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SAFETY BRIEF

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Quantification versus Go/No-Go Criteria*

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Abstract

Compliance or noncompliance with a sound safety code or standard is currently the most rational way of judging whether a product or system is sufficiently safe. Many such codes and standards specify minimum numerical criteria such as loading, tilt angle and duration time by which compliance may be judged. Usually it is more valuable to make judgments based on quantitative test data as opposed to meeting minimum criteria. For example, a lawn and garden tractor will remain stable when tilted laterally to 28.7° compared with the go/no-go minimum specification of 20°. This paper illustrates the richness of quantification for a number of different products including hook-on high chairs, grinding wheels, structural members and smoke detectors.

INTRODUCTION

This paper addresses safety criteria which can be expressed quantitatively, e.g., a handrail must support at least 890 N (200 lb).[1] It does not deal with safety specifications that are qualitative in nature which are the type that dominate safety codes and standards. Examples of qualitative specifications are: nip points must be guarded, hostage controls shall be used, or a single component failure must not lead to an injury.

Quantitative information is stated as go/no-go criteria which establishes the compliance or noncompliance with a code, standard, standard of care, state of the art or perhaps a subjective criterion created by an individual practitioner. When a manufacturer adopts the prevailing go/no-go safety criterion, he essentially satisfies the legal concept of negligence theory which requires him to behave like other manufacturers and designers in like or similar circumstances. There are legal doctrines which suggest that meeting a go/no-go criterion represents a rebuttable presumption of good safety design.[2] The legal concept of strict liability normally challenges go/no-go criteria by incorrectly characterizing them as "merely minimum safety standards."

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SAFETY COMPARISON

Theory

Most codes and standards which deal with quantitative criteria specify a go/no-go criteria in an unequal form. For example, a forklift truck shall remain stable on a tilt table at an angle of at least 10°.[3] These codes and standards address the design of a particular device or system as deterministic. The idea is that if one or a few prototypes comply with the code then all subsequent prototypes are characterized as safe.

Manufacturers will almost always set up a proof test at the go/no-go criterion. In the stability example, the forklift truck will be tested at exactly 10° to determine whether it passes or fails the test. The quantitative approach provides another way of characterizing the design. Here, the design is tested to failure. Of course, the proof testing information is still obtained together with the maximum performance and the associated ultimate failure mode.

The quantification approach may be used to characterize various models and competitors who manufacture similar devices. The quantification produces a ranking of the various candidates and indicates the weak link in each one. Note that the proof testing approach merely differentiates those candidates which pass and those which do not. In the legal setting, the quantification approach provides the jury with additional information it may think significant in judging a product. It may be persuasive to demonstrate that a product not only passes the go/no-go criterion, but also passes with a significant margin. On the other hand, when comparing various products, the discovery that one dog is the prettiest does not imply that the others are ugly.

Example: Hook-On High Chair

Description of Concepts. Portable legless hook-on high chairs such as those shown in Table 1 can be attached to a table edge in a variety of ways so that the surface of the table acts as the feeding surface for the infant occupant. The basic cantilever design allows the chair to be conveniently hooked onto and unhooked from the table edge. It depends on a child's weight to create the friction needed to hold the stationary arms and feet securely against the table. In comparison, the spring-biased locking bar design utilizes two independent pivoting locking bars covered by a gripping material which dig into the underside of the table to hold the chair stationary. Similarly, the pivoting gripper feet design relies on frictional contact between a pair of pivoting gripper feet which are latched into position and the undersurface of the table. Finally, the C-clamp design utilizes two independent adjustable screw C-clamp arms to secure the chair to the table top.

ASTM Standard. The performance requirements and test methods designed to ensure the satisfactory performance of the portable hook-on chair can be found in *Standard Specification for Consumer Safety for Portable Hook-on Chairs, ASTM F1235-89.*[4] Specifically, section 4.9 prescribes the procedure for the chair pull test which consists of securely affixing the chair to the table top, placing weights evenly distributed on a wood block on the center of the seat, and applying a static force away from the table from a point in the middle of the seat back along the same plane of the table, using a strap or belt for 10 seconds. Table 1 of the ASTM standard prescribes a pull-back force of 240 N (54 lb) for a 10.9 kg (24 lb) weight in the seat. The performance requirements in section 3.6 state that the chair shall remain attached to the table top when subjected to the test forces perpendicular to the table. After an initial pull-back force of 240 N (54 lb) was applied for 30 seconds, additional pull-back forces were added at 10 second intervals until the chair detached from the table.

Test Results. Pull-back tests on hook-on high chairs are nondestructive which makes it possible to test both exemplars (nominally identical) and the artifact (accident) high chair. A sample of candidate hook-on chairs was tested which included an artifact, an exemplar, and a group of competitive hook-on chairs. The failure loads and failure modes associated with this sample are displayed in Table 1 where it should be noted that the C-clamp design would have failed a go/no-go criterion of 240 N (54 lb). Most of the chairs significantly exceeded the ASTM criterion. Comparisons and ranking among the candidates must be carefully weighed, keeping in mind that the ranking is affected by the design concept, the execution of the concept, and the fidelity of the manufactured test specimen.

ROBUSTNESS

Theory

The term "robustness" is used in such areas as statistics, process control theory, and software design. Robust designs are characterized by their insensitivity to small departures from idealized states. A robust design will have greater resistance to misuse, aging, wear, and marginal maintenance.

The proof testing or go/no-go approach does not characterize a design so that it may be determined whether it passes the criteria "by the skin of its teeth." Framers of codes must be mindful to choose go/no-go levels which produce designs that manifest sufficient forgiveness. Another way of stating this is that the go/no-go criteria must reflect the minimum required safety factor; indeed, this is usually the case.

The quantitative approach enables one to state the safety factor precisely. For example, *American Standard Safety Code for Power Presses, ASA B11.1-1960*, requires that foot switch guards withstand a downward load of 90.7 kg (200 lb).[5] If we assume, for instance, that the quantitative approach reveals a 218 kg (481 lb) collapse load, it is then straightforward to state the safety factor associated with a 95th percentile man (94.8 kg/209 lb) standing on the foot switch cover. For example,

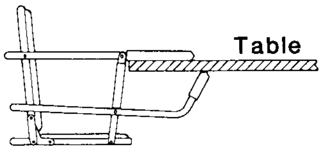
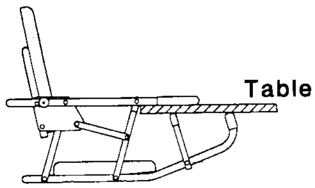
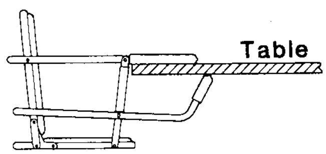
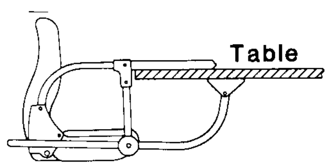
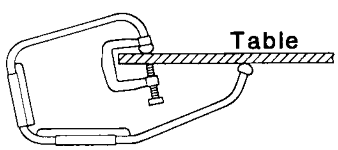
$$\text{Safety Factor}^1 = \frac{(218 - 94.8)\ \text{X}\ 100\%}{94.8} = 130\%$$

The robustness of the cover may be judged by its safety factor. On the other hand, a high safety factor may indicate that a cost savings is possible. Usually, the lowest permissible safety factor is associated with minimum cost design.

Example: Stab Lock

Description of Concept. Many modern appliances such as AC powered smoke detectors utilize the stab lock concept for their electrical power connections. In contrast to the classical connection which wrapped single or multiple conductors around a screw post, which is subsequently tightened, a solid conductor of a stripped wire is inserted into a hole where the stab lock automatically grips and holds it in position.

Table 1 Hook-On High Chair Pull-Back Tests

Test Chair Design		Failure Load - N (lb)	Failure Mode
Cantilever A		449 (101)	Arms & legs detach from table
Locking Bar A		351 (79)	Locking bars invert; Arms & legs detach from table
Locking Bar B		351 (79)	Arms & legs detach from table
Locking Bar C		338 (76)	Locking bars invert; arms & legs detach from table
Cantilever B		338 (76)	Arms & legs detach from table
Gripper Feet		280 (63)	Gripper feet & legs detach from table
C-Clamp		236 (53)	Left C-Clamp detaches from table & chair rotates counterclockwise

The elements of the stab lock concept are illustrated in Fig. 1.

UL Standard. When stab locks are used in smoke detectors, the structural integrity of the field wire leads is established by *Standard for Safety: Single and Multiple Station Smoke Detectors, UL 217.*[6] Section 68.4 states, "Each lead employed for field connections, including a battery clip lead assembly, shall withstand for one minute a pull of 10 pounds-force (44.5 N) without any evidence of damage or of transmittal of stress to internal connections." A slightly more sophisticated quantitative test program was established by subjecting candidate stab locks to pull-out forces of ever increasing magnitude where each loading increment was held one minute. An exemplar and candidates were tested until they failed by fracture or release of the wire lead.

Test Results. The pull-out test results on eight stab lock designs are found in Table 2 where we observe that all of the candidates have a pull-out resistance significantly greater than 44.5 N (10 lb). Indeed, one candidate was ten times the go/no-go criterion. It is easy to argue that pull-out forces of over 111 N (25 lb) are sufficiently robust to deal with wide ranging installation contingencies.

UNDERDESIGN AND OVERDESIGN

Weak Links

Proof testing generally gives unsatisfactory information relative to failure mode. Since most candidate designs pass the go/no-go criteria, no failure is experienced and no failure mode is observed. In circumstances where the proof test greatly exceeds the ultimate loading, the observed failure response may represent a number of failure modes rather than the mode associated with the weak link. The multiple failure modes may mask one another and may preclude the systematic reinforcement of the design so that the proof test criteria may be met effectively. When the quantitative approach is used, the generalized load is increased until the first failure is observed. This enables the designer to reinforce the weak link, which in turn, allows a device to achieve a greater resistance. Under the quantitative approach, the device contin-

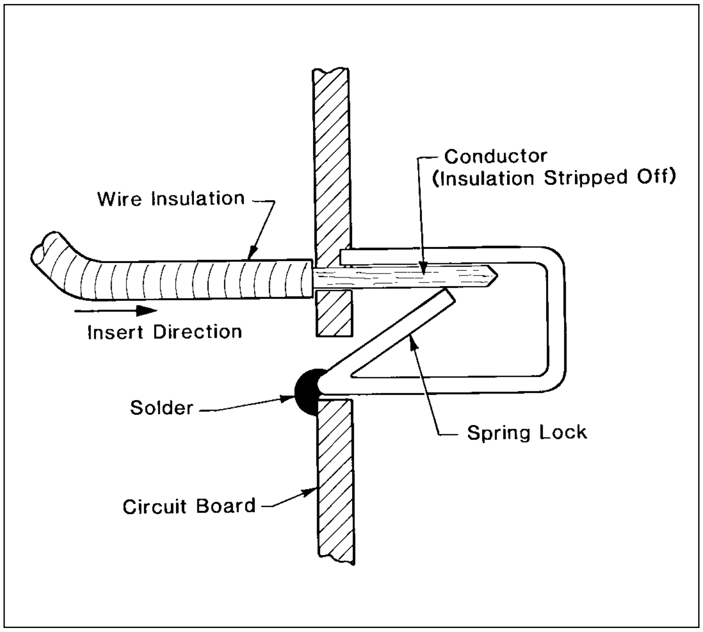


Figure 1. Stab Lock

Table 2 Stab Lock Pull-Out Tests for Smoke Detectors

Stab Lock	Pull-Out Force - N (lb)	Failure Mode
Leviton Outlet	454 (102)	Fractured housing
G.E. Switch	371 (61)	Slipped
Leviton Switch	254 (57)	Fractured housing
Ace (Eagle) Outlet	205 (46)	Fractured housing
Eagle Outlet	182 (41)	Slipped
BRK 2839ACI	169 (38)	Slipped
G.E. Outlet	160 (36)	Slipped
Eagle Switch	116 (26)	Fractured housing

ues to be tested until the next failure mode is observed and the associated weak link reinforced. The idea is to reinforce only those items that are not sufficiently strong.

Overdesign

In contrast with the proof testing procedure, the quantitative approach reveals the ultimate load which in some cases may be much higher than the go/no-go criteria. It should be remembered that the Engineering Code of Ethics requires that engineers shall hold paramount the public welfare (i.e., economic welfare) in the performance of their professional duties. Overdesign generally means that the device is too costly. Whereas the quantitative approach may be used to reduce systematically the strength and cost, the proof testing approach provides no useful information with respect to overdesign.

Example: Motorcycle Helmet Retaining System

To retain a motorcycle helmet in position on the user's head, a retention system is used which typically consists of a buckle, a chin strap, a helmet bracket, and sometimes hardware which attaches the chin strap to the bracket. The strap has stitching near the buckle and stitching near the helmet bracket. Each of the above elements may fail during an excursion when their structural integrity is exceeded. Furthermore, the geometry of the retention system may be compromised in the face of excessive strap elongation.

ANSI Standard. The performance of a motorcycle helmet retention system may be evaluated using *American National Standard Specifications for Protective Headgear for Vehicular Users, ANSI Z90.1-1971.*[7] Using a roller fixture specified by this standard and a standard headform described by the *Motorcycle Helmets Standard, FMVSS 218,*[8] the test fixture shown in Fig. 2 and Fig. 3 was designed and fabricated so that performance criteria for the helmet retention system stated in paragraph 11.2 of ANSI Z90.1-1971 could be evaluated:

> "The retaining system shall be tested for ultimate strength and for elongation under tension, as follows. After applying a 50 lb preload ±1 lb (23 kg ±0.5 kg) for no less than 30 s, an additional 250 lb -0, +5 lb (113.6 kg -0, +2.2 kg) weight or tension equivalent thereto shall be applied to the device retained by the chin strap for no less than 2 minutes. Any parting of the strap or its attachments, or elongation of more than 1 inch (25.4 mm) in the vertical distance of the chin strap from the helmet crown, as measured between preload and 300 lb (136 kg) load, shall result in failure."

Fig. 2 shows a helmet in the test apparatus in the 23 kg (50 lb) preload configuration and Fig. 3 shows the test apparatus in the 136 kg (300 lb) test load configuration.

Three sample Kiwi Model K-10 motorcycle helmets were tested and no parting of the chin strap or its attachments took place. The chin strap elongations are tabulated in Table 3 where it is observed that all elongations are 2.6 cm (1 in.) or less and therefore meet the ANSI criterion. We observe that the proof test merely demonstrates that the helmet satisfies ANSI, but gives no information relative to possible overdesign and certainly does not identify the weak link in the retention system. To develop this additional information, a destructive quantitative program was employed which incorporated the ANSI test fixture into a universal testing machine as illustrated in Fig. 4.

Using helmet samples 1 and 2 of the previously tested units, a continuously increasing tension was used to load the ANSI test fixture by an Acco-Riehle universal tension/compression tester. The failure loads and modes are indicated in Table 4 where we observed 119% and 129% increase in the chin strap resistance over the ANSI criterion. Furthermore, we observed that the weakest link in the helmet retention system was the shell bracket. With this information, the system strength can be increased by reinforcing the bracket until the next "weak link" appears. On the other hand, one may choose a lighter strap or a lower cost fastener since these elements are clearly too strong for the present system.

MINIMUM STANDARD ATTACK

A great many codes and standards use the word minimum somewhere in their foreword, scope or introduction. Because of

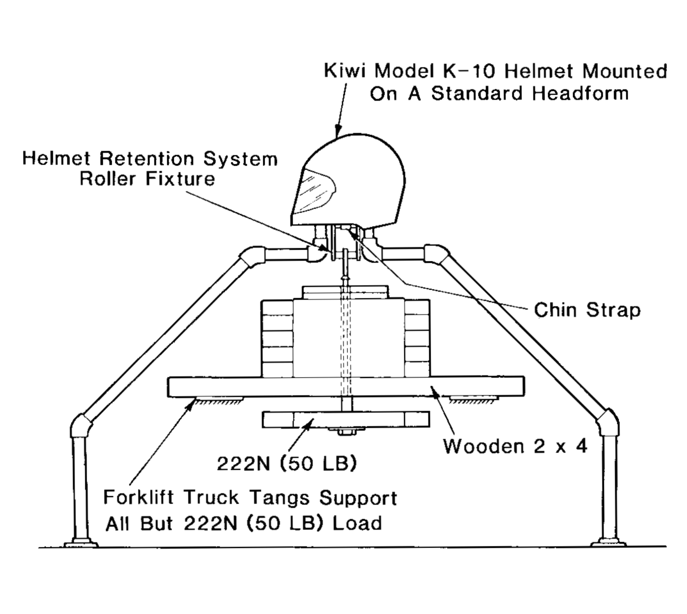


Figure 2. Helmet Retention System Preloading Apparatus

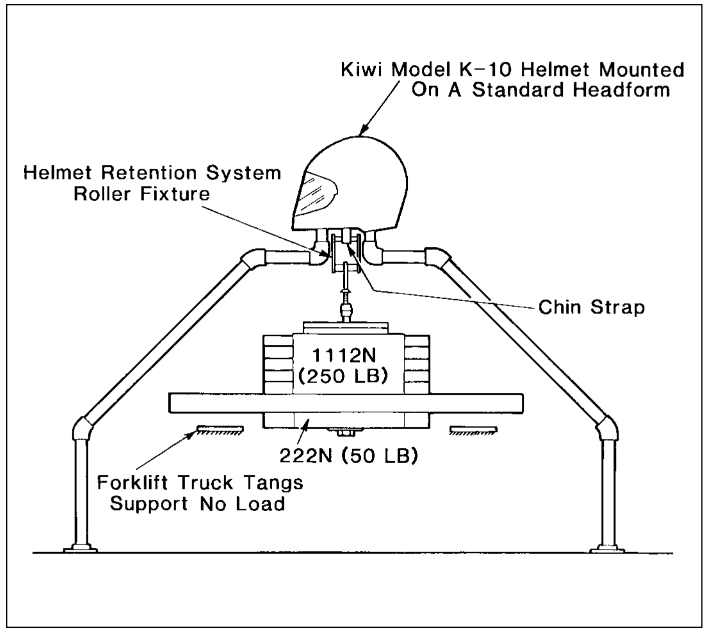


Figure 3. Helmet Retention System Testing Apparatus

this, the associated codes and standards are often characterized as "merely minimum safety standards." In fact, the standards are almost always maximum standards and the word minimum is used to describe the minimum requirements necessary to meet these maximum standards.[9] For example, the scope of *American National Standard Safety Requirements for Portable Wood Ladders, ANSI A14.1-1981*, states, "This standard prescribes rules and establishes minimum requirements for the construction, testing, care, and use of the common types of portable wood ladders described herein to ensure safety under normal conditions of usage."[10]

Compliance or noncompliance with go/no-go criteria does nothing to dispel this incorrect notion of the "minimum safety standard." On the other hand, quantification usually eliminates the minimum standard argument because most of the products sold by a manufacturer exceed the go/no-go criteria. Taking a strength example, a manufacturer has to achieve a high median strength for his production population in order to assure that his weakest members will pass the proof test. Consider a 15.2 cm (6 in.) cup grinding wheel manufactured by Gulf States Abrasives Mfg. with a maximum speed rating of 6,000 rpm. *American National Standard Safety Requirements for the Use, Care, and Protection of Abrasive Wheels, ANSI B7.1-1978*, requires that as part of the manufacturing process each wheel be proof tested by overspeeding it by 50%.[11] Triodyne Inc. performed an overspeed test on two wheels which fractured respectively at 13,400 rpm and 13,350 rpm. These wheels greatly exceed the 6,000 rpm rated speed and the 9,000 rpm proof test speed, making it extremely clumsy to argue that the wheel passes merely a minimum standard.

SUBJECTIVE CRITERIA

When welded structures fail at their welds, a manufacturer is frequently confronted with a personal subjective criteria espoused by expert metallurgists. The criticisms typically are nonquantitative and embrace geometric concepts such as undercutting, underfilling, overlapping and metallurgical concepts such as incomplete fusion, porosity and voids. Quantitative methods can often be used to challenge successfully these attacks by establishing the strength of bounded structures. A weldment may be bounded by producing a nominally identical structure whose welds are demonstratively inferior to the challenged structure. The inferior weld is then tested quantitatively to establish a large safety factor which demonstrates that the alleged condition of the weld is not a proximate cause of the failure.

As an example, consider the tensile box element illustrated in Fig. 5 which is comprised of six channel sections that have been staggered and welded by transverse and longitudinal butt welds. It was alleged that the short transverse welds were inad-

Table 3
Chin Strap Elongation for Motorcycle Helmets

Helmet Sample	Distance after 222 N (50 lb) Preload - cm (in.)	Distance after 1334 N (300 lb) Test Load - cm (in.)	Elongation - cm (in.)
1	29.8 (11.8)	32.4 (12.8)	2.6 (1.0)
2	28.3 (11.1)	30.0 (11.8)	1.7 (0.7)
3	28.9 (11.4)	30.2 (11.9)	1.3 (0.5)

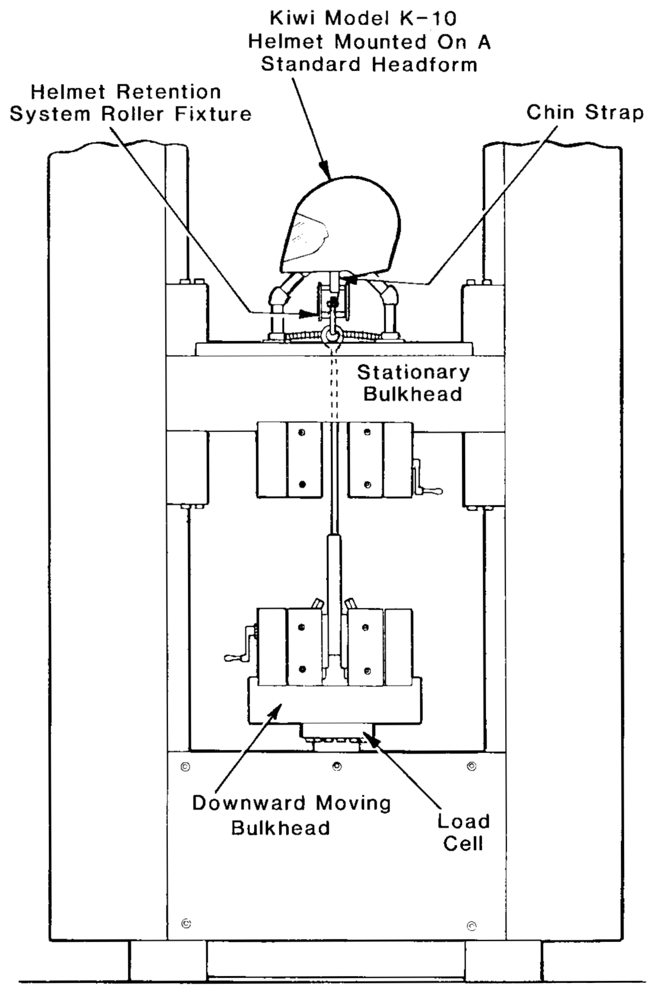


Figure 4. Helmet Retention System Apparatus for Loading to Failure

Table 4 Strength of Motorcycle Helmet Retention System

Helmet Sample	Failure Load N (lb)	Failure Mode
1	3060 (688)	Shell bracket fractured
2	2922 (657)	Shell bracket fractured

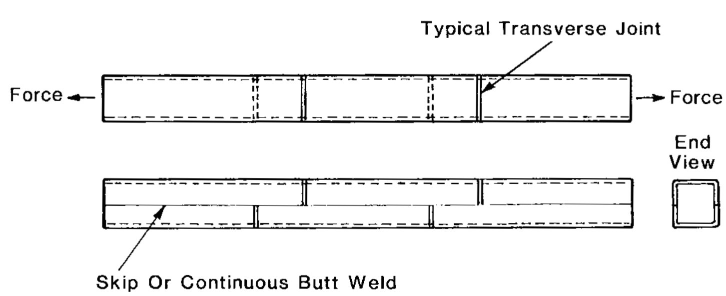


Figure 5. Tensile Box Element - No Transverse Welds

equate and compromised the tensile resistance of the box element. The approach followed in studying this member is based on a statement by the late Sidney Harris who was a drama critic for the *Chicago Tribune.* He raised the question, "If a play is not worth doing, is it worth doing well?" The transliteration of this inquiry to the structural problem involved the testing of two similar box elements where all of the transverse welds were omitted. In one of the box elements, the longitudinal weld was preserved; in the other, a skip weld was used involving the intermittent use of 5.08 cm (2 in.) of weld and 5.08 cm (2 in.) of space. The box elements were tested in tension by Construction Technology Laboratories, Inc. in Skokie, Illinois, where a maximum tensile load capacity of 238 kN (53,600 lb) was obtained for the skip weld assembly and 229 kN (51,500 lb) was obtained for the continuous weld assembly. The maximum anticipated tensile loading on the actual manufactured tensile box element was only 55.6 kN (12,500 lb). No welds at all produced a safety factor of over 300%; consequently, what role could possibly be played by poor welds? The true explanation of the failure was revealed by establishing wear patterns on the box member which grossly reduced the cross-sectional area at the failed section.

CONCLUSIONS

Proof tests which provide a go/no-go criteria for compliance or noncompliance with a safety standard, safety code, standard of care or the like provide no information on overdesign, underdesign, modes of failure, and robustness. Furthermore, one cannot make comparisons among candidates, and proof testing does not provide juries with all the information they may find helpful in judging the safety of a product.

Quantitative testing may usually be conducted for a small additional cost relative to proof testing. For example, tilting a tractor to a 42.5° angle on a tilt table is not much more expensive than tilting it to 30° in a proof test.[12] On the other hand, the richness of quantitative information enables a manufacturer to rank various models of his own products and to establish a hierarchy with competitive products. Products which do not pass a proof test can be improved by quantitative methods which establish both the failure loads and failure modes.

By reinforcing against the various failure modes encountered along the path to the go/no-go plateau, one can often achieve minimum cost and minimum weight designs.

Overdesign is always revealed by quantitative methods and once again mode/load information guides redesign in directions of lower cost and weight. Establishing the true safety factors through quantitative testing gives designers, manufacturers, code committees, and juries a clear picture of robustness and the associated properties of forgiveness, longevity, misuse resistance, and reliability. In addition, since most products exceed proof testing criterion, quantitative methods are effective in dispelling the false notion that codes and standards are "merely minimum safety standards." Finally, quantification is the worst enemy of the ephemeral and imposes a discipline on all safety investigators and failure analysts.

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