NBSIR 76-1139

Investigation of Guardrails for the Protection of Employees from Occupational Hazards

S. G. Fattal and L. E. Cattaneo

Center for Building Technology
Institute for Applied Technology
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Final Report

Prepared for
Occupational Safety and Health Administration
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ABSTRACT

State-of-the-art studies documented separately in a preceding report [3], together with experimental and analytical investigations, are conducted to determine structural and non-structural safety requirements for guardrails used for the protection of employees against occupational hazards. The critical aspects of guardrail safety were identified in the first phase of a two-phase research project through exploratory studies consisting of field surveys of prototypical installations, reviews of existing standards and industrial accident records, and compilation of relevant anthropometric data. These exploratory studies are utilized to establish an experimental program in the second phase consisting of resistance tests of guardrail components, static and dynamic load measurement tests using human subjects and an anthropomorphic dummy, and non-structural tests to determine geometric requirements for guardrail safety. Based on these investigations, a model performance standard and a design guide for the guardrails are proposed.

Key Words: Anthropometric measurements; anthropomorphic dummy; design; dynamic loads; guardrails; industrial accidents; non-structural safety; occupational hazards; performance standards; personnel railings; personnel safety; static loads; stiffness; structural safety.

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SI Conversion Units

In view of the present accepted practice for building technology in this country, common U.S. units of measurements have been used throughout this publication. In recognition of the position of the United States as a signatory to the General Conference on Weights and Measures, which gave official status to the International System of Units (SI) in 1960, conversions to SI units have been made for selected representative values to avoid confusion in tables. Readers interested in making further use of the coherent system of SI units are referred to the table below, and to: NBS SP 330, 1972 Edition, The International System of Units; and ASTM E380-76, Standard for Metric Practice.

Table of Conversion Factors to SI Units

To convert from	to	Multiply by
degree	radian	1.7453×10^{-2}
inch	meter	$2.54^{*} \times 10^{-2}$
in^2	m^2	$6.4516^{*} \times 10^{-4}$
in^3	m^3	1.6387×10^{-5}
in^4	m^4	4.1623×10^{-7}
foot	meter	$3.048^{*} \times 10^{-1}$
pound-force	newton	4.4482
lbf · ft	N · m	1.3558
lbf/ft	N/m	1.4594×10
lbf · in	N · m	1.1298×10^{-1}
lbf/in	N/m	1.7513×10^{2}
lbf/min	N/sec	7.4137×10^{-2}
mile/hour	km/h	1.6093
lbf/in^2 (psi)	pascal	6.8947×10^{3}

* Exact value; others are rounded to four digits.

1. Introduction

This report documents research studies conducted at the National Bureau of Standards (NBS) in response to a request by the Occupational Safety and Health Administration (OSHA) for technical assistance in developing performance standards and design guidelines for guardrails used to protect employees against occupational hazards. Under the Occupational Safety and Health Act of 1970, OSHA exercises a mandate over present employee safety regulations including prescriptive requirements for all guardrails that are installed in areas where employees conduct work-related activities [1, 2][1].

The general lack of technical literature to support the existing OSHA guardrail regulations and, for that matter, guardrail provisions of other mandatory or voluntary standards, has been one of the principal motivating factors behind the present research. Furthermore, the project recognizes a growing professional awareness of the need to develop performance-oriented guardrail design standards which are less restrictive with regard to the utilization of innovative products and design concepts than the materials-oriented prescriptive standards presently used.

The implementation of this project was carried out through the cooperative efforts of NBS research investigators from the structural, architectural and psychological disciplines in a two-phase effort. The results of the first phase, which was exploratory in nature and was intended to establish the state-of-art insofar as guardrail design is concerned, have been presented in a separate reference [3]. This report presents the results of the experimental program conducted during the second phase and an interpretation and discussion of the research findings from both phases. On this basis, a rational approach for guardrail design may be developed; Appendices A and B present a model performance standard and design examples for guardrails.

2. Scope and Objective

The scope of this project was established by mutual agreement between OSHA and NBS participants. It was agreed that NBS research should apply to temporary and permanent guardrails used for the protection of employees against occupational hazards, and therefore, should only consider factors associated with guardrail use by male and female adults during the conduct of their assigned tasks. It was further stipulated that NBS research should

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[1] Figures in brackets indicate literature references cited in section 7.

exclude consideration of guardrail loading situations arising through flagrant abuse or through the impact of power-driven vehicles or other heavy mobile objects. In addition, it was agreed that NBS research need not be concerned with investigations of conditions and situations for the purpose of determining whether or where the installation of guardrails will be required, since OSHA has mandate over such decisions.

The two principal objectives of the project were the development of basic technical information through research and the utilization of this information to prepare performance-oriented recommendations for the design, construction and evaluation of guardrail systems which come under the jurisdiction of OSHA.

The types of guardrail installations given high research priority by OSHA included the following, listed in the order of decreasing priority: (1) elevated walkways, (2) erected and swinging scaffolds, (3) balconies and mezzanines, (4) hot-dip galvanizing operations, (5) roofing operations, (6) cast-in-place concrete construction, (7) petrochemical towers, (8) mobile equipment, (9) elevated work or storage areas, and (10) marine dry docks. It was understood that as many of these installations should be examined as possible within the specified project resources without diluting the credibility of the end product. NBS researchers examined eight of these installations, the excluded ones being chemical towers and mobile equipment.

3. Approach

At the beginning of this project it was reasoned that if the principal factors contributing to the safe functioning of guardrails could be identified in some systematic fashion, the task of developing an effective approach to meet the specified project objectives would be simplified. Consequently, one of the early tasks was to devise a conceptual model of safety for structural systems and to proceed to treat guardrails within the framework of this model. The study of the safety aspects of structures and guardrails, considering both human and environmental factors and their interactions, is described in Reference [3].

Proceeding along the guidelines provided, a two-phase approach compatible with the stated project objectives was formulated. The tasks described under items (1) through (4) in the following list were conducted during the first phase of the project. These were more or less exploratory in nature and were intended to bring into focus the feasibility of the various lines of investigations which had been initially conceived.

(1) A literature research of available technical information and a study of the provisions of existing guardrail design standards.

(2) An analysis of employee accident records compiled by various agencies to determine the frequency and nature of those accidents which appear to be guardrail-related.

(3) A compilation of existing statistical data on the anthropometric and kinematic characteristics of the human body relevant to guardrail analysis.

(4) A field survey of prototypical guardrail installations (the eight types mentioned above), to become familiar with current practices and, if possible, to identify safe and unsafe employee activities and environmental characteristics.

Ref.[3] summarizes the results of this exploratory first phase. On the basis of these findings, the phase two tasks included:

(5) The preparation and subsequent conduct of an experimental-analytical program. These experiments involved simulations of critical accident situations, measurements of static and dynamic loads induced on instrumented mock-up rails by human subjects and an anthropomorphic dummy, resistance tests of typical guardrail components, and non-structural tests to acquire a data base for establishing the essential safety features of guardrail geometry.

(6) On the basis of information acquired from tasks (1) through (5) above, preparation of performance-oriented recommendations and a guide for the design and evaluation of guardrails.

The experimental program is described in appendix C and interpreted in section 4 of this report. For the most part, the guardrail design recommendations included in section 4 and appendices A and B draw upon the results obtained from these tests.

4. Analysis of Experimental Results

4.1 Introduction

The experimental research program constitutes the second phase of a two-phase research effort aimed at the development of structural and non-structural criteria for design, construction, and evaluation of guardrail systems. A complete documentation of the experimental investigations conducted at the National Bureau of Standards (NBS) is presented in appendix C. The structural investigations included selective resistance testing of common guardrail components which were loaded in flexure to failure, as well as static and dynamic load measurement tests using an instrumented mock-up rail to register loads induced by both human subjects and an anthropomorphic dummy. The non-structural tests were primarily aimed at studying overturning phenomena of a simulated human subject (an anthropomorphic dummy) in relation to guardrail height and/or width for the purpose of predicting the essential non-structural safety features of guardrail geometry. Sections 4.2 to 4.4 are devoted to the interpretation of these test results and the devleopment of a rational basis for the specification of height, width, loading and resistance requirements for guardrails.

4.2 Interpretation of Non-Structural Test Results

Three types of non-structural tests were conducted in an effort to develop an understanding of the safety features of guardrail geometry. These tests are summarized individually in sections 4.2.1 and 4.2.2, with details given in section C.3 of appendix C.

4.2.1 Tests Relating to Height and Width of Wall Barrier

Figure 4.1 describes a series of tests which were designed to examine the physical characteristics of a barrier that would discourage a person from placing a foot upon it to increase his reach. This situation was encountered during the field inspection of a hot-dip galvanizing plant where a worker was observed to assume a climbing posture over the wall of a kettle containing molten zinc in order to improve his reach. In these tests the subject was asked to assume a standing, or a stationary climbing posture with one foot on the floor and in either case extend his arm horizontally over a wall barrier as far as possible without losing his equilibrium. When the subject was in a standing posture he was allowed to lean on the barrier, if necessary, to increase his reach.

In section C.3.1, measurements of maximum horizontal reach were recorded for barrier heights between 24 in (61.0 cm) and 30 in (76.2 cm) using 2-in (50.8-cm) height increments. The result of these tests are presented in figure 4.1 in the form of plots of wall height vs. maximum reach for each posture. They show that a 24-in (61-cm) high wall will allow the person to increase his reach by more than 5 in (12.7 cm) when he assumes a climbing posture. As the height of the barrier is increased, the reach difference between the two postures decreases so that at a barrier height of 30 in (76.2 cm) the subject can no longer gain reach advantage by assuming a climbing posture. The reason for this appears to be the physical difficulty the subject in a climbing posture begins experiencing, in the sense of muscular exertion required to attain maximum reach, when the barrier approaches the equal-reach height.

The subject used in these tests was selected from a limited number of available personnel, for the proximity of both his height and weight to those of the 95th percentile U.S. male subject. The respective unshod height and weight of the test subject were 76.1 in (193.3 cm) and 204 lb (907 N) versus 73.2 in (185.9 cm) and 213.3 lb (948.8 N) for the 95th percentile composite adult male subject. These differences indicate that if the

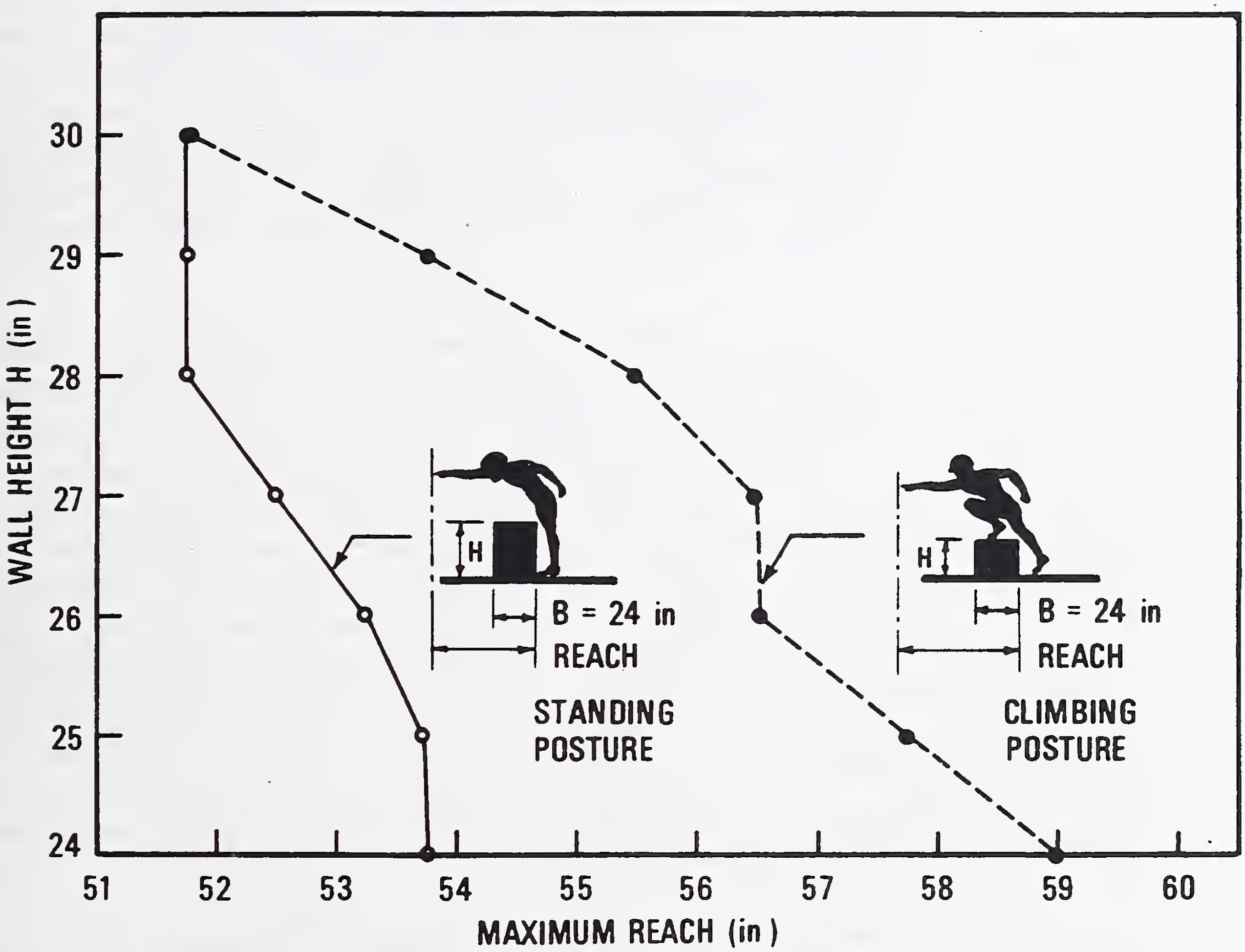


Figure 4.1 Relationship between barrier height and maximum horizontal reach of human subject over barrier for two different postures.

measurements of the test subject were the same as those of the 95th percentile male, the reach advantage gained from a climbing posture would have disappeared at a barrier height slightly below 30 in (76.2 cm). The reason for this appears to be the physical difficulty the subject in a climbing posture begins experiencing, in the sense of muscular exertion required to attain maximum reach, when the barrier approaches the equal-reach height. According to test observations, the top of the barrier should be a certain minimum distance below the hip joint of the subject to permit him to place a foot over the barrier and be able to reach out over the folded knee. Because of the difficulty of locating a subject's hip joint, no measurements of its height were attempted. However, the height of the hip joint may be estimated by noting its proximity to the ischium height (defined in [3]: section 3). According to the chart (figure 3.5, [3]), the ischium height of the 95 percentile male is 39 in (99 cm). The ischium height of the test subject would then be approximately 40.5 in (102.9 cm), or 1.5 in (3.8 cm) more than that of the 95th percentile male, assuming proportionality between ischium heights and total body heights. Therefore the equal-reach condition for the 95th percentile male test subject would probably have occurred at a barrier height of approximately 28.5 in (72.4 cm).

While the foregoing tests examined the minimum barrier height required to inhibit a voluntary risk situation, the series of tests described in section C.3.2 investigate the relationship between the height and width of a barrier to mitigate the consequences of a specific type of accident. They simulated the backward fall of the subject against a barrier causing his body to cross over or to come in contact with a hazardous substance on the opposite side. The output parameters of interest in these tests were the horizontal and vertical projections a and b of the body beyond and below the remote top corner of the barrier, respectively (figure 4.2). To avoid the potential risk of injury to human subjects, these tests, and any other tests involving a dynamic action, were conducted using a composite dummy having the combined anthropometric characteristics of the 95th percentile U.S. adult male subject. The word "composite" is used to designate a dummy which simultaneously incorporates several of the features at a given percentile level, as described in reference [C.1]. Specifically, the test dummy incorporated both the 95th percentile height and the 95th percentile weight.

The line drawings at the top of figure 4.2 schematically illustrate the test sequence described in section C.3.2. The variable parameters are height H and width B of the barrier and the subject's initial distance D from the near face of the barrier. The test setup was conservatively designed to simulate what was believed to be a critical accident situation, barring unanticipated "abnormal" behavior such as running, jumping or climbing in the vicinity of the wall. By having the dummy fall backward rather than forward or sideways, it was reasoned that a human subject facing away from the wall prior to the accident would physically be more handicapped to counteract his fall by reaching behind and placing his hands on the top of the barrier than if he were oriented otherwise. Similarly, the knee and hip joints of the dummy were tightened to a stiff condition before each test in order to have his body contact the near edge of the barrier at a lower point than would have been possible if those joints were kept loose and allowed to rotate prior to impact (i.e., simulation of a limp body condition or deliberate crouching behavior of a human subject

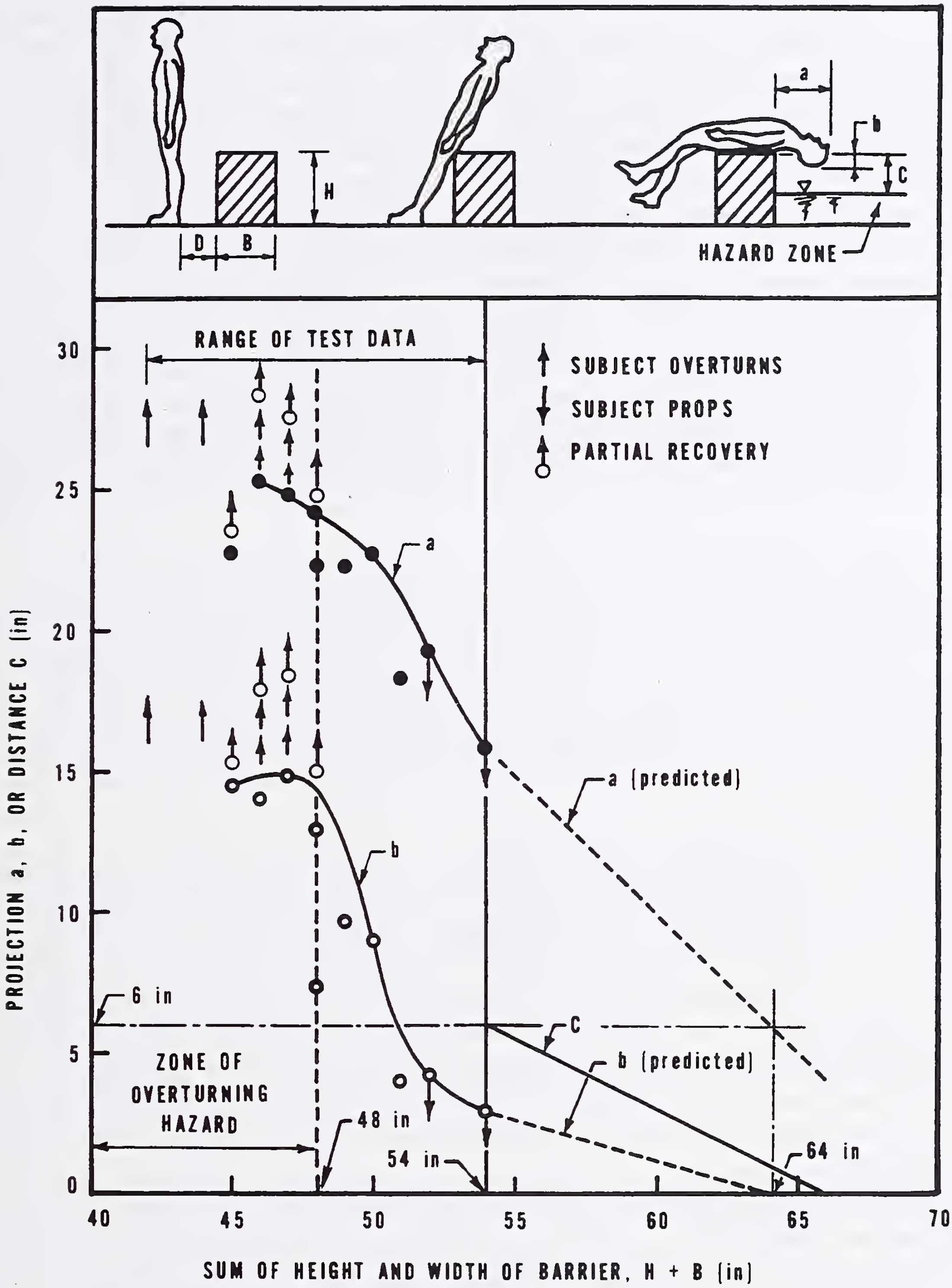


Figure 4.2 Interpretation of tests involving backward fall of dummy against wall barrier.

following loss of balance). The head/rubber neck assembly was left as fabricated to simulate the normal human range of flexion. The ankle joints were kept loose and acted as the center of rotation of the body prior to impact after discovering that these joints could not be sufficiently tightened to make the body pivot about the heels. The near edge of the barrier (square edge of plywood board) was sharp enough, and the frictional coefficient between the rubber sole of the work shoes and the concrete floor was sufficiently large, to make the body pivot about the near edge of the wall without slippage after contact. The top surface of the barrier was the finished surface of a plywood board. No attempt was made to measure the frictional coefficient between the dummy's "flesh" (neoprene) and the plywood surface. However, according to visual observations during the tests, the body remained in contact with the top surface of the wall only for an instant before it started pivoting about the far edge, and no sliding could be discerned during that brief interval. Since the impact velocity magnitudes were found (using energy principles) to be in the range of brisk walking speeds (about 4 mph (6.4 km/h)), tests simulating an accident situation in which the subject walks squarely against the barrier should not differ appreciably from the results of these backward fall tests.

The initial distance D of the heels of the dummy from the near face of the wall was varied from 6 in (15.2 cm) to 12 in (30.5 cm) to study the effect of the location of the accident relative to the wall on the test results. Falls from distances less than 6 in (15.2 cm) were not considered because of the likelihood that the body would prop against the wall rather than overturn. Falls from distances greater than 12 in (30.5 cm) were likewise excluded based on the premise that they would not control the outcome of the tests.

As shown in table C.3, body projections a and b decrease with increasing H and B. The results corresponding to a height of 30 in (76.2 cm) are generally consistent and relatively independent of D. At other heights, the tests exhibit a lack of trend with respect to D. For example, at H = 28 in (71.1 cm) and B = 21 in (53.3 cm), projection b triples as D is decreased from 12 in (30.5 cm) to 6 in (15.2 cm). In other cases, body projections increase with increasing D. This may be attributed to the presence of two compensating factors: falling from a greater distance, the body (1) develops greater momentum and increased tendency to propel over the wall, but (2) at the same time, the portion of the body above the point of impact becomes shorter reducing its tendency to overturn. Viewing the test results, three significant events are observed, namely, (a) the body "overturns" or passes entirely to the other side of the wall, (b) the subject remains on the wall but a portion of the body projects beyond its outer edge, and (c) the subject does not fall on the wall but remains propped against it in a leaning posture.

In situations where body projections may be tolerated, such as where the barrier is installed at the edge of an elevated area to prevent falls from heights, the controlling design parameter would be the combination of height and width of wall that will prevent overturning. The test results indicate that compliance with this condition would require parameter H + B to be greater than 47 in (119.4 cm). In situations where the barrier is installed to prevent people from coming in contact with a hazardous substance, such as molten zinc (hot-dip galvanizing plants), caustic chemicals or hot liquids, the dimensional requirements of the wall would be aimed at controlling or eliminating body projections a and/or b. The test results suggest a number of options a designer may exercise to meet this requirement. It is noted that at a wall height of 28 in (71.7 cm) to 30 in (76.2 cm), the body begins to exhibit a tendency to prop when falling from a distance of D = 6 in (15.2 cm), indicating that a sufficiently high wall, if practical, may be used to prevent the subject from falling on the top of the wall. To proportion the wall so that no projections occur would probably require a combined dimension of H + B = 70 in (117.8 cm), which is obtained by adding the 16-in (40.6-cm) horizontal projection to the corresponding sum of the maximum wall dimensions used in the test (H + B = 56 in or 142.2 cm). This requirement would be an appropriate design criterion in cases where the region beyond the vertical plane through the far edge of the wall is a hazard zone (such as where toxic fumes may be present), but may be somewhat too stringent in cases where the top surface of the hazard zone is at or below the top of the barrier (such as the walls of a galvanizing zinc kettle).

Figure 4.2 has been prepared from the test data given in table C.3 to assist in the formulation of a design approach. For a given height and width, body projections corresponding to three different values of D are averaged and plotted against the parameter H + B. The upward arrows indicate the occurrence of overturning. An upward arrow with a circle indicates that the actual projections might exceed the given values due to a recovery of body projections observed in some of the tests. A downward arrow designates propping of the subject against the wall observed in some of the replicate tests. The solid curves represent upper bound estimates of body projections a and b. The tendency to prop may be explained by noting that the 30-in (76.2-cm) height is 9 in (22.9 cm) above the kneecap height of the 95th percentile male or approximately midway between the hip and knee joints. The 9-in distance permits a person to exercise some leverage through muscular control (simulated by tight hip and knee joints in the dummy) to counteract his fall, assuming adequate friction exists between his shoes and the floor. As the height of the wall decreases, the kinetic energy of the falling person at the instant of first contact with the wall increases,making it more difficult for the subject to restore his equilibrium because of the greater likelihood that the increased dynamic forces might overcome the frictional resistance of the floor and overtake the subject's muscular capabilities.

At this stage it will be helpful to become familiar with the non-structural design Criterion for wall barriers by consulting section A.3.2 in appendix A. To inhibit accidental falls from heights, Criterion A.3.2 stipulates that parameter H + B should be equal to or greater than 48 in (121.9 cm) and the height H of the wall should be not less than 30 in (76.2 cm). The first requirement is the minimum combination of height and width for which no overturning of the subject occurred in the tests. This is represented by the vertical broken line shown in figure 4.2. The 30-in (76.2-cm) minimum height limitation is prescribed for reasons noted earlier.

To inhibit accidental contact of the human body with a hazardous liquid on the opposite side of the barrier, Criterion A.3.2 (b) stipulates that width B should be not less than 24 in (61 cm) and the parameter B + 2C should be equal to or greater than 36 in (91.4 cm), where C is the level of the liquid below the top of the wall (figure 4.2). Since the minimum wall height required by Criterion A.3.2 (a) is 30 in (76.2 cm), the minimum value of H + B required by Criterion A.3.2 (b) will be 54 in (137.2 cm) which is also the maximum combined dimension for which test data are available. This limit is indicated by the solid vertical line shown in figure 4.2. The solid line C plotted to the right of this line graphically designates the design requirement for parameter H + B for values of C equal to or less than 6 in (15.24 cm). For comparison, the predicted values of projections a and b are plotted in the same figure. At C = 6 in (15.24 cm), and the corresponding minimum recommended value for H + B of 54 in (137.2 cm), the average projections a and b as determined by tests are 16 in (40.6 cm) and 3 in (7.62 cm), respectively. This puts the subject's body within 3 in (7.62 cm) of the hazardous substance as represented by the difference between the ordinates of curves C and b at that point. The extensions of curves a and b for H + B > 54 in (137.2 cm) (or for H = 30 in (76.2 cm) and B > 24 in (61 cm)), are predicted by noting that an increment in B should, in effect, cause a corresponding decrease in a, so that at B = 34 in (86.4 cm) (or, H + B = 64 in (162.6 cm)), projection a, should be equal to 16 - 10 (increment in B) = 6 in (15.24 cm). But 6 in (15.24 cm) is approximately equal to the dimension from the top of the head of the dummy to the posterior base of its skull. Therefore, at a $\leq$ 6 in (15.24 cm), b should be equal to zero since the head cannot project below the top of the wall. Thus, the extension of curve b is predicted by assuming a gradual decrease from 3 in (7.62 cm) at H + B = 54 in (137.2 cm) to zéro at H + B = 64 in (162.6 cm).

4.2.2 Tests Relating to Height of Guardrail

The foregoing tests explored the relationship between the height and width of a barrier needed to mitigate the consequences of what were conceived to be critical accident situations. Criterion A.3.2 (a), which was formulated on the basis of these tests applies only when the guardrail width is greater than 6 in (15.24 cm). The tests described in sections C.3.3 were devised to develop an experimental basis for determining an appropriate guardrail height where width is not a factor. The critical accident situation in this case was that of a person squarely hitting the guardrail after walking towards it unaware of its existence.

The test simulation involved the use of the 95th percentile dummy and a carriage having a top rail attachment (figure C.4). This was a relatively unsophisticated test setup requiring no instrumentation or measurements. The object was simply to determine an appropriate height to prevent people from accidentally falling over a guardrail. The test variables were the speed of the carriage and the height of the rail. The two speeds used were, on the average, 2.5 mph (4.0 km/hr) and 3.3 mph (5.3 km/hr). The first of these is associated with the normal walking speeds of human subjects. The second value was the maximum attainable speed within the space constraints of the laboratory although the original intent was to develop the 4.5-mph (7.2-km/hr) brisk walking speed estimated for human adults. The net effect of using the 3.3-mph (5.3-km/hr) carriage speed as opposed to 4.5 mph (7.2 km/hr), should be a reduction in the tendency of the subject to fall over the rail since the body momentum is proportionately less. However, an examination of table C.4 shows that with the exception of two instances, the test data for the two speeds are identical. This indicates that the overturning tendency of the body is not likely to be very sensitive to variations in walking speeds.

Certain physical features built into these experiments tend to make the test results more critical than might be anticipated in the real accident situation simulated. For instance, it is impossible to devise a practical scheme that would allow instantaneous stoppage of the carriage upon impact with the fixed object. What actually happened in the tests was that the carriage recoiled about 6 in (15.24 cm) or less after impact, depending on the speed used. This recoil, in effect, increases the overturning tendency of the subject in relation to that in an actual accident situation. Similarly, by placing a loose layer of polyethylene sheeting around the rail, a reduction in its frictional resistance against overturning was effected. Since the clothing between the subject and the rail could act as a layer of lubricant, the use of the polyethylene sheeting is therefore conservatively realistic. Other measures included keeping the ankle joints of the test dummy loose and tightening its hip joints to a level of 1G (section C.3.3), which was the minimum tightness needed to maintain the initially straight posture before impact. In some of the replicate tests, the hip joints were tightened to a stiff condition. Judging from the results shown in table C.4, the effect of hip joint tightness does not seem to be very significant.

Prior to the tests, it could not be ascertained whether the frictional coefficient between the shoes of the dummy and the plywood platform mounted on the carriage would be a contributing factor. The overturning mechanism observed, however, led to the conclusion that tread friction is irrelevant to the test results. The reason for this is that as the upper body begins to swing over after the impact, the weight of the subject gets transmitted from the tread surface to the rail. This lifting action destroys the frictional resistance at the tread level and consequently, any stabilizing effect it might have on the subject.

There is also the possibility that once the accident is initiated, a person's behavior would mitigate the consequences of the accident whereas the use of a dummy precludes consideration of such behavioral factors. It may be argued, for instance, that a person might be able to avert his fall by grabbing the rail with his hands after the impact. The likelihood of such conduct will depend, among other factors, on his response time and his ability to exercise proper limb action in time. By considering the dynamic action of the upper body after impact and using the commonly accepted value of 3/4-second human response time, it can be shown that by the time the subject begins to respond, his upper body will have rotated (about the hip joints as pivot) through an angle greater than 90 degrees. Although this situation by itself does not rule out the possibility of human counteraction, it indicates that the probability of occurrence of such counteractive measures is small.

Figure 4.3 gives a condensed version of the test results compiled in table C.4 and an accompanying sketch describing the sequence of events observed in almost all the tests in which the rail height (i.e., always designates height of centerline of test rail) was set at 36 in (71.4 cm) and in about 50 percent of the tests involving a rail height of 38 in (96.5 cm). The fact that no overturning occurred at a rail height of 40 in (101.6 cm) suggests the presence of a critical relationship between the tendency of the body to overturn and the proximity of the rail to the hip joints of the subject. With shoes on, the dummy's hip joints were 40.4 in (102.6 cm) above the tread. If the hip joints clear the rail, the upper body can rotate freely. Conversely, if the rail is above the hip joints the portion of the body above the rail will offer greater resistance to overturning because the spinal column is far less articulated than the hip joints.

The fact that no overturning occurred when the rail centerline was set at 40 in (101.6 cm) or at 42 in (106.7 cm) above the tread surface is reflected in Criterion A.3.1 which stipulates a height of 42 in (106.7 cm), for guardrails having flexurally rigid top rails, with a 1-in (2.54-cm) tolerance (section A.3.1.1) to account for variations in construction, workmanship and other factors. The same Criterion specifies a greater height for flexurally non-rigid top rails to compensate for the greater deflection that occurs in these elements under the same loads.

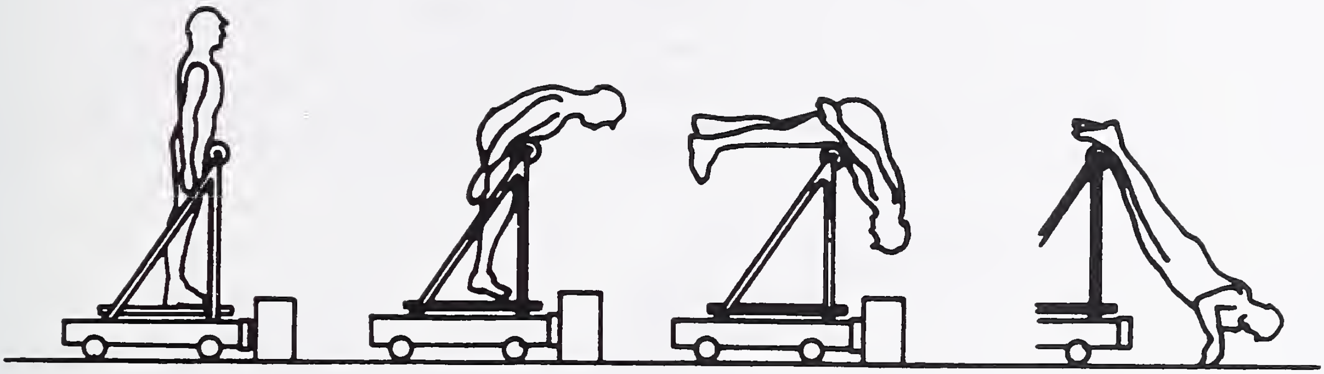
4.3 Interpretation of Static Load Measurement Tests

4.3.1 General

The static load tests described in detail in section C.4 were designed to gather basic data on the types and magnitudes of some of the stationary human loads that might be anticipated to occur in service. The principal load-measuring device for the static as well as dynamic load tests was a 10-ft (3.05-m) long 2024-T3 aluminum tubular rail of 2.25-in (5.72-cm) outside diameter, the ends of which were attached with ball-bearing type connectors to telescoping vertical posts braced and anchored to the test floor (refer to section C.4.1 for complete details). Five different types of static load tests were conducted in the experimental program. Four of these were miscellaneous tests involving human subjects selected for the proximity of their measurements to the 50th and 95th percentile U.S. male population. In the fifth series of tests, human male subjects as well as the anthropomorphic dummy were used to measure loads transmitted to a rail through backward leaning postures.

4.3.2 Backward Leaning Posture Tests

The principal static load tests were carried out using the standard body posture shown in figure C.8. Special emphasis was given to this posture because it also represents the neutral position (i.e., the static position which the mass of the body assumes under the action of gravity forces alone) for the dynamic tests discussed in section 4.4. The variable parameters in the static tests were the height H of the mock-up rail and the



GR HEIGHT	BRISK WALK ≈ 3⅓ mph	SLOW WALK ≈ 2½ mph
42"	NO	NO
40"	NO	NO
38"	YES and NO	YES and NO
36"	YES	YES

Figure 4.3 Experimental simulation of forward fall over toprail by human subject initially moving at the two walking speeds specified.

distance D of the subjects' heels from the centerline of the rail (figure 4.4). Both human subjects and an anthropomorphic dummy were used to gather the force data which is fully documented in section C.4.2.

Figure 4.4 presents a graphical summary of the test results for human subject 101 and the dummy. The force-to-weight ratio of each subject is plotted against heel distance D. The rapid increase in the force transmitted by the human subject against the 42-in (106.7-cm) rail when the heel distance is increased from 36 in (91.4 cm) to 42 in (106.7 cm) is probably caused by the wedging action of the body against the rail and the toe plate. Considering differences in height, weight and posterior body contour between the human subject and the dummy, the respective plots at a guardrail height of 42 in (106.7 cm) are in reasonably good agreement. Other points of interest are the tendency of the curves to level off at a heel distance greater than 30 in (76.2 cm) and the upward trend of the static loads due to a reduction in rail height.

4.3.3 Miscellaneous Posture Tests

The four types of static postures for which load measurments were made (section C.4.3) are illustrated in figure 4.5 together with a sampling of peak forces induced in each case. The data for postures (a), (b) and (c) in figure 4.5 provide partial information on the nature and intensity of loads falling within the category of basic live loads (L) defined under Criterion A.2.1. The information acquired from tests of the type shown in figure 4.5(d) provides a data base for specifying surge load (S) defined in the same Criterion.

The guardrail-bench combination shown in figure 4.5(a) is a common type of installation used around elevated decks, balconies and similar areas which often serve as places of assembly. The plane of the rail is usually inclined outward at an angle of 15 to 20 degrees with respect to the vertical to save floor space and to provide seating comfort. A peak loading situation occurs when the bench is fully occupied by people seated shoulder-to-shoulder. Forces are transmitted to the top rail and to intermediate elements through the bench. If the bench were not attached to the rail but rather, placed next to it, as is often done to provide backing, the force on the top rail will not be altered appreciably so long as the bench has sufficient stability against sliding and overturning when fully occupied. Thus, the simple test setup used offers an expedient means of measuring human-induced loads without having to contend with the complexities involved when the bench is built integrally with the rail.

The test results given in table C.9 represent loads transmitted to the 42-in (106.7 cm) high mockup rail when the subject is in a seated posture, or in a shoving posture achieved by placing both heels on the floor while remaining seated. Note that even though height and weight differences between the two subjects were small, (subject 108 is 2.6 in (6.6 cm) taller and 11 lb(49N) heavier than subject 101), in some cases the forces they transmitted to the rail were appreciably different. No special attempt was made to prescribe rigid posture specifications. It is likely that major differences in the results might have been caused by differences in posterior body contours of the two subjects. For instance, if the shoulder blades just clear the rail, the body might exert considerable downward force.

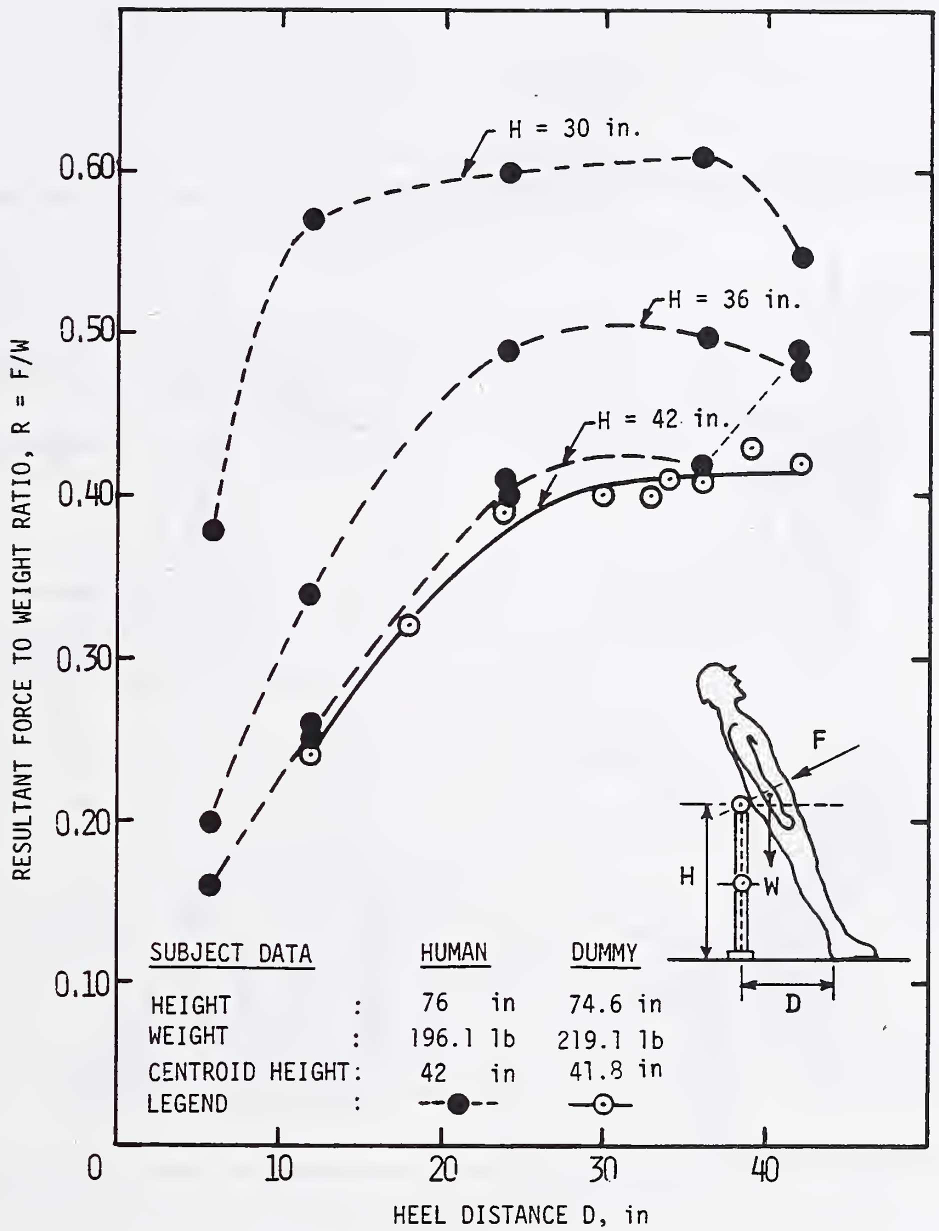


Figure 4.4 Static force vs. heel distance of human and dummy subjects leaning against mock-up rail.

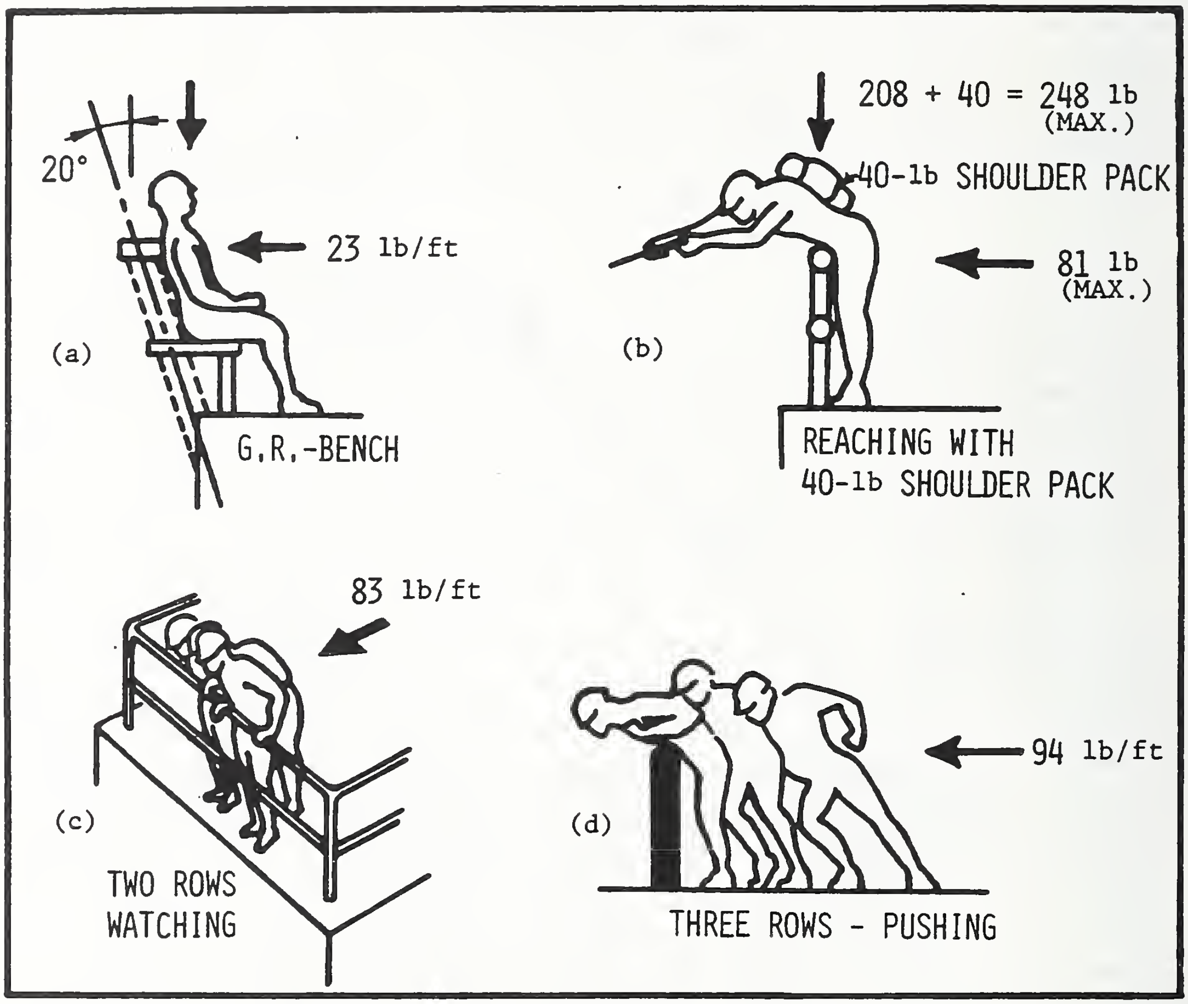


Figure 4.5 Miscellaneous static posture loads on guardrails.

For design purposes, the 23-lb/ft (336-N/m) force for the 20-degree guardrail inclination shown (table C.9) may be considered to represent a working load (unfactored design load) because even though both subjects had close to the 95th percentile male characteristics no consideration was given to such transient dynamic effects as would occur when a group of people simultaneously occupy or vacate the bench. The average body characteristics of a group will tend towards the 50th percentile level as the number of people in the group increases, and therefore a more comprehensive test setup should include measurement of forces induced by test subjects having the 50th percentile characteristics not only in a seated posture but also during the act of occupying and vacating the bench.

The shoving (thrusting) posture produces two to three times the loads (table C.9) corresponding to the normal seated leaning posture. The intent of the backward shoving posture tests was to measure peak loads which people can transmit to a guardrail through a special type of sitting configuration. It is possible that in the absence of a bench, intermediate rails could also be loaded in a this manner by a row of people seated on the floor.

The data gathered from tests corresponding to the leaning-reaching posture, which simulates a work activity such as encountered in a tree-spraying operation where the rail is mounted around a mobile truck platform, is presented in table C.10. The maximum possible static load that can be transmitted to the rail will occur when the subject is on the verge of overturning. Therefore, the 248-lb (1104-N) vertical load shown in figure 4.5(b) represents the total weight of the subject and the backpack. Although the statement is made in section C.4.3 that the subject reached over the rail just short of losing his balance, judging from the vertical component of the load induced on the rail, it may be concluded that in an actual situation the subject instinctively stops quite short of the overturning threshold. Thus, the 81-lb (360-N) average resultant force (figure 4.5 (b) and table C.10) may be representative of forces in a real situation. For design purposes, this force may be assumed as an unfactored point load acting in any direction between horizontal and vertical and the 248-lb (1104-N) vertical load may be treated as a factored load which the rail must support independently without structural failure.

The third stationary loading situation is depicted by two rows of people leaning over the rail to observe an event occurring below, as shown in figure 4.5(c). The test simulation of this condition and the measurements made are presented in section C.4.3(c) and table C.11. The reason for using subjects having close to the 50th percentile male characteristics is the large number of people involved (and hence, the tendency towards the median characteristics). It was further reasoned that a row of people standing shoulder-to-shoulder against the rail will probably permit only one additional row of people to view an event by leaning over the spaces between their heads.

The 83-lb/ft (1211-N/m) distributed force induced by the two rows of people shown in figure 4.5(c) is obtained by doubling the load increment induced by subject 502 in the second row, adding it to the total average force induced by subjects 503 and 105 in the first row, and dividing this sum by the sum of the shoulder widths of subjects 503 and 105 (see table C.11 for the pertinent data). Note that this distributed force has a 64-degree inclination with respect to the horizontal (table C.11).

For design purposes the 83-lb/ft (1211-N/m) force may be further adjusted by multiplying it by the ratio of the average weight of the 50th percentile male subject to the average weight of the test subjects. This gives a distributed force of 90 lb/ft (1313 N/m) which may be treated as an unfactored uniform load for design and may be conservatively assumed to act in any direction between horizontal and vertical that will produce the most critical stress condition.

The last series of miscellaneous static posture tests simulates three rows of people pushing against the guardrail (figure 4.5(d)) as in the case of a surging crowd seeking passage through exitways where guardrails are freqently mounted to direct pedestrain traffic and protect people from accidental falls. The same three subjects were used as in the preceding test (figure 4.5 (c)). The maximum distributed force of 94 lb/ft (1372 N/m) for the posture shown in figure 4.5 (d) is obtained by dividing the 137-lb (610-N) force exerted by the three subjects (table C.12) by the average shoulder width of the three subjects.

The 100-lb/ft (1459-N/m) surge load (S) specified in Criterion A.2.1 is based on the results of these tests after multiplying the 94-lb/ft (1372-N/m) distributed load by the ratio (1.08) of the weight of the 50th percentile subject to the average weight of the three subjects. Since according to table C.12 the resultant force is inclined with respect to the horizontal, Criterion A.2.1 conservatively stipulates that the specified surge load may be applied in any direction between horizontal and vertical to produce the most critical loading condition for design.

4.4 Interpretation of Dynamic Load Tests

4.4.1 General

The design of the dynamic load tests was motivated by the need to develop an understanding of guardrail response to forces produced by human body impact due to accidental falls. In the first series of tests the dummy was released from an initially erect position and allowed to fall backward against the instrumented mock-up rail which was kept at a constant height of 42 in (106.7 cm). In the second test series the dummy was released in the same manner and allowed to fall backward against a 42-in (106.7-cm) high rail without instrumentation, which caused it to jacknife and hit the instrumented mock-up rail placed at a lower height. The rationale for these particular accident simulations and the interpretation of the tests results are presented in subsequent sections 4.4.2 and 4.4.3. These tests are completely documented in sections C.4.4 and C.4.5 of appendix C.

4.4.2 Dynamic Loads on Top Rail

The results of the dynamic load tests on the "top" rail (section C.4.4) are graphically summarized in figure 4.6 where the resultant maximum force response of the rail is plotted against the heel distance D of the dummy from the centerline of the rail. For comparison, a plot of the resultant static force for the corresponding leaning posture (section 4.3.2) is shown in the same figure. Each point on the dynamic response curve represents the arithmetic mean value of five replicate tests (table C.13). The coefficient of variation in these tests was typically about 3 per cent. It is noted (table C.13) that the occurrence of the 566.7-lb (2521-N) maximum average response corresponds to a heel distance of 30 in (76.2 cm) while the absolute maximum response observed in all tests of 579.0 lb (2575N) occurred for a fall corresponding to an initial heel distance of 33 in (83.8 cm).

The test setup is based on the supposition that this accident mode will produce critical dynamic loads in relation to other types of accidents occurring in the vicinity of the guardrail. As noted in section 4.2.1, the backward orientation prior to the accident physically constrains the subject from reaching behind and grabbing the rail with his hands prior to body contact. The dummy's knee, hip and spinal joints were maintained at the stiff level (section C.4.4) to minimize shock absorption by the body through joint rotation. A comparison of the data in table C.13 with those in tables C.14 indicates a hip joint tightness of 1G or greater will not appreciably alter the forces transmitted to the rail while a loose hip joint for falls from a distance of 33 in (83.8 cm) will reduce the peak dynamic force by about 14 percent. Moreover, an analysis indicates that for backward falls from a distance of 32 in (81.3 cm), the centroid of the subject will attain a tangential velocity of 4.3 mph (6.92 km/hr) just prior to contact with the rail. The magnitude of this velocity is about the same as the 4.5-mph (7.25-km/hr) brisk walking speed previously noted. It thus appears that this test setup would account for the types of forces resulting from the accident situation used in the tests relating to guardrail height (section 4.2.2).

The possibility exists that a person walking towards the guardrail will trip and fall against it from, say, the optimum distance of 30 in (76.2 cm), in which case, the force on the guardrail will exceed that due to a fall from a stationary position. However, the likelihood of such an occurrence is relatively remote since it requires the simultaneous occurrence of two additional events, namely, the existence of motion and movement in a specific direction. It may also be argued that a person in a forward motion is less likely to trip over an object than if he were in a backward motion where the object is not within his field of vision. In addition, backward motion, if it occurs (say two people hauling a heavy object), is not likely to involve speeds significant enough to influence the results

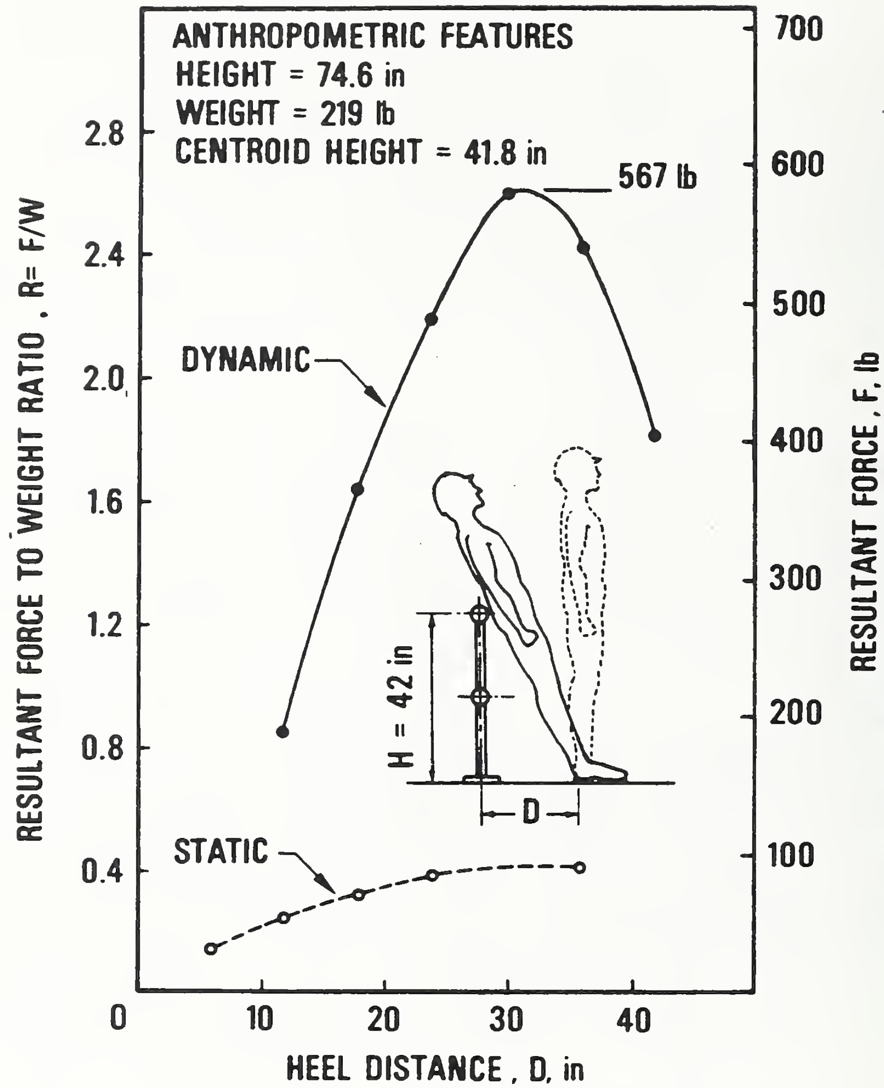


Figure 4.6 Dynamic and static force on top rail exerted by 95th percentile dummy vs. heel distance from centerline of rail.

of tests based on stationary postures prior to the accident. It should be emphasized that in the absence of meaningful statistical data on the probability of individual events contributing to an accident, no attempt was made to assess the actual probability of the accidents simulated by the tests.

Figure 4.7 represents a typical strip chart recording of the time history response of the mock-up rail under the impact by the dummy falling from a distance of 33 in (83.8 cm). After the first pulse, which has a typical duration of 0.2 sec, the body bounces off the rail for a period of 0.5 sec during which time free vibrations of small amplitude occur in the rail. This is followed by a succession of pulses of decaying amplitude until the dummy either comes to rest against the rail in a stationary static posture (as in section 4.3.2) or jackknifes and falls under the rail (figure C.14). It was observed (table C.13) that in falls from heel distances of 30 in (76.2) and less, and in some of the falls from a heel distance of 32 in (81.3 cm), the dummy propped against the rail while in falls from greater distances the dummy jackknifed and fell under the rail.

In each of the tests, the maximum response is represented by the resultant amplitude of the first pulse. For instance, the resultant "force" of 545 lb (2425N) for the pulse shown in figure 4.7 is obtained by the vector addition of the 378-lb (1682-N) vertical and 392-lb (1744-N) horizontal amplitudes of the first pulse. It is important to clarify the meaning of "force" as it relates to dynamic loads. This term may be visualized as a static point load producing the same strains in the rail as the maximum resultant dynamic response actually recorded. The rail itself may not necessarily experience the exertion of the maximum force at the same time as it develops its peak response (force and response may not be in phase). However, noting that the ratio of the time to maximum deflection (0.1 sec) is approximately 1.5 times the fundamental period of the rail (0.064 sec) (section C.4.1), it is reasonable to assume that the interactive force between the dummy and the rail is equal to, and in phase with, the dynamic force response registered on the strip chart recorder [4].

Figure 4.8 presents analytically derived expressions for the maximum force and strain energy in the rail based on a simplified model of the subject and rail system, and the assumption that the change in the potential energy is equal to the strain energy stored in the rail at the time when the peak displacement amplitude occurs (i.e.. principle of energy conservation). Figure 4.9 presents plots of the ratio of the maximum force on the rail to the weight W of the subject vs. heel distance D. Curve A was obtained by theory (fig. 4.8) while curve B was developed from the reduced test data. The difference in the ordinates of the two curves indicates the energy dissipated by the dummy. Note again the reversal in the trend of test results for $D > 30$ in (76.2 cm) attributable to body joint rotations which the theoretical approach does not take into account.

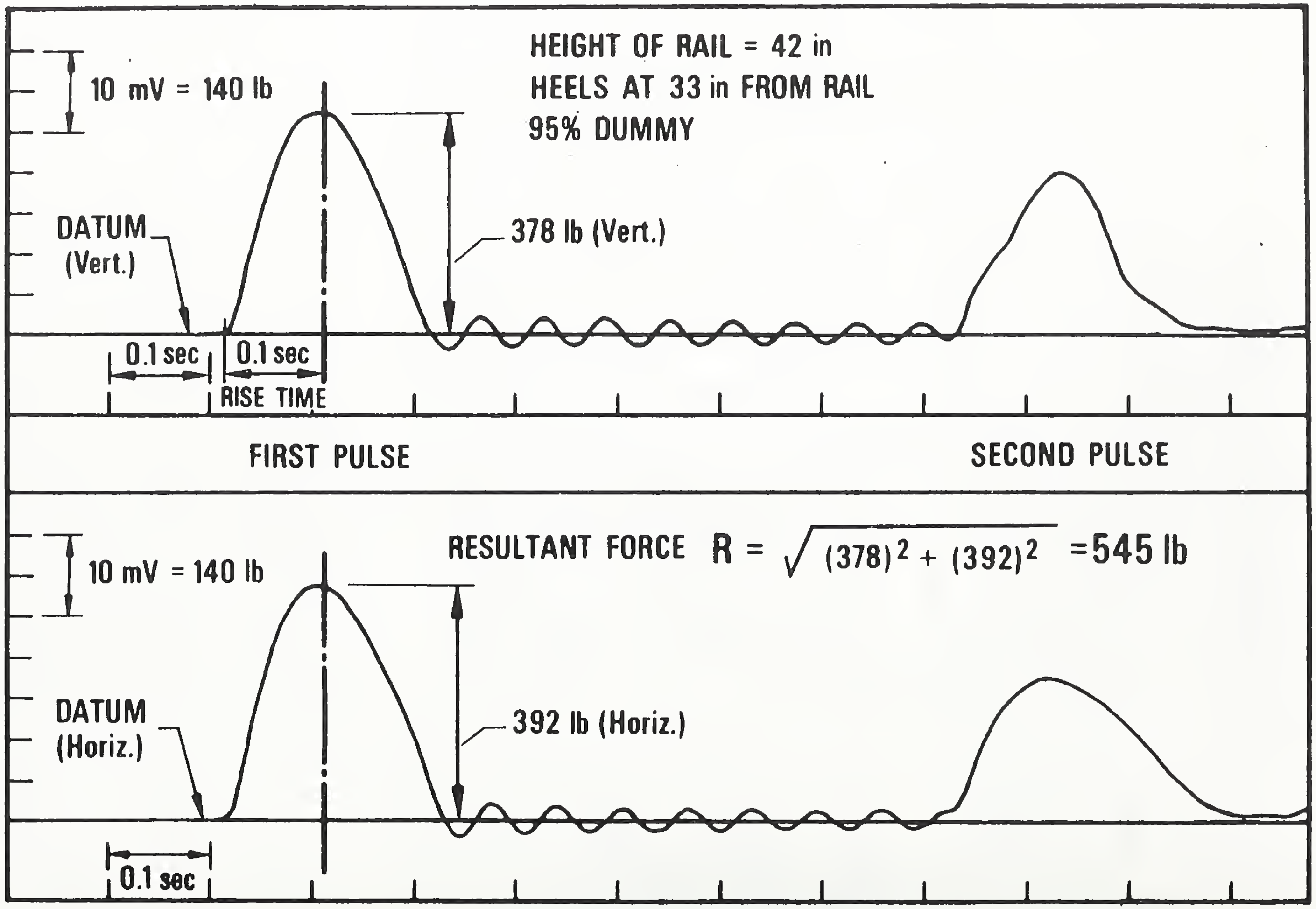
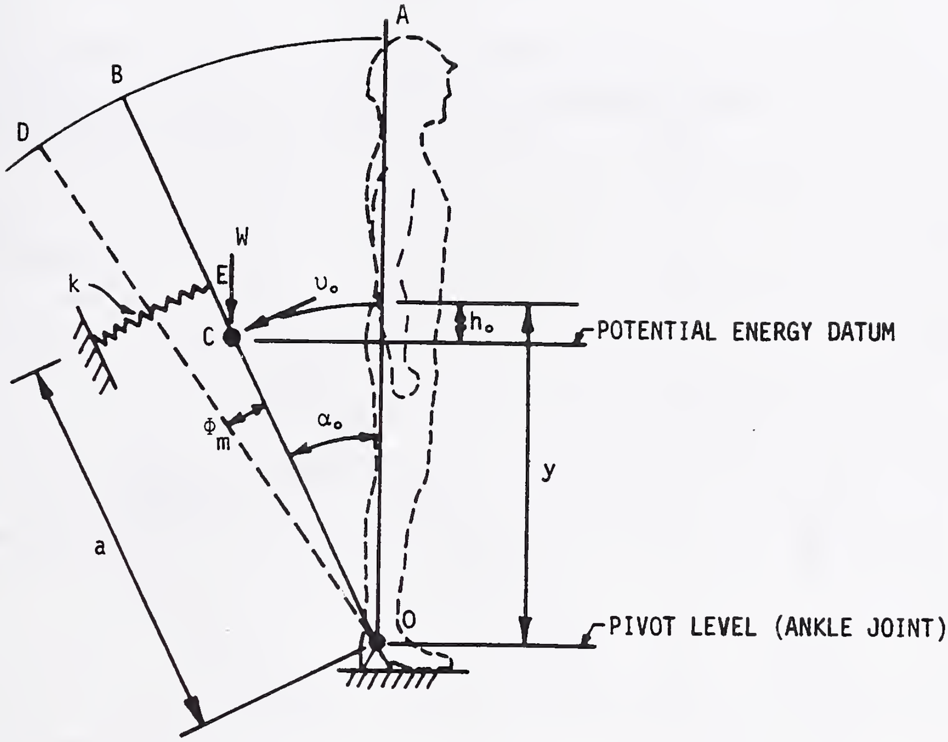


Figure 4.7 Time history of impact load on top rail.



$$\Phi_m = C_1 + \sqrt{C_1^2 + C_2}$$

$$\frac{F}{W} = Q_1 + \sqrt{Q_1^2 + Q_2 k}$$

$$U_s = \frac{k\,(a\Phi_m)^2}{2} = \frac{F^2}{2k}$$

$$C_1 = Wy \sin \alpha_o$$

$$C_2 = \frac{2Wh_o}{ka^2}$$

$$Q_1 = \frac{y \sin \alpha_o}{a}$$

$$Q_2 = 2h_o/W$$

υ_o	:	Tangential velocity of subject's centroid at instant of contact with spring (rail)
$\overline{OA}$	:	Initial vertical posture of subject
$\overline{OB}$	:	Posture of subject at instant of contact with spring (rail)
$\overline{OD}$	:	Posture of subject at instant of maximum contraction of spring (deflection of rail)
E	:	Point of initial contact of subject with spring (rail)
W	:	Weight of subject above pivot O
k	:	Constant of spring (equal to stiffness of rail at midspan)
Φ_m	:	Maximum angular rotation of subject relative to line $\overline{OB}$
C	:	Location of centroid of subject
F	:	Maximum force on the spring (rail) corresponding to Φ_m
U_s	:	Maximum strain energy in the spring (rail) corresponding to Φ_m
y	:	Height of subject's centroid above pivot O (ankle joint)
h_o	:	Vertical displacement of subject's centroid due to rotation α_o

Figure 4.8 Analytical prediction of maximum force on top rail induced by falling subject.

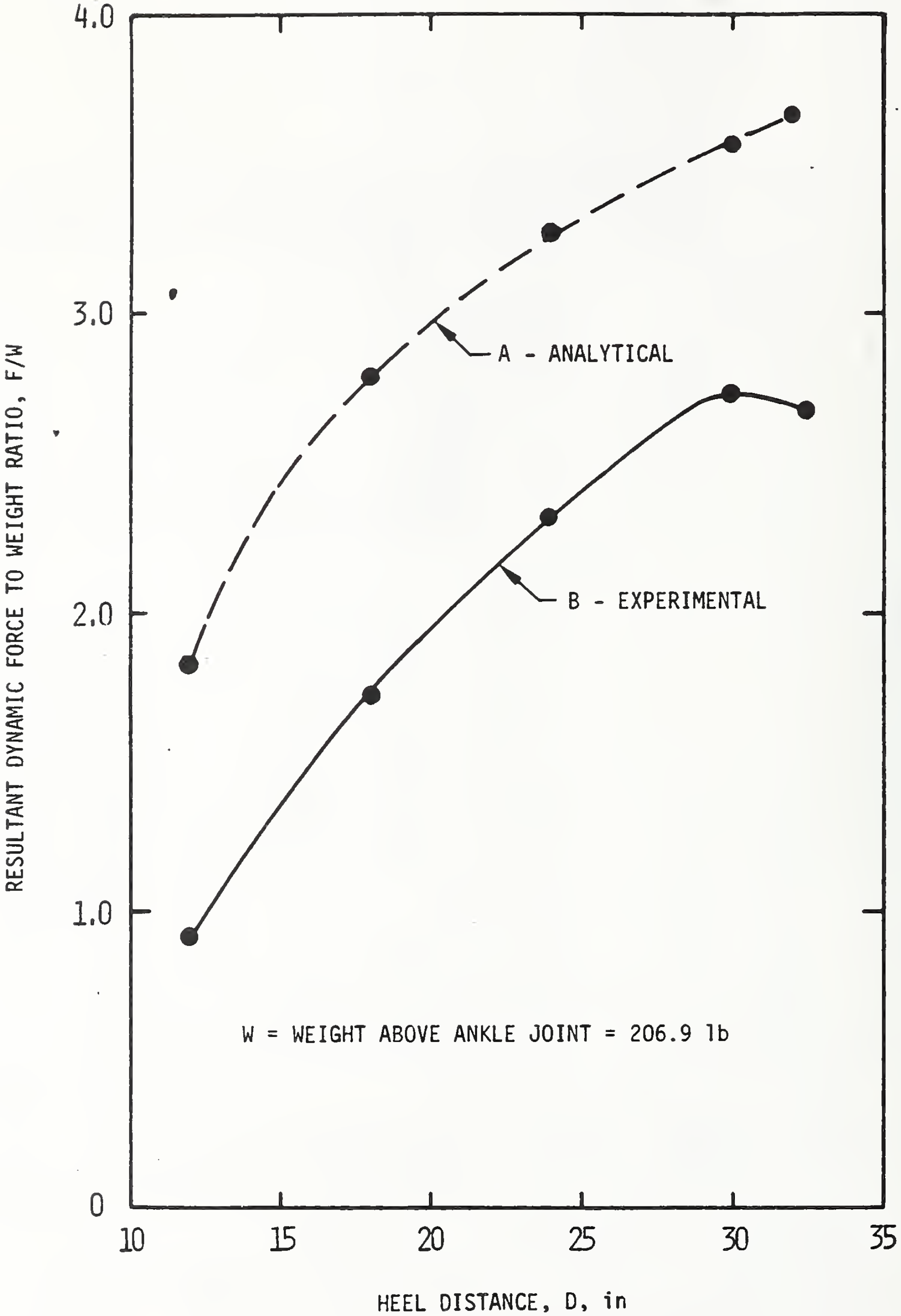


Figure 4.9 Resultant dynamic force induced on top rail by falling subject in relation to heel distance: (A) experimental, (B) analytical, assuming no energy loss due to viscous damping by subject's body.

Criterion A.2.1 defines the 300-lb (1335-N) accidental load (A) to be used as a basic unfactored load in the design of all guardrails used by employees. This load was obtained from the mean peak impact load of 566.7 lb (2522 N) recorded at D = 30 in (76.2 cm) as follows. First, this load was reduced by the ratio of the average weight of a male subject having the 95th percentile height (189 lb or 837 N), to the 95th percentile weight which was incorporated in the dummy used in the tests (214.1 lb or 953 N), both weights being taken above the ankle joint. This gives an adjusted peak load of 497.6 lb (2214 N). Next, the 497.6-lb (2214-N) load, which is considered as an ultimate factored load because it arises from a combination of extreme events as noted earlier, was reduced to 300 lb (1335 N) by multiplying it with a factor of 0.6 which is the reciprocal of the applicable safety factor used in the design of steel flexural elements [A.3: part 5, section 1.5]. It should be noted that even though, for the type of accident simulated, the vertical and horizontal components of the peak load is considerably less that the load itself, other accident situations could well create vertical or horizontal loads comparable in magnitude to the peak load measured. Accordingly, Criterion A.2.1 places no restrictions as to the direction of the accidental load. It is further noted that the dynamic loading rate is not high enough to produce strength gain except in wood for which appropriate provisions are made in the applicable standards [A.8].

A steel guardrail system based on the 300-lb (1335-N) load and designed in accordance with the AISC specifications [A.3], (adopted in Criterion A.2.3) will just yield under the 566.7-lb (2522-N) peak load. This is consistent with the design requirements for steel structural systems, and, in general, with the design requirements of most other metal standards which use safety factors comparable to that used for steel structures. It should be noted that codes and standards for other materials prescribe safety factors usually higher than used in metal structures, reflecting the effects of numerous factors such as ductility, energy absorptive and damping characteristics, variability of strength, stiffness, quality control, and so on. Therefore, the prescription of an unfactored load, rather than an ultimate load for design eliminates the need to prescribe safety margins which may be at variance with established practice in accordance with the various codes and standards.

Strictly speaking, since human-induced impact loads on guardrails are dependent on the stiffness characteristics of the system, the 566.7-lb (2522-N) peak force would occur only in systems having the same stiffness as the mock-up rail used in the tests. Stiffer systems will develop greater dynamic loads and vice versa. Figure 4.10 has been prepared to demonstrate graphically the relationship of the dynamic force normalized by the weight of the 95th percentile subject (F/W) and the stiffness of a system normalized by the stiffness of the mock-up rail (k_s/k_m). The top curve is developed using the theoretically-derived force-stiffness relationship. The middle curve is constructed by first plotting the point corresponding to the 566.7-lb (2522-N) force and the stiffness of the mock-up rail (ordinate: F/W = 566.7/206.9 = 2.74, abscissa : $k_s/k_m = 1.0$), and next reducing the other points on the theoretical curve by the ratio of the ordinate of the middle curve to the ordinate of the top curve at $k_s/k_m = 1.0$. Therefore, the middle curve assumes that force reduction attributable to energy absorbed by the subject's body varies in proportion to

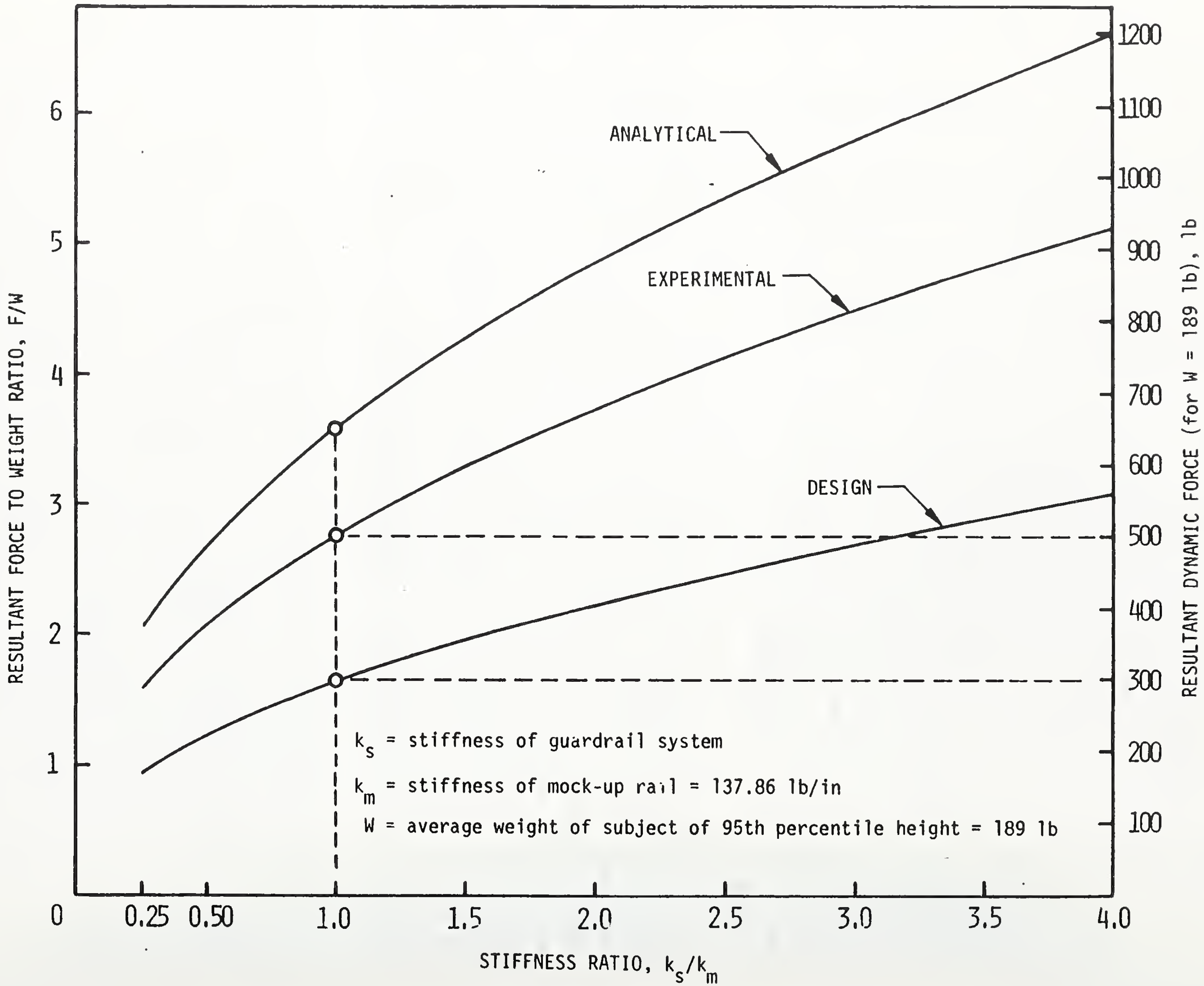


Figure 4.10 Relationship between dynamic force-to-weight ratio of subject and stiffness of guardrail system relative to the mock-up rail.

the total force that would occur if no energy were absorbed by the body. The bottom curve is developed by applying the reduction factor of 0.6 to the ordinates of the middle curve. The ordinate on the right-hand-side is the (predicted) design force as a function of the ratio k_s/k_m. In particular, the point on this curve having the 300-lb (1335-N) ordinate corresponds to an abscissa of unity ($k_s/k_m = 1$).

In the light of the foregoing discussions, it is seen for instance, that if a steel system designed on the basis of the 300-lb (1335-N) load turns out to have twice the stiffness of the mock-up rail it will have to be redesigned for a 400-lb (1780-N) load rather than the 300-lb (1335-N) load to have the same margin of safety (1/0.6 = 1.67) that a system of the same stiffness as the mock-up rail would have. Conversely, if the initial design for the 300-lb (1335-N) is maintained, the margin of safety against yielding will, in effect, be reduced.

An iterative design approach such as described above will lead to heavier sections than a design based on the 300-lb (1335-N) load prescribed in Criterion A.2.1 and may be too conservative for a number of reasons. In practice, guardrail support systems are probably more compliant than the complete fixity at the base of the posts, generally assumed in design. Support rotations reduce the stiffness of the system which in turn causes a reduction in the intensity of the dynamic load. In addition, the accident mode selected was one believed to be the most critical (barring abnormal actions such as running, jumping, etc., which are precluded from this study) since it encompassed the simultaneous occurrence of several extreme events.

4.4.3 Dynamic Loads on Intermediate Rail

Figure 4.11 offers a concise summary of the intermediate rail tests described in section C.4.5. In the figure, the resultant dynamic force on the intermediate rail caused by the impact of the falling dummy is plotted against the height of the rail for falls from heel distances of 33 in (83.8 cm) and 36 in (91.4 cm). Although the dummy's hip joints were kept loose in all these tests, falls from a distance of 30 in (76.2 cm) failed to produce impact on the intermediate rail because the body did not jackknife after hitting the top rail. The general trend of the test data indicates a reduction of the impact force with increasing intermediate rail height. This is understandable since the height of fall after primary impact with the top rail is reduced as the height of the intermediate rail is increased.

Figure 4.11 indicates that the maximum force of about 500 lb (2225 N) for both heel distances used is approximately the same and occurs when the intermediate rail height is 18 in (45.7 cm) above the tread surface. Figure 4.12 shows a typical force-time history of impact on the intermediate rail registered on the strip chart recorder. As in the top rail tests, the maximum amplitude occurs during the initial impact. The irregularity in the response curve such as the peaks occurring before the maximum amplitude of the first pulse is due to the dummy's hand hitting the rail before body impact.

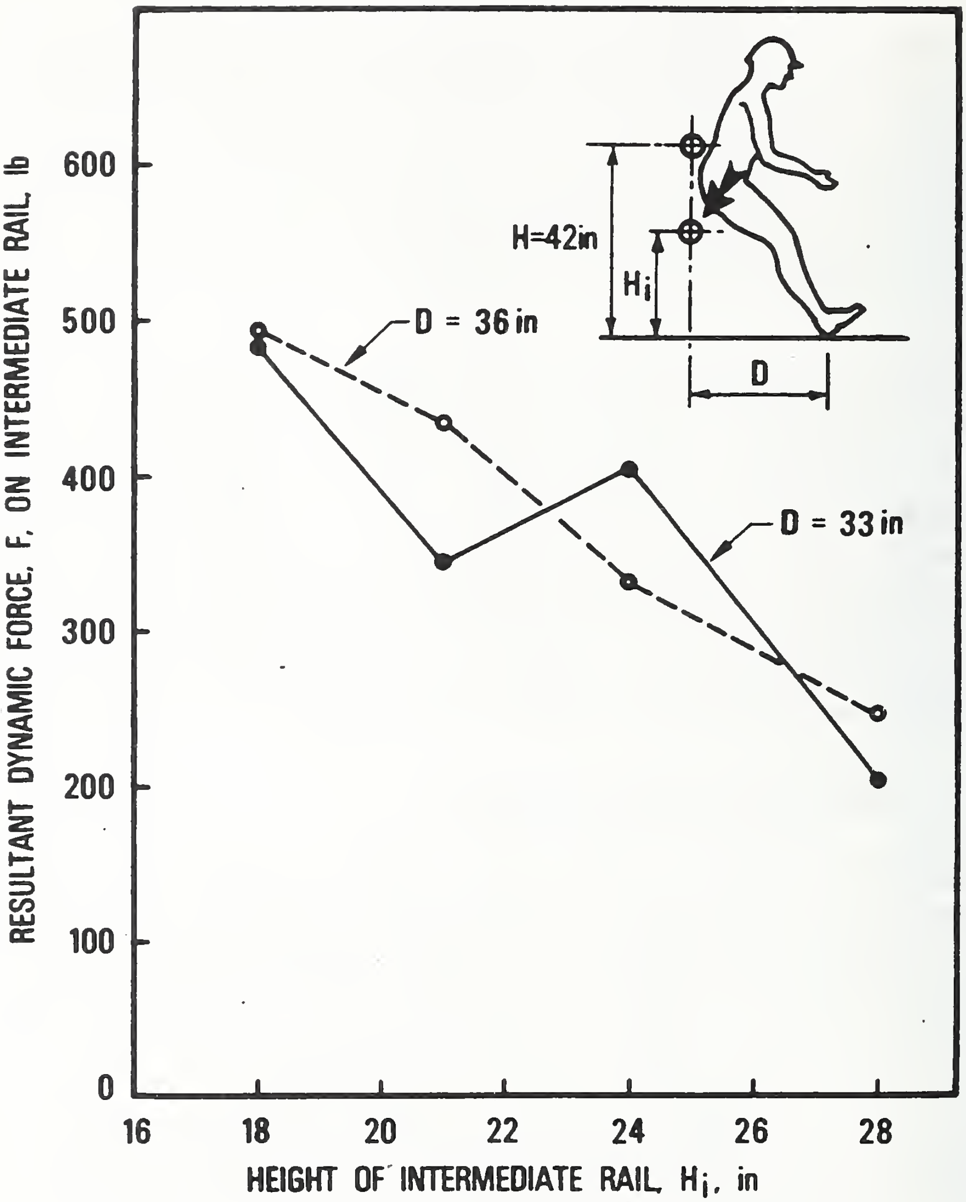


Figure 4.11 Resultant dynamic force on intermediate rail exerted by 95th percentile dummy vs. height of rail.

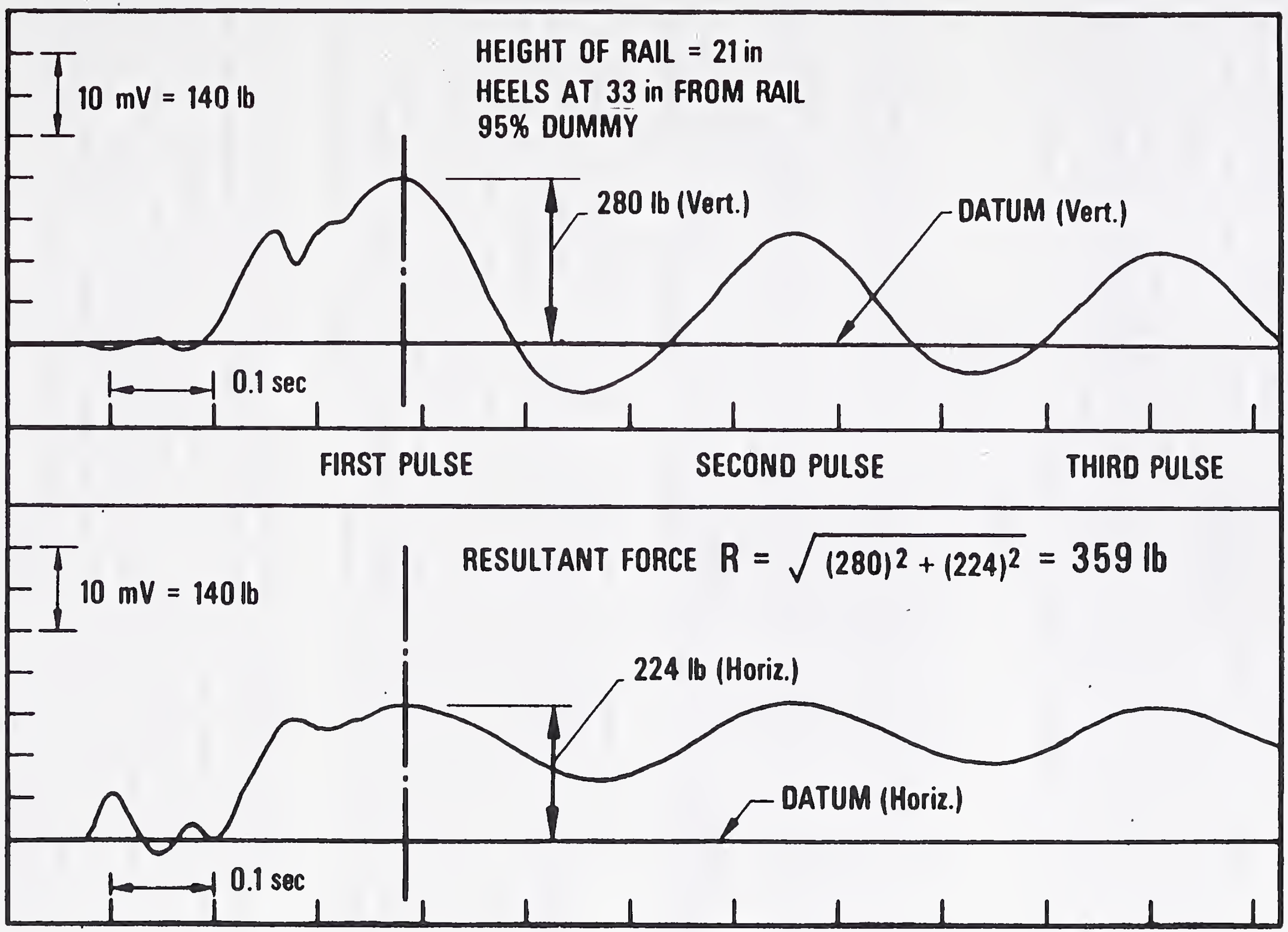


Figure 4.12 Time history of impact load on intermediate rail.

Criterion A.2.1 stipulates that in design, accidental load (A) is applicable at any point on the guardrail. The primary reason for prescribing the same concentrated load without any constraints on its point of application is that the maximum dynamic force on the intermediate rail (490.5 lb or 2182.7 N) and on the top rail (567 lb or 2523 N) are not appreciably different from a designer's point of view. It is further noted that the height of the intermediate rail of a two-rail system on posts, as governed by the maximum opening requirement stipulated in Criterion A.3.3, is not going to be appreciably different from the 18-in (45.7-cm) height for which the maximum impact loads occurred in the tests. In addition, the accident mode used in the intermediate rail tests may not necessarily be the most critical compared with other types of likely accidents involving direct impact of falling subjects against the midrail as opposed to the secondary impact used.

5. Summary

This report describes experimental investigations and the basis for a model performance standard for the design and evaluation of personnel guardrails used to protect employees against occupational hazards. It comprises the second phase of a two-phase research project conducted for the Occupational Safety and Health Administration. The first phase consisted of various studies on existing technical work and code provisions, a field survey, a compilation of relevant anthropometric data and an analysis of industrial accident statistics. These exploratory tasks are documented in a separate report to the sponsor: NBSIR 76-1132 [3].

The experimental work presented in appendix C was aimed at studying the critical aspects of guardrail safety to assist in the formulation of structural and non-structural design criteria for guardrail systems. The structural experiments included selective resistance tests of guardrail components and measurements of static and accidental impact loads induced on an instrumented mock-up rail by human subjects and an anthropomorphic dummy simulating the 95th percentile body characteristics of the adult U.S. male subject. The non-structural tests examined the safety aspects of guardrail height and/or width, and were aimed at establishing the essential geometry for the mitigation of the consequences of accidental falls.

The final objective of this study was the model performance standard for the design and evaluation of guardrails presented in appendix A. The recommendations contained therein are, for the most part based on the experimental work described in appendix C. Additionally, some of the criteria included in the standard were developed using the information acquired through the exploratory phase of the project as a guide. The recommendations of this standard are applicable to guardrails designed to protect employees during work-related activities; provisions for loads resulting from impact of power-driven objects or from flagrant abuse are precluded.

The main body of the report serves as the logical link between the appendices. It gives the rationale for the selection of the various accident modes simulated, interprets the individual test results and converts these data into implementable criteria. A significant finding in this research program was the order of magnitude of dynamic loads transmitted by subjects falling against the guardrail. Consequently the 300-lb (1335-N) maximum accidental load recommended represents a significant departure from the 200-lb (890-N) load specified in some existing guardrail provisions.

6. Acknowledgements

The contributions made by Drs. Robert A. Crist and Bruce R. Ellingwood in critically reviewing this report are gratefully acknowledged.

7. References

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APPENDIX A*

A MODEL PERFORMANCE STANDARD FOR GUARDRAILS

*Appendix A and Appendix B have been previously published in a separate report entitled: NBSIR 76-1131, "A Model Performance Standard for Guardrails" by S.G. Fattal, L.E. Cattaneo, G.E. Turner and S.N. Robinson, National Bureau of Standards, Washington, D.C. 20234.

A MODEL PERFORMANCE STANDARD FOR GUARDRAILS

Abstract

A model performance standard and design illustrations are presented for the design, construction and evaluation of guardrail systems, which will be used for the protection of employees against occupational hazards. The standard stipulates both structural and non-structural safety requirements. Each criterion includes a commentary section describing the rationale used in its formulation. This rationale is for the most part, based on independent experimental and analytical research investigations conducted at NBS in behalf of OSHA.

Key Words: Design; dynamic loads; guardrails; industrial accidents; non-structural safety; occupational hazards; performance standard; personnel railings; personnel safety; static loads; stiffness; structural safety.

Table of Contents

APPENDIX A

A Model Performance Standard for Guardrails

A.1 Introduction

This Standard documents recommendations for the design, construction and evaluation of guardrail systems which are installed for the purpose of protecting employees from occupational hazards during the conduct of their assigned tasks. The document makes no recommendations as to where or whether guardrails will be required, and is not applicable to situations where the guardrail may be exposed to forces resulting from the impact of power-driven objects or from flagrant abuse.

For the most part, these recommendations draw upon the results of tests and analytical investigations conducted at the National Bureau of Standards (NBS) in behalf of the Occupational Safety and Health Administration (OSHA) and documented in detail in the main body of the report. Where a specific recommendation is based on studies conducted elsewhere, the standard identifies the appropriate source in the bibliography * in Section A.5.

The performance approach usually permits the definition of a particular performance attribute without reference to the type of material or construction scheme employed. It is generally less restrictive than materials-oriented prescriptive standards with regard to the utilization of innovative products and design concepts. The terms "conventional" and "non-conventional" have been introduced to distinguish, when necessary, between traditional and innovative applications. Conventional systems or components are built with traditional construction materials (such as steel, aluminum, concrete, masonry and timber), which are deployed in the system in a manner that will constitute a conventional design and construction concept or application. Non-conventional systems or components consist of relatively untried materials or any other materials which are utilized in a manner that would constitute an innovative construction or design concept.

Unless otherwise noted, these recommendations apply to both conventional and non-conventional systems. Conventional systems should, in addition, comply with the appropriate design and construction requirements of the six nationally recognized standards [A.3 - A.8] adopted herein by reference. These standards were judged to have adequate provisions to permit the design of conventional guardrails without the need to prescribe supplementary requirements.

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*References are indicated by numbers in brackets.

A guardrail system is defined herein as a structural system which is designed and installed in a manner that will inhibit accidental passage of people or objects between the two adjoining regions it separates in the interest of improving the safety of the environment. Guardrails are distinguished from handrails in that handrails are normally installed for the purpose of assisting people in maintaining balance while in the act of walking, climbing and descending stairs, etc. However, in situations where handrails serve the function of guardrails, such as when located along the precipitous edge of a stairway or around elevated landings, they should also be designed as guardrails. This Standard includes provisions for the design of guardrails which are specifically called upon to support people or objects during the conduct of an activity. Additional design load requirements are specified for guardrails installed at or near areas where congested peak loading conditions are likely to be encountered in service.

Guardrail systems consist of elements, connections and anchorages. They encompass both temporary and permanent installation. Temporary guardrail systems are used in construction work. Permanent guardrail systems constitute a permanent part of a structure in service. Unless stated otherwise, the provisions of this standard apply to temporary as well as permanent guardrails.

The organization of this document is modeled after a fixed format consisting of Requirement, Criterion, Evaluation and Commentary ranked in that order. The Requirement is a qualitative statement of an expected performance attribute. It is a general statement of what the assembly should be able to do. The Criterion is a quantitative statement giving the level of performance necessary to meet the Requirement. In some cases, several Criteria are associated with each requirement. Evaluation sets forth the method(s) upon which an evaluative judgment of compliance with a Criterion can be based. It states the standards, contract documents, inspection methods, analysis and review procedures, or test methods which may be used in determining whether the system or system components comply with the Criterion. The Commentary provides background information for the reader and presents the rationale behind the Requirement, Criterion and Evaluation.

The Criteria in this standard are identified with one of two categories, namely, structural and non-structural. The structural Criteria specify the types of loads and load combinations to be considered in design, and resistance requirements with regard to strength, safety margins, stiffness properties and deformation tolerances in service. The non-structural Criteria pertain to the geometric configuration of guardrails as governed by the topography and physical characteristics of the surrounding environment and the relationships between perceptual and environmental factors.

A.2 Requirement - Structural safety

Guardrails and all components thereof shall be designed and constructed to support safely all loads anticipated in service.

A.2.1 Criterion - Basic loads

Design loads shall be derived from the following basic loads and their combinations:

(a) Dead load (D) shall consist of the actual weight of the materials incorporated in the construction and the weight of any appendage or attachment which becomes a permanent part of the guardrail system in service.

(b) Accidental load (A) shall consist of a concentrated force of 300 lb (1.335 kN) for tributary areas 36 in (91.5 cm) or greater in width, and 200 lb (0.890 kN) for tributary areas 24 in (61 cm) or less in width. For tributary areas between 24 in (61 cm) and 36 in (91.5 cm) in width, the concentrated force shall be determined by linear interpolation.

When combined with other basic loads in accordance with Criterion A.2.2, the point of application and direction of accidental load (A) shall be so determined as to produce the most critical configuration(s) for design.

For calculating local effects, the concentrated force representing accidental load (A) may be uniformly distributed over a 4-in (10.2-cm) length of a beam element or over a 16-in^2 (103.2-cm^2) square area of a plate element.

(c) Surge load (S) shall consist of a uniformly distributed load of 100 lb/ft (1.46 kN/m) applicable to the top of the guardrail at any inclination between and including horizontal and vertical.

(d) Live load (L) shall consist of any load for which the guardrail is anticipated to provide the means of structural support in service other than dead, accidental or surge load.

A.2.1.1 Evaluation

This Criterion will be evaluated by review of the contract documents (plans, specifications and structural calculations). The width of the tributary area will be measured horizontally as illustrated in figure A.2.

A.2.1.2 Commentary

This Criterion defines the nature and intensity of basic load types, combinations of which are specified for design. It is not the intent of this Criterion to include provisions for abnormal loads or loads resulting from flagrant abuse. Abnormal loads may be attributable to a rare but extreme event such as an explosion or impact by power-driven objects, while deliberate acts such as climbing or bouncing against the guardrail are construed as instances of flagrant abuse.

Unlike larger structures, the weight of the materials comprising the guardrail system will probably be small enough to be negligible in design. However, in some instances it could conceivably increase the calculated stresses by 10 per cent or more and the inclusion of dead load (D) in this Criterion is intended to serve as a reminder that it should not be routinely ignored or overlooked in design. Dead load should include the weight of any object which will become a permanent part of the guardrail in service. The weight of any temporary attachment should be treated as part of the live load (L).

Accidental load (A) represents a force transmitted by the accidental impact of human subjects or objects against guardrails. The 300-lb (1.335-kN) intensity is derived from the results of dynamic load tests using anthropomorphic dummies falling backward against an instrumented mock-up rail from a standing position. The height of the rail and the initial distance of the dummy from it were varied during the tests to measure the influence of these parameters on the magnitude of the impact load. It was observed, for instance, that the maximum load on the midrail was not substantially different from that obtained from top rail tests. This partly explains the rationale for prescribing the same concentrated load at locations other than the top of the guardrail as well. In addition, the Criterion recognizes the need to provide a minimum level of structural resistance against loads resulting from the accidental impact of rolling or sliding objects, or any equipment other than power-driven objects which may accidentally come in contact with the guardrail. It has been implicitly assumed that the magnitude of such loads would not be appreciably greater than those transmitted by accidental falls of human subjects.

The gradual reduction of the 300-lb (1335-N) force to 200 lb (890N) with the width of the tributary area varying from 36 in (91.5 cm) to 24 in (61 cm) is consistent with the experimentally observed force reduction for falls from an initial heel distance less than 30 in (76.2 cm). In this regard it is assumed that for a given width of tributary area, the maximum possible distance from which the subject can fall on the rail is about 6 in (15.3 cm) less than the width of that area.

No constraints are placed as to the direction of load (A) other than those which can be definitely eliminated by virtue of special characteristics of the environment. For instance, a guardrail without openings, installed to prevent accidental movement from area one into area two, will be subjected to accidental loads from one side only. Where guardrail openings are large enough to permit accidental wedging of humans or objects, forces of unknown intensity will be induced, and thus prudent design practice would select components to have a minimum level of resistance (usually 40 percent of maximum design resistance) in the weakest plane.

Provision A.2.1 (b) makes an allowance for the capacity of the human body to distribute the impact force over a finite length or area which, according to test observations, generally exceeds the specified values when the impact force is in the neighborhood of 300 lb (1.335 kN) or greater. This information is utilized in design to check sectional adequacy (i.e., shear crippling, bearing capacity, local stability etc.) in the vicinity of the applied force.

The provision for surge load (S) recognizes the need to mitigate structural failures under the action of a group of people pushing against the guardrail. Conditions for surge loading could develop as a result of a large number of people simultaneously seeking passage through an exitway or gangway. The 100-lb/ft (1.46-kN/m) uniform load intensity is based on experiments involving measurements of loads transmitted by a group of human subjects, three deep, pushing against an instrumented mock-up guardrail. The mean weight of the subjects selected for this experiment was approximately representative of the weight of the 50 percentile adult male population of the United States.

Live load (L) accounts for a wide variety of imposed loads which the guardrail may be called upon to resist during its service life other than those resulting from surge (S) or accidental impact (A). It is neither feasible nor necessary to identify precisely all the possible loads belonging to this category within the scope of this Criterion. It is possible, however, to identify a given live load with one of two categories: The first category includes all live loads associated with a specific use or activity for which the guardrail must provide structural support in service. In some cases, the intended structural function of the guardrail includes providing the means of support for workers and/or equipment during the routine conduct of work-related tasks. Specific instances are guardrails used as a bench, or as a lifeline, or for the support of workers and equipment in a tree-spraying operation. The second category includes all live loads which might be anticipated to occur in service as a result of human-environmental factors (other than flagrant abuse) which may generally be construed as guardrail misuse. The source of such imposed loads may not be readily obvious at the design stage. For instance, a guardrail may be exposed to a crowd leaning over it to watch an interesting event several stories below, or it may receive loads from people sitting on a nearby bench and leaning on it. Likewise, a midrail may invite several people to prop a foot or sit on it. Nevertheless, in most instances it is possible for the designer to identify the nature of such imposed loads through consideration of the relevant human and environmental factors inherent to the specific installation. Guidance on the intensities of certain types of imposed loads may be obtained from the experimental results presented in sections 4.3 and 4.4 of this report.

This Criterion does not advocate the explicit treatment of wind load as a basic load in guardrail design for a number of reasons. It is noted that both accidental load (A) and surge load (S) are peak loads of very short duration and are not likely to occur frequently in service. The probability of wind occurring at the same time and acting in the same direction as one of these loads is so low that it may be disregarded justifiably in design. Furthermore, the combination of wind and dead load alone is not likely to be more critical than the design loads prescribed in Criterion A.2.2, nor are the potential consequences of failure (i.e., risk of injury to workers) under such a combination likely to be as severe as those resulting from failures under the design loads specified by Criterion A.2.2. Nonetheless, it is not the intent of this Criterion to rule out consideration of wind effects in design under unusual circumstances. To cite an example, it is conceivable that a group of people leaning over a guardrail at the edge of an elevated exterior platform may experience and transmit signficant wind forces to the guardrail. Such wind-induced forces can be given consideration in design by treating them as part of the basic live load (L) defined in this Criterion. The designer may use engineering judgment to select wind pressures consistent with the type and duration of the anticipated live load. Usually checking for wind in regions experiencing 10-psf (479-N/m^2) or greater wind pressure is a good engineering design practice. In most instances, the wind load provisions of ANSI A58.1[A.1] used in conjunction with the 2-year wind map in reference [A.2] would probably be adequate.

A.2.2 Criterion - Design loads

The following basic load combinations shall be considered in the analysis and design of guardrail systems. These basic loads shall exclude all loads resulting from power-driven objects or from flagrant abuse.

(a) All guardrails shall be designed for load combination U defined by the following relationship:

$$U = c_1D + c_2A$$

where D and A are basic loads defined under Criterion A.2.1 and the subscripted letters are load factors specified as follows:

(1) For conventional systems designed in accordance with the working stress (or allowable stress) concept, $c_1 = c_2 = 1.0$.

(2) For conventional systems designed in accordance with the ultimate strength concept, c_1 and c_2 shall be the load factors specified by the applicable code or standard for the load combination U herein defined. The applicable codes and standards are specified in Criterion A.2.3 (a).

(3) For non-conventional systems, $c_1 = 1.4$, $c_2 = 1.7$.

(b) Guardrails installed at or near exitways serving the function of providing the safe and only means of discharge or egress of a tributary population equal to or in excess of 50 persons, shall be designed for the following load combination.

$$U = c_1D + c_2S$$

where D and S are basic loads defined under Criterion A.2.1 and load factors c_1 and c_2 are as specified in Criterion A.2.2(a).

(c) Guardrails used as the means of support of workers and/or objects during the conduct of a work task or any other activity not construed as flagrant abuse shall be designed for the following load combination

$$U = c_1D + c_2L$$

where D and L are basic loads defined in Criterion A.2.1 and load factors c_1 and c_2 are as specified in Criterion A.2.2(a). Live load L need not include loads resulting from misuse if the guardrail is designed to meet Criterion A.3.7.

A.2.2.1 Evaluation

This Criterion will be evaluated by examination and review of the contract documents.

A.2.2.2 Commentary

Criterion A.2.2 states design load requirements for guardrails. Requirement A.2.2(a) applies to the design of all guardrails while requirements A.2.2(b) and A.2.2(c) apply to guardrails subjected to surge and live loads, respectively.

Most guardrails will probably need only be designed for load combination A.2.2(a). In the interest of clarity, it should be noted that guardrails required to be designed for more than one loading combination should simultaneously satisfy the design requirements for each loading combination applied independently.

For conventional systems, load factors, c_1 and c_2 are introduced to arrive at design loads which would be consistent with the design approach used by the applicable code or standard. For instance, components designed in accordance with the allowable stress approach would be proportioned to resist the applicable design load of Criterion A.2.2, with the load factors equal to unity, without developing a maximum stress in excess of the allowable stress prescribed by the governing code or standard. On the other hand, a reinforced concrete element which is designed according to the ultimate strength approach prescribed by the ACI Code [A.5] would be proportioned to have a load-carrying capacity (specified by that Code) equal to or greater than the factored total load on the element specified in Criterion A.2.2, with the load factors $c_1 = 1.4$ and $c_2 = 1.7$ (also specified by that Code).

The Criterion requires that all non-conventional systems be designed by the ultimate strength concept. Accordingly, A.2.2(a)(3) prescribes the magnitudes of the load factors to be used in design. The specified dead and live load factors are consistent with those used in conventional design.

It should be noted that Criterion A.2.2(c) does not require consideration of loads resulting from misuse as part of live load(L) if criterion A.3.7 is complied with.

A.2.3 Criterion - Structural resistance

The design load resistance R of the system or any components thereof shall exceed the appropriate design load stipulated in Criterion A.2.2, or

$$R > U$$

where U is the design load specified by Criterion A.2.2.

(a) For conventional guardrail systems, the design load resistance R shall be determined in accordance with the applicable provisions of the latest editions of the following codes and standards:

(1) Steel: Manual of Steel Construction, American Institute of Steel Construction [A.3].

(2) Aluminum: Aluminum Construction Manual, Specifications for Aluminum Structures. the Aluminum Association [A.4].

(3) Concrete: ACI Standard 318-71, Building Code Requirements for Reinforced Concrete, American Concrete Institute [A.5].

(4) Masonry: Building Code Requirements for Masonry, ANSI A41.1 [A.6] and Building Code Requirements for Reinforced Masonry, ANSI A41.2 [A.7].

(5) Lumber: National Design Specification for Stress-Grade Lumber and Its Fastenings, National Forest Products Association [A.8].

(b) For non-conventional guardrail systems, the design load resistance R shall be derived from the mean load capacity R_m as follows:

$$R = fR_m c_u$$

where:

f = variability factor which should be such that approximately 95 percent of the system as a whole, or any component thereof, shall exceed fR_m in resistance. If this resistance has a normal probability distribution, $f = 1-1.65v$.

v = coefficient of variation of resistance with respect to R_m.

c_u = coefficient for ductility = $(u + 7)/12$, but not more than 1.0

u = minimum ductility factor under the appropriate design loading condition U defined in Criterion A.2.2.

A.2.3.1 Evaluation

For conventional systems, design compliance will be evaluated by review of contract documents. Construction compliance will be evaluated by field inspection and comparison of construction with the plans and specifications of the contract documents.

When adequate existing test data on the various material properties comprising the non-conventional system and system components are available, evaluation shall be performed using engineering analysis. When adequate test data is unavailable, system components and subsystems shall be evaluated in the laboratory using simulated static load levels consistent with the load combinations specified in Criterion A.2.2.

The ductility factor shall be evaluated as follows: For an ideal elastoplastic (elastic-perfectly plastic) resistance function (plot of applied load as ordinate and deflection as abscissa), the ductility factor is defined as the ratio of ultimate deflection to yield deflection ($u = d_u / d_{ye}$). For a linear resistance function to failure (brittle behavior), the ductility factor is 1.0. For an actual (nonlinear) load-deflection function, the ductility factor shall be computed from an "effective" function consisting of two straight lines (Figure A.1). The first line is drawn through the origin and a point on the actual function at which the resistance is 60 percent of its maximum load value (P_u). The second line is a horizontal line ending at the ultimate deflection (d_u), which is the abscissa of a point on the descending portion of the resistance function with the corresponding ordinate equal to 95 percent of the maximum load value. The horizontal line is located so that the area under the two lines forming the effective function is equal to the area under the actual function up to the point of ultimate deflection. Effective yield deflection (d_{ye}) is taken as the deflection at the point of intersection of the two lines, which is at a resistance level termed "effective yield resistance." The ductility factor is based on the effective resistance function: $u = d_u/d_{ye}$ [A.9].

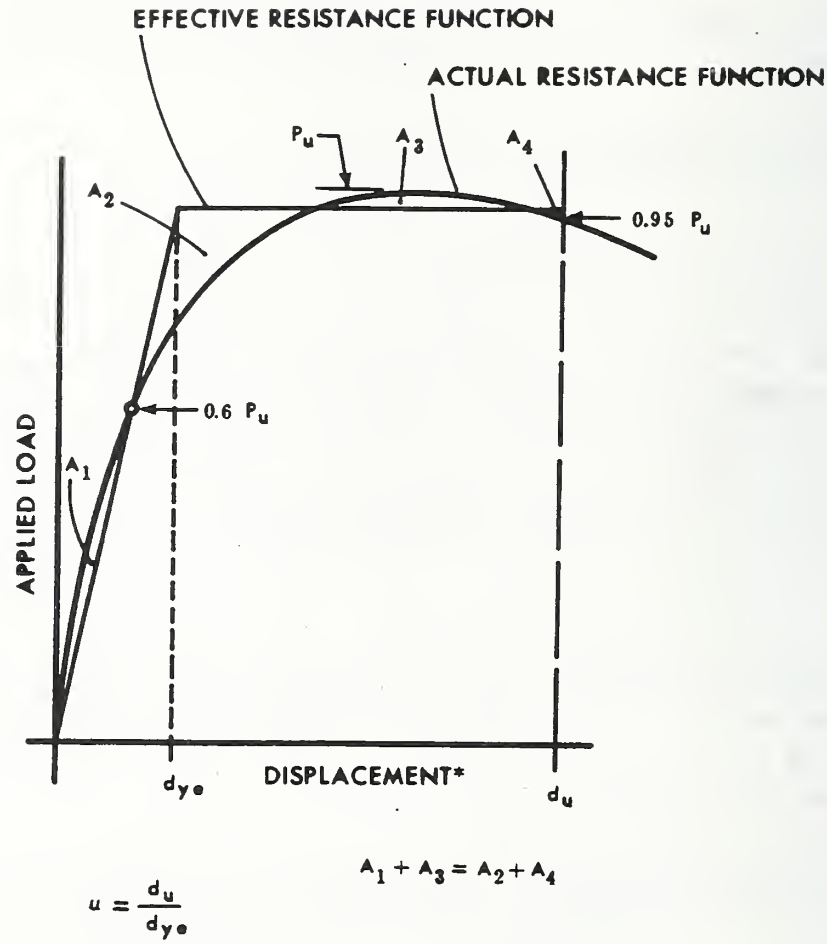
A.2.3.2 Commentary

The intent of Criterion A.2.3(a) is to require, to the extent possible, design and construction compliance with the provisions of nationally recognized codes and standards. Accordingly, Criterion A.2.3(a) gives a specific list of voluntary consensus standards which are judged to be applicable to conventional guardrail systems. The requirements of these standards should be used in conjunction with the design loads stipulated in Criterion A.2.2 and with the provisions of all the other criteria applicable to conventional systems. As a general guide, guardrail systems using structural steel, aluminum, timber, reinforced concrete or masonry do not need overall margins of safety greater than those found in structures designed in accordance with the design standards listed under Criterion A.2.3(a).

The intent of Criterion A.2.3(b), along with Criterion A.2.2, is to provide a minimum level of structural safety against situations which might be anticipated to occur during the service life of the system. The safety margin reflects possible sources of deficiencies such as variations in loading and resistance, as well as assumptions and simplifications made in analysis and design.

The load capacity is reduced from the mean strength value R_m using variability factor f to insure that approximately 95 percent of all systems or components thereof will have at least the required load capacity. The reduction provides for the combined effect of variability in material strength, workmanship, dimensions and quality control.

For relatively untried materials and construction concepts, a reasonable allowance must be made for lack of experience relative to structural response and for variability in material strength. It should be recognized that certain structural materials require a greater margin of safety than others because of either the more critical nature of failure or the greater variability in their strength.



(* Distortional displacement at and in the direction of applied load)

Figure A.1 Determination of the Ductility-Factor

Ductility as well as strength is vital to safety. Adequate ductility allows energy absorption under extreme dynamic or pulse loads, permits redistribution of local concentrations of force from fabrication errors, lack of construction fit or local loadings, and by perceptible inelastic deformations warns users of overloads before load capacity is lost. The coefficient for ductility $c_u = (u + 7)/12$ imposes an extra margin of strength for brittle materials, and becomes 1 at $u = 5$, which is considered representative of ductile structural systems.

A.2.4 Criterion - Foundations

Foundations shall provide the means for attachment of guardrail systems and shall be designed to safely transmit guardrail loads to the supporting structure.

A.2.4.1 Evaluation

The adequacy of the foundation will be determined by inspection and review of contract documents of the supporting structure including details of anchoring devices used for attachment of guardrail to the structure.

A.2.4.2 Commentary

This Criterion provides for the safe support of the guardrail system by the part of the structure to which it is attached. Foundation failures might affect the stability of the entire guardrail system and therefore can be potentially more hazardous in nature than the failure of a single element or connection. A case in point is the premature failures observed in concrete skirts supporting peripheral guardrails at elevated stairway landings attributable to several factors such as insufficient edge distance, shallow embedment of posts and anchors or inadequate reinforcement. The intent of the criterion is to design the supporting foundation to be at least as safe as the guardrail system and thereby reasonably assure against premature failures.

This Criterion also addresses a frequent problem which arises from the inability, on the part of the contractor, to attach guardrails to an otherwise adequate foundation to retrofit sections of a completed structure without exposing his employees to additional risk. This situation is encountered most commonly during the installation of temporary guardrails needed for construction or repair work and there have been instances where the potential risk of accident associated with the erection and removal of such guardrails could not be construed to be less than the risk of accidents attributable to the absence of a guardrail. This criterion therefore stipulates that foundations should be designed and constructed in a manner that would provide a practical and expedient means for the subsequent attachment of guardrails where required by law.

A.2.5 Criterion - Displacement control

Non-conventional systems shall comply with this Criterion. Conventional systems are deemed to satisfy this Criterion.

(a) With the full dead load 1.0D in place, the maximum displacement of any point on the guardrail due to the applied load of 1.5A sustained for one hour, shall not exceed 4 in (10.16 cm).

(b) With the full dead load 1.0D in place, the maximum vertical sag of any flexurally non-rigid element as installed shall not exceed 2 in (5.08 cm).

A.2.5.1 Evaluation

Criterion A.2.5 (a) will be evaluated by the physical simulation and laboratory testing of a suitable component or assembly of the system and/or by analysis based on performance data or available test data.

Criterion A.2.5 (b) will be evaluated in the field. The sag is the vertical distance between an imaginary straight line joining the two support points and the lowest point on the element.

A.2.5.2 Commentary

This Criterion introduces displacement limitations deemed necessary to reduce the likelihood of accidental passage of human subject and/or objects over or through the guardrail. Flexible cables such as wire rope will probably need to be maintained under a minimum level of tension in order to comply with Criterion A.2.5 (a). On the other hand, a certain amount of permanent sag may be tolerated in the case of chains which are quite stiff axially once they become taut. It should be noted that any element having the 2-in sag allowed by Criterion A.2.5 (b) will need to have a relatively high axial stiffness in order to meet the displacement limitation of Criterion A.2.5 (a) because the displacement attributable to sag will reduce the permissible displacement due to structural deformation. Additionally, Criterion A.2.5 inhibits the use of non-conventional products exhibiting excessively high creep deformations or low modulus of elasticity which makes them unsuitable for structural applications.

A.2.6 Criterion - Durability and maintenance

(a) Guardrails exposed to the exterior environment or to chemicals and other corrosive agents and conditions shall be adequately treated to resist the effect of such agents in service.

(b) Guardrails shall be periodically inspected for evidence of excessive wear, damage or understrength. Any element, connection or anchorage exhibiting 20 percent or more degradation in strength and/or stiffness shall be replaced or restored to its initial condition.

A.2.6.1 Evaluation

Durability characteristics and required maintenance will be determined by field inspection and/or testing and engineering analysis. Loss of stiffness can be evaluated in the field by measuring the deflection produced under a given load and comparing it with the deflection of new replicates tested in the laboratory, or, if sufficient test data are available, deflections from field tests may be compared with calculated deflections based on known material properties.

In the absence of an adequate field test method to measure strength degradation, it may be assumed that loss of strength is proportional to loss of stiffness.

A.2.6.2 Commentary

The intent of this Criterion is to insure that a minimum level of structural integrity is maintained during service. In many instances it is possible to identify damage such as dents, cuts, splits, bends, rust, abrasions, etc., by means of visual inspection. Slight shaking of the rail with the hand may reveal slack in the system and help identify loose connections or anchorages.

A.3 Requirement - Non-structural safety

A guardrail system separating two adjoining regions shall prevent and control the accidental passage of workers and objects from one region into the other.

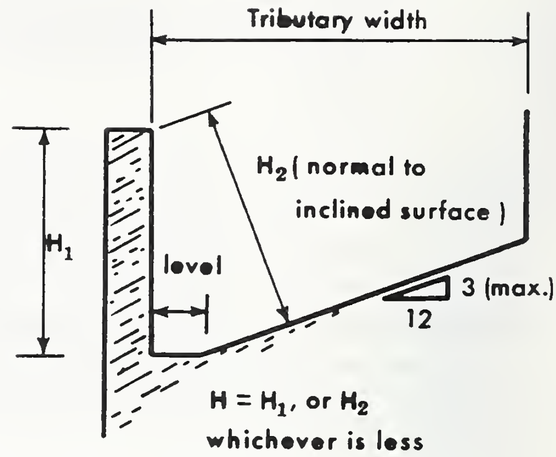
A.3.1 Criterion - Height of guardrail

Except as permitted by Criterion A.3.2, the minimum height H of the guardrail system relative to the adjacent floor or walking surface shall be 42 in (106.68 cm) except if the top rail is flexurally non-rigid H shall be 44 in (111.76 cm).

A.3.1.1 Evaluation

Height H will be measured within a tolerance of 1 in (2.54 cm) in the direction normal to the adjacent floor or walking surface as defined in figure A.2. Where any object large enough to be stood over is located on the floor adjacent to the guardrail, or where a layer of debris has accumulated on the floor adjacent to the guardrail, the effective height H will be measured relative to the top of such object or layer.

Note: Definition of tributary width applies to Criterion A.2.1 (b)



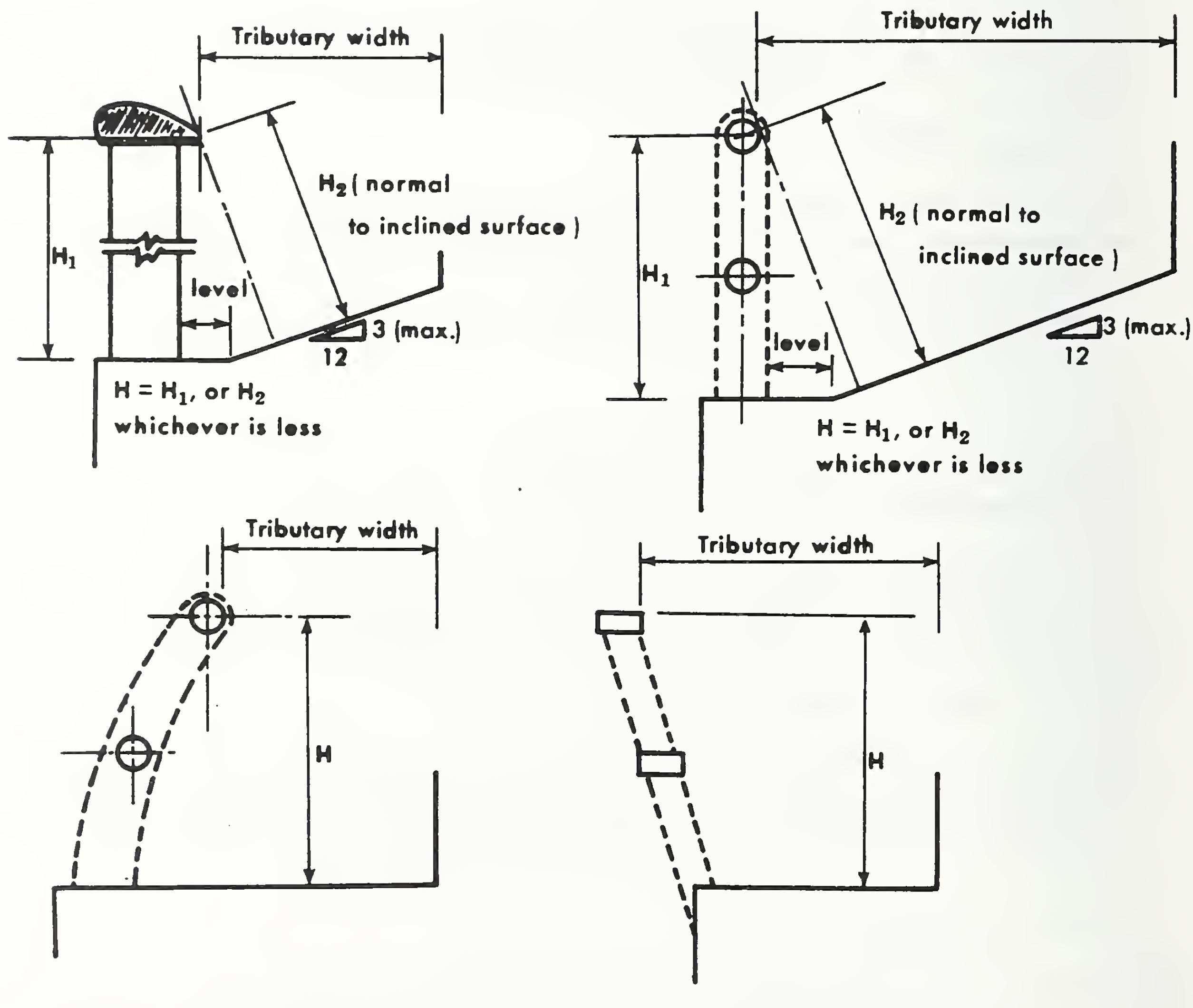


Figure A.2 Definition of guardrail height H

A.3.1.2 Commentary

The rationale for the height requirement is to inhibit accidental passage of the human body over the guardrail. The prescribed height of the guardrail system is set approximately equal to the height of the centroid of the 95 percentile composite adult male population in the United States [A.10]. The centroidal height of the subject is measured with the subject in a straight posture standing on a level surface. Tests using anthropomorphic dummies and mock-up guardrails have indicated that the chances of the dummy going over the guardrail increase rapidly when the top rail is positioned at heights lower than the centroid of the dummy. These tests involved simulation of various postures of human subjects leaning against the guardrail as well as human subjects moving at normal or brisk walking speeds and squarely impacting against the guardrail.

The increased height prescribed for flexurally non-rigid top rails such as tensioned cables or draped chains recognizes the need to compensate for height loss due to generally larger displacement of these elements relative to other top rails under the same anticipated service loads .

The 1-in tolerance specified under section A.3.1.1 is considered necessary to allow for the possible deviation from the prescribed 42-in height that may be anticipated to occur as a result of materials imperfections, settlements, creep, warping and miscellaneous other aging effects.

A.3.2 Criterion - Height in Relation to Width

The height requirement stipulated in Criterion A.3.1 may be relaxed under the following conditions:

(a) If the top surface of the guardrail is horizontal and has a width greater than 6 in (15.24 cm), and the floor surface of the interior adjoining region is level, the minimum height H of the guardrail shall be not less than,

$$H = K_1 - B$$

where B is the minimum width of the top surface of the guardrail and K_1 is 48 in (121.92 cm). However, in no case shall the minimum height be less than 30 in (76.2 cm).

(b) If, in addition to the conditions stipulated in (a) above, the projection of any part of the human body beyond the exterior edge of the top surface of the guardrail brings it in contact with a hazardous substance, the minimum width B of the top surface of the guardrail shall be not less than

$$B = K_2 - 2C$$

where C is the vertical distance of the boundary of the hazardous region below the exterior edge of the top surface of the guardrail and K_2 is 36 in (91.44 cm). However, in no case shall the minimum width be less than 24 in (60.96 cm).

A.3.2.1 Evaluation

Compliance will be determined by measurements and inspection in the field after installation. Height H and width B will be evaluated within a tolerance of 1 in (2.54 cm).

A.3.2.2 Commentary

The minimum height of 30 in (76.2 cm) is 9 in (22.86 cm) above the kneecap height of the 95 percentile adult male subject in the United States, measured from the floor where the subject is in straight standing posture on level surface. The 9-in (22.86 cm) distance permits the human subject to exercise leverage, assuming adequate ground friction, against overturning following his accidental backing onto the guardrail. In addition, tests have indicated that, at a guardrail height of 30 in (76.2 cm), the 95 percentile human male subject does not gain reach advantage when he assumes a climbing posture (with one foot on the floor and the other on top of the rail) as opposed to his reach when both his feet are on the floor.

The equation prescribed in Criterion A.3.2 (a) is based on 95 percentile dummy tests which indicate that a height less than 30 in (76.2 cm) increases the likelihood of total passage to the other side of the guardrail following an accidental fall. The minimum width of 24 in (60.96 cm) stipulated in Criterion A.3.2 (b) is likewise based on the same tests using the 95 percentile dummy.

A.3.3 Criterion - Size of openings

Any opening in the guardrail system shall reject passage of a spherical object 19 in (48.3 cm) and greater in diameter.

A.3.3.1 Evaluation

This Criterion will be evaluated by field measurement after installation using a 19-in (48.3-cm) spherical object. In the case of flexurally non-rigid elements with sag, the object should be forced only to the extent needed to take up the slack or to make such elements taut but without stretching them.

A.3.3.2 Commentary

The rationale for this criterion is to inhibit accidental passage of the human body through guardrail openings. The dimension given for the spherical object is slightly more than the shoulder width of the 50 percentile U.S. adult male population [A.10]. In this regard, it is noted that the chest depth for the 5 percentile U.S. male (which is less than the corresponding size of the 5 percentile U.S. female) is approximately 8 in (20.3 cm). Therefore, it is implicitly assumed that the subject will be capable of grabbing the guardrail or wedging himself by some other means and prevent his complete passage to the exterior after such passage is accidentally initiated.

A.3.4 Criterion - Passage of objects near the floor

Guardrails shall reject the passage of spherical objects 0.5 in (1.27 cm) and greater in diameter, up to a height of 5 in (12.7 cm) from the adjacent floor surface. This Criterion may be waived if it can be satisfactorily established that no risk of injury to personnel arises as a result of said waiver.

A.3.4.1 Evaluation

This Criterion will be evaluated by field inspection after installation. The 5-in (12.7-cm) height will be measured normal to the adjacent floor surface in a manner similar to measurement of guardrail height (refer to figure A.2).

A.3.4.2 Commentary

The rationale for this criterion is to prevent the shod foot, hand tools and miscellaneous small debris from falling, sliding or rolling under the guardrail. The 5-in (12.7-cm) minimum height dimension is approximately based on the ankle pivot height of the 95 percentile U.S. male wearing heavy winter footwear [A.10]. It is assumed that this height will be sufficient to prevent passage of hand tools and debris.

The specified waiver is predicated on the condition that no risk of injury to employees exists on either side of the guarded area by virtue of such omission. It is recommended that compliance with this criterion be required for all inclined work surfaces protected by gaurdrails installed on the downhill side, to provide an obstacle against, and thereby inhibit, accidental slippage of subjects under the guardrail. It is likewise recommended that compliance with this criterion be required in all cases where the risk of injury to employees exists as a result of loose objects accidentally leaving the guarded area.

A.3.5 Criterion - Smoothness of surfaces

The surfaces and edges of guardrail systems shall be smooth and void of characteristics that can capture clothing or cause cuts, snags, abrasions, or other injuries to the hands and other parts of the body as a person cames in contact with the guardrail while standing or conducting a work activity next to it.

A.3.5.1 Evaluation

Inspection and/or field testing after installation. Field testing will be conducted using one layer of a wet, commercially available chamois skin wrapped around a gloved hand. The chamois skin will be run along surfaces or edges exposed to body contact and observed for substantial cuts, tears, punctures or other major destruction to the surface. Any evidence of such destruction may be interpreted as failure of compliance with this Criterion.

A.3.5.2 Commentary

The intent of this Criterion is to reduce the potential risk of injury resulting from contact with rough surfaces. To satisfy this Criterion, surfaces should be void of sharp projections (screws, nails, threaded ends of bolts), substantial delaminations having sharp edges or points (cracked wood or metal skins), etc.

Although the field test suggested is rather crude (see reference [A.11] for additional information), it may be used together with visual inspection to provide an indication of relative roughness of surfaces. This test may be rendered more effective by specifying standards for the materials used (chamois skin and glove), the applied force, the contact area and the speed of the movement. For better control, a standard padded object may be used in lieu of the gloved hand.

A.3.6 Criterion - Visibility

The color or intensity of the guardrail system or the minimum dimension of any guardrail element shall be such that it can be readily seen at any distance from the guardrail up to 25 ft (762 cm) away.

A.3.6.1 Evaluation

This Criterion will be evaluated by analysis or by field inspection if deemed necessary. The minimum required dimension of any guardrail component will be determined according to the viewing distance formula [A.12, A.13]

$$t = 0.0025\ d_v$$

where t is the minimum dimension of the guardrail component and d_v is the viewing distance.

Field inspection will be conducted during the period when employees are on duty and under adverse environmental conditions (i.e., early morning or late afternoon, overcast skies, time of the year with short daylight, etc.).

A.3.6.2 Commentary

The intent of this Criterion is to provide for early visual perception of the guardrail and guardrail components (particularly the top rail) by prescribing a safe viewing distance. A commonly accepted value for human reaction time is 3/4 second (driver's handbooks, U.S. Bureau of Public Roads tests on average stopping distance of cars, etc.). The 25-ft (762 cm) distance includes a reaction distance of approximately 10 ft (304.8 cm) and an assumed stopping distance of 7 ft (213.36 cm) for a person running at a speed of 10 mph (16.1 km/hr). This allows him to stop 8 ft (243.84 cm) short of the guardrail.

The minimum dimension of guardrail components will probably be greater than 0.75 in (1.905 cm) when determined by the viewing distance formula in section A.3.7.1, with the exception of wire rope which might have a diameter less than 0.75 in (1.905 cm) as determined by structural design requirements. In the latter case, this Criterion can be met by attachment of signs of the appropriate size and at such intervals along the element that will make them visible from anywhere within the 25 ft (762 cm) viewing region.

In instances where the visually handicapped are required to come in contact with the guardrail, or in situations where the task being performed would prevent seeing the guardrail prior to contact with it, acoustic, tactile, and/or other cues should be provided.

A.3.7 Criterion - Warning signs

Warning signs stating that the guardrail is not to be sat on, stood on, used as a tool, or otherwise misused shall be applied to the guardrail in locations along its length where it is first encountered and at regular intervals elsewhere, and shall be legible at a viewing distance of 10 ft (305 cm). Guardrails designed to support all loads stipulated in Criterion A.2.2(c) including live loads attributable to misuse need not comply with this Criterion.

A.3.7.1 Evaluation

This Criterion will be evaluated by analysis using the viewing distance formula given in section A.3.6.1, and, if deemed necessary, by field inspection as specified under section A.3.6.1.

A.3.7.2 Commentary

This criterion attempts to eliminate, or at least limit, those loading situations for which the guardrail was not designed.

A.4 Definitions

Anchorage - component of guardrail used for securing guardrail system to a foundation.

Basic Loads - types of loads and their intensities in terms of which design loads are specified.

Component - unit used in assembly of guardrail system.

Connection - component of guardrail system used for attachment of guardrail elements.

Design Loads - specified combinations of basic loads used in the design of guardrail systems and their foundations.

Element - component or structural unit of guardrail system other than connection or anchorage.

Foundation - component of a structure providing support to guardrail system.

Guardrail - same as "Guardrail System."

Guardrail System - structural system serving the function of impeding accidental or inadvertant passage of humans and objects between two adjoining areas it separates.

Midrail - longitudinal element located at intermediate level between top of guardrail and floor.

Structural Systems - assembly of components serving a structural function.

Subsystem - assembly of portion of guardrail system consisting of more than one element and one or more connections and/or anchorages.

System - assembly of components serving a specified function. Same as "guardrail system" unless specified otherwise.

Toprail - longitudinal element located at top of guardrail.

Tread Surface - working surface adjacent to guardrail.

A.5 References in Model Performance Standard

A.1 Building Code Requirements for Minimum Design Loads in Buildings and Other Structures, ANSI A58.1-1972, American National Standards Institute, New York, New York, 1972.

A.2 Thom, H.C.S., New Distributions of Extreme Winds in the United States, Proceedings, Journal of the Structural Division, American Society of Civil Engineers, New York, New York, July, 1968.

A.3 Manual of Steel Construction, American Institute of Steel Construction, Inc., 101 Park Avenue, New York, New York 10017, 1973.

A.4 Aluminum Construction Manual, Specifications for Aluminum Structures, The Aluminum Association, 420 Lexington Avenue, New York, New York 10017, November, 1967.

A.5 Building Code Requirements for Reinforced Concrete, ACI 318-71, American Concrete Institute, Detroit, Michigan, 1971.

A.6 Building Code Requirements for Masonry, ANSI A41.1-1953 American National Standards Institute, New York, New York, 1970.

A.7 Building Code Requirements for Reinforced Masonry, ANSI A41.2-1960, American National Standards Institute, New York, New York, 1970.

A.8 National Design Specification for Stress-Grade Lumber and Its Fastenings, National Forest Products Association, Washington, D.C., 1973.

A.9 Newmark, N.M., and Hall, W.J., Procedures and Criteria for Earthquake Resistant Design, Workshop Proceedings on Building Practices for Disaster Mitigation, Wright, R., Kramer, S., and Culver, C., Editors, BSS-46, Building Science Series, National Bureau of Standards, Washington, D.C., February, 1973.

A.10 Diffrient, Niels, Tilley, Alvin R., and Bardagjy, Joan C., Humanscale 1/2/3, the MIT Press, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1974.

A.11 Synthetic Skins for Automotive Testing, SAE J202, SAE Handbook, Vol. II, Society of Automotive Engineers, Inc., 1975.

A.12 Woodson, Wesley E., and Conover, Donald N., Human Engineering Guide for Equipment Designers, Second Edition, University of California Press, Berkeley, California, 1973.

A.13 Safety Color Code for Marking Physical Hazards, ANSI Z53.1-1971, American National Standards Institute, New York, New York, 1971.

APPENDIX B

EXAMPLE DESIGNS OF GUARDRAILS

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APPENDIX B

Example Designs of Guardrails

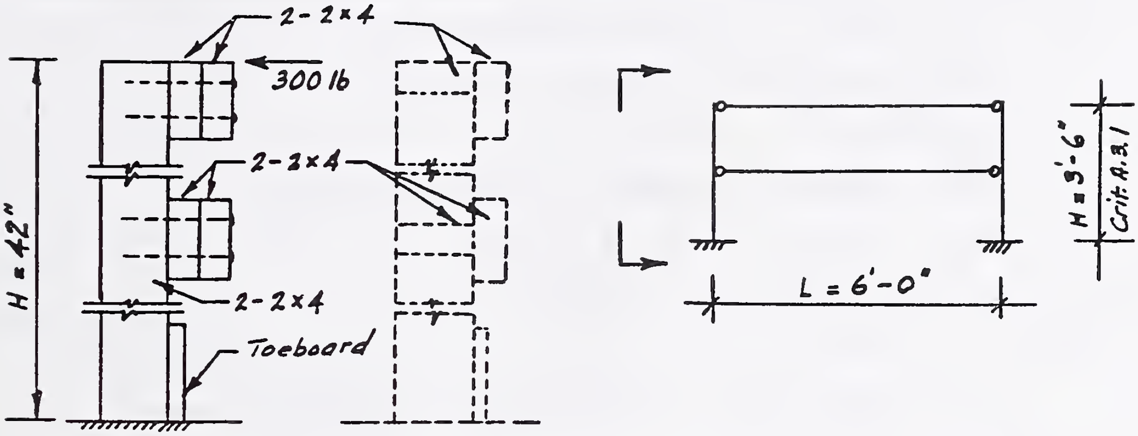
Introduction

This appendix presents numerical illustrations of standard design conforming with provisions of the foregoing Criteria. Included are designs of guardrails consisting of (a) nominal 2 x 4 wood sections (figure B.1), (b) aluminum pipe sections (figure B.2), and (c) single standard size steel angles (figure B.3).

The standard guardrail used in these illustrations consists of a top rail, intermediate rail and two posts anchored to the floor but not built continuous with the rails. This configuration produces conservative designs since no advantage is taken of the continuities between adjoining spans of systems with more than two posts. In each of the examples, the members are proportioned using the 300-lb (1335-N) concentrated accidental load (A) specified in Criterion A.2.1 for tributary areas equal to or greater than 36 in (91.4 cm) in width. The direction of this load is governed by the most critical stress condition it produces in the individual elements. The maximum deflections under a load of 1.5A are calculated and compared with the values stipulated in Criterion A.2.5.

The use of section standardization throughout a particular type of guardrail installation is usually governed by economic considerations and local availability of common stock items. The sizes used in these examples have been selected arbitrarily and therefore, are not necessarily those most readily available.

Wood Guardrail System



(a) (b) - Alternative Scheme

Design Conditions

	Reference
• Two posts + top rail + midrail	
• Posts fixed at base, rails simply supported	
• Southern pine, construction grade (19% max. m.c.)	NFPA table 1
• 300 lb accidental load (A).	Crit. A.2.2
Top & Mid Rails	
Assume $L = 6'\text{-}0"$, $M = PL/4 = 300(72)/4 = 5400$ in-lb	
$F_b = 1050 \times 2$ (impact) $\times 1.1 = 2310$ psi	NFPA table 1, footnote 4 & figure H-1
Try 2-2x4, Layout (a) above	
$S_{req'd.} = M/F_b = 5400/2310 = 2.34\ in^3$	
Assume no integral action betw. 2x4's (conserv.)	
$S_{suppl'd.} = 2^{No.}(1.5)^2(3.5)/6 = 2.62\ in^3 > 2.34\ in^3$ OK	
Check for 300 lb acting downward	
$S_{suppl'd.} = 1.5(3.5)^2/6 = 3.06\ in^3 > 2.34\ in^3$ OK	
Posts	
$M = PH = 300(42) = 12{,}600$ in-lb	
$S_{req'd.} = M/F_b = 12{,}600/(1050)(2) = 6.0\ in^3$	NFPA table 1 & figure H-1
$S_{suppl'd.} = 2^{No.}(1.5)(3.5)^2/6 = 6.12\ in^3 > 6.0\ in^3$ OK	
Check Deflection	
$I_{rail} = 2^{No.}(3.5)(1.5)^3/12 = 1.97\ in^4$, $I_{post} = (3)(3.5)^3/12 = 10.7\ in^4$	
$\Delta_{rail} = PL^3/48EI = (300 \times 1.5)(72)^3/48(1.4^6)(1.97) = 1.27$ in	Crit. A.2.5
$\Delta_{post} = (P/2)H^3/3EI = 225(42)^3/3(1.4^6)(10.7) = 0.37$ in	
$\Delta_{total} = 1.27 + .37 = 1.64$ in $<$ 4 in allow. OK	Crit. A.2.5

Figure B.1 Design of wood guardrail system

Design Conditions

- Two posts + Top Rail + Mid Rail
- Posts Fixed, Rails Simply Supported
- No Welds
- Use 6063-T6 Pipe (40 Schedule):

	Reference
$F_{ty} = 25\ ksi$, $F_{tu} = 30\ ksi$	ACM Table 3.3.1a
$n_y = 1.65$, $n_u = 1.95$	ACM Table 3.3.3
$F_{b1} = 1.17 F_{ty}/n_y = 1.17(25)/1.65 = 17.73\ ksi$ ← Use	"
$F_{b2} = 1.24 F_{tu}/n_u = 1.24(30)/1.95 = 19.08$ (not govern)	"
Use $L = 6'\text{-}0"$	
$M_{L/2} = 300^{\#}(6 \times 12)/4 = 5400$ in-lb	Crit. A.2.2
$S_{req'd.} = M/F = 5400/17{,}730 = 0.305\ in^3$	
Use Nominal $1\frac{1}{2}"\phi$ pipe (Schedule 40) Top & Mid rail	
$M_{post} = 300(42) = 12{,}600$ in-lb	Crit. A.2.2 & A.3.1
$S_{req'd.} = 12600/17730 = 0.710\ in^3$	
Use Nominal $2\frac{1}{2}"\phi$ pipe (Sch. 40) Posts @ 6'-0" o.c.	
($S_{supplied} = 1.06\ in^3 > 0.710\ in^3$ OK)	
Max. Deflections:	
$I_{rail} = 0.310\ in^4$; $I_{post} = 0.666\ in^4$	
$\Delta_{rail} = \dfrac{PL^3}{48EI} = \dfrac{(450)(72)^3}{48(10.1^6)(.310)} = 1.12"$	Crit. A.2.5
$\Delta_{post} = \dfrac{(P/2)H^3}{3EI} = \dfrac{(225)(42)^3}{3(10.1^6)(.666)} = 0.83"$	
$\Delta_{TOT.} = 1.95"$	
(< 4" allowed, ∴ OK)	Crit. A.2.5)

Figure B.2 Design of aluminum pipe guardrail system

A. <u>Using Angle Sections</u>

<u>Design Top & Mid Rails:</u>

Try $1 - 2\frac{1}{2} \times 2\frac{1}{2} \times \frac{3}{8}\ \angle$, A36 Steel

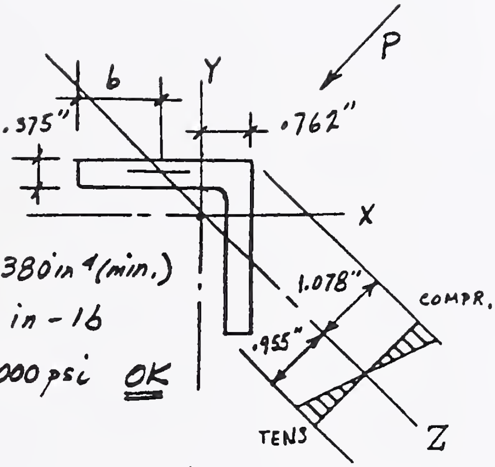
Wt. = 5.9 lb/ft

$A = 1.73\ in^2$, $r_z = .487''$, $I_z = Ar_z^2 = .410\ in^4$

$S_{tens.} = .410/.955 = .429$, $S_{compr.} = .41/1.078 = .380\ in^4\ (min.)$

Use $L = 8' = 96''$; $M_{L/2} = 300(96)/4 = 7200$ in-lb

$f = M/S_{min} = 7200/.38 = 18{,}950\ psi < 22{,}000\ psi$ <u>OK</u>



<u>Design of Posts:</u>

$M = 300(42) = 12{,}600$ in-lb, $I_x = .984\ in^4$

$S_{tens.} = .984/.762 = 1.29\ in^3$, $S_{comp.} = .984/1.738 = .566\ in^3$ (min.)

$b = 1.738''$, $b/t = 1.738/.375 = 4.63$

$76/\sqrt{F_y} = 76/\sqrt{36} = 12.7 \gg b/t$, way <u>OK</u> (AISC 1.9.1.2 & App. C)

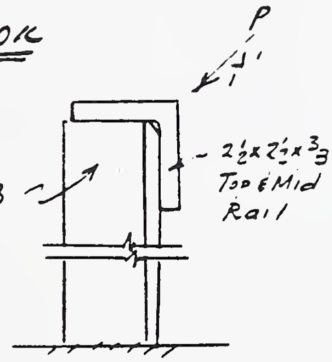
$f_b = M/S_{min} = 12\,600/.566 = 22{,}261 \approx 22{,}000$ allow. <u>OK</u>

<u>Check DL:</u> $M_{wt.} = 5.9(8)^2(12)/8 = 566.4$ in-lb

$f_{DL} = M/S_{x\,(tens.)} = 566.4/1.29 = 439\ psi$

$\therefore f_b$ (combined) $= 18\,950 + 439 = 19{,}290 < 22{,}000$ <u>OK</u>

$\therefore$ <u>Use $2\frac{1}{2} \times 2\frac{1}{2} \times \frac{3}{8}\ \angle$ for all members</u>



<u>Check Deflections:</u>

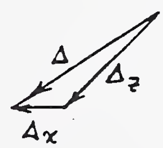
Top rail, @ z-axis:

$P = 450\#$ @ $L/2$, $\theta = 45°$

$$\Delta_z = \frac{450(96)^3}{48(29^6)(.410)} = 0.70\ in$$

Post load: $0.5P/\sqrt{2} = 450(.5)/\sqrt{2} = 159^{\pm}$

$$\Delta_x = \frac{PH^3}{3EI_x} = \frac{159(42)^3}{3(29^6)(.984)} = 0.21\ in$$



$$\Delta = \left\{\left[(.70/\sqrt{2}) + .21\right]^2 + \left[.70\right]^2\right\}^{1/2} = .99''$$

$\ll 4''$ allowed, way <u>OK</u>

B. <u>Using steel Pipe</u>

Calculations similar to fig. B.2 lead to following sections:

Top & Mid Rails: $1\frac{1}{2}''\phi$ standard pipe (sched. 40, A36 steel)

Posts: $2''\phi$ standard pipe (sched. 40, A36 steel) @ 3'-0" o.c.

Figure B.3 Design of steel guardrail systems

APPENDIX C

EXPERIMENTAL RESEARCH

Structural and Non-Structural Tests
of Guardrails Using Human Subjects
and an Anthropomorphic Dummy

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Appendix C
Experimental Research

Structural and Non-Structural Tests of Guardrails Using Human Subjects and an Anthropomorphic Dummy

C.1 Objectives and Scope of Tests.

In 1975, a survey of the existing literature on the general subject of guardrails disclosed no experimental research on personnel safety railings, but only studies of vehicular barriers for highways and bridges. The lack of substantiating research for the design of personnel safety railings suggested that the development of criteria for personnel guardrails should include generating anthropometric and loading data that would corroborate the recommended standards. The experimental techniques and resulting data pertaining to loads anticipated on safety railings are reported in this appendix.

The experimental phase had two objectives: (1) correlating the anthropometrically related aspects of guardrail design with the needs indicated by a review of currently available documented anthropometric data, and (2) evaluating forces exerted by bodies against various guardrail configurations to establish a basis for design load requirements. In addition, a limited amount of resistance testing was performed to determine the structural response of selected common guardrail system components to assist in the preparation of the design guide (appendix B).

The scope of the experiments undertaken, using human subjects and an anthropomorphic dummy included:

(1) Nonstructural tests to examine the relationship of human body measurements to activities associated with guardrail use.

(2) Structural tests to determine forces generated by the human body leaning against or falling on the rail.

Sections C.3 and C.4 document quantitative data which served as the basis for conclusions drawn in formulating many of the recommended criteria in the proposed standard for worker guardrails (appendix A). To the best of the authors' knowledge, test results such as those presented here have not been recorded elsewhere. Interlaboratory comparative studies must therefore await future collaborative research elicited by interest in the following data.

C.2 Description of Test Subjects

Those tests conducted with human subjects were primarily static load tests involving little or no risk to the subject. The majority of non-structural and structural load tests made use of an anthropometric dummy.

The human subjects who participated in the tests were selected for their proximity to the 95th and 50th percentile weights and heights for the U.S. adult male population. The 95th percentile subjects were used to measure guardrail loads induced by a single individual while the 50th percentile subjects were used to investigate load levels induced by a group of people.

An anthropomorphic dummy (figure C.1) of the type developed by **automotive** safety testing technology was employed in the dynamic load tests on the mock-up rail. Such human simulators are described in greater detail in references [C.1, C.2]. The test dummy is categorized as a 95th percentile U.S. adult male incorporating both the 95th percentile height and weight values of the U.S. adult males [C.1]. It has a realistically simulated skeletal structure of metal and plastic, covered with flesh of flexible foamed urethane and elastomeric skin. Its fully articulated joints provide limb action consistent with the normal human range of movements. The inherent flection characteristics of the head/rubber neck assembly, as fabricated, were not altered during the tests.

Preparation of the dummy for testing included certain joint adjustments. Where the effect of friction on joint rotation was considered critical to the results of a test, the tightness of the joint was prepared in one of three ways, as follows: (1) "loose" joint having no friction of consequence, (2) "1G" joint having just enough friction to resist rotation caused by gravity forces, and (3) "stiff" joint having the maximum possible tightness achieved by using a hand wrench.

The standing height of human and dummy subjects (vertical distance from tread surface to top of head) was measured with the aid of a try-square and tape measure. The subject stood erect with heels together, feet at a 45° angle, back straight and head in a horizontal plane. Measurements were made to the nearest 1/16 in (1.6mm). The height of the body center of gravity was determined by statics [C.4]. Typical replicate body measurements are illustrated in table C.1.

C.3 Non-structural Tests

C.3.1 Maximum Reach Over Wall Barrier

In these tests measurements were made of the effect of barrier height on the reach attained by a worker attempting to increase his reach over the barrier by placing one foot on the barrier to assume a climbing posture. The safety barrier was simulated by attaching a horizontal plywood board of constant width to the prongs of a forklift

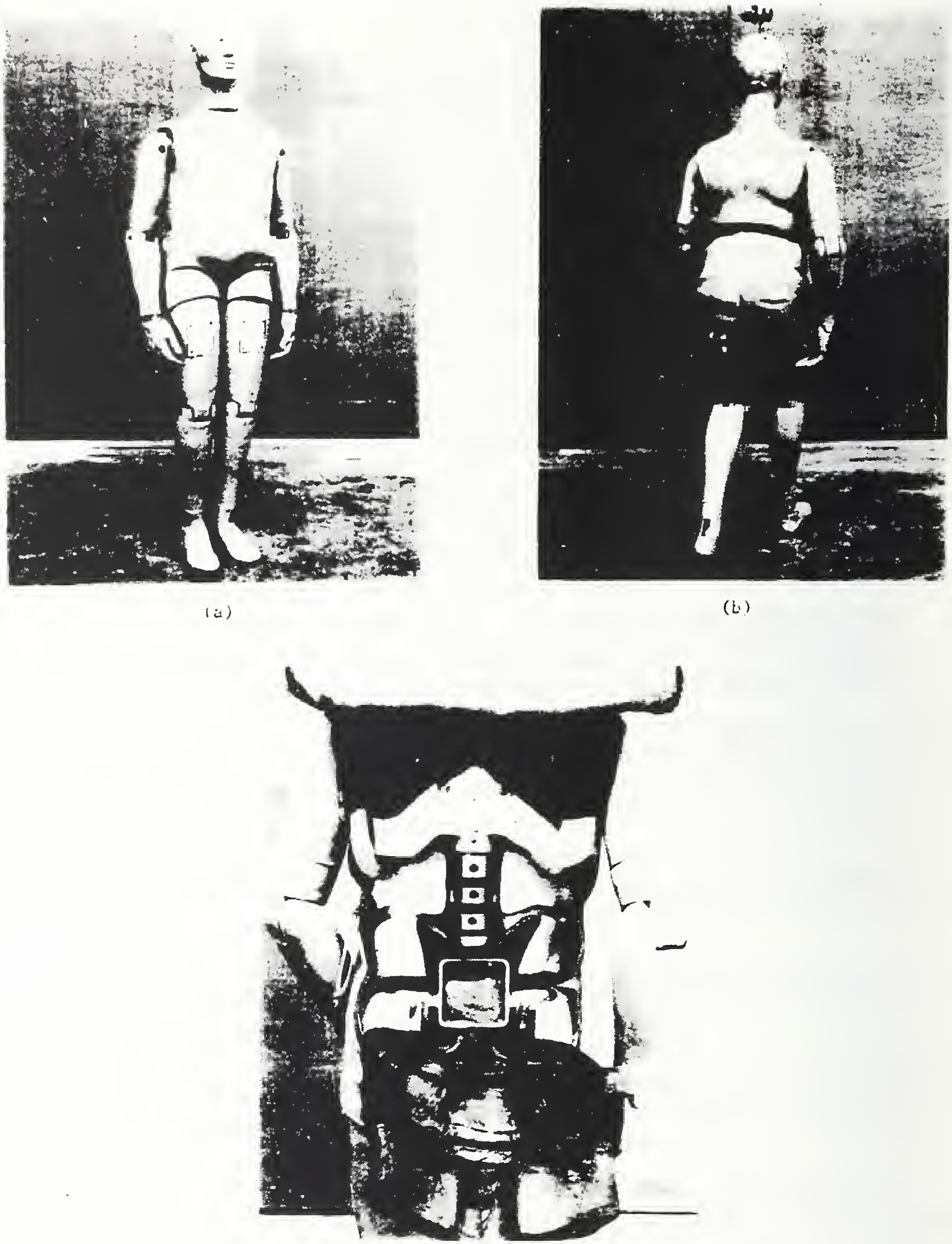
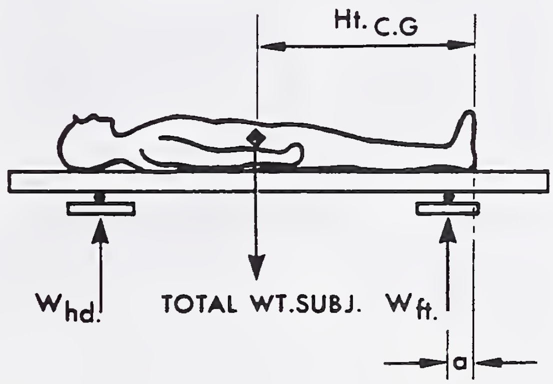


Figure C.1 Anthropomorphic dummy used in dynamic tests.

Table C.1 Typical dummy and human subject body measurement replications

							Average
95th Percentile Dummy	Height w/shoes, w/o hat, in (m)	74 5/8	74 9/16	74 9/16	74 9/16	74 5/8	74.59 (1.894)
	"Head" weight, lb (N)	110.9	119.6	109.8	116.3	117.9	--
	"Foot" weight, lb (N)	107.8	99.6	108.2	103.5	101.8	--
	Total weight w/shoes, w/hat, lb (N)	218.7	219.2	218.0	219.8	219.7	219.1 (974.6)
	Distance, a, in	5 1/4	2 9/16	5 9/16	3 7/8	3 3/16	--
	C.G. height, in (m)	41.8	41.8	41.8	42.0	41.8	41.8 (1.062)
Human Subject (No. 101)	Height clothed, w/o hat, in (m)	74 15/16	74 13/16	74 3/4	74 15/16	74 7/8	74.86 (1.901)
	"Head" weight, lb (N)	108.3	98.0	108.4	98.7	104.0	--
	"Foot" weight, lb (N)	89.0	99.1	89.1	98.5	93.4	--
	Total weight clothed, w/hat lb (N)	197.3	197.1	197.5	197.2	197.4	197.3 (877.6)
	Distance, a, in (mm)	3 1/8	6 7/8	3 5/16	6 7/8	4 15/16	--
	C.G. height	42.6	42.7	42.8	42.9	42.9	42.8 (1.087)



positioned at a stated height, as shown in figure C.2. Such simulated wall barriers were used to limit overreaching actions of a human subject, to observe the influence of barrier dimensions on such activity, and to block the fall of a dummy in observing fall phenomena.

Measurements were made of the maximum reach attained by a human subject, first standing with both feet at floor level against the outside of the wall barrier [figure C.2(a)] and then assuming a climbing posture [figure C.2(b)]. The simulated barrier height was varied from 24 in (0.610m) to 30 in (0.762m) at which height no additional reach advantage was gained by the climbing posture. Barrier width (depth) was kept constant at 24 in (0.610m), a size found to be ample for accommodating the subject's foot in the climbing posture. Repeated trials showed that the optimum initial position of the subject's foot for maximum reach on any of the barrier heights used in the climbing posture tests was with the heel at approximately 7 in (180mm) forward of the back edge (outside) of the barrier. Although the foregoing location measurement was made with the heel initially in full bearing, both heels were lifted in maximizing the reach. In the standing posture tests both heels were kept flat on the floor. Measurements were made with a tape measure to the nearest 1/4 in (6mm). The human subject that performed these tests was 77.5 in (1.969m) tall. Barrier heights and reach measurements are given in table C.2.

Table C.2 - Maximum reach for standing and climbing postures over different wall barrier heights*

Wall Barrier Height inch (m)	Standing Reach inch (m)	Climbing Reach inch (m)
24 (0.610)	53 3/4 (1.365)	59 (1.499)
25 (0.635)	53 3/4 (1.365)	57 3/4 (1.467)
26 (0.660)	53 1/4 (1.353)	56 1/2 (1.435)
27 (0.686)	52 1/4 (1.327)	56 1/2 (1.435)
28 (0.711)	51 3/4 (1.314)	55 1/2 (1.410)
29 (0.737)	51 3/4 (1.314)	53 3/4 (1.365)
30 (0.762)	51 3/4 (1.314)	51 3/4 (1.314)

* ± 1/8 in (3mm)

(a) Standing posture

(b) [illegible]

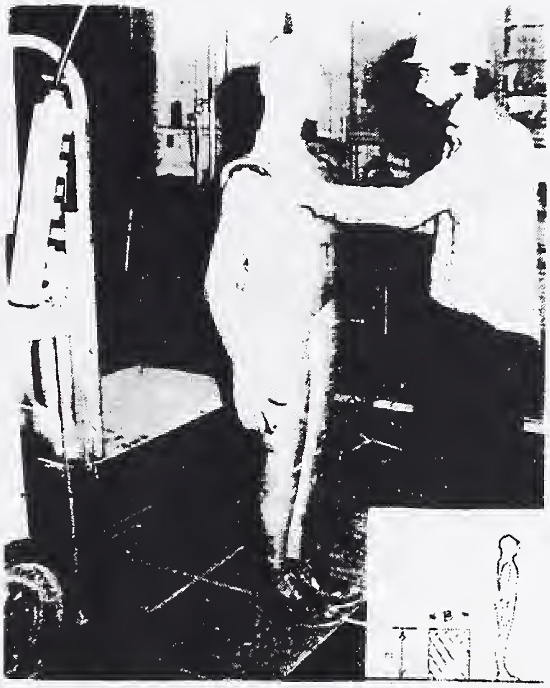
Figure C.2 Maximum reach versus wall barrier height tests.

C.3.2 Dummy Fall Against Wall Barrier

Tests were performed to gather data to show whether a given barrier height requirement could be relaxed when an appreciable compensating width (depth) of barrier is provided. Using the apparatus described in C.3.1, tests were conducted with the 95% dummy to observe the outcome of the subject's backward fall against the barrier. The interaction of three parameters was observed. These were (1) height of barrier (H), (2) width of barrier (B) and (3) the initial distance (D) of the subject's heels from the outside face of the barrier. With the dummy in a balanced, erect starting position [figure C.3(a)] it was allowed to fall backwards against the barrier. For these tests the knee and hip joints of the dummy were tightened to a stiff condition. Depending on the values of the three parameters, the subject landed on the barrier as illustrated in figure C.3(b) or overturned completely [figure C.3(c)]. Two measurements of the final position were made when the test ended as in figure C.3 (b): (a) the distance which the body protruded beyond the inside face of the wall barrier and (b) the vertical distance of the lowest point on the head, below the top surface of the barrier. Test parameters (measured to the nearest 1/8 in (3mm)) and final position measurements to the nearest 1/4 in (6mm) are given in table C.3. In cases where the outcome of a fall (such as overturning or propping) appeared to be questionable, replicate tests were run.

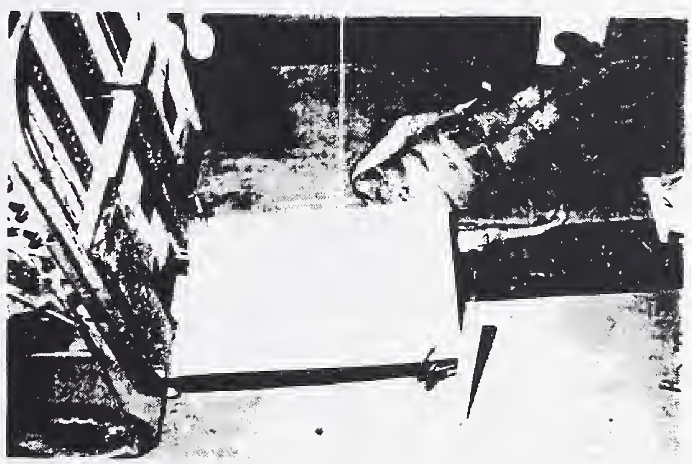
C.3.3 Dummy Fall Over Top Rail

The following tests simulated a person walking directly into a guardrail and tending to be propelled beyond it because of walking speed inertia. The parameters were guardrail height and walking speed. The test apparatus used a steel carriage containing a plywood tread surface and a rigid steel frame which supported a 2-in (51-mm) diameter solid aluminum



(a) Starting position

(b) Case 1: Final position on wall barrier



(c) Case 2: Final position - complete overturn

Figure [illegible]. Dummy f[illegible] [illegible]ast wall barrier.

Table C.3 Data for dummy falling against wall barrier

	Width, B, in (mm)	18 (457)				21 (533)				24 (610)			
	Height H, (in) mm	24 (610)	26 (660)	28 (711)	30 (762)	24 (610)	26 (660)	28 (711)	30 (762)	24 (610)	26 (660)	28 (711)	30 (762)
Projection, b, in (mm)	D = 6 in (152)	OT	OT	$15\frac{1}{2}^{(2)*}$(OT) (394)	$8^{(3)}$ (203)	14* (356)	OT	15 (381)	5 (127)	$13\frac{1}{2}$* (343)	$12\frac{1}{2}$ (317)	$4^{(2)}$(P) (102)	$3^{(2)}$(P) (76)
	D = 9 in (229)	OT	OT	$15^{(2)*}$(OT) (381)	$7\frac{1}{2}^{(3)}$ (191)	13* (330)	$14\frac{1}{2}$* (368)	9 (229)	4 (102)	$14\frac{1}{2}$* (368)	$9\frac{1}{2}$ (241)	$4\frac{1}{2}^{(3)}$ (114)	$3^{(3)}$ (76)
	D = 12 in (305)	OT	$OT^{(3)}$	$12\frac{1}{4}^{(3)}$ (311)	$6\frac{3}{4}^{(3)}$ (171)	$16\frac{1}{2}$* (419)	15* (381)	5 (127)	3 (76)	$10\frac{3}{4}$* (273)	5 (127)	$3\frac{3}{4}$ (95)	3 (76)
Projection, a, in (mm)	D = 6 in (152)	OT	OT	$24\frac{3}{4}^{(2)*}$(OT) (629)	$23^{(3)}$ (584)	$23\frac{1}{2}$* (597)	OT	$24\frac{1}{2}$ (622)	$19\frac{1}{2}$ (495)	$24\frac{1}{2}$* (622)	$23\frac{1}{2}$ (597)	$19\frac{1}{2}^{(2)}$(P) (495)	$16^{(2)}$(P) (406)
	D = 9 in (229)	OT	OT	$26^{(2)*}$(OT) (660)	$23\frac{1}{4}^{(3)}$ (591)	23* (584)	25* (635)	$22\frac{1}{2}$ (571)	19 (483)	25* (635)	$24\frac{1}{2}$ (622)	$19\frac{1}{2}^{(3)}$ (495)	$16^{(3)}$ (406)
	D = 12 in (305)	OT	$OT^{(3)}$	$25\frac{1}{4}^{(3)}$ (641)	$20\frac{1}{2}^{(3)}$ (521)	$21\frac{1}{2}$* (546)	$24\frac{1}{2}$* (622)	$19\frac{1}{2}$ (495)	16 (406)	23* (584)	20 (508)	19 (483)	$15\frac{3}{4}$ (400)

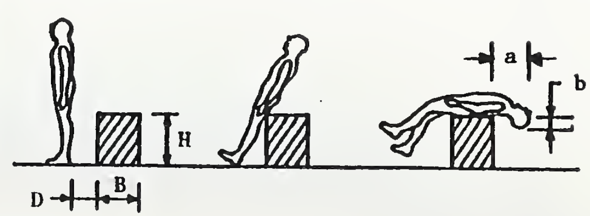
(2) = Average of 2

(OT) = Overturned once

(3) = Average of 3

(P) = Propped against barrier once

* = Partial recovery: body dipped lower inertially and recovered



rod toprail 4 ft (1.219m) long as shown in figure C.4. The height of the toprail was adjustable. In use, the carriage, carrying a dummy subject standing erect and in contact with the guardrail, was pushed along a marked straight path on a concrete laboratory floor. The forward motion of the carriage was terminated suddenly by impact against a steel block anchored to the laboratory tie-down floor. Inertial tipping of the carriage was restrained by an added nosewheel. The walking speeds were measured with a stopwatch over a 24-ft (7.315-m) distance. The coefficients of variation for the velocities of 12 tests run at an average 3.3 mph (5.3 km/h) and 12 at 2.5 mph (4.0 km/h) were 0.05 and 0.08 respectively. Results of the tests are listed in table C.4. As indicated in the table, some tests were run with the dummy's hip joints made stiff (as opposed to the 1G condition used in the majority of these tests).

Table C.4 Data for tests of overturning due to walking speed inertia

Guardrail Height inch (m)	Run No.	Speed mph (km/h)	Overturn	Run No.	Speed mph (km/h)	Overturn
	1	3.36 (5.41)	no	4	2.08 (3.35)	no
42	2	3.36 (5.41)	no	5	2.85 (4.59)	no
(1.067)	3	3.29 (5.30)	no	6	2.35 (3.78)	no
	7	3.03 (4.88)	no	9	2.39 (3.85)	no
40	8	3.61 (5.81)	no	10	2.35 (3.78)	no
(1.016)	23	3.41 (5.49)	no*	24	2.45 (3.94)	no*
	15	3.29 (5.30)	yes	17	2.52 (4.05)	yes
38	16	3.36 (5.41)	no	18	2.52 (4.05)	no
(0.965)	19	3.36 (5.41)	yes*	20	2.45 (3.94)	no*
	11	3.14 (5.50)	yes	13	2.52 (4.05)	yes
36	12	3.36 (5.41)	yes	14	2.52 (4.05)	yes
(0.914)	21	3.36 (5.41)	yes*	22	2.67 (4.30)	no*

* Stiff hip joints; all other tests, 1G hip joints

C.4 Structural Tests

C.4.1 Structural Properties of Mock-up Guardrail

The apparatus shown in figure C.5 is a force transducer having the general configuration of a guardrail, and was used in the static and dynamic load tests described in following sections. Details of its construction are given in the drawing of figure C.6. The device was calibrated so that measured values of longitudinal strain in the rail, when deflected, were converted to corresponding values of transverse force.

The rail and its supports were fabricated with minimal machining from off-the-shelf stock 2024-T3 aluminum and steel. The rail posts were adjustable in height and the diagonal braces, self-adjusting when unlocked. Ball joint rod ends used as bearings for the aluminum tube rail permitted it to act as a simply supported beam. An adjustable footstop consisting of a wooden block attached to a slotted board (figure C.5) assisted the subjects in maintaining body positions with respect to the instrumented rail in static tests. At the time of testing the footstop was bolted to the test floor at an appropriate distance from the centerline of the mock-up rail. The carpet padding seen in the area of the laboratory setupup was provided for the protection of human subjects in case of accidental falls.

The middle 24-in (0.610-m) length of the tube was flanked by electrical resistance strain gages as shown in figure C.6 to measure longitudinal strain at locations equidistant from the midlength. The 4 gages in each of the 2 sets (one in the vertical plane, and one in the horizontal) constituted the 4 legs of a Wheatstone bridge. The outputs of the vertical and horizontal bridge circuits were attributed, respectively to the vertical and horizontal components of the corresponding transverse force. The orientation of the instrumented vertical and horizontal planes of the tube was maintained by the springs [K = 11.4 lb/in (2.0 N/mm)] shown anchored to the post tops (figure C.6). This arrangement of the strain gages permitted the application of a given transverse load (concentrated or distributed) at any point(s) between the gage locations (which were equidistant from the rail midlength) without changing the readout. Using influence lines for moments (M_L, M_R) at left and right sections equidistant from the midlength of a simple beam, it may be shown that the sum of the resisting moments at the two equidistant sections is constant for any arbitrary location of a given load applied between the sections. In particular, when a force, P, is located anywhere between sections L and R, (separated by a distance 2a) the constant value of the sum of the moments ($M_L + M_R$) is equal to twice the moment at either section produced by the force P, when located at the midlength ($\frac{\ell}{2}$).

$$M_L + M_R = P\left(\frac{\ell}{2} - a\right) \qquad \text{C.1}$$

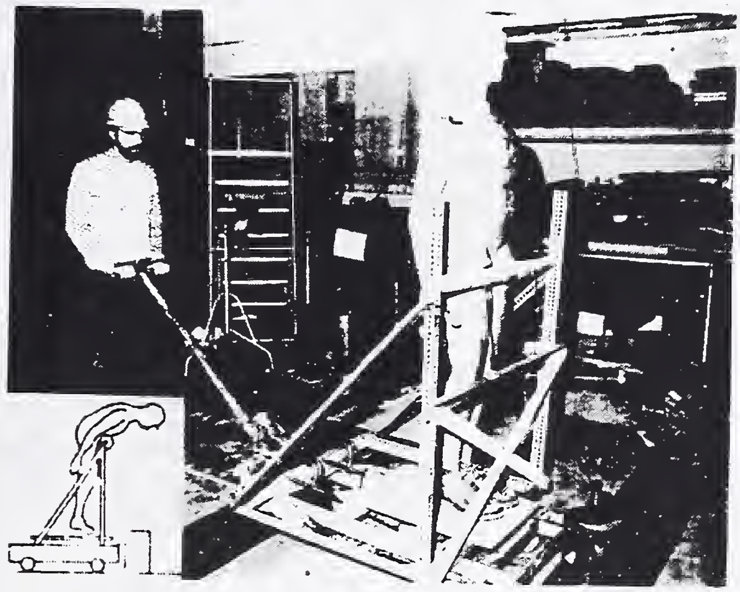


Figure C.4 Inertia-test carriage.

Figure C.5 Laboratory guardrail force transducer.

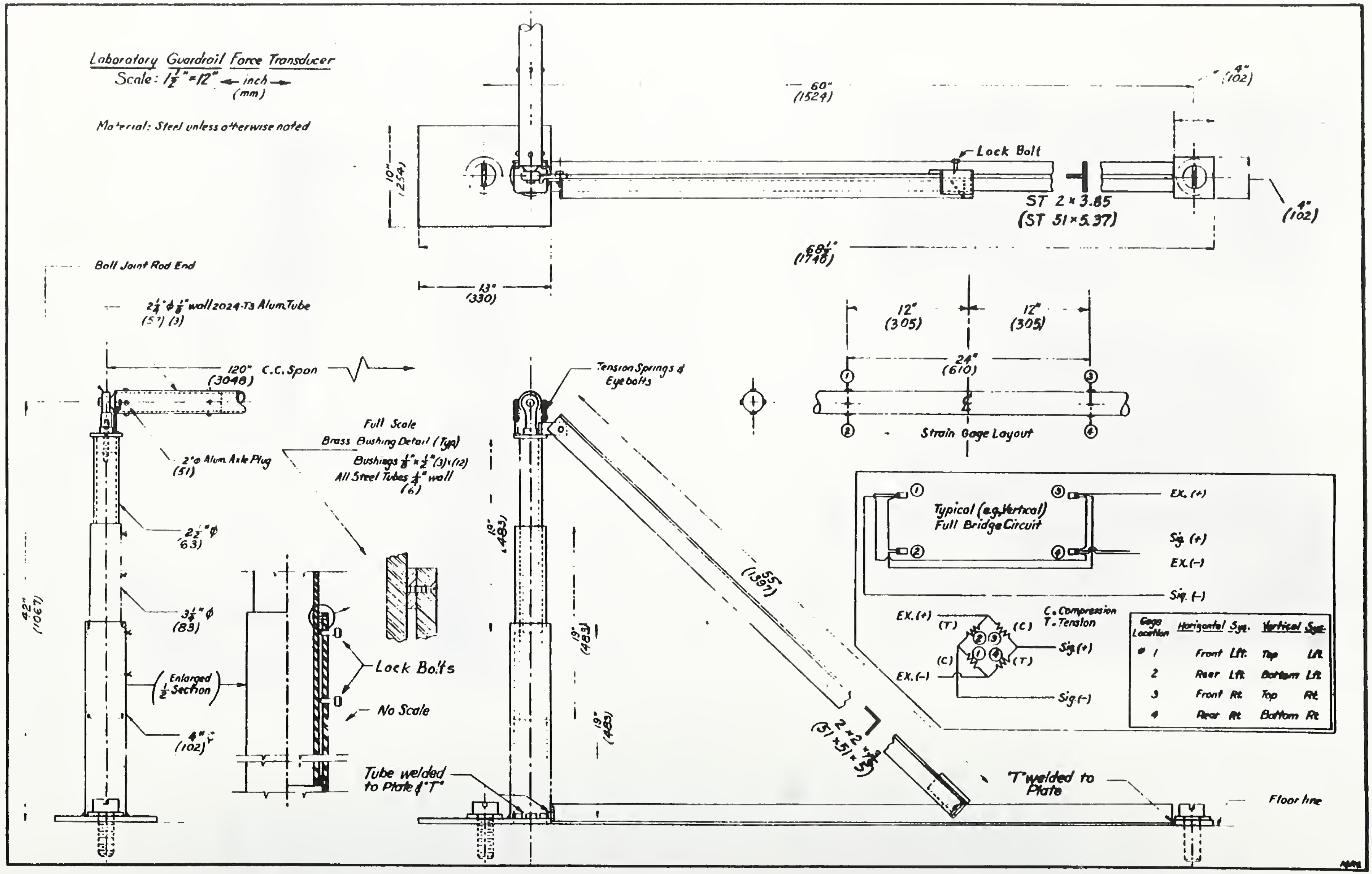


Figure C.6 Assembly and strain gage instrumentation of laboratory guardrail force transducer.

Calibration of the instrumented rail was performed for its vertical plane circuit with the rail in a normal (as used) position, and separately for its horizontal plane circuit by rotating the front of the rail (the side facing test subjects when in use) to the top before calibrating. Digital voltmeters (DVM) and strip chart recorders were used in reading strain gage outputs. Table C.5 gives the calibration results (average of 4 runs and normalized by initial offset readings) for the separate direct loading of the vertical and horizontal circuits. The linear relation between applied load and output may be observed. Additional 4-run checks were made of the response of the instrumented planes by loading through intermediate planes which were normally at 30°, 45° and 60° from horizontal within the upper front quadrant of the tube. The results of these check runs are also given in table C.5 and show the correlation of the vector sums of vertical and horizontal outputs with the applied load.

To investigate further the physical properties of the aluminum tubing rail used in the apparatus, but without risking damage to the calibrated mock-up a companion specimen of the same stock, 6 ft (1.829m) long was loaded beyond its yield strength as a simple beam on a 66-in (1.676-m) span as shown in Fig. C.7. The longitudinal strain gages shown were on the top-, and bottom-most elements of the tube and were individually read and recorded every 10 seconds. Load values were obtained from a transducer in the testing machine. The load was applied at the rate of 120 lb/min (8.9 N/sec). A load-strain monitoring curve was obtained from one tension gage by an xy recorder and is shown in figure C.7. The modulus of elasticity (E) of the tube material (2024-T3 aluminum), based on the digital test data, was 10.5×10^6 psi (72.4×10^9 Pa). The maximum test load was 2400 lb (6.227 kN). Comparison of the geometries of this test specimen and the mock-up rail (figure C.6) showed that (a) an equivalent maximum moment-producing central force on the mock-up would have been 920 lb (4.092 kN); (b) the mock-up rail was found to have a yield strength concentrated load capacity of 850 lb (3.785 kN); and (c) the linear ($\pm$ 2%) calibration of the mock-up could be extrapolated to a maximum load of 600 lb (2.669 kN) located at any point within the central 2-ft (0.610-m) length.

The natural frequency of the mock-up rail was calculated (and corroborated by experiment) for correlation (section 4.4.2) with the rise-time of dynamic test loads. Equation C.2 will be recognized as the expression for the fundamental frequency (f_n) of a simply supported uniform, slender elastic beam having mass (m), length (l) modulus of elasticity (E) and moment of inertia (I).

$$f_n = 1.478\sqrt{\frac{EI}{ml^3}} \qquad \text{C.2}$$

For 2024-T3 Al, f_n is computed as 15.5 hertz. For comparison, the experimental determination of f_n showed the fundamental frequency to be 16 Hz.

Table C.5 Calibration of the mock-up rail

Average value of calibration constant for resultant output = 13.98 lb/mV (62.2 N/mV)

	Vertical Circuit plane loading		Horizontal Circuit plane loading		Load at 30° from horizontal circuit plane					Load at 45°					Load at 60° from horizontal circuit plane				
Applied load lb	Vert output mV	Vert. lb/mV	Horiz. output mV	Horiz. lb/mV	Vert. output mV	Horiz. output mV	Arctan V/H degree	Result output mV	Result lb/mV	Vert. output mV	Horiz. output mV	Arctan V/H degree	Result output mV	Result lb/mV	Vert. output mV	Horiz. output mV	Arctan V/H degree	Result output mV	Result lb/mV
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0.72	13.89	0.72	13.89	0.36	0.64	29.3	0.73	13.70	0.54	0.55	44.5	0.77	12.99	0.63	0.38	58.9	0.73	13.70
20	1.44	13.89	1.43	13.99	0.71	1.25	29.6	1.44	13.89	1.04	1.04	45.0	1.47	13.61	1.23	0.72	59.7	1.43	13.99
30	2.14	14.02	2.13	14.09	1.06	1.85	29.8	2.13	14.09	1.54	1.53	45.2	2.17	13.83	1.84	1.08	59.6	2.13	14.09
40	2.87	13.94	2.86	13.99	1.42	2.48	29.8	2.86	13.99	2.06	2.05	45.1	2.91	13.75	2.47	1.44	59.7	2.86	13.99
50	3.61	13.85	3.59	13.93	1.79	3.11	29.9	3.59	13.93	2.58	2.56	45.2	3.63	13.77	3.10	1.81	59.7	3.59	13.93
100	7.17	13.95	7.14	14.01	3.57	6.17	30.1	7.13	14.03	5.11	5.04	45.4	7.18	13.93	6.18	3.58	59.9	7.14	14.01
150	10.68	14.06	10.65	14.09	5.35	9.19	30.2	10.63	14.11	7.62	7.49	45.5	10.68	14.05	9.22	5.32	60.0	10.64	14.10
200	14.22	14.07	14.17	14.11	7.17	12.24	30.4	14.19	14.09	10.15	9.95	45.6	14.21	14.07	12.29	7.07	60.1	14.18	14.10
250	17.74	14.09	17.69	14.13	8.97	15.23	30.5	17.67	14.15	12.68	12.39	45.7	17.73	14.10	15.34	8.80	60.1	17.68	14.14
300	21.25	14.12	21.18	14.16	10.79	18.24	30.6	21.19	14.16	15.20	14.81	45.7	21.22	14.14	18.37	10.53	60.2	21.17	14.17
avg		13.99		14.04					14.01					13.82					14.02

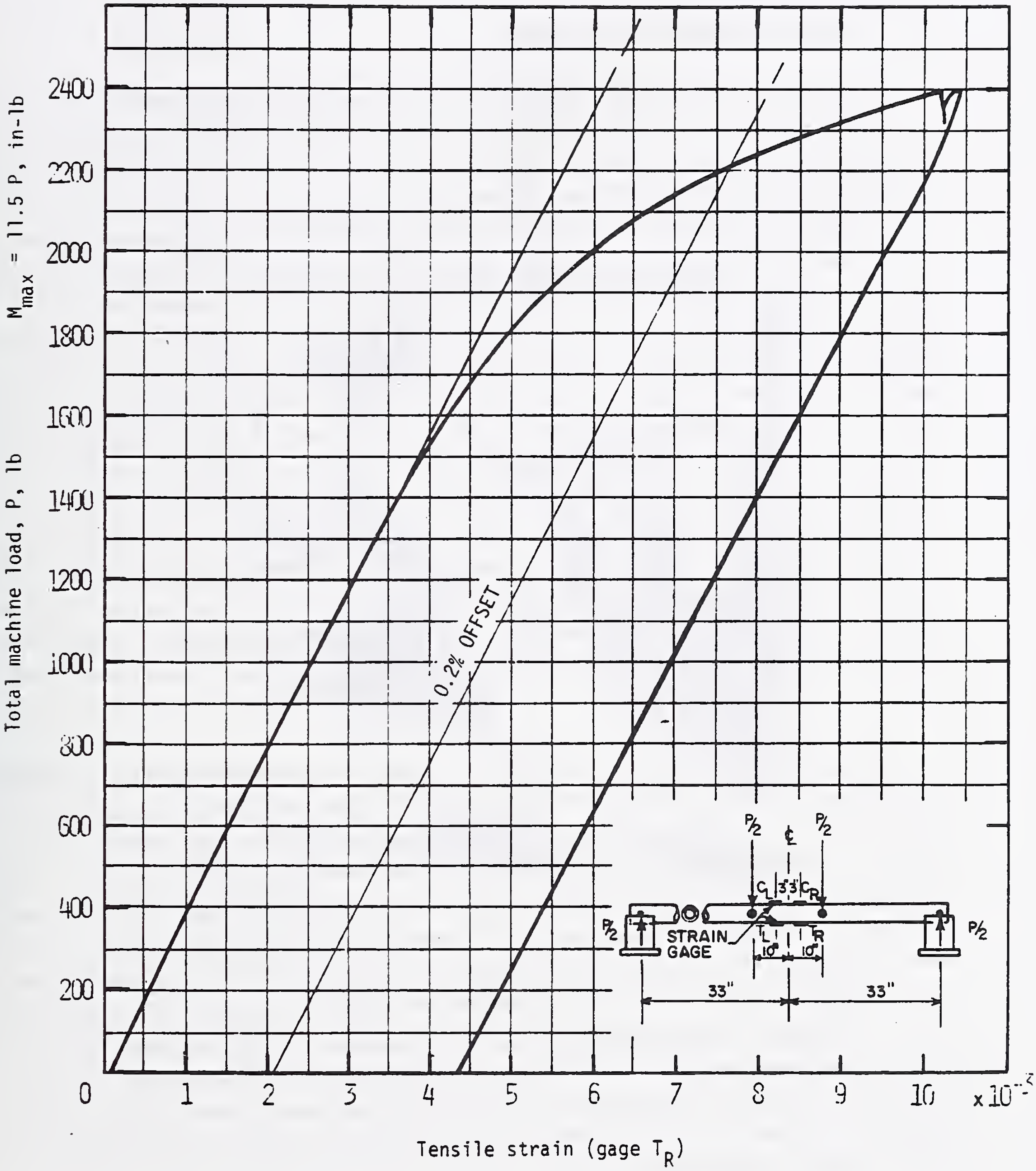


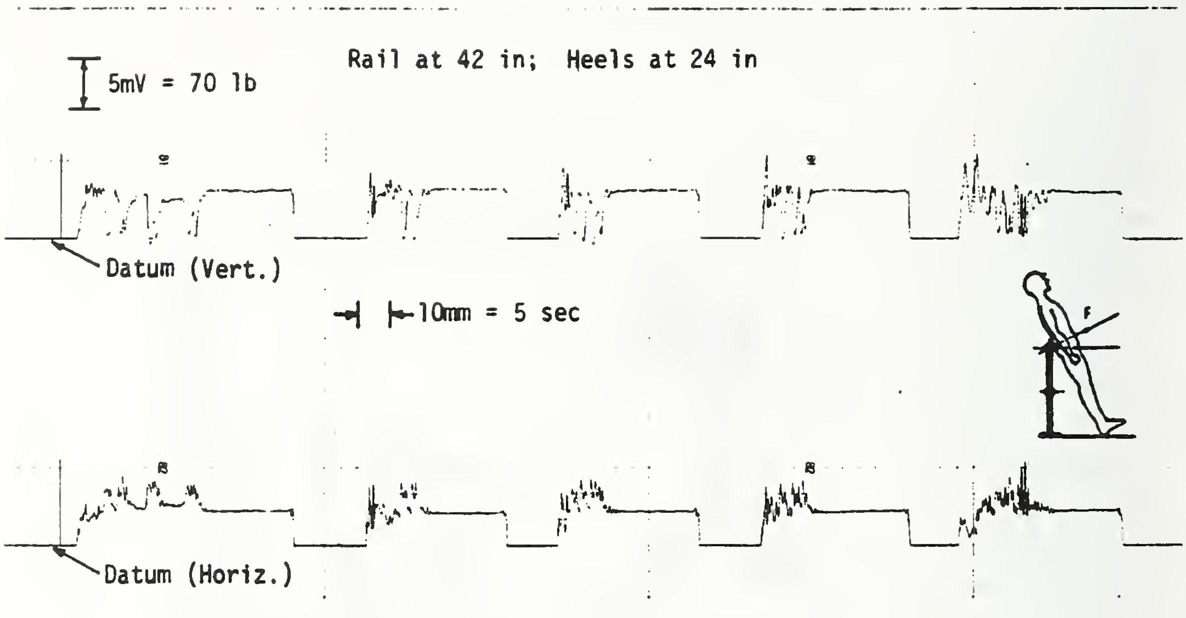
Figure C. 7 Load-tensile strain curve of mock-up rail stock specimen.

C.4.2 Backward Leaning Posture Tests.

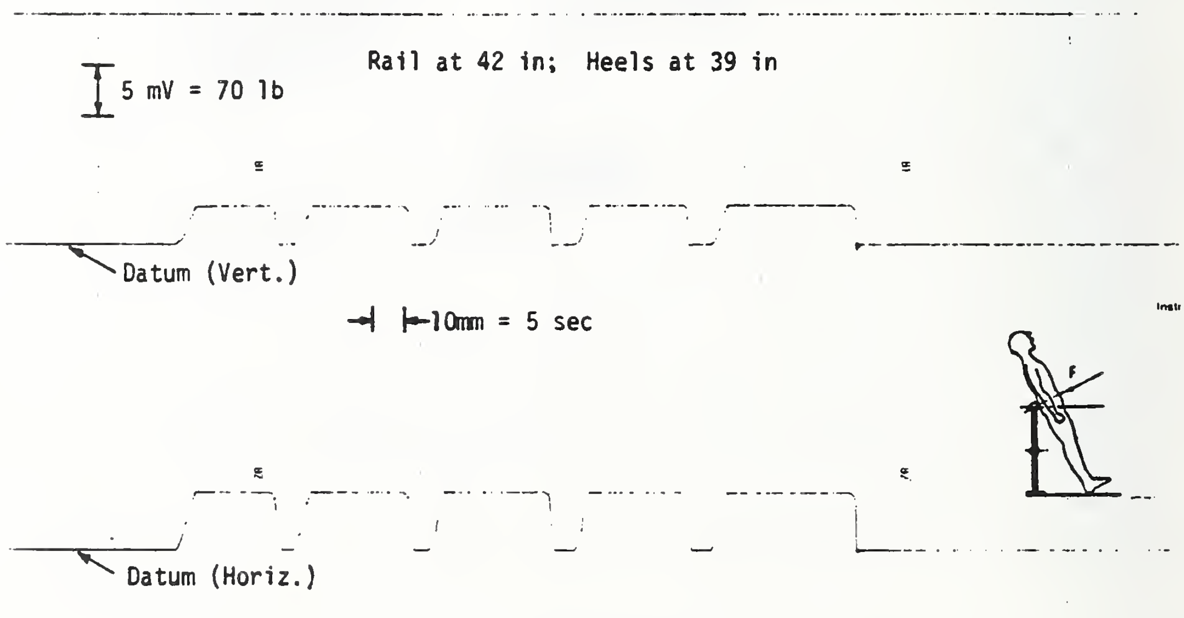
In conducting the static load tests it was considered more feasible, after trying other body positions, to have the subjects (both human and dummy) lean backwards against the mock-up rail force transducer described in section C.4.1 as illustrated in figure C.8. Such factors as less discomfort and better replication of body positions together with their effects on reduction of measurement scatter determined this procedure. Human subjects were guided by an observer in attaining an inclined, straight body position. The dummy (with knee, hip and spine joints made stiff) was alined with a straight edge before being lowered to the leaning position. While the subject was leaning, his feet were kept from slipping by the wood toe-stop. Body distances from the centerline of the rail were measured to the back of the shoe heels, and rail height, from its centerline to the tread surface. The feet were kept flat on the floor and the body was kept straight. The inclined position of the body was, in effect, the result of rotation about the ankles from an erect position. The central portion of the test rail was encircled with a loose sheath of polyethylene to eliminate friction drag at the body contact area. Separate positionings of the subject preceded each replicate reading. Figure C.9 shows two examples of static load strip chart records. The static load data are presented in tables C.6 thru C.8. Force values were calculated from mV values read on the DVMs or from number of strip chart divisions using the guardrail transducer calibration factor of 14.0 lb/mV; force values were rounded to 0.1 lb.

The data in table C.6 were generated by a male adult whose measurements approximated 95th percentile values. The negative values of force and direction angle (which occurred at small-distance positions) indicate an upward thrust against the rail (rather than a generally expected downward one) caused by body contours when standing close to the rail. Table C.7 contains data corresponding to the preceding table but generated by a male adult having approximate 50-percentile measurements. The shorter stature of this subject prevented his reaching the rail at a bearable body contact point (it was above the shoulders) from certain rail-to-heel distances. Table C.8 (95-percentile dummy) was obtained for 5-run replication for the purpose of comparing human-, and dummy-generated static load data. Table C.8 also contains replicate static load values for a full range of distances from the rail and was generated as a basis for comparison with results of subsequent dynamic tests. The rail height was limited to a 42-in (1.067-m) position on the strength of the findings of earlier non-structural tests (section C.3.3).

Figure C.8 Position of subjects in static load tests.



(a) Human subject



(b) Dummy subject

Figure C.9 Records of static load tests.

Table C.6 Static load of a "97.5-percentile" male adult* leaning backwards against top rail

*Human subject No. 101: Wt. = 196.1 lb (872.2N); Ht. = 75.2 in (1.910 m); C.G. = 42.6 in (1.082 m)

Run No.	Distance from ℄ rail in (m)	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Force-to-weight ratio
			Top Rail at 42 in (1.067 m)			
1	6	-0.7	35.5	35.5	-1.1	
2	(0.152)	-1.4	27.1	27.1	-2.9	
3		-2.1	30.2	30.3	-4.0	
avg				31.0 (137.9)	-2.7 -(0.047)	0.16
1	12	0	51.5	51.5	0	
2	(0.305)	10.5	50.7	51.7	11.7	
3		7.7	51.8	52.4	8.4	
avg				51.9 (230.9)	6.7 (0.117)	0.26
1		64.3	46.3	79.3	54.2	
2	24 (0.610)	68.5	43.9	81.4	57.3	
3		61.5	48.3	78.2	51.9	
avg				79.6 (354.1)	54.5 (0.951)	0.41
1		52.3	62.9	81.8	39.7	
2	36 (0.914)	48.5	65.1	81.2	36.7	
3		48.9	66.0	82.1	36.6	
avg				81.7 (363.4)	37.7 (0.657)	0.42
1		35.9	85.3	92.6	22.8	
2	42 (1.067)	27.8	95.7	99.7	16.2	
3		32.9	91.4	97.1	19.8	
avg				96.5 (429.2)	19.6 (0.342)	0.49

Table C.6 Static load of a "97.5-percentile" male adult* leaning backwards against top rail (continued)

Run No.	Distance from ℄ rail in (m)	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Force-to-weight ratio
			Top Rail at 36 in (0.914 m)			
1	6	18.7	34.4	39.2	28.6	
2	(0.152)	15.2	33.4	36.7	24.5	
3		18.0	37.1	41.2	25.9	
avg				39.0 (173.5)	26.3 (0.460)	0.20
1		39.7	53.8	66.8	36.5	
2	12 (0.305)	33.4	57.7	66.7	30.1	
3		37.2	57.3	68.3	33.0	
avg				67.3 (299.3)	33.2 (0.579)	0.34
1		62.4	71.3	94.7	41.2	
2	24 (0.610)	61.8	76.2	98.1	39.0	
3		60.0	77.1	97.7	37.9	
avg				96.8 (430.6)	39.4 (0.687)	0.49
1		81.0	52.9	96.7	56.8	
2	36 (0.914)	85.9	45.3	97.1	62.2	
3		83.5	51.1	97.9	58.5	
avg				97.2 (432.3)	59.2 (1.033)	0.50
1		66.4	67.8	94.9	44.4	
2	42 (1.067)	64.5	69.5	94.8	42.9	
3		65.5	69.6	95.5	43.2	
avg				95.1 (423.0)	43.5 (0.759)	0.48

Table C.6 Static load of a "97.5-percentile" male adult* leaning backwards against top rail (continued)

Run No.	Distance from ℄ rail in (m)	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Force-to-weight ratio
			Top Rail at 30 in (0.762 m)			
1		21.6	70.9	74.1	16.9	
2	6 (0.152)	27.3	73.1	78.0	20.5	
3		22.5	68.2	71.8	18.3	
avg				74.6 (331.8)	18.6 (0.324)	0.38
1		60.0	92.1	109.9	33.1	
2	12 (0.305)	70.1	91.1	114.9	37.6	
3		64.9	91.1	111.8	35.5	
avg				112.2 (499.1)	35.4 (0.618)	0.57
1		79.6	83.7	115.5	43.6	
2	24 (0.610)	82.2	87.2	119.8	43.3	
3		78.6	86.7	117.1	42.2	
avg				117.5 (522.6)	43.0 (0.751)	0.60
1		115.9	32.9	120.5	74.2	
2	36 (0.914)	113.6	36.1	119.1	72.4	
3		113.4	34.1	118.4	73.3	
avg				119.3 (530.6)	73.3 (1.279)	0.6
1		94.8	49.5	107.0	62.4	
2	42 (1.067)	97.1	44.8	106.9	65.2	
3		97.6	43.7	106.9	65.9	
avg				106.9 (475.5)	64.5 (1.126)	0.55

Table C.7 Static load of a "50-percentile" male adult* leaning backwards against top rail

*Human subject No. 505: Wt. = 163.8 lb (728.6 N); Ht. = 68.3 in (1.735 m); C.G. = 41.1 in (1.044 m)

Run No.	Distance from ℄ rail in (m)	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Force-to-weight ratio
			Top Rail at 42 in (1.067)			
1		1.7	21.6	21.7	4.4	
2	6 (0.152)	1.3	23.9	23.9	3.0	
3		1.1	20.2	20.2	3.2	
avg				21.9 (97.4)	3.5 (0.062)	0.13
1		7.1	37.3	38.0	10.8	
2	12 (0.305)	10.3	39.0	40.4	14.9	
3		11.1	37.3	38.9	16.5	
avg				39.1 (173.9)	14.1 (0.245)	0.24
1		41.1	43.2	59.7	43.6	
2	24 (0.610)	41.1	41.1	58.1	45.0	
3		44.3	40.0	59.7	47.9	
avg				59.2 (263.3)	45.5 (0.794)	0.36
1		22.0	70.6	73.9	17.3	
2	36 (0.914)	20.8	70.6	73.6	16.4	
3		23.6	69.6	73.5	18.7	
avg				73.7 (327.8)	17.5 (0.305)	0.45
1						
2	42 (1.067)	Subject unable to maintain leaning position at this distance.				
3						
avg						

Table C.7 Static load of a "50-percentile" male adult* leaning backwards against top rail (continued)

Run No.	Distance from ℄ rail in (m)	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Force-to-weight ratio
			Top Rail at 36 in (0.914)			
1		11.7	24.7	27.4	25.4	
2	6 (0.152)	11.1	23.6	26.0	25.1	
3		11.3	24.3	26.8	25.0	
avg				26.7 (118.8)	25.2 (0.439)	0.16
1		36.9	37.2	52.4	44.8	
2	12 (0.305)	33.3	41.4	53.1	38.8	
3		34.1	39.7	52.4	40.7	
avg				52.6 (234.0)	41.4 (0.723)	0.32
1		42.5	57.4	71.4	36.5	
2	24 (0.610)	48.1	57.4	74.9	40.0	
3		47.4	57.5	74.6	39.5	
avg				73.6 (327.4)	38.7 (0.675)	0.45
1		60.7	45.3	75.7	53.2	
2	36 (0.914)	61.4	45.5	76.4	53.5	
3		60.1	46.7	76.1	52.1	
avg				76.1 (338.5)	52.9 (0.924)	0.46
1						
2	42 (1.067)	Subject unable to maintain leaning position at this distance				
3						
avg						

Table C.7 Static load of a "50-percentile" male adult* leaning backwards against top rail (continued)

Run No.	Distance from ℄ rail in (m)	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Force-to-weight ratio
			Top Rail at 30 in (0.762 m)			
1		19.6	53.5	56.9	20.1	
2	6 (0.152)	21.5	55.6	59.6	21.2	
3		22.9	57.0	61.4	21.9	
avg				59.3 (263.8)	21.1 (0.368)	0.36
1		41.8	67.2	79.2	31.9	
2	12 (0.305)	39.7	73.1	83.2	28.5	
3		41.8	72.1	83.4	30.1	
avg				81.9 (364.3)	30.2 (0.527)	0.50
1		62.8	67.5	92.2	42.9	
2	24 (0.610)	67.4	63.9	92.9	46.5	
3		70.5	61.5	93.5	48.9	
avg				92.9 (413.2)	46.1 (0.805)	0.57
1		107.4	28.2	111.0	75.3	
2	36 (0.914)	85.2	31.0	90.6	70.0	
3		85.5	30.5	89.8	70.2	
avg				97.1 (431.9)	71.8 (1.254)	0.59
1		59.3	59.1	83.7	45.1	
2	42 (1.067)	66.1	51.4	83.7	52.2	
3		64.6	51.2	82.4	51.6	
avg				83.3 (370.5)	49.6 (0.866)	0.51

Table C.8 Static load of "95-percentile" dummy* leaning backwards against top rail at 42 in (1.067 m)

* Wt. = 219.1 lb (974.6N); Ht. = 74.6 in (1.895 m); C.G. = 41.8 in (1.062 m)

Run No.	Distance from ℄ rail in (m)	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Force-to-weight ratio
1		11.1	51.5	52.7	12.1	
2		11.6	51.9	53.2	12.6	
3	12 (0.305)	10.9	50.8	52.0	12.1	
4		11.9	52.2	53.6	12.8	
5		11.5	50.0	51.3	12.9	
avg				52.6 (234.0)	12.5 (0.218)	0.24
1		35.0	63.0	72.1	29.1	
2		36.4	60.2	70.3	31.1	
3	18 (0.457)	36.4	60.2	70.3	31.1	
4		43.4	56.0	70.8	37.8	
5		42.0	57.4	71.1	36.2	
avg				70.9 (315.4)	33.1 (0.577)	0.32
1		54.4	63.9	83.9	40.4	
2		53.0	65.6	84.3	39.0	
3	24 (0.610)	51.8	66.4	84.2	37.9	
4		58.1	62.9	85.6	42.7	
5		54.7	64.9	84.8	40.1	
avg				84.6 (376.3)	40.0 (0.698)	0.39
1		63.0	63.0	89.1	45.0	
2		63.0	61.6	88.1	45.6	
3	30 (0.762)	61.6	63.0	88.1	44.3	
4		63.0	63.0	89.1	45.0	
5		61.6	63.0	88.1	44.3	
avg				88.5 (393.6)	44.8 (0.783)	0.40

Table C.8 Static load of "95-percentile" dummy* leaning backwards against top rail at 42 in (1.067 m) (continued)

Run No.	Distance from ℄ rail in (m)	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Force-to-weight ratio
1		63.0	63.0	89.1	45.0	
2		60.2	64.4	88.1	43.1	
3	32 (0.813)	61.6	63.0	88.1	44.3	
4		61.6	63.0	88.1	44.3	
5		60.2	63.0	87.1	43.7	
avg				88.1 (391.9)	44.1 (0.769)	0.40
1		58.8	64.4	87.2	42.3	
2		60.2	64.4	88.1	43.1	
3	33 (0.838)	60.2	64.4	88.1	43.1	
4		60.2	64.4	88.1	43.1	
5		60.2	64.4	88.1	43.1	
avg				87.9 (391.0)	42.9 (0.749)	0.40
1		56.0	70.0	89.6	38.7	
2		56.0	70.0	89.6	38.7	
3	34 (0.864)	57.4	68.6	89.4	39.9	
4		57.4	70.0	90.5	39.3	
5		56.0	70.0	89.6	38.7	
avg				89.7 (399.0)	39.1 (0.682)	0.41
1		62.9	62.5	88.7	45.2	
2		63.8	61.5	88.6	46.1	
3	36 (0.914)	64.8	60.9	88.9	46.7	
4		66.9	59.4	89.4	48.4	
5		69.4	61.2	92.5	48.6	
avg				89.6 (398.5)	47.0 (0.820)	0.41

Table C.8 Static load of "95-percentile" dummy* leaning backwards against top rail at 42 in (1.067 m) (continued)

Run No.	Distance from ℄ rail in (m)	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Force-to-weight ratio
1		51.8	77.0	92.8	33.9	
2		51.8	78.4	94.0	33.5	
3	39 (0.991)	51.8	78.4	94.0	33.5	
4		51.8	78.4	94.0	33.5	
5		51.8	77.0	92.8	33.9	
avg				93.5 (415.9)	33.7 (0.587)	0.43
1		70.0	56.0	89.6	51.3	
2		65.8	63.0	91.1	46.2	
3	42 (1,067)	67.2	63.0	92.1	46.8	
4		67.2	63.0	92.1	46.8	
5		63.0	65.8	91.1	43.7	
avg				91.2 (405.7)	47.0 (0.820)	0.42

C.4.3 Miscellaneous Posture Tests

In this group of tests, sample evaluations were made of 4 types of static loadings exerted on guardrails by workers engaged in miscellaneous activities. In all cases, the toprail was simulated with the instrumented rail described in section C.4.1. The 4 actions which were simulated and observed in the laboratory are described below:

(a) Sitting on a bench seat which serves as a midrail and leaning against the toprail (e.g., in a deck design lunch area): Tests were conducted with the instrumented mock-up rail at the 42-in (1.067-m) height and the seat surface at 21 in (0.533 m). The seat surface was simulated as shown in figure C.10. The different back inclinations from vertical were defined by a line from the back edge of the 12-in (0.305-m) board seat to the centerline of the top rail. It was noted that the (human) subjects found the 20-deg (0.349-rad) inclination to be the most comfortable of the 3 values tried. The resulting force measurements are shown in table C.9 tabulated as nominal values (visual average of irregular chart trace for normal sitting and body movement of the subject) and as peak values (developed by the subject in a back-shoving posture with both shoe heels (rubber) flat on the wood tread surface and deliberately thrusting against the top rail from a sitting position). Nominal forces were converted to distributed forces over shoulder widths.

Table C.9 Static load of "97.5-percentile" male adult* seated on midrail bench seat and leaning against top rail at 42-in (1.067 m) height

*Human Subject No. 101: Wt = 197.0 lb (876.2N); Shoulder Width = 18.5 in (0.470 m).
Human Subject No. 108: Wt = 208.0 lb (925.1N); Shoulder Width = 19.5 in (0.495 m).

Run No.	Value	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Distributed force lb/ft (N/m)	Force-to-weight ratio
			No. 101 at 10 deg (0.174 rad)				
1	nominal	0	25	25 (111)	0	16 (233)	0.13
	peak	0	77	77 (342)	0	-	0.39
			No. 108 at 10 deg (0.174 rad)				
2	nominal	0	14	14 (62)	0	9 (131)	0.07
	peak	0	77	77 (342)	0	-	0.37
			No. 101 at 20 deg (0.349 rad)				
3	nominal	0	35	35 (156)	0	23 (336)	0.18
	peak	49	49	69 (307)	45 (0.79)	-	0.35

Table C.9 Static load of "97.5-percentile" male adult* seated on midrail bench seat and leaning against top rail at 42-in (1.067 m) height (continued)

Run No.	Value	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Distributed force lb/ft (N/m)	Force-to-weight ratio
				No. 108 at 20 deg (0.349 rad)			
4	nominal	35	14	38 (169)	68 (1.187)	23 (336)	0.18
	peak	77	70	104 (463)	48 (0.83)	-	0.50
				No. 101 at 30 deg (0.523 rad)			
5	nominal	-7	42	43 (191)	-9 (-0.16)	28 (409)	0.22
	peak	13	62	63 (280)	12 (0.21)	-	0.32
				No. 108 at 30 deg (0.523 rad)			
6	nominal	28	21	35 (156)	53 (0.93)	22 (321)	0.17
	peak	0	63	63 (280)	0	-	0.30

(b) Leaning over a top rail used for support while carrying an additional weight (e.g., back-packing a reservoir tank while spraying from an elevated mobile scaffold): In this test the subject carried a 40-lb (177.9-N) water tank by a shoulder strap and simulated stretch-reaching over the instrumented rail, but just short of losing his balance (figure C.11). The results of this test are the nominal values listed in table C.10 derived from visually determined averages of strip chart records.

Table C.10 Static load on top rail at 42-in (1.067-m) height, of a "97.5-percentile" male adult* carrying 40 lb (177.9N) while reaching over rail

*Subject No. 108: Wt = 208.0 lb (925.1N) + 40 lb (177.9N)

Run No.	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Force-to-weight ratio
1	52	42	67	51	
2	56	49	74	49	
3	80	56	98	55	
4	70	49	85	55	
avg			81 (360)	53 (0.93)	0.21
N.B.	248	0	248 (1.103 k)	90 (1.57)	1.00

N.B.: Possible maximum (not measured)

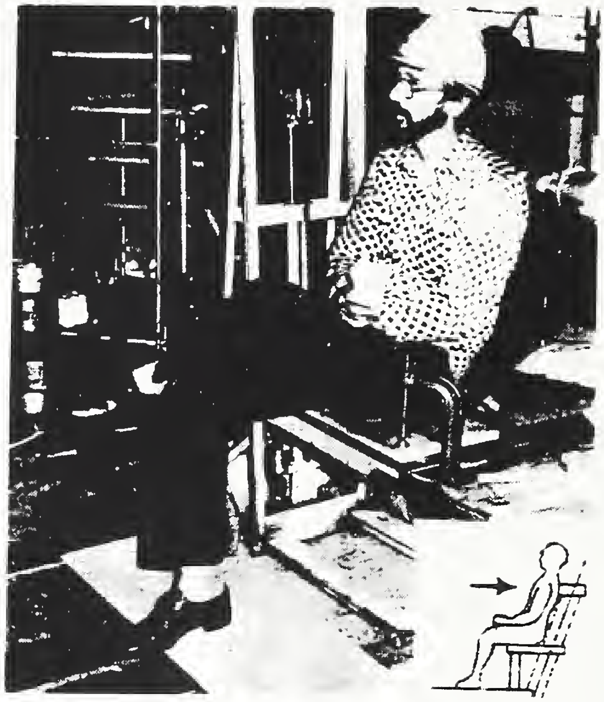


Figure C.10 Simulated guardrail bench seat and toprail.

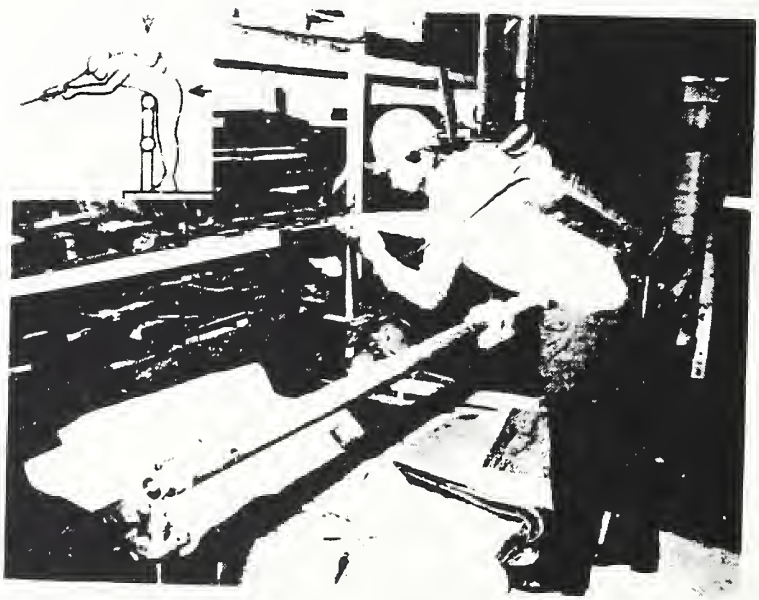


Figure C.11 Leaning on toprail for support while carrying additional weight.

(c) Leaning "over" a guardrail from a second-rank position (e.g., attempting to observe an occurrence at a lower floor level - perhaps an accident - while striving to see over another's shoulders): Figure C.12 illustrates the distribution of subjects during this test. Two formed part of a first rank contiguous with the instrumented toprail while a third subject represented the second rank trying to obtain a view beyond the first. The positions are also indicated diagramatically in table C.11 together with nominal values of static load for the incremental arrangements.

(d) Pressing against a guardrail in multiple ranks (e.g., a disorderly exodus, as from an assembly or in an emergency situation): Each of the subjects in figure C.13 represents one person in each of 3 longer ranks all pushing in tandem against the instrumented top rail. The results of this test are given in table C.12 as nominal static load values.

C.4.4 Dynamic Load Tests on Top Rail

All of the dynamic load tests were conducted using the dummy as subject and keeping the mock-up rail at the 42-in (1.067-m) height (tread surface to centerline). Each test run consisted of a backward free-fall of the dummy standing at a given distance from the rail and pivoting about its ankle joints until it struck the rail. For these tests the dummy's knee, hip, and spinal joints were made stiff. The dummy was positioned at the required distance, and its body segments were alined. No footstop was used in these tests. The dummy was balanced by hand and then unbalanced just enough to cause it to fall freely toward the rail without pushing and to strike within the central 2-ft (0.610-m) section. (This length was ample to receive the body without the gages being contacted; nevertheless, they were protected with sponge padding.) The impact was recorded by strip chart. Figure C.14(a) shows the dummy just after having struck the rail and continuing to the end of a fall below the rail (figure C.14(b). Figure C.14(c) illustrates the end of a run in which the dummy remained propped against the rail. The record of a typical dynamic load test (top rail) is shown in figure C.15. Trace records following the first pulse represent free vibration of the rail when (and if) the dummy lost contact with the rail, and repeated loadings (pulses) caused by bouncing. Load data derived from such records were converted using the calibration factor (section C.4.1). Table C.13 presents values of maximum reaction to the first impact of the dummy experienced by the rail in each test run. Table C.14 shows the results of running top rail dynamic load tests with the dummy's hip joints set at 1G friction, and loose, as opposed to the stiff hip-joints of the tests in table C.13.

Figure C.12 Two ranks of subjects watching over and below toprail.

Figure C.13 Three ranks of subjects pushing against toprail.

Table C.11 Static load on top rail at 42-in (1.067-m) height of "50-percentile" male adults* watching and leaning over rail

*Subject No. 105: Wt. = 169.0 lb (751.7N); Shoulder width = 17 1/2 in (0.445 m)
Subject No. 502: Wt. = 167.0 lb (742.8N); Shoulder width = 18 in (0.457 m)
Subject No. 503: Wt. = 140.0 lb (622.7N); Shoulder width = 17 in (0.432 m)

Run No.	Subject No. and position	Vertical Component lb	Horizontal Component lb	Resultant Force lb (N)	Angle from Horizontal deg (rad)	Distributed Force lb/ft (N/m)	Force-to-Weight ratio
1	↑ 503	28	28	40 (178)	45 (0.79)	29 (423)	0.29
2	↑ 503 105	98	14	99 (440)	82 (1.43)	34 (496)	0.32
3	↑ 503 105	105	49	116 (516)	65 (1.13)	40 (584)	0.37
4	↑ 503 105 502	160	78	178 (792)	64 (1.12)	83 (1.18k)	0.37

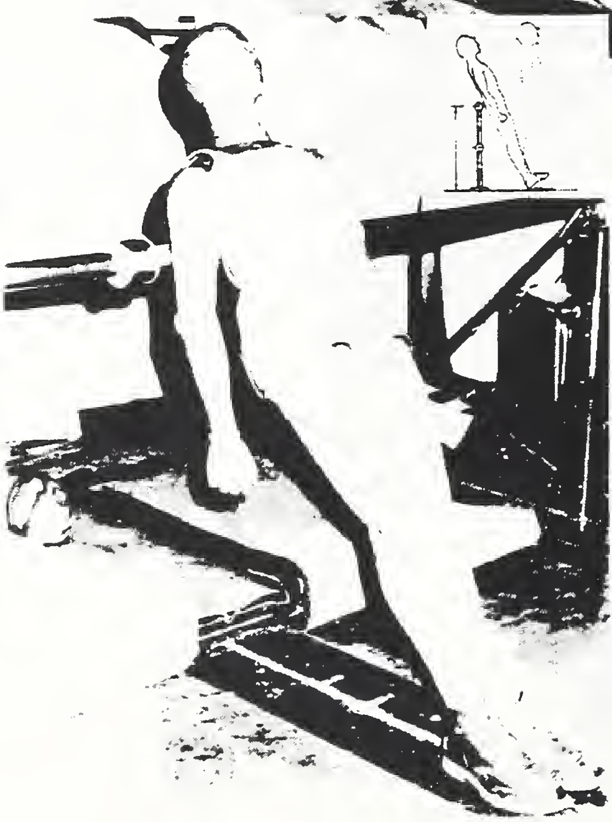
Table C.12 Static load on top rail at 42-in (1.067-m) height, of "50-percentile" male adults* in 3 ranks pushing against top rail

*Subject No. 105: Wt. = 169.0 lb (751.7N); Shoulder width = 17 1/2 in (0.445 m)
Subject No. 502: Wt. = 167.0 lb (742.8N); Shoulder width = 18 in (0.457 m)
Subject No. 503: Wt. = 140.0 lb (622.7N); Shoulder width = 17 in (0.432 m)

Run No.	Subject No. and position	Vertical Component lb	Horizontal Component lb	Resultant Force lb (N)	Angle from Horizontal deg (rad)	Distributed Force lb/ft (N/m)	Force-to-Weight ratio
1	↑ 503	51	7	51 (227)	82 (1.43)	36 (525)	0.36
2	↑ 503	49	9	50 (222)	80 (1.40)	36 (525)	0.36
3	↑ 503 105	69	25	73 (325)	70 (1.22)	50 (730)	0.24
4	↑ 503 105 502	129	45	137 (609)	71 (1.24)	94 (1.36k)	0.29

(a) Dummy falling to floor after striking top rail.

(b) Dummy at end of a complete fall to floor after striking top rail.



(c) Dummy at end of a dynamic load test in which it remained propped against top rail.

Figure C.1. Top rail dynamic load testing.

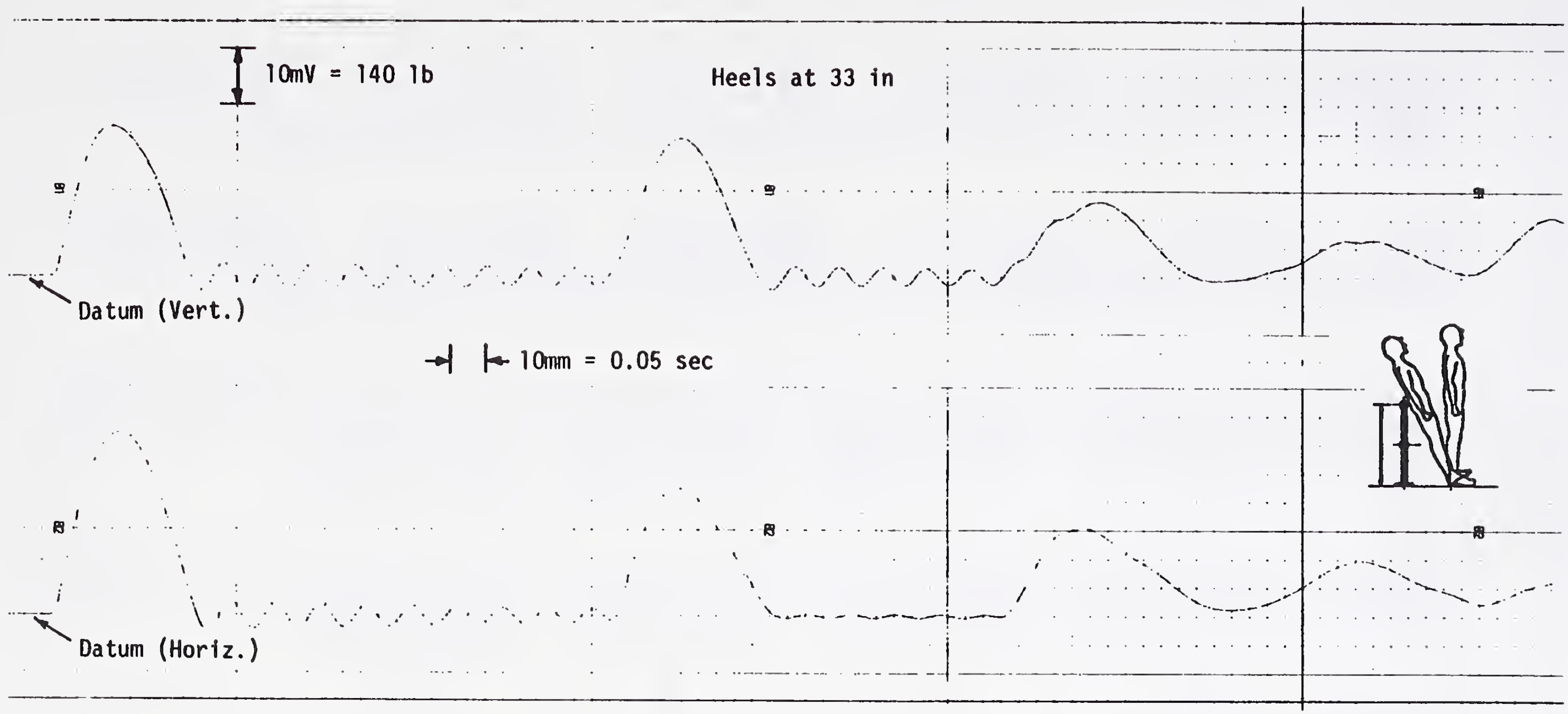


Figure C.15 Record of a dynamic load test of 95-percentile dummy on top rail at 42-in (1.067-m) height.

Table C.13 Dynamic load (backward fall) of 95-percentile dummy* on top rail at 42-in (1.067-m) height (stiff joints)

*Wt. = 219.1 lb. (974.6N); Ht. = 74.6 in. (1.895 m); C.G. = 41.8 in. (1.062 m)

Run No.	Distance from ℄ rail in (m)	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Force-to-weight ratio	Remarks
1		43.4	187.6	193.2	13.0		propped against rail
2	12	42.0	184.8	189.0	12.8		" " "
3	(0.305)	44.8	182.0	187.6	13.8		" " "
4		42.0	177.8	183.4	13.3		" " "
5		46.2	180.6	186.2	14.4		" " "
avg				187.9 (835.8)	13.5 (0.235)	0.86	
1		173.6	322.0	365.4	28.3		propped etc; feet slipped forward 6 in (152 mm)
2	18	165.2	310.8	351.4	28.0		
3	(0.457)	179.2	322.0	368.2	29.1		
4		179.2	299.6	348.6	30.9		" " "
5		175.0	310.8	357.0	29.4		" " "
avg				358.1 (1.593 k)	29.1 (0.509)	1.63	
1		275.8	376.6	463.4	36.2		propped etc.
2	24	285.6	396.2	488.6	35.8		" " "
3	(0.610)	273.0	392.0	477.4	34.9		" " "
4		259.0	415.8	490.0	31.9		" " "
5		257.6	401.8	477.4	32.7		" " "
avg				479.4 (2.132 k)	34.3 (0.599)	2.19	
1		294.0	488.6	569.8	31.0		propped etc.
2	30	294.0	490.0	571.2	31.0		" " "
3	(0.762)	306.6	480.2	571.2	32.6		" " "
4		296.8	484.4	568.4	31.5		" " "
5		312.2	457.8	554.4	34.3		" " "
avg				566.7 (2.521 k)	32.1 (0.560)	2.59	

Table C.13 Dynamic load (backward fall) of 95-percentile dummy* on top rail at 42-in (1.067-m) height (stiff joints) (continued)

Run No.	Distance from ℄ rail in (m)	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Force-to-weight ratio	Remarks
1		296.8	470.4	555.8	32.2		propped etc.
2		297.1	476.0	561.4	32.1		" "
3	32	296.8	464.8	551.6	32.6		fell below rail
4	(0.813)	291.2	470.4	553.0	31.8		" "
5		280.0	471.8	548.8	30.7		" "
avg				554.1 (2.465 k)	31.9 (0.556)	2.53	
1		366.8	448.0	579.0	39.3		fell below rail
2		379.4	401.8	552.6	43.4		" "
3	33	355.6	425.6	554.6	39.9		" "
4	(0.838)	348.6	435.4	557.7	38.7		" "
5		319.2	446.6	548.6	35.6	2.55	" "
avg				558.6 (2.485 k)	37.0 (0.646)		
1		403.2	369.6	547.4	47.5		fell below rail
2	34	406.0	365.4	546.0	48.0		" "
3	(0.864)	414.4	392.0	569.8	46.6		" "
4		429.8	351.4	555.8	50.7		" "
5		428.4	362.6	561.4	49.8		" "
avg				556.1 (2.473 k)	48.5 (0.847)	2.54	
1		336.0	420.0	537.6	38.7		fell below rail
2		226.0	448.0	520.8	30.7		" "
3	36	280.0	434.0	516.6	32.8		" "
4	(0.914)	345.8	424.2	547.4	39.2		" "
5		312.2	442.4	541.8	35.2		" "
avg				532.9 (2.370 k)	35.3 (0.616)	2.43	
1		289.8	280.0	404.6	46.0		fell below rail
2		289.8	268.8	394.8	47.2		" "
3	42	294.0	277.2	404.6	46.7		" "
4	(1.067)	317.8	240.8	399.0	52.8		" "
5		295.4	259.0	393.4	48.8		" "
avg				399.3 (1.776 k)	48.3 (0.843)	1.82	

Table C.14 Effect of hip joint condition (1G, loose) on dynamic load of 95-percentile dummy on top rail at 42-in height (cf. table C.13)

Run No.	Distance from ℄ rail in.	Vertical component lb	Horizontal component lb	Resultant force lb	Angle from horizontal deg	Force-to-weight ratio	Remarks
1	30	302.4	487.2	573.4	31.8	2.62	1G-hips;fell below rail
1	33	434.0	340.2	551.4	51.9	2.52	" "
2	33	443.8	371.0	578.4	50.1	2.64	" "
1	36	280.0	434.0	516.5	32.8	2.36	" "
1	42	301.0	254.8	394.3	49.7	1.77	" "
2	42	296.8	253.4	390.3	49.5	1.78	" "
1	33	242.2	413.0	478.8	30.4	2.19	Loose hips; jack-knifed below rail

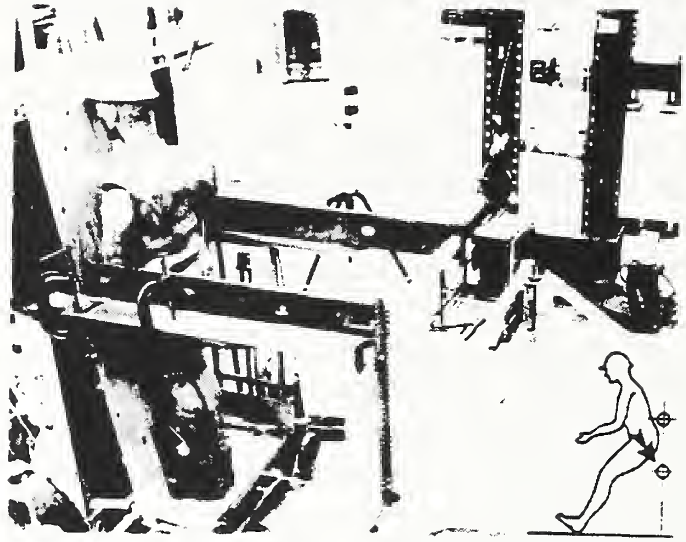
C.4.5 Dynamic Load Tests on Intermediate Rail

Figure C.16 shows an experimental setup for simulating a 2 rail (top and intermediate) guardrail used to investigate the impact experienced by a midrail when struck by a body which first hit the toprail. These tests were performed with the instrumented mock-up rail representing different intermediate heights in a 42-in (1.067-m)-high guardrail system at which secondary impact might occur after a falling body struck the top rail. The apparatus was devised to avoid readjusting the instrumented rail to different test heights repeatedly. The instrumented rail was fixed at 34 in (0.864 m) above the laboratory floor for convenience and the top rail and tread platform were positioned above and below it to achieve the desired effective intermediate rail height. The toprail of the apparatus was a 2-in (51-mm) diameter solid aluminum rod (not instrumented) which was positioned directly above and parallel to the instrumented intermediate rail and end-bolted to 2 structural steel angles clamped as extensions to the forks of a heavy lift truck. The adjustable tread surface was provided by a plywood board attached to the tines of a manual forklift. The top rail was always placed at 42 in (1.067 m) above the level of the tread platform. Body-rail distances were set by shifting the entire tread platform lift truck laterally. The vertical plywood board seen in figure C.16(a) (against which the dummy subject is leaning) was used to "launch" the dummy from an erect position into a backward fall against the toprail with zero initial velocity. A small diagonally braced toe board (figure C.16) was used in these dynamic load tests to attain reproducible falling action prior to secondary impact. On the basis of preliminary testing, the hip joints of the dummy were loosened to "zero" friction to facilitate jackknifing after impacting the top rail.

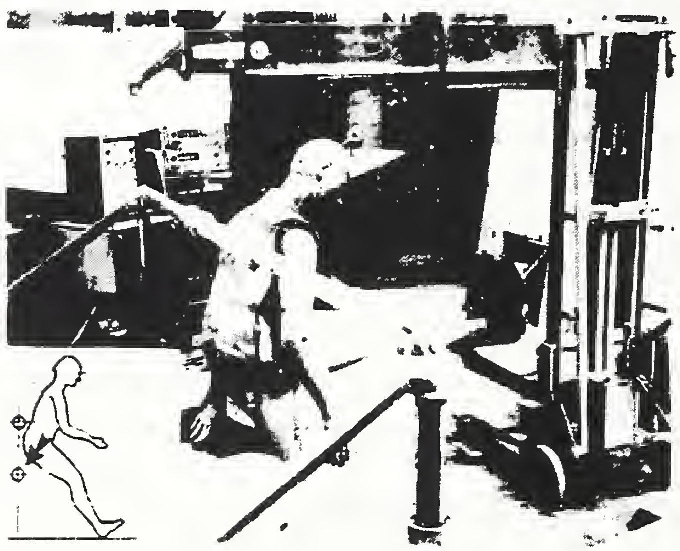
Table C.15 presents the values of maximum reaction experienced by the intermediate rail from impact by the dummy following its initial contact with the top rail. In the test involving a fall from 30 in (0.838 m) on the intermediate rail at 21 in (0.533 m) only the first trial resulted in jackknifing. Figure C.17 is a representative strip chart record of an intermediate-rail dynamic load test. The greater irregularity of loading (in contrast with that of the top rail tests) apparent in the traces reflects the interrrupted falling of the subject. The small perturbations preceding the first impulse were caused by the dummy's swinging arms striking the instrumented rail before the major impact.

C.4.6 Load-Displacement Tests for Wire Rope

The experimental setup to demonstrate interaction of wire rope tension, transverse load, and deflection used a stiff, bolted structural bent as a supporting frame for the cable. For these tests a 1/2-in (12.7-mm) diameter, non-preformed wire rope of traction steel, 8 x 19 Seale Patent, right regular lay construction was stretched across a nominal 14-ft (4-m) clear-span between columns. Bushings in the oversize through holes of the columns provided a snug running fit for the cable. Tensioning of the cable was done by a



(a) Before test



(b) After test

Figure C.16 Midrail dynamic load test setup.

Table C.15 Dynamic load (backward fall) of 95-percentile dummy* on intermediate rail after striking top rail at 42-in (1.067-m) height (loose hips)

*Wt. = 219.1 lb (974.6N); Ht. = 74.6 in (1.895 m); C.G. = 41.8 in (1.062 m)

Run No.	Height of intermediate rail in (m)	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Force-to-weight ratio	Remarks
			Distance from ℄ of rail = 30 in (0.762 m)				
1 (of 6)	21 (0.533)	324.8	198.8	380.8 (1.694 k)	58.5 (1.021)	1.74	Only one jack-knife in 6 trials
			Distance from ℄ of rail = 33 in (0.838 m)				
1		103.6	138.6	173.0	36.8		Hit midrail;
2	28 (0.711)	134.4	180.6	225.1	36.7		bounced once; brushed past.
3		121.8	183.4	220.2	33.6		" " " "
avg				206.1 (916.7)	35.7 (0.623)	0.94	
1		382.2	158.2	413.6	67.5		Hit midrail;
2	24 (0.610)	329.0	189.0	379.4	60.1		bounced once; brushed past.
3		375.2	200.2	425.3	61.9		" " " "
avg				406.1 (1.806 k)	63.2 (1.102)	1.85	
1		263.2	232.4	351.1	48.5		Dummy wedged
2	21 (0.533)	254.8	203.0	325.8	51.5		against midrail; feet flat on tread.
3		280.0	224.0	358.6	51.3		" " " "
avg				345.1 (1.535 k)	50.4 (0.880)	1.57	
1		463.4	236.6	520.3	62.9		Hit midrail; bounced twice; fell sideways
2	18 (0.457)	460.6	74.2	466.5	80.8		Hit midrail; bounced once;
3		408.8	214.2	461.5	62.3		rested on midrail.
avg				482.8 (2.147 k)	68.7 (1.198)	2.20	

Table C.15 Dynamic load (backward fall) of 95-percentile dummy* on intermediate rail after striking top rail at 42-in (1.067-m) height (loose hips) (continued)

Run No.	Height of intermediate rail in (m)	Vertical component lb	Horizontal component lb	Resultant force lb (N)	Angle from horizontal deg (rad)	Force-to-weight ratio	Remarks
			Distance from ℄ of rail = 36 in (0.914 m)				
1		-15.4	247.8	248.3	-3.5		Hit midrail; bounced once; brushed past.
2	28 (0.711)	-14.0	256.2	256.6	-3.1		
3		144.2	196.0	243.3	36.3		" " " "
avg				249.4 (1.109 k)	--	1.14	
1		308.0	210.0	372.8	55.7		Hit midrail; bounced once; brushed past.
2	24 (0.610)	148.4	235.2	278.1	32.2		
3		270.2	217.0	346.5	51.2		" " " "
avg				332.5 (1.479 k)	46.4 (0.809)	1.52	
1		434.0	88.2	442.9	78.5		Hit midrail; fell clear.
2	21 (0.533)	406.0	126.0	425.1	72.7		
3		420.0	124.6	438.1	73.5		" " " "
avg				435.4 (1.937 k)	74.9 (1.307)	1.99	
1		357.0	337.4	491.2	46.6		Hit midrail; bounced twice; fell clear.
2	18 (0.457)	520.8	77.0	526.5	81.6		Hit midrail; bounced once; brushed past.
3		434.0	133.0	453.9	73.0		Hit midrail; lingered; fell clear
avg				490.5 (2.182 k)	67.1 (1.171)	2.24	

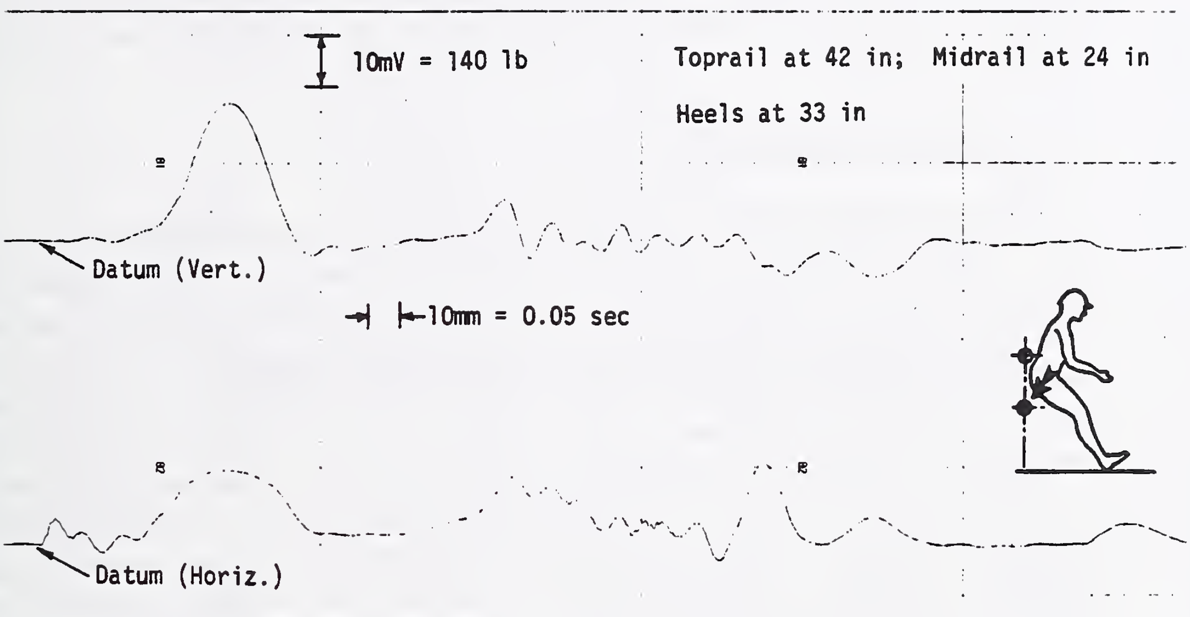


Figure C.17 Record of a dynamic load test on intermediate rail at 24-in (0.610-m) height by 95-percentile dummy.

center-hole, manually pumped, hydraulic jack and measured by a hollow-cylinder force transducer placed in tandem over the cable. Anchorage at both ends of the cable was supplied by split-cone wedge grippers as used in prestressing of strands. Deflection of the cable was produced by pulling at its midlength with a hook, linked to a force transducer (similar to that described above) and attached to the tine of a fork lift. The force measuring systems were accurate to within ± 1%. Deflections of the cable were measured with a scale to the nearest 1/32 in (0.8mm).

As indicated in table C.16 each run consisted of (1) applying the desired level of initial cable tension, (2) applying the transverse load and measuring the resulting deflection and tension, and (3) removing the transverse load and measuring the final cable tension. The initial tension was then readjusted to the desired value before applying the next transverse load.

C.4.7 Destructive Flexural Tests

Figure C.18 shows the equipment used in conducting resistance tests of common guardrail stock. Forces were applied at midlength to specimens (supported as simple beams) by the loading head of a hydraulic testing machine, and an xy recorder plotted load and deflection. The span length used in testing the steel pipe rails was set at 10 ft (3.048 m) for convenience. To insure stability, the pipe, at the fulcrum reactions, rested in cradles formed by (hot-melt) gluing small wooden uprights to the 6 x 6 x 1/4-in (152 x 152 x 6.3 mm) steel bearing plates; also, a wooden block, grooved to fit the outside diameter of the pipe, was placed between the specimen and the central load applicator. Load was applied at a rate of 100 lb/min (7.41 N/sec), and measured with a 500-lb (2.224-kN)-capacity force transducer connected to the xy recorder. Tests of the pipe rail were terminated after reaching either a permissible 110% capacity overload of the force transducer or the 6-in (152.4 mm) capacity of the LVDT displacement transducer. Loads were removed and permanent deformations measured. The results of the tests on Schedule 40 1 1/4-in (31.7-mm) and 1 1/2-in (38.1-mm) pipe specimens are given in figure C.19.

The simple beam span length used in testing the construction grade Hem-Fir 2 x 4's (with the long side horizontal) was 6 ft (1.829 m). This span was chosen to make possible one test of a specimen containing only a single "factory-made" glued finger splice placed at the midspan. The specimens were placed on 6 x 6 x 1/4-in (152 x 152 x 6.3-mm) steel bearing plates at the fulcrums and the bottom of the central load applicator was given a 6-in (152.4-mm) radius of curvature to allow for flexing of the specimens. Load was applied at a rate of 100 lb/min (7.41 N/sec). The test of the specimen containing the finger splice at midspan (run no. 1) was terminated by fracture of the specimen at the splice by a load of 315 lb (1.401 kN). The specimen with no splices in a span length equal to that of run no. 1 was tested (run no. 2) to destruction at 730 lb(3.247 kN). The splintering rupture at midspan is seen in figure C.18. The results of the flexure tests are given in figure C.20.

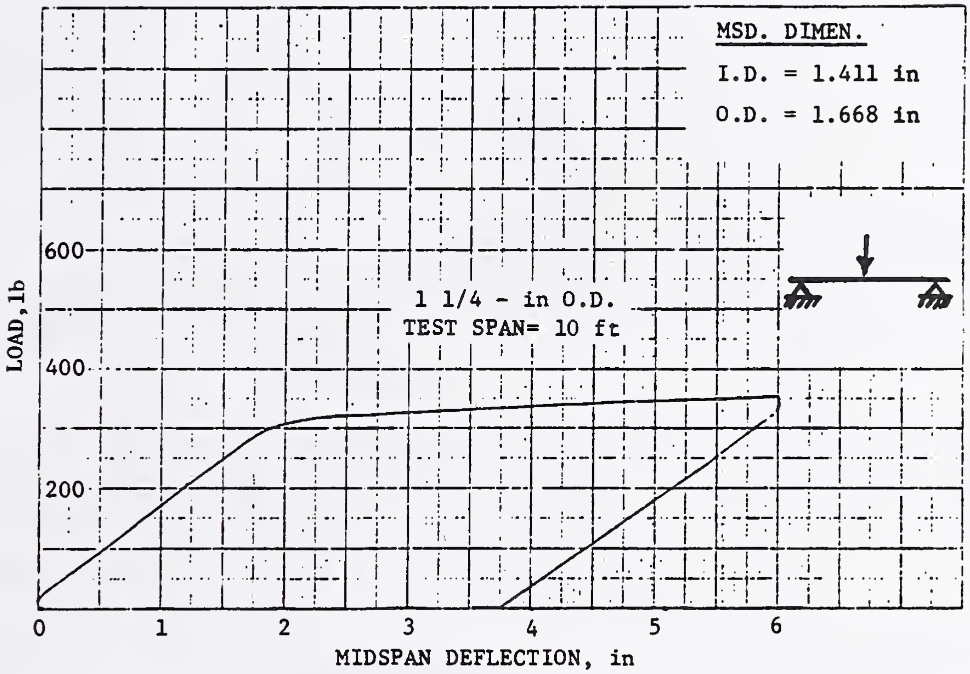
Table C.16 Interrelationship of tension, transverse load and deflection in a 1/2-in (12.73-mm) diameter wire rope over a 14-ft (4-mm) span*

	Initial Cable Tension	2000 lb (8.896 kN)			4000 lb (17.792 kN)			6000 lb (26.688 kN)	
Run No.	Transverse Mid-length Load lb (kN)	Cable Tension lb (kN)	Deflection in (mm)	Run No.	Cable Tension lb (kN)	Deflection in (mm)	Run No.	Cable Tension lb (kN)	Deflection in (mm)
	0	2000	0		4000	0		6000	0
1	100 (0.445)	2165 (9.630)	1 13/16 (46.0)	6	4041 (17.974)	15/16 (23.8)	11	6014 (26.750)	5/8 (15.9)
	0	1863	0		3547	0		5121	0
	0	2000	0		4000	0		6000	0
2	200 (0.890)	2618 (11.645)	3 5/16 (84.1)	7	4234 (18.833)	1 15/16 (49.2)	12	6110 (27.177)	1 3/8 (34.9)
	0	1904	0		3890	0		5753	0
	0	2000	0		4000	0		6000	0
3	400 (1.779)	3511 (15.617)	5 3/16 (131.8)	8	4879 (21.702)	3 21/32 (92.9)	13	6522 (29.010)	2 3/4 (69.9)
	0	1959	0		3986	0		5959	0
	0	2000	0		4000	0		6000	0
4	600 (2.669)	4308 (19.162)	6 7/16 (163.5)	9	5511 (24.513)	5 (127.0)	14	6893 (30.660)	4 (101.6)
	0	2000	0		4000	0		5986	0
	0	2000	0		4000	0		6000	0
5	800 (3.558)	4967 (22.093)	7 3/8 (187.3)	10	5868 (26.101)	6 5/32 (156.4)	15	7016 (31.207)	5 5/16 (134.9)
	0	2000	0		4000	0		5986	0

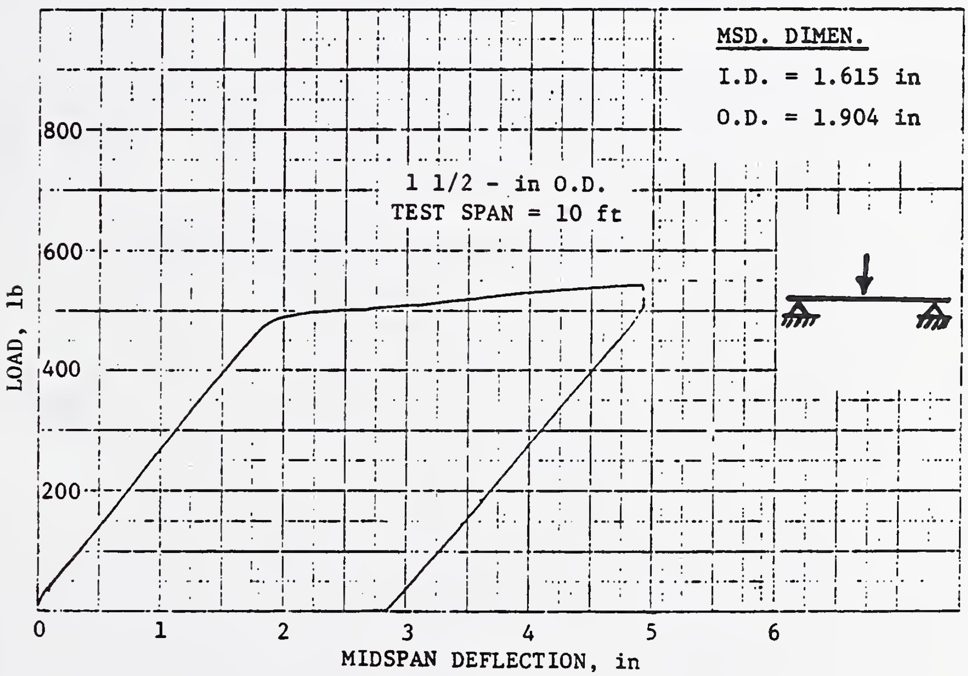
*Wire rope: non-preformed traction steel, 8 x 19 Seale Patent; span = 14.31 ft (4.362 m)

Manufacturer's properties: Breaking strength = 14,500 lb (64.496 kN)
Modulus of Elasticity = 13 x 10^6 psi (8.96 x 10^7 kPa)
Weight = 0.36 lb/ft (5.25 N/m)

Figure C.18 Resistance testing of rail stock.

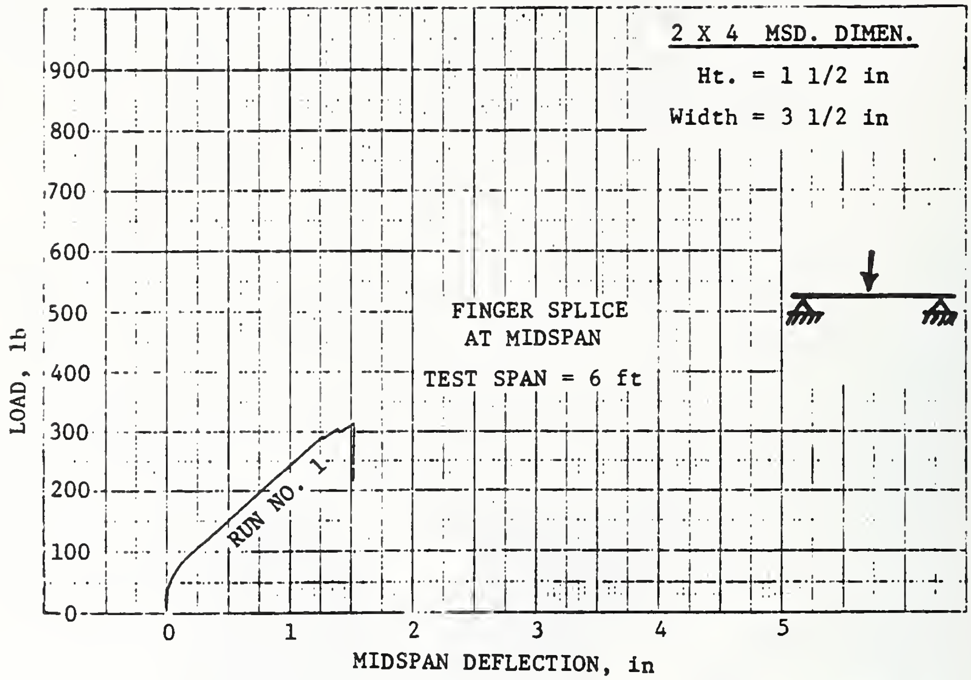


(a) Load - deflection record of transverse central static loading on schedule 40 1 1/4-in (32-mm) steel pipe rail.

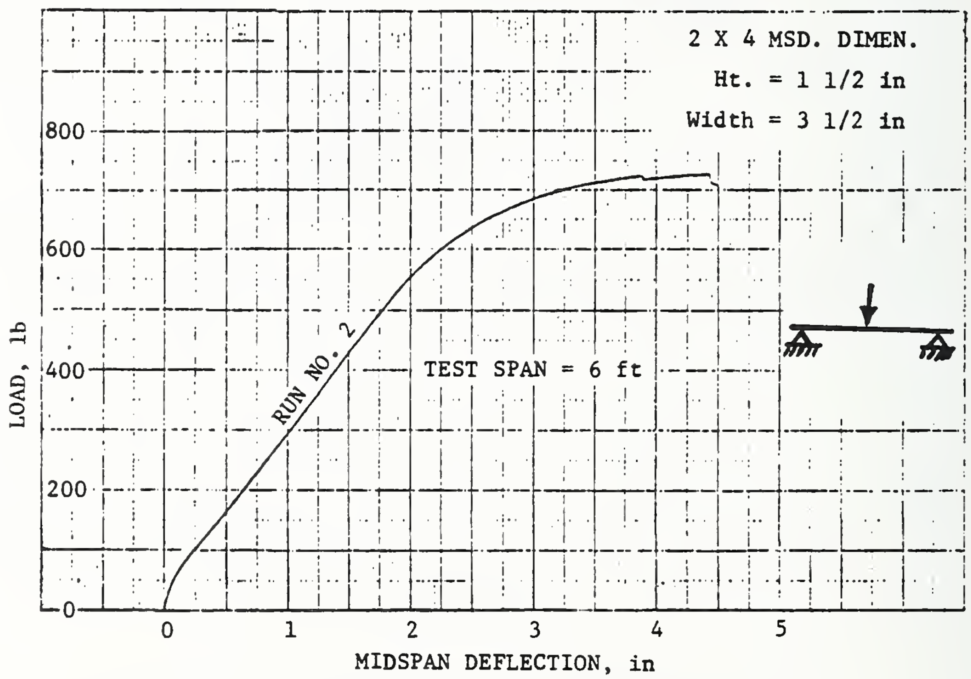


(b) Load - deflection record of transverse central static loading on Schedule 40 1 1/2-in (38-mm) steel pipe rail.

Figure C.19 Results of destructive flexural tests on pipe.



(a) Load - deflection record of transverse central static loading on construction grade Hem-Fir 2 x 4 rail containing finger-splice.



(b) Load - deflection record of transverse central static loading on unspliced construction grade Hem-Fir rail.

Figure C.20 Results of destructive flexural tests on 2 x 4's.

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16. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.*)

State-of-the-art studies, together with experimental and analytical investigations, are conducted to determine structural and non-structural safety requirements for guardrails used for the protection of employees against occupational hazards. The critical aspects of guardrail safety have been identified through exploratory studies consisting of field surveys of prototypical installations, reviews of existing standards and industrial accident records, and compilation of relevant anthropometric data. These exploratory studies are utilized to establish an experimental program consisting of resistance tests of guardrail components, static and dynamic load measurement tests using human subjects and an anthropomorphic dummy, and non-structural tests to determine geometric requirements for guardrail safety. Based on these investigations, a model performance standard and a design guide for guardrails are proposed.

17. KEY WORDS (*six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*) Anthropometric measurements; anthropomorphic dummy; design dynamic loads; guardrails; industrial accidents; non-structural safety; occupational hazards; performance standards; personnel railings; personnel safety; static loads; stiffness; structural safety.

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