ISSN 1041-9489

SAFETY BRIEF

March, 2001 Volume 18, No. 1

Triodyne Inc.
Consulting Engineers & Scientists – Safety Philosophy & Technology
5950 West Touhy Avenue Niles, IL 60714-4610 (847) 677-4730
FAX: (847) 647-2047
e-mail: infoserv@triodyne.com
www.triodyne.com

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Case Study
The Safety of Wood Railings

By Ralph L. Barnett* and William G. Switalski**

Abstract

When the handrail assembly broke away from a wooden deck attached to the rear of a private residence, the victim fell 12 feet to the lawn and sustained injuries rendering him a quadriplegic. Although the local building code required the handrail to withstand a 200 lb load applied in any direction at any point on the handrail, no guidance was given to the do-it-yourselfer who built the deck and railings to assure him that the final construction would produce an acceptable railing. The authors conducted testing and a statistical analysis of railing strength comparing the construction method used by the builder of the accident railing to another construction method utilizing a commercially available handrail bracket. The test program demonstrates that the strength of the wood used to build handrails can vary greatly and that a controlled method of building a handrail is necessary to ensure the integrity of a product intended to be consumer customized and assembled. It is necessary to have acceptable methods of railing construction because the failure of a railing joint can be life threatening. This is especially true in the consumer/do-it-yourself market where the designer/builder is not necessarily knowledgeable about building codes or construction methods.

I. Accident Scenario

A homeowner with ordinary craft skills built a wooden deck which was elevated twelve feet above his backyard. Except for the railings, the construction features were unremarkable. The building supplier furnished railing components consisting of lathe turned spindles and posts together with a milled handrail. The project was undertaken without a building permit, a kit, standardized drawings, or advice from the building supplier. The only fasteners that were furnished were 2-1/2 inch deck screws.

After the deck was completed, an invited neighbor used it to play catch with children in the yard below. While attempting to snag a ball which had fallen short, the neighbor pushed against a corner railing as he leaned over it and reached downward; the railing broke and he fell 12 feet and became a quadriplegic. Examination of the railing system after the accident revealed that the two deck screws that secured the handrail to the posts by "toenailing" were bent but intact in the posts. Wood divots pulled from the end grain of the handrail provided an escape geometry which released the handrail.

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* Professor, Mechanical and Aerospace Engineering, Illinois Institute of Technology, Chicago, IL and Chairman, Triodyne Inc., Niles, IL

** Senior Mechanical Engineer, Triodyne Inc., Niles, IL

No Charge

II. Railing Construction

The railing structure involved in this case study is depicted in Fig. 1 where the toenails in the handrail were inserted into pilot holes drilled by the homeowner that angled upward and into the page:

Corner Post Screw

36° above the horizontal in the vertical plane;
13.5° from the centerline of the handrail in the horizontal plane

Side Post Screw

26° above the horizontal in the vertical plane;
18° from the centerline of the handrail in the horizontal plane

The handrail is 29-1/16 inches in length and supports the tops of four balusters; the bottom of the balusters engage a 2 x 4 of the same length. A single deck screw is used at each joint. The 2 x 4 is fastened into mating posts with four deck screws; two at either side. All joints in the railing system were fastened together using 2-1/2 inch deck screws and pre-drilled using a 1/8 inch diameter drill bit.

All components of the railing system were constructed from treated southern yellow pine. Concentrating on the handrail, its cross section has been superimposed onto a typical tree section in Fig. 2. Radical differences in grain structure are observed depending on the orientation of the lumber when sawn. Wood strength is highly dependent on the grain orientation.[1]

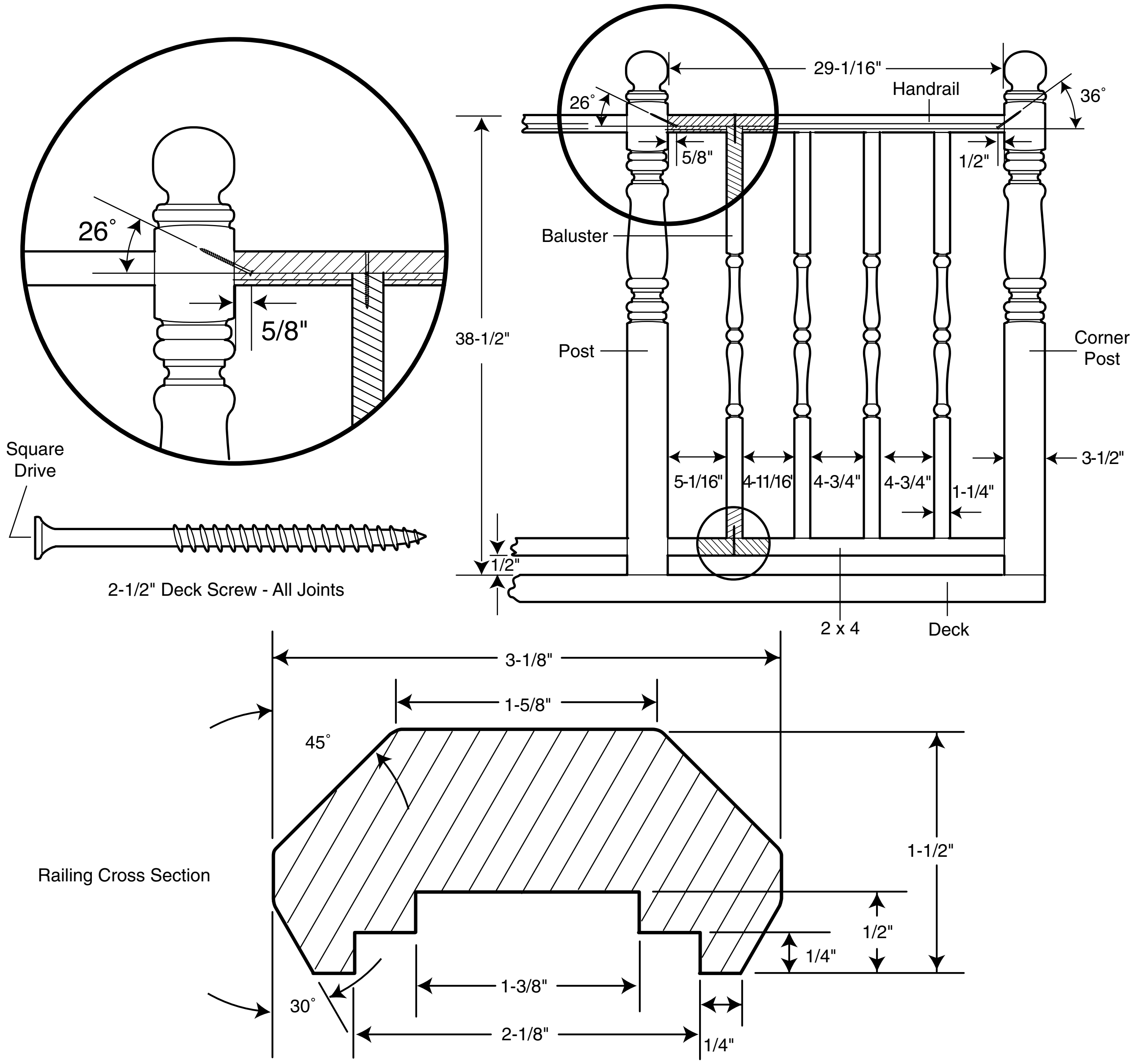

Figure 1 - Case Study Railing System

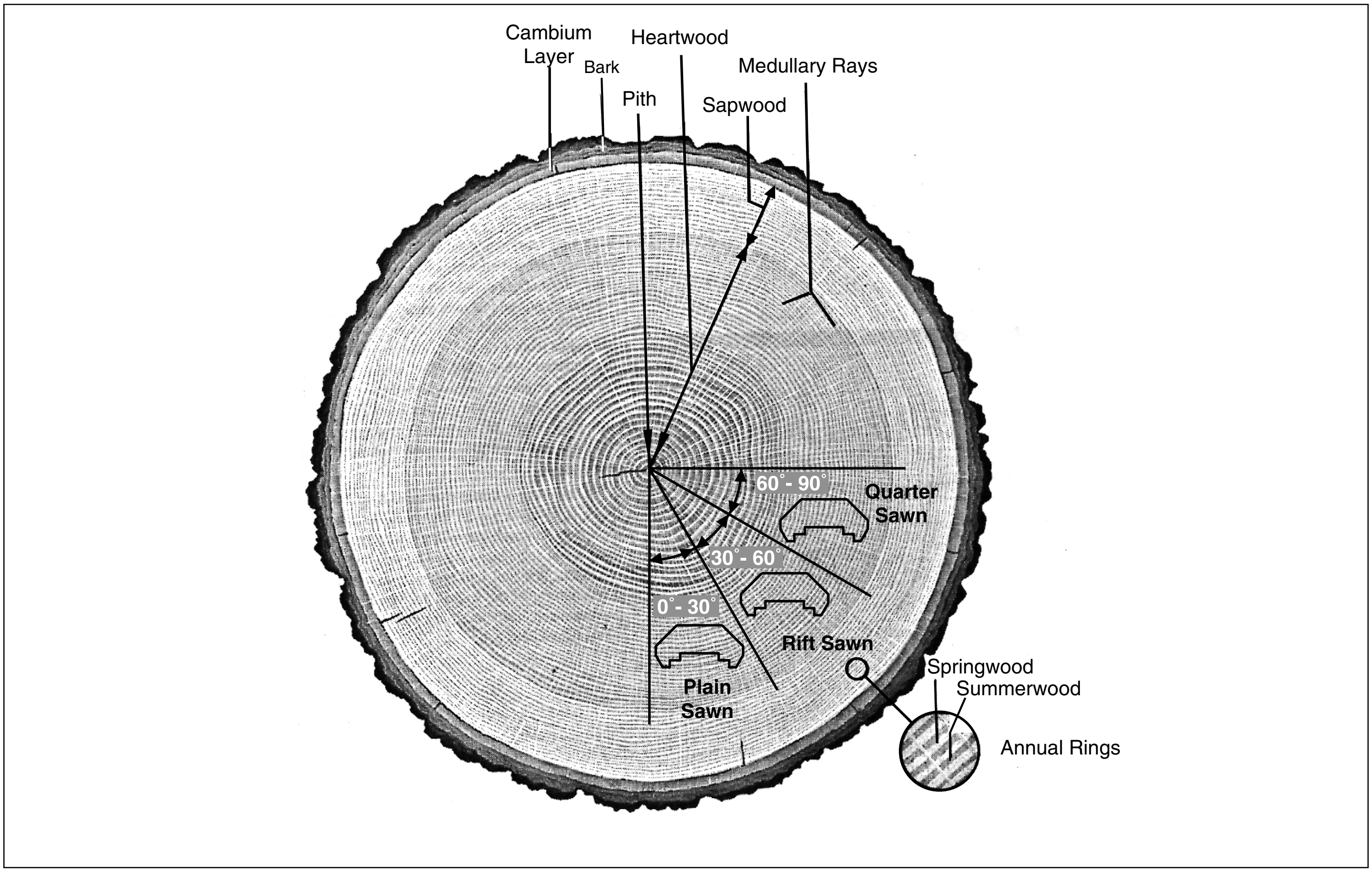

Figure 2 - Typical Cross Section of a Tree Trunk

Tree growth takes place only in the cambium layer by cell division. It follows that an ideal tree is axisymmetric and wood is both orthotropic and nonhomogeneous. Every year long tube-like vertical fibers are formed around the entire trunk; these fibers bond to their circumferential neighbors grown in the same year and to their radial neighbors grown in the previous year. Consequently, the strength and stiffness properties are different in the axial, radial, and circumferential directions which are all perpendicular to each other. Noting that radial bonding may vary between years because of dissimilar climatic conditions, it follows that wood may not be homogeneous in the radial direction.

Because wood is obtained from many trees that are randomly sawn, and since wood is orthotropic and nonhomogeneous, the *in situ* strength of nominally identical members will vary stochastically. This statistical notion is particularly poignant when the resistance of only a small region of wood is challenged, e.g., the end of the railing where it is toenailed into a post.

III. Railing Performance Requirements – A Brief History

The first American safety standard to address railing design (except residential railings) was the *American Standard Safety Code for Floor and Wall Openings, Railings and Toe Boards*, ASA A12-1932.[2] Pertinent technical terms were defined for the first time:

> ***Handrail*** *– A single bar or pipe supported on brackets from a wall or partition, as on a stairway or ramp, to furnish persons with a handhold in case of tripping.*
>
> ***Standard Railing*** *– A vertical barrier erected along exposed edges of a floor opening, wall opening, ramp, platform, or runway to prevent falls of persons.*

The standard specifically addressed wood railings, pipe railings and structural metal railings stating:

> *The anchoring of posts and framing of members for railings of all types shall be of such construction that the completed structure shall be capable of withstanding a load of at least 200 pounds applied in any direction at any point of the top rail. [Section 7.3(d)]*

This requirement remained unchanged in the 1967 revision of the safety standard, USAS A12.1-1967.[3] When the Occupational Safety and Health Act became law in 1971, the 1967 revision of the safety standard was adopted and remains the law in effect today. However, confusion sometimes arises because the federal government never updated its regulations to keep pace with the subsequent revisions of A12.1 in 1973 and its successor standard, A1264.1 in 1989 and 1995.

In the 1973 revision of A12.1[4], the railing performance requirement was completely revamped to read:

> *The completed railing shall be designed and constructed to withstand a load of 25 pounds per lineal foot applied in any direction at the top railing. The intermediate rail shall be capable of withstanding a horizontal load of 20 pounds per lineal foot. The end of terminal posts shall be capable of withstanding a load of 200 pounds applied in any direction at the top of the post. The above loads are not additive. [Section 7.3.1]*

New terminology also appeared in 1973 when "Guard Railing" replaced the previously used "Standard Railing":

The Guard Railing is an assembly consisting of a top rail, intermediate rail and posts with vertical height in the range of 36 to 42 inches.

Concurrent with the A12.1 standard for railings was the USAS A64.1-1968[5] standard for Fixed Industrial Stairways. The A12.1 and A64.1 code committees combined in 1989 to form the A1264.1 committee and published a revised standard entitled, *American National Standard Safety Requirements for Workplace Floor and Wall Openings, Stairs, and Railing Systems.*[6] The scope of the new standard was limited to industrial and workplace situations. Construction, residential and commercial occupancies are excluded except where necessary maintenance or workstation access may be required.

Once again, new technical terminology emerged to replace the previous "Guard Railing":

> ***Guardrail/Railing System/Stair Railing System*** – *Framework of vertical, horizontal or inclined members, grillwork or panels, or combinations thereof, supporting a handrail and acting as a safety barrier for protection of persons at or near the outer edge of stair, ramp, landing, platform, hatchway, manhole, or floor opening.*
>
> ***Handrail*** – *Horizontal, sloping, or vertical member normally grasped by hand for support. This member may be part of a railing system and is often, but need not be, a top member (top rail) of a railing system.*

The Railing System is an assembly consisting of a top rail, intermediate rail or equivalent protection, and posts having a vertical height in the range of 40 to 44 inches (another significant revision). In addition, the strength requirements for a Railing System were changed from a load based criteria to a deflection based criteria:

> *The completed railing systems shall be designed and constructed for its intended use to preclude system failure. As a minimum, it shall withstand a concentrated load of 200 pounds (90.7 kg) applied in any direction, except upward, at the mid-point between posts without exceeding maximum allowable deflection. The intermediate rail shall be capable of withstanding a horizontal load of 80% of the above stated load applied at mid-point and mid-height without exceeding the maximum allowable deflection. The end of terminal post shall be capable of withstanding a load of 200 pounds (90.7 kg) applied in any direction at the top of the post. The above loads are not additive. [Section 5.6.1]*

The 200 pound load specified in the standard is applied at the mid-point of the railing span because this is the location where the deflection in the rail will be the greatest. Although the maximum allowable deflection is left to the Railing System designer, the standard offers the suggestion (not a requirement) that a residual deflection in excess of one-half inch may indicate potential failure. [Ref. Section E5.6.1]

The Railing System requirements remained unchanged in the 1995 revision of the A1264.1 safety standard.[7]

It should be observed that ANSI A1264.1-1995 is not as stringent as its predecessor ASA A12 -1932 or the current OSHA Standard 29 CFR Ch.XVII.(7-1-99 Edition) 1926.451(g)(4)(vii).[8] Two hundred pounds applied midspan gives rise to an end shear of only 100 lbs in the handrail. On the other hand, when 200 lbs is applied at every point along the handrail, the critical end shear is developed when the load is located next to the post in a horizontal direction; here the shear is 200 lbs or double that specified by the current ANSI standard. At present, the highest standard for handrail design is set by the BOCA National Building Code, 1993:[9]

> ***1615.8.1 Handrail design and construction****: Handrails shall be designed and constructed for a concentrated load of 200 pounds (91 kg) applied at any point and in any direction. Handrails located in other than dwelling units in occupancies in Use Groups R-2 and R-3 shall also be designed and constructed for a uniform load of 50 pounds per foot (74 kg/m) applied in any direction. The concentrated and uniform loading conditions shall not be applied simultaneously.*

IV. Toenail Joint

When an outward facing horizontal concentrated load is applied to the right end of the handrail shown in Fig. 1, it is resisted entirely by the toenailed deck screw at the right post; none of the other thirteen joints in the railing system feel any load at all. Since this is the "worst case" loading of the railing system, the strength of the toenail joint is equivalent to the strength of the entire railing structure. This strength was characterized with five exemplar railings that were constructed to be nominally identical to the artifact. These were located in the corners of the 8 ft x 8 ft test deck shown in Fig. 3. Using the test setup depicted in Fig. 3, the handrails were tested to failure using a horizontal force applied 3 inches from the corner post. The force was applied tangent to the top handrail surface through a manual winch. The magnitude of the applied force was measured with a Chatillon digital force gauge and accompanying load cell.

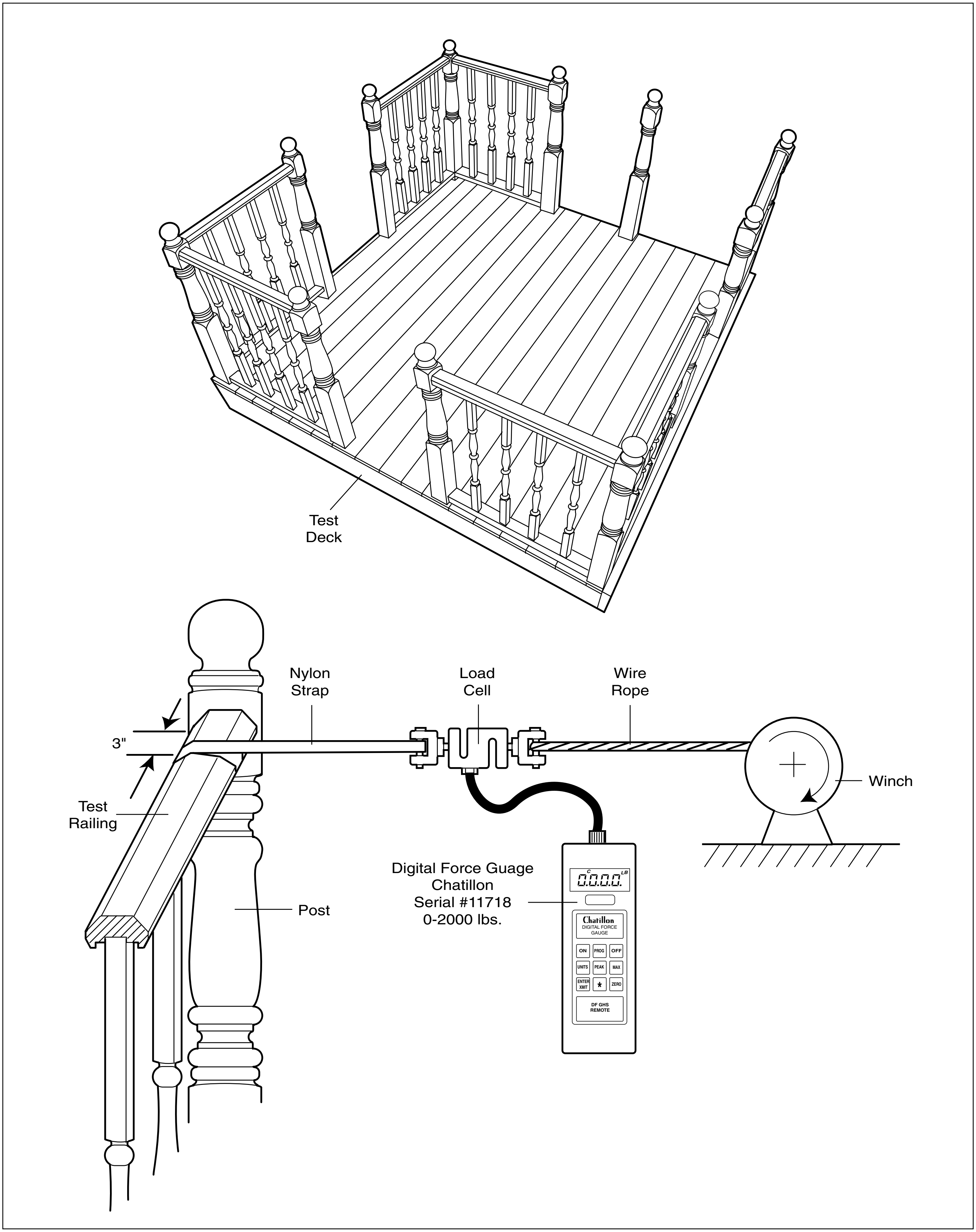

Figure 3 - Test Deck and Instrumentation

The five fracture loads measured for the five toenail joints are recorded in Table I together with their mean, standard deviation, and coefficient of variation. These data lead to a "bell shaped" curve that may be represented by a Gaussian Distribution Function[10] as illustrated in Fig. 4. The area beneath the probability density curve from the extreme left up to 200 lbs is the probability of failure under a load of 200 lbs or the percentage of railings that will break under a 200 lb load; the same applies to any load including 100 lbs which is important here. Using conventional procedures, the following statistical inferences can be drawn:

a. The probability of the railing fracturing under a 200 lb load is 26.3%, i.e., about one chance in four.

b. The probability of the railing fracturing under a 100 lb load is 2.43%, i.e., about one chance in forty.

A two hundred pound man wearing workshoes cannot develop a static push of 100 lbs on a railing. Consequently, a homeowner or an inspector has less than one chance in forty of ever detecting a bad railing joint under extreme exertion. On the other hand, even mild dynamic impacts on the railing will develop 100 lbs.

In each of the five tests, the end grain was pulled from the handrail and the deck screws remained in the posts; in all cases, their appearance resembled the artifact. The higher failure loads were associated with more closely spaced growth rings in the handrail lumber. As a final observation, the 30% coefficient of variation is quite high and indicates very large variability in the fracture loads.

V. Metal Bracket

A specialized metal bracket manufactured under the name Create-A-Rail®, is available for fastening the handrail to the posts. This connector is depicted in Fig. 5. The bracket is screwed directly into the post using three similar deck screws(5a). The handrail sits in a saddle and is secured with two 2-1/2 inch deck screws toenailed into both sides (5b).

Five railing systems were constructed with the same wooden components shown in Fig. 1. They were strength tested using the same test deck and testing protocol adopted for the "toenail" joint. The results of these tests are tabulated in Table I; the associated Gaussian or normal probability density curve is shown in Fig. 4. The following statistical infer-

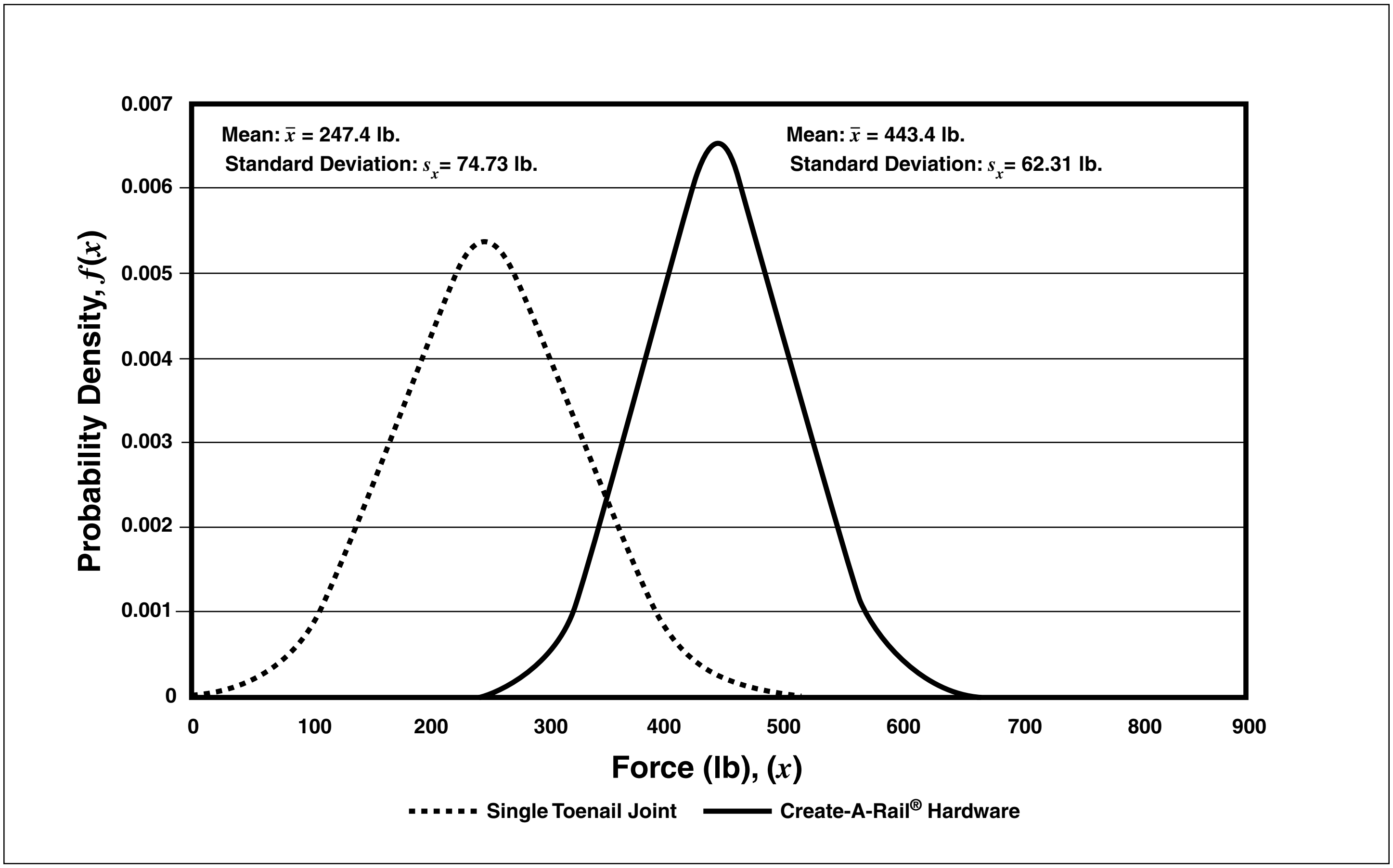

Figure 4 - Gaussian Strength Distribution: $f(x) = \dfrac{1}{s_x\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\bar{x}}{s_x}\right)^2}$

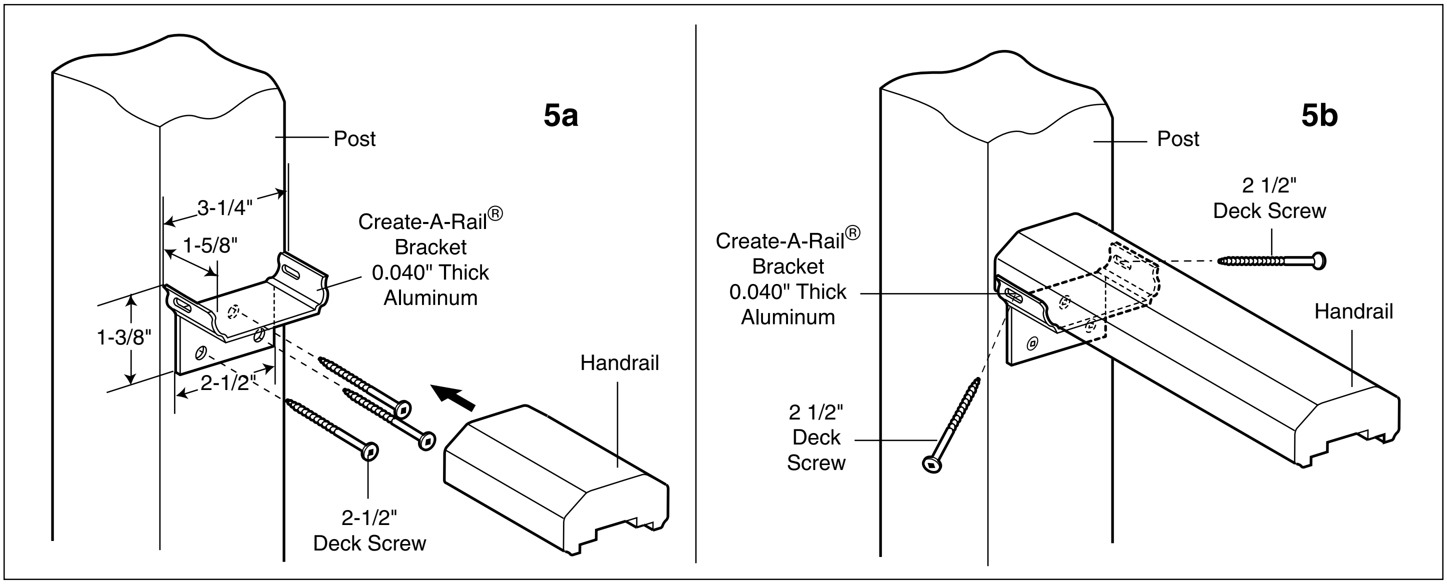

Figure 5 - Create-A-Rail ® Connector

Table I. Railing Strength, lb.

Handrail Specimen	Toenail Joint	Metal Connection
1	**250**	
2	**297**	
3	**215**	
4	**334**	
5	**141**	
6		**417**
7		**351**
8		**487**
9		**509**
10		**453**
Mean Fracture Load, $\bar{x}$ **Standard Deviation,** s_x **Coefficient of Variation,** $s_x/\bar{x}$	**247.40 lb** **74.73 lb** **30.2%**	**443.40 lb** **62.31 lb** **14.1%**

ences may be drawn from the normal distribution function:

a. The probability of the railing system fracturing under a 200 lb load is 4.6884 x 10^{-5}, i.e., one chance in 21,329.

b. The probability of the railing system fracturing under a 100 lb. load is 1.7869 x 10^{-8}, i.e., one chance in 55,962,841.

Comparing the Create-A-Rail® connector to the "toenail" joint shows that under a 200 lb load, the Create-A-Rail® will fail once in every 21,000 applications whereas the "toenail" joint fails in one out of four railings. For 100 lbs., the Create-A-Rail® virtually never fails; however, the "toenail" joint fails on the average once in every forty railings. The Create-A-Rail® design allows four times the purchase of the deck screws compared to the "toenail" joint; it's much more difficult to encounter a "weak" spot. As shown in Fig. 5b, the saddle alone provides lateral resistance independent of the wood properties.

The stronger railings associated with the Create-A-Rail® connectors once again displayed closely spaced growth rings. The scatter in fracture load data, as measured by the 14% coefficient of variation, is much smaller than that associated with the "toenail" joint.

VI. Discussion and Conclusions

1. Handrails and railing systems should be designed and constructed for a concentrated load of 200 pounds applied at any point and in any direction on the top rail.

2. One of the usual top rail fabrication systems for the subject railing involves the use of six screws; four into each of the four balusters and a toenail screw into each of two vertical posts. Six 2-1/2 inch deck screws in such a short railing span will generally be conceived as a very substantial construction by a homeowner or do-it-yourself craftsman.

3. Forces applied to the "toenailed" railing in the upward or downward direction are resisted by an extremely efficient structural system. The standard 200 pound loading will always be accommodated in the vertical plane. Checking the railing by pushing down or lifting up on the handrail will always produce a tactile feedback of a rigid member.

4. If a concentrated horizontal force is applied at the center of the top rail, each post connection resists the load equally due to symmetry. If the load is applied at either end of the railing, all of the load is transferred to a single post and a single joint adjacent to the load. This latter result is true

regardless of the type of end connection (e.g. simply supported or fixed-fixed). Note that railing design follows the "worst case scenario" philosophy; a 200 pound load in any direction at any location along the railing. Clearly, the horizontal force applied near the post is the critical railing load.

5. Differences among nominally identical trees, random trunk location of sawn lumber, nonhomogeneous growth patterns, and orthotropic behavior beget the exceptional variability in wood strength found in small samples.

6. The single "toenail" joint between the post and handrail is literally the "weakest link" in the railing. When this fact is combined with the stochastic nature of wood, the expected railing performance will exhibit high variability. The railing addressed in this case study violates the 200 pound load standard 26.3% of the time.

7. The "toenail" joint will fail under a 100 pound load 2.43% of the time, i.e., once in every 20 railings (two joints each). A strength level in the neighborhood of 100 pounds is virtually undetectable. Neither a home craftsman nor a building inspector can challenge this resistance without special loading.

8. The Create-A-Rail® connector will almost never fail under a load of 100 pounds (one chance in 56 million). Only one in 21,000 connectors will fail below 200 pounds. This superior performance is reflected in both higher strength and small variability. The forgiving nature of the Create-A-Rail® design is attributable to the saddle construction together with five deck screws that are optimally deployed.

9. Effective alternate designs can be fashioned without specialized hardware. For example, a six baluster design, Fig. 6, may be employed which places a baluster flush against each post. Two or three deck screws may be driven through this member directly into the post. In the normal manner, one or two vertical deck screws will secure the handrail to the baluster which fits into the milled slot on the bottom of the handrail. This provides an interference against any outward movement.

10. The handrail/post connection in a wooden railing system is a critical structural joint whose failure is life threatening. Do-it-yourself homeowners will not understand how to control the "weakest link" and stochastic nature of this connection. Furthermore, they will not be able to properly proof test the joint after construction to assure its structural integrity. Safety demands that proper instructions and warnings accompany the sale of the railing components.

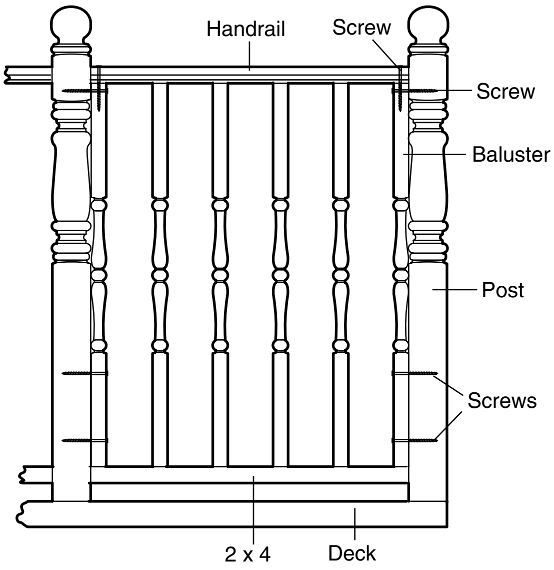

Figure 6 - Six Baluster Design

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SAFETY BRIEF

March, 2001 – Volume 18, No. 1

Editor: Paula L. Barnett

Illustrated and Produced by

Triodyne Graphic Communications Group