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Structural Code Considerations for Solar Rooftop Installations

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Abstract

Residential rooftop solar panel installations are limited in part by the high cost of structural related code requirements for field installation. Permitting solar installations is difficult because there is a belief among residential permitting authorities that typical residential rooftops may be structurally inadequate to support the additional load associated with a photovoltaic (PV) solar installation.

Typical engineering methods used to calculate stresses on a roof structure involve simplifying assumptions that render a complex non-linear structure to a basic determinate beam. This method of analysis neglects the composite action of the entire roof structure, yielding a conservative analysis based on a rafter or top chord of a truss. Consequently, the analysis can result in an overly conservative structural analysis.

A literature review was conducted to gain a better understanding of the conservative nature of the regulations and codes governing residential construction and the associated structural system calculations.

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NOMENCLATURE

AFPA	American Forest & Paper Association
ALS	American Lumber Standards
ASD	allowable stress design
ASTM	American Society for Testing and Materials
FS	factor of safety
ICC	International Code Council
IRC	International Residential Building Code
LRFD	load and resistance factor design
MOE	modulus of elasticity
MOR	modulus of rupture
NDS	National Design Specification
PV	photovoltaic
USDA	United States Department of Agriculture

1.0 Introduction

Increased desire to install residential solar photovoltaic (PV) roof systems has prompted a more detailed structural capacity evaluation of residential roof structures. Permitting authorities typically default to a conservative view that residential wood roofs may not be able to carry the additional dead load associated with installing a roof-top PV array. This report looks at the uncertainty surrounding the International Residential Building Code's (IRC's) assumed factor of safety (FS) in determining safe roof loading. The IRC is prescriptive in nature and consequently does not account for designs based on material properties and site-specific conditions. Given the code's prescriptive nature, the FS is not specified and assumptions regarding system-component behavior are not offered. This lack of information limits a designer's understanding of a roof system's capacity.

A more comprehensive understanding of residential roofing system capacities to support PV installations can lead to improved acceptance of roof-top PV installations. Knowledge gained by empirical testing can support improving the regulatory approval process. Improvements in regulatory guidance may enhance a regulator's ability to permit installations without costly professional engineering certification. These proposed improvements in the permitting process would clearly lower PV system costs, ultimately resulting in more PV installations.

In 2013, PV system installations nationwide accounted for more than 5,000 MW of new power generation—of which 16% (800 MW) is within the residential market sector (Solar Energy Industries Association, 2013). In addition, that 16% increase in PV power generation for residences corresponds to 90% of all PV installations nationwide. The average residential installation is 6.2 kW, at an average cost of about $23,000 (Interstate Renewable Energy Council, 2013). This yields a total cost across the United States for PV residential installations of 2.4 to 3.5 billion dollars.

2.0 Literature Review

2.1 Introduction to Literature Review

At present, residential roof structural engineers use design tables included in the IRC, or allowable stresses provided by the National Design Specification (NDS) to select or evaluate roof structure beams. In either case, the FS is not made explicit. This project seeks to assess the FS built into current design code specifications and make comparisons to our empirical-testing-derived FS (Dwyer et al 2014, in print).

This report provides a brief history of stress grading; a review of the adopted codes and testing standards associated with the IRC, the NDS, and the testing standards of American Society for Testing and Materials International (ASTM); and lastly a review of research conducted at United States Department of Agriculture (USDA) Forest Service, Forest Products Laboratory.

2.2 History of Stress Grading

The visual stress grading of lumber has existed since the early part of the twentieth century when, in 1923, the USDA Forest Service Forest Products Laboratory published a set of basic rules with assigned stress values (Galligan & McDonald, 2000). During World War II these assigned stress values were increased by 85% as a result of the United States Army dictating an increase to initial design values as a consequence of the war effort. After the war ended, some of the changes made by the military became permanent design values. The changes made by the military and demand for lumber created constant changes to the lumber grading system—and therefore uncertainty in the design values. To aid the process of creating standard design values and increase confidence in these values, changes to visual grading procedures came with the adoption of American Lumber Standards (ALS) PS 20-70. The standards set by the ALS brought recognition to several factors such as moisture content and shrinkage that influence grading. Under the ALS, a National Grading Rule was developed (Galligan & McDonald, 2010).

The newly developed grading rule established uniform grading methods that could be applied to all lumber species. While standardized grading rules now existed, the need to verify baseline design values was becoming increasingly important. In 1977, the North American In-Grade Testing Program went into effect in hopes of standardizing design values with the use of proof testing of full-size samples. As a consequence of such testing, the current visual grading system can claim to be based on empirical full-scale testing. Due to these empirical tests, changes to historical design values were made.

Concurrent with standardizing visual grading of lumber, a new method of machine rating was gaining acceptance within the lumber industry. This new method of machine rating made use of an observed statistical correlation between stiffness and strength that was found to exist in all species of wood. By employing this nondestructive machine testing to find a modulus of elasticity (MOE, i.e., stiffness), the machine rating method was also able to assign an associated strength or stress grade. As of 1996, the amount of machine stress rated lumber produced in the United States had increased from insignificant levels of production to 1.1 billion board feet annually (Galligan & McDonald, 2010). Machine stress rated lumber reached an all-time high in 2005, with an estimated production of almost 3 billion board feet (Logan, Allen, Uskoski, & Nelson, 2010). Currently, it is becoming increasingly difficult to acquire purely visually rated dimensional lumber as machine-rated lumber allows for higher efficiency in lumber production and is used almost exclusively.

2.3 International Residential Building Code

One of the most commonly adopted building codes in the United States, the IRC, is authored by the International Code Council (ICC), which was founded in 1994 by the merger of several regional councils to form a “comprehensive and coordinated national model of construction codes” (ICC, 2013 p.7). ICC founding members include three regional councils:

1. the Building Officials and Code Administrators International, Inc., used throughout the east coast and the midwest portions of the United States;
2. the International Conference of Building Officials, used in the western United States, and;
3. the Southern Building Code Congress International, Inc., implemented in the southern region of the country.

Predating the ICC, establishing building codes was the responsibility of these three regional councils and local governments were encouraged to adopt the building codes of the council nearest in proximity. While the ICC publishes building codes based upon these three regional councils, a United States governmental-mandated building code does not officially exist. All fifty states and incorporated municipalities are allowed to adopt codes of their own choosing; however, most municipalities have partially or fully adopted the IRC codes put forth by the ICC.

A resource within the IRC are span tables as shown in Table 1, which presents an example of a span table produced by the IRC. Span tables allow users to choose from several species of dimensional lumber and from several dead- and live-load combinations to determine the required lumber dimension for a given span. The IRC also takes into account the spacing between joists, ‘rafter spacing,’ when determining a required span length. With regard to the rafter spacing, the IRC allows users to choose between four rafter-spacing values: 12", 16", 19.2", and 24" on center. The four species of lumber listed by the IRC include Douglas fir-larch, hem-fir, southern pine, and spruce-pine fir. Variations in allowable spans also take into account various grades of lumber ranging from SS (select structural), #1, #2, and #3. In the IRC, the spans of dimensional lumber are limited to two dead-loading situations; 10 psf and 20 psf. The IRC also provides four live-load conditions 20 psf, 30 psf, 50 psf, and 70 psf. As shown by the highlighting in Table 1, if a user wished to specify a joist that could accommodate a 10 psf dead load with a 20 psf live load, spanning 23', with a 24" on-center spacing, the code would specify a 2" × 10" Hem-fir #1, or a 2" × 10" Southern pine #2.

Table 1. Span Table Adapted from the IRC

Ceiling Joist Spacing (inches)	**Species and Grade**	Dead Load = 10 psf Live Load = 20 psf			
		2 × 4	2 × 6	2 × 8	2 × 10
		Maximum Ceiling Joist Spans (Feet-Inches)			
12	Douglas fir-Larch SS	13-2	20-8	—	—
	Douglas fir-Larch #1	12-8	19-11	—	—
	Douglas fir-Larch #2	12-5	19-6	25-8	—
	Douglas fir-Larch #3	10-10	15-10	20-1	24-6
	Hem-fir SS	12-5	19-6	25-8	—
	Hem-fir #1	12-2	19-1	25-2	—
	Hem-fir #2	11-7	18-2	24-0	—
	Hem-fir #3	10-10	15-10	20-1	24-6
	Southern pine SS	12-11	20-3	—	—
	Southern pine #1	12-8	19-11	—	—
	Southern pine #2	12-5	19-6	25-8	—
	Southern pine #3	11-6	17-0	21-8	25-7
	Spruce-pine-fir SS	12-2	19-1	25-2	—
	Spruce-pine-fir #1	11-10	18-8	24-7	—
	Spruce-pine-fir #2	11-10	18-8	24-7	—
	Spruce-pine-fir #3	10-10	15-10	20-1	24-6
24	Douglas fir-Larch SS	10-5	16-4	21-7	—
	Douglas fir-Larch #1	10-0	15-9	20-1	24-6
	Douglas fir-Larch #2	9-10	14-10	18-9	22-11
	Douglas fir-Larch #3	7-8	11-2	14-2	17-4
	Hem-fir SS	9-10	15-6	20-5	—
	Hem-fir #1	9-8	15-2	19-7	23-11
	Hem-fir #2	9-2	14-5	18-6	22-7
	Hem-fir #3	7-8	11-2	14-2	17-4
	Southern pine SS	10-3	16-1	21-2	—
	Southern pine #1	10-0	15-9	20-10	—
	Southern pine #2	9-10	15-6	20-1	23-11
	Southern pine #3	8-2	12-0	15-4	18-1
	Spruce-pine-fir SS	9-8	15-2	19-11	25-5
	Spruce-pine-fir #1	9-5	14-9	18-9	22-11
	Spruce-pine-fir #2	9-5	14-9	18-9	22-11
	Spruce-pine-fir #3	7-8	11-2	14-2	17-4

Due to the IRC span tables' prescriptive nature, the question arises as to how the authors arrived at their prescribed spans and what was the presumed factor of safety while developing the tables. An investigation of the FS built into the IRC span tables highlights the lack of any documented FS explicitly or implicitly stated within the code. Although the IRC states no FS, there is a reference that credits the span tables to another organization, the American Forest & Paper Association (AFPA). In 1944, the AFPA, also known as the American Wood Council, put forth an additional set of standards for building known as the National Design Specification (NDS 2012).

2.4 National Design Specification (NDS)

While the IRC is a code of prescribed requirements in tabular form, the NDS is numerically specific with adjustable design values allowing users more specificity in designing members. The NDS is the preferred code of engineers. As shown in Table 2, adjustment factors are used to adjust baseline design values to better match site conditions. In order to adjust lumber's baseline allowable properties, the NDS provides a table that helps users gather applicable factors and apply them to a base design value. Developing a design value based on the adjustment factor approach is shown in Table 2.

Table 2. Applicability of Adjustment Factors for Sawn Lumber (adapted from NDS).

	ASD	ASD and LRFD											LRFD		
	Load Duration Factor	Wet Service Factor	Temperature Factor	Beam Stability Factor	Size Factor	Flat Use Factor	Incising Factor	Repetitive Member Factor	Column Stability Factor	Buckling Stiffness Factor	Bearing Area Factor	Format Conversion Factor	Resistance Factor	Time Effect Factor
$F_b' = F_b$ X	C_D	C_M	$C\iota$	C_L	C_F	C_{fu}	C_i	C_r	—	—	—	K_F	ϕ_b	λ
$F_t' = F_t$ X	C_D	C_M	$C\iota$	—	C_F	—	C_i	—	—	—	—	K_F	ϕ_t	λ
$F_v' = F_v$ X	C_D	C_M	$C\iota$	—	—	—	C_i	—	—	—	—	K_F	ϕ_γ	λ
$F_{c\perp}' = F_{c\perp}$	—	C_M	$C\iota$	—	—	—	C_i	—	—	—	C_b	K_F	ϕ_e	λ
$F_c' = F_c$ X	C_D	C_M	$C\iota$	—	C_F	—	C_i	—	C_p	—	-	K_F	ϕ_e	λ
$E' = E$ X	—	C_M	$C\iota$	—	—	—	C_i	—	—	—	—	—	—	—
$E_{min}' = E_{min}$ X	—	C_M	$C\iota$	—	—	—	C_i	—	—	C_T	—	K_F	ϕ_ξ	—

ASD = allowable stress design, LRFD = load and resistance factor design

The current NDS contains design values for both visually rated lumber and mechanically graded dimensional lumber. For visually graded lumber, the NDS contains 29 different species of wood and six corresponding design values for each species. Such design stress values include fiber bending (F_b), tension parallel to grain (F_t), shear parallel to grain (F_v), compression perpendicular to grain (F_{ct}), compression parallel to grain (F_c), and MOE (E). Mechanically graded lumber has tables like those for visually graded lumber; however rather than listing values for every species, the tables for mechanically graded lumber ignore species type and simply list grades that correspond to mechanically determined values of E and F_b.

While mechanically graded lumber tables still use adjustment factors to arrive at design values, there is an implicitly generated grade name that is representative of a presumably mechanically derived E and F_b values. For example, the machine stress rated grade name of 900f-1.0E corresponds to $F_b = 900$ psi and $E = 1{,}000{,}000$ psi, $F_t = 350$ psi, and $F_c = 1050$. Design values for machine stress graded lumber rely upon grade types that are presumably found from a machine test. Variations due to lumber species are not directly addressed within the NDS; however the notes associated with the design tables state:

> *for any given bending design value, F_b, the modulus of elasticity, E, and tension parallel to grain, F_t, design value may vary depending upon species, timber source or other variables. The "E" and "F_t" values included in the "$F_b - E$" grade designations in Table 4c are those usually associated with each F_b level. Grade stamps may show higher or lower values if machine rating indicates the assignment is appropriate (NDS, 2012 p. 43).*

This note in the design tables casts doubt on the accuracy of the design tables and allows properties to be changed, presumably based upon the judgment of machine rating operators and managers. Further doubt is cast upon the accuracy of the design values due to an additional note that indicates "the gain in load carrying capacity due to increased strength and stiffness resulting from drying more than offsets the design effect of size reductions due to shrinkage" (NDS Supplement, 2012 p. 43). This statement highlights that the effect of shrinkage is neglected and that any change in cross-sectional area is more than counterbalanced by increases in capacity due to drying. The phrase "more than offsets," does not quantify the gains in strength due to drying. Beyond this statement, the NDS provides no further explanation as to the increase in capacity due to drying effects.

Although the NDS addresses many different properties of wood, the present study mostly pertains to wood properties associated with bending. Due to this focus, the NDS was examined with the specific interest in fiber bending strength (F_b). One of the overarching factors affecting a joist's strength, and therefore a roof system's strength, is the system itself. A system's ability to resist more load than the sum of its individual components is referred to within the industry as a system effect. Due to system effects, the NDS allows users to increase a joist's load-carrying capacity if it is a member of a composite assembly. The increase in capacity due to system effects is represented by a 'repetitive member factor' (C_r), and provides an increase to allowable design values of 15% if the joists meet specific requirements. These requirements are stated as follows:

> bending design values F_b, for dimensional lumber 2" to 4" thick shall be multiplied by the repetitive member factor $C_r = 1.15$, when such members are used as joist, truss cords, rafters, studs, planks, decking or similar members which are in contact or spaced not more than 24" on center; are not less than 3 in number; and are joined by floor, roof, or other load distributing elements adequate to support the design load (NDS 2012).

Note that the repetitive member factor, C_r, is a factor that is not influenced by any observed or measurable characteristic of sawn lumber; but rather the increase in allowable capacity is based solely on the geometric properties of the assembly, which provide more loading than the sum of individual components.

Unlike the IRC, the NDS provides more design flexibility with variation factors than the IRC allowing its users the ability to determine the design values that best reflect in situ conditions. The NDS lacks a stated value for the nominal FS. Furthermore, the NDS casts doubt upon both the accuracy and final design values by allowing offset of unquantified strength losses, due to shrinkage, with supposedly greater unquantified strength gains, due to drying.

Ultimately, the NDS provides valuable design information for a wide array of various usages and types of lumber; however the NDS does not contain enough information to quantify a FS. Although the NDS does not provide explicit FSs, it does refer users to the ASTM standards and the North American In-Grade Testing Program. The commentary of the NDS Section 4.2.3.2 states:

> Changes in the *1991 NDS* to dimension lumber design values are based on a comprehensive testing program conducted by the North American forest products industry called In-Grade Testing…. A new test method standard, ASTM D4761, was developed to cover the mechanical test methods used in the program. A new standard practice, ASTM D1990, was developed to codify procedures for establishing design values for visually graded dimension lumber from test results obtained from in-grade test programs (NDS, 2013).

This new insight into the genesis of design values leads us to investigate the testing procedures and standards that have been published by the ASTM wood subcommittee D07 and to investigate the North American In-Grade Testing Program.

2.5 ASTM International

ASTM International publications have greatly influenced the field of structural lumber testing and current wood design standards. While ASTM once stood for American Society for Testing and Materials, the current organization does not recognize the acronym and is simply named ASTM International. The ASTM wood subcommittee (D07) is tasked with the responsibility of quantifying and documenting testing procedures. To fulfill this responsibility, ASTM determines the procedures for establishing the mechanical properties of all wood-based products. As earlier indicated, the NDS specifies some adjustment factors based on various characteristics of both the material and the systems; however the NDS does not specify how those factors were found, but rather refers the users to ASTM standards. For example, the addition of a 15% increase due to repetitive-member performance, stated as appropriate by the NDS stems from ASTM Standard *Evaluating System Effects in Repetitive-Member Wood Assemblies*.

The ASTM D6555-03 standard recognizes an increase in load-carrying capacity due to three factors which include: load sharing, composite action, and residual capacity. Within this standard, a method for quantifying system effects using empirical test results is presented. The ASTM standard indicates that at least 28 assemblies need to be tested in order to quantify system effects (ASTM D6555 Section 8.3). The sample size of 28 specimens stems from ASTM Standard D2915 titled "*Standard Practice for Evaluating Allowable Properties for Grades of Structural Lumber."* ASTM D 2915 seeks to identify grade assignments based on empirically derived mechanical properties found during the testing of representative samples. By this standard, a lumber grade can be established which is statistically representative of a sample population. Due to this representation, ASTM D2915 allows small sample sizes for empirical testing, thus increasing efficiency for both visually and mechanically graded lumber.

To establish a grade, empirical testing is conducted on a sample size that is representative of the total population, which ASTM has established at a lower bound of 28. An example of this process is shown in Figures 1 and 2. After testing is completed, a regression line to the data is determined. The regression line is then shifted downward to ensure that 95% of the data points fall above the regression line. This new offset regression line is then said to be indicative of the population and cutoffs can be established to represent different grades within the entire population.

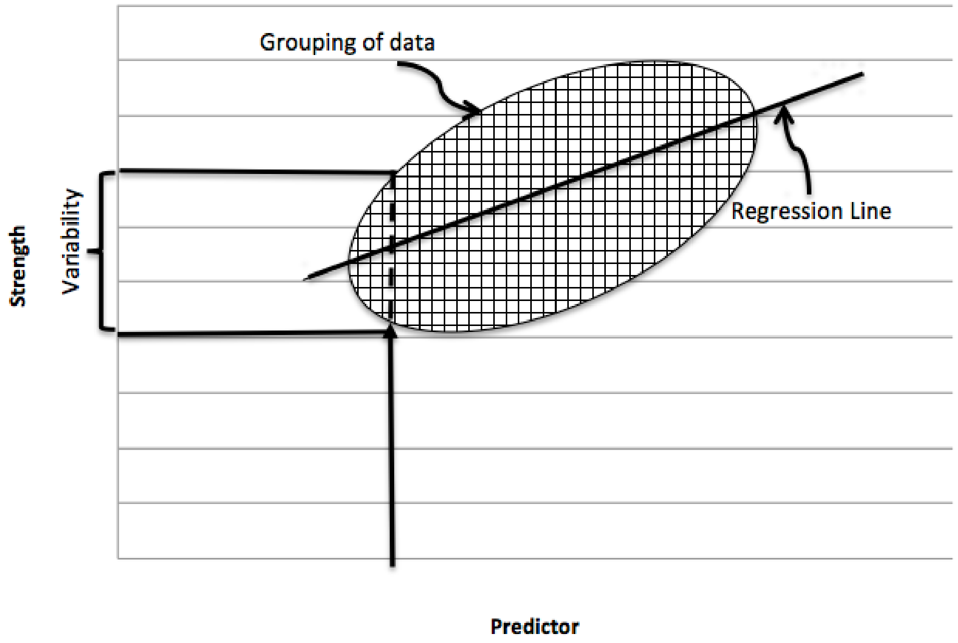

Figure 1. Example of prediction of strength by regression analysis.

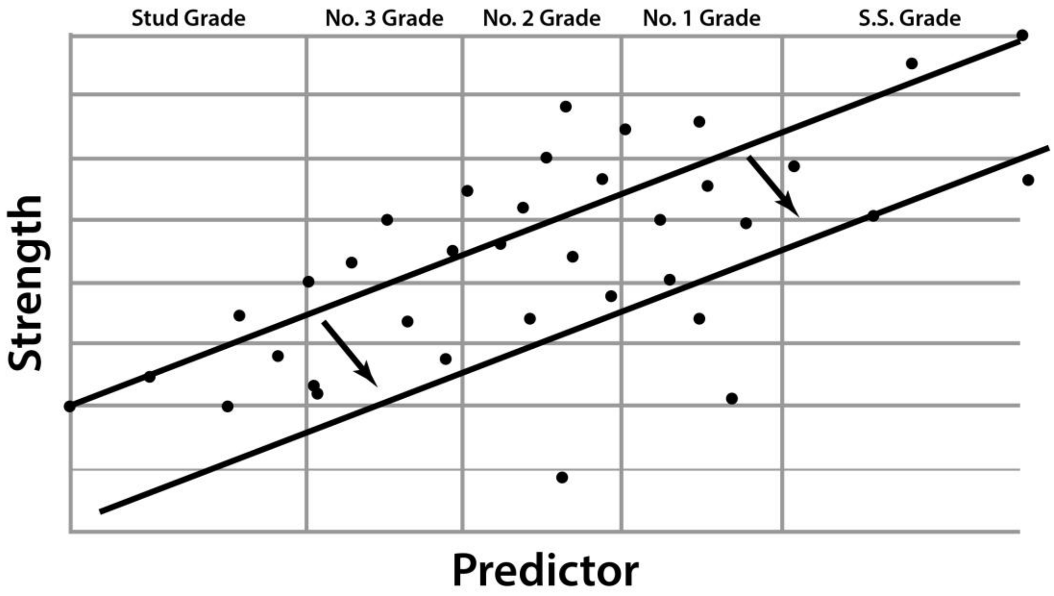

Figure 2. Example of the typical relationship between strength predictor (MOE) and strength (MOR). Regression line is shifted downwards to below 95% of the data.

In addition to ASTM Standard D2915, machine stress rated lumber is assigned design values using ASTM Standard D6570 *Standard Practice for Assigning Allowable Properties for Mechanically Graded Lumber*, which includes factors aimed at addressing multiple scenarios and factors including: multiple-member systems, normal duration of load, growth ring position, moisture content, size factors, different than normal duration of load, decay, treated wood, temperature, and bearing areas. In addition to discussing these factors and scenarios this ASTM standard helps to allow nondestructive rating of lumber by relating a physically found MOE to a hypothetically correlated modulus of rupture (MOR). This hypothetical correlation between stiffness and bending strength is the basic assumption in nondestructive testing.

In the 1960s, the correlation between MOE and MOR had been recognized, and the lumber rating industry began to develop machines that could quickly test individual pieces of lumber. More recent development of these machines incorporates components that not only determine MOE values but also automatically inspect for visual characteristics such as knots and grain pattern using optical scanners. These characteristics also influence final grade assignments. Due to the widespread acceptance of mechanically graded lumber beginning in the 1970s, the vast majority of all dimensional lumber available today is machine stress rated.

The correlation presented in ASTM Standard D6570 between MOE and MOR provides an efficient and accurate assignment of grades; however it does not provide explicit information concerning the FS that is built into the grading system. In the continued search for an established underlying FS, additional information can be located in ASTM Standard D245 *Standard Practice of Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber*. Within this standard, the method of establishing allowable properties is addressed in Section 6.2, which indicates, "properties when divided by the factors given in Table 8 give the respective allowable design properties for clear straight-grained wood. The factors include an adjustment for normal duration of load and a factor of safety”. Table 3 is an example of adjustment factors provided by ASTM D245 Table 8.

Table 3. Adjustment Factors To Be Applied To the Clear Wood Properties Provided by ASTM (adapted from ASTM D245 Table 8)

Adjustment Factors to be Applied to the Clear Wood Properties						
	Bending Strength	Modulus of Elasticity in Bending	Tensile Strength Parallel to Grain	Compressive Strength Parallel to Grain	Horizontal Shear Strength	Proportional Limit and Stress at Deformation in Compression Perpendicular to Grain
Softwoods	2.1	0.94	2.1	1.9	2.1	1.67
Hardwoods	2.3	0.94	2.3	2.1	2.3	1.67

Additionally, ASTM D245 provides examples of stress-grade development that clearly show how adjustment factors affect the overall design values of mechanically and visually rated lumber. Tables 4 and 5 provide examples of how ASTM implements adjustment factors. ASTM D245 contains the first explicit mention of a FS, which is an established factor of 2.1. However, this factor does not apply to all wood properties. As can be seen in Table 3, FSs vary in both property type and wood classification. It is important to note that any prescribed FS is applied in addition to the statistical 5% exclusion limit. ASTM D245 also addresses the age of lumber and its working stress values, indicating that old lumber can be assigned the same working stress values as new lumber.

Table 4. Example of How ASTM Implements Adjustment Factors for Limiting Characteristics

Selection of Limiting Characteristics			
Property	**Limiting Characteristic**	**Strength Ratio %**	**From Table**
Bending	Narrow face knot = ¾ in	62	2
	Knot centerline of wide face = 2⅜ in	60	3
	Knot at edge of wide face = 1⅜ in	60	4
	Slope of grain 1 in 10	61	1
Compression strength parallel to grain	Knot on any face = 2½ in	61	1
Shear	Slope of grain 1 in 8	66	1
	Size of shake or check = ½ in	50	1
	Length of end split = 4¼ in	50	1

Table 5. Example of ASTM's Allowable Properties for the Sample Stress-Grade

Allowable Properties for the Sample of Stress-Grade						
Property	**Strength Value psi**	**Adjustment Factor**	**Strength Ratio**	**Seasoning Adjustment**	**Special Features**	**Allowable Property psi**
Bending	4432	1/2.1	0.6	1.25	0.89	1400
Compression parallel to grain	2174	1/1.9	0.65	1.5	—	1100
Horizontal shear	576	1/2.1	0.5	1.08	—	150
Tension parallel to grain	4432	1/2.1	0.60 × 0.55	1.25	—	850
Modulus of elasticity	1304000	1/0.94	1	1.14	—	1580000
Compression Perpendicular [A]	282	1/1.67	1	1.5	—	225
Compression Perpendicular [B]	491	1/1.67	1	1.5	—	440

[A] Compression perpendicular to grain for proportional limit stress.
[B] Compression perpendicular to grain at 0.04 in (1 mm) deformation.

Out of the three entities providing recommendations to the construction industry, ASTM standards are the only set of guidelines that provide an explicit FS. In addition to providing a FS, the ASTM standards provide insight into how grades are assigned using both the correlation between MOE and MOR and visual inspection. ASTM also has increased the efficiency of grading lumber by setting standards associated with empirically testing small samples of wood species to gain knowledge about the larger population.

2.6 USDA Forest Service, Forest Products Laboratory

During the middle of the 20th century, a need developed within the United States lumber industry to quantify and verify the mechanical properties of various species of 2" thick dimensional lumber. During that time frame, the bulk of lumber sold in the US was visually graded, and although machine stress grading standards had already been established, industry acceptance had not yet been realized. In 1977, in order to verify mechanical properties and further the accuracy of machine stress grading, the USDA Forest Service's Forest Products Laboratory implemented the North American In-Grade Testing Program that included:

> Testing of more than 70,000 specimens, totaling approximately 1,000,000 board feet of lumber, in bending, tension parallel to grain, and compression parallel to grain. This 10 year, 7 million dollar effort was one of the largest single research efforts ever undertaken in forest products research (Kretsmann, 2010).

The North American In-Grade Testing Program was a coordinated effort that used ASTM standards to test wood specimens to validate current design standards. The testing program also helped to establish new standards such as ASTM D 1990 *Standard Practice for Establishing Allowable Properties for Visually Graded Dimensional Lumber from In-Grade Tests of Full Size Specimens.* This standard addresses concerns associated with rapid rates of loading due to mechanical testing.

To accomplish the task of validating current design values, the North American In-Grade Testing Program incorporated many local agencies that independently evaluated lumber at a local level. The In-Grade Testing Program involved 33 species, or species groups, of lumber with considerations given to several different parameters such as temperature, humidity conditions, moisture content, and differences in moisture meter reading. The testing program’s goals were not only to provide mechanical properties of various lumber species but also to produce models that could be used to predict the strength of light-framed wood assemblies.

The culmination of this research helped to verify many historic lumber design values that had existed for over seventy years. After the testing was completed in 1988, the results were quickly adopted by the NDS. The research also helped to adjust behavioral equations for column, beam, and beam-column design. To this day, the NDS still reflects the results of the North American In-Grade Testing Program.

3.0 Summary

The mechanical properties of sawn lumber have been extensively studied and the methods of testing wood specimens are well documented. However, questions still remain regarding the exact testing standards used to develop building codes. This lack of clarity has caused uncertainty in identifying FSs that exist within the governing codes. From the literature reviewed it can be concluded that a numerical FS does not actually exist, but rather a range or a probability of failure would better describe how allowable values have been determined. Moreover, the added weight applied to a roof system due to a PV installation is not a question of encroaching on the FSs but rather an issue that must be analyzed as to how it affects the probability of failure.

In order to further explore the performance of wood roof systems, full-size laboratory testing was conducted as a means of observing the structural behavior of roof systems (Dwyer et al. 2014, in print).

4.0 References

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