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An optimization model for the design of network arch bridges

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ABSTRACT

A new design methodology, which evaluates the optimum configuration of network arch bridge schemes is proposed. A three-step optimization algorithm is implemented in a FE model, with the purpose to evaluate the bridge optimum configuration, involving the lowest material quantity and the best strength performance level in all structural members of the bridge. The stability and the efficiency of the formulation were verified with respect to several bridge configurations ranging from small to large spans. Moreover, parametric results are presented to investigate the interaction between cable-system, girder and arch, giving rise to specific analyses useful for design purposes.

1. Introduction

Tied arch bridges can be considered as enhanced construction schemes, which are able to provide aesthetic, structural and economic performances to overcome small, medium and large spans [1]. Most of the existing bridge configurations consist of an arch and a girder, whose internal transferring forces are guaranteed by the cable system, typically formed by cable elements. The cable arrangement plays a fundamental role in the structural behavior, since it is able to strongly influence the internal stress distribution as well as the deformability properties of the entire bridge structure [2]. Several hanger geometries, such as vertical, inclined V-shaped or network, are frequently utilized for design purposes in tied arch bridges. From the structural point of view, V-shaped or network (inclined hangers with multiple intersections) arch bridges are preferred to conventional vertical hanger bridge typologies, since they are able to guarantee a high efficient response, which minimizes bending effects in both arch and girder [3]. However, the hanger arrangement, especially in network arch bridges, can be considered as a complex structural system, whose elements, i.e. the hangers, interact by means of tension only internal forces with girder and arch [4]. In particular, each element of the cable-system is affected by geometrical nonlinearities arising from cable sag effects, which strongly influence the actual stress distribution in the bridge components. As a consequence, a fundamental task to be achieved is the evaluation of the initial configuration under dead loads in terms of internal stresses and strains of bridge constituents, by means of a nonlinear field model, avoiding unexpected and unrealistic stresses distribution in the cable due to compressive forces. Moreover, it is required to identify the optimum design configuration consistently with a performance based approach, in which a proper choice of hangers, arch and girder dimensioning should be determined to take into account external loads [5,6].

In the literature, most of the analyses are carried out for conventional vertical hanger bridge schemes, in which heuristic models and preliminary design rules can be adopted because of the quite standard stress distribution in the bridge components. As a matter of fact, under live loads, the design of the main constituents is not complex at all, since the cable elements interact with the arch and girder by means of uncoupled vertical forces. In this framework, the evaluation of the initial configuration can be identified by using traditional "*zero displacement*" method, enforcing the girder to remain straight under the application of the dead loads [7–11]. The extension of the structural analysis in the framework of arch bridges with inclined hanger elements is not straightforward, especially in those cases in which a large number of variables is involved in the analysis, i.e. in long span bridges. In this framework, the determination of the initial cable configuration under dead loads as well as the design of the bridge components under the action of the external loads should be considered as an important task to be achieved. A review of the literature dealing with the analysis of network arch bridges denotes that although such structures are receiving much attention in the last decades, many points still remain to be addressed satisfactorily. Most of the present studies on network arch bridges propose design specifications and guidelines on bridge dimensioning by means

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of preliminary design rules [3,4]. Notable parametric studies and relevant guidelines useful for design purposes are proposed in [2], in which investigations, in terms of arrangement of the hangers, arch configuration and geometrical characteristics of the bridge constituents, are carried out. Moreover, fatigue behavior of cable system elements in terms of hanger arrangements is investigated in [12], in which comparisons, in terms of hanger distribution based on radial, constant or constant change slope configurations are proposed. However, most of the models available in the literature do not enter in detail in the calculation of the bridge configuration under dead loads, in terms of both initial cable force distribution and arch-tie geometric profile. The identification of such configuration is quite important, in relationship to the nonlinear behavior of the cable-system elements, which could be affected, under the external loads, by unexpected relaxation effects of the hangers, producing overstressing in the adjoining hanger elements and in both girder and arch [5,13]. Another important issue is that preliminary design rules, available from the literature, provide information on a reasonable dimensioning of the structural components, but not on the best distribution of material according to the Performance Based Approach (PBA) [14].

Currently, tied arch bridges are designed by using conventional methodologies, which consist of heuristic procedures based on the experience and expertise of the designer. Although parametric studies are carried out on several classes of structures, the procedure to reach the best possible performance design solution still remains extensive and quite difficult to be achieved. In the framework of tied arch bridges, to the best Authors' knowledge only very few models are concerned to investigate the optimum bridge configuration. Preliminary works are developed in [2,15], in which parametric studies in terms of hanger arrangement with the purpose to minimize bending moments in both arch and girder are presented. Moreover, a design methodology based on classical structural optimization is proposed in [16], in which the optimum configuration of vertical hanger bridge arrangement is discussed in terms of hanger cable-force distribution and material quantity involved in the bridge constituents. The optimum design configuration of network arch bridges is investigated in [17], in which an optimization method is developed to minimize the cost of superstructure (arch and hangers) in terms of geometric shape, rise to span ratio, cross sections of arch and hangers. In this framework, relevant results and guidelines for the design of network arch bridges are proposed. Optimization methods are typically employed to determine the bridge dimensioning, by minimizing a convex scalar function, which combines variables concerning the geometry of the structure and the internal stress/strain distribution. However, the use of pure optimization methods, especially in the case of complex and large structures, such as the network arch bridges, are affected by convergence problems in the solving procedure, due to the large number of variables. Moreover, the consistency of the solution is not guaranteed in the final optimum configuration, since the solving procedure may lead to a local minimum or unpractical results from the engineering point of view [10,14,18]. Alternatively, advanced formulations based on metaheuristic algorithms are frequently utilized in those cases in which, multivariable or multicriteria affect the final optimum configuration. However, although the basic idea of heuristic methods is conceptually simple, the application of a generic metaheuristic to a generalized optimization problem requires a laborious implementation with specific guidelines, which introduce numerical complexities in the formulation. Therefore, in order to avoid such problems, in the present paper a design procedure based on an iterative methodology developed in the framework of performance-based optimization techniques is proposed. Despite existing methods available from the literature, a simple and effective methodology, easy to be implemented in several FE software, is proposed. The design variables are the post tensioning forces in the hangers and the initial strains in the girder and arch, which identify to the initial configuration under dead and permanent loads. Moreover, under the external loads, bridge geometric characteristics, which involve the lowest possible material in the cable system, girder, and arch and verify prescriptions arising from external loads, are determined. In order to prove the effectiveness of the proposed model, parametric studies in terms of cable system configurations on several bridge schemes are proposed. The outline of the paper is as follows. In Section 2, the formulation of the design methodology, bridge modeling, together with the description of the iterative procedure is presented. In Section 3, numerical details on the design method are reported, whereas in Section 4, numerical comparisons and parametric results are presented.

2. Formulation of the procedure

2.1. Bridge modeling

The bridge typology, reported in Fig. 1a, refers to a generalized tied arch scheme, in which arch and girder are connected between themselves at the bridge extremities, whereas the girder is assumed to be simply supported to the foundation system. Moreover, the hangers may be arranged in various configurations such as vertical, V-shaped or network. Without loss of generality, the arch and girder are assumed to be in steel, whereas hangers are made of steel cable, requiring prestressing forces. The proposed optimization method, is presented for a Network Arch Bridge (NAB) scheme, which is, in comparison to the existing ones based on vertical or V-shaped (Fig. 1b), the most complex configuration to be analyzed. However, the theoretical formulation of the proposed model is quite general to be implemented also for conventional vertical or V-shaped cable arrangements.

The proposed strategy, despite existing optimization methods, identifies the optimum configuration on the basis of a step-by-step procedure, in which the solution is enforced by using physically based expressions. The heuristic nature of the proposed procedure does not ensure a priori that the predicted solution is a global optima. However, the optimum solution is determined, iteratively, by means of successive approximations of the final configuration by solving separate optimization problems implemented in different substeps. The proposed design methodology is based on a three-step analysis, described in the next three subparagraphs, in which the optimum solution is determined by using an iterative procedure based on results obtained under Dead Loads (*DL*) and Live Loads (*LL*) combinations. In the present approach the design variables are the initial stresses in the hangers under *DL*, the cross sections of the hangers, girder and arch, whereas the characteristics of the cable-system (angle, number of cables) are typically assumed by the designer due to aesthetic requirements and thus are not included as variables in the optimization procedure.

2.2. Analysis under the action of dead loads (STEP 1)

Under the action of *DL*, it is required to evaluate internal stresses and deformations, which enforce the prescribed design geometry, known in the literature as "zero configuration". In this framework, the unknown quantities are represented by the internal stresses of the cable-system elements, the initial position of the arch and the girder, which are determined in such a way to reproduce the design undeformed configuration. The hangers should be designed in terms of post-tensioning forces to reproduce the initial configuration under dead loads, i.e. zero configuration. Moreover, the cross-sections are calculated to verify strength prescriptions (maximum and fatigue stresses) under the action of