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Finite Element Analysis of the Anchorage Forces of Mast Climbers

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Abstract: Mast climbing work platforms (MCWPs) or mast climbers have been widely available and applied in the United States, although occurring rarely, may potentially cause more fatal consequences, compared with non-fatal incidents involving slip, trip, and fall hazards. However, little systematic study has been done on the structural stability of mast climbers. For high-rise building construction, anchored MCWPs are widely used. The vertical mast of a MCWP is a slender structural component, which needs the anchorages to maintain its stability. From a perspective of structural stability, the anchorages and their attachments are among the weakest locations for the entire MCWP setups. Failures at one of the anchoring locations may cause loading redistribution among the entire anchoring system and other MCWP components, resulting in instability or collapse of the mast climbers. In the current study, we analyzed, using the finite element (FE) method, the anchorage forces of a vertical mast climber when the platform is operating at different locations (heights). The FE models were constructed using a commercial software (ABAQUS) and based on representative setups of anchored MCWPs as specified in manufacturers' manuals. Our analysis shows that the platform operation height has effects on the anchorage forces. When the platform operates at a height of approximately 75% of the anchorage interval distance from an anchorage, it will cause the maximal anchorage forces among the examined scenarios. Our findings may help MCWP designs and safety interventions.

***Keywords**:* Mast climbing work platforms, Finite element analysis, Anchorage, Structural stability

1. Introduction

Mast climbing work platforms (MCWPs) have been increasingly used for construction projects because of their advantages to increase efficiency, flexibility, and productivity. MCWP equipment is generally considered to be inherently safe, consequently, limited studies have been conducted on MCWPs independent of the manufacturers' design and testing. Previous studies experimentally tested the stability of a freestanding mast climber that was subjected to impacts due to a fall-arrest situation (Wimer et al., 2017). It was found that, when the equipment was erected and used according to the manufacturers' recommendations during a fall-arrest condition (Harris et al., 2010), destabilizing forces were small and would not potentially cause a MCWP collapse (Wimer et al., 2017). Wang et al. (2017) analyzed the mechanical characteristics of MCWP systems for prefabricated construction using finite element (FE) models. Their study was focused on the strength and deflections of the work platform. They found that the highest stress concentration was in the cantilever of the platform. Their study suggested that the construction platform should not be overloaded or be subjected to a concentrated loading and that the materials' loading should be evenly and symmetrically distributed to reduce the stress level in the platform. However, a literature review in the current study did not find any relevant study that systematically characterized the critical forces on the anchorages.

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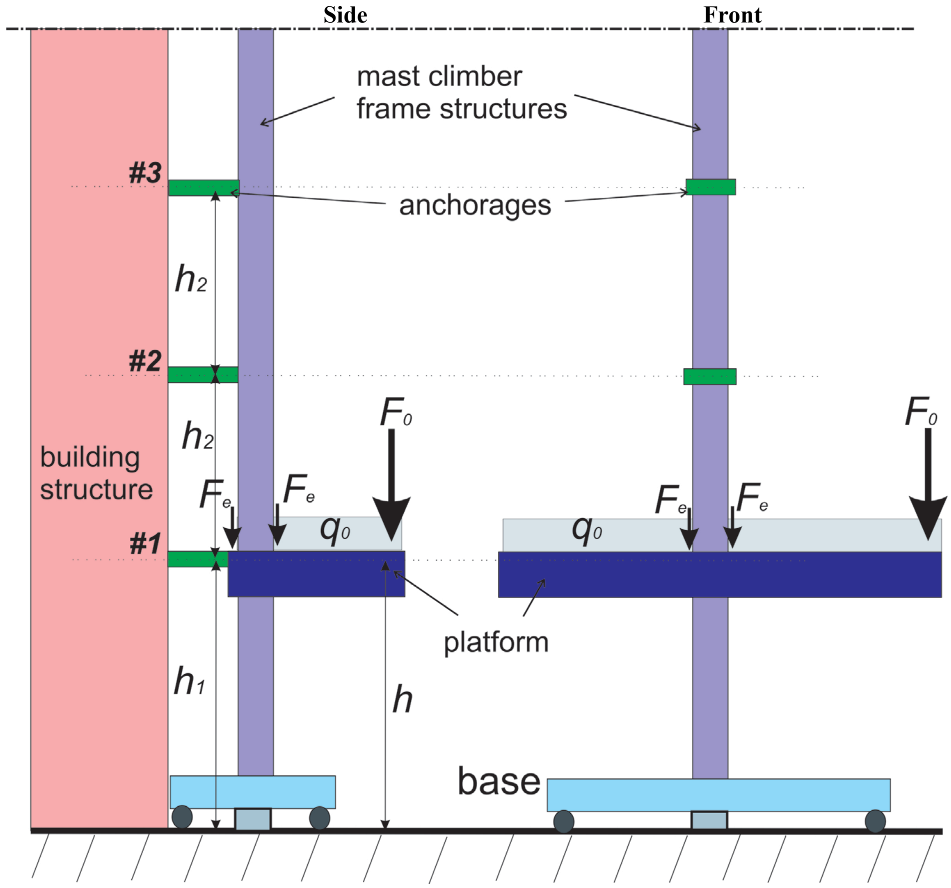


Figure 1. Conceptual design of the numerical simulations. The simulation model consists of three parts: a base, a mast, and a platform. The mast has a height of 33.60 m and is connected to the construction building via three anchorages.

The vertical mast of a MCWP is a "slender" structural component, which needs the anchorages to maintain its stability. From a view of structural stability, the anchorages and their attachments are among the weakest locations for the entire MCWP setups. Failures at one of the anchoring locations may cause loading redistribution among the entire anchoring system and other MCWP components, resulting in instability or collapse of the mast climbers. Computer modeling, especially FE modeling will make it possible to obtain a comprehensive understanding of the basic characteristics of the anchoring forces and the related failure mechanisms of the MCWPs under various working conditions, which may be technically difficult or unsafe to evaluate using any experimental approaches. The specific aims of the current study were to develop FE models of a representative MCWP system and apply them to characterize the anchoring forces in response to different loading conditions on the platform that is operating at various heights along the mast.

2. Methods

A typical single MCWP was considered in this study (Fig. 1). The simulation model included only the major components of the MCWP system, which are related to the stiffness of the system: a supporting base, a mast structure, and a platform. The work platform had a dimension of 4.48 x 1.83 (m). The mast had a total height of 33.6 m and was connected to a construction building via three anchoring sites (#1, #2, and #3). The construction building structure was considered as rigid-it has no deformation and will not be damaged under any loading conditions. The anchorage #1 was installed at a height (h_1) of 12.70 m; the distance between two anchorages was h_2 = 9.05 m. The platform was assumed to operate at nine different positions (heights): h_i (Pi) = $h_1 + (1/4) * (i\text{-}1) * h_2$ (i = 1, 2, .., 9), where Pi represents nine platform operation locations.

The detailed structures of the FE models used in the study are illustrated in Fig. 2. The FE models were developed using a commercially available FE software (Abaqus, Dassault Systemes, France). The entire models were constructed using

Euler-Bernoulli-type beam elements of different cross sections. The three-dimensional MCWP FE model contained a total of 6,558 truss elements, 18,751 nodes, and 36,114 degrees of freedoms (DOFs). All construction components were assumed to be made of common structural steels (Young's modulus, E = 210 GPa; Poisson's ratio, $\nu = 0.3$; yield stress, σ_Y = 275-355 MPa, and tensile ultimate stress, σ_T = 400-470 MPa) (BS, 2019). FE models of the MCWP systems for the scenarios when the work platform operates at nine different heights (i.e., P1, P2, ..., P9) were constructed.

The effects of loading condition and platform operation height on the anchorage loading were simulated. All anchorages are assumed to be well installed, i.e., the boundaries between the anchorage supporting feet and construction structure are considered to be "fixed" in the FE model. An evenly distributed loading (q_o = 1.0 kN/m^2), which mimicked the weights of the structural components and materials, was applied on the platform working surface. In addition, a concentrated load (F_o = 10 kN) was applied on one of the three selected locations (A, B, and C, as shown in Fig. 2A). Four concentrated forces (F_e = 1.0 kN) were applied on the platform close to the mast structure (as shown in Fig. 1), simulating the equipment weight. The total weight of the mast structure was assumed to be 12 kN and was simulated by applying small, concentrated loads (250 N) on 48 locations at 12 distributed heights along the mast. There is a total of 27 different loading and structural testing combinations [3 (loading conditions) x 9 (platform heights) = 27].

From the FE analysis, we calculated the x, y, and z components of the reaction forces and reaction moments at each of the supporting feet (right, left, and center) and at each of the anchorage sites (#1, #2, and #3). First, the resultant reaction forces and the resultant reaction moments at a supporting foot (Right, Center, and Left) were calculated. Secondly, the maximal reaction anchorage forces (RF_{max}) and moments (RM_{max}) at an anchorage site were estimated:

$$RF_{max} = RF_{right} + RF_{center} + RF_{left};\ RM_{max} = RM_{right} + RM_{center} + RM_{left}$$

The maximal reaction anchorage forces (RF_{max}) and moments (RM_{max}) are the upper limits of the maximal reaction force and the maximal reaction moment, respectively, that can possibly be reached at an anchorage site.

3. Results

The predicted maximal anchorage forces (RF_{max}) and moments (RM_{max}) as a function of the platform operation height for different loading cases are shown in Fig. 3(A) and (B), respectively. The trends of the dependencies of RF_{max} and RM_{max} on the platform operation heights and the loading cases are clearly demonstrated. Loading case A resulted in the greatest RF_{max} and RM_{max}, whereas loading case C resulted in the least RF_{max} and RM_{max}. For anchorage #1, RF_{max} and RM_{max} reach their maximums when the platform operates at heights around P3-P4, which is approximately 50-75% of the anchorage intervals (h_2) from the anchorage site. The similar trends were also observed for anchorage #2, in which RF_{max} and RM_{max} reach the maximum when the platform operates at heights around P2-P3 and P9, which are approximately 75-100% of h_2 away from the anchorage site. For anchorage # 3, the maximal RF_{max} and RM_{max} were observed when the platform was at a position P9, the anchorage site #3. The variations of RM_{max} due to the platform operation height variations and for different loading cases are smaller than those observed for RF_{max}.

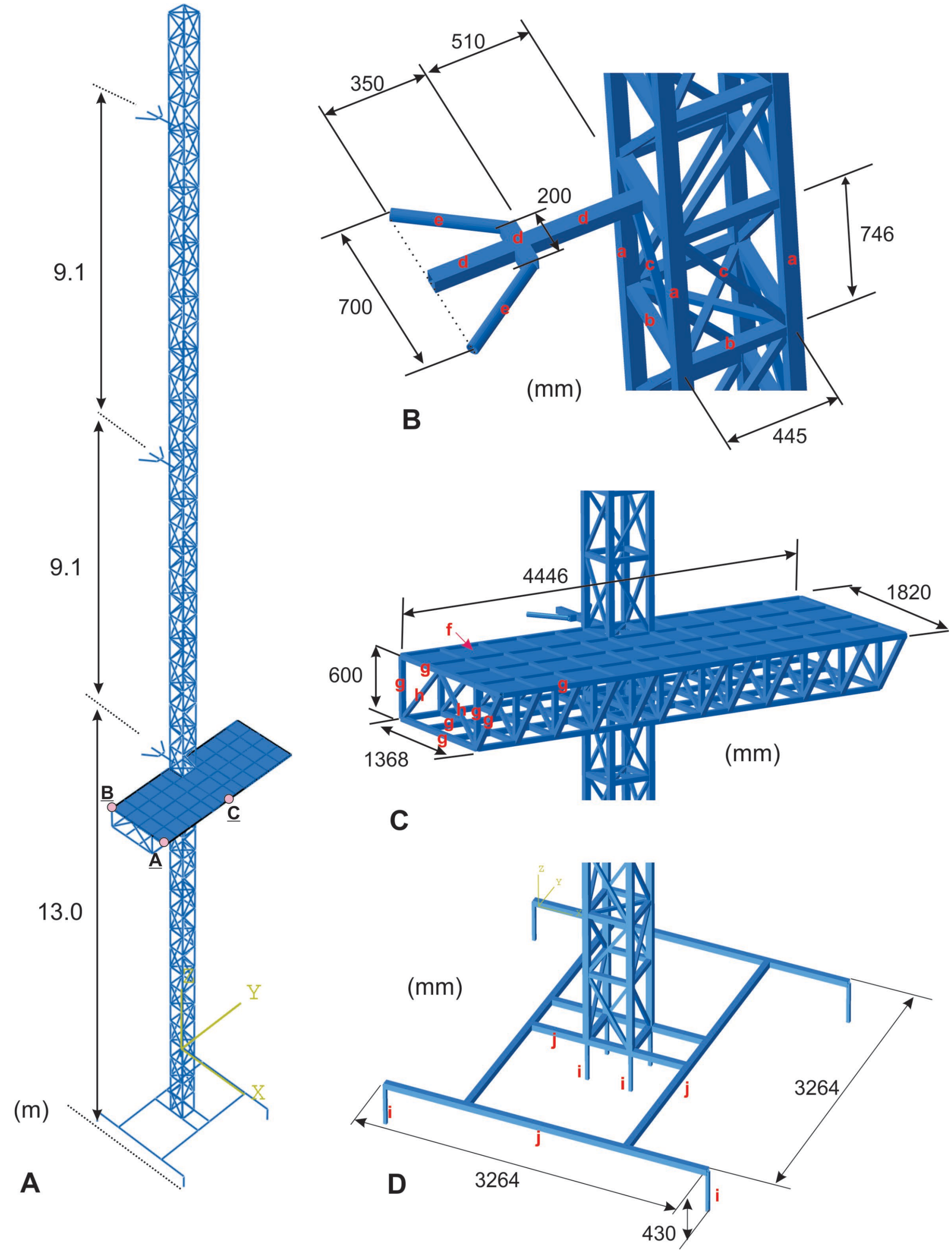
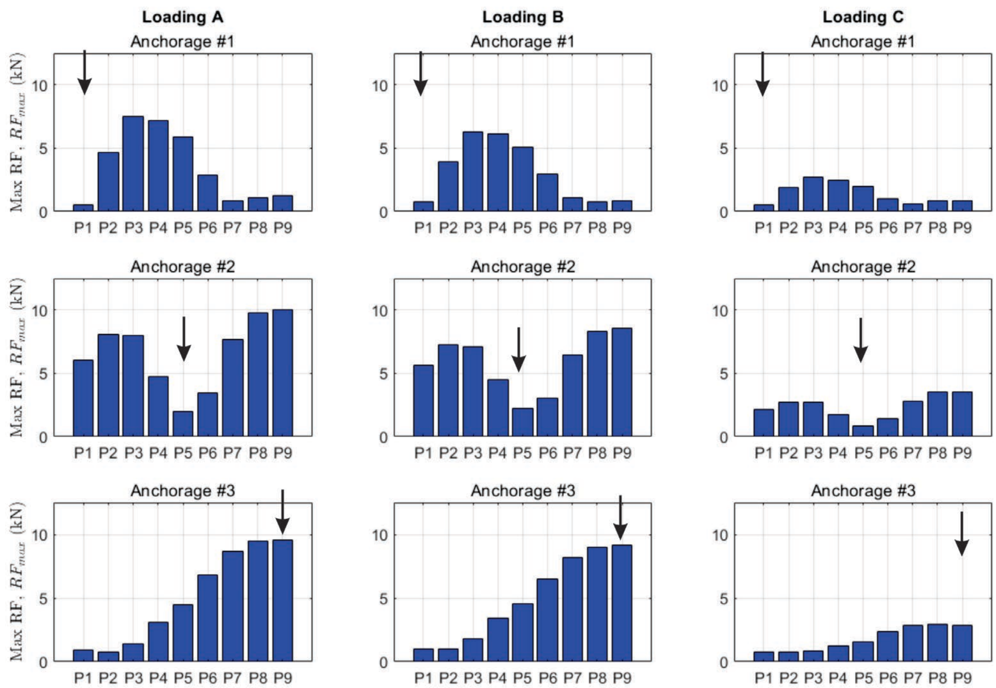
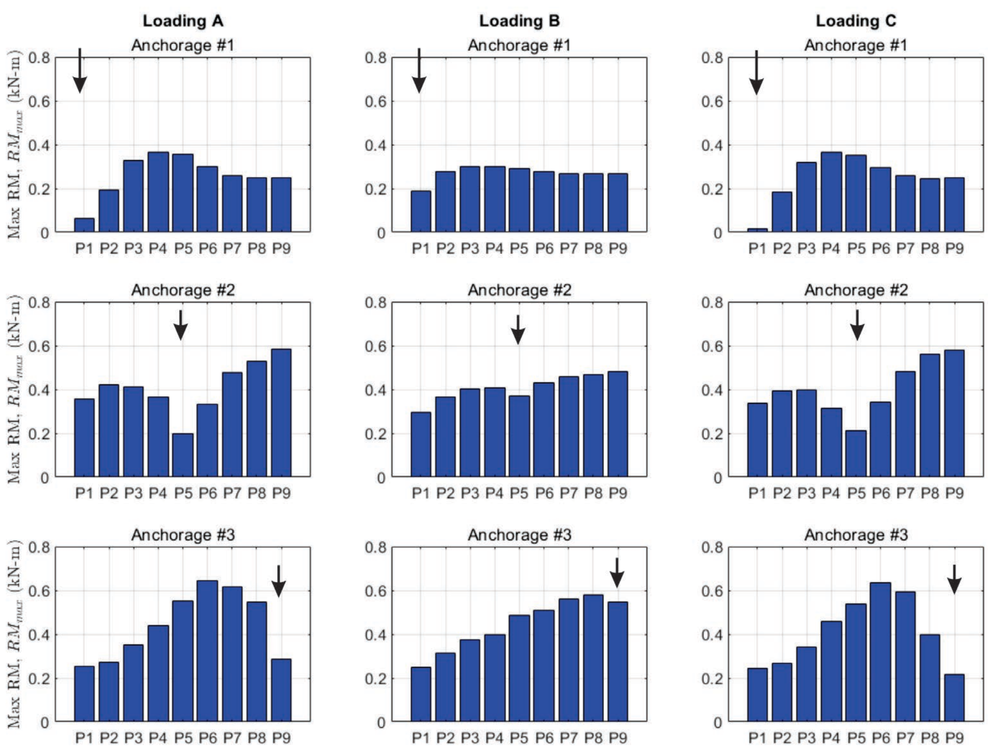


Figure 2. Finite element models. **A**: Entire model. **B**: Structural details of the anchors and mast structure. **C**: Structural details of the platform. **D**: Structural detail of the supporting base. A concentrated loading was applied on location 'A', 'B', or 'C', as in plot **A**. Labels (a, b, c, d, e, f, g, h, I, and j) in plots **B-D** represent components of different cross-sections.



A



B

Figure 3. The maximal anchorage force (RF_{max}) and moment (RM_{max}) as a function of the platform operation location (height). **A**: Maximal anchorage force (RF_{max}). **B**: Maximal anchorage moment (RM_{max}). Loading A, B, and C represent three loading cases, where the concentrated loading (F_o) is applied at the platform locations A, B, and C, respectively. P1, P2, ..., P9 are nine height positions, at which the platform operates. The arrows represent the positions of the anchorages. The anchorage #1, #2, and #3, respectively, is in position P1, P5, and P9.

4. Discussion and Conclusion

The anchorages of a MCWP system are essential to maintain the structural stability, especially when the MCWP system is extremely loaded or subjected to extreme weather conditions. The anchorages and their attachments may involve factors that are beyond the MCWP manufacturers' quality control, such as the structural conditions of the buildings to be anchored and the customers' setups and installations. Therefore, to closely monitor the anchorage loading and to avoid the anchorage overloading would help to reduce the risks of the MCWP collapse incidents. The current study found that the reaction forces at the anchorages are dependent on the loading conditions of the platform and the height where the platform operates. The knowledge obtained in the study can be used to help operate the MCWP appropriately to minimize anchoring forces and to develop methods and technologies for monitoring and controlling the safety status of the system.

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Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

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