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

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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. Analysis indicates the designed system will be capable of withstanding applicable forces and safely arresting a worker in the event of a fall.

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.

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 adopted 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 featuring a Personal Energy Absorber (PEA). Figure 1 portrays a basic HLL system:

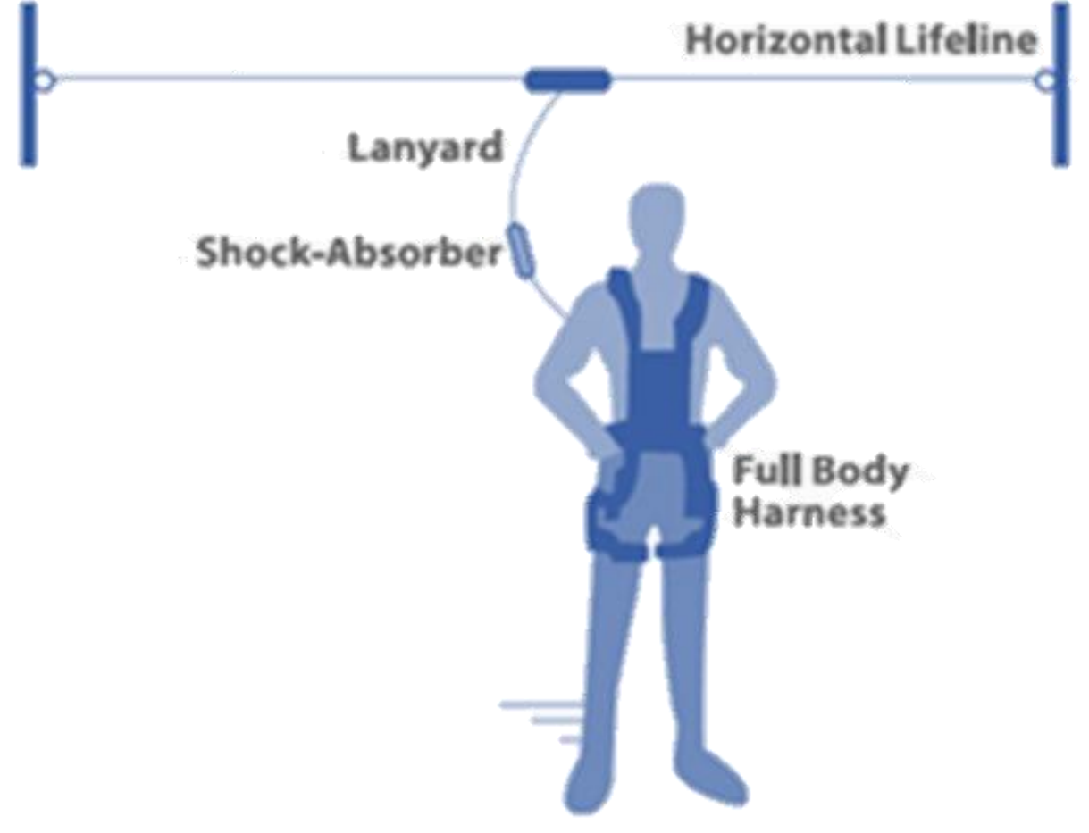

Figure 1
Basic HLL System

Problem Statement

Cardinal Health in Guaynabo, P.R. is requesting the design of a fall protection system capable of providing safe working conditions for the installation and maintenance of a photovoltaic (PV) system atop the roof of their Building 10 facilities, as well as general roofing maintenance and drain clearing.

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. 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 [2].

Worksite Assessment - Scheduled worksite visits will be performed to assess site conditions, determine work areas, existing hazards, access points and maintenance equipment locations.

HLL Design - From data drawn of initial site, worker and task assessments, basic design requirements will be identified and calculations performed to ensure compliance. The HLL must be able to withstand and arrest a fall within the clearance distance as to avoid worker injury.

Anchorage Points - HLL system anchorage points will be selected based on worksite requirements and equipment availability. Roof locations for anchor posts will be determined via analysis in compliance with regulations.

Static HLL Design - Adequate cable sag and tension at rest is crucial in the HLL design analysis. Values will be assigned from data obtained on readily available cable commonly used for HLL applications.

Fall Arrest Onset - In the initial stage of a fall, the HLL cable will begin to sag until taut by the lanyard prior to providing any significant deceleration force to arrest the fall. This is referred to as the cusp sag.

Fall Energy Absorption - Beyond the point of the cusp sag, the HLL cable is now elongating and the worker's fall is being arrested. The cable will continue to elongate until the force exerted on the lanyard F exceeds the deployment force F_{PEA} of the PEA. Once reached, the PEA will now deploy and is assumed to absorb the remainder if the fall force. The PEA will continue to extend until all kinetic energy is absorbed and remaining energy U_k reaches zero.

Energy Balance Analysis - As noted, fall energy generated by the worker's free fall will be absorbed initially by the HLL and further by the PEA. 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 $F = F_{PEA}$. Furthermore, as the PEA extends, a second energy balance analysis will be performed until total energy U_k reaches zero.

Fall Clearance - Elongation of the HLL and PEA systems shall provide adequate clearance preventing the worker from contacting lower levels, obstacles 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. Required fall clearance shall consider the clearance margin E, the total fall distance h_{TFD}, as well as the HLL and PEA elongations. In addition, the fall clearance must also account for harness stretch and D-ring shift x_w.

Results and Discussion

From the process described and pre-determined equations [3], the following results were obtained with the use of customer inputs, analytical assumptions, and equipment and materials data:

Static HLL System - Initial HLL system conditions based on selected cable and parameters are as follows:

Cross-sectional area A of HLL cable:

$$A = \pi \frac{d^2}{4} = 3.14 \frac{{}^{5}/_{16}{}^{2}}{4} = 0.077\ in^2 \qquad (1)$$

Cable sag s_i as consequence of its own weight:

$$s_i = \frac{wL^2}{8T_i\sqrt{1-\left(\frac{wL}{2T_i}\right)^2}} = \frac{0.011(468)^2}{8(225)\sqrt{1-\left(\frac{0.011(468)}{2(225)}\right)^2}} = 1.388 in \qquad (2)$$

Initial cable length l_i:

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

Unstressed HLL cable length l_0:

$$l_0 = \frac{l_i}{1+\left(\frac{T_i}{AE}\right)} = \frac{468.010}{1+\left(\frac{225}{0.0769(9.398\times10^6}\right)} = 467.864\ in \qquad (4)$$

HLL cable stiffness k_{HLL}:

$$k_{HLL} = \frac{AE}{l_0} = \frac{0.077\left(9.398\times10^6\right)}{467.864} = 1540.656\ lbf/in \qquad (5)$$

Fall Arrest Onset - Once loaded, the HLL cable will be taut up to the cusp sag condition.

Cusp Sag s_c:

$$s_c = \frac{1}{2}\sqrt{{l_i}^2 - L^2} = \frac{1}{2}\sqrt{468.010^2 - 468^2} = 1.546\ in \qquad (6)$$

Free Fall Distance FF:

$$FF = h_D + s_c - s_i + L_y = 48 + 1.546 - 1.338 + 72$$
$$= 120.207\ in \qquad (7)$$

Energy stored in HLL cusp sag:

$$U_{HLL_0} = \frac{1}{2}k_{HLL}{s_c}^2 = \frac{1}{2}(1540.656)(1.546)^2$$
$$= 1840.153\ in - lb \qquad (8)$$

HLL Energy Absorption – Using the energy balance method, tension must reach the deployment force of the PEA.

Table 1
PEA Deployment Iteration

Midpoint sag (in)*	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) $x_{HLL} = l_0 - l$ (10)	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 $F = F_{PEA} = 900\ lbf$

PEA Energy Absorption - Arbitrary values assigned to the PEA extension x_{PEA} as the total energy U_k approaches zero.

Table 2
PEA Energy Absorption Iteration

PEA Extension x_{PEA} (in)*	40	41	41.343
Total fall distance (in) $h_{TFD} = FF - s_c + s + x_{PEA}$ (13)	184.202	185.202	185.545
Fall Energy (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	36900	37209.1
Total energy (in-lb) $U_k = U_W + U_{HLL_0} - U_{HHL} - U_{PEA}$ (16)	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.

Clearance margin E:

$$E = 24 + 0.1(s - s_c) = 24 + 0.1(25.540 - 1.546)$$
$$= 26.399\ in \qquad (17)$$

Fall Clearance Required C_p:

$$C_p = h_{TFD} + x_w + E = 185.545 + 12 + 26.399$$
$$= 223.944\ in \approx 19 feet \qquad (18)$$

HLL Installation Layout

Figure 2
HLL and Anchorage Layout

Conclusions

Drawing from the data and analysis performed, the recommended design and configuration will grant the customer a safe and reliable installation in conformance with OSHA and ANSI requirements for adequate design, use and performance.

References

[1] Nowak, M., "Rooftop Guardrail Versus Horizontal Lifelines— Selecting the Proper Fall Protection System," *Diversified Fall Protection", 2019.*

[2] Galy, B., & Lan, A. "Design of Horizontal Lifeline Systems for Fall Protection," I.R.S.S.T., Montréal, Québec, Rep. 971 2017.

[3] Pin, H. Y., & Miang, G. Y. "Designing and Calculating for Flexible Horizontal Lifeline Based on Design Code CSA Z259.16." Ontario, Canada, 2014.