

Designing with LRFD for Wood

by

Robert J. Taylor, Ph.D., P.Eng., M.ASCE, Assoc. AIA

Many engineers (especially seasoned engineers) ask, "Why should I switch from allowable stress design (ASD) to LRFD design for wood?" Experienced engineers are comfortable with the method they have been using for years and need to find a real benefit before they take the time to learn a new method. Young engineers are more receptive to LRFD because they may already have been taught this approach through college curricula.

Load and Resistance Factor Design (LRFD) has been used for some time in countries around the world and is commonly practiced for many different materials. This article will discuss how similar the LRFD code for wood is to the ASD code and how painless the switch can be. It also explains some of the benefits for making the switch.

LRFD philosophy

The underlying goal in structural design is for the capacity of the structure to be greater than or equal to the expected demand. The demand is affected by the type, magnitude, and placement of loads on the system and the interaction with the system's formal geometry. The capacity of the system is provided through a combination of material type, section and formal geometry, and the system behavior under demand. The structural design process involves five key components: load, geometry, support conditions, material, and performance. Other considerations such as economics and aesthetics may enter into an iterative design process at later stages and are initially of secondary importance to safety and serviceability concerns.

A limit state is the point at which the structure fails to serve its intended purpose in some way. Two broad limit states can be identified for structures - safety and serviceability. For safety, the designer may desire some rationally-derived margin against failure or collapse. For serviceability, the designer wants to assess real world performance in service. There are many limit states of concern under these two broad classes of safety and serviceability.

Serviceability limit states appraise the structure in terms of its everyday usefulness. A way of looking at this is to consider average material elasticity values in combination with real load magnitudes as a measure of actual structural performance. Outside of code serviceability limits, designers may choose their own more restrictive limiting values based on experience or client expectations. In serviceability design, it is possible

to determine structural performance with a good level of precision.

Safety, on the other hand, can be thought of in statistical terms — probability of failure, or conversely, probability of survival. Using statistics, one can appraise the safety of a structure in terms of measurable probability. In the LRFD method, load factors, material reference strengths, and resistance factors are all tied to statistical data.

Let's look first at the capacity side of the equation - the material. Figure 1 is a representation of the structural property variability for a variety of wood products, plotted for illustration purposes at a common mean property value.

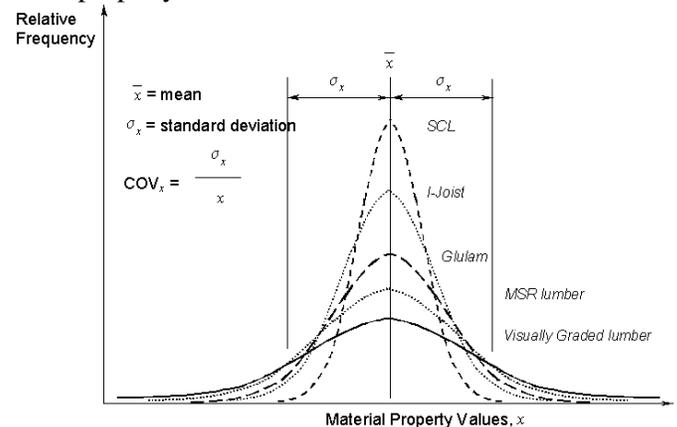


Figure 1 Representation of structural property variability among various wood products

The same statistical form can be applied to all other building products. The plot relates the relative frequency of occurrence of the actual property values from testing. Structural testing in specific modes is performed on these products to produce the data set that makes up these curves. Each curve (normal distributions shown here, although other distribution types are often possible) can be described by its statistical measures — mean and standard deviation (a measure of the spread of the curve).

The area underneath the normal distribution curve equals 1.0. This is equivalent to saying that the probability of occurrence is equal to 100 percent. As an example of its use, someone can determine the percentage of members that will fail at or above a particular structural property value. He or she can also determine how many standard deviations (the distance) it is away from the mean. Note that at the 5th percentile, 5 percent of the samples fail at this property value while 95 percent of the samples survive.

Figure 2 plots sample distributions of load (S) and resistance (R). Each of the curves has its own unique statistical description (mean and standard deviation values), and may or may not have the same distribution type. Normal distribution types are shown here, but there are many other types that can be chosen to fit or model the test sample data points best. Note that the resistance

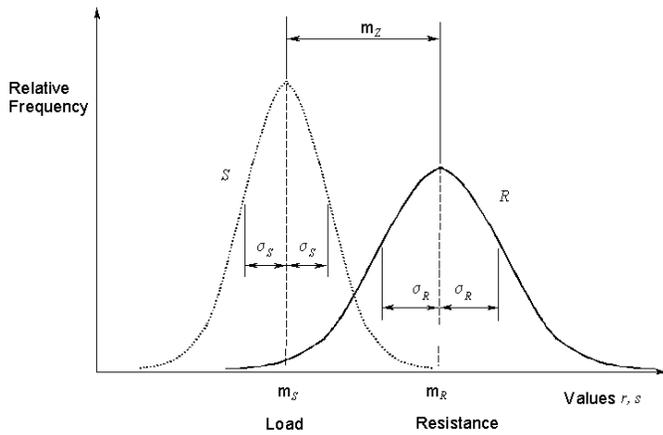


Figure 2 Sample distributions of load (S) and resistance (R)

curve is to the right of the load curve, and that the curves overlap. The overlap depicts the region where load is greater than resistance, hence failure.

The overlap, or failure zone, can be represented in a more useful way. If the load and resistance distributions are normalized to the same type, then subtracting the load distribution from the resistance distribution can create a performance distribution (Z).

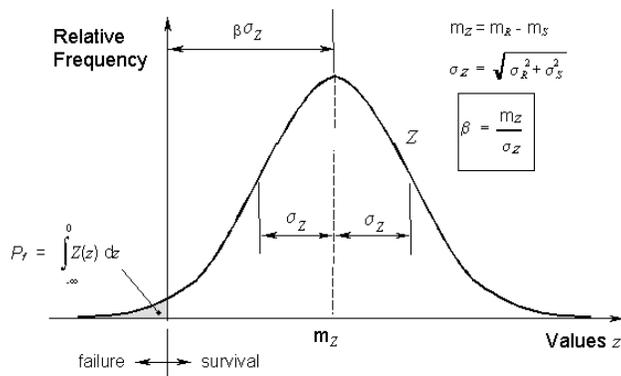


Figure 3 Performance Distribution (Z)

The statistics of Z are determined (see Figure 3) as well as Z itself. In this plot, the area under the Z distribution that falls in the region of property values less than zero represents the probability of failure of the structure in this particular mode of testing. This provides a measurable probability of failure. It can be further described in terms of the number of standard deviations away from the mean of the performance distribution. The Greek letter beta (β), known as the safety (or reliability) index, is used to describe this multiple. Thus, β is directly tied to the probability of failure. For large values of β , the probability of failure is very small. For small β values, the probability of failure is much larger. In structural design, many materials typically have values for β between 2.6 to 2.9, not just wood. It is interesting to note the corresponding probability of failures of 1:63 and 1:251 respectively. These are levels at which designers have historically been designing buildings, and target β values are set by consensus

agreement in a committee process to strive for a balance between safety and economy.

How is β used in design? β is actually invisible in the design process. It is tied to two other factors: the resistance factor ϕ (used on the capacity side of the equation) and the load factor α (used on the demand side of the equation). To design for any demand with any material to a target β , it is prudent to fix the value of the load factor α (standardized values for all materials), and derive resistance factors ϕ for various structural properties of various materials. This process is known as calibrating the resistance factor. For wood, calibration needs to cover all of the relevant factors such as the load and variability of the member strength based on species, grade, and type of application. Generally, the 5th percentile of the strength test data is used for the resistance side, while load statistics are obtained from extensive studies of structures in all climatic zones and with different occupancies. The accuracy of the lower tail of the material data is the most important because the low strength members are the ones most vulnerable to failure. Statistical distribution models need to be well chosen for use in the calibration to better represent the lower end of the test data set (the lower 15 percent). This will ultimately produce a much narrower range of ϕ values for a target β . Plotting the β - ϕ (α fixed) correlation using a well-fit lower tail model yields a satisfying result — typically ϕ values that are consistent with that found in the current design code equations.

The mathematically sophisticated procedure to calibrate the α - ϕ code values with a probability analysis is not typically an issue for the designer. However, an understanding of the concepts behind the code is useful so that the designer can make rational decisions when the code does not provide direction.

Design process — LRFD vs. ASD

When we talk about ASD for wood, we are referring to the *National Design Specification® for Wood Construction* ((ANSI/AF&PA NDS®-1997). The way safety is addressed in the ASD and LRFD approaches is fundamentally different. ASD makes use of a very real reduction that is applied to very real material stress test data. Controversy often surrounds the rigorous derivation of the ASD reduction because the methods used to develop the design method are a bit ambiguous. ASD also involves the comparison of stresses in the demand/capacity relations.

LRFD features a rational statistical basis for a measurable probability of failure and thus insures a measurable level of safety. Factored load equations (with concrete as an exception) for safety design are standardized across all material groups. Resistance values are only modified by a resistance factor that varies by material and mode of use. In the

demand/capacity relations, loads or moments are typically compared.

Table 1 lists the six fundamental factored load combinations from Minimum Design Loads for Buildings and Other Structures (ANSI/ASCE 7-88) used for safety analysis in LRFD. They are the same LRFD load relations used for steel, and are really meant to become a common load basis for strength of all materials. Careful inspection of the combination of load terms in each of the equations tells what kind of environmental event the structure is being subjected to, such as a fully occupied building in a blizzard. Many more equations can be derived from these equations when direction is taken into account for wind and seismic events, as well as distribution patterns.

Table 1: ASCE 7 LRFD standard factored load equations (strength) with wood time effect factors

Factored Load Case Combination*	Time Effect Factor λ
1.4 D	0.6
1.2 D + 1.6 L + 0.5 (L _r or S or R)	0.8
1.2 D + 1.6 (L _r or S or R) + (0.5 L or 0.8 W)	**
1.2 D + 1.3 W + 0.5 L + 0.5 (L _r or S or R)	1.0
1.2 D + 1.0 E + 0.5 L + 0.2 S	1.0
0.9 D - (1.3 W or 1.0 E)	

* direction must be taken into account
 ** L_{storage} $\lambda = 0.7$; L_{occupancy} $\lambda = 0.8$; L_{impact} $\lambda = 1.25$

The basic form of the demand / capacity relation for LRFD looks like this:

$$\text{Demand} \leq \text{Capacity}$$

$$\sum_{i=1}^n \alpha Q_i \leq \lambda \phi R_n$$

β

Notice how the safety index (β) underlies the strength relation. With α fixed by prescription, ϕ varies by material and strength mode (for example, bending, shear, compression, et cetera). The LRFD resistance factors for wood are shown in Table 2 for member properties and connections. The lower the number, the

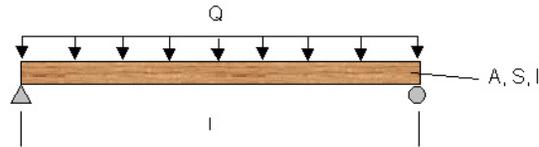
Table 2: Wood LRFD resistance factor ϕ values

Mode	ϕ
Compression	0.90
Flexure	0.85
Tension	0.80
Shear	0.75
Connections	0.65

more variable the material is in the respective mode. Because these factors vary by material and by mode of use, designers can compare resistance factor values for different materials to learn which materials are most efficient in a given mode, provided the materials use the same load factor equations.

LRFD for wood introduces a new terminology for time effect, formerly known as load duration in ASD. The Time Effect factor (λ) is replaced by the ASD load duration factor (C_D) on the capacity side of the relation. The λ factor in LRFD uses a different baseline. For example, using ASD, $C_D=1.0$ for 10 years and with LRFD, $\lambda = 1.0$ for 10 minutes. By prescription, this new baseline ties λ to the ASCE 7 LRFD load combination equations (see Table 1).

The simple beam design example shown on this page illustrates the similarities between the LRFD and ASD design processes. LRFD requires the use of load and resistance factors. Engineers that currently use the LRFD method for concrete or steel are already familiar with these factors. I will point out later in the article how LRFD can provide cost savings due to reduced sections, especially if the problem is governed by a safety limit state. For more information on LRFD for wood, see the Standard for LRFD Design in Wood, AF&PA/ASCE 16-953.



DEMAND LOADS	LRFD	ASD
Safety	$w_f = \sum \alpha Q$	$w = \sum Q$
Serviceability	$w_L = \sum Q_L$	$w_L = \sum Q_L$
<div style="border: 1px solid black; padding: 2px; display: inline-block;">Safety Limit State 1</div>		
SHEAR	$\frac{w_f L}{2} \leq \frac{2}{3} \lambda \phi_v F_v' A$	$\frac{w L}{2} \leq \frac{2}{3} F_v' C_D A$
<i>Prime denotes inclusion of applicable C_f factors except C_D</i>		
<div style="border: 1px solid black; padding: 2px; display: inline-block;">Safety Limit State 2</div>		
FLEXURE	$\frac{w_f L^2}{8} \leq \lambda \phi_b F_b' S$	$\frac{w L^2}{8} \leq F_b' C_D S$
<i>Prime denotes inclusion of applicable C_f factors except C_D</i>		
<div style="border: 1px solid black; padding: 2px; display: inline-block;">Serviceability Limit State</div>		
DISPLACEMENT	$\frac{L}{360} \geq \frac{5}{384} \frac{w_L L^4}{E I}$	$\frac{L}{360} \geq \frac{5}{384} \frac{w_L L^4}{E I}$

Example

Look at the example of a simple beam shown above as Figure 5 that compares the two design processes. The beam is under uniform load and has the given section properties and a displacement limit state (maximum) of span/360 under live load.

Because of the two different limit states that are compared, both methods require the designer to determine the safety and serviceability demand loads. Note the inclusion of the prescribed load factor(s) in the LRFD demand safety load. The serviceability loads are the same for both approaches.

Consider two safety limit states — shear and flexure. The demand / capacity relations for shear are shown. ASD modifies the capacity with the C_D factor for load duration. The LRFD capacity equation includes the time effect factor λ and the resistance factor for shear ϕ_v . Note that factored LRFD loads are used in calculating the demand. The demand / capacity relations for flexure are similar. Again, ASD modifies the capacity with the C_D factor for load duration, but the LRFD capacity equation includes the time effect factor λ and the resistance factor for bending ϕ_b .

The serviceability limit state considered here is maximum displacement of span/360 under service live load w_L . Both approaches use the same displacement equation with very little difference. The important note here is that LRFD uses unfactored actual loads and mean E values, just like ASD, because the designer wants a real measure of actual performance.

The same design process familiarity exists between LRFD and ASD/NDS for columns, beam-columns, connections, fasteners, and other elements. For ease of use, even the respective manuals are formatted the same.

Material design values - LRFD vs. ASD

Determining material design values is beyond the scope of AF&PA or ASCE. Therefore, the American Society for Testing and Materials developed ASTM D5457-93 *Standard Procedure for Computing Reference Resistance Values for Wood and Wood-Based Connections for LRFD*. This standard is used to determine and compile all reference strength material data used by the AF&PA / ASCE LRFD Standard.

To arrive at appropriate LRFD material resistance values, ASTM D5457-93 gives two approaches: first is soft conversion from ASD. For most wood design values, assuming a 3:1 live to dead load ratio, they used a conversion factor of $2.16 f / \phi$ (where f is the ASD allowable stress, and ϕ is the reliability index for the mode of interest). For compression perpendicular-to-grain, the conversion factor is $1.875 f / \phi_{c\perp}$. These relations allow soft conversion of ASD allowable stress values such as those from the NDS Supplement.

After examination of various design cases across a range of load ratios, the 3:1 live/dead load ratio was chosen to retain approximately the same level of reliability as has been proven to be acceptable based on historic and current design practice. By choosing a single calibration point, roof strength capacities for snow will stay about the same under LRFD. Floor strength capacities will increase, which is conservative since they are typically deflection controlled. Roof strength capacities will decrease for construction loads, which is acceptable since those are being designed to the extreme

limit in sun load areas like Arizona. The standards committee deemed this judgement appropriate.

The second method (hard conversion) in the ASTM standard allows calculation of design values using actual material test data sets. By using LRFD through the second approach, materials with lower material property variability can take advantage of this characteristic in the design process. This second approach moves toward true reliability-based design (RBD).

The characteristic strengths (LRFD) or allowable stresses (ASD/NDS) are founded on products that are dry, untreated, and under normal load, known as reference conditions. Modification factors need to be applied to these values for any situations that lie outside the reference conditions. Modification factors are tabulated and detailed in the supplements to both the LRFD and ASD Manuals. These factors are the same for both methods, with limited exceptions.

Benefits of using LRFD

As an example of the benefits of designing with LRFD, consider the University of Maine Advanced Engineered Wood Composites Laboratory (shown in Figure 6) built with 30 foot long glulam columns and 70-foot long glulam beams. Using LRFD, the columns for this project could have been 15 percent smaller than those using ASD.

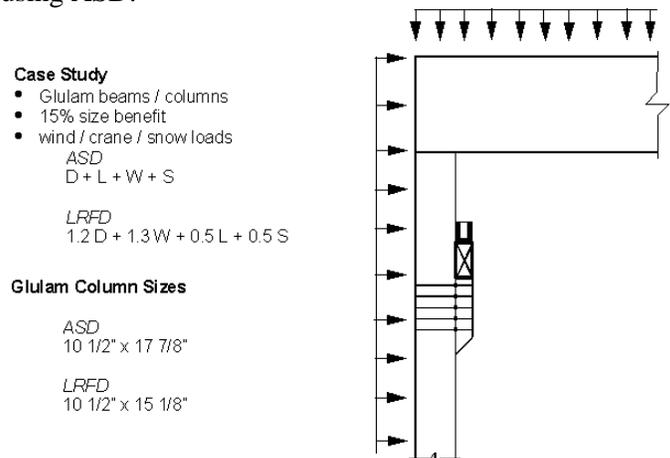


Figure 6 Case Study – University of Maine glulam columns

In a second example, consider the headers for a typical two-story structure (shown in Figure 7) with roof and floor loads applied. Multiple transient loads are treated with weighted factoring in LRFD, but they are directly summed in ASD. This results in 30 percent smaller cross sections. Refer to ASAE Paper #9840065 for details. In the same example shown in Figure 7, LRFD indicates 2-2x10 vs. 2-2x12 #2 southern pine for ASD; or 3 1/8 x 6 7/8 (LRFD) vs. 3 1/8 x 8 1/4 (ASD) glulam; or two 1-3/4"x7-1/4" (LRFD) vs. two 1-3/4"x5-1/2" (ASD) LVL 1.8E.

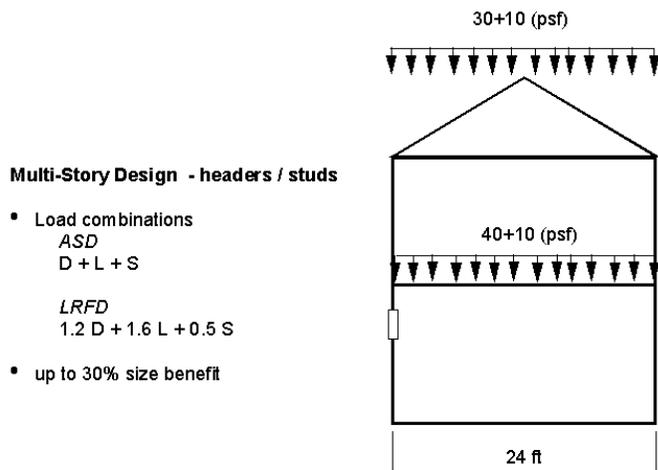


Figure 7 Case Study – headers for typical two-story structure

ASCE 7 also permits load factoring for extraordinary event load combinations based on probability of occurrence of live loads during a fire.

The apparent, more rational combination of loads in LRFD can ultimately lead to more economical strength design than ASD.

Designer support tools

AF&PA’s American Wood Council (AWC) has produced a variety of literary and software design aids including the *LRFD Manual* (Figure 8) to assist the designer in achieving a safe, serviceable, durable, and long-lasting result. Referenced by all model building



Figure 8 AWC LRFD Manual Package

codes nationwide and by many local codes, these sources can be relied upon for dependable information on wood design and the use of wood products. The AWC web site, www.awc.org, is the first point-of-contact for many designers to acquire information, design documents, codes/standards, industry links, design software, or help with a specific wood design issues. Two of the most widely used documents are the *Allowable Stress Design (ASD) Manual for Engineered Wood Construction*, and the *Load and Resistance Factor Design (LRFD) Manual for Engineered Wood Construction*. The *ASD Manual* is based on the 1997 NDS, while the *LRFD Manual* is founded on limit states concepts also commonly found in current concrete and

steel manuals. The AF&PA/ASCE LRFD Standard is also referenced by all model building codes. Design professionals will find that LRFD for wood is similar to the design processes for steel and concrete in terms of the way demand loads are calculated for safety and serviceability limit states and the way resistance factors are used in capacity equations. These manuals are formatted in a very user-friendly manner with descriptive diagrams and pictures.

To assist a designer that is new to LRFD for wood, a manual of solved example problems has also been developed and is currently available. The manual has been written in such a way that solutions can readily be adapted to most engineering software, thus automating design solutions. A compendium of informational sources on wood and wood design is also available from the publisher or www.awc.org.

Conclusion

Is LRFD for wood for you? If you are familiar with LRFD, then support for wood design in this method is now available in print, web, and other tools. If your ASD designs are particularly strength-driven and if you have multiple transient loads, then savings can be realized with LRFD over ASD without sacrificing safety. The LRFD design process does not present much of a change from the ASD design process, with which most designers are accustomed.

Web Links

- www.awc.org American Forest & Paper Association/American Wood Council
- www.cwc.ca Canadian Wood Council
- www.afandpa.org American Forest & Paper Association
- www.beconstructive.com Be Constructive - Wood Initiative

BIOGRAPHY

Dr. Robert J. Taylor, P.Eng., is the Director of Technology Transfer for the AF&PA / American Wood Council. Previously, Dr. Taylor was a Professor of Structures at the School of Architecture, Montana State University- Bozeman. As a licensed professional engineer with over 25 years of experience in academia, industry, and government, he has published extensively and designed many building projects in Canada, USA, Japan, and Korea. Dr. Taylor guides AWC’s technology transfer efforts, focusing on communicating a greater understanding of wood and its capabilities to AWC’s technical audiences of engineers, architects, and building officials. He can be contacted by email at robert_taylor@afandpa.org or by phone at 202/463-2771.