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Analysis of stabilizing process for stress-erection of Strarch frame

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ABSTRACT

The stress-erection process is a unique feature of the Strarch system; this study examined the stabilizing process for this method. In the stress-erection process, post-tensioning is performed by installing a jacking tendon force inside the bottom chord member to determine the structural shape and initial stability. Before erection is completed, the structural system of a Strarch frame is unstable. The prestress installation process of the Strarch system is similar to that of a cable dome, which is also an unstable structure. Therefore, the dynamic relaxation method with kinetic damping, which is a stabilizing process for unstable structures, can be used for the Strarch system. The stabilizing process was verified by comparing the results of simple calculations and an experimental study using an actual-scale Strarch frame unit. The numerical applicability and accuracy of the method was further validated by analysis of the stabilizing process for the stress-erection of different Strarch models.

1. Introduction

Strarch developed a unique structural system that has been applied to many long-span projects throughout the world over the last three decades. As shown in Fig. 1, the most unique feature of the Strarch system [1–7] is the post-tensioning stress-erection process. It erects the Strarch frame into the designed final curved arch shape and imparts structural stability. In contrast, other prestressed (PS) concrete structures only obtain stability from post-tensioning. The Strarch system shows similarities to unstable structures [8–10] such as cable domes despite the difference in shape and system. The Strarch system and cable dome are unstable before being prestressed by a jacking tendon force. The structural shape and stability are obtained at the same time via the post-tensioning process. After erection is completed, these systems behave as a pin-jointed structure, not rigid.

The unstable nature of the cable dome permits joints to rotate freely. Geometrically large rigid body rotation by the jacking tendon or cable during the erection process is possible. However, the top chord of the Strarch system is continuous in the initial assembly state; a certain structural change should be introduced for the structure to rotate freely as a rigid body. To analyze the stabilizing or erection process of an unstable structure, Hangai et al. [8–10] developed a shape finding method to determine erected or stable shapes. Their method does not involve stress analysis; therefore, their work cannot be applied to the stress-erection process.

Strarch International and other researchers [1–7] developed details for the Strarch system to allow free rotation. As shown in Fig. 1, each flexible bottom chord member has a gap and sleeve, and one support is free to slide to the other side. If the zero-length concentrated plastic hinge concept [11–23] with Eulerian finite rotation [23–27] for a rigid body is applied to simulate the flexible top chord member, the joint can rotate freely like a hinge joint rather than being rigid.

The dynamic relaxation method (DRM) [28–38] proposed by Day [28] can be used for unstable structures such as cables, fabric membranes, and cable domes [33–41] because of its vector equation of explicit numerical features with viscous damping [29–31] or kinetic damping [32–38]. It has also been successfully used for the elastic stability problem of post-buckling [42–46].

Stabilizing process analysis [38] can be applied to the unstable Strarch system to simulate the erection process for the final shape and member forces simultaneously by using DRM with the kinetic damping technique [32–38]. Numerical results for the stress-erection process have not yet been reported because of difficulties with the high nonlinearity of the elements and numerical method [6]. However, the nonlinear relationship among member forces and the implicit FE formulation have been comprehensively studied, and a design methodology that considers initial imperfections has been developed for a flexible top chord.

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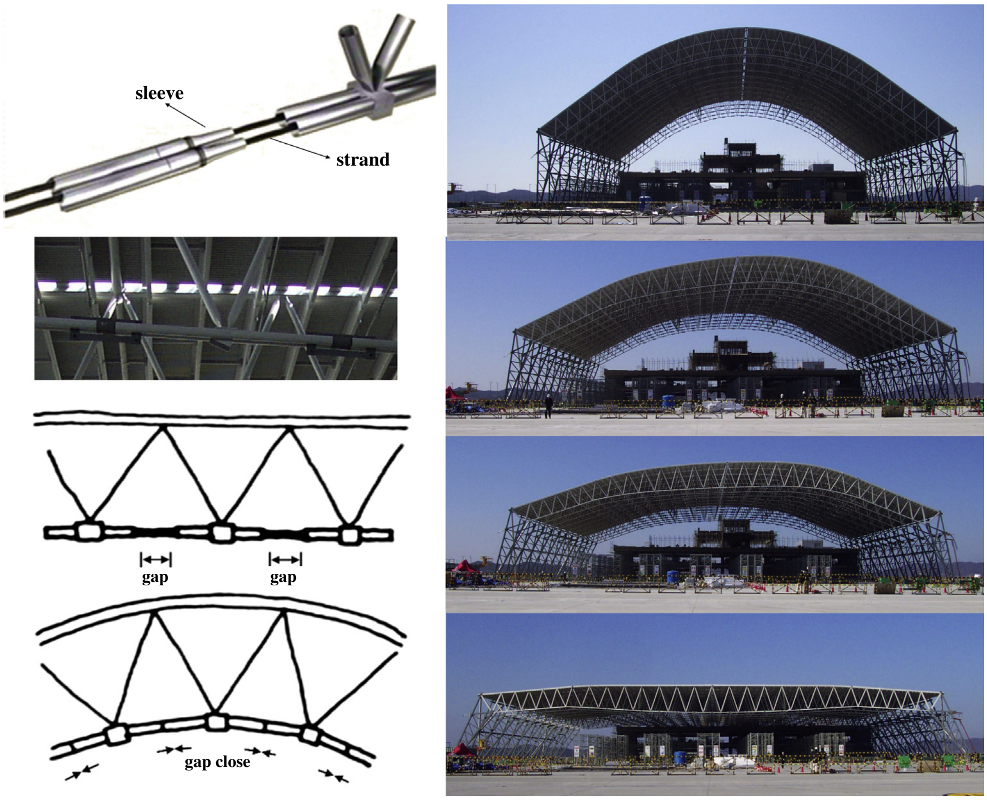

Fig. 1. Stress-erection process of Starch building.

In this study, explicit DRM [38] was used to analyze the stabilizing process of the unstable stress-erection process for the Strarch system and reveal the numerical and structural features. This method was used to analyze a Strarch building and test the stress-erection process. The effects of friction losses of the tendon and sliding support were omitted to simplify the numerical calculations. The structural features of the Strarch system for the stress-erection process and the numerical method for the stabilizing process were defined. The jacking force and resulting flexible top and bottom chord member forces were tested and verified by comparing the experimental values for a unit Strarch frame with the expected values using the developed numerical methods. The numerical applicability and accuracy of the method were verified by analysis of the stabilizing process for the stress-erection of different Strarch models.

2. Strarch system and stress-erection process

As shown in Fig. 2, the Strarch frame is divided into flexible and fixed sections with many sophisticated details. The spans of this Strarch building before and after construction are 110 and 87 m, respectively; it can hold a commercial Boeing 747. As shown in Fig. 2, the bottom chord contains special gaps that close during the stress-erection process. In Strarch International's design methodology, these gap lengths control the final design shape of the curved arch [6,7]. Typically, the initial curvature resulting from the stress-erection process exceeds the yielding strain k_{Yn}, and the flexible top chord member is plastic during and after erection. However, the fixed section of the haunch and column do not change their relative geometry and remain elastic.

Simulating the stress-erection process is difficult; the flexible top chord member should include the effects of geometric nonlinearity from rigid body rotation and material nonlinearity from yielding and plasticity. For the flexible bottom chord member, the material and geometric effects of the gap element should be included, such as friction loss and gap opening/closing [6]. The geometric nonlinearity of the truss element for web and fixed haunch members and the prestressing effect of the tendon element should also be included.

Before erection is completed, the Strarch frame can be regarded to be an unstable structural system such as cable domes, cable links, and fabric membranes. Without the jacking tendon force and scaffolding under the bottom chord, the Strarch frame will collapse from the sliding gap support. The jacking tendon force during the stress-erection process allows the Strarch system to realize the final shape design and structural stability. The Strarch system can be considered as an unstable structure that may experience a geometrically large rigid body rotation before construction is completed.

Until now, there have been no reports on numerical methods or software tools to analyze the stress-erection process completely because of the highly nonlinear behavior of this process. Thus, accurately predicting the shape and changes in member force during the stress-erection process has been impossible until now.

The stabilizing process for an unstable structure is defined as a process of state change [38]: unstable to stable or vice versa. The easiest method for externally determining the state change is to introduce prestress to a member such as a cable or tendon. The cable dome is a well-known unstable structure and can be erected by the stabilizing process, as shown in Fig. 3.

Figs. 4 and 5 show the stress-erection process of the Strarch building when the flexible top chord member has rigid and hinge joints, respectively, using the stabilizing process. In Fig. 4, the top chord member is continuous and has a rigid joint beam–column element; after erection is completed, plastic hinges occur at the ends of the top chord member in the flexible region. Fig. 5 shows a pin-jointed truss element; the pin joint is free to rotate. These Figs. show that unstable structures can be erected with the