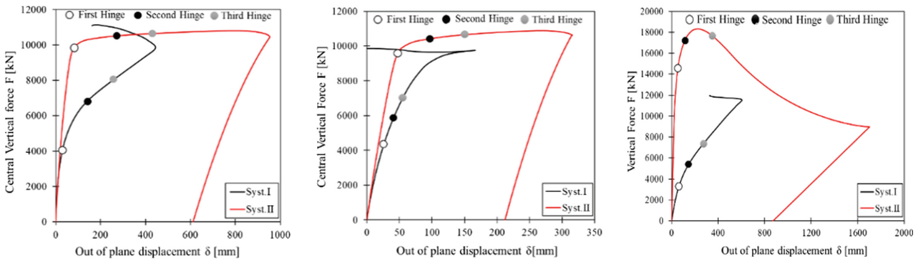


Fig. 5. 3D FEM model of a network arch bridge

4 Lateral Displacement of Network Arch Bridges

In order to investigate the lateral sensitivity of the arches in network arch bridges, a geometrically and materially nonlinear analysis with imperfections (GMNIA) have been considered. Since the effect of traffic loads was primary investigated, analysis of the model with only permanent loads is run firstly. Then, progressively increasing the live loads to better figure out the influence of traffic loads in the out-of-plane structural response.

The results obtained from different braced length showed almost the same behaviour. The first hinge is formed when the vertical force in the arch is more or less 4000 kN for unbraced arches following successively the formation of second and third hinges. It is worth noting that the successive hinges in the arches are formed shortly after the first hinge. Figure 6 shows the stress level inducing the formation of the first three hinges. The benefit of wind bracing in the increase of lateral stiffness is evident as soon as both cases are drawn in the same graph. As soon as the length of the braced zone of the arch increases, the critical load increases faster than the lateral displacement. For unbraced arches, the behaviour observed is the same for different cases studied while the situation is quite different for braced arches. In fact, for arch length braced up to 80 and 90%, softening behaviour is observed after the critical load is reached (Fig. 6c). When the free end portal increase for arches with syst.1, a slight softening is observed after the critical buckling load of the arch.



(a) (b) (c)

Fig. 6. Vertical live loads – lateral deflection curves for unbraced and braced arch bridge; (a) L^{Braced} = 50 m; (b) L^{Braced} = 70 m; (c) L^{Braced} = 90 m.

Other results from FEM analysis showed that in general, the lateral sensitivity of both braced and unbraced arch bridges subjected to vertical loads is characterized by 3 states: one linear and two non-linear. From a stress point of view, the load increases linearly with the lateral displacement until the material reaches the yielding stress at point 2. Thus, the first hinge is formed with the partial plasticization of the section and will end the linear phase as shown in Fig. 7. The location of the first hinge may vary depending on the length of the arch where lateral bracing has been applied. It is worth noting that the first hinge is prone to be formed near the support due to the reaction of the abutment.

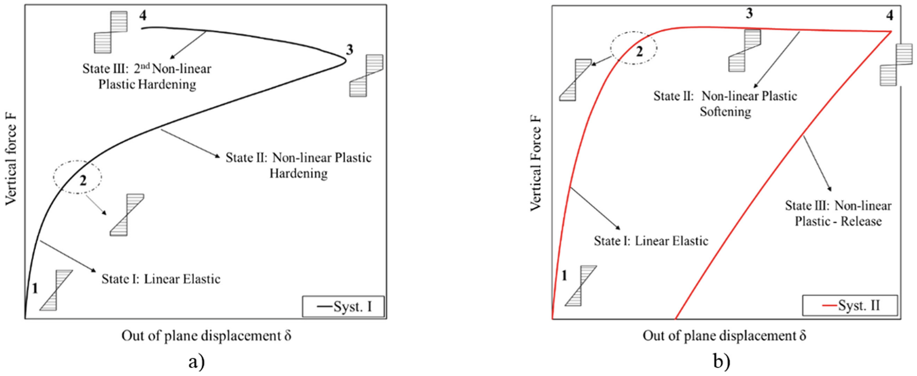


Fig. 7. Global lateral behavior of the network arch bridge under vertical loads; (a) Stress variation in the section of unbraced network arch bridge; (b) Stress variation in the section of braced network arch bridge

5 Conclusion

The global out-of-plane behavior of network arch bridge has been studied in this paper through intensive nonlinear analysis. The results from finite element models show a gradual yielding of arch either from the support toward the arch midspan or from the arch midspan toward the support. The yielding process is fast for the early case and the hinges are formed rapidly until the braced region of the arch while in the latter case, the development of yielding is prevented by the bracing system. On the other hand, for arches without lateral bracing, multi-shape modes are observed. The arches move to the second buckling mode at the end of the first nonlinear phase. During this phase, an increase of vertical loads is still visible. On the other hand, another behavior is observed for braced arches, which display a slight softening at the end of the first nonlinear phase.

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