Horizontal Fall Arrest and Restraint System Design for High Altitude Construction and Maintenance Work

Milton L. Landron Torres, BSME, EIT
Master of Engineering in Mechanical Engineering
Rafael Salgado, Ph.D.
Mechanical Engineering Department Polytechnic University of Puerto Rico

Abstract *— Horizontal fall arrest system design and implementation for future construction and maintenance work atop Building 10 of the International Distribution Center facilities of Cardinal Health located in Guaynabo, Puerto Rico. The fall arrest system shall be in place prior to, and designed around the installation and maintenance of a proposed photovoltaic system; and be in conformance with all Occupational Health and Safety Administration established regulations and applicable state laws. The installation is intended to be permanent as to provide access to general roofing maintenance, rain gutter and drain clearing, photovoltaic system and existing Heating Ventilation and Air Conditioning system maintenance and servicing. Analysis indicates the designed system is capable of withstanding applicable forces and safely arresting a worker in the event of a fall.*

Key Terms *— Fall Arrest, Fall Protection, Horizontal Lifeline, Personal Energy Absorber, Workplace Safety.*

INTRODUCTION

As required by state and federal law, and the Occupational Health and Safety Administration (OSHA) regulations, all elevated work areas where a fall to a lower level risk is present must be protected by a fall arrest and restraint system. When used in conjunction with personal protection equipment (PPE) such as body harnesses and lanyards, horizontal lifeline (HLL) systems shall be capable of minimizing fall related injuries and fatalities as well as limiting work areas to prevent workers from reaching unprotected leading edges. As requested by the customer, an HLL system design will be proposed for implementation in conformance with specified customer requirements.

BACKGROUND

From their conception and use, fall safety systems have drastically reduced the primary cause of worksite injuries and fatalities; falls from high altitudes. The HLL system, the most commonly adapted form of fall protection, is currently in service across numerous industries.

Designs and installations of numerous HLL systems are in place today; each with their specific applications with respect to varying conditions. These may vary by permanent or temporary installations, load requirements, roofing types, local laws and regulations, etc. [1]. In its simplest form, an HLL system consists of a cable (commonly steel) and two or more anchor points to which the cable is attached. Workmen wearing a full body harness will secure themselves to the HLL with the use of a lanyard. Figure 1 portrays a basic HLL system and components.

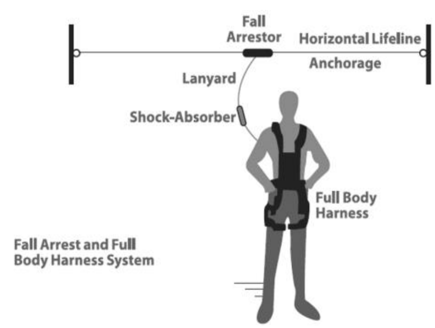

Figure 1
Basic HLL System

The HLL system grants workers a wide range of motion, as the fall arrestor device translates along the lifeline cable. In the event of a fall, the HLL system along with the lanyard will serve to dampen the force of the fall while keeping the worker from further lesions of falling onto a lower level.

Prior to OSHA regulations being enacted, fall protection systems were unregulated while the employer did not hold responsibility for providing a safe work environment. Some safety belts were available but often unused as workers found them cumbersome and restrictive for performing their work duties. Individual workers bore the responsibility for their own safety while employer provided protections amounted to verbal warnings and posted signs. As workplace fatalities increased from the rapid rate of industrialization, along with increased costs to employers due to litigation related to onsite deaths and injuries, new incentives were created to minimize safety hazards. Employers in the mining, construction and manufacturing industries began providing increased safety measures; however industry standards were yet to be in place.

Upon its creation in 1970, OSHA implemented regulations for fall protection along with additional workplace safety standards, enforcing these via unannounced spot inspections and heavy fines for noncompliant sites. Safety equipment such as harnesses, anchorage points and lanyards were closely modeled after rock-climbing and mountaineering equipment. Use of such equipment became the norm across industries thus greatly reducing workplace deaths and injuries.

As technology progressed, additional features were added to fall protection systems and equipment. Workers' body belts were required to be secured by two lanyards to ensure workers remained anchored during transitions of work areas. One lanyard would remain attached to the original anchor point, while the second would be relocated to the following anchor, followed then by the remaining lanyard thus achieving '100% tie-off'. Following additional advancements, belts were replaced by full body harnesses which added protections not only to impacts from falls, but also from the forces exerted on the body from suspension thus protecting the worker from spinal and other internal injuries. Anchorage point relocation provided by the dorsal 'D ring' on the harness served for better weight distribution, resulting in less risk of injury to the worker. Materials advancements also served to increase safety and comfort to the worker with additional resistance to abrasives, corrosives and general wear and tear. Furthermore, the introduction of self-retracting lanyards improved deceleration, shortened fall distances and prevented sudden stops on suspension.

PROBLEM STATEMENT

Cardinal Health in Guaynabo, P.R. is planning the installation of a photovoltaic (PV) system atop the roof of their Building 10 facilities where access and safety systems shall be in place for contractor use of initial install and continued maintenance. Plant workers shall also be granted access to perform continued maintenance to the building's roof panels, gutters, drains and existing heating, ventilation and air conditioning (HVAC) systems. In compliance with regulations, a permanent HLL system will be designed and implemented, and routed around aforementioned existing and future installs.

Research leading up to the design and execution of an effective HLL system will be conducted. Local laws and regulations will be assessed along with the study of existing systems and applications. Different design alternatives shall be evaluated as to select the most appropriate system with respect to cost, maintenance and durability for existing worksite conditions.

Objectives will be aligned with the execution of a well-designed system granting safe access to contractors and plant maintenance workers in compliance with all applicable laws and regulations. Initial assessment of the worksite and future construction plans will drive the HLL system design. Construction and maintenance routes and areas will be established in order to ensure all necessary regions are serviceable.

An official design proposal will be submitted for customer evaluation along with related documentation and research leading up to the chosen system design and routing. Mechanical analysis and calculations will be performed to ensure safety regulation compliance.

METHODOLOGY

Data drawn from worksite conditions, access areas, worker tools and type of work to be performed shall be incorporated into the analysis as to conform to customer and safety requirements. Inputs provided will serve to develop an HLL system capable of withstanding applicable loads as well as safely arresting forces generated in the event of a fall. The analysis will be segregated into different phases of a fall, where energy will be generated and absorbed in combination by the elongating HLL and PEA systems.

Worksite Assessment

Scheduled worksite visits will be performed to assess site conditions, determine work areas, existing hazards, access points and maintenance equipment locations. Lower level areas where risk of falling is present will be documented. The HLL system will be designed for the shortest fall distance in the worksite, while retaining the necessary fall length for proper damping system function. Building plans and drawings will be requested for roofing and structure locations to be used as possible anchor points, along with detailed drawings of PV system locations and equipment. Roofing panels will be considered for direct anchorage of HLL posts. Meetings to be called with onsite health and safety officials, and facilities maintenance leadership and workers for discussion on expected work to be executed; with emphasis on equipment, hoists and tools needed for assigned tasks.

HLL Design

From data drawn of initial site, worker and task assessments, basic design requirements will be identified and calculations performed to ensure compliance. Initially, the minimum fall distance must be calculated as this will drive the primary restriction in which the system will operate. The HLL must be able to withstand and arrest a fall within the fall clearance distance as to avoid worker injury. Following a fall clearance analysis, the HLL system will be evaluated under three conditions: before a fall, onset of fall arrest, and energy absorption. To this end, the analysis shall be performed using the energy balance method. This approach balances the energy generated during the fall and the energy dissipated during the arrest. Further calculations and requirements will be detailed with respect to applicable regulations.

Anchorage Points

HLL system anchorage points will be selected based on worksite requirements and equipment availability. Anchor posts will be preferably selected from readily available manufacturers with respect to requirements as to avoid the added costs of designing job specific anchors. Alternatively, if no posts are available in the market in compliance to requirements, new designs will be proposed and submitted to the customer for evaluation. Anchorage loads and characteristics will be derived from customer meetings and site evaluations. Roof locations for anchor posts will be determined via analysis in compliance with local regulations. Direct anchoring to roofing panels will be allowed and preferred as a lesser cost alternative. Where additional anchor loads are required, building structure beams will be considered.

Force calculations will be performed to determine the systems maximum arrest load (MAL) exerted on the HLL and the maximum arrest force (MAF) applied to the worker in the event of a fall. MAL, in accordance with ANSI Z359.1-2007 shall not exceed 5000 pounds force, while MAF shall not exceed 1800 pounds force with a test weight of 220lbs [2]. To avoid the expected MAF to exceed imposed limits, a personal energy absorber device (PEA) will be incorporated into the system. PEA systems are readily available in the market and serve to reduce shock loads to the worker.

Static HLL Design

Adequate cable sag and tension at rest is crucial in the HLL design analysis. From data obtained on readily available cable commonly used for HLL applications, the following equations shall be used to determine the initial system parameters [3]:

Cross-sectional area A of HLL cable:

$$A = \pi \frac{d^2}{4} \quad (1)$$

Cable sag s_i as consequence of its own weight:

$$s_i = \frac{wL^2}{8T_i \sqrt{1 - \left(\frac{wL}{2T_i}\right)^2}} \quad (2)$$

Initial cable length l_i:

$$l_i = L\left(1 + \frac{8}{3}\left(\frac{s_i}{L}\right)^2\right) \quad (3)$$

Unstressed HLL cable length l_0:

$$l_0 = \frac{l_i}{1 + \left(\frac{T_i}{AE}\right)} \quad (4)$$

HLL cable stiffness k_{HLL}:

$$k_{HLL} = \frac{AE}{l_0} \quad (5)$$

where for the above equations: d is the nominal cable diameter, w is the nominal cable unit weight, L is the span length, T_i is the pre-tension force, and E is the nominal cable modulus of elasticity.

Fall Arrest Onset

As a worst case, the fall will be analyzed acting on the mid-span of the HLL. In the initial stage of a fall, the HLL cable will begin to sag prior to providing any significant deceleration force to arrest the fall. This is referred to as the cusp sag, which describes the state in which the initial cable length at its pretension force is pulled into two straight lines from the anchor points to the point of the applied force of the fall. To calculate the cable displacement due to the cusp sag s_c, the following will be used [3]:

$$s_c = \frac{1}{2}\sqrt{{l_i}^2 - L^2} \quad (6)$$

In the event of a fall, the worker is essentially experiencing free-fall from the point of the initial fall to the point in which the cable reaches its cusp sag. From the data drawn on previous equations, the following calculates the free fall FF distance:

$$FF = h_D + s_c - s_i + L_y \quad (7)$$

where h_D is the D-ring height above the HLL anchorage point and L_y is the unstressed lanyard length.

Fall Energy Absorption

Beyond the point of the cable cusp sag, the worker's fall is now being arrested. The HLL system will act to absorb the kinetic energy generated during free fall initially by elongating the cable past cusp sag. The cable will continue to elongate until the force exerted on the lanyard F exceeds the deployment of the PEA. Once reached, the PEA will now deploy and is assumed to absorb the remainder if the fall force. It is assumed that the HLL cable will not elongate further at this point. The PEA will continue to extend until potential energy is absorbed and remaining energy U_k reaches zero.

Energy Balance Analysis

As noted, all energy generated by the worker's free fall will be absorbed initially by the HLL and further by the PEA system until brought safely to rest. To do so, the value of the HLL sag s at midpoint in which instant the force F exerted by the lanyard is equal the deployment force of the PEA must be calculated. An iterative approach is used by substituting the vertical midpoint sag s for an arbitrary value until $F = F_{PEA}$ in the following equations:

Midpoint sag s:

$$s = \frac{1}{2}\sqrt{(l^2 - L^2)} \quad (8)$$

Rearranging (8) to find cable length l for a given sag s:

$$l = \sqrt{(L^2 - 4s^2)} \quad (9)$$

HLL elongation x_{HLL}:

$$x_{HLL} = \frac{T}{k} \quad (10)$$

Rearranging (10) to find tension in cable T:

$$T = k_{HLL} x_{HLL} \tag{11}$$

Force in lanyard F:

$$F = 4T\left(\frac{s}{l}\right) \tag{12}$$

When the PEA force is reached, the initial sagging of the HLL has absorbed a portion of the fall energy U_{HHL}. As the PEA extends through its length x_{PEA} it continues to absorb the remainder of the fall energy U_{PEA}. While the fall is being arrested, however, the worker is still falling thus energy continues to be generated in addition to the already present from the free fall. This energy U_w continues through the total fall distance h_{TFD}. Additional energy now stored in the HLL at cusp sag U_{HLL_0} must also be absorbed for the worker to reach a full stop. To satisfy this condition the following equations will be used through an iterative method, such as employed previously, where an arbitrary value will be assigned to x_{PEA} until the remaining fall energy U_k reaches zero:

Total fall distance h_{TFD}:

$$h_{TFD} = FF - s_c + s + x_{PEA} \tag{13}$$

Energy generated by falling worker U_w:

$$U_w = W h_{TFD} \tag{14}$$

where W is the weight of the worker including tools and equipment.

Energy absorbed by PEA extension U_{PEA}:

$$U_{PEA} = F_{PEA} x_{PEA} \tag{15}$$

Energy stored in HLL at cusp sag U_{HLL_0}:

$$U_{HLL_0} = \frac{1}{2} k_{HLL} {s_c}^2 \tag{16}$$

Energy absorbed by HLL elongation U_{HLL}:

$$U_{HLL} = \frac{1}{2} k_{HLL} {x_{HLL}}^2 \tag{17}$$

Remaining energy U_k:

$$U_k = U_w + U_{HLL_0} - U_{HHL} - U_{PEA} \tag{18}$$

Once U_k reaches zero, all energy from the fall has been absorbed by the HLL and PEA, thus the fall is now fully arrested. Data drawn from the analysis will be compared to the equipment and anchor limits, as well as the allowable fall clearance. If within parameters, the selected system is accepted.

Fall Clearance

Elongation of the HLL and PEA systems shall provide adequate clearance preventing the worker from contacting lower levels, objects or other surfaces. A clearance margin E must also be applied, featuring a 10% of the midpoint and cusp sags with an additional 24 inches of clearance.

Clearance margin E:

$$E = 24 + 0.1(s - s_c) \tag{19}$$

Required fall clearance shall consider the clearance margin E, the total fall distance h_{TFD} which includes the free fall distance as well as the HLL sag, and material and PEA elongations. In addition, the fall clearance must also account for harness stretch and D-ring shift x_w, which is typically assumed to be 12 inches for compliant harnesses.

Fall Clearance Required C_p:

$$C_p = h_{TFD} + x_w + E \tag{20}$$

The minimum fall clearance shall be less than the shortest lower level at risk in the worksite. The HLL system sag shall be designed to comply with the minimum fall distance as well as providing necessary damping and protection for the falling worker.

RESULTS AND DISCUSSION

From the process described above, the following results were obtained with the use of customer inputs, analytical assumptions, and equipment and materials data.

Customer Inputs and Site Assessment

Meetings conducted with facilities, safety, and contractor personnel to determine maintenance and access needs. Customer requires access to PV panels and rain gutters located on the north and south sides of the building. The proposed PV panel layout is shown in Figure 2. A single worker is expected to perform maintenance duties with the use of hand tools carried on the worker's belt or a small tool bag. No additional specialized equipment is required. Customer requires HLL system to be a permanent installation requiring minimal maintenance and in compliance with OSHA 1926.500 and 1910.66, stating anchorage supports used for fall arrest systems must be independent from any equipment or platform supports and able to withstand a minimum of 5000 pounds per worker attached; and in compliance with ANSI Z359.1-2007 requiring the system be capable of sustaining static loads applied in all permitted directions by the system with a safety factor of at least two. Workers are expected to employ full body harnesses and energy absorbing lanyards marked ANSI Z359.13 when attached to the HLL system. Combined weight of worker and tools is not expected to exceed 220 pounds.

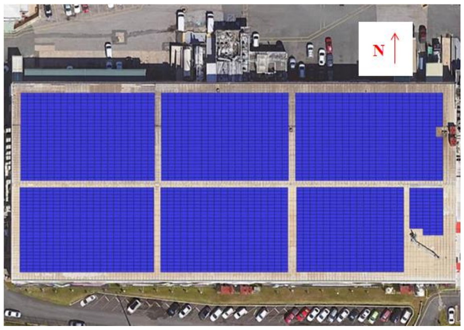

Figure 2
PV Panel Layout

Site surveyed for conditions, structure, dimensions and access routes. Roof is constructed from ribbed metal roof decks of 22 gauge with 10 inch rib spacing. Worksite is absent of skylights or other potential fall through hazards. Roof dimensions are 443 feet on the north and south sides, and 192 feet on east and west sides. Roof slope does not exceed a 3:12 pitch. No insulation or coatings present on outer side of roof decks. As shown in Figure 3, roof panels exhibit weathering; however appear to be in good condition and free of deformations. No customer concerns of thermal bridges into warehouse area. Roof edges are protected with the use of angle plates. Concrete rain gutters present in north and south side building edges. No sharp edges at risk of damaging PEA lanyards are present. Roof is accessed through a single, permanent vertical ladder with bird cage guards on the east side. Lower level platform with least fall clearance located on east side of the building with a distance of 30 feet from roof edge to platform. Equipment located on adjacent platform measuring a maximum of 4 feet, reducing the nearest fall distance to 26 feet. No risk of contact on adjacent structures present in the event of a pendulum fall.

Figure 3 image showing roofing panel conditions taken from east facing access ladder looking west. North facing concrete rain gutter displayed in image. Roofing panel fasteners installed per building code and appear to be in good condition. HLL anchorage acceptable directly on roofing panels with the use of anchor plates.

Figure 3
Building Roof Condition

Assumptions

Design assumptions drawn for worst case design with safety factors incorporated. HLL analytical fall arrest loads will be applied mid-span with maximum permitted worker weight. PEA deployment force assumed at upper limit of 900 pounds force. Selected HLL cable breaking strength shall exceed two times the maximum arrest force. Anchor supports are assumed rigid and noncontributing to the fall arrest.

Analysis

Data, specifications and assumptions drawn above will be incorporated into the analysis. Factors affecting fall energy absorption are cable build, size and material properties, as well as initial pre-tension force and span length. These variables must be brought to balance in order to assure proper system function. It is important to note these values must be initially assumed and iterated until a conforming outcome is reached. Selected cable for strength and durability is 7x7, 5/16 inch 316 Stainless Steel wire rope. A cross section of the selected cable is presented in Figure 4.

Figure 4
7x7 Wire Rope Cross Section

Additional cable material properties are as follows [4]:

- Nominal Elastic Modulus $E = 9.398 \times 10^6\ psi$
- Nominal cable unit weight $w = 0.011\ lb/in$
- Cable breaking strength $S_u = 8542\ lbs$

Initial conditions per design:

- Anchor to anchor span length $L = 468\ in = 39\ ft$
- Pretension force $T_i = 225\ lb$f

Static HLL System

Prior to external loads applied, the initial HLL system conditions based on selected cable and parameters are as follows:

Cross-sectional area A of HLL cable:

$$A = 3.14 \frac{{{}^{5}\!/_{16}}^{2}}{4} = 0.077\ in^2 \tag{1}$$

Cable sag s_i as consequence of its own weight:

$$s_i = \frac{0.011(468)^2}{8(225)\sqrt{1-\left(\frac{0.011(468)}{2(225)}\right)^2}} = 1.338\ in \tag{2}$$

Initial cable length l_i:

$$l_i = 360\left(1+\frac{8}{3}\left(\frac{1.338}{468}\right)^2\right) = 468.010\ in \tag{3}$$

Unstressed HLL cable length l_0:

$$l_0 = \frac{468.010}{1+\left(\frac{225}{0.0769(9.398 \times 10^6}\right)} = 467.864\ in \tag{4}$$

HLL cable stiffness k_{HLL}:

$$k_{HLL} = \frac{0.077(9.398 \times 10^6)}{467.864} = 1540.656\ lbf/in \tag{5}$$

Fall Arrest Onset

Once loaded, the HLL cable will be displaced up to the cusp sag condition where it is not expected to elongate, therefore no energy is absorbed. This displacement however, will contribute to the free fall distance and consequently the energy generated by the falling worker. Per ANSI Z359.13-09 and specifications [5]:

- PEA deployment force $F_{PEA} = 900\ lbf$
- PEA max extension $x_{max} = 42\ in$
- Lanyard length $L_y = 72\ in$

Additional analysis conditions:

- Worker weight (equipment included) $W = 220\ lbs$
- D-ring height above HLL anchorage $h_D = 48\ in$

Cusp Sag s_c:

$$s_c = \frac{1}{2}\sqrt{468.010^2 - 468^2} = 1.546\ in \tag{6}$$

Free fall distance FF:

$$FF = 48 + 1.546 - 1.338 + 72 = 120.207\ in \tag{7}$$

As a consequence of deflection up to the cusp sag, energy is stored during the initial stages of the fall in the HLL. Although expected to be of a lesser amount, this energy U_{HLL_0} must be accounted for and balanced in subsequent analyses:

Energy stored in HLL cusp sag:

$$U_{HLL_0} = \frac{1}{2}(1540.656)(1.546)^2 = 1840.153\ in - lb \quad (16)$$

HLL Energy Absorption

During the initial stage of the fall arrest, the HLL cable will elongate to absorb a portion of the energy generated by the fall until the deployment force of the PEA system is reached. Therefore, using the energy balance method, the tension force in the cable must reach the deployment force of the PEA. Force is calculated as a function of the cable sag; therefore values for sag must be iterated as shown in Table 1 until F_{PEA} is reached.

Table 1
PEA Deployment Iteration

Midpoint sag (in)* $s = \frac{1}{2}\sqrt{(l^2 - L^2)}$ (8)	24	25	25.540
Cable length for given sag (in) $l = \sqrt{L^2 - 4s^2}$ (9)	465.532	465.321	465.204
HLL elongation (in) $x_{HLL} = l_0 - l$ (21)	2.332	2.543	2.660
Tension in cable (lbf) $T = k_{HLL}x_{HLL}$ (11)	3593.137	3917.537	4098.303
Force in Lanyard (lbf) $F = 4T\left(\frac{s}{l}\right)$ (12)	740.961	841.899	**900.000**

*Arbitrary values assigned to s until $F = F_{PEA} = 900\ lbf$

Interpreting the data above, from iterating arbitrary values for the midpoint sag, the HLL cable will sag a total of 25.540 inches while absorbing energy produced by the fall prior to the release of the PEA system. The HLL cable will elongate a total of 2.660 inches with a tension of 4098.303 pounds force. At this point the HLL has fully absorbed its corresponding amount of energy U_{HHL}.

Energy absorbed by HLL elongation U_{HLL}:

$$U_{HLL} = \frac{1}{2}(1540.656)(2.660)^2 = 5450.956\ in - lb \quad (17)$$

The PEA system, now deployed, will absorb the remaining energy U_{PEA} as it extends through x_{PEA}.

PEA Energy Absorption

For a fall to be fully arrested, the energy absorbed as the PEA system extends must balance that not absorbed by the HLL. The arrest must be achieved prior to the PEA reaching full extension x_{max}. During iteration, if x_{max} is reached, the PEA has essentially bottomed out and will no longer continue energy absorption, thus transmitting a sudden halt onto the falling worker resulting in possible injury. Arbitrary values are now assigned to the extension of the PEA x_{PEA} as the total energy U_k approaches zero as presented in Table 2.

Table 2
PEA Energy Absorption Iteration

PEA Extension (in)* x_{PEA}	40	41	41.343
Total fall distance (in) $h_{TFD} = FF - s_c + s + x_{PEA}$ (13)	184.202	185.202	185.545
Energy generated by falling worker (in-lb) $U_W = Wh_{TFD}$ (14)	40524.34	40744.34	40819.90
Energy absorbed by PEA (in-lb) $U_{PEA} = F_{PEA}x_{PEA}$ (15)	36000.00	36900.00	37209.10
Total energy (in-lb) $U_k = U_W + U_{HLL_0} - U_{HHL} - U_{PEA}$ (18)	913.542	233.542	**0**

*Arbitrary values assigned to x_{PEA} until $U_k = 0$

The data above indicates the fall energy has been completely absorbed by the HLL and PEA systems. For these conditions, the PEA is expected to extend 41.343 inches, which is within the PEA extension limit of 42 inches.

Clearance margin E:

$$E = 24 + 0.1(25.540 - 1.546) = 26.399\ in \quad (19)$$

Fall Clearance Required C_p:

$$C_p = 185.545 + 12 + 26.399 \\ = 223.944\ in \tag{20}$$

With safety factors incorporated, the minimum fall clearance to a lower level or object is 223.944 in, or approximately 19 feet from the platform height.

Design Acceptance Criteria

Fall clearance: Site assessment determined the shortest distance to an object in the event of a fall is 26 feet. Current HLL configuration requires approximately 19 feet, therefore sufficing the requirement

HLL strength: cable breaking strength as indicated by the manufacturer is 8542 pounds force. Analysis performed indicates a MAL of 4098.303 pounds force. Determining the safety factor:

$$S.F. = \frac{S_u}{MAL} = \frac{8542}{4098.303} = 2.084 \tag{22}$$

As previously stated, ANSI Z359.1-2007 requires the MAL not to exceed 5000 pounds force, and an HLL to withstand a MAL with a safety factor of at least two; therefore the criteria are met.

Maximum arrest forcer: ANSI Z359.1-2007 specifies a MAF limit of 1800 pounds force to be exerted on the worker to avoid serious injury. From the design conditions presented, the worker is not expected to suffer an arresting force greater than 900 pounds force once the PEA is deployed. As the capacity and extension of the PEA system were not exceeded in the analysis, no sudden stop is expected from the PEA system bottoming out; therefore no additional forces will be transferred to the falling worker and the requirement is met.

Anchorage strength: OSHA 1926.500 and 1910.66 require anchorage supports with a minimum rating of 5000 pounds force per worker attached. Furthermore, the MAL exerted on the anchors of 4098.303 pounds force present a margin of approximately 18% with respect to the anchor post rating, thus meeting the requirement.

HLL Installation Layout

HLL anchors shall be installed around the roof perimeter with spans of 39 feet. Anchor posts shall be installed no less than 6 feet from the roof's edge. HLL segments leading up to the roof's edge shall provide workers safe anchorage when approaching the roof perimeter, thus assuring the worker is secured prior to reaching the fall risk area. Access to the roof's edge shall be free of obstructions or trip hazards caused by the HLL or anchors. Openings in the HLL perimeter shall allow workers to walk through without the need to climb over or under the HLL cable. The HLL system shall be routed according to the layout in Figure 5:

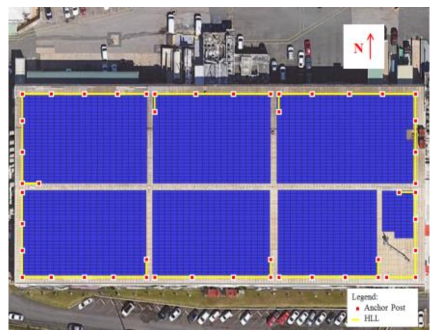

Figure 5
HLL and Anchorage Layout

The HLL system shall be comprised of 48 anchor posts and a total of 1872 feet of cable. Anchor posts shall be 12 inches in height and not include additional energy absorbing features, while in compliance with OSHA 1926.1-07 and 1910.140913, and ANSI Z259.11-05 and A10.32.2012. Anchor plates shall be secured directly on the roof panels with the use of 16 total (4 on each corner) blind rivets with sealing washers, measuring 5/16 x 1 inch [6]. HLL shall be pre-tensioned to 225 pounds force with turnbuckles.

CONCLUSIONS

Drawing from the data and analysis performed, the recommended design and configuration of the fall arrest system will grant the customer a safe and reliable installation in conformance with established requirements and regulations. The system adheres well to the imposed regulations dictated by OSHA and ANSI for adequate design, use and performance. In the event of a fall, the worker will be provided with a safe arrest with minimal to no injury. Forces exerted on the worker are limited to 900 pounds force, distributed throughout a full body harness therefore minimizing the risk of sustained injury from a sudden stop. The elongation of both the HLL cable and PEA systems serve to absorb all energy generated during a fall event; and in conjunction with the proposed anchorage configuration, the worker is kept from reaching lower level obstacles. The selected HLL cable and configuration is expected to subject to a total tension force of approximately 4100 pounds force. With a breaking strength of approximately 8500 pounds force, the selected HLL cable is capable of withstanding applied forces with a compliant safety factor. The initial pre-tension specified of the HLL cable aids to minimize the freefall experienced by the worker, prompting the engagement of the cable sooner and in turn reducing the energy generated.

The proposed system layout safely grants access to all designated work areas of the building roof. Placed 6 feet from the building's edge, the worker will be within reach of access to service the drainage system, PV panels and existing HVAC components. Spacing of anchor posts approaching the upper permissible span limit of 40 feet serves to minimize the number of anchors, while providing a longer length of HLL cable capable of increased energy absorption by elongation. Additional HLL spans leading up to the building's edge through all access corridors will assure the worker is protected prior to reaching the fall risk area. In addition, the worker will be immediately within reach of the HLL system once gaining access to the roof via the vertical ladder in place, thus meeting the 100% tie-off requirement when in proximity to a fall hazard space. Anchorage supports in compliance with regulations for minimum strength requirements are expected to be capable of withstanding the predicted maximum arrest load limited to approximately 4100 pounds force. Furthermore, site survey determined the roofing panels provided a direct anchorage location for end posts, significantly reducing costs, parts and additional analysis.

Once implemented, the designed fall protection system shall serve to safely arrest a worker's fall with minimal injury. The system, in compliance with applicable requirements and customer specifications, will provide a low cost and maintenance solution that is permanent and available for both contractors and onsite workers.

FUTURE WORK

Additional analysis and considerations may be taken in regards to anchorage post contributions to energy absorption. Although assumed fully rigid in the analysis herein, anchor post deflection is expected to absorb a portion of the fall energy. Furthermore, recent anchor post designs incorporate additional energy absorption features which may serve to further dampen a fall arrest.

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