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Evaluating the stability of a freestanding Mast Climbing Work Platform

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ABSTRACT

Mast Climbing Work Platforms (MCWPs) are becoming more common at construction sites and are being used as an alternative to traditional scaffolding. Although their use is increasing, little to no published information exists on the potential safety hazards they could pose for workers. As a last line of defense, a personal fall-arrest system can be used to save a worker in a fall incident from the platform. There has been no published information on whether it is safe to use such a personal fall-arrest system with MCWPs. In this study, the issues of concern for occupational safety included: (a) the overall stability of the freestanding mast climber during a fall-arrest condition and (b) whether that fall-arrest system could potentially present safety hazards to other workers on the platform during a fall-arrest condition. This research project investigated those safety concerns with respect to the mast climber stability and the workers using it by creating fall-arrest impact forces that are transmitted to the equipment and by subsequently observing the movement of the mast climber and the working deck used by the workers. This study found that when the equipment was erected and used according to the manufacturer's recommendations during a fall-arrest condition, destabilizing forces were very small and there were no signs of potential of MCWP collapse. However, potential fall hazards could be presented to other workers on the platform during a fall arrest. Workers near an open platform are advised to wear a personal fall-arrest system to reduce the risk of being ejected. Due to the increasing use of MCWPs at construction sites, there is a corresponding need for evidence and science-based safety guidelines or regulations and further research should be conducted to continue to fill the knowledge gap with MCWP equipment.

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1. Background

Mast Climbing Work Platforms (MCWPs), or mast climbers, are a type of construction elevating equipment used as an alternative to traditional tube and coupler scaffolding. They are equipped with a powered drive unit for propelling the work platform up and down a vertical mast structure. Compared with traditional scaffolding, MCWPs are capable of handling larger loads (workers and materials) and reaching greater heights, thus improving the efficiency of construction projects. A mast climber can be configured in many different ways with different types of supporting bases, with single or dual masts, and different platform arrangements, including specialized shapes/sizes to conform to the adjacent structure being worked on. Most mast climbers can regularly handle a loading of 8000–20,000 lb (3600–9070 kg) for a single mast configuration, and the heights they can provide access to are only limited to the height of the specific structure the mast is affixed to. Configurations on skyscrapers and other tall structures have seen mast climbers reach heights well over 1000 ft (305 m). Mast climbers can be used in two methods: freestanding and anchored configurations. Although mast climbers are generally safe for the workers using them, some risks do still exist, such as fall hazards from open edges, tripping hazards from construction materials on the platform, and moving platforms due to worker movement, shifting loads, winds, etc. Most of these risks are mitigated by thorough operator and user training courses, daily on-site equipment inspection, and by using personal protective equipment when necessary.

Research on stability of equipment during a fall arrest has been completed on traditional scaffolds and other equipment, such as scissor lifts, that fall under the current OSHA scaffold standards (Harris, Powers, Pan, & Boehler, 2010). However, little research has been done on mast climbers in general, and with their increasing use comes a new set of occupational safety challenges and concerns to investigate. The fact that MCWPs are increasingly being used in U.S. construction and are rapidly replacing traditional elevating equipment, coupled with the absence of regulations specific to this type of equipment, calls for research focusing on the safety hazards of MCWPs (Pan, Chiou, Hsiao, & Keane, 2012). Of particular concerns are the stability of freestanding MCWPs, their contribution to fall-related injuries, and the potential for catastrophic failure. This article describes the ongoing research at the National

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Institute for Occupational Safety and Health (NIOSH) that focuses on the stability, functionality, and safety hazards of MCWPs.

1.1. MCWP use and injury statistics

MCWPs have been available in the United States since the 1980s, with usage increasing to present day. The increase in adoption is largely because of the advantages offered over tube and coupling scaffolding, which include increased productivity, increased flexibility, and increased capacity. More commonly used in the construction industry in Europe and Canada, current configurations of MCWPs offer great variability; they range from quickly deployed freestanding models used with abbreviated working heights to anchored models capable of reaching heights over 1000 ft (305 m).

There are an estimated 5600 mast climbers in the United States, mostly found on construction sites. Each day, up to 16,800 workers may be using mast climbers at any given time. Each mast climber can be dis-assembled and re-erected multiple times per year, creating up to 3.3 million man-hours in the moving process of MCWPs each year (Susi et al., 2010).

Over the past decade, numerous incidents have occurred using mast climbers, resulting in serious injuries, or in some cases, worker fatalities. In 2008, Ayoub, O'Shea, and Susi individually presented data on fatal and nonfatal injury incidents to the Advisory Committee on Construction Safety and Health and identified potential hazards such as inadequate anchoring, improper or no training, platform working conditions, platform guarding, and failure to follow manufacturer's recommended guidelines for assembly/disassembly (Occupational Safety and Health Administration, 2008a, 2008b; Occupational Safety and Health Administration (OSHA), 2008). These incidents have frequently resulted from fall hazards due to catastrophic failure of the equipment; slip, trip, and fall hazards; and fall-related hazards pertinent to construction (e.g., lack of fall-arrest protection). Other than occurring at elevation on an extendable platform, there are few factors common to these hazards because of the widely varying configurations of MCWPs. This study focuses on the scenario where the platforms were subjected to destabilizing forces leading to possible catastrophic failure and subsequent collapse leading to injury events. The hazards related to slip, trip, and fall injuries found at numerous construction sites are significant but do not form the focus of the present work.

Recent incidents have recorded a number of equipment failures and subsequent fatal injuries caused by platform collapses. From 1990 to 2010, twelve documented incidents resulted in 18 deaths (Susi et al., 2010). In March of 2015, an incident in Raleigh, North Carolina, resulted in three worker fatalities and one serious injury (Kenney & Bracken, 2015). These incidents were of concern for occupational safety researchers, and all involved failures of MCWPs. This concern led to basic and advanced research on worker exposures to falls as a function of work on MCWPs.

1.2. Fall-arrest requirements for MCWP use

Mast climbers are considered by the Occupational Safety and Health Administration (OSHA) regulations to be a "scaffold" structure. OSHA regulation (29 CFR 1926 Subpart L) requires the use of guardrails or personal fall-arrest systems as primary safety controls for MCWPs, aerial lifts, as well as traditional scaffolding (Occupational Safety and Health Administration [OSHA], 1999). Under these OSHA regulations, a person must use a personal fall-arrest system both while working at elevation and assembling/dismantling the structure when an open edge of the working platform is present and when a guardrail system is not present.

1.3. Problem statement and scope of study

Currently, the OSHA regulation 29 CFR 1926 Subpart L encompasses types of equipment other than traditional scaffolding, such as certain types of aerial work platforms. Research has been completed on types of equipment that would fall under this regulation; Harris et al. (2010) found that a scissor lift would remain stable during a fall-arrest scenario, even under adverse conditions, as long as it was used within the manufacturer's recommended parameters. However, very little research has been completed on MCWPs outside of manufacturer testing, and no published data has been found on fall-arrest hazards of mast climbers.

Mast climber equipment has been thought to be inherently safe, although performance under certain scenarios is not fully understood (Pan, Chiou, et al., 2012). Most mast climbers are anchored to the adjacent structure, while others are used in a freestanding configuration. Anchoring may prevent equipment failure due to added stability. If a fall-arrest event occurred on a freestanding configuration, however, it is unknown if the mast climber could become unstable allowing potential for tip-over, failure, or collapse, and pose a risk to workers on the platform.

Mast climbers are sometimes used in a manner in which a fall hazard is only occasionally present, such as if the platform is raised on a building that has multiple levels causing the working platform and the building face to be non-contiguous. During such scenarios as this, workers will generally wear a PFAS, if a guardrail or guarding is not placed over the open edge. In the event of a fall, having the lanyard and harness secured with one end attached to the worker and the other to the platform, subjects the platform to potentially destabilizing forces. Further research is needed on MCWPs using previous NIOSH published test methods and results for aerial lifts, to examine these potentially destabilizing forces and their contribution to catastrophic failure and collapse leading to injury (Harris et al., 2010; Pan, 2016; Pan, Powers, et al., 2012).

The focus of this study is to better understand the stability of the freestanding MCWP when subjected to conditions requiring fall-arrest. Stability was measured by the working platform displacement, accelerations measured at the MCWP base and working platform under loading, and the ability of the unit to remain in an uncompromised position. For this study, an uncompromised position was defined as the mast climber remaining in an upright posture, where it would remain stable and not present any excess movement, potential tip-over, or collapse, or move in such a way to pose a safety hazard to the workers on the main platform. The most unstable conditions possible for a fall-arrest situation to create a worst case scenario were investigated, as severe injury events generally occur as a function of tip over/collapse/fall events. This research was designed to address two questions: (a) will a freestanding MCWP, under normal work conditions, remain stable if a fall-arrest event occurs? and (b) in the incident of a fall-arrest event, what, if any, additional fall hazard risks exist to other workers on the platform?

1.4. Limitations of current study

The popularity of MCWPs has increased due to various benefits over traditional methods of working at height, one of which is the versatility of equipment set-up, allowing different working areas to be reached more effectively. This benefit also lends itself to an added limitation of our current study. The current testing only investigates the stability of a freestanding mast climber on one configuration from one manufacturer. The equipment configuration was chosen to allow the highest/largest freestanding configuration allowable by the manufacturer, which would also lend itself to the most suspected unstable condition. The equipment was also fully set up to the manufacturer's recommended usage guidelines, including proper platform sizes, outrigger/base support, bolt torque specifications, and drive unit. It could be of great use for future work to investigate fall arrest testing with different platform loading, platform configurations, and base/outrigger support to greater increase the understanding of how mast climbers might react to fall arrest loading with different equipment configurations.

2. Methods

The methods used to determine the stability of a freestanding MCWP under potentially destabilizing conditions were designed to be similar to other construction equipment studies (Harris et al., 2010; Pan, Powers, et al., 2012; Wu, Powers, & Harris, 2011), and are consistent with the existing ANSI standard for fall protection (Z359.1-2007).

Two scenarios were examined to recreate fall arrest events that could cause the destabilized conditions. In the first, a dead weight—consisting of weighted plates—was dropped from a fixed anchorage point on the platform that would generate the maximal rotational force about the centerline of the mast. In the second scenario, an Advanced Dynamic Anthropomorphic Manikin (ADAM) was dropped from three initial conditions of platform loading according to the MCWP manufacturer's load chart: (a) an unloaded platform, (b) a fully loaded platform specific to the MCWP configuration used in the manufacturer's load chart, and (c) an overloaded platform.

2.1. Mast Climbing Work Platform

A freestanding Fraco ACT8 mast climber was used for all testing. The Fraco ACT8 consisted of the following:

- Freestanding ground base with outriggers placed according to manufacturer recommendations,
- 45-foot mast height with no anchor point,
- Diesel drive unit,
- Six 10-foot (3.05-m) sections of platform for a total of 30 ft (9.14 m) on each side of the drive unit with platform outriggers to form a lower working platform (step deck) created with planking, and
- One section of I-beam Monorail system used for tying off at the end of the platform.

The mast climber base was placed on a large outdoor concrete pad. All manufacturers recommend that during installation of freestanding mast climber equipment, all mast bases should be properly supported by stable extending outriggers in their appropriate position. For this project, the outrigger arms were extended to their maximum distance: 48 in. (1.23 m) for front stabilizers and 28 in. (0.71 m) for rear stabilizers. The outriggers were placed on wooden pads that measured approximately 18 × 18 in. (0.46 × 0.46 m) and were 6 in. (0.15 m) tall. Lag bolts were placed in the concrete and chains were draped loosely over the outrigger legs of the base for safety purposes, allowing 3 to 4 in. of vertical travel room for the leg to move without allowing the unit to fully detach from the outrigger pad. The chains were loose enough so that if the base began to rise from the ground, the legs would lift several inches before contacting the chains. For safety purposes, a mobile crane was also attached to the top of the mast via straps (with 3–5 ft (0.92–1.52 m) of travel).

The six platform sections that were fixed to the drive unit also included movable outriggers located 2 ft below the height of the main working deck. These outriggers can be pulled out and planking can be affixed to them to create a lower working deck on which workers commonly stand to perform tasks. This lower working deck configuration was also used for the study. An overview of the MCWP test configuration used is shown in Fig. 2.

To create the most unstable condition under fall-arrest loading, where the equipment could potentially tip-over or a fall hazard could be presented to the workers, the load point was placed at the furthest end of the working platform to create a greater tipping moment of the equipment.

2.2. Independent test variables

Due to the many ways that a mast climber can be configured, only certain configurations and test conditions were used for this initial study. The controlled independent variables were the overall base/mast/platform configuration, the dead weight/ADAM manikin fall arrest input, and the platform weight loading. The controlled variables, particularly the base/mast/platform configuration, were chosen to best represent how a freestanding mast climber would generally be installed.

2.3. Dependent test variables

The dependent variables, which were to be measured as an overall evaluation of the mast climber, were the platform displacement in the vertical direction along the loaded side of the platform, the platform and base accelerations at various locations, and the input force observed from the fall arrest itself. Assessment of these dependent variables will give an indication, albeit not definitive, of whether the mast climber is likely to remain stable during fall arrests.

A total of 29 different test conditions were performed. The most unstable conditions created the most movement of the platform of the mast climber. The results of the dead weight drop tests, as well as six specific fall-arrest scenarios using the ADAM manikin for the unloaded, max load, and overloaded platform conditions (tests 24–29) were deemed to be the worst case scenarios. As discussed in Section 3.2, the other twenty-three trials did not create recorded data measurements that posed the greatest risk for the equipment to become unstable.

2.4. Dead-weight drop tests

2.4.1. Nystron rope break in

To test the stability of the MCWP, dead weights were used in conjunction with a Nystron rope (Gravitec Systems Inc., Bainbridge Island, WA and Samson Rope Technologies Inc., Ferndale, WA) to create an impact that would meet and surpass the ANSI standard for maximum allowable force transmitted to the worker. The ANSI Z359.1-2007 standard sets the maximum allowable force applied to the harness portion of a personal fall-arrest system at 1800 lb (8000 N) (ANSI/ASSE, 2007). In conjunction with the 1800-pound maximum arresting force (MAF), a 2400-pound (10,675-N) MAF force was also used to check the safety margin/factor of the MCWP.

Nystron rope consists of a polyester jacket with a double-braided nylon core. To break in the rope and eliminate the construction stretch, a procedure similar to the one utilized by Harris was used (Harris et al., 2010). A 6-foot (1.83-m) Nystron rope, 5/8 in. (0.127 m) in diameter with split thimble ends, was affixed to a set of rigid weights on a threaded rod with locking hardware. The Nystron rope break-in configuration can be seen in Fig. 1.

The rope length was measured with a string potentiometer [Celesco model SP2-50, Chatsworth, CA] to ensure that all the stretch was removed. The string potentiometer was then used to detect the vertical linear position from which the weights needed to be dropped to achieve the desired 1800-pound (8000-N) and 2400-pound (10,675-N) impact forces. The weight and drop height configurations needed to achieve these forces were calculated at 118 lb (53.5 kg) at 30.5 in. (0.77 m), and 168 lb (76.2 kg) at 30.5 in. (0.77 m) respectively.

2.4.2. Instrumentation and materials

The configuration consisted of a Fraco ACT8 (described in Section 2.1.) with dead weights attached to the end anchor point of the platform. A 3000-pound (13,400 N) Interface (Interface Inc., Scottsdale, AZ) S-type load cell was used to record the force transmitted between the Nystron rope eyelet and the last anchor point. Shackles and eye bolts were used to make the connection. The load cell signal was passed through a signal conditioner and connected to a National Instruments 9191 wireless data acquisition device (National Instruments Corporation, Austin, TX) that was connected to a laptop.

Fig. 1. Fraco ACT8 Mast Climbing Work Platform.

2.4.3. Procedure

The first portion of testing consisted of using dead weights to create a maximum allowable force (which would be transferred to the worker during fall arrest) transmitted through the Nystron rope to an anchor point on the platform. To achieve the 1800-pound (8000-N) and 2400-pound (10,675-N) impact forces needed, the dead weights were attached to the Nystron rope and lifted to the corresponding heights. The Nystron rope was affixed to the weights with a turnbuckle and to the platform wall side at the furthest anchor point from the drive unit. The weights were hoisted to the desired height by a hand-operated

Fig. 2. Nystron rope "break-in" configuration.

Fig. 3. Dead-weight drop test configuration.

Fig. 4. Accelerometer on the outrigger pad column.

winch connected to the platform by the I-beam Monorail system. An electromagnetic disconnect was used to hold the weights at the desired height. The ACT8 drive unit was raised by remote control to its maximum allowable freestanding height of approximately 38 ft (11.58 m). The electromagnet was then deactivated by a remote control to release the weights that create the desired forces. Data recording began before the start of the weights' free-fall and continued until the platform rocking motion had stopped (approximately 15 s). The dead-weight testing configuration is shown in Fig. 3.

2.5. Drop tests recreating a fall-arrest scenario

2.5.1. Instrumentation and materials

An ADAM was used as a human surrogate for the fall-arrest testing. ADAM was designed to replicate joint articulation and dynamic body responses of a human since it represents the 95th percentile for height and weight of a U.S. male. ADAM was equipped with a PFAS, work boots, and coveralls - resulting in an overall height of 6 ft 2 in. (1.88 m) and weight of approximately 220 lb (99.8 kg).

The second component of a PFAS was the connecting device. Various combinations of market-available, shock-absorbing lanyards were used, including: 6-foot (1.83-m) shock-absorbing lanyards that had two plated, double-locking snap hooks with 3/4-inch (0.019-m) throat openings and an integral shock absorber, and 6-foot (1.83-m) shock-absorbing lanyards with a one plated, double-locking snap hook and one plated, double-locking rebar hook. The third component of a PFAS was the full-body harness. A vest-type harness, from the same manufacturer as the shock-absorbing lanyard, was used.

The Interface S-type load cell was used to record the force transmitted between the snap hook eyelets and the last anchor point. The load cell signal was passed through a signal conditioner and connected to a National Instruments 9191 wireless data acquisition device (National Instruments Corporation, Austin, TX) connected to a laptop. Five in-house packaged tri-axial accelerometers (Kionix, Model KXRB5, Ithaca, NY) were attached to the MCWP for vibration measurement. They were placed on the main platform section of the steel truss structure at evenly spaced 5-foot (1.53-m) increments from the end going inwards on the platform on one side of the drive unit. Two accelerometers were also placed on the outrigger pad columns at the base of the MCWP for measurement, one on the top section of each leg and secured with double sided tape, as shown in Fig. 4.

The accelerometers operated at 3.3 V and measured accelerations with values at ± 6 G with the sensitivity of 220 mV/G. The signals from the accelerometers were input to the wireless data acquisition system (National Instrument Analogue Input Module 9205 with Compact DAQ chassis 9191) and a LabVIEW program was developed to record, store, and display the acceleration time history data in real time.

Fig. 5. Fall-arrest scenario configuration.

2.5.2. Procedure

To re-create a fall-arrest scenario using the MCWP, the ADAM manikin was dropped from the far end of the main working platform. The platform weights for the specific testing configuration—unloaded, fully loaded, and overloaded—were put into place before each test. The ADAM manikin was outfitted with a randomly selected PFAS that included a harness and 6-foot (1.83-m) energy-absorbing lanyard. The lanyard snap hook was tied to the D-ring of the harness on one end, and an eye bolt that was attached to the force gauge on the other end. The force gauge was hooked by another eye bolt to the last anchor point on the platform's end that was furthest from the drive unit. The total force gauge configuration was approximately 12 in. (0.305 m) in length. The data recorded during the experiment included the arrest forces measured by the force gauge, vertical platform displacement measured by the string potentiometers, and the overall stability of the MCWP system as per visual observation, photos and videos.

The ADAM manikin was hooked to the I-beam Monorail tie-off system via a winch and pulley and was raised into position. ADAM was held to the cable by the electromagnetic disconnect system. A small section of the second step-down planking was removed to allow ADAM to free fall without interference. All data, photo, and video recordings began prior to the first drop. The ACT8 drive unit was raised to its maximum allowable freestanding height, and once stabilized, the ADAM manikin was released and allowed to free fall. Once the mast climber (entire structure) stopped moving, the drive unit was lowered and reset. The fall-arrest scenario test configuration is shown in Fig. 5.

3. Experimental results

The results of the experiment included the arrest forces measured by the force gauge, vertical platform displacement measured by the string potentiometers, and the overall stability (defined in Section 4.1) of the MCWP system.

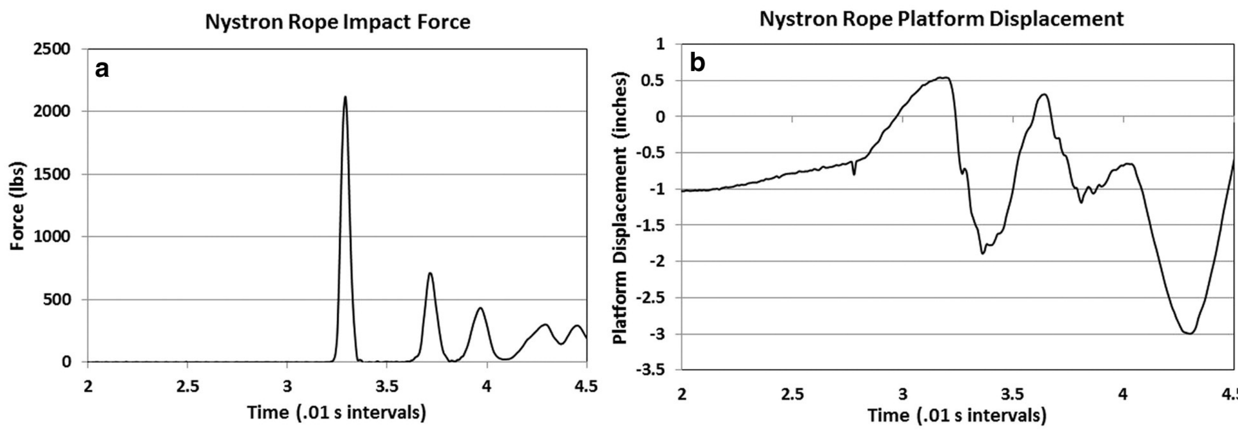

Fig. 6. Nystron rope dead-weight drop impact force and platform displacement.

3.1. Dead-weight drop test results

As discussed in Section 2.2., dead-weight impact forces of 1800 lb (8000 N) and 2400 lb (10,675 N) were created by dropping dead weights at pre-determined heights using the Nystron rope. While the base of the MCWP remained stable during these tests, the greatest platform instability occurred during the 2400-pound (10,675-N) force.

To achieve the 2400-pound (10,675-N) MAF, the 168-pound (76.2-kg) dead weight was dropped 30.5 in. (0.77 m), the height used during the Nystron rope break in. Using the configuration of the 2400-pound (10,675-N) MAF, an impact force of 2120 lb (9430 N) was achieved with the platform flexibility dampening the response. The impact force, recorded at the furthest end of the platform, is shown in Fig. 6.a.

Platform displacement measurements were taken at three locations along the main platform. The potentiometers were mounted to a fixed structure and the strings were affixed to the platform outriggers and were placed at increments of 80 in. (2.03 m) starting at the end of the platform furthest from the mast. The last string potentiometer (furthest from the drive unit) consistently measured the greatest displacement. For the 2400-pound (10,675-N) MAF test, the platform displacement measured a vertical change of approximately 2.5 in. (0.064 m) over a course of 0.15 s. Fig. 6.b. shows the measurement during impact of the string potentiometer furthest from the drive unit. The platform travels upward vertically for approximately 0.5 in. (0.013 m) at the moment the weight is released, prior to the imposition of impact force. All data past 4.5 s for the dead-weight drop tests were not considered in the analysis because the sway displacement (left to right platform movement) was largely responsible for invalidating data recorded after this time. The third platform displacement (between 4 and 4.25 s) exceeded the first two impacts due to the overall sway of the platform and mast.

During both the 1800-pound (8000-N) and 2400-pound (10,675-N) MAF impact force tests, the MCWP remained stable. The outriggers did not move from the outrigger pads and the MCWP base did not move. Although the platform moved vertically downward 2.5 in. (0.064 m), the motion (horizontal and vertical sway) quickly subsided and the MCWP returned to its full, stable resting position.

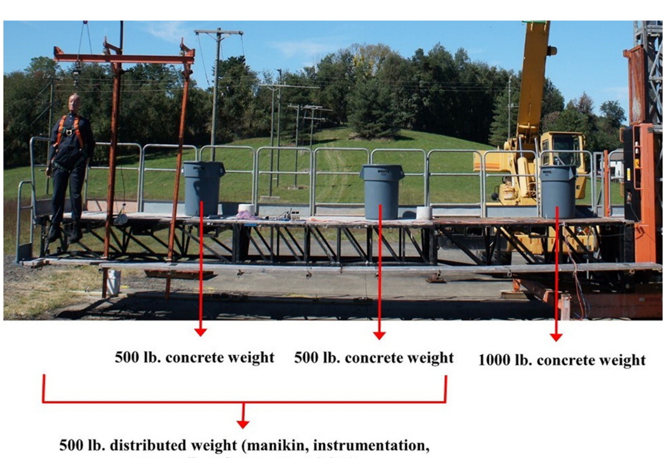

Fig. 7. Platform loading for the "overload" testing scenario.

3.2. Fall-arrest scenario test results

For this testing the Fraco ACT8 used a variation of platform loading using concrete weights. According to the ACT8 user's manual (Fraco, 2015), for the configuration used with a cantilevered platform measuring 30 ft (9.14 m) in length, a reduced load of 50% must be used on both sides of the drive unit. To achieve the most unstable scenario, the Fraco ACT8 had 60 ft (18.29 m) of platform but loading was only completed on one side of the drive unit. The maximum allowable load was 1500 lb (680.39 kg) located 5 ft (1.53 m) from the center of the mast, and 500-lb (226.8 kg) distributed throughout the rest of the platform length. For all scenarios, the 500-lb (226.8-kg) weight was distributed throughout the rest of the main platform independent of the 1500-lb (680.39-kg) load and 5 ft (1.53 m) from mast center. The configuration included the ADAM manikin, I-beam Monorail system, instrumentation, and small concrete weights. The platform loading weight distribution with the overloaded weight scenario is shown in Fig. 7.

There were a total of 29 configurations tested. The platform began unloaded for the first test, and weights were added and then shifted away from the mast as the tests progressed. The final four tests were completed as the weights were unloaded and are reported below. The final six tests were an overloaded platform, fully loaded platform, and finally an unloaded platform. The final six test configurations for the testing are shown in Table 1. No scientific Mast Climbing Work Platform testing has been completed outside of manufacturer's own testing. Due to this fact, the first 23 tests were essentially pilot tests leading to the final six testing configurations which are discussed below. This methodology approach was taken to ensure that the equipment being tested was not damaged or that no excessive safety hazard issues were created during the testing for the investigators. The other 23 trial test configurations included platform loading and lower fall heights

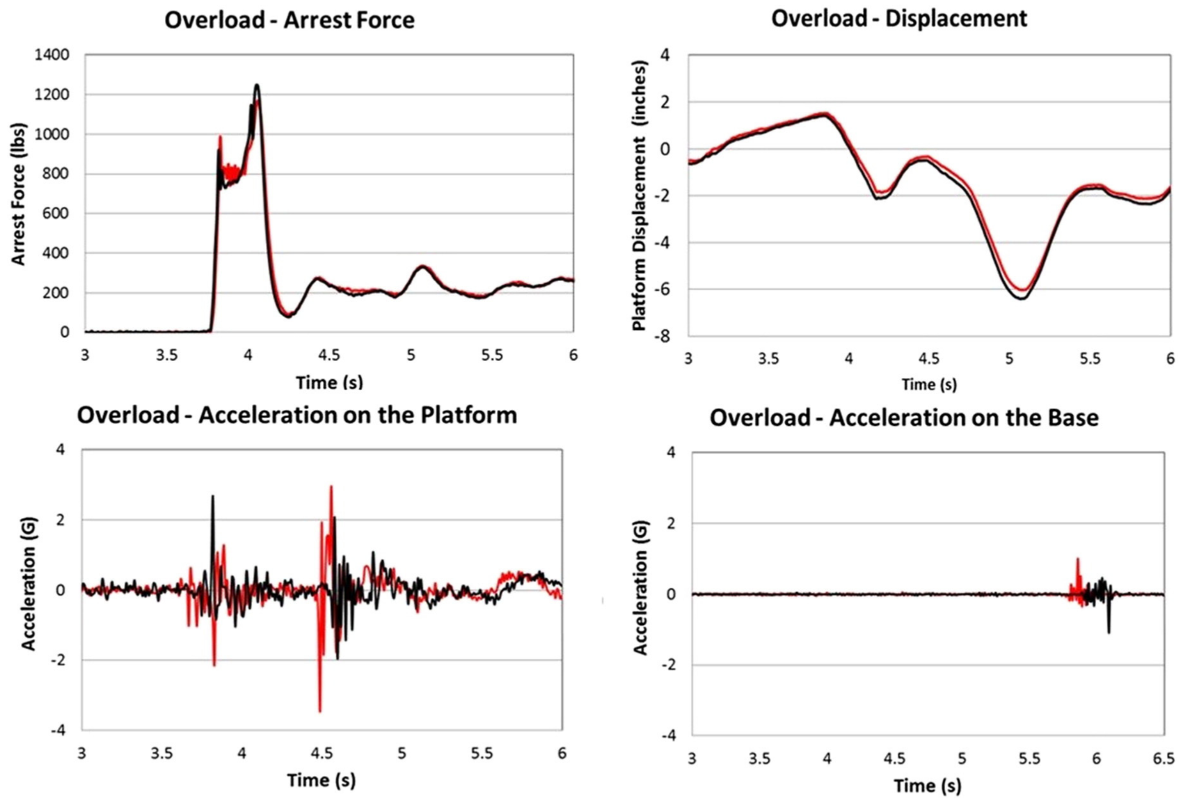

Fig. 8. MCWP measurements for the platform overload condition.

that did not show recorded MAF and platform displacements that were great enough to create the most unstable test configurations for the testing.

In Table 1, *Torque* (ft∗lbs about mast center) is calculated from the weight about the center of the mast. *Percent (%) of the Max Load* is based on a 100% maximum load with 1500 lb (680.39 kg) centered

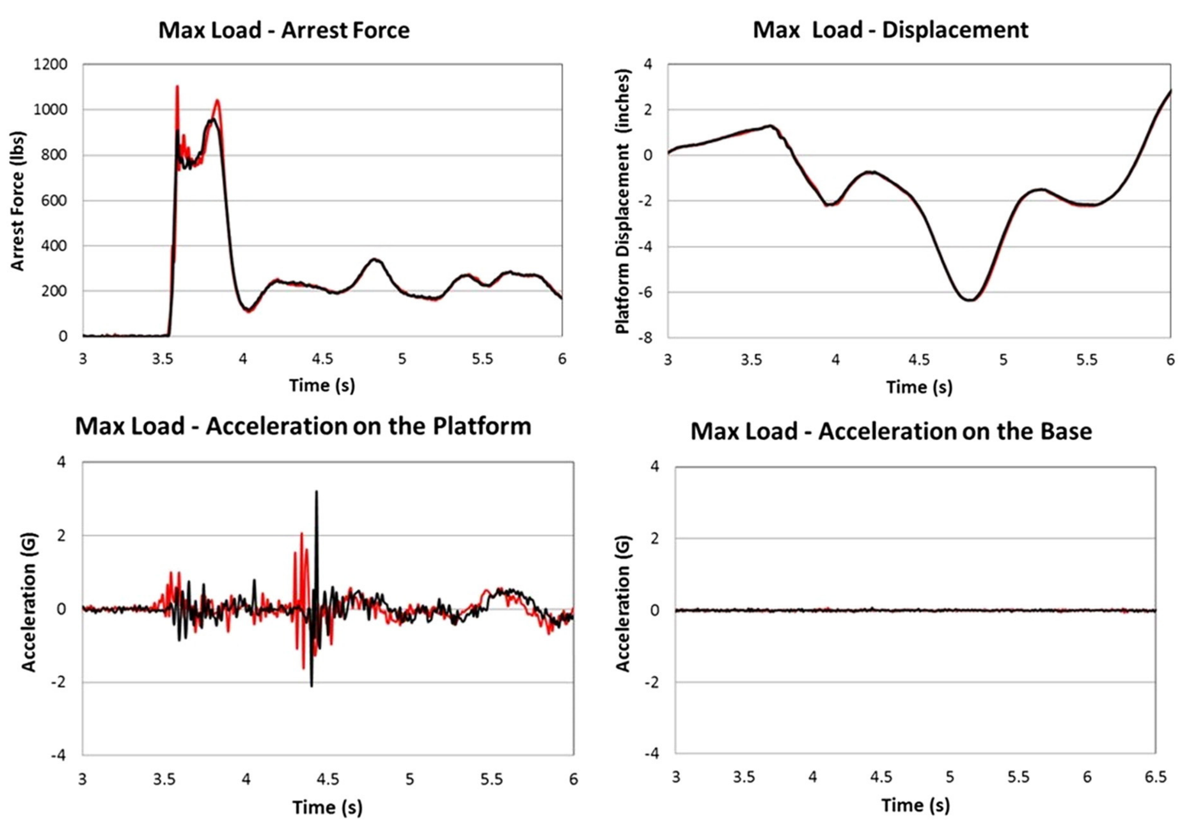

Fig. 9. MCWP measurements for the maximum loaded condition.

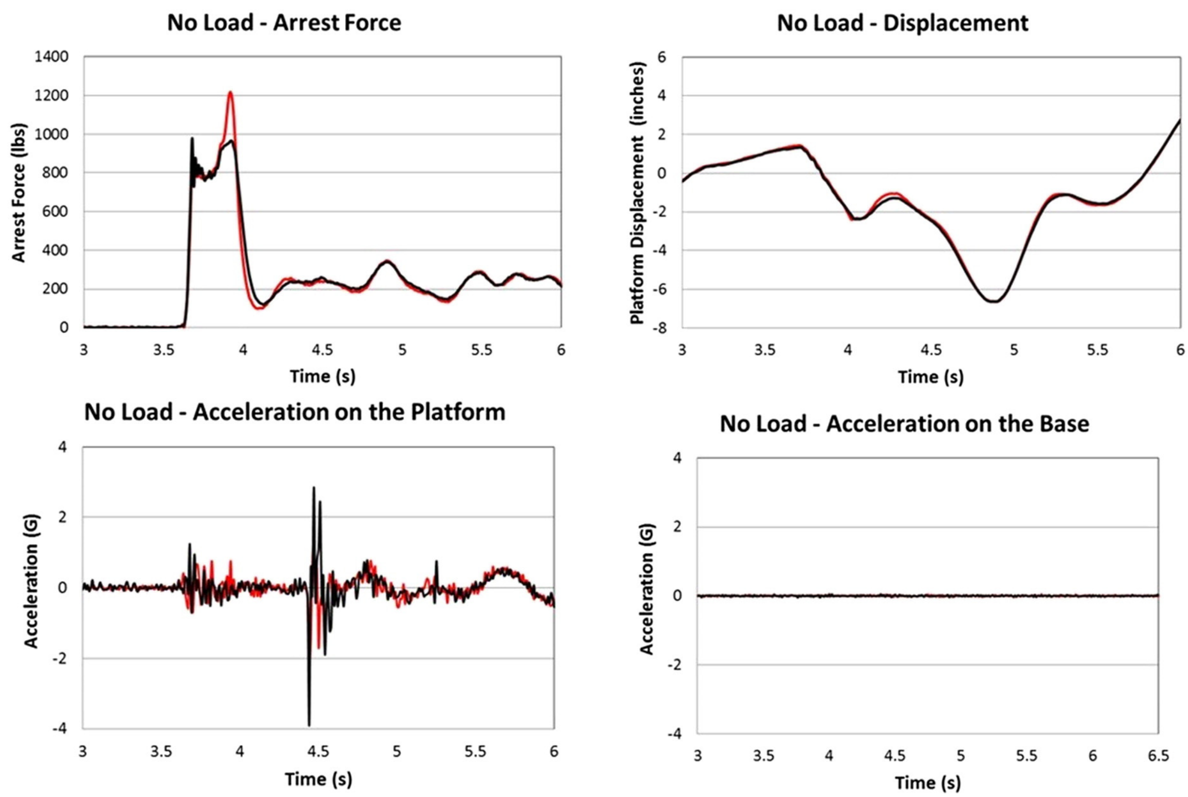

Fig. 10. MCWP measurements for the unloaded platform condition.

5 ft (1.53 m) from the mast, and 500 lb (454 kg) distributed throughout the rest of the platform (centered halfway from the 1500-pound (680.39-kg) load and the end of the platform furthest from the mast). The *Max Force Recorded* is the vertical force applied to the load cell from the end hook of the energy-absorbing lanyard. The *Maximum Initial Vertical Platform Displacement* is measured by string potentiometers from the moment the platform begins its downward movement (not the rising movement from the weight release of the ADAM manikin) until it begins its upward movement. For every trial, the results were expected since the maximum initial vertical recorded platform displacement was at the platform's end furthest from the center of the mast with platform weights.

Also shown in Table 1, the forces recorded for the final six trials were between 950 and 1250 lb (4226 and 5560 N) with a maximum initial vertical platform displacement of 3.3 to 3.8 in. (0.084 to 0.096 m). The other twenty-three trials showed maximum force values and platform displacement values similar to the results in Table 1. It should also be noted the maximum allowable force applied to the harness portion of the personal fall-arrest system was under the 1800 lb (8000 N) ANSI Z359.1-2007 standard (ANSI/ASSE, 2007) for all trials.

The accelerometers located on top of the outrigger arms at the base structure showed the accelerometer on the front arm, located furthest from the ADAM manikin, indicated the greatest amount of movement and acceleration. There were no noticeable accelerations for any trial during the maximum loaded and unloaded platform conditions. The overloaded platform had accelerations of approximately 1G (9.8 m/s^2) for both trials. In one trial, the outrigger arm lifted approximately 1/2 in. off the wooden box and immediately returned to its position, hence resulted in the 1G accelerations. The mast climber remained stable throughout the test. It is significant that for the unloaded and maximum loading conditions indicating no noticeable recorded accelerations at the base, confirming that the equipment remained motionless and did not pose unstable conditions.

The most interesting results were ones that created the most unstable platform. The following figures illustrate the greatest platform displacements and accelerations recorded at the furthest end of the platform. Each figure contains the two repeated trials for each condition - shown in red and black, respectively. Figs. 8–10 contain the graphs of the fall-arrest force, platform displacement, acceleration at the end of the platform, and acceleration at the outrigger arm base for the various platform conditions.

Also of note, as shown in the aforementioned figures, an initial vertical rise was shown in the platform displacement at the release of ADAM as expected. Upon the lanyard deployment, there was an initial downward displacement of the platform approximately 4 in. (0.102 m) for each scenario, followed by a brief rise of the platform of

Table 1
Test matrix and results for specific cases.

Test number (29 total)	1000 lb (454 kg) W distance from mast	500 lb (227 kg) W#1 distance from mast	500 lb (227 kg) W#2 distance from mast	500 lb (227 kg) W#3 (ADAM, instr., etc.) distance from mast	Torque (ft∗lbs. about mast center)	% of max load (moment based)	Max force recorded (lbs)	Maximum initial vertical platform displacement (inches)
24	5′	14′6″	25′6″	20′	35,000	200%	1247	3.6
25	5′	14′6″	25′6″	20′	35,000	200%	1169	3.3
26	5′	5′	NA	20′	17,500	100%	959	3.5
27	5′	5′	NA	20′	17,500	100%	1103	3.4
28	NA	NA	NA	20′	10,000	57%	979	3.7
29	NA	NA	NA	20′	10,000	57%	1218	3.8

2 in. (0.051 m). After the deployment, another platform drop of 4 to 6 in. (0.102 to 0.152 m) was observed for each trial.

The first acceleration peak on graphs 8, 9, and 10 correspond to the initial force placed on the lanyard and its full impact force after the energy-absorbing portion had fully deployed. The overloaded platform scenario found both peaks were approximately 2 G (19.6 m/s^2) to 3 G (29.4 m/s^2). The maximum loaded and unloaded platform scenarios found the first peak to be near 1 G (9.8 m/s^2) and the second peak to be approximately 3 G (29.42 m/s^2).

Fig. 9 shows the corresponding graphs of the maximum loaded platform condition.

Fig. 10 shows the corresponding graphs of the unloaded platform condition.

4. Discussion and conclusion

4.1. Stability of the MCWP

This research project investigated whether a freestanding MCWP under normal work conditions would remain stable should a fall-arrest event occur. For this study, a stable position was defined as the mast climber equipment remaining in an upright posture, akin to its original starting position, where it would remain balanced and not presenting any excess movement, potential tip-over, collapse, or move in such a way to pose a safety hazard to the workers on the main platform. The MCWP was erected and tested under both the manufacturer's recommended operating conditions, as well as misuse scenarios that could potentially occur during equipment use. The methods used to evaluate stability of aerial work platforms during fall-arrests followed the ANSI standard for fall protection to determine a baseline testing condition (Pan, 2016).

To evaluate the stability of the mast climber, vertical platform displacement and acceleration, acceleration at the MCWP base, and the fall-arrest forces were measured. The stability of the mast climber inherently relies on the performance of the mast base as it is the foundation of a freestanding configuration. Therefore, the base of the MCWP was configured to exact manufacturer and industry recommendations for every test scenario.

However, manufacturers recommend that the outrigger pad supports be checked every day before work begins. During the drop arrest trials the mast climber remained stable and little to no movement was visible at the outrigger pads. Manufacturers also indicated that improperly supported, positioned, or worn outrigger pad or base could lead to catastrophic failure. Outrigger supports should always be checked before MCWP use, especially if there is any potential for the pad support to become unstable, such as in the case of inclement weather or extreme movement from the equipment.

The arrest force, platform displacements, and platform accelerations were consistent with the anticipated results from previous aerial work platform fall-arrest research (Harris et al., 2010; Pan, 2016). During the three tested conditions, the MCWP remained upright and posed limited threat to potentially tip over. The results of this study suggest a personal fall-arrest system can be used in conjunction with freestanding mast climber equipment under the recommended guidelines from the manufacturer and the assumption that the equipment is properly assembled/erected when used.

4.2. Stability of the working platform

Another unresolved issue addressed was possible fall hazard risks for other workers on the platform in the event of a fall-arrest from a worker using a harness/lanyard system. During the evaluation of the overall stability, the platform movement was thoroughly considered and evaluated during the ADAM manikin drop tests because it closely simulated a real work case scenario. The six trials concentrated on an improper tie-off position (at foot level) with varying platform loadings. In each of the arrest force graphs there were two peaks during each trial. The first peak occurred when the ADAM manikin had fallen and the lanyard/harness began to stop its descent. The rising portion after the first peak was the deployment of the energy-absorbing portion of the lanyard, and the second peak was when the lanyard had fully deployed causing a higher arrest force. The fall-arrest force levels were lower than the standard maximum allowable force transmitted to a worker found in the OSHA fall-arrest standards, even for a misuse scenario (Occupational Safety and Health Administration [OSHA], 1999; Pan & Chiou, 1999). The arrest force graph shapes were found to be independent of the platform loading.

While there is little to no research on vertical platform perturbations, there has been scientific research on platform oscillations and other motion-based movements' effects on human response and performance, such as working on a ship deck at sea or on public transportation while moving (Wertheim, 1998). Lateral sinusoidal oscillations from 0.5–2 Hz and accelerations from 0.1–2.0 m/s^2 (0.33–6.56 ft/s^2) were shown to cause postural instability and the perceived risk of falling (Sari & Griffin, 2014). Repeated exposures to platform motions can also affect the human response—the more exposure to the movement, the better the adaptation to the movement (Duncan, Langlois, Albert, & MacKinnon, 2014). Platform motions that would occur due to a fall arrest would most likely not be repeated movements, however, giving a worker little or no time to adapt. The platform movement found in the overloaded and maximum loaded scenarios approached 3 G (29.42 m/s^2) and had a displacement of 4 to 6 in. (0.102 to 0.152 m) occurring over the 0.75-second time interval.

While workers are not required to tie off for general mast climber use, if an open edge is present they must do so under OSHA requirements. In many circumstances the tie off point is at the leading edge of the main working platform deck. If a worker was to fall while standing on the main deck and is tied off at foot level, it would create an approximate 11-foot fall. This study created this scenario for testing, it was considered the misuse scenario. The platform motions caused by the fall-arrest conditions evaluated in this study were similar to or worse than those found in the aforementioned studies (Duncan et al., 2014; Sari & Griffin, 2014; Wertheim, 1998).

If a worker were standing on either the upper or lower working deck of the mast climber, these results suggest that it is very likely their postural stability could be compromised during a fall-arrest incident, thus creating a potential fall hazard. The fall hazard could be greater the closer the worker would be to an open and unprotected edge of the working platform. If any worker were tied off while working at a stationary height on the mast climber deck, all other workers near an open edge of the platform should also be tied off. The tie off points should be corresponding to those found by the manufacturer related to the specific mast climber equipment being used.

5. Impact

The research team will share the study recommendations with the OSHA construction directorate and relevant ANSI standards committees for consideration in updating appropriate regulatory and consensus standards. The study results will also be shared with the Advisory Committee on Construction Safety and Health and the Building & Construction Trades Department, Safety and Health Committee to establish MCWP safety guidelines. As the use of MCWPs continues to increase at construction sites, there will be a commensurate need for evidence and science-based safety guidelines or regulations.

Disclaimers

The findings and conclusions in the report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of company names or products does not imply endorsement by NIOSH. In addition, citations to websites external to NIOSH do not constitute NIOSH endorsement of the sponsoring organizations or their programs or products. Furthermore, NIOSH is not responsible for the content of these websites. All web addresses referenced in this document were accessible as of the publication date.

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