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Standard Guardrails and Related Systems – Challenge and Opportunities

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Abstract Safety fences define safe from unsafe regions and safeguard against falls into such regions. Standards define their required strength and stiffness and specify critical aspects of their geometry. It is implicit that the community of users of safety fences are responsible adults with the further understanding that all ambulatory humans can willfully breach these structures. Despite their de minimis design constraints, technologists have not understood nor met the safety challenges posed by these simple, classical, and ubiquitous structures. The purpose of this paper is to identify a few of the safety shortcomings of fence technology which include the fundamental problem of anthropometric guarding, improperly written standards, the challenge of corrosion, dangerous testing protocols, and the creation of testing hardware.

Keywords: *guardrail, fence, railing, parapet, safety railing, handrail, barrier*

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1. Introduction

1.1. Historical Notes

Birds construct nests to protect their hatchlings from falling before they are flight worthy. These nests fence off a region that differentiates a safe area from one that is unsafe. The parapet presents a very early example of mankind's effort to accomplish the same task; indeed, the Old Testament provides an admonition in Deuteronomy 22:8, "When thou buildest a new house, then thou shalt make a parapet for thy roof, that thou bring not blood upon thy house, if any man fall from thence." When such a structure is reduced to its simplest form, we achieve the so-called Standard Guardrail shown in Figure 1. It is noteworthy that all the members of the guardrail are beams. In 1638, Galileo Galilee introduced his famous book "Two New Sciences" [1] which constitutes the first publication in the field of strength of materials and includes a detailed account of the strength of beams.

1.2. Standard Guardrail Geometry

The critical geometry, the strength, and the stiffness of a standard guardrail are characterized in the American National Standard, ANSI/ASSE A1264.1-2007, Safety Requirements for Workplace Walking/Working Surfaces and their Access; Workplace, Floor, Wall and Roof Openings; Stairs and Guardrails Systems: [2]

Section 5.4 Guardrail System. A railing system shall consist of top rail, intermediate rail or equivalent protection, and posts, and shall have a minimum vertical height of 42 inches (1.1 m) from upper surface of top rail to floor, platform, runway, stair landing, or ramp level. The top rail shall be smooth surfaced throughout the length of the railing. The intermediate rail shall be approximately halfway between the top rail and the floor, platform, runway, stair, or ramp. The ends of the rails shall not overhang the terminal post, except where such overhang does not constitute a projection hazard. Spacing between the guardrail system(s) and adjacent structure(s) shall not exceed 2 inches (51 mm), where a fall hazard exists.

Section E5.4 Generally speaking, guardrails are 42 inches to 45 inches in height. However, guardrails that are higher than 42 inches may need additional horizontal intermediate rails. Guardrail systems are for guarding open-sided floors, platforms, ramps, runways, and stair landings.

Where vertical or horizontal barriers are not effective a personal fall arrest system should be considered.

The preceding two paragraphs were quoted from a voluntary consensus standard, ANSI/ASSE 1264.1-2007. Corresponding regulations are provided by the Occupational Safety and Health Administration, OSHA, which is an administrative code. The following excerpts were taken from 1910 Subpart D, Standard Number 1910.29, Fall protection Systems and Falling Object Protection – Criteria and Practices, 84 FR 68796, December 17, 2019: [3]

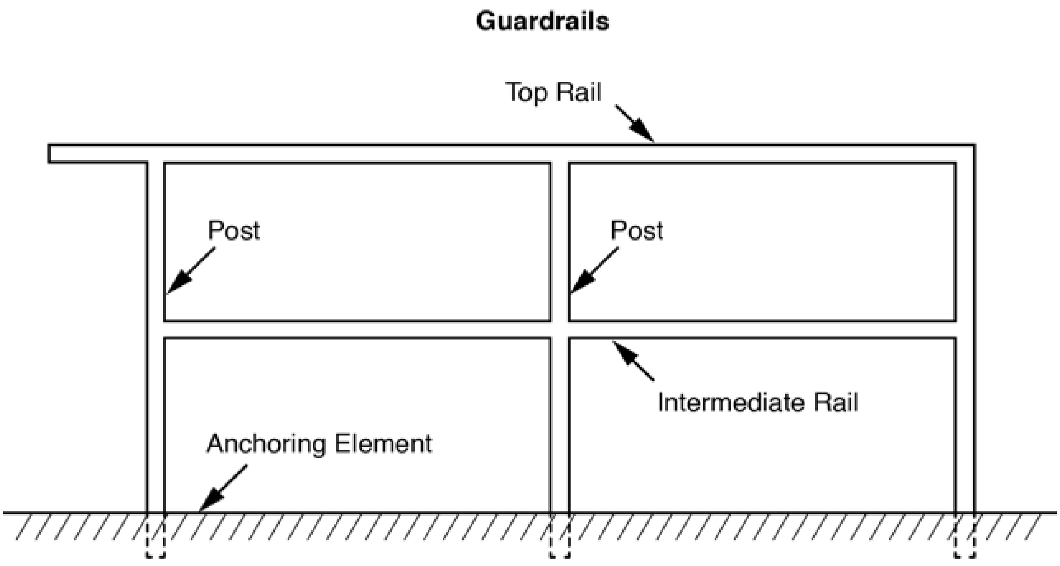

Figure 1. Guardrails

Subparagraph 1910.29(b) (1): The top edge height of top rails, or equivalent guardrail system members, are 42 inches (107 cm), plus or minus 3 inches (8 cm) above the walking-working surface. The top edge height may exceed 45 inches (114 cm), provided the guardrail system meets all other criteria of paragraph b of this section (see Figure 1).

Subparagraph 1910.29(b)(2): Midrails, screens, mesh, intermediate vertical members, solid panels, or equivalent intermediate members are installed between the walking-working surface and the top edge of the guardrail system as follows when there is not a wall or parapet that is at least 21 inches (53 cm) high.

Over the years, ANSI had OSHA specified various height requirements for the top rail of Standard Guardrails. These height specifications have been summarized and presented in Table 1. The following observations are noteworthy:

1. The Standard Guardrail is apparently not standard.
2. The most popular height for the Standard Guardrail is 42”.
3. As time progresses, the required minimum height of the guardrail has decreased.
4. After 1971 OSHA and ANSI provide different height criteria for the safety guardrail.
5. After 1978 both OSHA and ANSI allow guardrail heights greater than 42”.
6. At heights greater than 45” an infill structure consisting of a single intermediate rail is unacceptable.

1.3. Standard Guardrail Strength

Having addressed the functional aspects of the Standard Guardrail, ANSI and OSHA both undertook the characterization of its strength. The OSHA regulations and the ANSI standards have maintained their traditional dogmatic posture of presenting their requirements without providing a basis or explanation that can guide practitioners through the design process. The various codes and standards cited in Table 1 dealing with geometry are summarized in Table 2 with respect to strength characterization.

The following definition of a structure may be useful in understanding the shortcomings of the ANSI and OSHA specifications.

Table 1. Specified Top Rail Height History (ANSI and OSHA)

Standard Identity	Strength Specifications	Comments
ASA A12-1932 [4]	42”	Requires st’d. intermediate rail
USAS A 12.1-1967 [5]	42” Nominal	Requires st’d. intermediate rail
OSHA 1910.23-1971 [6]	42” Nominal	Requires st’d. intermediate rail
ANSI A12.1-1973 [7]	36” to 42” Nominal	Requires st’d. intermediate rail
OSHA 1910.23-1978 [8]	42” Nominal	Requires st’d. intermediate rail
ANSI 1264.1-1989 [9]	40” to 44” Nominal	Requires st’d. intermediate rail
ANSI A1264.1-1995 [10]	40” to 44” Nominal	Requires st’d. intermediate rail
OSHA 1926.502-1995 [11]	39” to 45” Hts. > 45”	Requires st’d. intermediate rail Requires Infill Structures
ANSI A1264.1-2002 [12]	40” to 44” Nominal	Requires st’d. intermediate rail
ANSI/ASSE 1264.1-2007 [1]	42”to 44” Minimum	Hts. > 42” may require additional horizontal intermediate rails.
OSHA 1910.29-2019 [2]	39” to 45” Hts. > 45”	Requires st’d. intermediate rail Requires Infill Structures

Def: The intermediate Rail shall be approximately halfway between the top rail and the floor.
Def: Infill Structures consist of midrails, screens, mesh, intermediate vertical members, or equivalent intermediate structural members, or solid panels installed between the top edge of the guardrail system and the walking/working surface.

Def: Structure. A structure is an organization of materials (solid, liquid, gas) and perhaps force fields that will reliably maintain a specified geometry, within limits, when exposed to a generalized loading environment (mechanical, thermal, chemical, magnetic, radiation, and biological).

The following features of Table 2 are important:

1. Some of the strength specifications are incomplete (e.g., [2]).
2. With one exception, a concentrated 200-pound load is specified for the strength of the top rail; Reference [7] requires a uniform load of 25 pounds per linear foot.
3. With two exceptions the strength of a completed railing is specified explicitly. [2,11]
4. With two exceptions the strength specifications apply to railings of all types. Two OSHA specifications apply only to the guardrail system, [2,11].
5. Safety factors (factors of ignorance) are either unspecified or are adopted from unknown structural engineering standards.

Five references require that the railing systems be designed using standard engineering practices, references [1,7,9,10,12]. Standard guardrails are almost never designed by structural engineers.

1.4. Standard Guardrail Stiffness

An examination of Table 2 reveals that some of the referenced standards identify the existence of deflection limits for the top rail, References 1, 9, 10, and 12. Maximum allowable deflection is defined as the "deflection of whole system at design load." References 9, 10 and 12 provide no numerical limits in the standard; however, the following statement may be found under Explanatory Information, Section E.5.6.1, "From a safety viewpoint, a residual deflection in excess of one-half inch may indicate potential failure." Reference 1 provides expanded information under Explanatory Information, Section E.5.6.1, "For more information please reference ASTM E985-00e1 [13], *Standard Specification for Permanent Metal Railing Systems and Rails for Buildings*, Section 6, for metal railings. Note, References 9, 10 and 12 are probably in error for not including the cited ASTM information.

Table 2. Specified Top Rail Strength History (ANSI and OSHA)

ASA A12-1932 [4]: **Strength Specifications** - Completed Structure: 200 pounds applied in any direction at any point of the top rail. **Comments** - Applies to railings of all types.
USAS A 12.1-1967 [5]: **Strength Specifications** - Completed Structure: 200 pounds applied in any direction at any point of the top rail. **Comments** - Applies to railings of all types.
OSHA 1910.23-1971 [6]: **Strength Specifications** - Completed Structure: 200 pounds applied in any direction at any point of the top rail. **Comments** - Applies to railings of all types.
ANSI A12.1-1973 [7]: **Strength Specifications** - Completed Railings: 25 pounds per linear foot applied in any direction at the top of the railing. The intermediate rail shall be of withstanding a horizontal load of 20 per linear foot. The end terminal posts shall be capable of withstanding a load of 200 pounds applied in any direction at the top of the post. The above loads are not additive. **Comments** - Applies to railings of all types. Use st'd. engineering practices for stresses, safety factors, etc.
OSHA 1910.23-1978 [8]: **Strength Specifications** - Completed Structure: 200 pounds applied in any direction at any point of the top rail. **Comments** - Applies to railings of all types.
ANSI 1264.1-1989 [9]: **Strength Specifications** - Completed Railings: 200 pounds applied in any direction, except upward, at the mid-point between posts without exceeding maximum allowable deflection. The intermediate rail shall be capable of withstanding a horizontal load of 80% of the above stated load applied at mid-point and mid-height without exceeding the maximum allowable deflection. The end of terminal post shall be capable of withstanding a load of 200 pounds applied in any direction at the top of the post. The above loads are not additive. **Comments** - Applies to railings of all types. Use st'd. engineering practices for stresses, safety factors, etc.
ANSI A1264.1-1995 [10]: **Strength Specifications** - Completed Railings: 200 pounds applied in any direction, except upward, at the mid-point between posts without exceeding maximum allowable deflection. The intermediate rail shall be capable of withstanding a horizontal load of 80% of the above stated load applied at mid-point and mid-height without exceeding the maximum allowable deflection. The end of terminal post shall be capable of withstanding a load of 200 pounds applied in any direction at the top of the post. The above loads are not additive. **Comments** - Applies to railings of all types. Use st'd. engineering practices for stresses, safety factors, etc.
OSHA 1926.502-1995 [11]: **Strength Specifications** - Guardrail Systems: 200 pounds within 2 inches of the top edge, in any outward or downward direction, at any point along the top edge.
ANSI A1264.1-2002 [12]: **Strength Specifications** - Completed Railings: 200 pounds applied in any direction, except upward, at the mid-point between posts without exceeding maximum allowable deflection. The intermediate rail shall be capable of withstanding a horizontal load of 160 pounds force applied perpendicularly at mid-point and mid-height without exceeding the maximum allowable deflection of three inches. The end or terminal post shall be capable of withstanding a load of 200 pounds applied in any direction at the top post. The above loads are not additive. **Comments** - Applies to railings of all types. Use st'd. engineering practices for stresses, safety factors, etc.
ANSI/ASSE 1264.1-2007 [1]: **Strength Specifications** - Completed Railings: 200 pounds applied in any direction, except upward, at the mid-point between posts without exceeding maximum allowable deflection. The intermediate rail shall be capable of withstanding a horizontal load of 160 pounds force applied perpendicularly at mid-point and mid-height without exceeding the maximum allowable deflection of three inches. The end or terminal post shall be capable of withstanding a load of 200 pounds applied in any direction at the top post. The above loads are not additive. **Comments** - Applies to railings of all types. Use st'd. engineering practices for stresses, safety factors, etc.
OSHA 1910.29-2019 [2]: **Strength Specifications** - Guardrail Systems: 200 pounds applied in a downward or outward direction within 2 inches of the top edge, at any point along the top rail.

In 2016 Armando Pinto and Luis Reis presented a paper on barriers (guardrails and balustrades) at the XV Portuguese Conference on Fracture, Paco de Arcos, Portugal. In this paper, "Barrier for buildings: Analysis of Mechanical Resistance Requirements," [14], the authors compare fence standards from Portugal, Spain, France, UK, USA, and Brazil that were applicable in 2015.

2. Railing Height – 42" Rule

Consider the hypothesis, "If a standing adult male from the US is supported on a frictionless floor and is thrust into a Safety Guardrail at a right angle, he will not flip over if his center of gravity is lower than the top rail height." Any tendency to flip under the fence is countered by the standard intermediate rail. In Figure 2, the applicable 1966 anthropometric data is presented for a 97.5 percentile standing adult male. The data was taken from sheet A1 of "The Measure of Man, Human Factors in Design," Revised and Expanded 2nd Edition, by Henry Dreyfuss [15]. Dreyfuss also indicates in sheet G1 that the average height of a man's shoe heel is 1.1 inches. When this height is combined with the elevation of his center of gravity, 40.9 inches, one obtains 42 inches which was the most common speculation for railing height in 1966. Note that only 2.5% of males were taller than 6'2" and weighed more than 208.9 pounds.

It should be noted that floor friction increases the resistance to flip over. Further, during the past half-century, Americans have grown taller. This is consistent with the trend in standards development to allow for ever-increasing top rail heights.

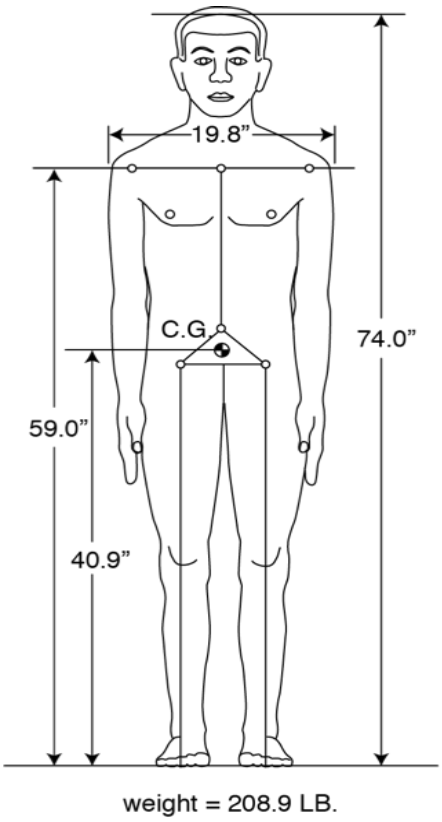

Figure 2. Anthropometric Data of 97.5 Percentile Standing Adult Male

3. Structural Integrity

Codes and standards have attempted to define the structural integrity of fences by specifying the resistance in terms of force alone. For example, a standard guardrail should withstand a 200-pound force applied in every direction at any point on the top rail. From a technical point of view, this early specification does not characterize the structural integrity of the fence. Some of the later codes and standards have added additional requirements,

a. Deformation requirements in the form of deflection specifications
b. Safety Factor requirements
c. Integrity requirements for structural elements other than the top rail
d. Different types of loading (e.g., uniform loads) and different locations for the load applications
e. Different stress analysis methodologies

These additional requirements are not adopted uniformly in the more recent codes and standards. Furthermore, the ANSI standards and the OSHA regulations are often different for the same time periods. There is an extensive literature dealing with the structural integrity of fences that greatly expands on the simplistic treatment presented by ANSI and OSHA. Some of the additional topics include,

a. Fatigue
b. Impact with Soft and Hard bodies
c. Wind Loading
d. Durability of materials
e. Constitutive Material Relationships (Almost all solid materials have been adopted for fences at one time or another.)
i. Perfectly elastic (e.g., wood, high-strength steel)
ii. Perfectly plastic (e.g., structural steel)
iii. Elastic-Perfectly Plastic (e.g., structural steel)
iv. Viscoelastic (e.g., plastic)
v. Deterministic (e.g., all metals, sandbags)
vi. Stochastic (e.g., glass)

There are two major areas where a structural integrity capability is required, Guardrail Design and Guardrail Analysis.

3.1. Guardrail Design

Conventional design procedure involves a repetition of the process of informed guessing at the geometry and materials of a complete fence system followed by a structural integrity analysis that is conducted using either testing methodology or structural analysis based on criteria specified in a particular standard or code. For each guess, structural elements display either insufficient or excessive integrity. The process continues until the structure is both safe and reasonable in its cost or weight. Testing methodology requires a prototype and apparatus for applying and measuring the test forces. No physical entities are needed to conduct a structural analysis, only intellectual procedures are involved. On the other hand, the geometry and material used in each structural element must be characterized. It is implicit in both the testing and structural analysis procedures that the final fence structure involves only new materials.

3.2. Guardrail Analysis

Structural analysis cannot be used to determine the strength of a guardrail system that has been degraded by corrosion. Even in those instances where the material surfaces can be examined in the field, there is no technology that will enable one to characterize the material properties in the face of corrosion. Stress analysis and strength analysis both require that the state of a material be known together with its loading history.

The fact that the simple, classical, and ubiquitous guardrail system gives rise to such an intractable technical problem is indeed humbling. Similar challenges have taken the following forms:

a. Structures and components have been treated by machines that accelerate the corrosion process which in turn is correlated with field tests.
b. Duplicate structures are set up in various locations around the country and allowed to corrode over time.
c. Aircraft manufacturers continually fatigue test components throughout the life of their aircraft. If a component failure occurs, all members of the fleet are critically examined or replaced.
d. Expiration dates are displayed on products.

With respect to guardrails, the most popular method of assessing their structural integrity is by conducting in situ testing programs using criteria associated with a particular code or standard. Technical guidance for conducting such tests is provided by ASTM International. Typically, guardrail systems are installed for long periods of time. They are seldom tested even after they have failed and perhaps caused injuries. There are serious downsides associated with testing protocols,

a. Testing is hazardous (see next section).
b. Standard testing equipment, fixtures, and protocols are not available.
c. Testing data is usually in the form of Pass/Fail. (Estimating residual strength is not straightforward).
d. Testing is very expensive when applied to a complete fencing system.
e. Testing may compromise the integrity of the fencing system.
f. Selecting the applicable code or standard for conducting a testing program may involve a dozen or more candidates and several points of view.

4. Safety – Guardrail Testing Programs

Failures which occur during the testing of guardrails are often life-threatening. Frangible materials and corroded materials often fall suddenly in a frangible fashion, that is, without ductility. For example, when a sudden failure of the top rail occurs while pushing in the direction of the pit, two serious hazards occur simultaneously. The guardrail or its components may fall onto workers in the pit and/or testing personnel may fall into the pit along with the guardrail. Confronted with a missing or damaged guardrail, the testing crew together with other workmen are no longer protected. This situation is usually mitigated by compromised makeshift concepts that serve until a replacement guardrail is installed. Properly equipped professional fence contractors carry replacement guardrails in their truck. Such contractors invariably employ fall protection equipment for their staff during testing.

Because standardized test fixtures are almost nonexistent, most testing situations are custom designed. Safety training is compromised when every job is different. The equipment used to apply and monitor concentrated and uniform loading is not standard and is certainly not benign. Furthermore, support structures for safety guardrails that are heavily corroded may not provide the temporary integrity required by fall protection systems.

In light of the anticipated occasional failure of a guardrail system during testing, a fencing contractor should develop a remediation strategy containing the following typical concepts:

a. First Responder notification
b. Accident Site management
c. Guardrail Reinforcement including walkway remediation
d. Guardrail Replacement including walkway reconstruction
e. Deployment of additional fall protection
f. Installation of temporary safety railings and safety barriers
g. Display of temporary safety signage and hazard identification tape
h. Safety Status Communications (Plant Manager Notification, OSHA, Insurance Carriers, etc.)

In general, a reasonable testing capability might include the following elements:

a. Field Equipment inventory
b. Written testing protocols reflecting the requirements of a specific code or standard
c. Fence Loading Methodology: Custom design capability for loading fixtures
d. Safe Testing Protocols: Personnel safety equipment in the light of fence failure during testing
e. Fall Protection: (safety harnesses, safety lines, tie off points, safety netting, safety signage, etc.)
f. Test Failure Remediation Strategy:
    1. Worksite management
    2. First Responder Notification
    3. Install temporary safety fencing or safety barriers
    4. Immediate installation of a fall protection system
    5. Installation of new replacement safety fencing
    6. Deploy temporary warning signs and hazard identification tape
    7. Worksite cleanup
g. Safety Status Communications (Plant Manager Notification, OSHA, Insurance Carrier, etc.)

5. Loading Fixtures

5.1. Manual Testing

In the absence of standardized loading fixtures, the structural integrity of guardrails is usually tested using manual force applied directly to the fencing components. The weight of a maintenance worker is always available for approximating a downward 200-pound loading on the top rail or the intermediate rail. Manually applied upward forces of 200 pounds face challenges such as physical limitations for repeated applications, human factors admonitions against lifting 200 pounds, codes and statutes which prohibit upward loading of a fencing component, and weightlifting next to a fall hazard.

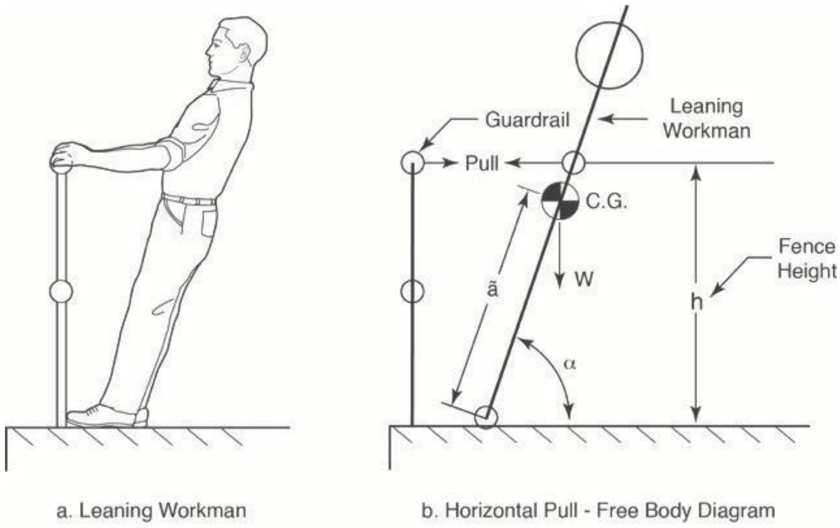

Figure 3. Horizontal Pull

The most critical loading is the 200-pound horizontal outward loading of the top rail. The next most critical loading is the 200-pound inward loading of the top rail. Can these loads be developed manually by a workman standing on the walking surface next to a guardrail? Simple static models provide estimates of the pushing and pulling capability of workmen using a dozen different strategies; see for example, "Human Push Capability," R.L. Barnett and T. Liber, Ergonomics, Vol. 49, No. 3, Feb. 2006 [16]. Consider the horizontal Pull scenario shown in Figure 3a. The associated free-body diagram is depicted in Figure 3b where W is the weight of the workman, $\bar{a}$ is the location of his center of gravity, α is his lean angle, μ is the floor/footwear coefficient of friction, and h is the guardrail height. The pull force is described by Equation 1 and its maximum value by Equation 2 which is the maximum frictional resistance. Note that a 200-pound man cannot develop a 200-pound pulling force even with a high friction coefficient of μ = 0.7.

$$Pull = \frac{W\bar{a}\cos\alpha}{h} \tag{1}$$

$$\left(Pull\right)_{\max} = \mu W \tag{2}$$

Figure 4 illustrates three pushing configurations that would allow a workman to develop an outward test force on a guardrail. Depending on the scenario, human push capability involves strength, weight, weight distribution, push angle, footwear/floor friction, and the friction between the upper body and the pushed object. As an example, consider a rigid human form leaning against a fence where there is no jacking force arising from axial thrust. This model is represented by the free body diagram shown in Figure 5 where the subscripts t and b indicate the top contact with the guardrail and the bottom contact respectively. H is a horizontal force vector and V is a vertical force vector. The body model is hyperstatic to the first degree, the bounds on the push force H_t is given in Equation 3,

$$\frac{W\left(\bar{a}/L\right)}{\mu_t + \tan\alpha} \le H_t \le \frac{W\left(\bar{a}/L\right)}{\tan\alpha} \tag{3}$$

where W is the weight of the workman, $\bar{a}$ is location of the center of gravity, α is lean angle, and μ_t is the coefficient of friction between the workman's clothing and the guardrail. The maximum push, $(H_t)_{max}$ is described in Equation 4,

$$\left(H_t\right)_{\max} = \frac{\mu_b W}{\left(1+\mu_t\mu_b\right)} \tag{4}$$

where μ_b is the coefficient of friction between the footwear and the floor. Observe that the maximum push capability is improved by decreasing the friction at the guardrail and increasing the friction at the floor level.

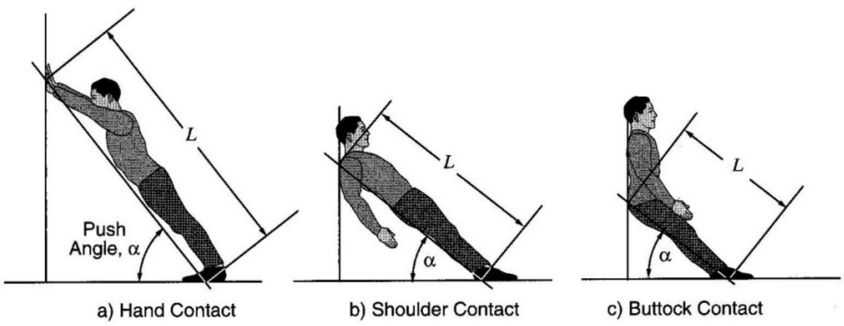

Figure 4. Pushing Configurations

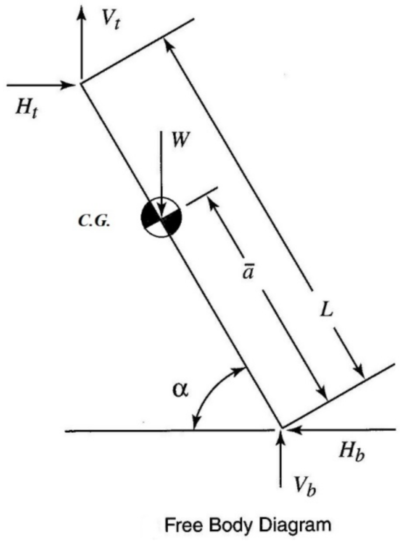

Figure 5. Leaning Rigid Body (Reaction Forces are shown in their positive directions)

Referring to Figure 5, a very large axial thrust of any magnitude will change the direction of V_t to downward which will give rise to the maximum push, $(H_t)_{max}$, given in Equation 5,

$$\left(H_t\right)_{\max} = \frac{\mu_b W}{\left(1-\mu_t\mu_b\right)} \tag{5}$$

Note that the maximum push becomes unbounded as the product $(\mu_t\mu_b)$ approaches unity.

5.2. Current Examples of Proposed Test Figures

Four concepts for guardrail test fixtures are presented in the form of three patents and one technical note. The current state-of-the-art is reflected by these examples.

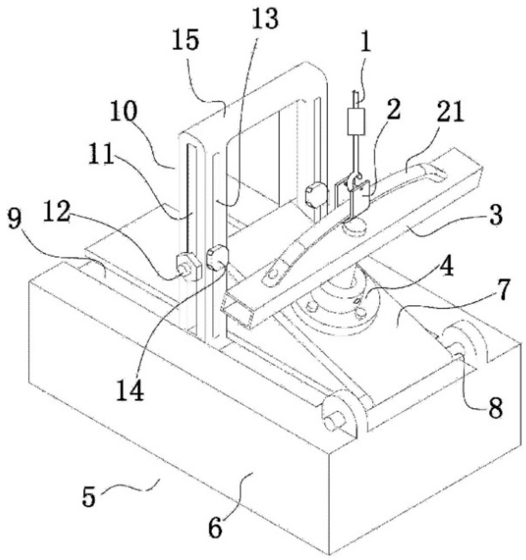

Exhibit 1. Handrail Testing Apparatus [17]

Patent CN103033347A [17] Abstract: “The invention discloses a handrail testing device and a test method of handrail strength. The handrail testing device and the test method of handrail strength can stimulate practical using conditions, can have a more comprehensive test on a handrail from different angles and can carry our (sic) an accurate judgement on strength performance of the handrail and safety when a passenger uses the handrail. The handrail testing device comprises a tension machine, an upper soleplate, a lower soleplate used for fixing the handrail and an angle adjustment seat, wherein an angle of inclination of the angle adjustment seat can be adjusted. The lower soleplate is arranged on the angle adjustment seat, and the upper soleplate is used for being connected with the handrail and the tension machine. The test method of handrail strength is carried out by fixing the handrail on the lower soleplate.”

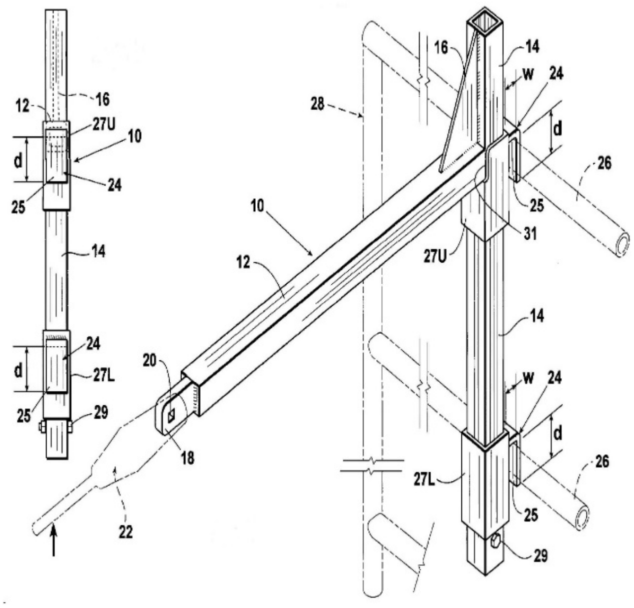

Exhibit 2. Handrail Testing Structure [18]

International Patent WO 02/27291 A2 [18] Abstract: “An apparatus for testing the structural integrity of a hand rail structure. The hand rail having a plurality of substantially horizontal parallel rail members. The apparatus has an elongate lever arm and a mounting portion on the lever arm. The mounting portion is sized to span at least two rail members. A receptacle on the mounting portion opposite the lever arm receives one of the railmembers and vertically supports the lever arm and mounting portion. A force is applied through the lever arm and transmitted to the hand rail. The force is measured by a torque wrench on the lever arm.”

Field Testing Device for Railing Systems and Rails [19] Abstract: “A simple, portable, field testing device is described that allows instantaneous determination of the static performance of installed railing systems and rails in order to ascertain whether they conform with applicable specifications and meet governing code requirements and agency regulations.”

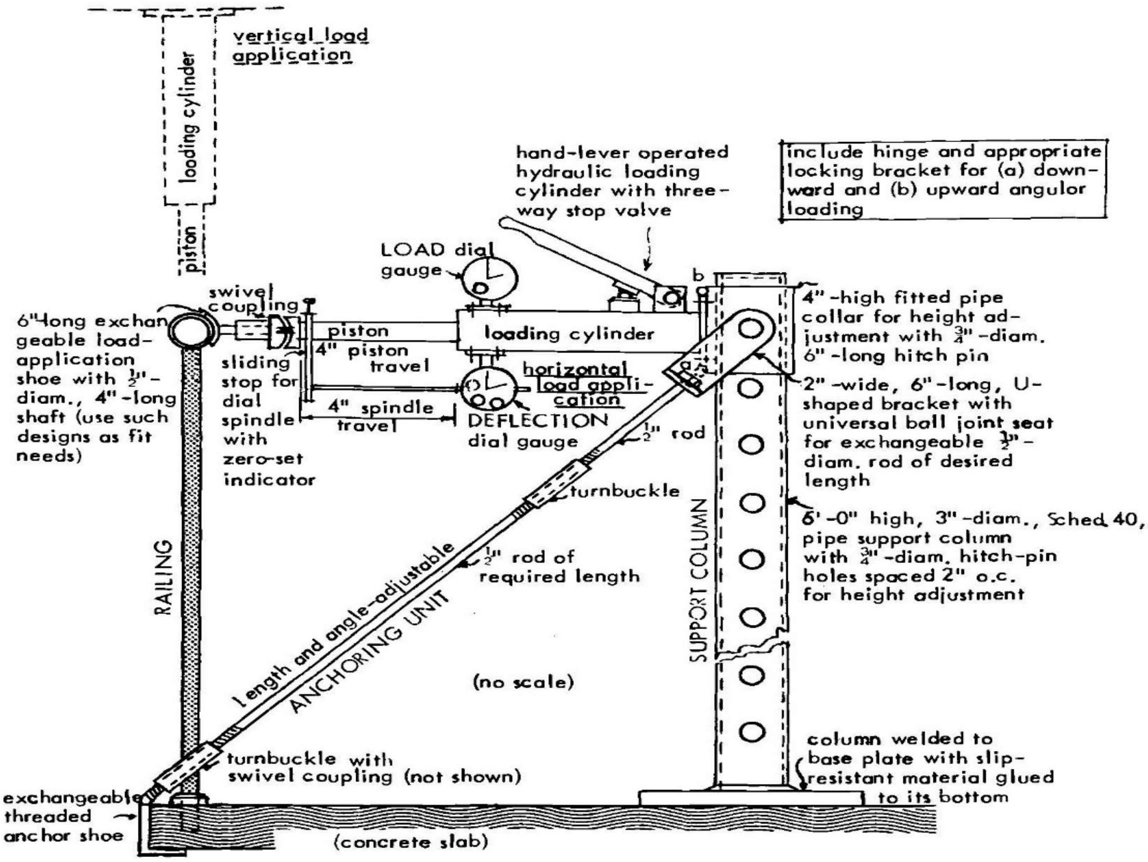

Exhibit 3. Field Testing Device for Railing Systems [19]

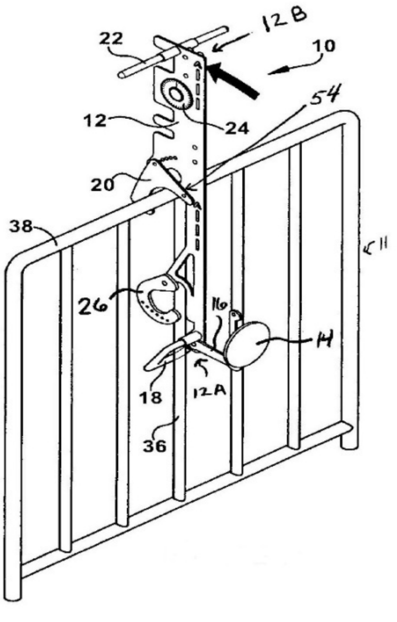

Exhibit 4. Handrail Testing Device [20]

US Patent US 2008/0276715 A1 [20] Abstract: "A handrail testing device having a lever arm having a first end and a second end, a mounting portion connected to the lever arm capable of pivotally securing the first end on or near a handrail, a load portion connected to the lever arm and capable of engaging the handrail to transmit a force applied to the second end of the lever arm to the handrail, and a measurement portion connected to the lever arm."

5.3. Challenge and Opportunity

Safety practitioners need efficient and safe standard test fixtures for evaluating the structural integrity of guardrails that have been compromised by the environment. A promising candidate is outlined in this section that is based on jujitsu. With respect to guardrail standards that require concentrated loading of the guardrail components, such loads can be applied using only internal self-equilibrating clamping and distending double acting pneumatic actuators.

Visualize a sequence of contiguous guardrails of the type shown in Figure 1. The most critical and dangerous test scenario is the horizontal loading of the posts in the direction of the hazard zone. Figure 6 illustrates a telescoping test beam which is parallel to the top rail. It is clamped to the outside posts and supports a Ball Joint Clamp fastened to the center post as close to the top as possible. The test beam provides a symmetrical support for a double acting pneumatic actuator that can push outward (toward the danger zone) with a force P (usually 200 pounds). The reactions to the test force P is P/2 which is transferred to each of the outside posts. If the three posts are approximately of equal strength, the middle post will always fail first or not at all. If the middle post does fail, it will not fall into the danger zone and become a potential hazard. Because of the ball joint, the pneumatic actuator can pull against the middle post to establish the complete structural integrity of the middle post and top rail. This completes the out-of-plane testing program.

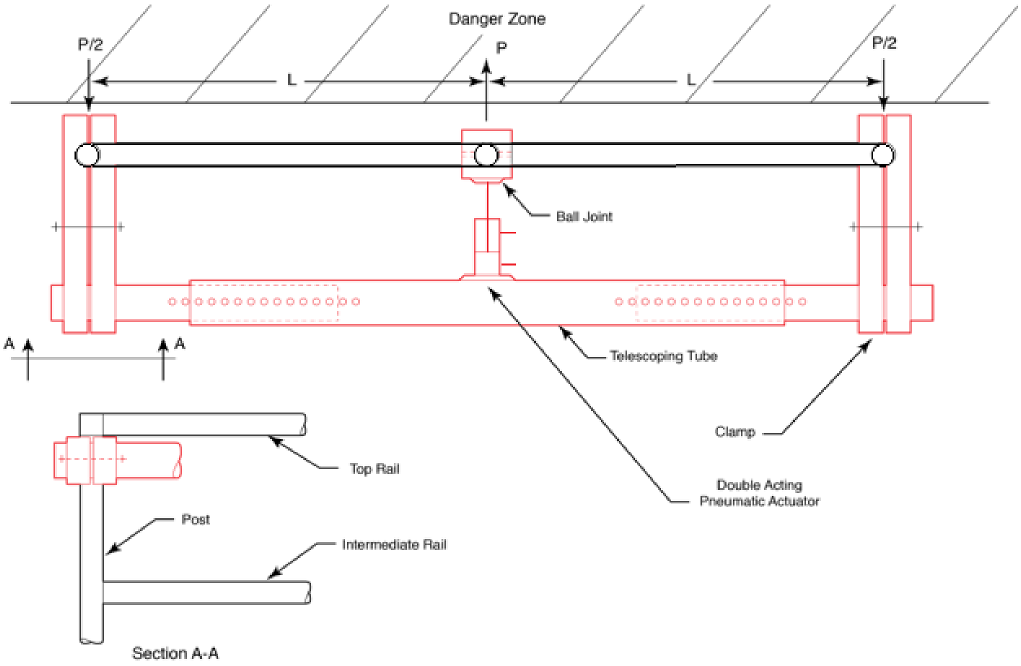

Figure 6. Horizontal Guardrail Test Fixture

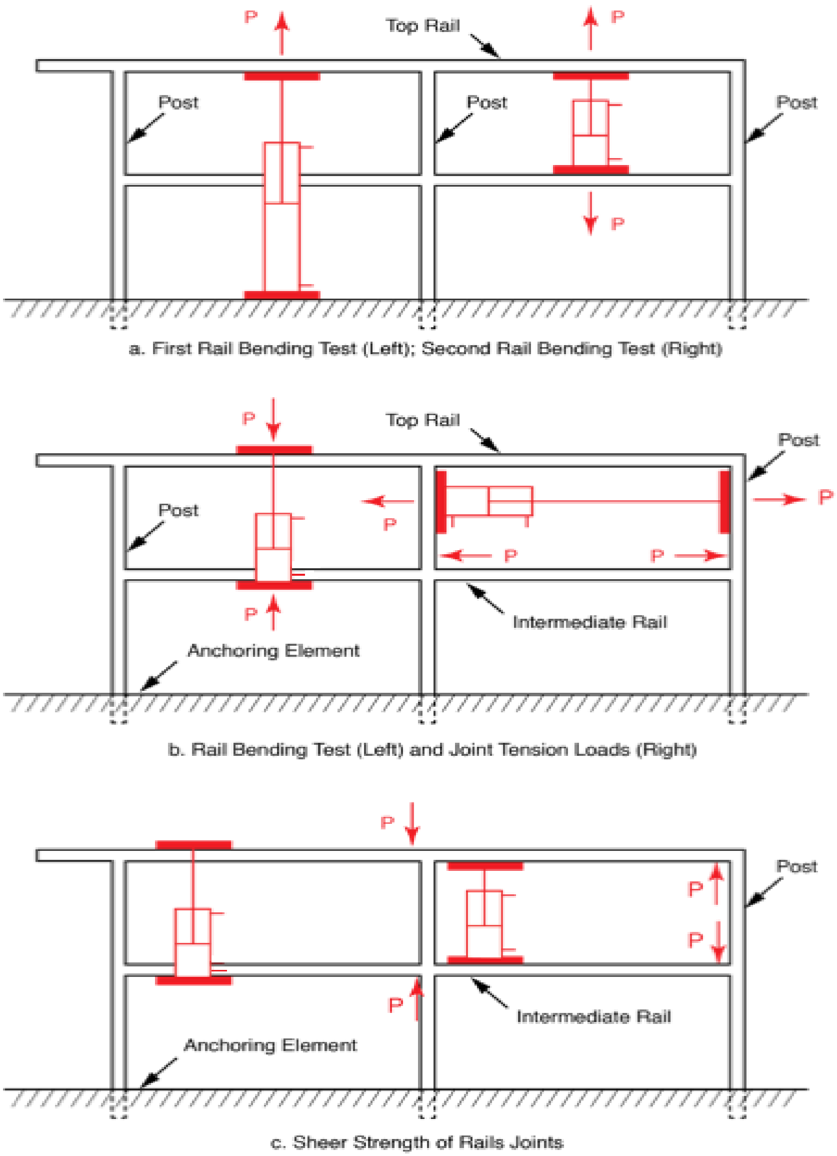

Figure 7. In-Plane Bending, Shear, and Tensile Tests of Guardrail Members

All of the important In-Plane tests of the guardrail members can be executed using double acting pneumatic actuators with a capacity of ± P (P is usually 200 pounds). Figure 7 illustrates most of the test setups required for In-Plane testing. The pneumatic actuators may incorporate appropriate end effectors depending on the shapes of the guardrail members.

6. Comments and Conclusions

- Can you imagine writing a definitive work on fences? Surely, Mother Nature would be represented for her work on mountain ranges which define and protect valleys. Creatures which predate humankind such as birds provided the architectural and structural skills to create protective nests for their offspring. Would such a treatise deal with the Great Wall of China, the Berlin Wall, the Wailing Wall, and the recent walls of Israel which separate so many first cousins? Controversial songs must be included such as "Don't Fence Me In" together with sage comments represented by "Good Fences Make Good Neighbors." Is there a solid material that has not been used at some time to construct a fence? It is a joyful illusion to think of a white picket fence being painted by Tom Sawyer's friends. Nostalgia would not be the same without the stone fences of Ireland and the wood fences of America's West. As a Civil Engineer, I cannot imagine excluding earthen dams and waterways from an exposition on fences any more than I would overlook Hollywood's representation of King Kong's massive enclosure. Finally, we arrived at the most ubiquitous and simplistic of all safety fences, the Standard Guardrail.
- America's most prestigious consensus standard, ANSI, and its most authoritative regulatory safety code, OSHA, have both attempted to define and regulate the Safety Guardrail over the past half century. They have embarrassed us all with a technical piece of nonsense which compromises the entire safety community. They have committed this atrocity in the face of a vital and extensive research literature authored by an international community. OSHA enlisted the services of the National Bureau of Standards (NBS) to study guardrail systems. NBS produced three substantial high-quality reports that have been extensively ignored by OSHA at the expense of the US taxpayer. ANSI has missed every opportunity to read, study, and reflect on the technical literature concerning guardrails. Their standards provide an object lesson – a system using full-time professional engineers is superior to ANSI's voluntary consensus system.
- The design of candidate guardrail systems is straightforward and may reflect talents that are both meager and sophisticated. Fortunately, candidate guardrail systems are inexpensive to construct for testing purposes and are inexpensive to analyze by a myriad of technical protocols. If there is a weak link in this creative system, it is most certainly the guidelines provided by ANSI and OSHA.
- The guardrail faces one of our most pernicious earthbound technical challenges, environmental degradation. Along with the infrastructure, guardrails shall return to the dust. Because one cannot characterize environmentally degraded structures that have been exposed to long-term histories of fatigue, our stress analysis capabilities are impotent as analysis tools for judging the structural integrity of guardrail systems. We must therefore turn to testing alone to determine the continuing adequacy of aging guardrails.
  Several shortcomings are encountered when testing is used to measure structural integrity:
  i. Standard testing fixtures are not presently available for loading guardrails in accordance with ANSI and OSHA protocols.
  ii. Guidelines are not prescribed by ANSI and OSHA for safely conducting structural testing of guardrails.
  iii. ANSI and OSHA presently provide only Go/No-Go integrity criteria. To assess the residual safety margins in aging guardrails, quantitative strength measurements together with acceptability criteria are required.
  iv. Testing of even modest expanses of guardrail systems will be very expensive.
  v. Both ANSI and OSHA have failed to specify specific safety factors for the various types of guardrail construction.

As an antidotal observation, field testing of guardrail systems is seldom conducted.

- In the face of an intractable analysis capability, specialists in guardrail technology have not picked up the gauntlet. Workaround strategies that deal with environmental degradation have not been invoked in spite of great ingenuity demonstrated by technologists. We suggest, as a beginning, that each guardrail be permanently marked with its manufacturing date, the manufacturer's name, the certification standard, and a required recertification (or replacement) date.
- The isolated examples of guardrail testing fixtures must be expanded into systematic developments of safe, quantitative, accurate, and economical testing gear that can be operated using ordinary skill.
- The OSHA regulations and ANSI standards must be modified to reflect the technical state-of-the-art. Both organizations should review the international standards on guardrail systems [21-30].

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