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Flexural Strength Reliability of Visually Graded Southern Pine Dimensional Lumber

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FLEXURAL STRENGTH RELIABILITY OF VISUALLY GRADED SOUTHERN PINE DIMENSIONAL LUMBER

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ABSTRACT

The reference design values published in the National Design Specification (NDS) for Wood Construction are derived from full-scale testing of lumber samples performed in the 1980s. This testing program is commonly known as the *In-Grade* Test Program. Selective annual sample tests of visually graded Southern Pine lumber from 1994 to 2010 revealed an overall decreasing trend in the mechanical properties. Because of this alarming observation, a new round of full-scale *In-Grade* test of visually graded Southern Pine was initiated in 2010. The new test data indicated significant reductions in certain design values published in the current design code (2005 NDS). The new reference design values have been adopted by the 2012 NDS. Compared to the 2005 NDS, the 2012 NDS reference design values for modulus of elasticity (MOE) and modulus of rupture (MOR) were reduced by approximately 0.0 to 14.3% and 11.4 to 41.7%, respectively. This suggests that the underlying reliability of structures constructed recently using Southern Pine might not meet the minimum target flexural reliability speculated in the design code. The main goal of this study was to assess the reliability of flexural members constructed using visually graded Southern Pine lumber and designed using the 2005 NDS design values to determine if they meet the minimum target reliability of wood construction.

The new MOE and MOR data were obtained from the Southern Pine Inspection Bureau (SPIB). Probability distribution fitting was performed to determine the best-fit

statistical distributions for the new MOE and MOR data. Five distributions were considered: Normal, Lognormal, Gumbel, Frechet and Weibull distributions. The fitted distribution parameters were used to assess the reliability of visually graded Southern Pine floor joists subjected to uniformly distributed dead and live loads.

Two scenarios were considered in the reliability analyses conducted in this study. The first scenario assessed the reliability of flexural members designed using the 2005 NDS reference design values which are derived from the 1978 *In-Grade* test data. The second scenario assessed the reliability of flexural members designed using the new reference design values for visually graded Southern Pine lumber which are derived from the new (2010) *In-Grade* test data. The analysis results showed that the reliability of *Scenario 1* designs (i.e. designs based on the 2005 NDS values) are lower than that of *Scenario 2*. However, the overall influence of reductions in new reference design values of visually graded Southern Pine on the reliability or safety of bending members is not as significant as expected. This is because the design of flexural members, in particular for *No. 2* and better grades, often is controlled by the serviceability limit state (deflection) and not the strength level limit state.

Using both the 2005 NDS and 2012 NDS design values, maximum span lengths for floor joists for common ranges of live load-to-dead load ratios, joist spacings and joist dimensions were computed and tabulated in a series of tables. These tables can be used by practitioners as design guides to quickly determine if the floor joists designed based on the 2005 NDS are at-risk or required rectification. Since shear failure usually does not control in the design of floor joists, only the bending strength and serviceability (deflection) limit states were considered in the maximum span tables. Comparison between the maximum span lengths determined from the 2005 NDS and 2012 NDS revealed that the reduction in allowable span lengths is a function of lumber grade, in which the reductions in maximum span lengths for lower grade lumbers are more significant than that of higher grade lumbers. There are no reductions for the maximum span lengths of *Select Structural* (*SS*) grade lumber while the maximum span lengths of *No. 3 & Stud* grade floor joists are reduced by 7.7 to 13.4%.

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CHAPTER ONE

INTRODUCTION

1.1 Introduction

The reference design values of dimensional lumber in the National Design Specification (NDS) Supplement are assigned based on the wood species, dimension, intended use and mechanical properties. Wood is a biological building material. Compared to other building materials, for example steel, the structural properties of individual lumber pieces harvested from forest may vary significantly. In order to facilitate engineering design, reference design values are assigned to lumber based on a standardized lumber testing and grading system agreed upon by the various stakeholders of the timber industry. The assignment of predictable reference design values to standardized lumber grades allows engineers to perform engineering calculations without having to consider the variability of mechanical properties between lumber pieces.

The reference design values in the existing U.S. building codes were established based on testing of large number of lumber pieces from 1978 to 1990 (Evans, 2001). This large scale lumber testing program is known as the *In-Grade* Test Program (IGTP). Since then, limited number of lumber samples are selected from various lumber mills and tested annually to ensure that the lumber properties do not deviate significantly from that established in the 1978 IGTP. Based on the annual monitoring test data, an overall decreasing trend of the bending stiffness of visually graded Southern Pine lumber was observed for data collected from 1994 to 2010. This prompted a new IGTP test for visually graded Southern Pine lumber in 2010 and revision of a new set of reference design values for visually graded Southern Pine lumber (SPIB, 2012). These new reference design values are overall lower than that published in the 2005 version of timber design code (AF&PA, 2005).

The main objective of this study was to assess the impact of recent changes in reference design values of visually graded Southern Pine lumber on the reliability of bending members. The rest of this Chapter provides information on lumber grading system and the background information leading to the recent revision in reference design values. The last part of this Chapter outlines the organization of this thesis.

1.2 Lumber Grading System

The nominal dimensions of structural lumber are typically 2 to 4 inches thick and at least 2 inches wide. A dimensional piece of lumber with nominal 2-inch thickness and 4-inch width is designated as “2x4”. Individual pieces of dimensional lumber are graded usually based on the edgewise bending strength and stiffness (see Figure 1.1). Dependent on the intended use, lumber is sometimes graded based on the flatwise bending, tensile or compressive strength. Each lumber grade is assigned a commercial designation which qualifies the lumber grade for certain predefined reference design values for engineering design purposes. There are three methods used to grade and classify lumber, namely, visual grading, machine stress rated and machine evaluated grading.

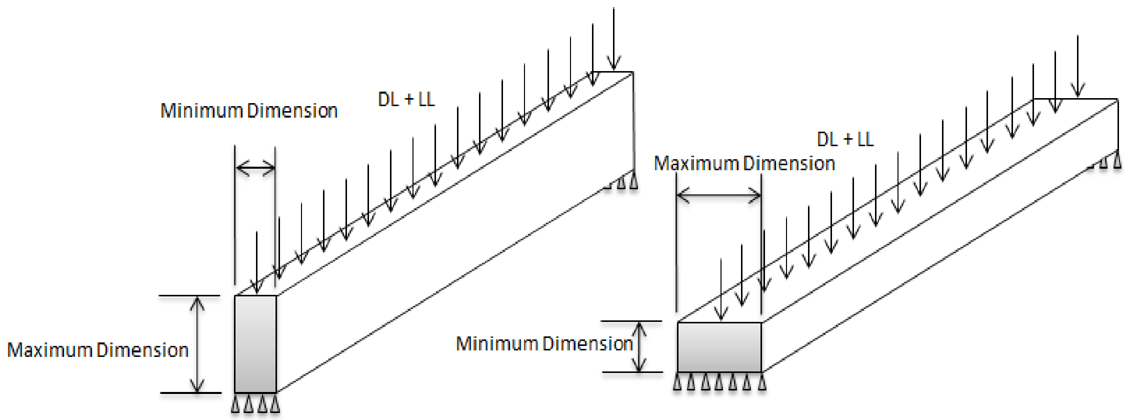


Figure 1.1: Edgewise (left) and flatwise (right) bending.

1.3 Machine Stress Rated Lumber and Machine Evaluated Lumber

Machine Stress Rated (MSR) lumber is graded by mechanical stress rating equipment. Each piece of MSR lumber is evaluated via non-destructive bending to determine its modulus of elasticity (MOE). In addition to the modulus of elasticity, each piece must also meet certain visual restrictions before it can be assigned a MSR grade designation. For example, a MSR lumber stamped with “2400F 2.0E” means the lumber qualifies for a reference design edge bending strength (F_b) of 2400 psi and an MOE of 2.0 x 10^6 psi (see Figure 1.2 for a sample MSR stamp). The procedure for assigning design values to MSR lumber is outlined in ASTM (American Society for Testing and Materials) standard D6570, “Standard Practice for Assigning Allowable Properties for Mechanically-Graded

Lumber" (ASTM, 2004). Note that the bending strength (Fb) is thought to correlate well with the bending stiffness (MOE). Hence, only the bending strength is shown in the MSR stamp.

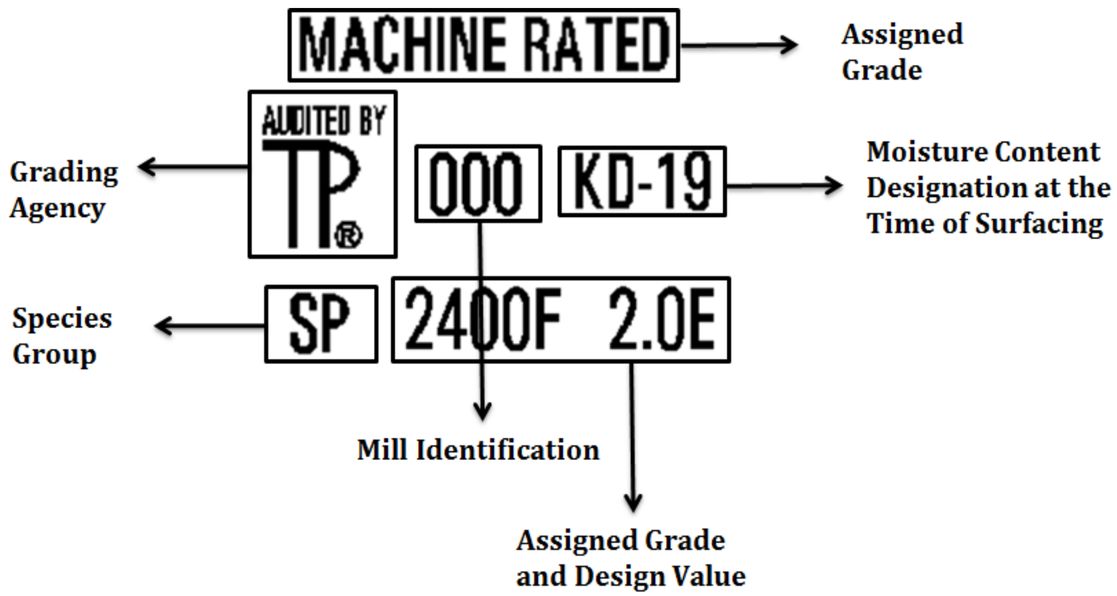


Figure 1.2: Sample stamp of MSR lumber (adapted from SBCA (2009)).

Machine Evaluated Lumber (MEL) is similar to MSR. Each piece of MEL is evaluated and sorted into various bending strength and tension strength using a non-destructive grading equipment. Each piece must also meet certain visual restrictions before it can be assigned a MEL grade designation. For example, a MEL lumber stamped with "2400fb 1900ft 1.8E" means the lumber qualifies for a reference design edge bending strength (F_b) of 2400 psi, tension strength (F_t) of 1900 psi and an MOE of 1.8 x 10^6 psi (see Figure 1.3 for a sample MEL stamp).

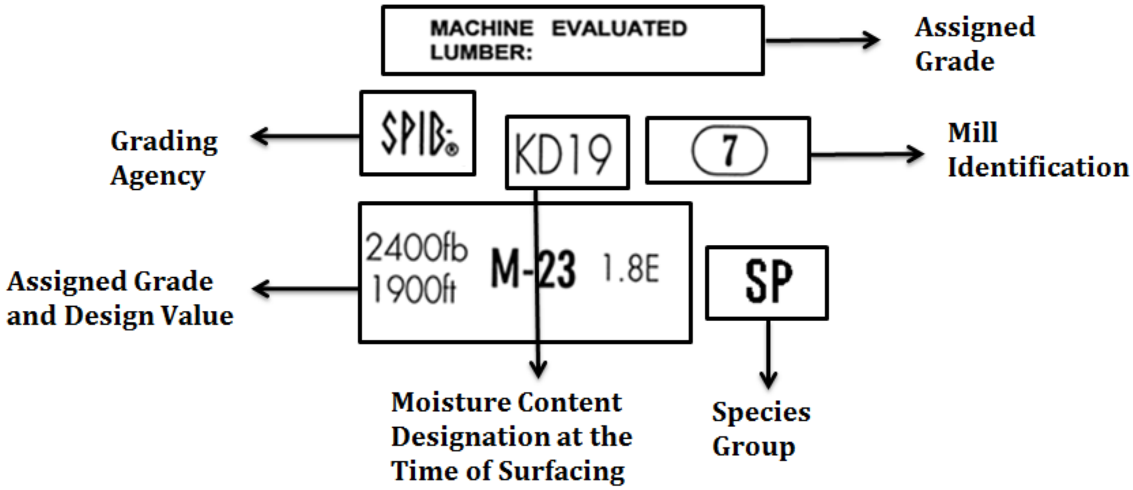


Figure 1.3: Sample stamp of MEL lumber (adapted from SPIB (2005)).

1.4 Visually Graded Lumber

Visually graded lumber is graded by manually inspecting the visual characteristics of lumber and identifying the number, size and location of knots and other strength compromising defects in the lumber. Visually graded lumber is assigned a grade name of either "*Select Structural*", "*No. 1*", "*No. 2*", "*No. 3*", "*Stud*", "*Construction*", "*Standard*" or "*Utility*". An example commercial grade stamp for visually graded lumber is shown in Figure 1.4. The density of lumber affects the strength, in particular the connection strength. Although not as common, lumber grades based on wood density are also available (e.g. "*dense No.1*" and "*dense No.2*" grades).

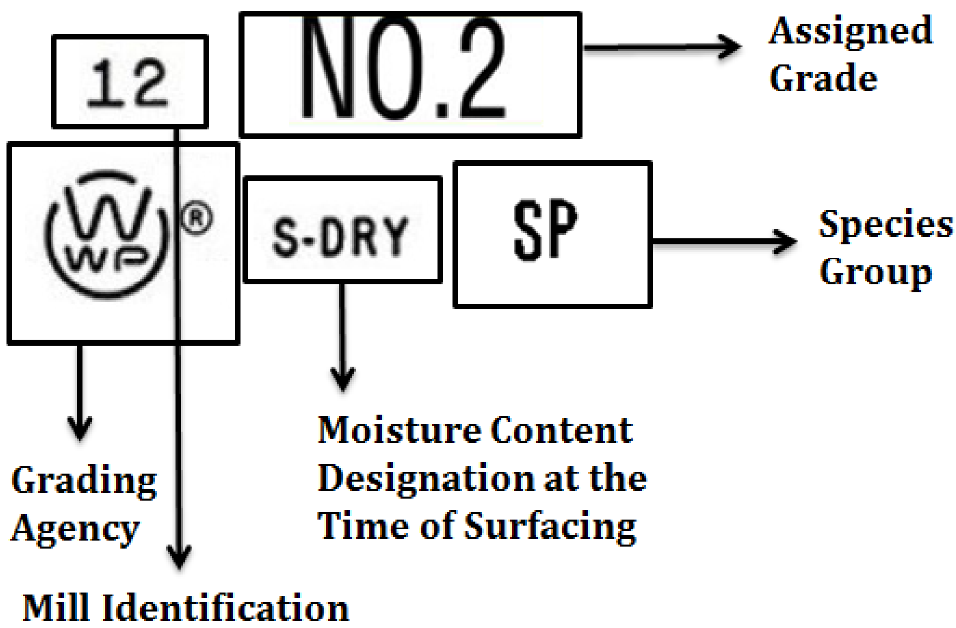


Figure 1.4: Sample stamp of visually graded structural lumber (adapted from WWPA (1997)).

The grading standards and procedures of visually graded lumber are described in ASTM D245, "Methods for Establishing Structural Grades for Visually Graded Lumber" (ASTM, 2011). ASTM D245 standard defines the reduction factors which are applied to the reference design values of clear wood[1] to derive the design values for lumber grades. Example reduction factors are shown in Table 1.1 (Kretschmann, 2010). The reference design values of visually graded lumber are established in accordance to ASTM D1990, "Standard Practice for Establishing Allowable Properties for Visually Graded Dimension Lumber from *In-Grade* Tests of Full-Size Specimens" (ASTM, 2007) which outlines the

[1] Clear wood is wood without any strength reducing defects such as knots and splits which may compromise the structural integrity of a dimension lumber.

criteria to analyze the data obtained from a testing procedure known as *In-Grade* test (Kretschmann, 2010).

Table 1.1: Bending strength ratios of visually graded lumber (Kretschmann, 2010).

Lumber Classification	Grade name	Bending strength ratio(%)
Light framing	Construction	34
	Standard	19
	Utility	9
Structural light framing	Selet Structural	67
	1	55
	2	45
	3	26
Stud	Stud	26
Structural joists and planks	Selet Structural	65
	1	55
	2	45
	3	26

1.5 *In-Grade* Test Program

The first major organized lumber test program for establishing mechanical properties and design values of lumber species in the United States can be traced back to 1920s (Kretschmann, 2010). Several ASTM standards (e.g. D198, D245 and D2555) were established to support the test program. In 1977, ASTM Standard D1990 was published. ASTM D1990 outlines the criteria for interpreting the data of full-size lumber tests to determine the design values of visual lumber grades. After the ASTM D1990 standard was established, *In-Grade* Testing Program (IGTP) was initiated in 1978 and it took 12 years to test over 70,000 pieces of full-size dimension lumber. The main objectives of the 1978 IGTP were to establish a statistical database for mechanical properties of various lumber species and to establish reference design values. Bending, shear, tension and compression capacities were evaluated in this test program for various common U.S. lumber species which included Douglas Fir-Larch, Hem-Fir and Southern Pine as species group together with other individual species. The reference design values derived from the 1978 IGTP were first appeared in the 1991 version of the U.S. timber design code (AF&PA, 1997).

1.6 Motivation

After the initial IGTP design values were published in 1991, trade associations and grading agencies for different wood species such as the Southern Pine Inspection Bureau (SPIB) and the West Coast Lumber Inspection Bureau (WCLIB) each have established an annual resource monitoring program for their respective lumber species. The main purpose of this annual resource monitoring program is to test selected sample lumber pieces from various lumber mills to determine whether the mechanical properties deviate significantly from the initial design values published in 1991.

According to the SPIB, the measured MOE values obtained from the Southern Pine monitoring program from 1994 to 2010 show an overall decreasing trend. The reductions in the measured Southern Pine MOE of individual years never reached the threshold value which would trigger a full-scale *In-Grade* test. Nevertheless, in 2010, the SPIB and Timber Products Inspection voluntarily tested the stiffness (i.e. MOE), bending, and tension strength of representative visually graded *No.2* and *Select Structural* grades Southern Pine lumber. The test data indicated significant reductions in the design values compared to that initially published in 1991 (see Table 1.2). It can be seen that the reference design MOEs dropped by approximately 12% and the MORs dropped by approximately 15 to 27% for *Select Structural* and *No.2* grades. Note *In-Grade* tests were performed only for *Select Structural* and *No.2* grades, the design values for other lumber grades were derived from the test results of *Select Structural* and *No.2* grades. During the writing of this manuscript, a set of new design values for Southern Pine have been submitted to the American Lumber Standard Committee for review and approval (AF&PA, 2012). This suggests that the underlying reliability of floor joists constructed recently using Southern Pine might not meet the minimum target reliability speculated in the National Design Specifications (NDS) for Wood Construction (AF&PA, 2005).

Table 1.2: Reference design MOR (F_b) and MOE (E) values of visually graded Southern Pine lumber[2].

Dimension	Grade	E			F_b		
		2005 NDS (million psi)	Proposed (million psi)	Diff (%)	2005 NDS (psi)	Proposed (psi)	Diff (%)
2x4	SS	1.8	1.8	0.0	2850	2350	17.5
	No.2	1.6	1.4	12.5	1500	1100	26.7
2x8	SS	1.8	1.8	0.0	2300	1950	15.2
	No.2	1.6	1.4	12.5	1200	925	22.9
2x10	SS	1.8	1.8	0.0	2050	1700	17.1
	No.2	1.6	1.4	12.5	1050	800	23.8

1.7 Research Objective

Prior to the announcement of the new design values for visually graded Southern Pine lumber in October 2011, engineers would use the design values published in the 2005 edition of National Design Specifications (NDS) for Wood Construction (AF&PA, 2005) to perform engineering calculations when specifying Southern Pine lumber as the construction material. According to the recent SPIB test data, the actual design values for Southern Pine are approximately 12 to 27% lower than the design values published in the 2005 NDS. This suggests that engineers may have overestimated the capacities of the Southern Pine lumber used in recently constructed light-frame wood structures (i.e. prior to the announcement of the new design values). In other words, the actual reliability of

[2] The notations "E" and "F_b" are used in this thesis to denote the reference design values for modulus of elasticity (MOE) and modulus of rupture (MOR), respectively. The reference value, E is derived from the mean value of MOE and F_b is derived from the 5 percentile value of MOR.

Southern Pine structures constructed recently may have been lower than the minimum reliability speculated in the design code.

The main goal of this research was to assess the reliability of flexural members designed and constructed using the 2005 NDS design values for visually graded Southern Pine. The main goal was achieved through the following sub objectives:

(1) to determine the best-fit statistical distributions for modulus of elasticity (MOE) and modulus of rupture (MOR) of visually graded Southern Pine lumber using the new *In-Grade* test data;

(2) to evaluate the reliabilities and failure probabilities of flexural members designed using the 2005 NDS design values and the new design values in the 2012 NDS; and

(3) to develop design charts for maximum allowable span lengths using the new reference design values.

1.8 Thesis Organization

In Chapter 1, the background information on reference design values of dimension lumber are provided and the motivation of study is discussed. Chapter 2 presents the analyses performed to determine the best-fit statistical distribution for the latest In-Grade test data for visually graded Southern Pine lumber. Chapter 3 presents the methodology used to assess the reliability of flexural members. Two scenarios are discussed in Chapter 3. The first scenario assesses the reliability of flexural members designed using the 2005 NDS values which are based on the 1978 *In-Grade* test data. The second scenario assesses the reliability of flexural members designed using the new reference design values for visually graded Southern Pine lumber which are derived from the latest *In-*

Grade test data. Chapter 4 presents the results of reliability analyses and summarizes the changes (mainly reductions) to maximum allowable spans for visually graded Southern Pine of different sizes and grades. In the last Chapter, summaries of the major findings and recommendations for further research are presented.

CHAPTER TWO

NEW TEST DATA

The current reference design values for structural dimension lumber were derived from the 1978 IGTP data. This Chapter presents the results of probability distribution fitting for the new *In-Grade* test data of visually graded Southern Pine dimension lumber performed by SPIB. From the new test data, distribution parameters for modulus of elasticity (MOE) and modulus of rupture (MOR) were fitted. The fitted distributional parameters were used for reliability analyses (discussed in Chapter 3).

2.1 Test Description

The test samples for the 2010 *In-Grade Test Program* (2010 IGTP) for visually graded Southern Pine lumber were collected from lumber mills based on the sampling rules defined in ASTM D2915 (ASTM, 2010) These sampling rules were initially developed for the 1978 IGTP (Jones, 1988). The use of these sampling rules ensures that the collected samples were representative of the actual Southern Pine lumber population.

According to ASTM D1990 at least two visual grades and three sizes for each grade are required to be tested in order to derive the reference design values (ASTM, 2007). In the 2010 IGTP for Southern Pine, *Select Structural (SS)* and *No.2* grades were selected and nominal 2x4, 2x8 and 2x10 sizes were tested for each of the selected grade (SPIB, 2012). Based on the Southern Pine lumber population, a minimum sample size of

360 specimens for each grade and size combination was deemed adequate (ASTM, 2007). The actual number of samples tested for the grade and size combinations considered in the 2010 Southern Pine IGTP were from 400 to 420. While four mechanical properties, namely, Modulus of Elasticity (MOE), Modulus of Rupture (MOR), Ultimate Tensile Stress (UTS) and Ultimate Compression Stress (UCS) were evaluated via the 2010 IGTP, only the MOE and MOR were utilized and fitted to statistical distributions in this study.

2.2 Adjustments of Test Data to Standardized Conditions.

The mechanical properties of dimensional lumber can vary due to moisture content, temperature and actual size. In order to derive a set of standardized reference design values, the measured mechanical properties from tests were adjusted to a standardized environmental condition (i.e. moisture content and temperature). The measured MOR and MOE values were adjusted to standard conditions (e.g. moisture content, size and etc.) based on the requirements in ASTM D1990 (ASTM, 2007). The adjustment procedure is summarized in Figure 2.1 in the form of a flow chart.

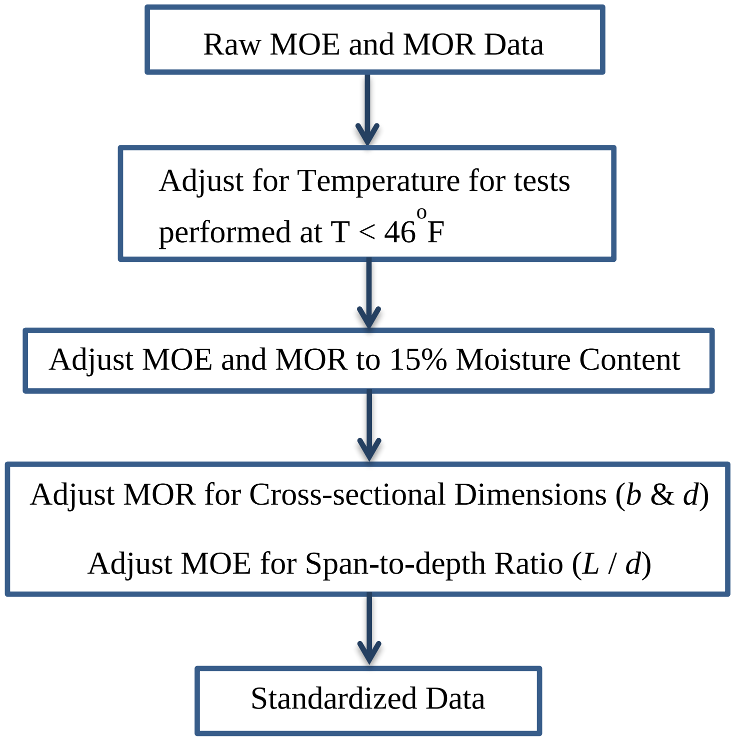


Figure 2.1: Flow chart for data adjustment.

2.2.1 Adjustments for Temperature

Temperature adjustment is required only for tests conducted at a temperature below 46°F (Barrett, 1989). No temperature adjustment was applied to the test results since all Southern Pine samples were tested above 46°F.

2.2.2 Adjustments for Moisture Content

The moisture content was measured using a 2-pin DC resistance meter (Garrahan, 1988). The measured raw MOR values were adjusted to standard moisture content (MC) of 15% using Equations 2.1 and 2.2 (ASTM, 2007):

$$MOR_2 = MOR_1 + \frac{MOR_1 - 2415}{40 - MC_1} \times (MC_1 - MC_2) \quad (2.1)$$

$$MOE_2 = MOE_1 \times \frac{1.857 - (0.0237 \times MC_2)}{1.857 - (0.0237 \times MC_1)} \tag{2.2}$$

where, MC_1 and MC_2 are the measured and target moisture contents, respectively. MOR_1 and MOE_1 are the measured (unadjusted) modulus of rupture and modulus of elasticity, respectively. MOR_2 and MOE_2 are the adjusted modulus of rupture and modulus of elasticity at moisture content equal to MC_2. Note that Equation 2.1 is only applicable to samples with a measured MOR of greater than 2415 psi. No adjustment for moisture content was made when the measured MOR was lower than 2415 psi. Equation 2.2 was applied to all measured MOE values.

2.2.3 Adjustments for Dimension

Two adjustments were made to account for the dimensions of the test samples. The first adjustment (Equation 2.3) accounts for the effects of shrinkage or swelling in lumber width and thickness due to moisture content:

$$d_2 = d_1 \times \frac{1 - \frac{a - b \times MC_2}{100}}{1 - \frac{a - b \times MC_1}{100}} \tag{2.3}$$

where d_1 is the measured (unadjusted) width or thickness at moisture content MC_1 and d_2 is the adjusted width or thickness at moisture content MC_2.The values for a and b are listed in Table 2.1.

Table 2.1: Coefficients *a* and *b* for size adjustment of Southern Pine (Evans W. J., 2001).

	Width	**Thickness**
a	6.031	5.062
b	0.215	0.181

2.2.4 Span-to-depth Adjustment for MOE

The Southern Pine lumber pieces were tested on a span-to-depth ratio *(L/d)* of 17:1. The published reference design values are based on a uniformly loaded lumber with a span-to-depth ratio of 21:1. Therefore, measured MOE were adjusted to the standard span-to-depth ratio of 21:1 using Equation. 2.4 (SPIB, 2012):

$$E_{21:1} = E_{17:1} \times \frac{1 + 0.939(\frac{1}{17})^2 \frac{E}{G}}{1 + 0.960(\frac{1}{21})^2 \frac{E}{G}} \quad (2.4)$$

where *E/G* is the ratio of the shear free modulus of elasticity to the modulus of rigidity (assumed to be 16 for lumber) (Evans W. J., 2001).

2.3 Grade Model

Using the adjustment equations discussed in previous sections, the adjusted MOE and MOR values for *SS* and *No.2* grades were calculated. A *Grade Quality Index (GQI) Model* was then used to determine the characteristic values for those untested grades, namely *No.1*, *No.3*, *Stud*, *Construction*, *Standard* and *Utility* grades. The *GQI* is based on the ASTM D245 (ASTM, 2011) strength ratio concept which is used by the National

Grading Rule to derive the grades of visually graded lumber (Kretschmann, 2010). The strength ratio is defined as the ratio of the target strength (MOR) or stiffness (MOE) to that of the clear wood. As outlined in section X12.5.6 of ASTM Standard D1990, the target *GQI* levels for *No. 2* and *Select Structural* grades are 45[3] and 65, respectively (Kretschmann, 2010). In other words, the strength ratios for *No. 2* and *Select Structural* are 0.45 and 0.65, accordingly. Linear interpolation was used to compute the MOE and MOR values of the untested grades (see Table 2.2). More details on the development of Southern Pine grade models for MOE and MOR are discussed in (SPIB, 2012).

Table 2.2: Interpolated MOR and MOE strength ratios

Grade name	Strength ratio(%)
Selet Structural	65
1	55
2	45
3	26
Stud	26
Construction	34
Standard	19
Utility	9

2.4 Probability Distribution Fitting

After the MOE and MOR values of the 2010 IGTP were adjusted to the standardized conditions for all grades of Southern Pine, distribution fittings were performed to find the

[3] GQI of 45 for No. 2 grade means the target strength and stiffness of No. 2 lumber are 45 percent of the clear wood.

best-fit statistical distribution for each of the size and grade combination. Five types of distributions were considered in this study: Normal, Lognormal, Gumbel, Frechet, and two-parameter Weibull distributions.

The cumulative distribution function (CDF) for the normal distribution is:

$$F(x) = \int_{-\infty}^{x} \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right) dx \tag{2.5}$$

where, μ and σ are the mean and standard deviation. Here, x denotes the adjusted MOE or MOR values of a specific size and grade combination.

The CDF for the lognormal distribution is:

$$F(x) = \int \frac{1}{\sigma_Y x\sqrt{2\pi}} exp\left(-\frac{1}{2}\left(\frac{ln(x)-\mu_Y}{\sigma_Y}\right)^2\right) dx \tag{2.6}$$

where, μ_Y and σ_Y are the logarithmic mean (location parameter) and logarithmic standard deviation (scale parameter) of x.

The CDF for the Gumbel distribution is:

$$F(x) = exp(-e^{-(\frac{x-\mu_n}{\beta_n})}) \tag{2.7}$$

where, μ_n and β_n are the location parameter and scale parameter of x.

The CDF for the Frechet distribution is:

$$F(x) = e^{-(\frac{v_n}{x})^{k_n}} \tag{2.8}$$

where, v_n and k_n are the location parameter and shape parameter of x.

The CDF for the two-parameter Weibull distribution is:

$$F(x) = 1 - exp\left[-\left(\frac{x-\omega}{u-\omega}\right)^k\right] \tag{2.9}$$

where,ω is the location parameter (ω = 0 for two-parameter distribution). k is the shape parameter (>0). u is the scale parameter (>0).

The probability plotting approach was used to fit the distribution parameters presented in Equations 2.5 to 2.9. The probability plot is created by transforming each of the cumulative distribution function (Equations 2.5 to 2.9) into a linear equation of the following form:

$$Y = mX + c \tag{2.10}$$

The *Y*, *X*, *m*, and *c* variables for each distribution are listed in Table 2.3. Figure 2.2 shows an example fit using the probability plot approach for the *Select Structural* grade 2x8 Southern Pine MOR data. A linear regression was performed to obtain the slope (*m*) and the Y-intercept (*c*). For the two-parameter Weibull distribution, the shape parameter k = $1/m$ and the scale parameter u = $\exp(c)$. Note that the location parameter was assumed to be zero ($\omega = 0$).

Table 2.3: *Y*, *X*, *m* and *c* variables for each distribution.

Distribution Type	*Y*	*X*	*m*	*c*
Normal	x	$\Phi^{-1}(F(x))$	σ	μ
Lognormal	ln(x)	$\Phi^{-1}(F(x))$	σ_Y	μ_Y
Gumbel	x	-ln(-ln(F(x)))	β_n	μ_n
Frechet	ln(1/x)	ln(-ln(F(x)))	$1/k_n$	$\ln(\nu_n)$
Two-para Weibull	ln(x)	ln(-ln(1-F(x)))	1/k	ln(u)

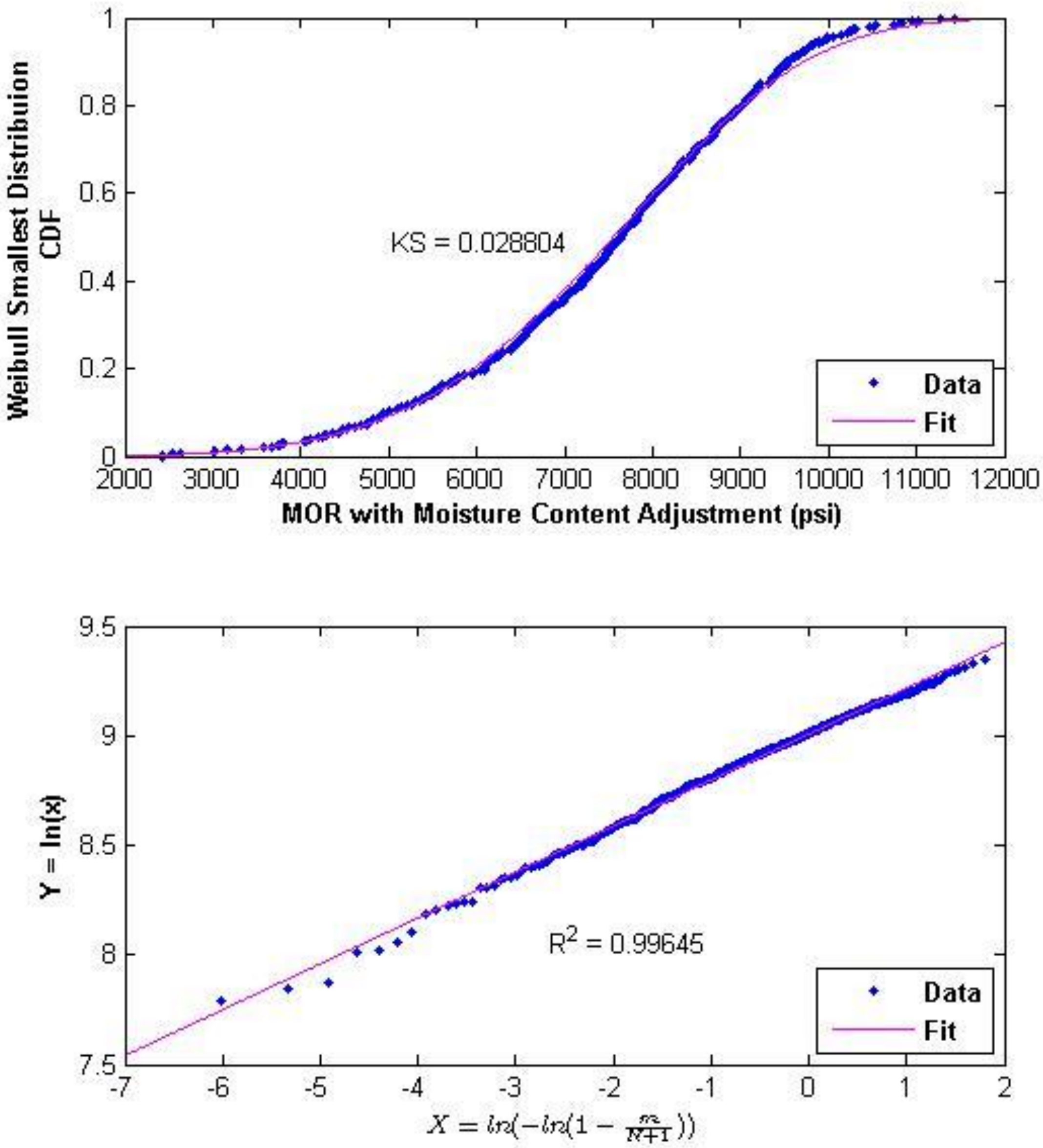


Figure 2.2: *Select Structural* 2x8, Weibull distribution fit for MOR, (a) cumulative distribution plot and (b) probability fit plot.

The complete list of the fitted distribution parameters for visually graded Southern Pine lumber using the 2010 IGTP data are shown in Table 2.4. These distributions were used in Chapter 3 to assess the reliability of flexural members constructed using visually graded Southern Pine lumber.

Table 2.4: Statistical distribution parameters for MOR and MOE.

MOR Distribution Parameter Estimates for Southern Pine (15% moistrue)											
Dimension	Grade	Normal		Lognormal		Gumbel		Frechet		Two-para Weibull	
		σ (psi)	μ (psi)	σ_Y	μ_Y	β_n (psi)	μ_n (psi)	k_n	v_n (psi)	k	u (psi)
2x4	SS	2496.2	9440.6	0.282	9.115	1922.7	8341.5	4.819	8077.1	4.461	10337.8
	No.2	2472.7	5863.4	0.439	8.584	1972.1	4736.3	3.016	4424.3	2.953	6489.1
2x8	SS	1738.6	7472.5	0.256	8.888	1296.7	6731.4	5.437	6518.8	4.773	8162.5
	No.2	1993.4	5353.6	0.409	8.509	1546.5	4469.5	3.329	4175.2	3.079	5968.8
2x10	SS	1196.9	6282.6	0.202	8.726	910.6	5762.1	6.758	5660.8	6.160	6759.3
	No.2	1616.5	4778.2	0.389	8.402	1228.1	4076.2	3.576	3799.2	3.147	5345.8

MOE Distribution Parameter Estimates for Southern Pine (15% moistrue)											
Dimension	Grade	Normal		Lognormal		Gumbel		Frechet		Two-para Weibull	
		σ (10^6 psi)	μ (10^6 psi)	σ_Y	μ_Y	β_n (10^6 psi)	μ_n (10^6 psi)	k_n	v_n (10^6 psi)	k	u (10^6 psi)
2x4	SS	0.393	1.84	0.224	0.586	0.302	1.67	6.029	1.63	5.589	1.99
	No.2	0.382	1.36	0.294	0.263	0.301	1.18	4.544	1.15	4.329	1.48
2x8	SS	0.405	1.79	0.239	0.555	0.309	1.61	5.686	1.57	5.264	1.94
	No.2	0.377	1.47	0.262	0.355	0.298	1.30	5.054	1.27	4.888	1.60
2x10	SS	0.377	1.77	0.223	0.547	0.290	1.60	6.048	1.57	5.644	1.91
	No.2	0.384	1.50	0.261	0.376	0.302	1.33	5.079	1.30	4.937	1.64

2.4.1 Goodness-of-fit

Two goodness-of-fit tests were utilized to quantify the quality of fit for each lumber size and grade combination. For each of the fitted distribution, the nonparametric *Kolmogorov-Smirnov* (*K-S*) test and the R^2 of probability plot were used to determine the goodness-of-fit.

Kolmogorov-Smirnov Test

Figure 2.2(a) show an example fit of the *Select Structural* grade 2x8 Southern Pine MOR data to Weibull (Type III smallest) distribution. The empirical cumulative distribution of the MOR data and the fitted Weibull CDF curve are shown in Figure 2.2(a). The *K-S* value for the fitted Weibull distribution was 0.0288. The *K-S* value is defined as the largest vertical distance (or "error") between the actual data points and the corresponding values on the fitted CDF curve. The fitted distribution is rejected if the *K-S* value is greater than the critical *K-S* value computed using Eqn. 2.11 for significance level (α) equal to 0.1 (Bilal M. A., 2002):

$$KS_{\alpha=0.1} = \frac{1.22}{\sqrt{n}} \tag{2.11}$$

where *n* is the number of samples. The sample size for each lumber dimension and grade combination is provided in Table 2.5.

Table 2.5: Sample size and critical *K-S* value for each grade and dimension.

	Sample Size (n)	**Critical *K-S***
SS 2X4	420	0.0595
No2 2x4	409	0.0603
SS 2x8	409	0.0603
No2 2x8	420	0.0595
SS 2x10	410	0.0603
No2 2x10	420	0.0595

R^2 of Probability Plot

Figure 2.2(b) show the probability plot of the fitted MOR data of *Select Structural* grade 2x8 Southern Pine lumber to Weibull distribution. R^2 is the coefficient of determination, which describes how well the regression line fit the data. The R^2 value was computed using the following equations:

$$R^2 = 1 - \frac{SS_{err}}{SS_{tot}} \tag{2.12}$$

$$SS_{err} = \sum_{i=1}^{i=n} (Y_i - Y)^2 \tag{2.13}$$

$$SS_{tot} = \sum_{i=1}^{i=n} (Y_i - mean(Y))^2 \tag{2.14}$$

where, Y_i is the transformed data points on the probability plot (see Table 2.3 for the transformation for each distribution type) and Y is the least-squares regression line. A R^2 value of unity denotes a perfect fit.

Tables 2.6 and 2.7 summarize the *K-S* and R^2 values for the MOR and MOE fits, respectively. The best-fit distributions for individual size and grade combinations, based on each of the goodness-of-fit criteria are shaded in Tables 2.6 and 2.7. Both the Normal and 2-parameter Weibull distributions fit the MOR data well (Table 2.6). As the MOR must assume a positive value, the Weibull distribution is deemed more appropriate to describe the distribution of MOR. Note that normal distribution can assume negative values which make it less desirable for modeling MOR. Except for the *No. 2* 2x8 MOE fit, the best-fit distributions for individual size and grade combinations can be clearly identified as both the R^2 and *K-S* tests agree with each other. For the *No. 2* 2x8 MOE fits, the Lognormal distribution is deemed the best-fit because among the two candidate distributions (Normal and Lognormal), the R^2 values for both the normal and lognormal distributions are very close to each other while the *K-S* value of the lognormal distribution (0.0306) is significantly lower than that of the normal distribution (0.0607). Note that all the *K-S* values for the lognormal distribution fits of MOE data meet the critical KS values. More details on the probability distribution fitting can be found in Appendix A.

Table 2.6: *K-S* and R^2 values for MOR fits.

	Normal		Lognomal		Gumbel		Frechet		Weibull		Sample	Critical
	R^2	*KS*	R^2	*KS*	R^2	*KS*	R^2	*KS*	R^2	*KS*[1]	Size (n)	*K-S*
***SS* 2X4**	0.998	0.0267	0.970	0.0712	0.957	0.0793	0.852	0.1374	0.994	0.0311	420	0.0595
***No2* 2x4**	0.955	0.1178	0.989	0.0570	0.981	0.0597	0.910	0.1182	0.950	0.1076	409	0.0603
***SS* 2x8**	0.987	0.0437	0.923	0.0970	0.887	0.1122	0.768	0.1658	0.996	0.0288	409	0.0603
***No2* 2x8**	0.989	0.0455	0.970	0.0574	0.962	0.0555	0.846	0.1288	0.990	0.0385	420	0.0595
***SS* 2x10**	0.995	0.0249	0.940	0.0558	0.930	0.0842	0.818	0.1245	0.984	0.0418	410	0.0603
***No2* 2x10**	0.995	0.0362	0.923	0.1154	0.928	0.1029	0.770	0.1816	0.994	0.0473	420	0.0595

[1] *KS* for *No.2* 2x4 failed to meet the critical *K-S* for both Weibull and Nomal distribution.

Table 2.7: *K-S* and R^2 values for MOE fits.

	Normal		Lognomal		Gumbel		Frechet		Weibull		Sample	Critical
	R^2	*KS*	R^2	*KS*	R^2	*KS*	R^2	*KS*	R^2	*KS*[1]	Size (n)	*K-S*
***SS* 2X4**	0.995	0.0401	0.960	0.0501	0.949	0.0633	0.848	0.1127	0.987	0.0626	420	0.0595
***No2* 2x4**	0.984	0.0721	0.981	0.0491	0.985	0.0350	0.890	0.0826	0.981	0.0834	409	0.0603
***SS* 2x8**	0.999	0.0205	0.971	0.0568	0.941	0.0859	0.852	0.1266	0.994	0.0391	409	0.0603
***No2* 2x8**	0.979	0.0607	0.979	0.0306	0.987	0.0450	0.902	0.0954	0.964	0.0656	420	0.0595
***SS* 2x10**	0.997	0.0341	0.967	0.0545	0.953	0.0582	0.859	0.1048	0.986	0.0556	410	0.0603
***No2* 2x10**	0.981	0.0489	0.993	0.0407	0.983	0.0445	0.916	0.0969	0.969	0.0549	420	0.0595

[1] *KS* for *No.2* 2x4 failed to meet the critical *K-S* for Nomal distribution.

2.4.2 Comparison Between the 1978 and 2010 IGTP Data

Table 2.8 shows the distribution parameters for visually graded Southern Pine lumber derived from the 1978 IGTP data (Green and Evans, 1987). The parameters shown in Table 2.8 represent the underlying MOE and MOR distributions of visually graded Southern Pine lumber population in 1980s. The 1978 IGTP data were used to develop the reference design values in the 2005 or the older versions NDS. For comparison purpose, the 2010 IGTP data was presented in Table 2.9.

Table 2.8: 1978 IGTP Southern Pine MOE and MOR properties for bending analysis.

Two Parameter Weibull Estimates for Southern Pine (15% moistrue)															
Dimension	Grade	MOE (million psi)						MOR (ksi)						b	d
		1978 IGTP					2005 NDS	1978 IGTP					2005 NDS		
		mean	COV	stdev	2-para Weibull shape(k)	2-para Weibull scale(u)	design	mean	COV	stdev	2-para Weibull shape(k)	2-para Weibull scale(u)	design		
2x4	SS	1.824	0.182	0.332	5.940	1.960	1.8	10.976	0.235	2.583	4.690	11.990	2.85	1.5	3.5
	No.1	1.634	0.201	0.329	5.210	1.770	1.7	9.165	0.277	2.540	3.830	10.120	1.85	1.5	3.5
	No.2	1.531	0.239	0.366	4.520	1.670	1.6	7.975	0.374	2.979	2.850	8.960	1.5	1.5	3.5
	No.3	1.447	0.270	0.391	3.940	1.600	1.4	7.166	0.373	2.672	2.890	8.050	0.85	1.5	3.5
2x6	No.2	1.561	0.234	0.366	4.700	1.710	1.6	7.058	0.399	2.815	2.740	7.960	1.25	1.5	5.5
2x8	SS	1.886	0.197	0.372	5.550	2.040	1.8	8.553	0.235	2.009	4.750	9.330	2.3	1.5	7.25
	No.1	1.539	0.212	0.327	5.150	1.670	1.7	6.113	0.338	2.068	3.190	6.830	1.5	1.5	7.25
	No.2	1.596	0.278	0.443	3.770	1.760	1.6	6.292	0.385	2.422	2.840	7.070	1.2	1.5	7.25
	No.3	1.404	0.302	0.424	3.470	1.560	1.4	5.305	0.452	2.396	2.390	6.000	0.7	1.5	7.25
2x10	SS	1.771	0.171	0.303	6.370	1.900	1.8	7.411	0.171	1.268	6.430	7.940	2.05	1.5	9.25
	No.1	1.557	0.185	0.288	5.640	1.680	1.7	6.044	0.272	1.643	4.130	6.660	1.3	1.5	9.25
	No.2	1.491	0.254	0.378	4.370	1.640	1.6	5.903	0.313	1.850	3.560	6.560	1.05	1.5	9.25

Table 2.9: 2010 IGTP Southern Pine MOE and MOR properties for bending analysis.

Two Parameter Weibull Estimates for Southern Pine (15% moistrue)														
Dimension	Grade	2010 IGTP											b	d
		MOE (million psi)						MOR (ksi)						
						2-para Weibull						2-para Weibull			
		mean	COV	stdev	design	shape(k)	scale(u)	mean	COV	stdev	design	shape(k)	scale(u)		
2x4	SS	1.841	0.211	0.388	1.8	5.589	1.99	9.441	0.262	2.471	2.35	4.461	10.3	1.5	3.5
	No.2	1.377	0.281	0.387	1.4	4.329	1.48	5.849	0.430	2.515	1.1	2.953	6.5	1.5	3.5
2x8	SS	1.791	0.219	0.392	1.8	5.264	1.94	7.472	0.232	1.730	1.95	4.773	8.2	1.5	7.25
	No.2	1.496	0.256	0.383	1.4	4.888	1.60	5.354	0.370	1.982	0.925	3.079	6.0	1.5	7.25
2x10	SS	1.771	0.213	0.377	1.8	5.644	1.91	6.282	0.189	1.186	1.7	6.160	6.8	1.5	9.25
	No.2	1.503	0.254	0.382	1.4	4.937	1.64	4.778	0.335	1.603	0.8	3.147	5.3	1.5	9.25

Figure 2.3 shows the probability density functions (PDFs) of the bending strength (MOR) for *No. 2* 2x4, 2x8 and 2x10 lumber derived from the 1978 IGTP and 2010 IGTP data. As can be clearly seen, the new MOR distribution for each corresponding size has shifted to the left. Similar patterns were also observed for the MOE distribution of *No.2* lumber, and the MOE and MOR distributions of the *Select Structural* grade (see Appendix B).

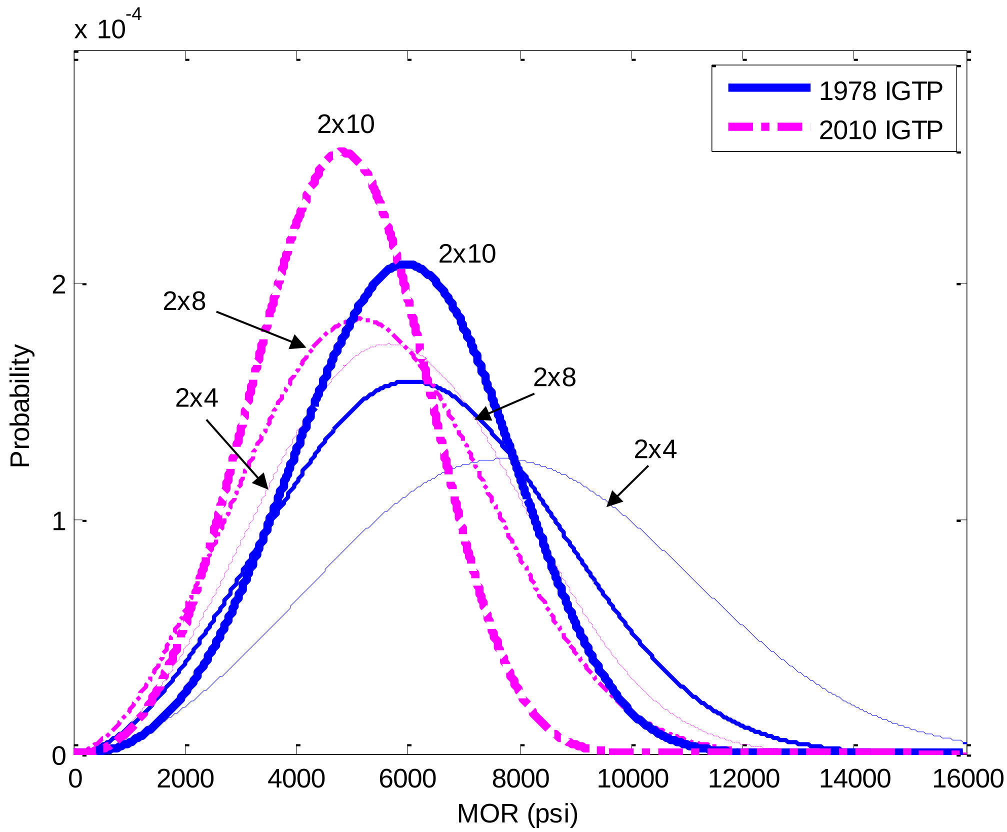


Figure 2.3: Comparison of 2x4, 2x8 and 2x10 *No. 2* Southern Pine MOR distributions derived from 1978 and 2010 IGTP tests.

CHAPTER THREE

RELIABILITY ANALYSIS

3.1 Introduction

The data of recent full-scale *In-Grade* test of Southern Pine lumber conducted by the SPIB reveal drops in the mechanical properties of Southern Pine lumber (SPIB, 2012). Based on the new test data, a new set of reference design values have been proposed by the SPIB and submitted to the American Lumber Standard Committee (ALSC) for review and approval (AF&PA, 2012). These new reference design values are lower than the design values published in the 2005 version of wood construction design code (SPIB, 2012). One of the main goals of this study was to evaluate the impact of changes in reference design values of visually graded Southern Pine lumber on the reliability of flexural members, particularly those designed and constructed recently using the old reference design values, namely those published in the 2005 or older versions of National Design Specifications (NDS) for Wood Construction (AF&PA, 2005).

3.2 Analysis Scenarios

In this study, the Advanced First Order Reliability Method (AFORM) method was utilized to assess the reliability of Southern Pine flexural members (i.e. floor joists) subjected to gravity loadings (dead and live loads). Reliability analyses were performed for the following two scenarios:

1) Flexural members designed using the old Southern Pine reference design values (i.e. NDS 2005 or older versions); and

2) Flexural members designed using the new Southern Pine reference design values (derived from the 2010 *In-Grade* test).

In *Scenario 1*, the flexural members were designed in accordance to the 2005 version of NDS (i.e. using the Southern Pine reference design values in the 2005 NDS). The AFORM was utilized to determine the reliabilities of the as-designed flexural members. The main purpose of *Scenario 1* analyses was to determine if any of the *Scenario 1* designs are unsafe or have reliability lower than the target code-minimum reliability for wood construction.

In *Scenario 2*, the flexural members were designed in accordance to the 2005 NDS design procedure; however, with the new reference design values for Southern Pine. It was hypothesized that the reliabilities of *Scenario 2* designs meet and exceed the target code-minimum reliability.

3.3 Design of Flexural Members

The flexural members considered in this study were floor joists. Figure 3.1 shows the floor joist configuration. The floor joists were subjected to both dead and live loads.

Floor joists constructed of three different dimensions and two grades (2x4, 2x8, and 2x10 with *Select Structural* and *No.2 grades*) were investigated. The joist spacings used for reliability analyses were 12, 13.7, 16, 19.2 and 24 inches. Live load-to-dead load ratios ranged from 0 to 5 were analyzed. In the design process, two limit states were specifically considered, namely, strength and serviceability limit states. The strength limit state is governed by the bending capacity of floor joist while the serviceability limit state is governed by the bending stiffness. Table 3.1 lists the current and proposed reference design values for MOE (bending strength). Note that in *Scenario 1* design, the reference bending strengths, F_b, were taken from Table 4D in the 2005 NDS. The *Scenario 1* F_b values were derived from the 1978 IGTP data (AF&PA, 2005). In *Scenario 2* design, the proposed F_b values were derived from the new 2010 Southern Pine IGTP data. For each of the lumber size and grade combination, a maximum allowable span length was determined by considering both the strength and serviceability limit states. Note that shear limit state was not considered in this study since shear failure mode usually does not control the design of floor joists.

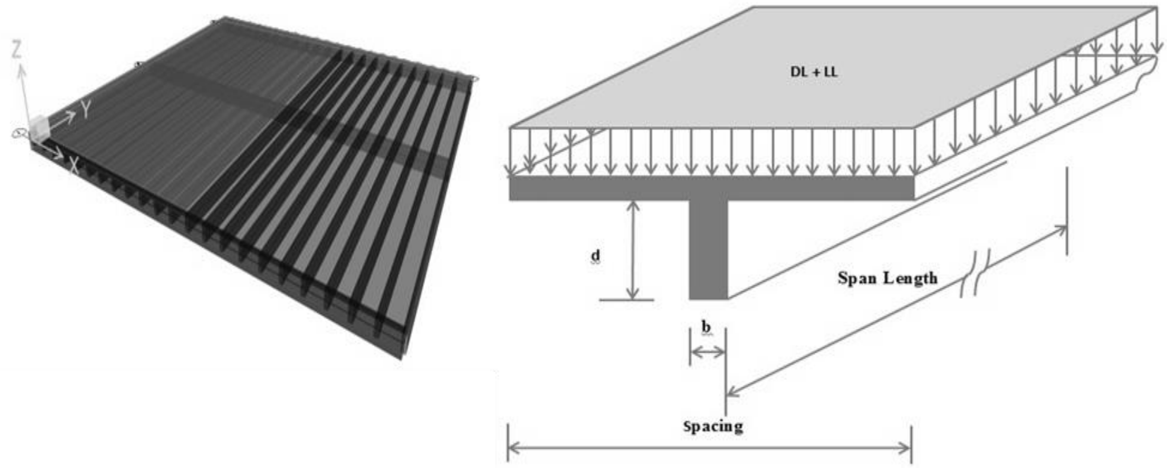


Figure 3.1: Floor joist configuration and details.

Table 3.1: NDS design value for MOR and MOE[4].

Dimension	Grade	E			F_b		
		2005 NDS (million psi)	Proposed (million psi)	Diff (%)	2005 NDS (psi)	Proposed (psi)	Diff (%)
2x4	SS	1.8	1.8	0.0	2850	2350	17.5
	No.2	1.6	1.4	12.5	1500	1100	26.7
2x8	SS	1.8	1.8	0.0	2300	1950	15.2
	No.2	1.6	1.4	12.5	1200	925	22.9
2x10	SS	1.8	1.8	0.0	2050	1700	17.1
	No.2	1.6	1.4	12.5	1050	800	23.8

[4] The notations "E" and "F_b" are used in this thesis to denote the reference design values for modulus of elasticity (MOE) and modulus of rupture (MOR), respectively. The reference value, E is derived from the mean value of MOE and F_b is derived from the 5 percentile value of MOR.

3.3.1 *Strength Limit State*

The strength limit state is given by the following equation:

$$\phi_b M_n \geq M_u \quad (3.1)$$

where ϕ_b is the resistance factor which is equal to 0.85 for bending members (AF&PA, 2005). M_n is the nominal moment capacity. M_u is the factored moment:

$$M_u = \frac{w_u S_b L^2}{8} \quad (3.2)$$

where, S_b is the center-to-center spacing of the floor joists and L is the span length. Note that Eqn. 3.2 assumes the floor joist is simply supported and the maximum applied factored moment occurs at the mid span. Here, w_u is taken as the maximum of the following two load combinations for floor joists:

$$w_u = \max \begin{cases} 1.4DL \\ 1.2DL + 1.6LL \end{cases} \quad (3.3)$$

where DL is the dead load and LL is the live load.

The nominal moment capacity was computed as the adjusted bending strength, F'_{bn}, times the section modulus, S, of the joist:

$$M_n = F'_{bn} S \quad (3.4)$$

The section modulus for a rectangular section is:

$$S = \frac{bd^2}{6} \tag{3.5}$$

where b and d are the width and depth of the floor joist, respectively. According to the 2005 NDS (AF&PA, 2005), the reference bending strength, F_b, is to be adjusted as following:

$$F'_{bn} = K_F\ \phi_b\ \lambda\ F_b\ C_r\ C_M\ C_t\ C_L\ C_F\ C_{fu}\ C_i \tag{3.6}$$

where C_r is the repetitive member factor which accounts for the load sharing effect when the floor joists act as a system. C_M is the wet service factor. C_t is the temperature factor. C_L is the beam stability factor. C_F is the size factor. C_{fu} is the flat use factor. C_i is the incising factor. The floor joists were assumed to be in an indoor environment with moisture content below 19%. Thus, all adjustment factors were assumed to be 1 except for the repetitive member factors, C_r, which was taken as 1.15 per Section 4.3.9 of NDS (AF&PA, 2005).

In Equation 3.6, the Load Resistance Factor Design (LRFD) to Allowable Stress Design (ASD) format conversion factor K_F is equal to $2.16/\phi_b$ (AF&PA, 2005). λ is the load duration factor which is a function of the applied load types and combinations. λ = 0.6 for dead load only and λ = 0.8 when considering both the dead load and live load (live load is assumed to be an occupancy load).

3.3.2 *Serviceability Limit State*

The serviceability limit state is defined by the following expression:

$$\frac{5wS_bL^4}{384EI} \leq \Delta_{lim} \quad (3.7)$$

where E is the reference modulus of elasticity and I is the edge-wise bending moment of inertia. Δ_{lim} is the deflection limit. In this study, three deflection limits were considered. These deflection limits were $L/360$, $L/240$ and $L/180$. In Equation 3.7, deflections were calculated using unfactored live load (i.e. $w = LL$).

Similar to the strength limit state design, the *E* values for *Scenario 1* designs were taken from 2005 NDS while the *E* values for *Scenario 2* designs were taken from the new Southern Pine reference design values (see Table 3.1).

3.3.3 *Maximum Allowable Span Length*

For each design (with lumber size and grade, spacing, load ratio combination), a maximum allowable span length *L* was calculated based on the strength and serviceability (deflection) limit states. The maximum allowable span length for strength limit state can be derived by substituting Equation 3.4 into Equation 3.2 and solving for L:

$$L = \sqrt{\frac{8\phi_b F'_{bn} S}{w_u S_b}} \quad (3.8)$$

Similarly, the maximum allowable span length under serviceability limit state can be determined by solving for L from Equation 3.7:

$$L = \sqrt[4]{\frac{384\Delta_{lim}EI}{5wS_b}} = \sqrt[3]{\frac{384n_\Delta EI}{5wS_b}} \quad (3.9)$$

Note that *w* in the above equation contains only the unfactored live load (LL) and n_Δ is the denominator term of the deflection limit (e.g. 360, 240, 180 and etc.). Finally, the allowable design span length for each lumber size and grade combination was taken as the minimum between the strength controlled and deflection controlled (i.e. service level) allowable span lengths.

The maximum design span lengths for loading representative of residential buildings (*DL* = 10 psf, *LL* = 30 psf) are shown in Table 3.2. The results reveal that the maximum span lengths determined using the new reference design values for *No.2* grade are all lower than that computed using the 2005 NDS design values. For *Select Structural*, the maximum span lengths are controlled by serviceability limit state which is governed by the MOE values. Since the new reference MOE values for *Select Structural* grade remain the same as the 2005 design values, the analyses results show no changes to the maximum allowable span lengths for *Select Structural* grade. Overall, the maximum span lengths reduced by approximately 0% to 13% for *No.2* grade, in particular, *No.2* 2x10 floor joists spaced at 24 inches have the largest reduction in maximum allowable span length (13%). Same trend of reduction are observed for *DL* = 10 psf, *LL* = 40 psf and *DL* = 10 psf, *LL* = 50 psf. The relative changes of maximum span lengths can be found in Tables 3.3 and 3.4.

Table 3.2: Maximum design floor joist span lengths based on both the 2005 and 2012 NDS design values (*DL* = 10 psf, *LL* = 30 psf).

Maximum Design Floor Joist Span Length																
Dimension	Grade	2005 NDS (in)					New Proposed (in)					Reduction (%)				
		Spacing (in)					Spacing (in)									
		12	13.7	16	19.2	24	12	13.7	16	19.2	24					
2x4	SS	94	90	85	80	74	94	90	85	80	74	0%	0%	0%	0%	0%
	No.2	90	86	82	77	72	86	82	78	74	68	4%	5%	5%	4%	6%
2x8	SS	194	186	176	166	154	194	186	176	166	154	0%	0%	0%	0%	0%
	No.2	187	179	170	160	148	179	171	162	153	139	4%	4%	5%	4%	6%
2x10	SS	248	237	225	212	197	248	237	225	212	197	0%	0%	0%	0%	0%
	No.2	238	228	216	204	189	228	218	202	184	165	4%	4%	6%	10%	13%

Table 3.3: Maximum design floor joist span lengths based on both the 2005 and 2012 NDS design values (*DL* = 10 psf, *LL* = 40 psf).

Maximum Design Floor Joist Span Length																
Dimension	Grade	2005 NDS (in)					New Proposed (in)					Reduction (%)				
		Spacing (in)					Spacing (in)									
		12	13.7	16	19.2	24	12	13.7	16	19.2	24					
2x4	SS	85	81	77	73	68	85	81	77	73	68	0%	0%	0%	0%	0%
	No.2	82	78	74	70	65	78	75	71	67	62	5%	4%	4%	4%	5%
2x8	SS	176	169	160	151	140	176	169	160	151	140	0%	0%	0%	0%	0%
	No.2	170	162	154	145	135	162	155	147	138	124	5%	4%	5%	5%	8%
2x10	SS	225	215	204	192	179	225	215	204	192	179	0%	0%	0%	0%	0%
	No.2	216	207	197	185	168	207	194	179	164	147	4%	6%	9%	11%	13%

Table 3.4: Maximum design floor joist span lengths based on both the 2005 and 2012 NDS design values (*DL* = 10 psf, *LL* = 50 psf).

Maximum Design Floor Joist Span Length																
Dimension	Grade	2005 NDS (in)					New Proposed (in)					Reduction (%)				
		Spacing (in)					Spacing (in)									
		12	13.7	16	19.2	24	12	13.7	16	19.2	24					
2x4	SS	79	76	72	68	63	79	76	72	68	63	0%	0%	0%	0%	0%
	No.2	76	73	69	65	60	73	70	66	62	58	4%	4%	4%	5%	3%
2x8	SS	164	157	149	140	130	164	157	149	140	130	0%	0%	0%	0%	0%
	No.2	157	151	143	135	125	151	144	137	126	112	4%	5%	4%	7%	10%
2x10	SS	209	200	190	179	166	209	200	190	179	166	0%	0%	0%	0%	0%
	No.2	201	192	182	171	153	188	176	163	149	133	6%	8%	10%	13%	13%

3.4 Load Statistics

The distributional information for dead and live loads used in reliability analyses are given in Table 3.5 (Ellingwood, 1980). The dead load was assumed to be a normal distribution with a mean to nominal ratio of 1.05 and a coefficient of variation (CoV) of 0.1 (Ellingwood, 1980). The live load was modeled using a Gumbel Largest Distribution with a mean to nominal ratio of 1.0 and a CoV of 0.25 (Ellingwood, 1980). For the floor joist reliability analyses, a constant design dead load of 10 psf was assumed and the design live load was varied. Note that the design loads are the nominal values. To obtain the mean values of the load distributions, the nominal design loads were divided by the corresponding mean-to-nominal ratios (MtN) shown in Table 3.5. The method of moments approach was used to estimate the distributional parameters for reliability analyses.

Table 3.5: Load statistics for reliability analyze.

Load	**Mean-to-nominal**	**COV**	**Distribution**
Dead	1.05	0.1	Normal
Live	1	0.25	Type I

3.5 Reliability Analyses

In this study, the Advanced First Order Reliability Method (AFORM) method (Achinty H., 1999) was utilized to assess the reliability of floor joists. The failure of a flexural member can be expressed in terms of the following performance function g(x):

$$g(x) = R(x) - D(x) \tag{3.10}$$

where, $R(x)$ and $D(x)$ denote the resistance (capacity) of the flexural members and demand (load) applied on the flexural members, respectively. Here, x represents the relevant resistant and load variables (e.g. MOR or MOE and applied loads). A failure occurs when the value of the performance function is less than zero. The performance function for the strength limit state is:

$$g = MOR \times S - \frac{(DL + LL)S_b L^2}{8} \tag{3.11}$$

In the above performance function, the section modulus (S), joist spacing (S_b) and design span length (L) were kept constant while the modulus of rupture (MOR), dead and live loads were modeled as random variables. In Chapter 2, it has been shown that the two-parameter Weibull distribution can be used to adequately describe the distribution of MOR data and Lognormal distribution can be used to represent the distribution of the MOE data. As the AFORM analysis was based on strength limitation, the two-parameter Weibull was used in the AFORM reliability analyses. Tables 2.8 and 3.6 summarize the Weibull distribution parameters used for both *Scenarios 1* and *2*.

Table 3.6: New IGTP Southern Pine properties for bending analysis.

Two Parameter Weibull Estimates for Southern Pine (15% moistrue)															
		2010 IGTP													
		MOE (million psi)						MOR (ksi)							
						2-para Weibull						2-para Weibull			
imensi	Grade	mean	COV	stdev	design	shape(k)	scale(u)	mean	COV	stdev	design	shape(k)	scale(u)	b	d
2x4	SS	1.841	0.211	0.388	1.8	5.589	1.99	9.441	0.262	2.471	2.35	4.461	10.3	1.5	3.5
	No.2	1.377	0.281	0.387	1.4	4.329	1.48	5.849	0.430	2.515	1.1	2.953	6.5	1.5	3.5
2x8	SS	1.791	0.219	0.392	1.8	5.264	1.94	7.472	0.232	1.730	1.95	4.773	8.2	1.5	7.25
	No.2	1.496	0.256	0.383	1.4	4.888	1.60	5.354	0.370	1.982	0.925	3.079	6.0	1.5	7.25
2x10	SS	1.771	0.213	0.377	1.8	5.644	1.91	6.282	0.189	1.186	1.7	6.160	6.8	1.5	9.25
	No.2	1.503	0.254	0.382	1.4	4.937	1.64	4.778	0.335	1.603	0.8	3.147	5.3	1.5	9.25

3.6 Advanced First-Order Second-Moment Procedure

The reliability of the floor joists is quantified using a reliability index, β.

$$\beta = \Phi^{-1}\left(1 - P_f\right) \tag{3.12}$$

where $\Phi^{-1}(.)$ is the inverse standard normal cumulative distribution function and P_f is the probability of failure, occurs when the value of the performance function $g < 0$. Rearranging Eqn. 3.12 yields the following equation:

$$P_f = 1 - \Phi(\beta) \tag{3.13}$$

where $\Phi(.)$ is the standard normal cumulative distribution function. The Advanced First-Order Reliability Method (AFORM) was used to solve the reliability index (β). The AFORM procedure is summarized in Figure 3.2.

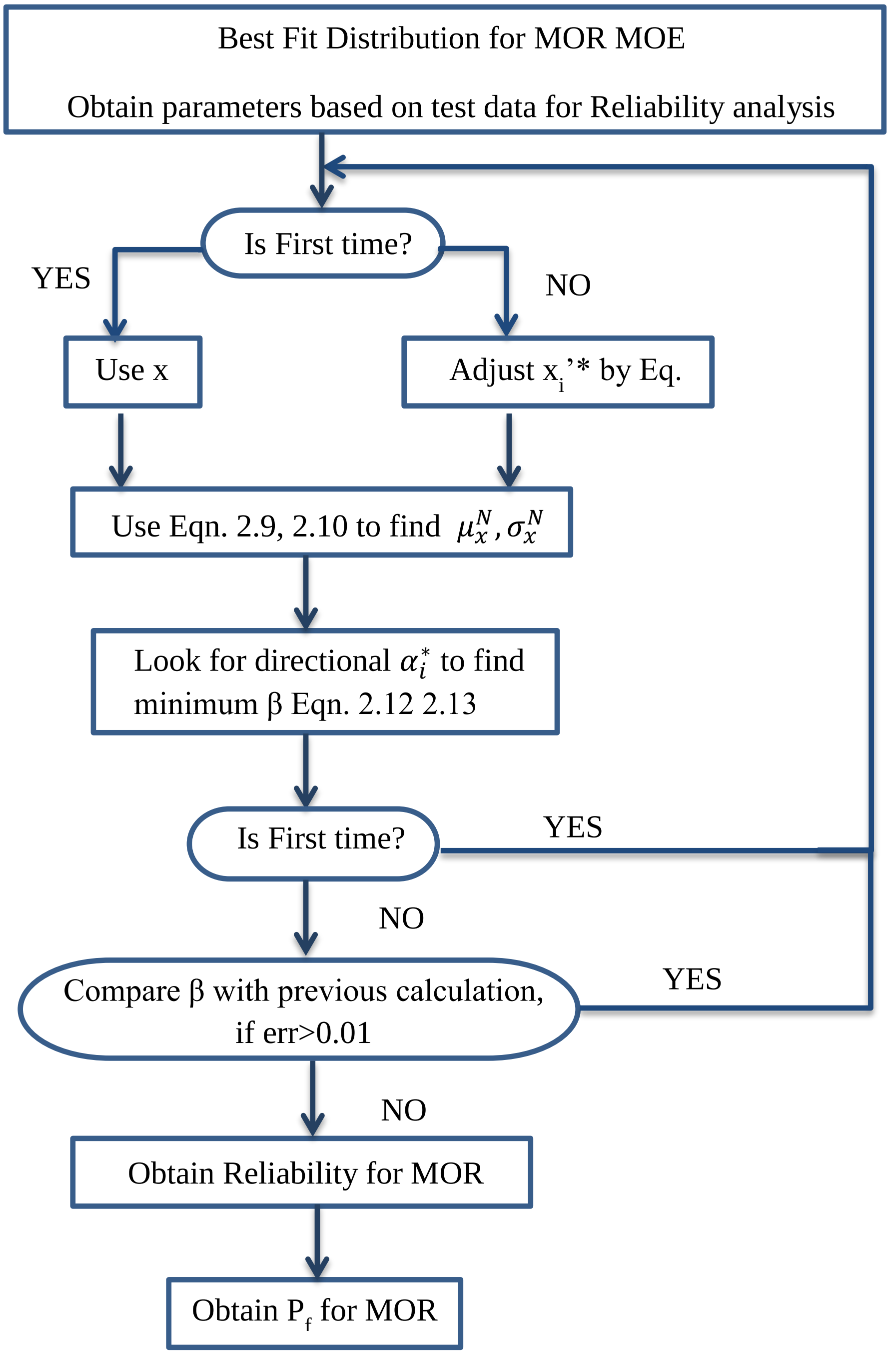


Figure 3.2: Flowchart for AFORM.

Figure 3.3 depicts a nonlinear performance function in a transformed coordinate system. The dashed curve represents the limit state boundary in which the value of the performance function is equal to zero. A point on the limit state curve represents a combination of random variables (e.g. MOR, dead and live loads) which would result in failure. The point of minimum distance from the origin to the limit state boundary is called the *design point*. This design point represents the most probable failure point. The task at hand is to find the design point and the corresponding distance between the design point and the origin. The shortest distance between limit state curve and the origin is the reliability index.

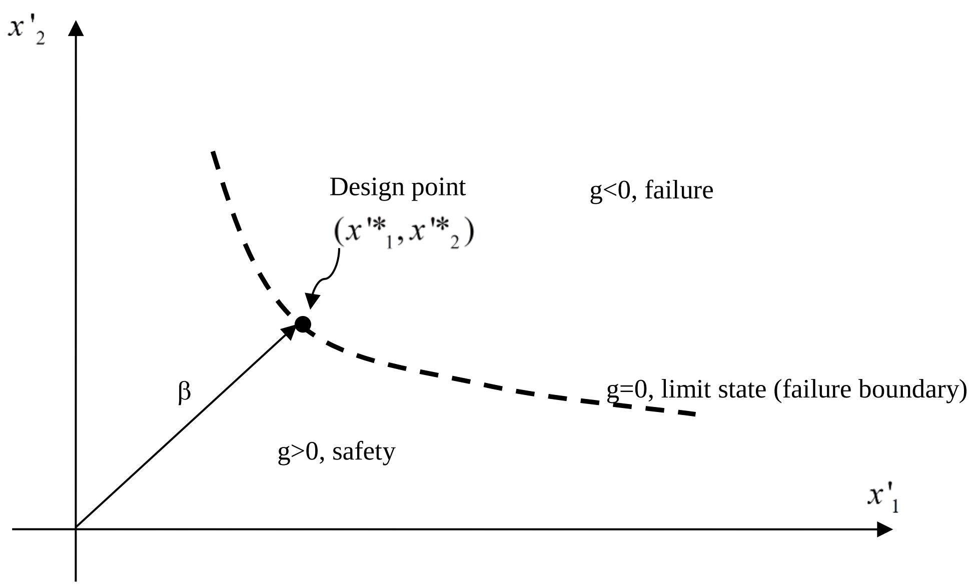


Figure 3.3: Depiction of nonlinear limit state in a transformed coordinate system.

For a nonlinear limit state, the process of finding the design point and reliability index is an iterative optimization problem. The algorithm to find the design point and reliability index was first proposed by Rackwitz (Rackwitz, 1976). The algorithm is summarized in the following steps and more details can be found in many reliability analysis textbooks including (Achinty H., 1999).

Step 1) Define the limit state function. The strength limit state function considered in this study is shown in Equation 3.11.

Step 2) Assume initial values for the design point $x*_i$ in original coordinate system. The initial values were taken as the mean values of the applied loads and MOR of the joist.

Step 3) Compute the transformed variables using the following equation:

$$x'^*_i = \frac{x_i^* - \mu_{xi}}{\sigma_{xi}} \tag{3.14}$$

Step 4) Take the partial derivatives of the performance function (g) with respect to each of the transformed variables (x'_i) and evaluate the partial derivative at the transformed design point.

$$\left(\frac{\partial g}{\partial x'_i}\right)_* = \left(\frac{\partial g}{\partial x_i}\right)_* \sigma_{x_i}^N \tag{3.15}$$

where, $\sigma_{x_i}^N$ is the standard deviation of an equivalent normal distribution used to approximate the actual distribution of the ith variable. Here $\mu_{x_i}^N$ is the mean of the equivalent normal distribution.

$$\sigma_x^N = \frac{\phi[\Phi^{-1}(F_x(x^*))]}{f_x(x^*)} \tag{3.16}$$

$$\mu_x^N = x^* - \Phi^{-1}\big(F_x(x^*)\big)\sigma_x^N \tag{3.17}$$

$f_{x_i}(x_i^*)$ is the probability density function (PDF) of the ith variable evaluated at the design point. $F_{x_i}(x_i^*)$ is the cumulative distribution function (CDF) of the ith variable evaluated at the design point. $\Phi^{-1}(.)$ is the inverse of the standard normal cumulative function and $\phi(.)$ is the standard normal probability density function.

Step 5) Compute the direction cosines along the transformed coordinate axes $x_i^{'}$ at the design point:

$$\alpha_i^* = \frac{\left(\frac{\partial \mathrm{g}}{\partial x_i}\right)_*}{\sqrt{\sum_{i=1}^{n}\left(\frac{\partial \mathrm{g}}{\partial x_i}\right)_*^2}} \tag{3.18}$$

Step 6) Express the design point in original coordinate system in terms of the directional cosines and reliability index:

$$\mathrm{x}_i^* = \mu_{x_i}^N - \alpha_i^* \sigma_{x_i}^N \beta \tag{3.19}$$

Note that the reliability index β is an unknown quantity in this step.

Step 7) Substitute the design points determined in Step 6 into the limit state equation (g). Set g = 0 and solve for β.

$$g[(\mu_{x1}^{N} - \alpha_1^{*}\sigma_{x1}^{N}\beta), (\mu_{x2}^{N} - \alpha_2^{*}\sigma_{x2}^{N}\beta), \ldots] = 0 \quad (3.20)$$

Step 8) Update the design point (x_i^*) by substituting the β value obtained in Step 7 into Eqn. 3.14.

Step 9) Repeat Steps 3 to 8 using the updated design point (x_i^*) until the β value converge to a predefined tolerance.

Step 10) Compute the probability of failure using Equation 3.13.

The AFORM procedure was used to analyze the reliability of the floor joists. The results of reliability analyses for both *Scenarios 1* and *2* are discussed next in Chapter 4.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

The reliabilities of flexural members (floor joists) constructed of visually graded Southern Pine were analyzed using the Advanced First-Order Reliability Method (AFORM) discussed in Chapter 3. Two different design scenarios were analyzed. In *Scenario 1*, it was assumed that the floor systems were designed and constructed using the 2005 NDS reference design values for visually graded Southern Pine lumber (AF&PA, 2005). In *Scenario 2*, it was assumed that the floor systems were designed using the new reference design values (2012 NDS) which were derived using the new *In-Grade* test data (AF&PA, 2012). In general, the new MOE and MOR reference design values are approximately 0-14.3% and 11.4-41.7% lower than that published in the 2005 NDS, respectively. Since the new reference design values were derived from the recent test data, which are representative of the actual mechanical properties of the lumber harvested in recent years, one would expect the flexural members of *Scenario 2* designs to be more reliable than that of *Scenario 1*. The design values in 2005 NDS and new design values (2012 NDS) are shown in Table 4.1. Also shown in the table are the percent reductions in the reference design values from the 2005 NDS to the 2012 NDS design values. Note a positive percentage indicates a reduction in the reference design value.

Table 4.1: 2005 NDS and 2012 NDS design values.

Dimension	Grade	Fb (psi)			E (10^6 psi)		
		2005 NDS	2013 NDS	% diff	2005 NDS	2013 NDS	% diff
2x4	Dense SS	3050	2700	12.96	1.9	1.9	0.00
	SS	2850	2350	21.28	1.8	1.8	0.00
	Non-D SS	2650	2050	29.27	1.7	1.6	6.25
	No.1 Dense	2000	1650	21.21	1.8	1.8	0.00
	No.1	1850	1500	23.33	1.7	1.6	6.25
	No.1 Non-D	1700	1300	30.77	1.6	1.4	14.29
	No.2 Dense	1700	1200	41.67	1.7	1.6	6.25
	No.2	1500	1100	36.36	1.6	1.4	14.29
	No.2 Non-D	1350	1050	28.57	1.4	1.3	7.69
	No.3 & Stud	850	650	30.77	1.4	1.3	7.69
2x6	Dense SS	2700	2400	12.50	1.9	1.9	0.00
	SS	2550	2100	21.43	1.8	1.8	0.00
	Non-D SS	2350	1850	27.03	1.7	1.6	6.25
	No.1 Dense	1750	1500	16.67	1.8	1.8	0.00
	No.1	1650	1350	22.22	1.7	1.6	6.25
	No.1 Non-D	1500	1200	25.00	1.6	1.4	14.29
	No.2 Dense	1450	1050	38.10	1.7	1.6	6.25
	No.2	1250	1000	25.00	1.6	1.4	14.29
	No.2 Non-D	1150	950	21.05	1.4	1.3	7.69
	No.3 & Stud	750	575	30.43	1.4	1.3	7.69
2x8	Dense SS	2450	2200	11.36	1.9	1.9	0.00
	SS	2300	1950	17.95	1.8	1.8	0.00
	Non-D SS	2100	1700	23.53	1.7	1.6	6.25
	No.1 Dense	1650	1350	22.22	1.8	1.8	0.00
	No.1	1500	1250	20.00	1.7	1.6	6.25
	No.1 Non-D	1350	1100	22.73	1.6	1.4	14.29
	No.2 Dense	1400	1000	40.00	1.7	1.6	6.25
	No.2	1200	975	23.08	1.6	1.4	14.29
	No.2 Non-D	1100	925	18.92	1.4	1.3	7.69
	No.3 & Stud	700	525	33.33	1.4	1.3	7.69

Table 4.1 (continued)

2x10	Dense SS	2150	1850	13.95	1.9	1.9	0.00
	SS	2050	1700	17.07	1.8	1.8	0.00
	Non-D SS	1850	1450	21.62	1.7	1.6	5.88
	No.1 Dense	1450	1150	20.69	1.8	1.8	0.00
	No.1	1300	1050	19.23	1.7	1.6	5.88
	No.1 Non-D	1200	950	20.83	1.6	1.4	12.50
	No.2 Dense	1200	850	29.17	1.7	1.6	5.88
	No.2	1050	800	23.81	1.6	1.5	6.25
	No.2 Non-D	950	725	23.68	1.4	1.3	7.14
	No.3 & Stud	600	450	25.00	1.4	1.3	7.14
2x12	Dense SS	2050	1750	14.63	1.9	1.9	0.00
	SS	1900	1600	15.79	1.8	1.8	0.00
	Non-D SS	1750	1400	20.00	1.7	1.6	5.88
	No.1 Dense	1350	1100	18.52	1.8	1.8	0.00
	No.1	1250	1000	20.00	1.7	1.6	5.88
	No.1 Non-D	1150	900	21.74	1.6	1.4	12.50
	No.2 Dense	1150	825	28.26	1.7	1.6	5.88
	No.2	975	750	23.08	1.6	1.5	6.25
	No.2 Non-D	900	700	22.22	1.4	1.3	7.14
	No.3 & Stud	575	425	26.09	1.4	1.3	7.14

4.2 Strength and Serviceability Reliability Indices of Floor Joists

Figure 4.1 shows examples of reliability versus live load-to-dead load ratio (*LL*/*DL*) plots for *No. 2* 2x4 floor joists spaced at 16 in. on-center for both the strength and deflection control limit states for *Scenario 2*[5]. Two design load combinations were considered (*1.4DL* and *1.2DL + 1.6LL*). For each load combination, a maximum allowable span

[5] The description of *scenarios 1* and *2* are given in *Section 3.2* . For *Scenario 1*, it was assumed that the floor joists were designed using the 2005 NDS values. For *Scenario 2*, it was assumed that the floor joists were designed using the new reference design values derived from the 2010 IGTP (i.e. 2012 NDS).

length was determined for each *LL*/*DL* ratio. Similarly, for the serviceability limit state (i.e. deflection control), a maximum allowable span length was computed for each *LL*/*DL* ratio. The deflection limit (Δ_{lim}) shown in Figure 4.1 is $\frac{L}{360}$ where *L* is the maximum allowable span length in inches. Each of individual reliability versus *LL*/*DL* ratio curves represents the reliability one would obtain if only one of the limit states (or load combinations) was considered in the design.

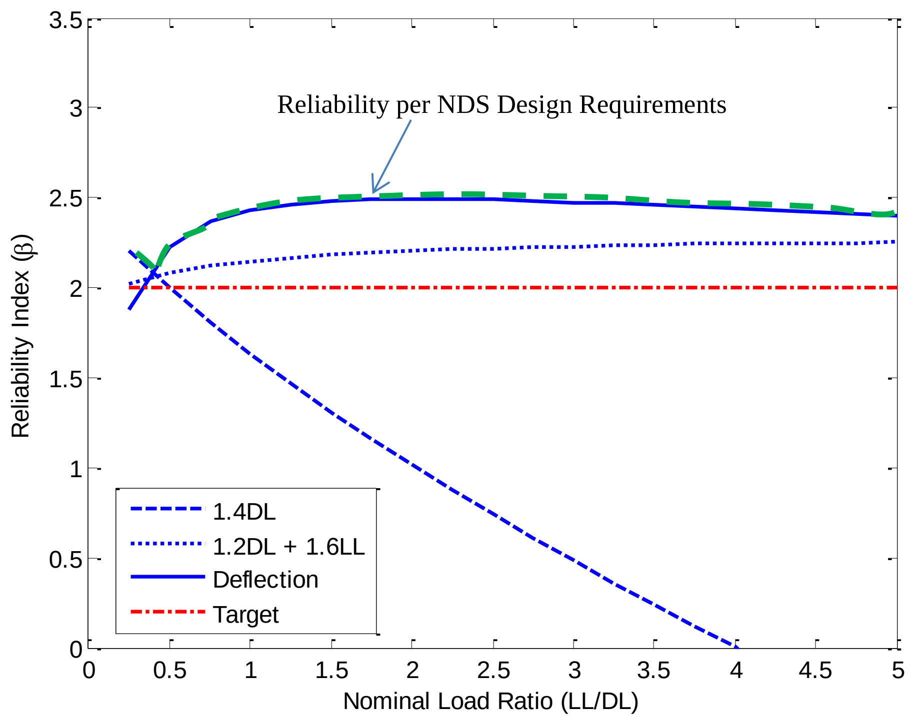


Figure 4.1: Reliability of *No. 2* 2x4 Southern Pine floor joists, strength and serviceability limit states.

The green dashed curve represents the design code reliability curve. For this particular lumber size, grade and joist spacing combination, the *1.2DL + 1.6LL* load combination did not control the design. The design reliability was governed by the *1.4DL* strength limit state when there was no or with negligible live load. The serviceability (deflection) limit state governed when the *LL/DL* ratio was greater than 0.25. Also shown in Figure 4.1 is the target reliability of wood construction code which is 2.0 (Rosowsky, 2011). As can be seen, this particular floor joist and spacing combination (*No.2* 2x4 at 16 inches on center) for *Scenario 2* met the code specified target reliability index.

4.2.1 Summary of Floor Joist Reliability Curves

The results for floor joist reliability analyses for all size and grade combinations are summarized in Figure 4.2. The range of *LL/DL* ratio considered was from 0 (i.e. no live load) to 5. Live load-to-dead load ratios of 3 to 4.5 are considered to be the most common load conditions for residential building floor systems (ASCE7, 2010). This range is shown in Figure 4.2 as "Typical Range". As expected, *Scenario 2* designs are more reliable than *Scenario 1*. In other words, the *Scenario 2* curves are all either equal or above the corresponding *Scenario 1* curves of the same size and grade.

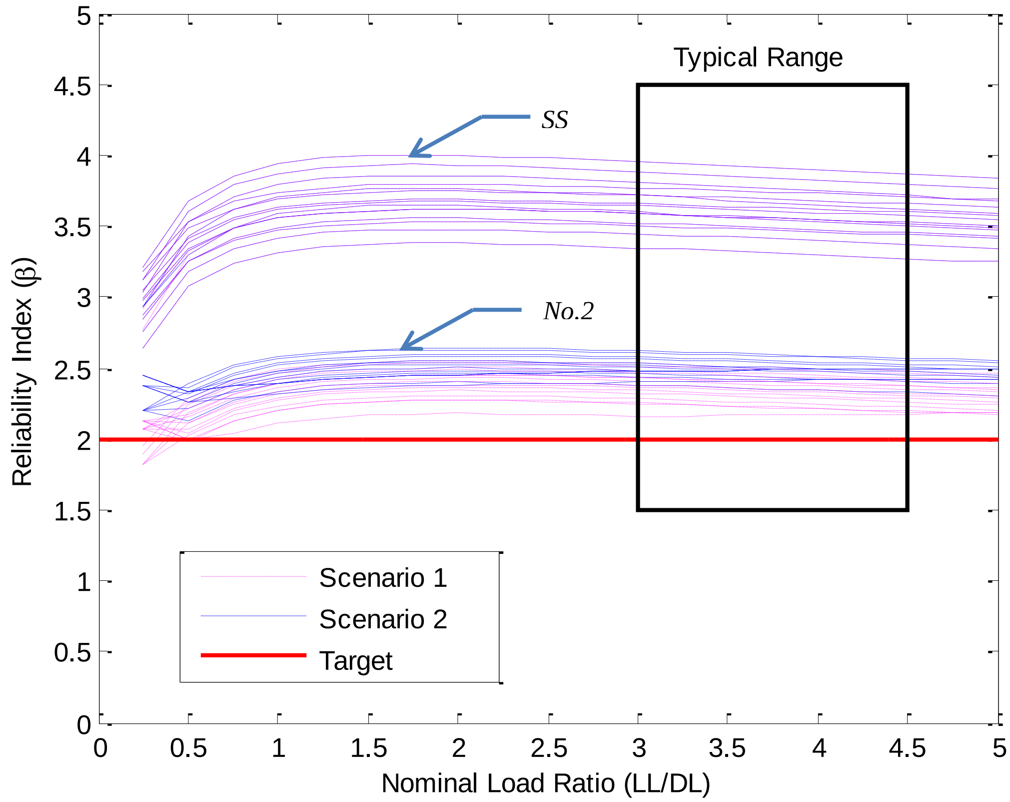


Figure 4.2: Comparison between the reliabilities of *Scenario 1* (2005 NDS) and *2* (2012 NDS), strength and deflection limit states.

From Figure 4.2, it can be seen that there are two groups of reliability indices. The reliability indices of *Select Structural* (*SS*) grade range between 3.0 and 4.0 while the *No.2* grade floor joist reliability indices range between 2.0 and 2.5. The reliability indices of *SS* grade are higher because the maximum span lengths for *SS* grade are limited by deflection limit state. Note that there is no change in the design modulus of elasticity (E) for *SS* grade in the new NDS. Due to this reason, the reliabilities of *SS* grade floor joists are equal for both *Scenario 1* and *2* (see Figure 4.2).

Figure 4.3 shows the failure probabilities of *Scenarios 1* and *2* designs. The failure probabilities were computed by substituting the reliability indices shown in Figure 4.2 into Eqn. 3.13. Figure 4.4 plots the increases in failure probabilities when comparing *Scenario 1* designs to *Scenario 2* designs (i.e. failure probability of *Scenario 1 – Scenario 2*). The maximum increases in failure probability are summarized in Table 4.2. The *No. 2* 2x4 floor joists show the highest increase in failure probabilities (increased by 1.19 to 2.01%).

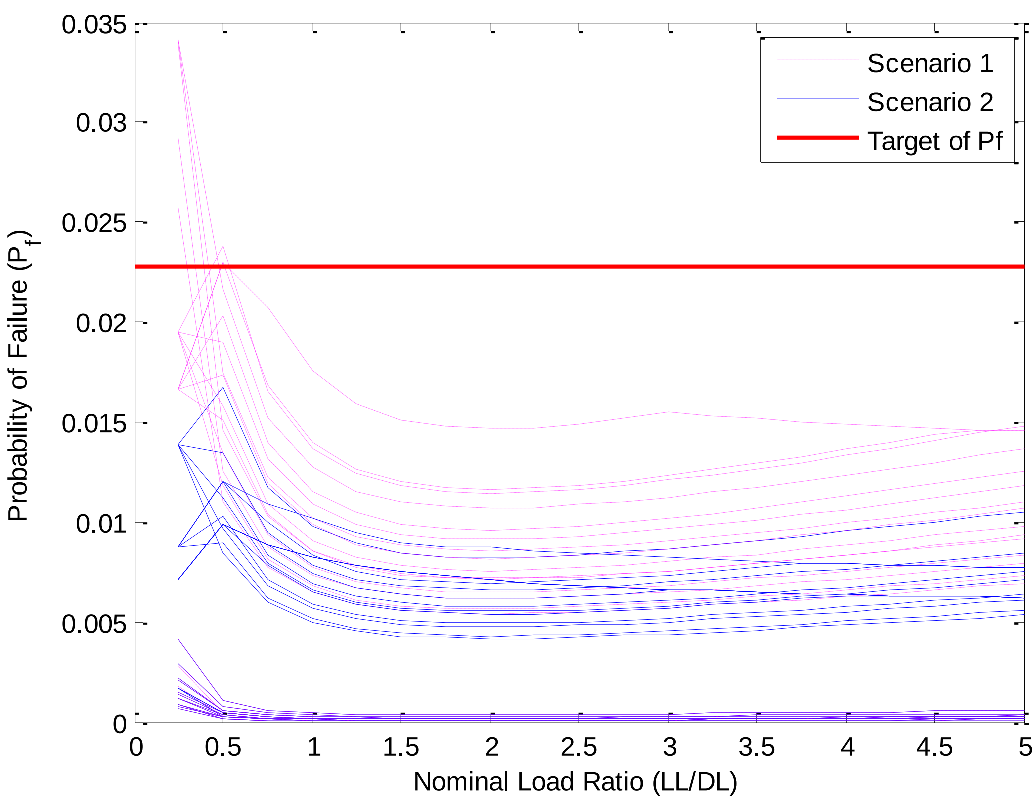


Figure 4.3: Comparison between failure probabilities of *Scenario 1* and *2*, strength and deflection limit states.

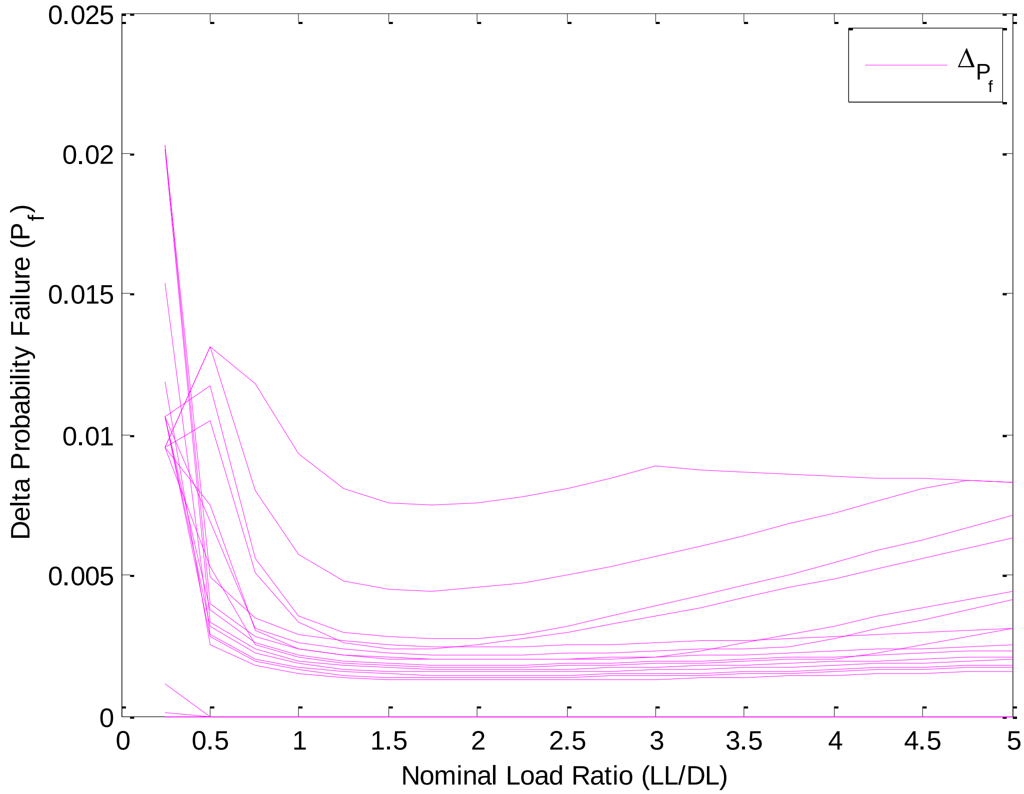


Figure 4.4: Difference between failure probabilities of *Scenario 1* and *2*.

Table 4.2: Failure probabilities of *Scenario 1* and *2*, strength and deflection limit states.

Grade and Dimension	ΔP_f					P_f *Scenario 1 /Scenario 2*				
	Spacing(in)					Spacing(in)				
	12	13.7	16	19.2	24	12	13.7	16	19.2	24
SS 2X4	0.00%	0.00%	0.00%	0.00%	0.00%	1.00	1.00	1.00	1.00	1.00
No.2 2x4	1.19%	1.54%	2.01%	1.88%	1.54%	1.86	2.11	2.45	2.22	1.82
SS 2X8	0.00%	0.00%	0.00%	0.00%	0.00%	1.00	1.00	1.00	1.00	1.00
No.2 2x8	0.91%	0.76%	0.74%	0.74%	1.18%	1.88	1.64	1.61	1.61	1.97
SS 2X10	0.00%	0.00%	0.00%	0.01%	0.12%	1.00	1.00	1.00	1.08	1.70
No.2 2x10	0.68%	0.75%	1.05%	1.31%	1.31%	1.69	1.76	2.07	2.33	2.33

The maximum, minimum and average reliability indices versus *LL*/*DL* ratio are shown in Figure 4.5. The dotted lines in Figure 4.5 represent the reliabilities of designs based on the 2005 NDS code (*Scenario 1*) and the dashed lines represent the reliabilities of designs based on the new 2012 NDS reference design values (*Scenario 2*). While the reliabilities of *Scenario 1* are lower than that of *Scenario 2*, the *Scenario 1* designs are still considered to be safe. Except for the very low *LL*/*DL* ratio range, the reliabilities of all *Scenario 1* designs, particularly those in the typical *LL*/*DL* range, are above the code target reliability level.

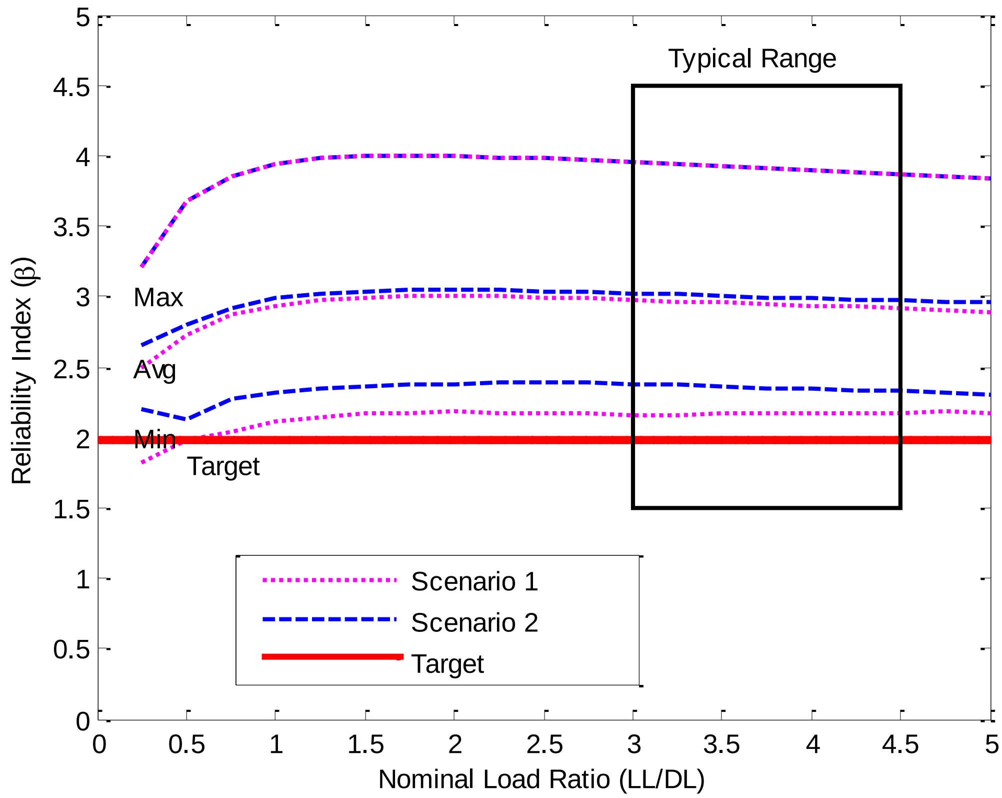


Figure 4.5: Maximum, minimum and average reliability for strength limit state and *L/360* deflection limit state.

4.2.2 Effect of Deflection Limit State

Figure 4.6 shows the minimum, maximum and average reliabilities of floor joists without considering the deflection limit state. From this Figure, significant drops of reliability can be observed from *Scenarios 1* to *2* when the deflection limit state is not considered. Although the reference bending strength (F_b) values reduced by as much as 27% (see Table 3.1), the reliabilities of *Scenario 1* are still above the code target reliability level (see Figure 4.2). This is because the floor joist designs are usually governed by the deflection (serviceability) limit state. While the design bending strengths dropped by as much as 27%, the maximum reduction in the reference design values for bending stiffness (E) is only about 12.5%. The analysis results show that the deflection limit state in NDS code serves as a safeguard for the design of floor joists which makes the safety (or reliability) of floor joists less sensitive to fluctuation or drop in the bending strength.

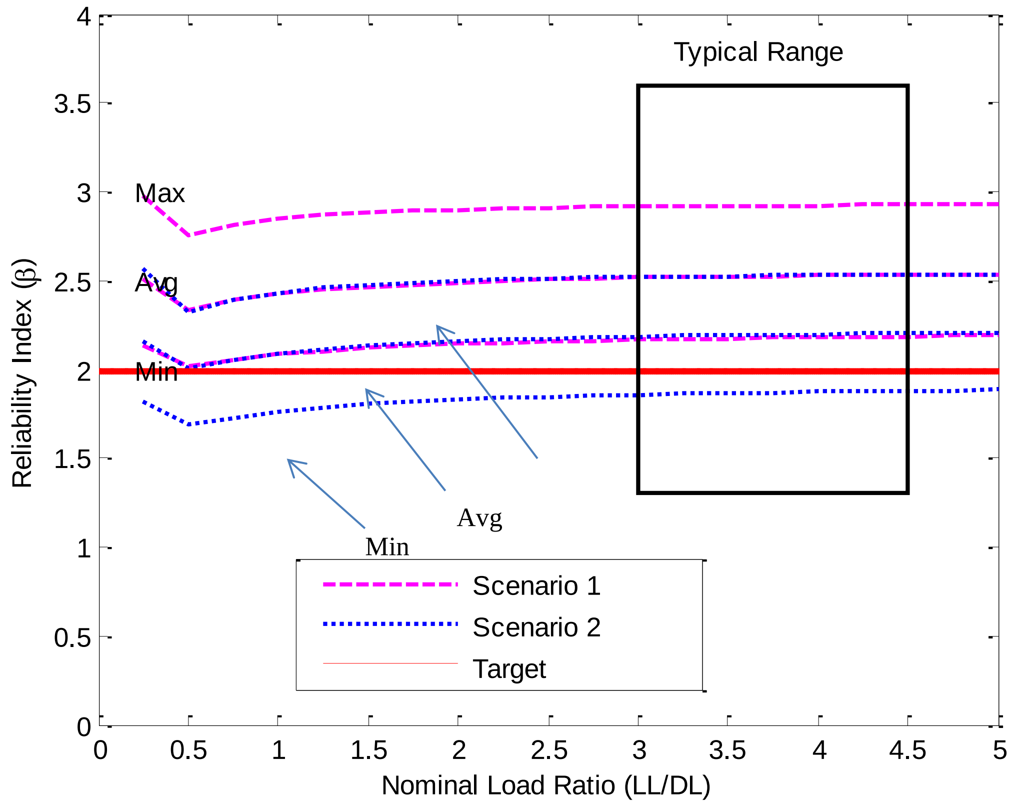


Figure 4.6: Maximum, minimum and average reliability for strength only limit state (no deflection limit state).

4.2.3 Effects of Lumber Size

Figure 4.7 shows the results of reliability analyses performed for floor joists constructed of *No.2* 2x4, 2x8, and 2x10 Southern Pine lumber spaced at 12 in. on-center. As expected, the reliabilities of *Scenario 1* floor joists of the same dimension are lower than that of the *Scenario 2*. While *Scenario 1* designs are not as safe as *Scenario 2* designs, in general, the reliabilities of *Scenario 1* are still above the code target reliability (i.e. $\beta = 2.0$). A zoomed-in view of the circled area in Figure 4.7 is shown in Figure 4.8. From the zoomed-in view, one can see that the reliability reduces as the lumber dimension increases. This trend was also observed in a previous study by Bulleit (1985).

This is because the mean of the MOR of lumber of larger dimensions is generally lower than lumber of smaller dimensions (see Figure 2.3).

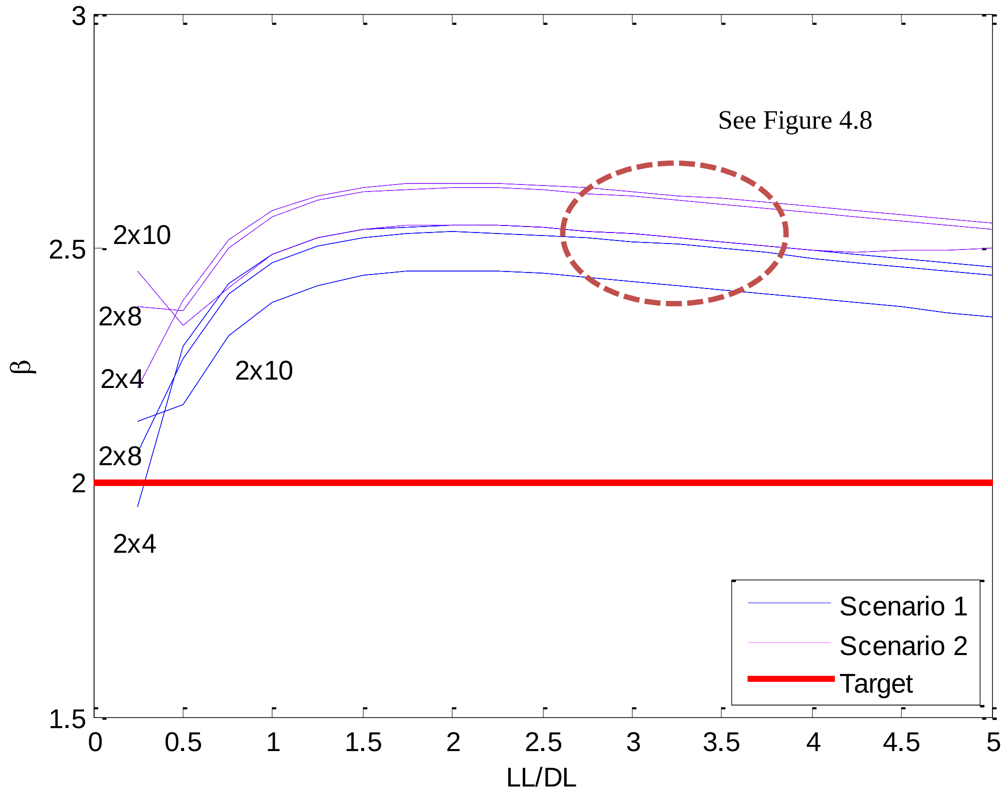


Figure 4.7: Comparison between the reliability of *Scenarios 1* and *2* for *No.2* floor joints spaced at 12 in on-center, *L/360* deflection limit.

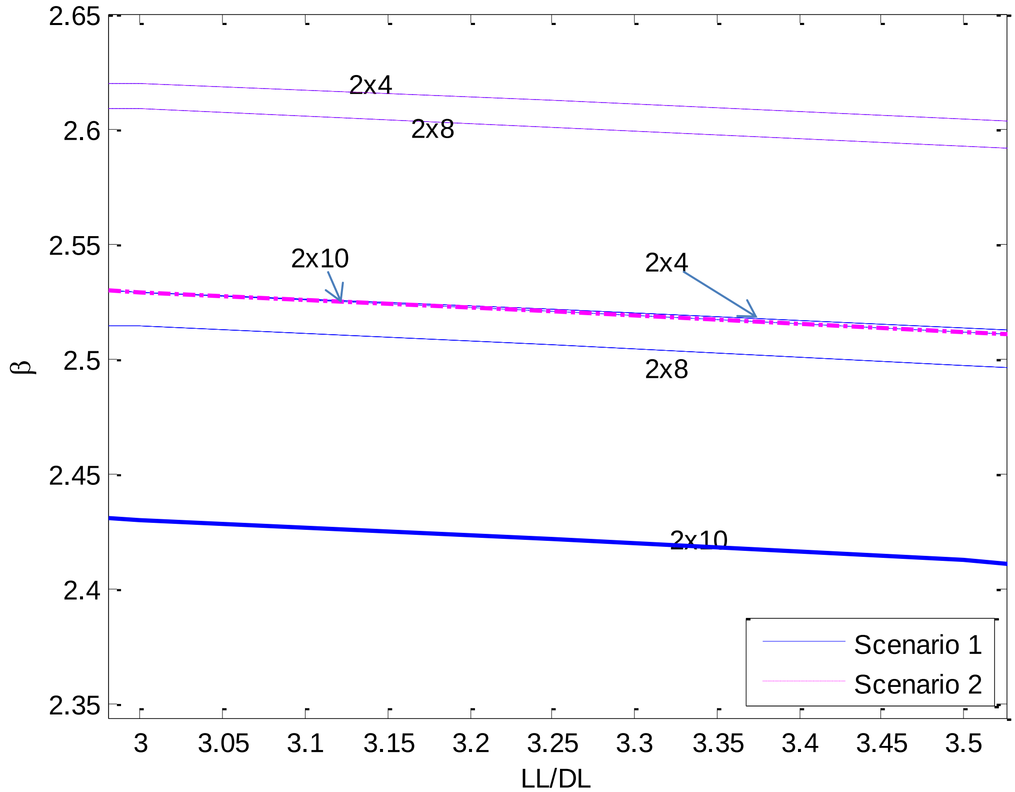


Figure 4.8: Comparison between the reliability of *Scenarios 1* and *2* for *No.2* floor joints spaced at 12 in on-center, *L/360* deflection limit.

4.3 Maximum span length analysis

Based on the new design value for stiffness (E) and bending capacity (F_b), new maximum span lengths for different grade and size combinations were calculated and compared with the published maximum span length values (SPC, 2010). Comparisons are made between the maximum span lengths determined via the new and old design values. The maximum span lengths are function of the live load to dead load ratio (LL/DL), joist spacing (S_b) and joist dimensions. As discussed in Chapter 3, shear strength typically does not control the design of floor joist; the maximum span length of floor joist is controlled by the shorter span length of the two limit states, namely, *strength limit state* and *serviceability limit state*. In general, the maximum span lengths of floor joists of higher grade lumber are limited by the deflection limit state (see Figure 4.9). Compared to the 2005 NDS, the overall reduction of the 2012 NDS reference design values of bending strength are significantly more than that of bending stiffness. These result in the controlling limit state of several lower grade lumbers changed from deflection-control to strength-control. More details on the influences of each of these factors on the maximum span length are discussed next in the following sections.

4.3.1 Effect of Joist Dimension

Figure 4.9 shows the maximum span length versus lumber grade plots for floor joists with live load to dead load ratio of 3 and joist spacing of 16 inches on center. The maximum span lengths were determined using the new reference design values (i.e. 2012 NDS). In Figure 4.9, the horizontal axis shows the lumber grades with the lowest *No.3* (*#3*) lumber grade to the highest *Select Structural* (*SS*) lumber grades plotted from left to right. The label of “D” represents Dense and label “ND” represents Non-Dense. The categories of dense and non-dense are specified for *SS*, *No.1* and *No.2* grades. Solid lines with circular markers represent the strength control limit state and dashed lines with triangular markers represent the deflection control limit state. Also shown in Figure 4.9 is the transition boundary of deflection-control and strength-control limit states (green dashed line). As can be seen, the left side of the transition boundary line is controlled by strength limit state while the right side is controlled by deflection limit state. In other words, floor joists of higher grade lumbers are controlled by deflection limit state while the lower grade counterparts are controlled by strength limit state. For a given lumber grade, as the depth of the floor joist increases, the controlling limit state changes from deflection-control to strength-control limit state. This is because the stresses in the extreme fibers at the top and bottom of joist increase in proportion to the joist depth. The same trends are also observed for the maximum span length figures developed using the 2005 NDS. The comparisons between the 2005 NDS and 2012 NDS plots are discussed in a later section. The complete set of maximum span length versus lumber grade plots for other *LL/DL* ratios and joist spacings are represented in Appendix C.

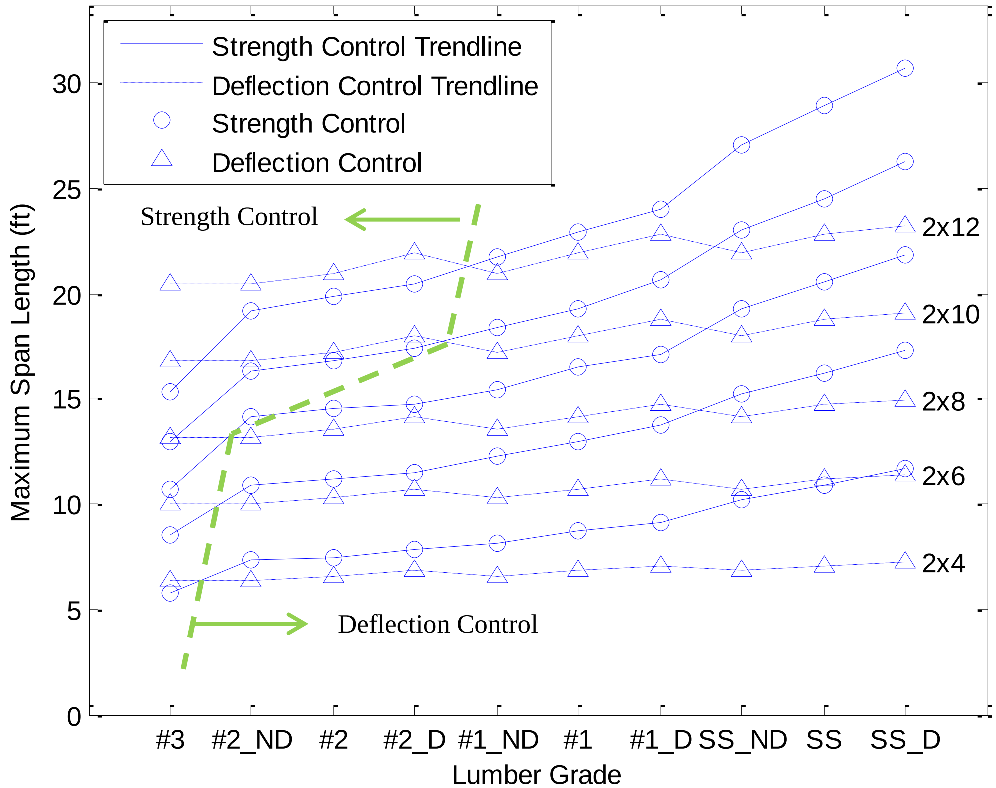


Figure 4.9: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 16 in. on-center and *LL/DL* ratio of 3 (2012 NDS).

4.3.2 Effects of Live Load to Dead Load Ratio

The effects of live load to dead load ratio on the maximum span length are investigated. In this study, the dead load was maintained at 10 psf and the three levels of live load (30 psf, 40 psf and 50 psf) which are representative of the loading in light-frame wood residential and commercial buildings are considered. Figure 4.10 shows the maximum span lengths for different grades of 2x10 floor joists at 16 inches on center spacing with three different levels of live load determined based on the 2012 NDS design values.

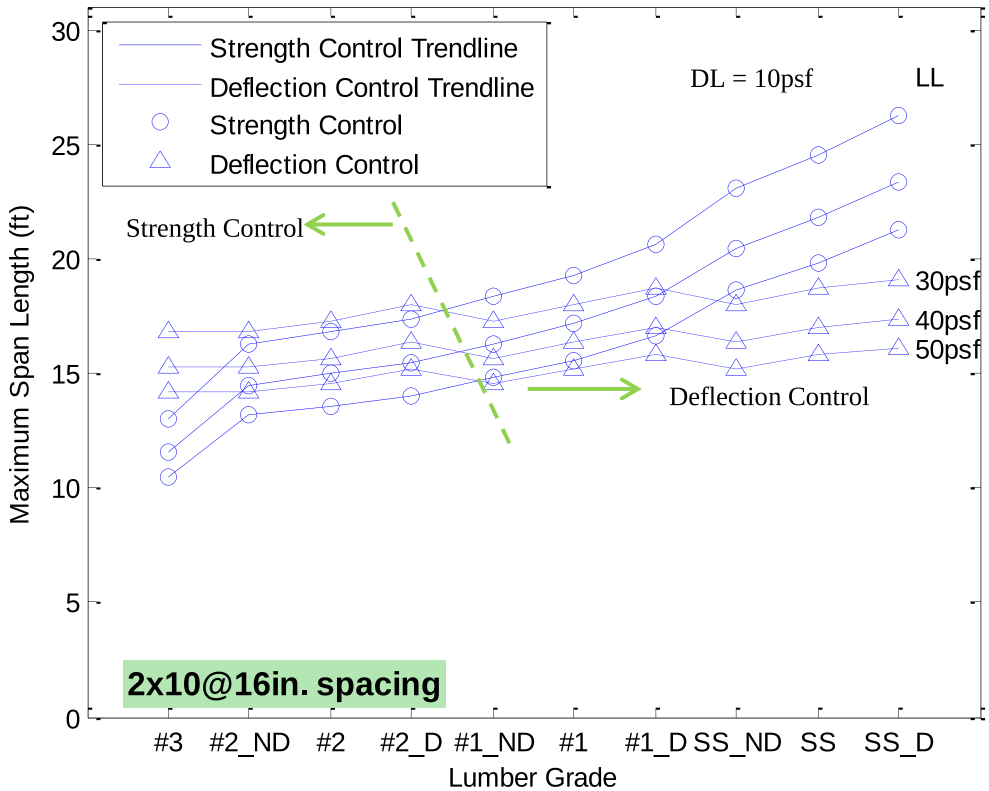


Figure 4.10: Effects of live load on maximum span length for 2x10 Southern Pine floor joists at 16 inch on center (2012 NDS).

Form Figure 4.10, it is obvious that the increase in live load leads to decrease in maximum span length. The green dashed line on the figure represents the intersection of strength limit state and serviceability limit state. Similar to Figure 4.9, the left side of the dashed line is governed by strength limit state and the right side of the dashed line is controlled by deflection limit state. The deflection-strength control boundary line shows that, for a given lumber grade, as the live load increases the maximum span length reduces and the controlling limit state shifts from deflection to strength control. The influences of live loads on maximum span length for other dimension and spacing cases are shown in Appendix D for both the 2005 NDS and 2012 NDS designs.

4.3.3 Effects of Spacing

Maximum span length is a function of the magnitude of the applied loads, lumber grade, dimensions of lumber and joist spacing. In previous sections, the influences of dimensions and applied loads are discussed. In this section, the effects of joist spacing on maximum span length determined from the 2012 NDS are examined for one particular dimension and load case. Figure 4.11 shows the maximum span length versus grade for 2x10 floor joist with *LL/DL* equal to 3. Three spacings, 12 inches o.c. (on-center), 16 inches o.c. and 24 inches o.c., were evaluated in this study.

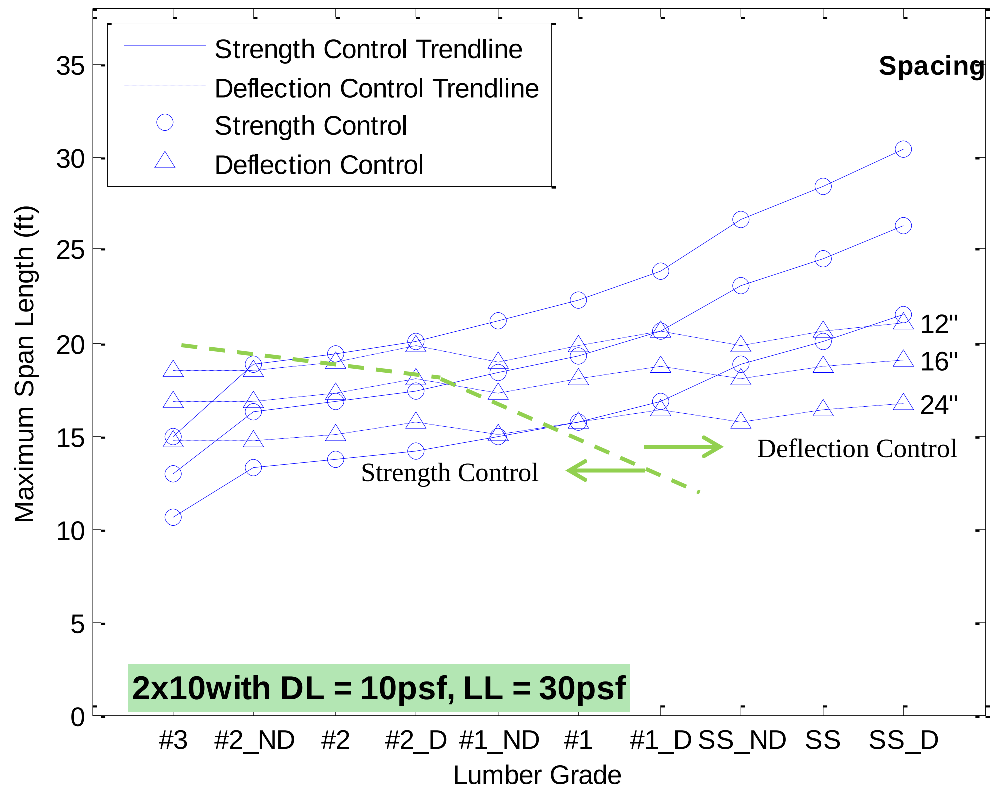


Figure 4.11: Effect of joist spacing on maximum span length for 2x10 Southern Pine floor joists with *LL/DL* equal to 3 (2012 NDS).

Figure 4.11 shows the maximum span length versus lumber grade curves for 2x10 joists with 10 psf of *DL* and 30 psf of *LL* for all three different spacings. The green dashed line shows the transition between strength control and deflection control limit states. As can be seen, for a given lumber grade, wider joist spacing leads to reduction in the allowable maximum span length and the controlling limit state shifts from deflection to strength control. This observation is similar to that observed when the magnitude of live load is increased (see Figure 4.10). This is because increase in joist spacing also results in increase of the effective load carried by the joist. The effects of joist spacing on maximum span length for other *LL/DL* ratios and joist dimensions are given in the figures in Appendix E.

4.3.4 Effects of Change in Design Capacities (2005 versus 2012 NDS)

Two scenarios were studied in this thesis. In *Scenario 1*, the design span length was calculated based on the 2005 NDS, and in *Scenario 2*, the design span length was calculated based on the 2012 NDS. In general, the new design values in the 2012 NDS for deflection (E) and bending strength (F_b) are lower than the previous NDS (2005) by 0 to 14.3% and 11.5 to 41.7%, respectively (see Table 4.1). The *Scenarios 1* and *2* designs were determined using these two sets of design values.

Figure 4.12 shows the change in maximum span length from the designs based on the 2005 NDS to 2012 NDS. The markers on the figure represent the actual maximum span lengths for a given lumber grade and dimension. Circular markers show the design maximum span lengths that are controlled by strength and triangle markers show the design maximum span lengths that are controlled by deflection. The green dotted line represents the intersection of strength control and deflection control for *Scenario 1* (2005 NDS) and the thicker green dashed line represents the intersection of the two limit states for *Scenario 2* (2012 NDS). Similar to the previous Figures 4.9 to 4.11, the left side of the intersection curves is controlled by strength limit state and the other side is controlled by deflection. Comparison between the two scenarios show that the strength-deflection control intersection curve for 2012 NDS shifted to the right. In other words, *Scenario 2* (2012 NDS) contains more designs that are controlled by strength than *Scenario 1* (2005 NDS). This figure can be used by practitioners to quickly determine if a particular floor system based on the 2005 NDS is potentially unsafe and requires retrofit. For example, the maximum span length for a floor system with 2x12 floor joists spaced at 12 inches o.c. (on center) under 10 psf *DL* and 30 psf *LL* is reduced by 14.5%.

From Table 4.1, it clearly shows that the elastic modulus design values in 2012 NDS are not changed for *Dense SS*, *SS* and *No.1 Dense* grades. Since the controlling limit state for higher lumber grades is deflection, the maximum span lengths for the aforementioned lumber grades are not affected in the 2012 NDS (see Figure 4.12). In contrast, the impact of reduction in bending strength for lower lumber grades is more pronounced as the maximum span length for lower grade lumbers are controlled by strength. This is because the reductions of the reference design values for strength (F_b) in the 2012 NDS are more significant than the changes in the reference design values for stiffness (E). These trends are also observed for other load cases and spacings, and figures showing these trends are provided in Appendix F.

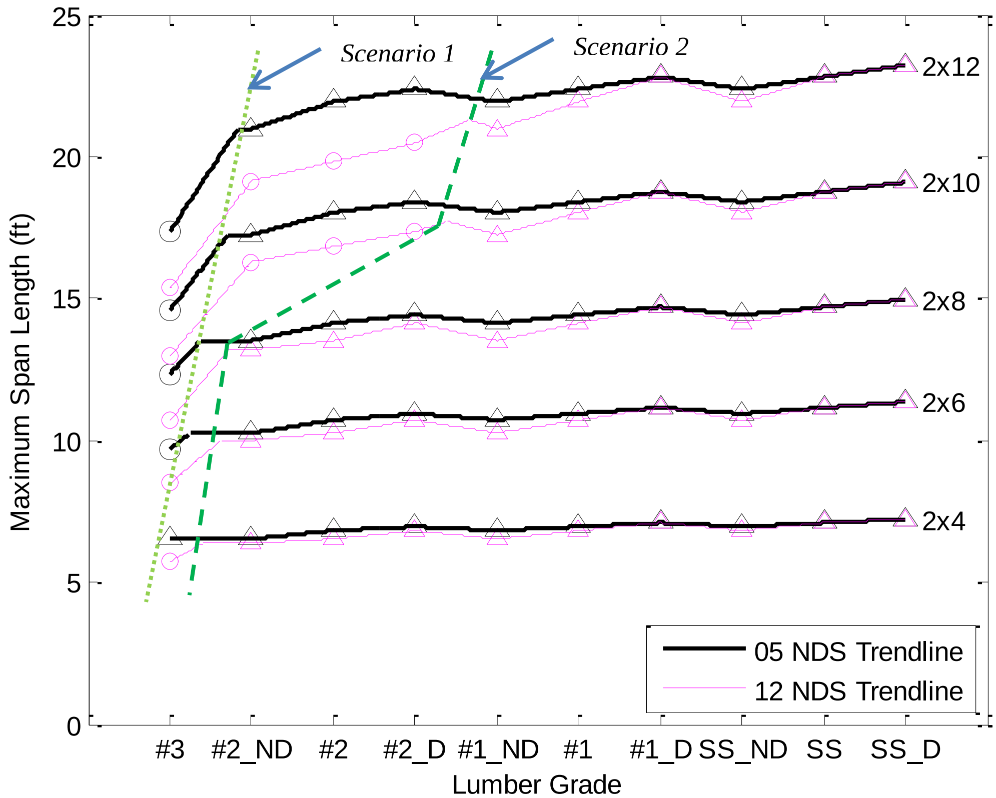


Figure 4.12: Comparison between the maximum span lengths of 2005 NDS and 2012 NDS for Southern Pine floor joists spaced at 16 inches on center with *LL/DL* ratio at 3.

Tables 4.3 and 4.4 summarize the maximum span lengths for live load to dead load ratio of 3.0 for visually graded Southern Pine floor joists designed in accordance to the 2005 NDS and 2012 NDS. Similar tables for other *LL/DL* ratios are presented in Appendix F.

Table 4.3: Maximum span lengths based on 2005 NDS.

2005 NDS Maximum Span length for DL = 10 psf LL = 30 psf (ft)											
		Grade									
Dimension	Spacing	D SS	SS	N-D SS	No.1 D	No.1	No.1 N-D	No.2 D	No.2	No.2 N-D	No.3 & Stud
2x4	12"	8.0 (d)	7.8 (d)	7.7 (d)	7.8 (d)	7.7 (d)	7.5 (d)	7.7 (d)	7.5 (d)	7.2 (d)	7.2 (d)
	16"	7.2 (d)	7.1 (d)	7.0 (d)	7.1 (d)	7.0 (d)	6.8 (d)	7.0 (d)	6.8 (d)	6.5 (d)	6.5 (d)
	24"	6.3 (d)	6.2 (d)	6.1 (d)	6.2 (d)	6.1 (d)	6.0 (d)	6.1 (d)	6.0 (d)	5.7 (d)	5.4 (b)
2x6	12"	12.5 (d)	12.3 (d)	12.0 (d)	12.3 (d)	12.0 (d)	11.8 (d)	12.0 (d)	11.8 (d)	11.3 (d)	11.2 (b)
	16"	11.4 (d)	11.2 (d)	10.9 (d)	11.2 (d)	10.9 (d)	10.7 (d)	10.9 (d)	10.7 (d)	10.3 (d)	9.7 (b)
	24"	9.9 (d)	9.7 (d)	9.6 (d)	9.7 (d)	9.6 (d)	9.4 (d)	9.6 (d)	9.4 (d)	9.0 (d)	7.9 (b)
2x8	12"	16.5 (d)	16.2 (d)	15.9 (d)	16.2 (d)	15.9 (d)	15.6 (d)	15.9 (d)	15.6 (d)	14.9 (d)	14.3 (b)
	16"	15.0 (d)	14.7 (d)	14.4 (d)	14.7 (d)	14.4 (d)	14.1 (d)	14.4 (d)	14.1 (d)	13.5 (d)	12.3 (b)
	24"	13.1 (d)	12.8 (d)	12.6 (d)	12.8 (d)	12.6 (d)	12.3 (d)	12.6 (d)	12.3 (d)	11.8 (d)	10.1 (b)
2x10	12"	21.0 (d)	20.6 (d)	20.3 (d)	20.6 (d)	20.3 (d)	19.8 (d)	20.3 (d)	19.8 (d)	19.0 (d)	16.8 (b)
	16"	19.1 (d)	18.8 (d)	18.4 (d)	18.8 (d)	18.4 (d)	18.0 (d)	18.4 (d)	18.0 (d)	17.2 (d)	14.6 (b)
	24"	16.7 (d)	16.4 (d)	16.1 (d)	16.4 (d)	16.1 (d)	15.8 (d)	16.1 (d)	15.7 (b)	15.0 (b)	11.9 (b)
2x12	12"	25.6 (d)	25.1 (d)	24.6 (d)	25.1 (d)	24.6 (d)	24.1 (d)	24.6 (d)	24.1 (d)	23.1 (d)	20.0 (b)
	16"	23.2 (d)	22.8 (d)	22.4 (d)	22.8 (d)	22.4 (d)	21.9 (d)	22.4 (d)	21.9 (d)	21.0 (d)	17.4 (b)
	24"	20.3 (d)	19.9 (d)	19.5 (d)	19.9 (d)	19.5 (d)	19.2 (d)	19.5 (d)	18.5 (b)	17.7 (b)	14.2 (b)

*Highlighted cells indicate bending limit state controls. The "(d)" and "(b)" indicate the respective designs are controlled by deflection and bending (strength) limit states, respectively.

Table 4.4: Maximum span lengths based on 2012 NDS.

2012 NDS Maximum Span length for DL = 10 psf LL = 30 psf (ft)											
		Grade									
Dimension	Spacing	D SS	SS	N-D SS	No.1 D	No.1	No.1 N-D	No.2 D	No.2	No.2 N-D	No.3 & Stud
2x4	12"	8.0 (d)	7.8 (d)	7.5 (d)	7.8 (d)	7.5 (d)	7.2 (d)	7.5 (d)	7.2 (d)	7.0 (d)	6.6 (b)
	16"	7.2 (d)	7.1 (d)	6.8 (d)	7.1 (d)	6.8 (d)	6.5 (d)	6.8 (d)	6.5 (d)	6.4 (d)	5.7 (b)
	24"	6.3 (d)	6.2 (d)	6.0 (d)	6.2 (d)	6.0 (d)	5.7 (d)	6.0 (d)	5.7 (d)	5.6 (d)	4.7 (b)
2x6	12"	12.5 (d)	12.3 (d)	11.8 (d)	12.3 (d)	11.8 (d)	11.3 (d)	11.8 (d)	11.3 (d)	11.0 (d)	9.8 (b)
	16"	11.4 (d)	11.2 (d)	10.7 (d)	11.2 (d)	10.7 (d)	10.3 (d)	10.7 (d)	10.3 (d)	10.0 (d)	8.5 (b)
	24"	9.9 (d)	9.7 (d)	9.4 (d)	9.7 (d)	9.4 (d)	9.0 (d)	9.4 (b)	9.0 (b)	8.7 (b)	6.9 (b)
2x8	12"	16.5 (d)	16.2 (d)	15.6 (d)	16.2 (d)	15.6 (d)	14.9 (d)	15.6 (d)	14.9 (d)	14.5 (d)	12.3 (b)
	16"	15.0 (d)	14.7 (d)	14.1 (d)	14.7 (d)	14.1 (d)	13.5 (d)	14.1 (d)	13.5 (d)	13.2 (d)	10.7 (b)
	24"	13.1 (d)	12.8 (d)	12.3 (d)	12.8 (d)	12.3 (d)	11.8 (d)	12.0 (b)	11.8 (b)	11.5 (b)	8.7 (b)
2x10	12"	21.0 (d)	20.6 (d)	19.8 (d)	20.6 (d)	19.8 (d)	19.0 (d)	19.8 (d)	19.0 (d)	18.5 (b)	15.0 (b)
	16"	19.1 (d)	18.8 (d)	18.0 (d)	18.8 (d)	18.0 (d)	17.2 (d)	17.4 (b)	16.8 (b)	16.3 (b)	13.0 (b)
	24"	16.7 (d)	16.4 (d)	15.8 (d)	16.4 (d)	15.7 (b)	15.0 (b)	14.2 (b)	13.7 (b)	13.3 (b)	10.6 (b)
2x12	12"	25.6 (d)	25.1 (d)	24.1 (d)	25.1 (d)	24.1 (d)	23.1 (d)	23.6 (b)	22.9 (b)	22.1 (b)	17.7 (b)
	16"	23.2 (d)	22.8 (d)	21.9 (d)	22.8 (d)	21.9 (d)	21.0 (d)	20.5 (b)	19.8 (b)	19.2 (b)	15.4 (b)
	24"	20.3 (d)	19.9 (d)	19.2 (d)	19.6 (b)	18.7 (b)	17.7 (b)	16.7 (b)	16.2 (b)	15.6 (b)	12.5 (b)

*Highlighted cells indicate bending limit state controls. The “(d)” and “(b)” indicate the respective designs are controlled by deflection and bending (strength) limit states, respectively.

In Tables 4.3 and 4.4, both shaded areas represent the maximum span lengths that are controlled by strength limitation. In these tables, “(d)” indicates that the maximum span length is controlled by deflection and (*b*) indicates that the maximum span length is controlled by strength. The capital letter “D” in the header of the column means “dense” and “N-D” represents “non-dense” for *SS*, *No.1* and *No.2* grades. The percent reductions in maximum span lengths by switching from the 2005 NDS to 2012 NDS are summarized in Table 4.5.

Table 4.5: Percent reductions in maximum span lengths (2005 NDS versus 2012 NDS) for *DL*=10 psf and *LL*=30 psf.

		Maximum Span length for DL = 10 psf LL = 30 psf (ft)									
		Grade									
Dimension	Spacing	D SS	SS	N-D SS	No.1 D	No.1	No.1 N-D	No.2 D	No.2	No.2 N-D	No.3 & Stud
2x4	12"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	7.7
	16"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.0
	24"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.6
2x6	12"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.4
	16"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.4
	24"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.4
2x8	12"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	13.4
	16"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	13.4
	24"	0.0	0.0	2.0	0.0	2.0	4.4	4.4	4.4	2.4	13.4
2x10	12"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	11.0
	16"	0.0	0.0	2.0	0.0	2.0	4.4	5.7	6.6	5.5	11.0
	24"	0.0	0.0	2.0	0.0	2.0	4.9	11.9	12.7	11.1	11.0
2x12	12"	0.0	0.0	2.0	0.0	2.0	4.4	4.0	5.2	4.2	11.5
	16"	0.0	0.0	2.0	0.0	2.0	4.4	8.5	9.6	8.7	11.5
	24"	0.0	0.0	2.0	1.6	4.4	7.4	14.5	12.3	11.8	11.5

Comparison between the maximum span lengths of 2x8 and 2x10 lumber, which are among the two most common sizes for floor joists, shows that more designs are now governed by the strength limit state (2012 NDS). As can be seen, for lower grade lumbers, the reductions in maximum span lengths are less significant (and no change in some cases). This is because the maximum span lengths of these lower grade lumbers are governed by deflection and the largest reduction in the reference design value for stiffness is only 14.3% versus up to 41.7% reduction in the reference design value for bending strength (2012 NDS). The largest reduction in maximum span length (14.5%) occurred in the design of 2x12 floor joists spaced at 24 inches on center (see Table 4.5).

CHAPTER FIVE

CONCLUSIONS

This research studied the impact of recent changes in the 2012 NDS reference design values of visually graded Southern Pine lumber on the reliabilities of floor joists. Recent full-scale *In-Grade* test of visually graded Southern Pine lumber indicated significant reductions in the design values published in the previous design code (2005 version of NDS). The new reference design values for modulus of elasticity (MOE) and modulus of rupture (MOR) are reduced by approximately 0% to 14.3% and 11.4% to 41.7%, respectively (see Table 4.1). This suggests that the visually graded Southern Pine construction in recent years based on the 2005 NDS might be potentially unsafe.

Reliability analyses were performed using the Advanced First-Order Reliability Method (AFORM) method on one type of flexural members, namely floor joist, to access the impact of the recent changes in reference design values on the safety of Southern Pine floor construction. Two Scenarios were analyzed. *Scenario 1* designs were assumed to base on the 2005 NDS reference values. The *Scenario 1* designs represent constructions completed in recent years prior to the announcement of the reductions in reference design values. In *Scenario 2*, the flexural members were designed using the new reference design values (NDS 2012).

The new MOE and MOR test data obtained from the Southern Pine Inspection Bureau (SPIB) were used in reliability analyses. The MOE and MOR data were fitted to five statistical distributions. These distributions were Normal, Lognormal, Gumbel, Frechet and Weibull distributions. Based on the Kolmogorov Smirnov goodness-of-fit test, it was determined that the two-parameter Weibull distribution can be used to adequately characterize the MOR distributions of visually graded Southern Pine lumber while lognormal distribution can be used to characterize the MOE distributions of visually graded Southern Pine lumber.

As expected, the results of the reliability analyses revealed that the reliabilities of the floor joists designed using the 2005 NDS are lower than that of the 2012 NDS. However, the impact of the changes in reference design values is less severe than expected. Although the reference bending strengths or MORs (F_b) for certain grade and size combinations are reduced by as much as 41.7% , the reliabilities of *Scenario 1* designs (NDS 2005) for common residential loading (live load to dead load ratio between 3 to 4.5) are still above the code target minimum reliability index (β=2.0). This is mainly attributed to the designs of bending members are mainly governed by serviceability (or deflection) limit state and not strength limit state. The bending stiffness reference value (*E*) which is associated with the serviceability limit state is reduced by no more than 14.3%. In this case, the deflection limit state in NDS acts as a safeguard for the safety or reliability of floor joists.

Comparison between the allowable maximum span lengths of 2005 NDS and 2012 NDS was also discussed in the thesis. The largest reduction in maximum span length (from 2005 to 2012 NDS) for floor joists is around 16.6%. A series of allowable maximum span length tables were create to assist practitioners in identified the percent reductions in span lengths. These tables can be used to quickly determine if a particular floor system designed using the 2005 NDS is unsafe and needs remedy.

In summary, the impact of reductions in MOE and MOR of visually graded Southern Pine lumber on the reliability (safety) of floor joist is not very significant, in particular, for No.1 and higher grade lumbers. While the reliability indices of floor joists of 2005 NDS are lower than the 2012 NDS, the overall reliability indices are still above the code minimum. The No. 2 and lower grade lumber affected by the reduction in design values the most. This is because for lower grade lumber the controlling limit state is bending (strength) while for higher grade lumbers the controlling limit state is deflection. In the 2012 NDS, the reference design values for MOR have been reduced by as much as 41.7% while the largest reduction in the reference design value for MOE is only 14.3%. In addition to lumber grade, the change (or reduction) in allowable maximum span length is also a function of the depth of the lumber. Low grade deep floor joists (e.g. No.2 2x10 and 2x12) have been negatively affected by the changes in reference design values more than shallower floor joists.

The scope of this study is only for bending capacity of southern pine. Drops in bending stiffness and bending strength are also observed for other wood species. Further studies can focus on evaluating the impacts of changes in reference design values on other types of structural member capacities (e.g. compression and tension members) for other wood species (e.g. Douglas Fir and Hem fir).

APPENDICES

Appendix A

Best Fit Distributions

a. Normal Distribution

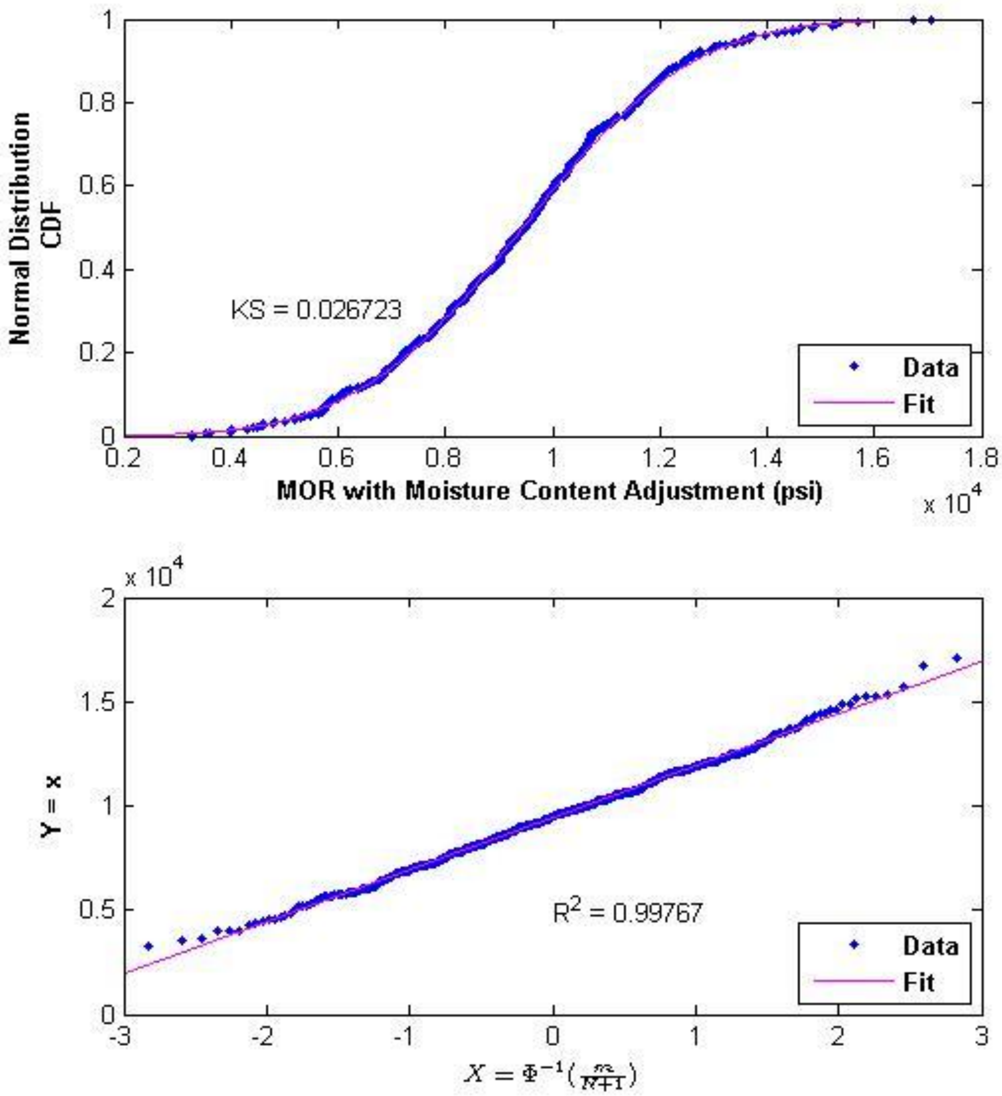


Figure A.1: K-S fitness and probability fit plot for *SS* 2x4 Normal Distribution.

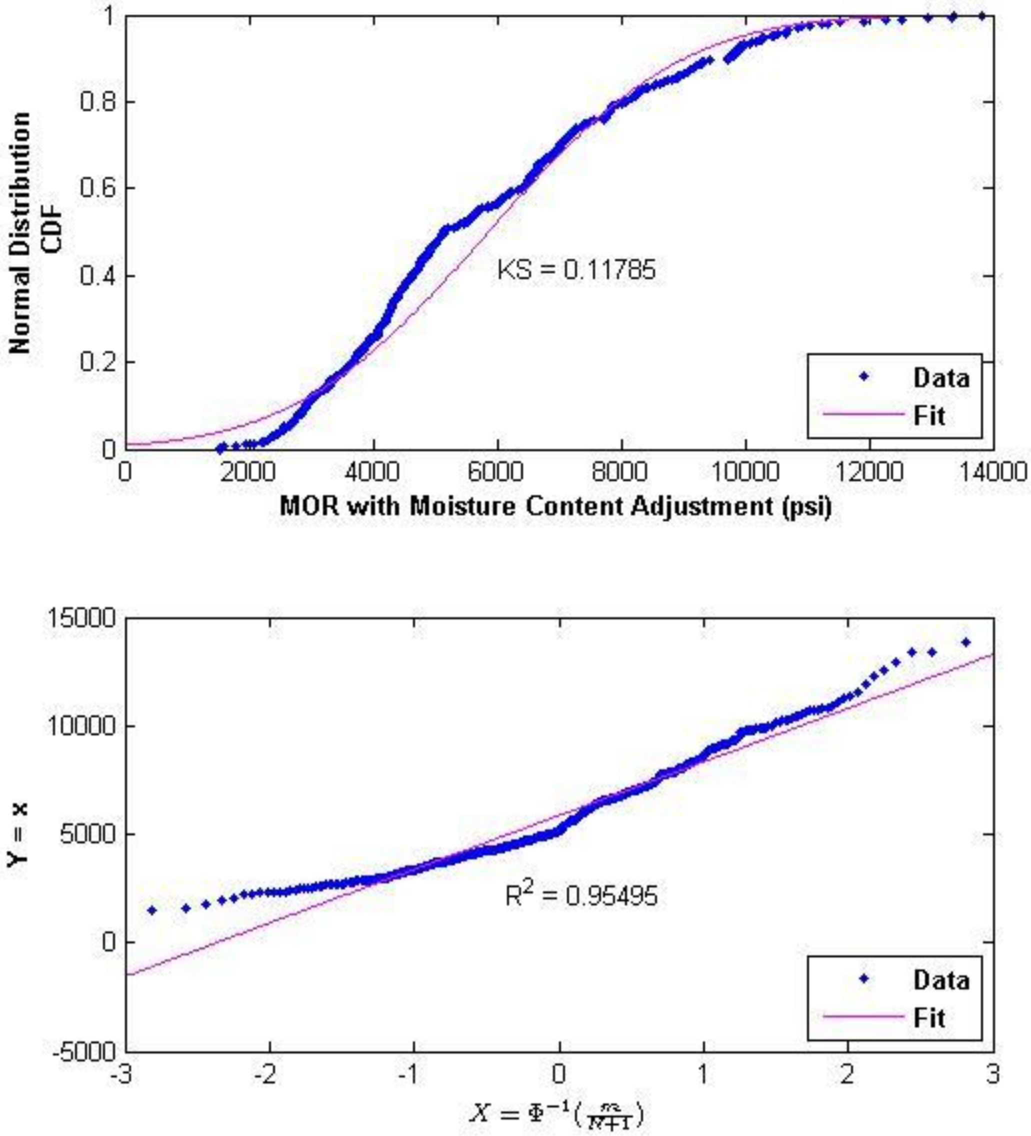


Figure A.2: K-S fitness and probability fit plot for *No.2* 2x4 Normal Distribution.

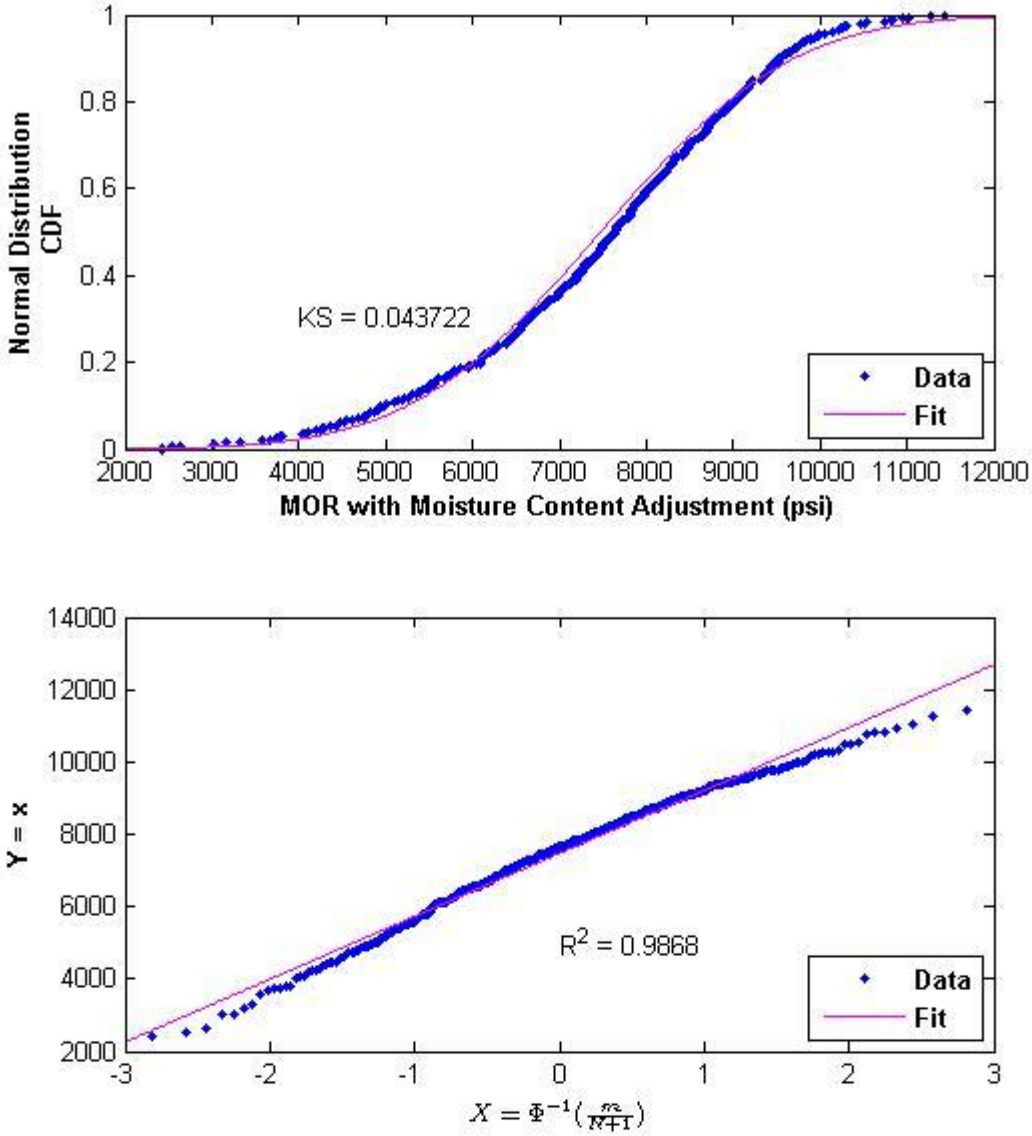


Figure A.3: K-S fitness and probability fit plot for *SS* 2x8 Normal Distribution.

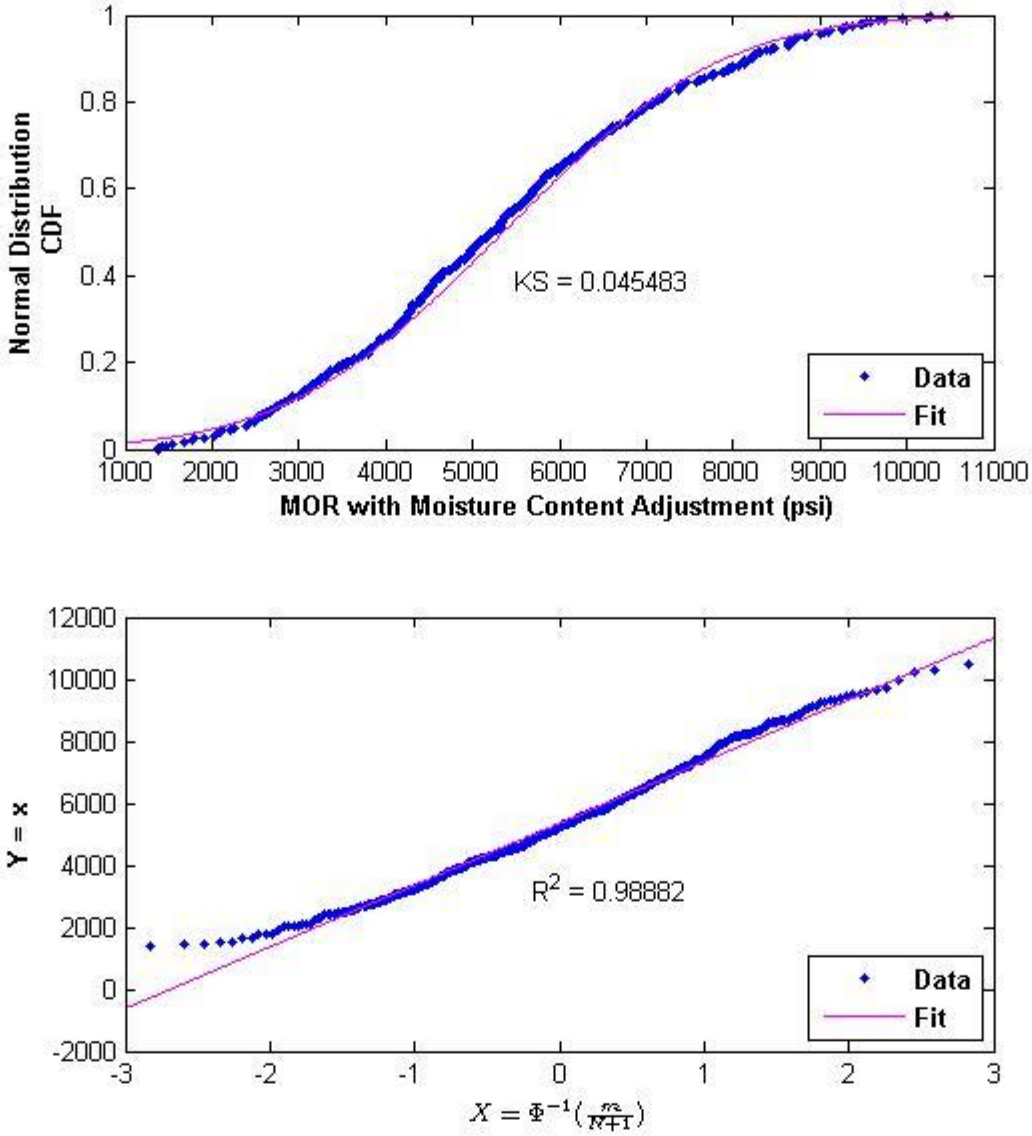


Figure A.4: K-S fitness and probability fit plot for *No.2* 2x8 Normal Distribution.

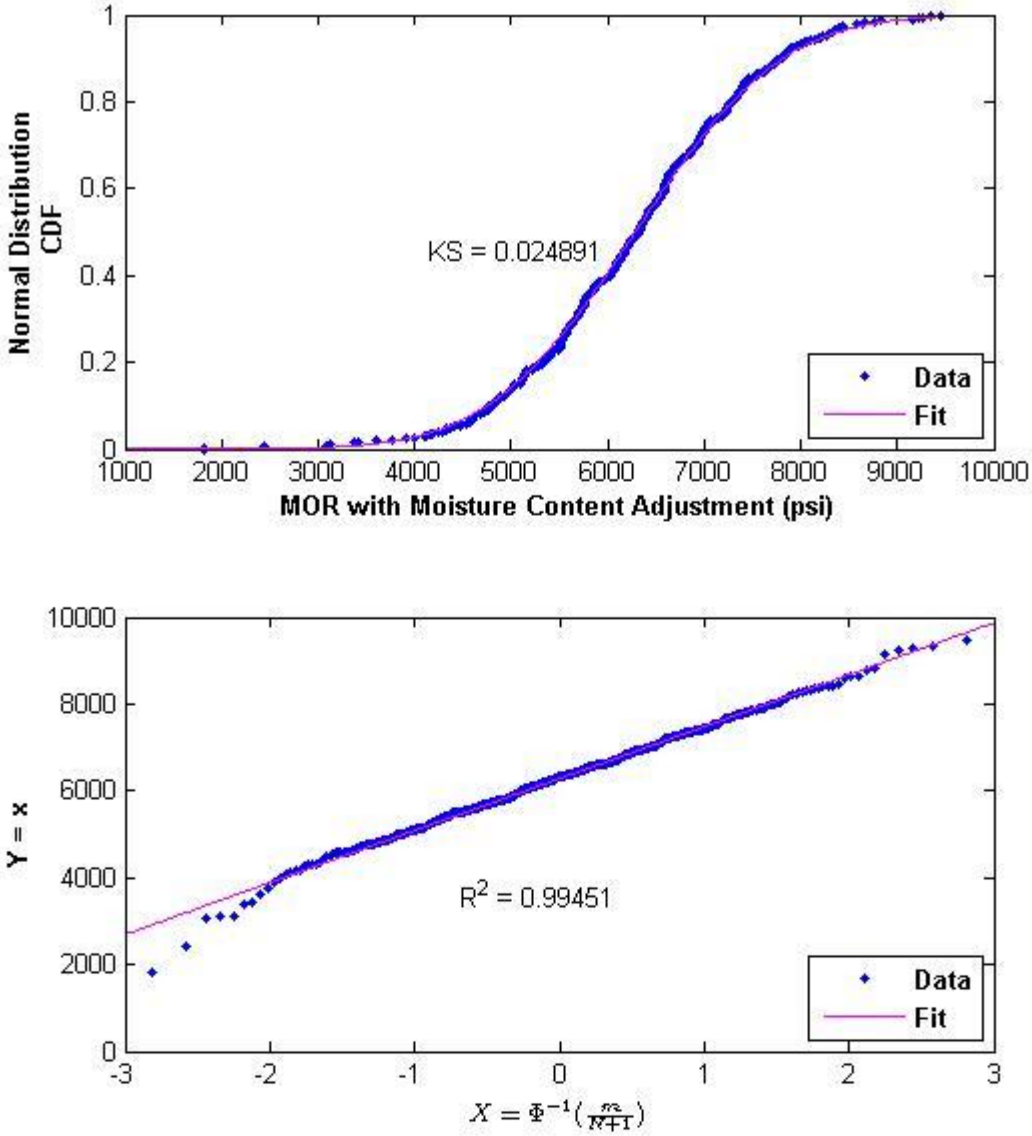


Figure A.5: K-S fitness and probability fit plot for *SS* 2x10 Normal Distribution.

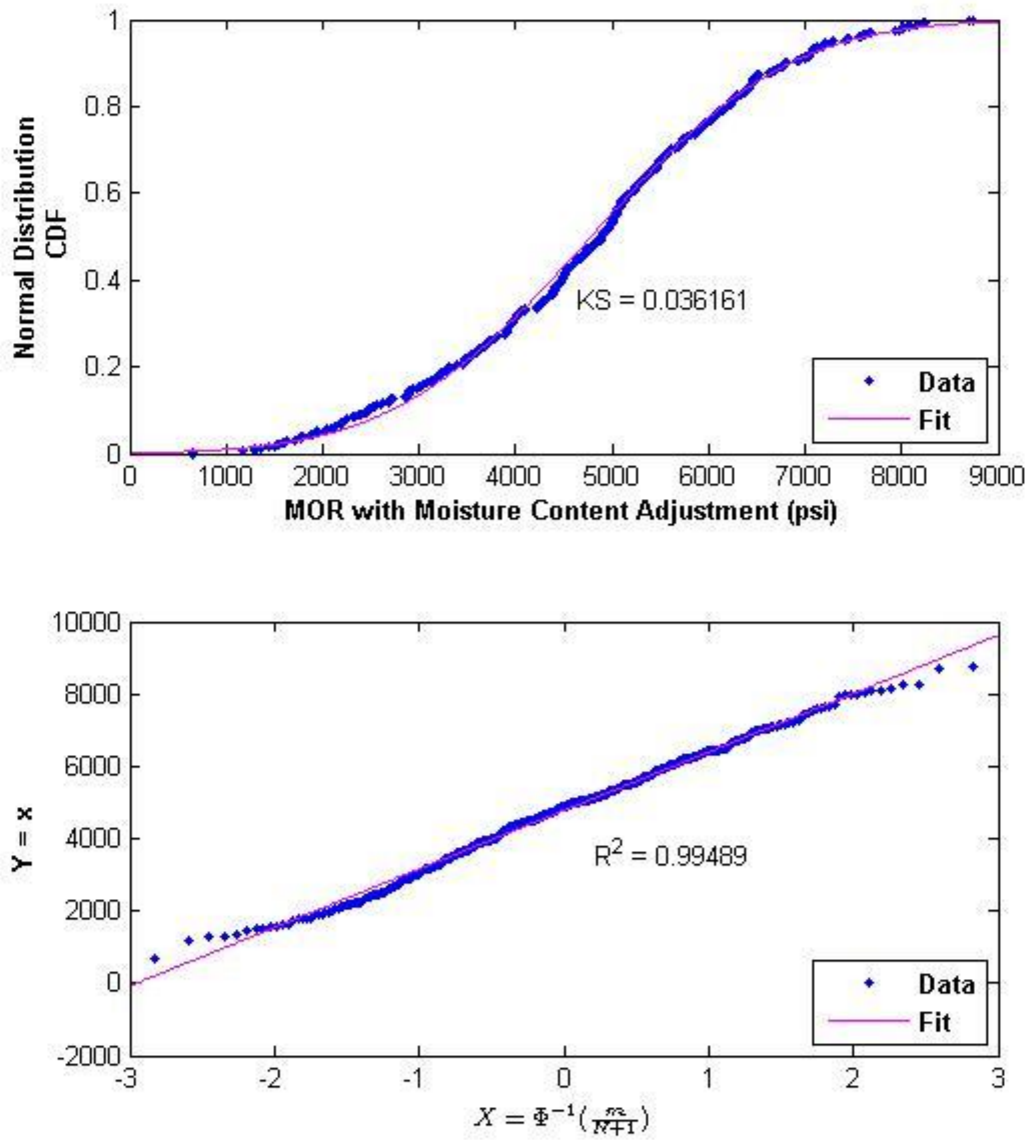


Figure A.6: K-S fitness and probability fit plot for *No.2* 2x10 Normal Distribution.

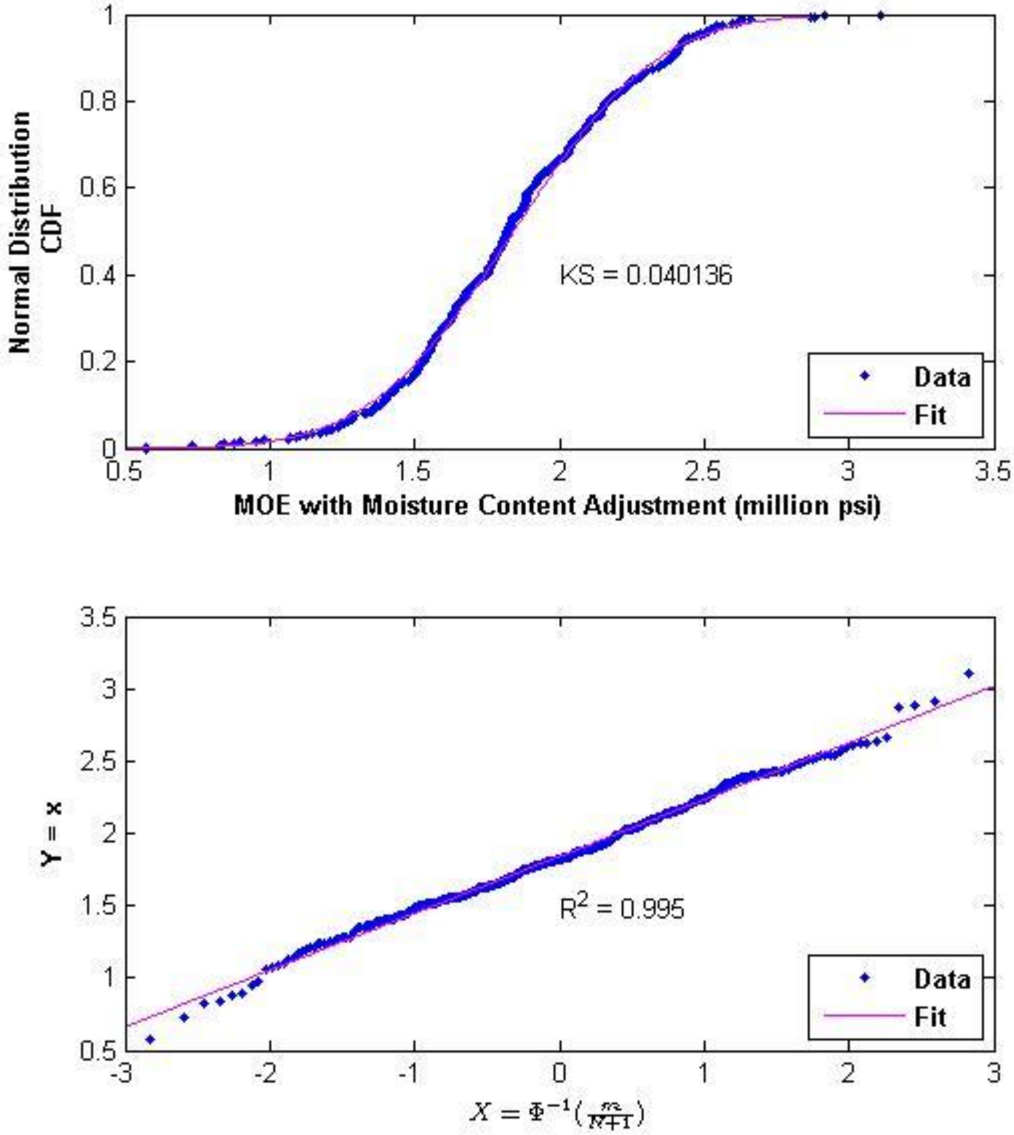


Figure A.7: K-S fitness and probability fit plot for *SS* 2x4 Normal Distribution.

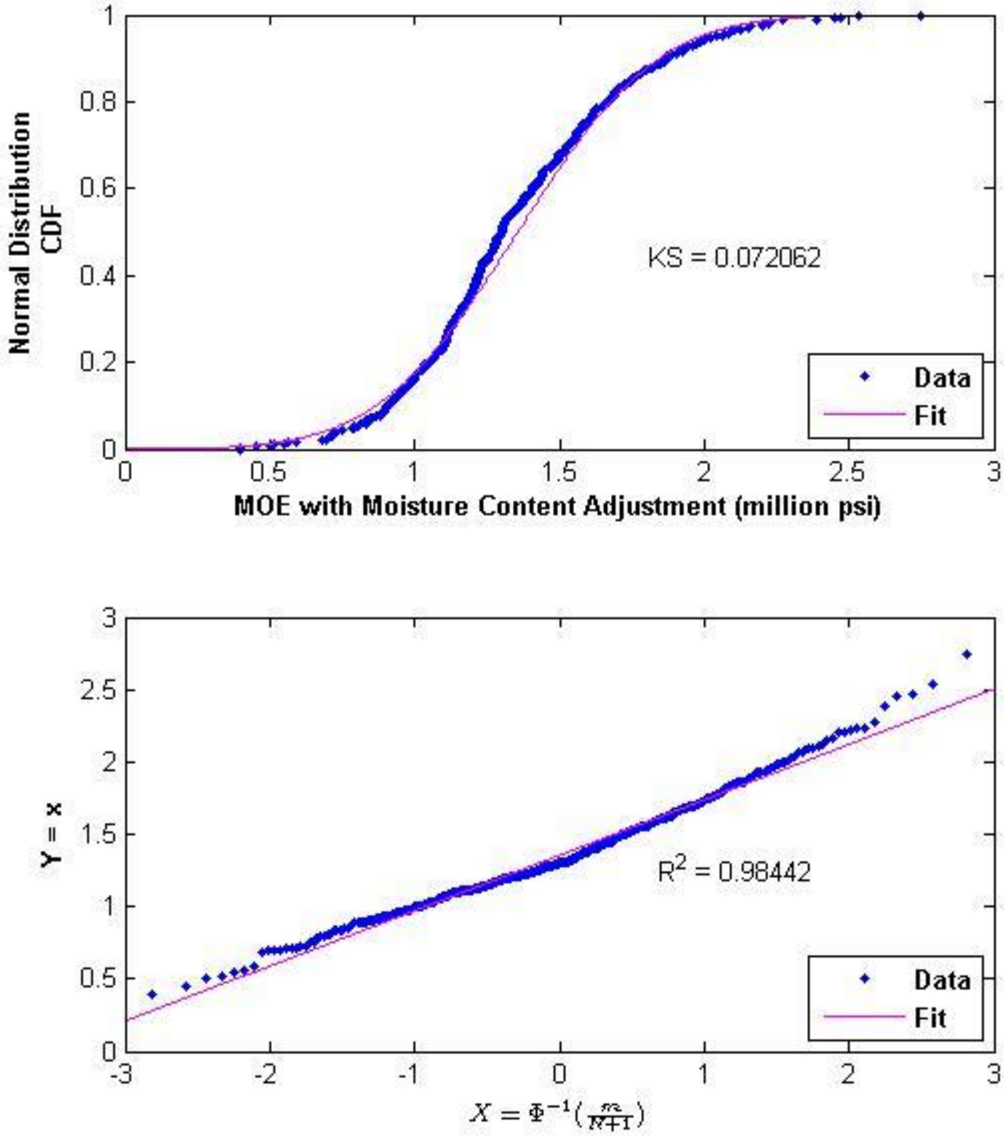


Figure A.8: K-S fitness and probability fit plot for *No.2*2x4 Normal Distribution.

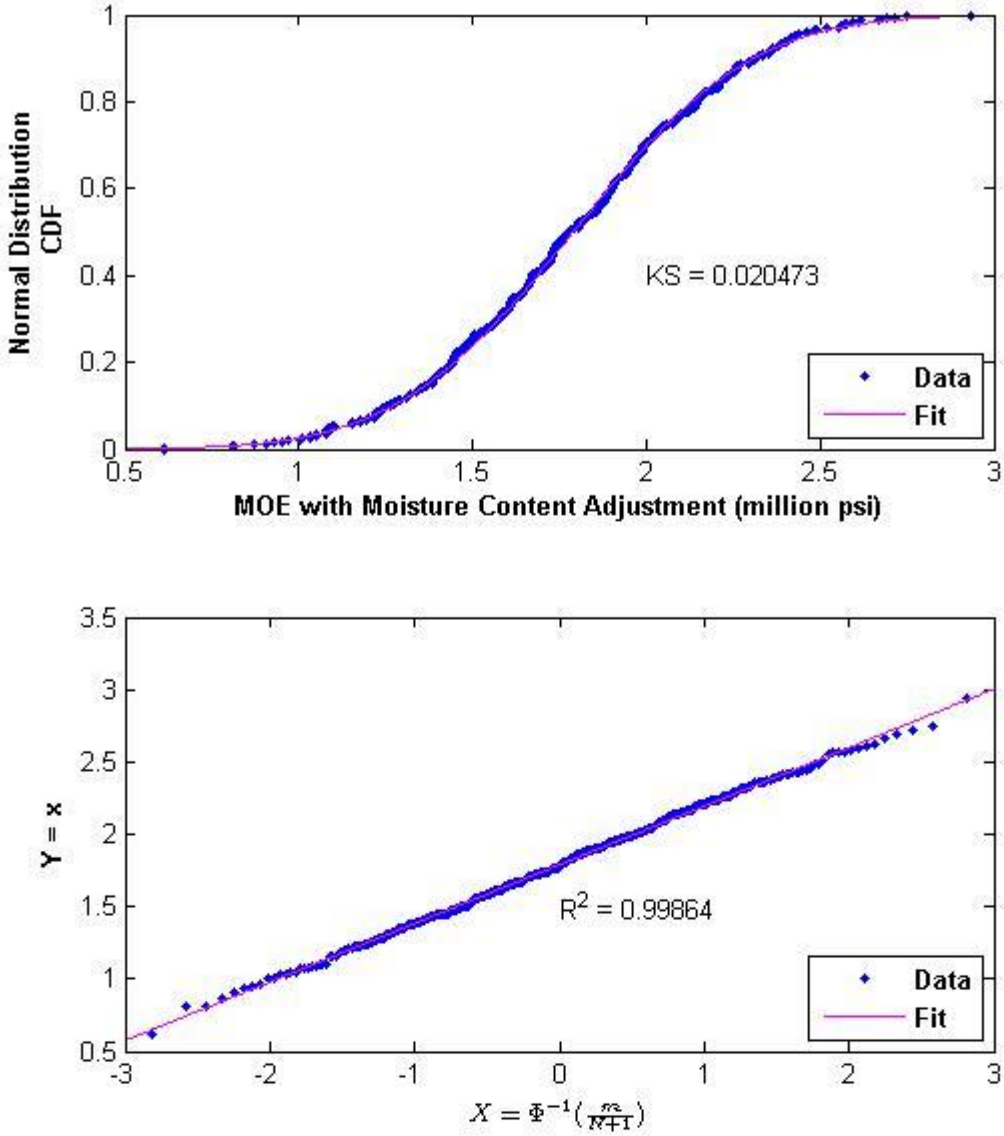
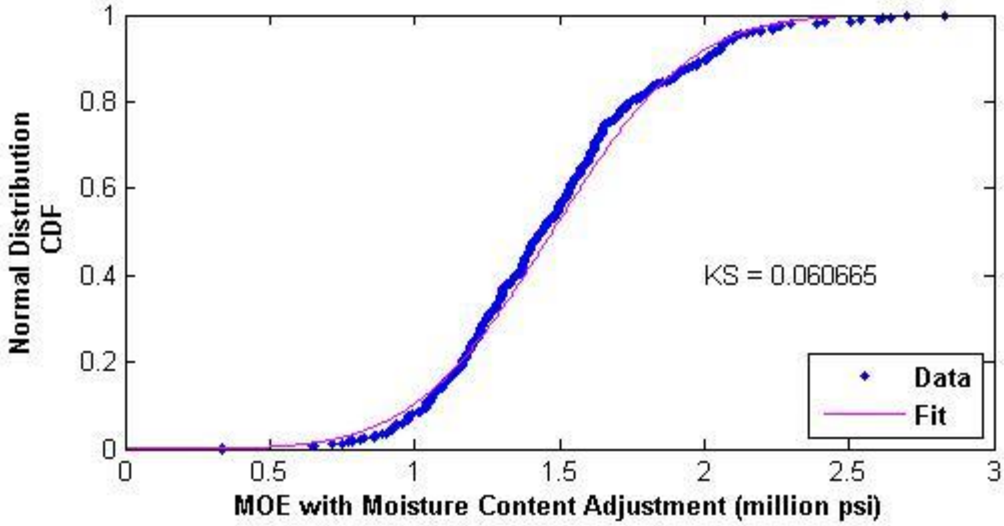


Figure A.9: K-S fitness and probability fit plot for *SS* 2x8 Normal Distribution.



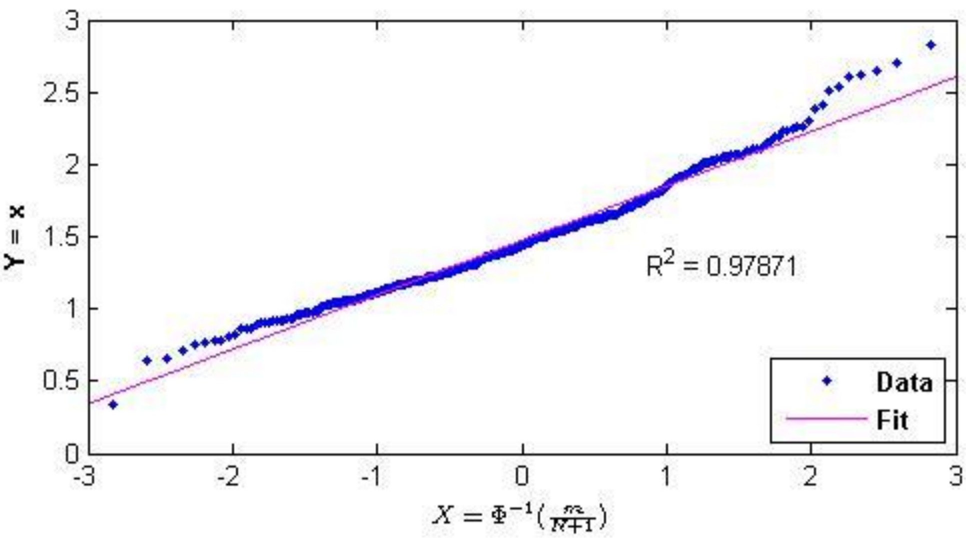


Figure A.10: K-S fitness and probability fit plot for *No.2* 2x8 Normal Distribution.

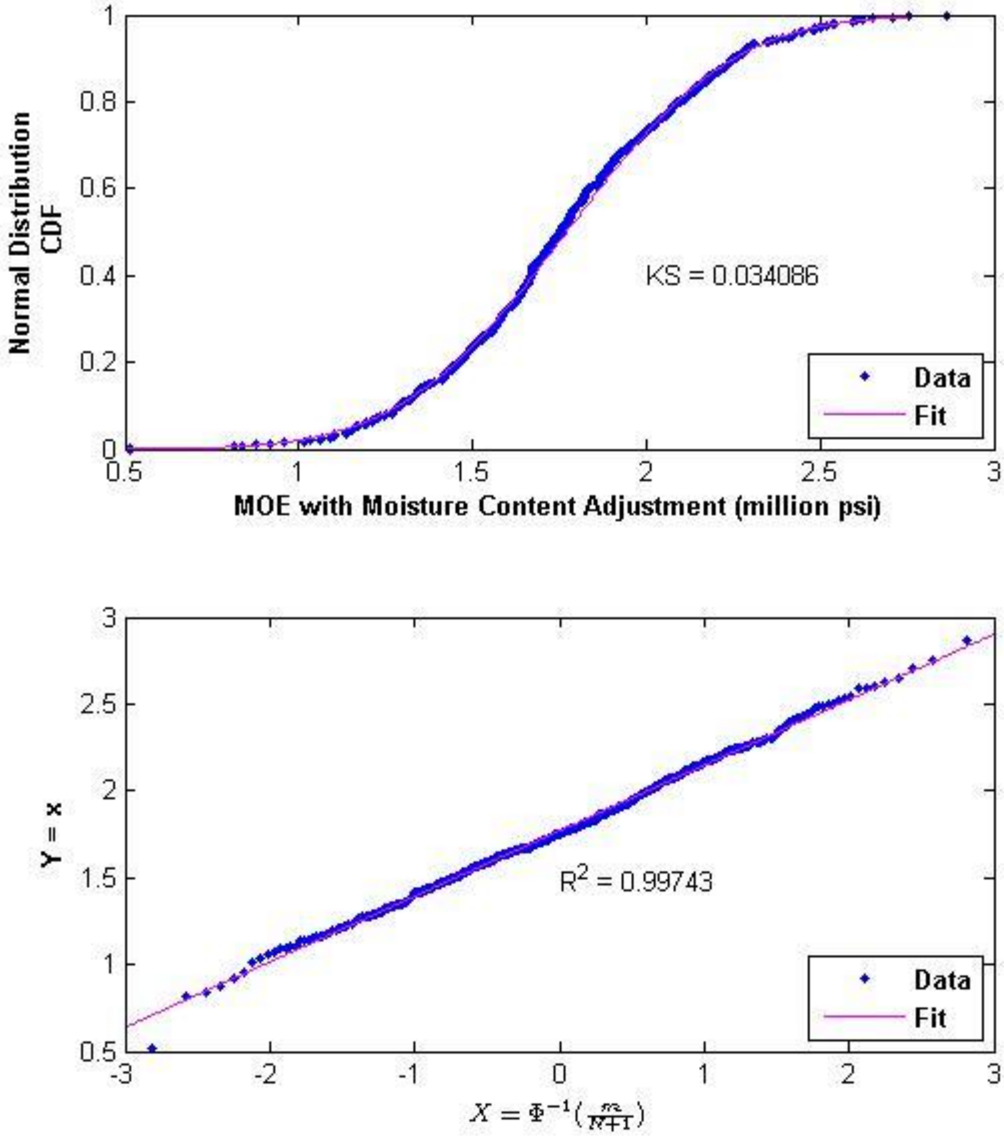


Figure A.11: K-S fitness and probability fit plot for *SS* 2x10 Normal Distribution.

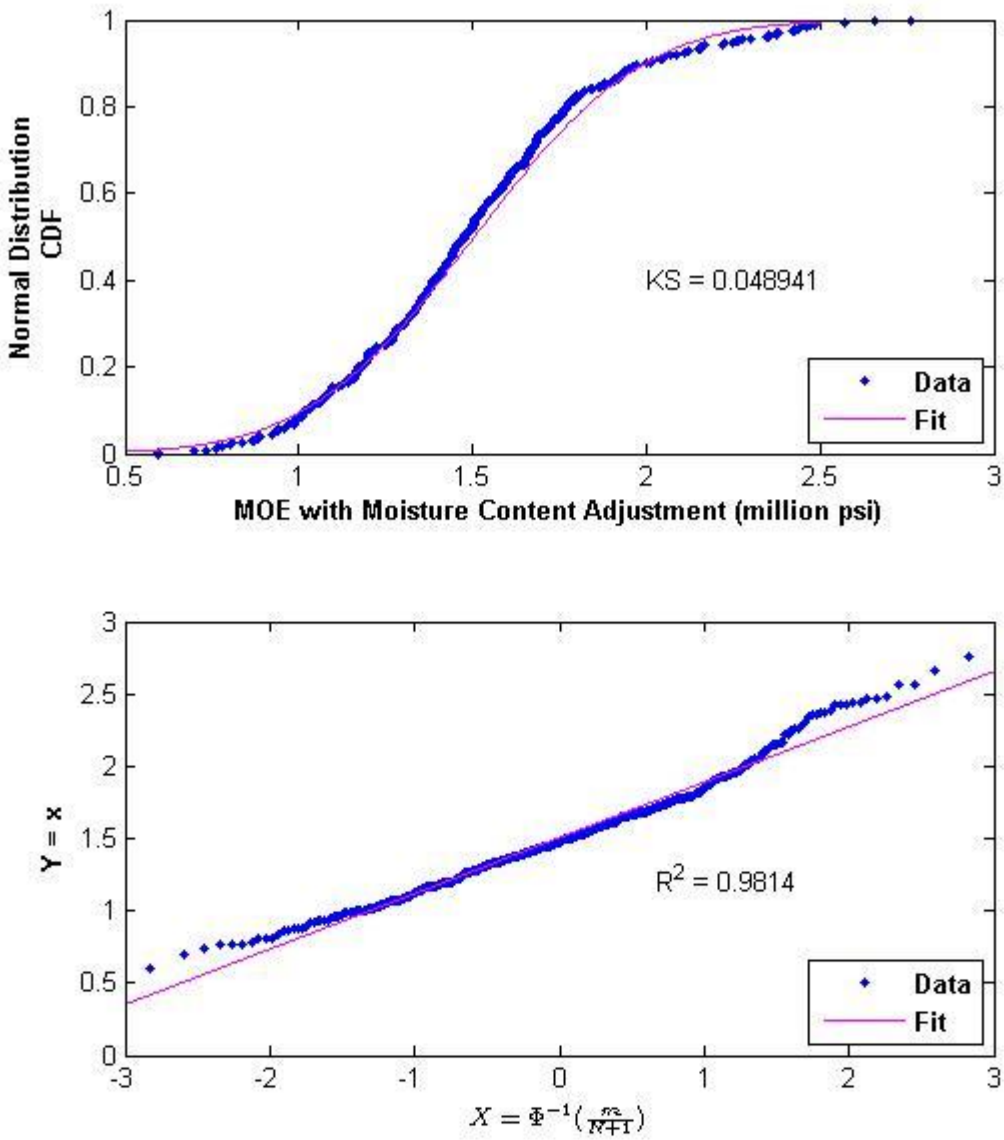


Figure A.12: K-S fitness and probability fit plot for *No.2* 2x10 Normal Distribution.

b. Lognormal Distribution

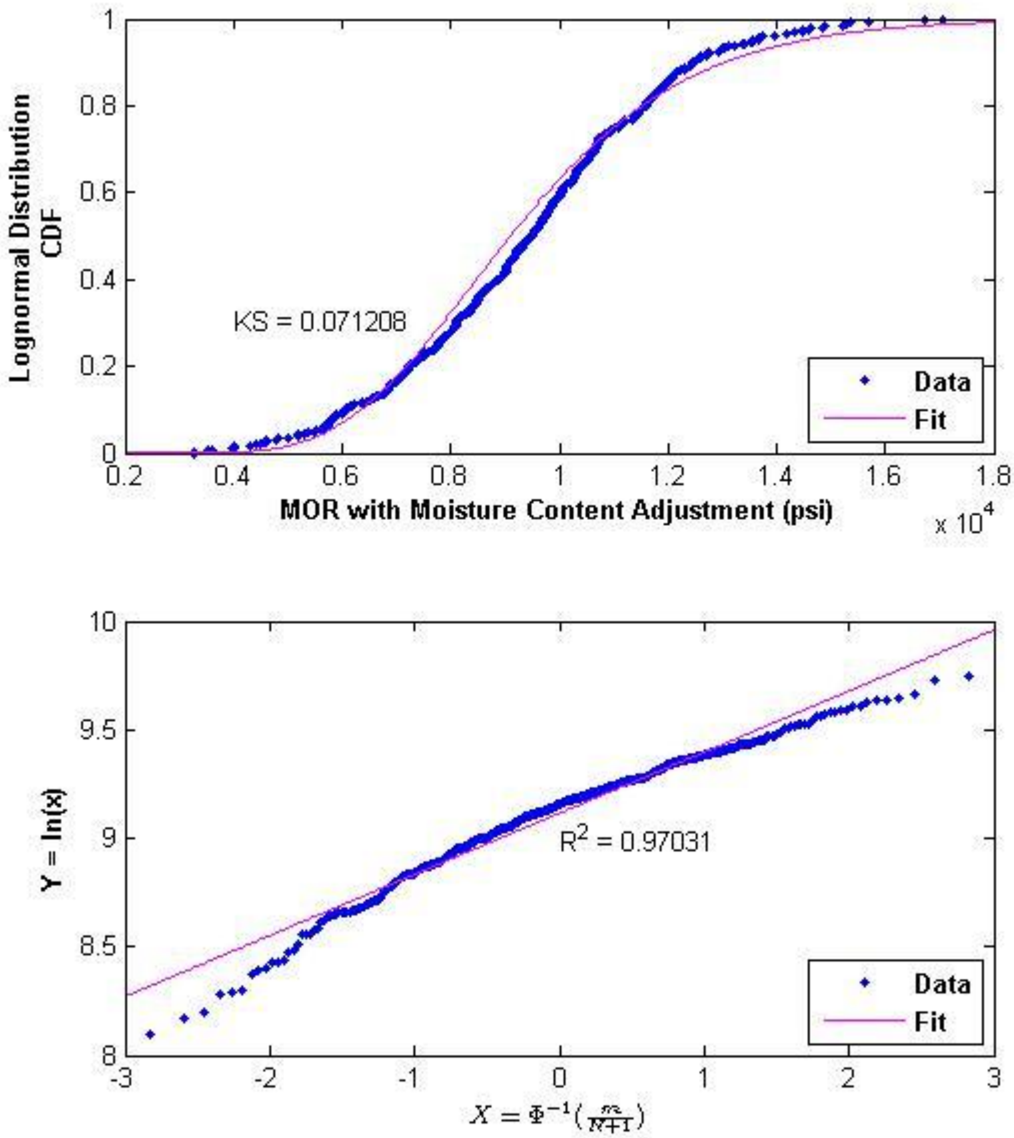
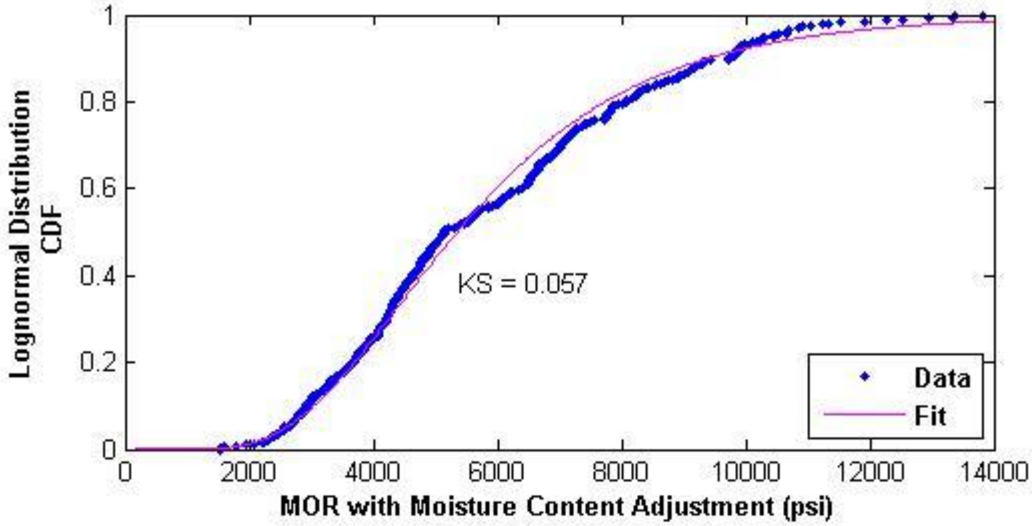


Figure A.13: K-S fitness and probability fit plot for *SS* 2x4 Lognormal Distribution.



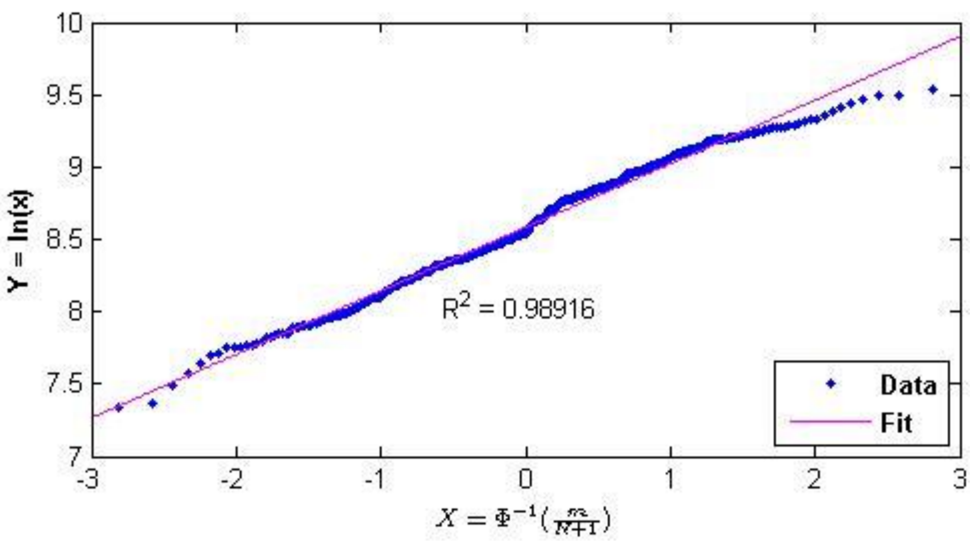


Figure A.14: K-S fitness and probability fit plot for *No.2* 2x4 Lognormal Distribution.

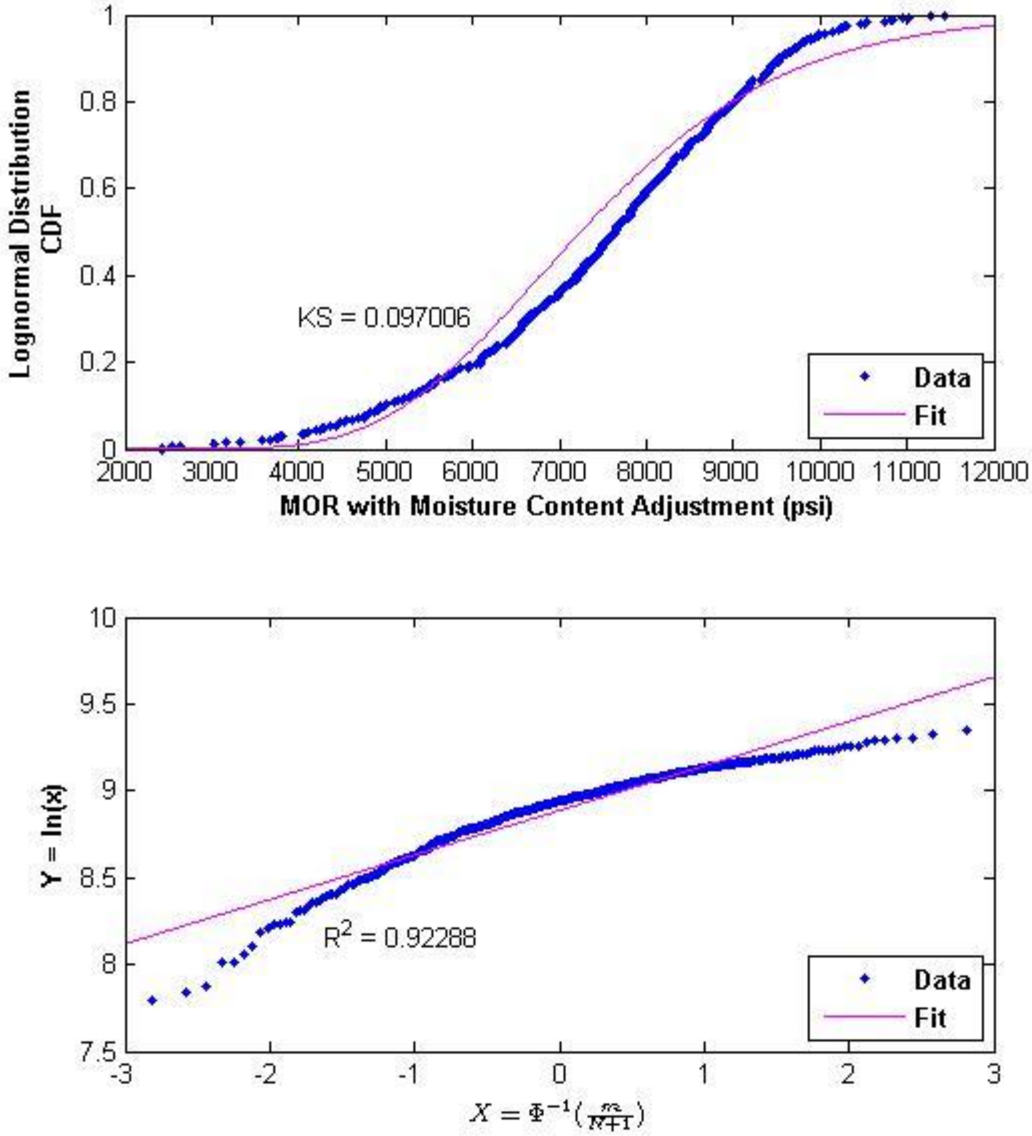


Figure A.15: K-S fitness and probability fit plot for *SS* 2x8 Lognormal Distribution.

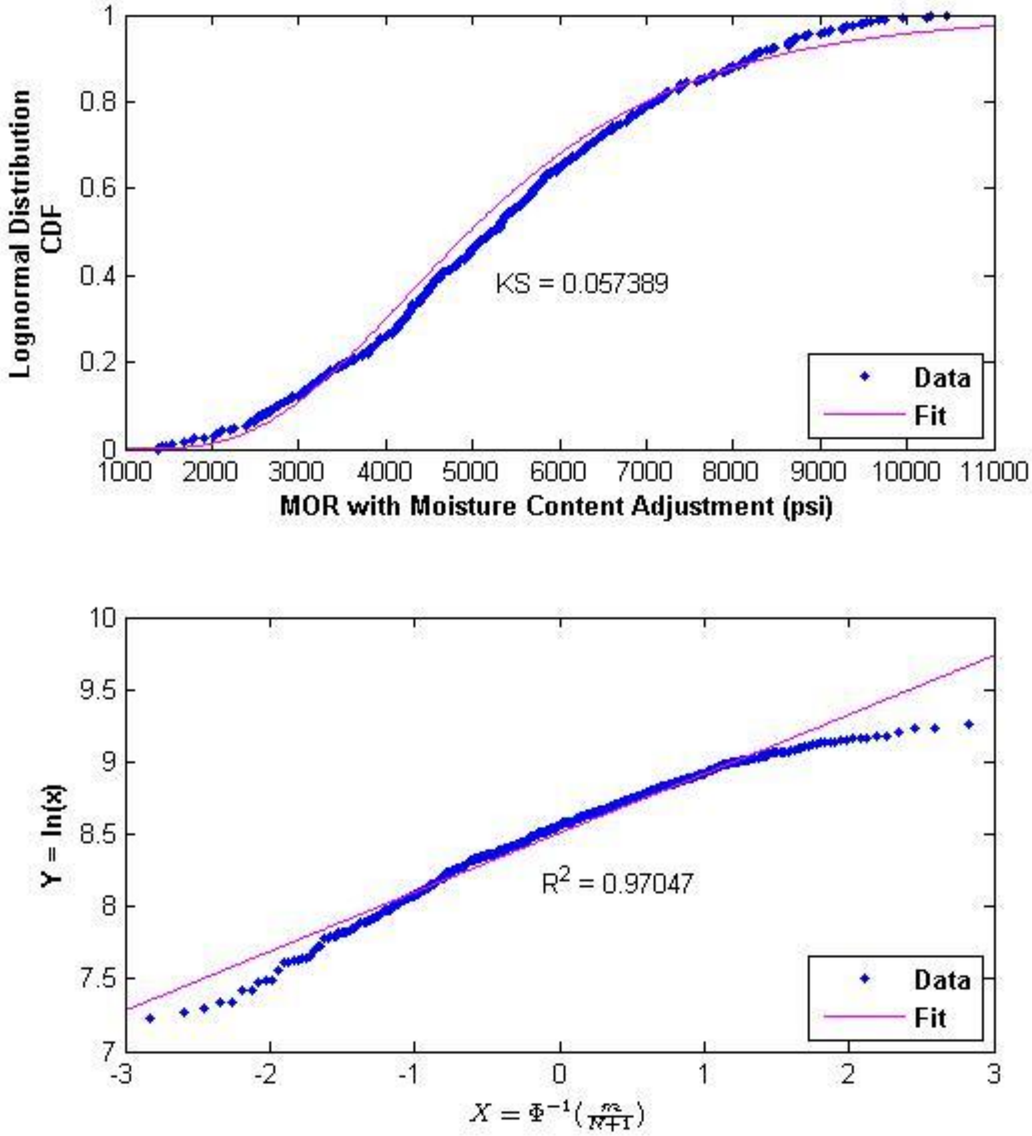
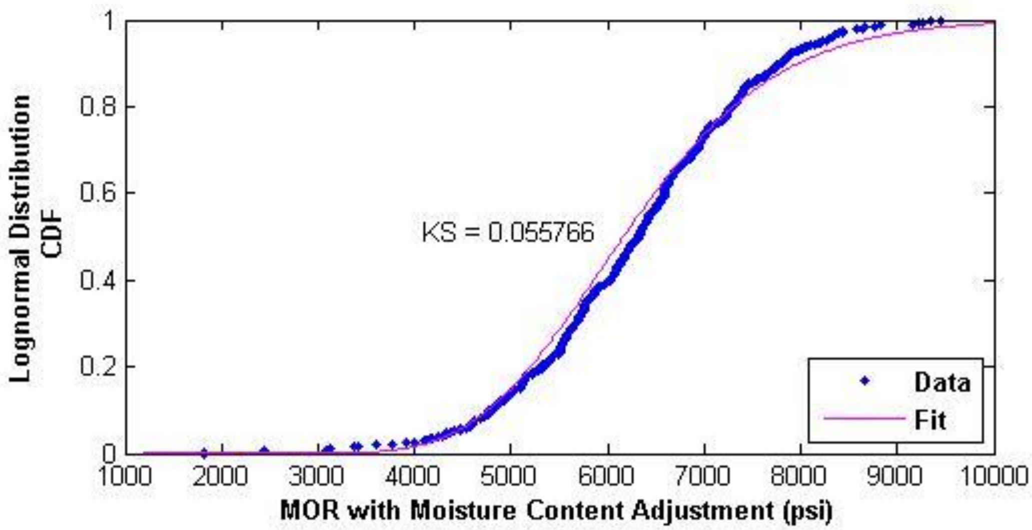


Figure A.16: K-S fitness and probability fit plot for *No.2* 2x8 Lognormal Distribution.



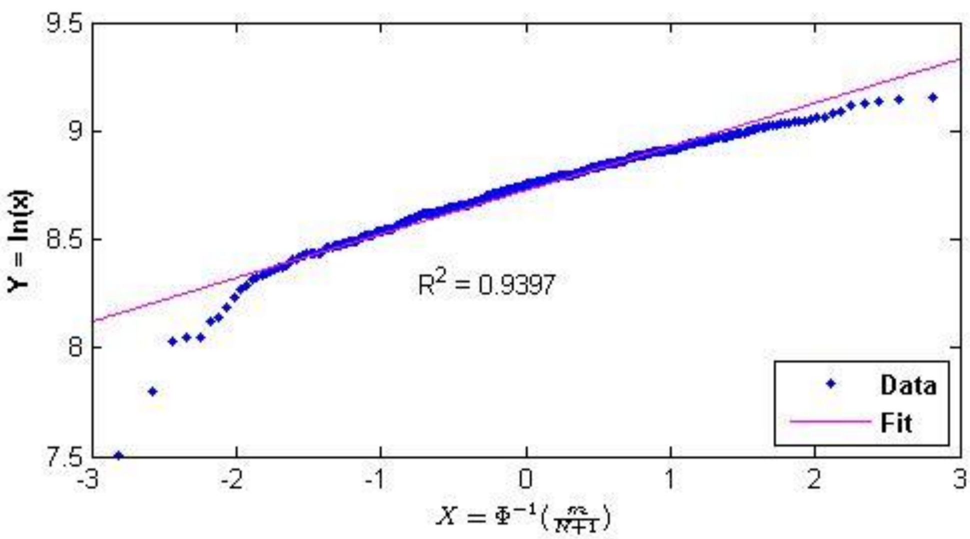


Figure A.17: K-S fitness and probability fit plot for *SS* 2x10 Lognormal Distribution.

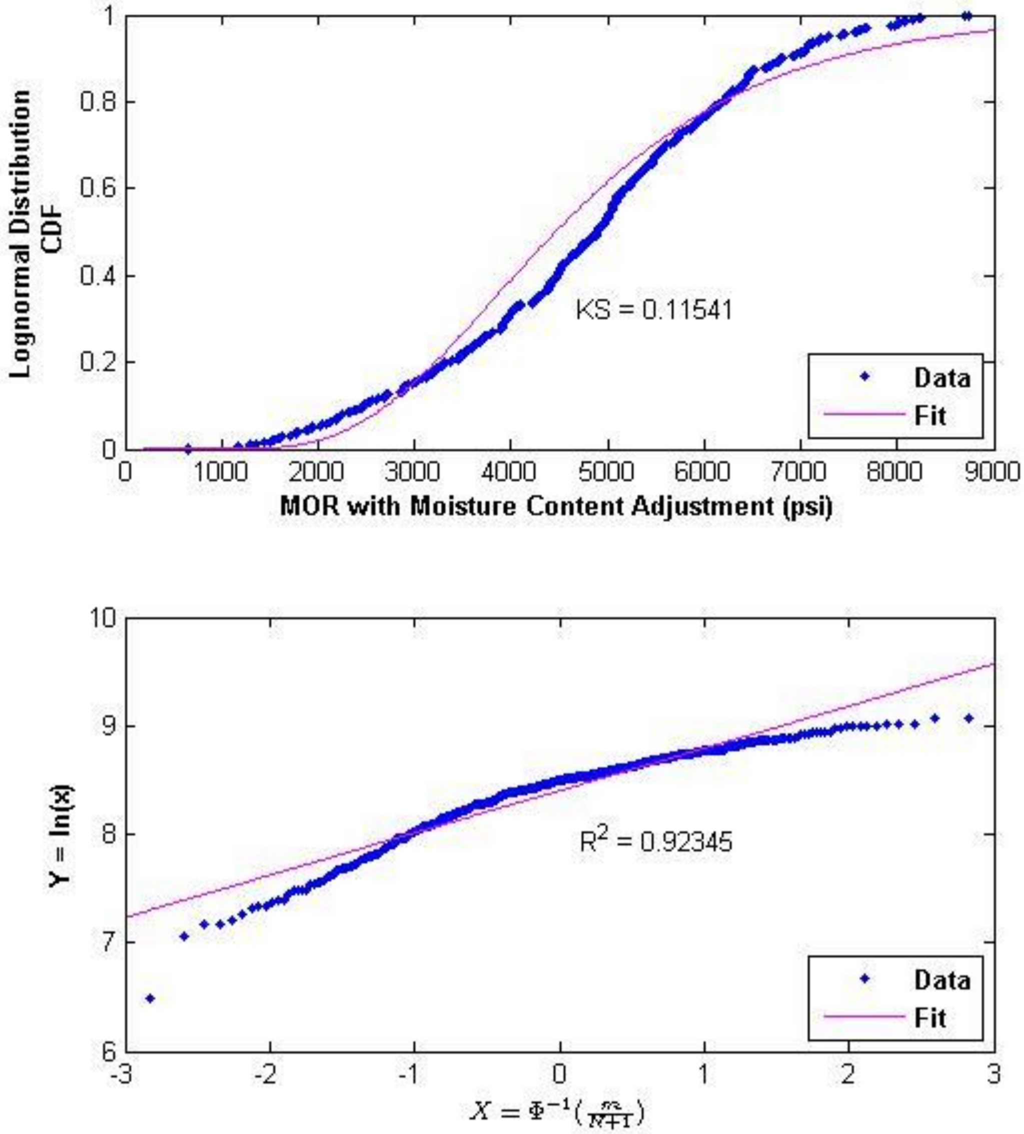
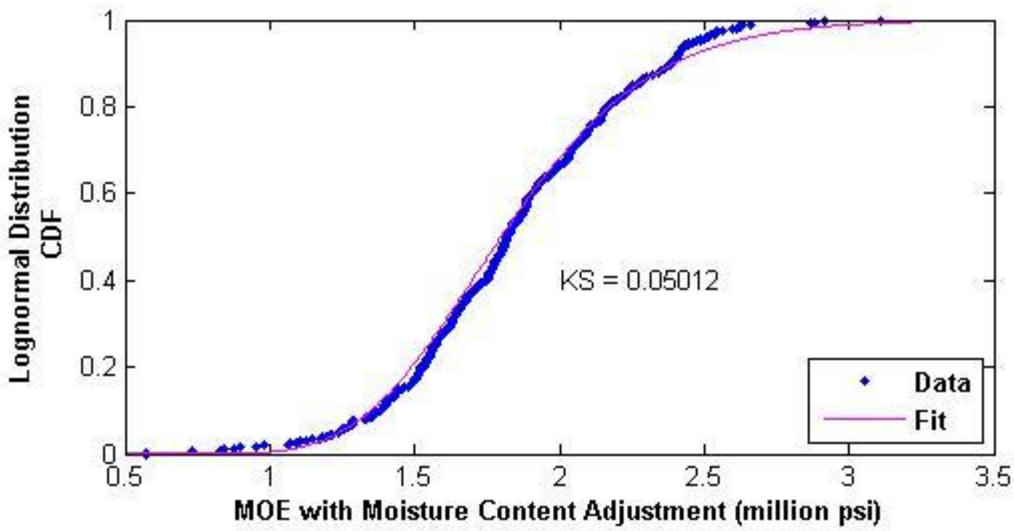


Figure A.18: K-S fitness and probability fit plot for *No.2* 2x10 Lognormal Distribution.



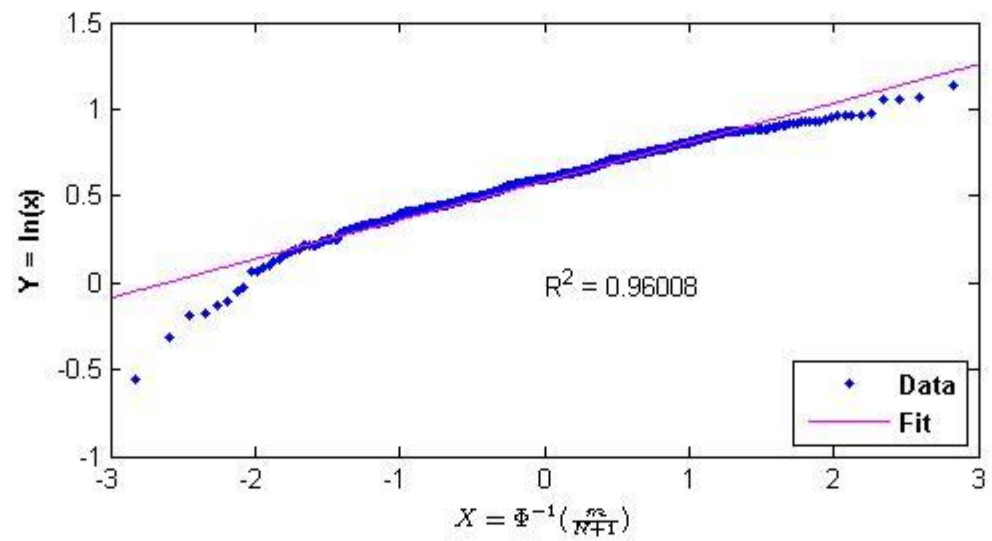


Figure A.19: K-S fitness and probability fit plot for *SS* 2x4 Lognormal Distribution.

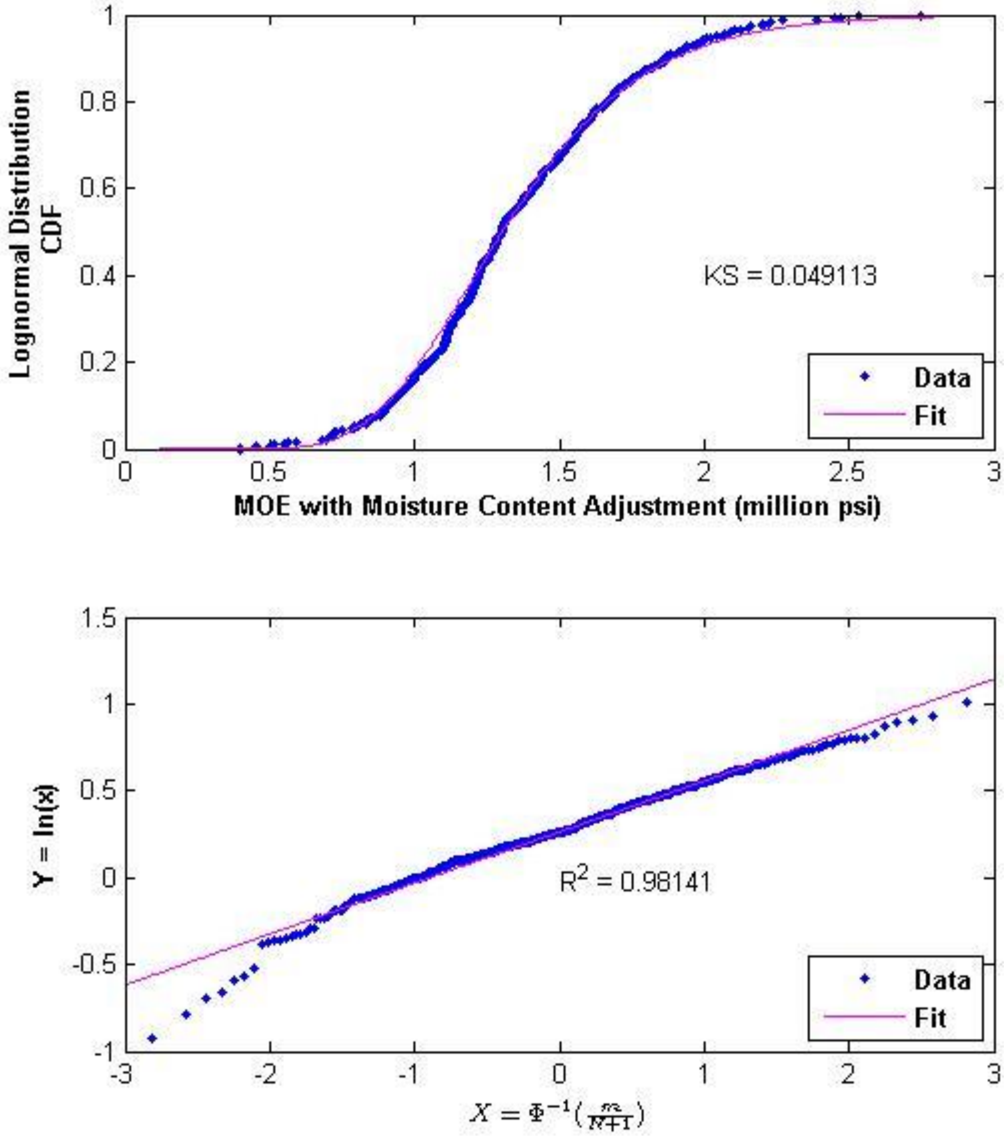


Figure A.20: K-S fitness and probability fit plot for *No.2* 2x4 Lognormal Distribution.

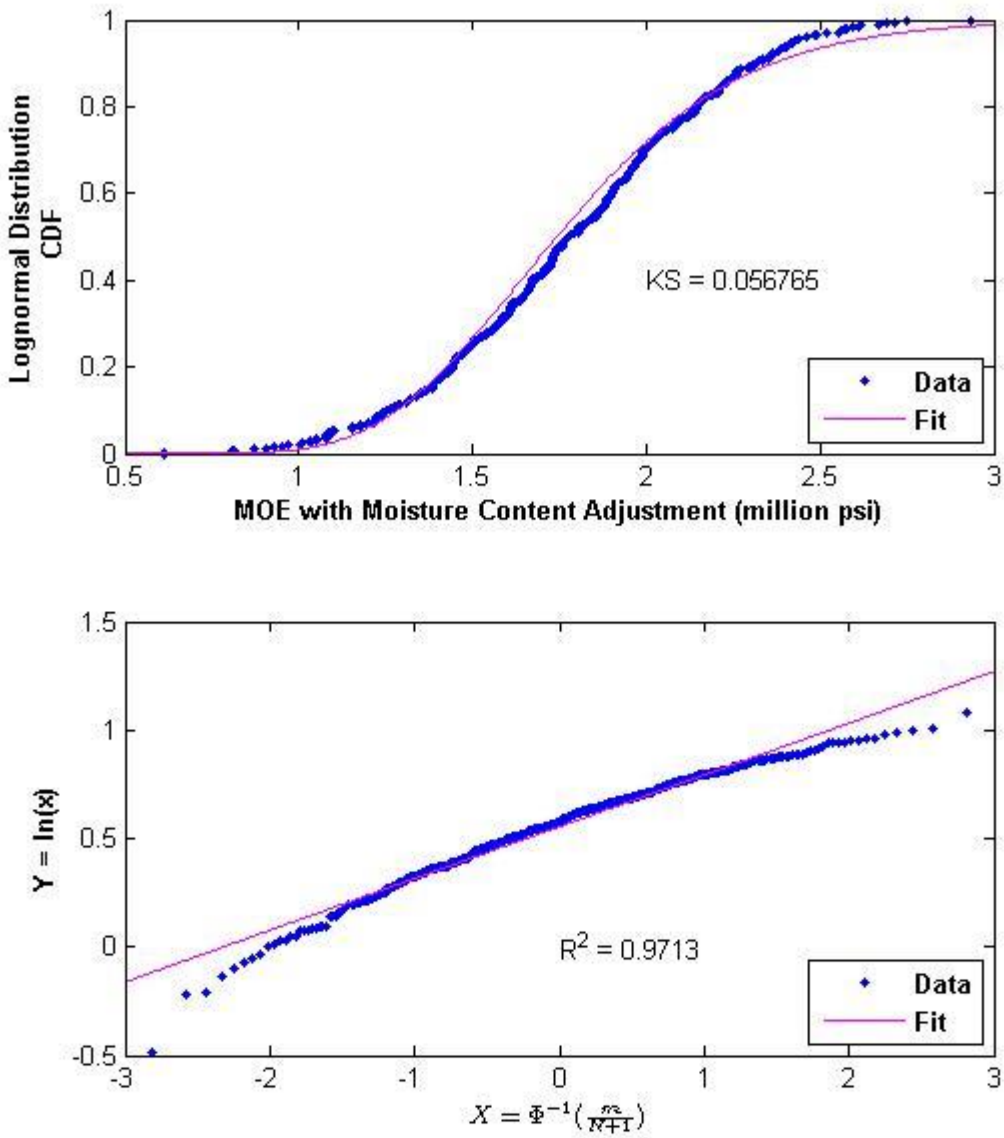


Figure A.21: K-S fitness and probability fit plot for *SS* 2x8 Lognormal Distribution.

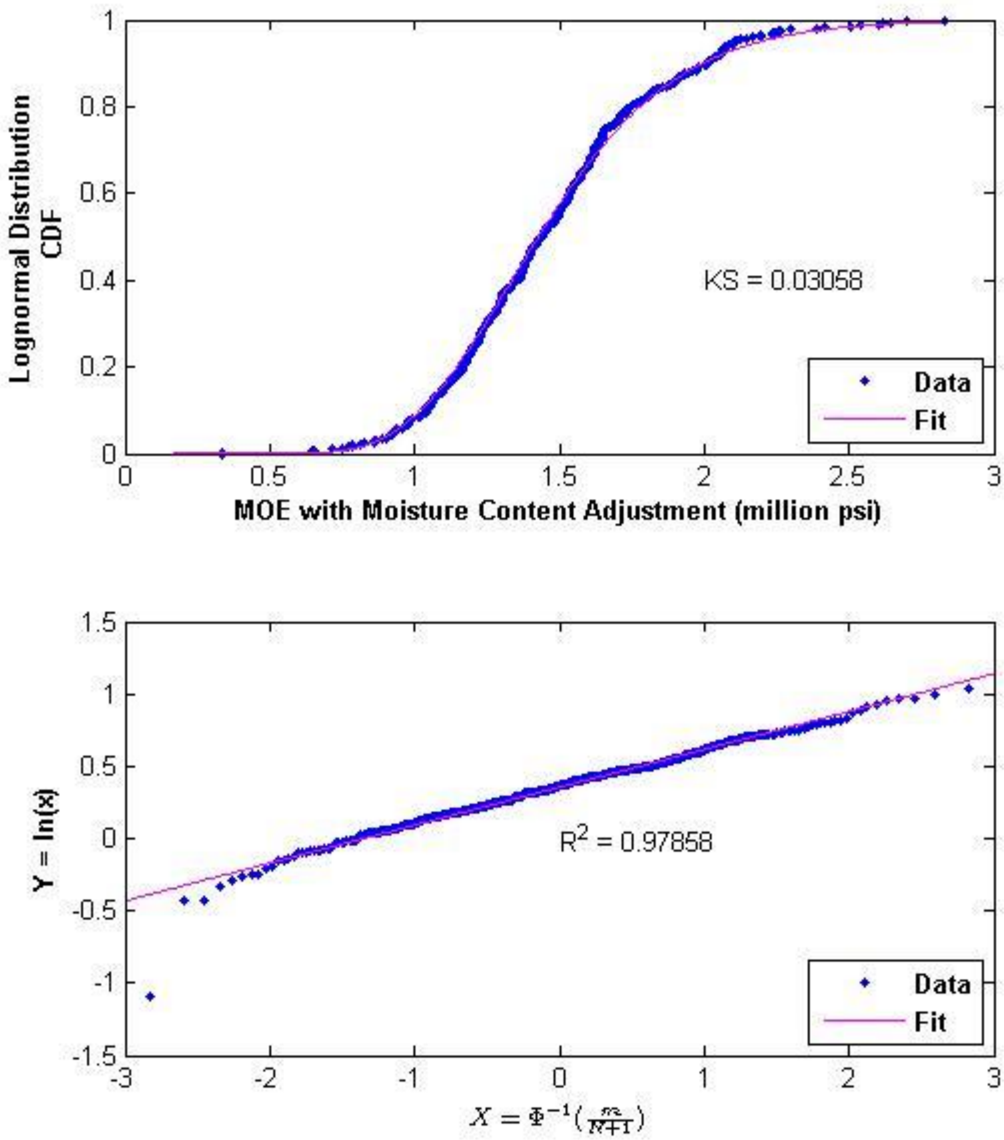


Figure A.22: K-S fitness and probability fit plot for *No.2* 2x8 Lognormal Distribution.

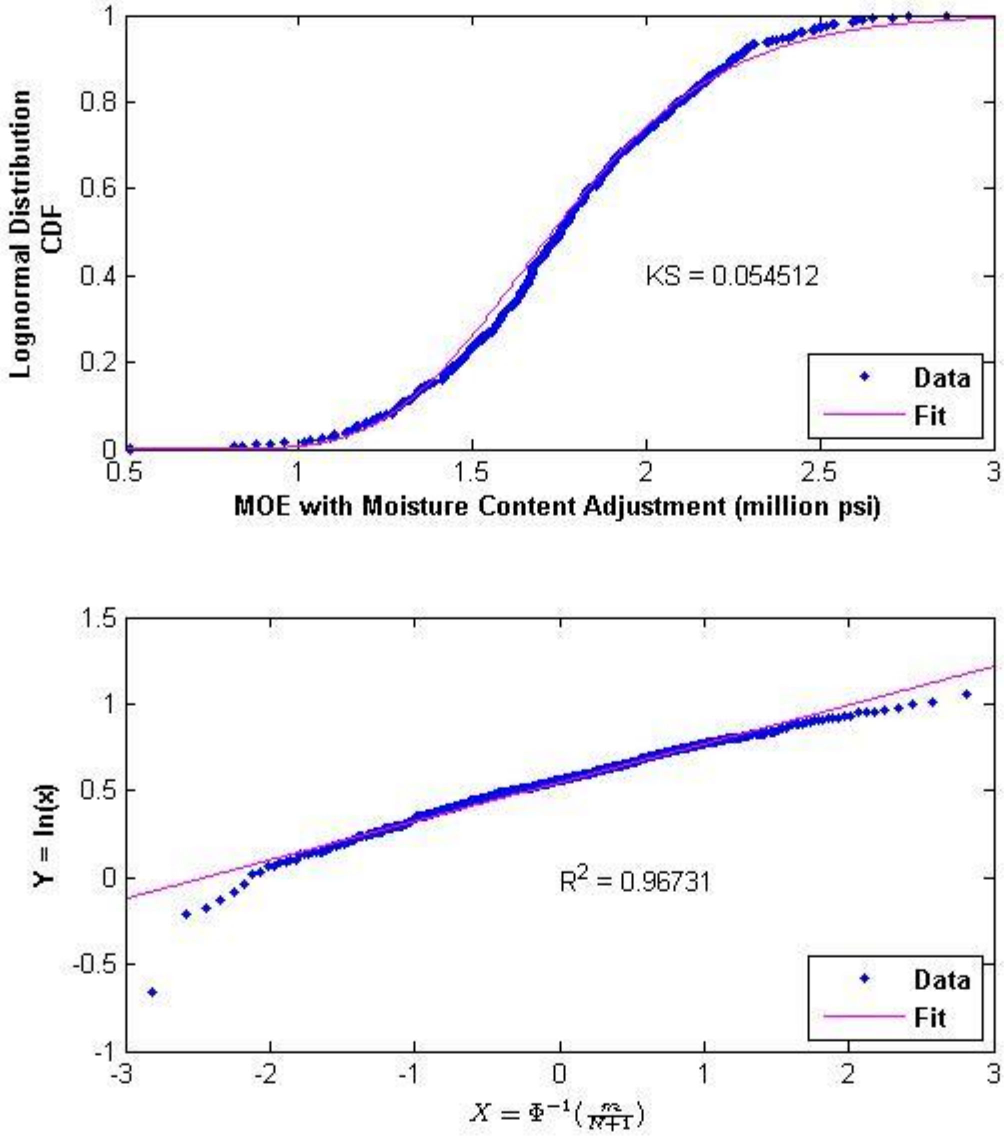
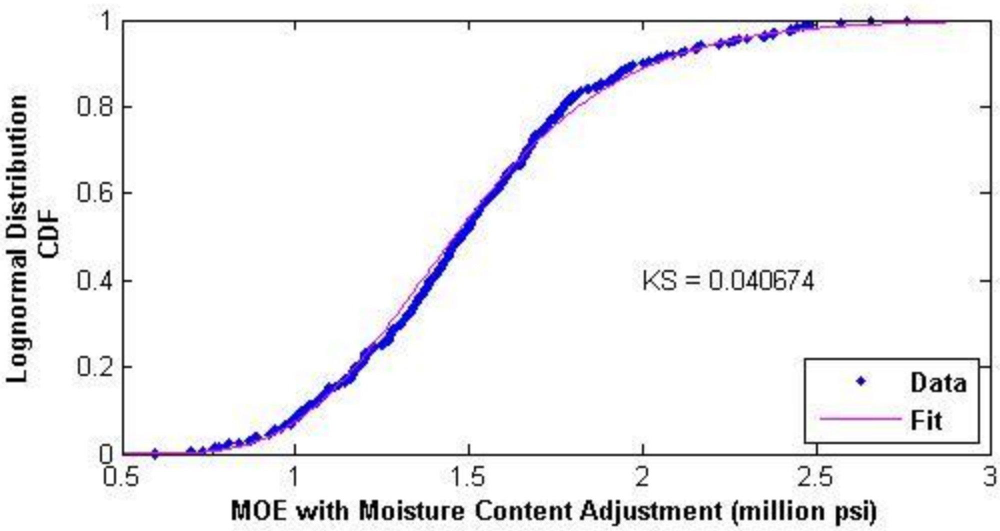


Figure A.23: K-S fitness and probability fit plot for *SS* 2x10 Lognormal Distribution.



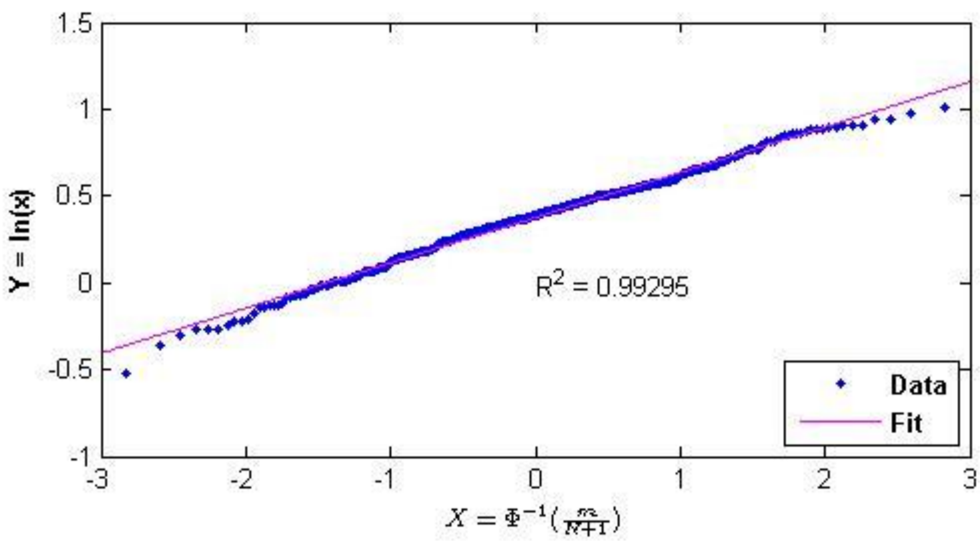


Figure A.24: K-S fitness and probability fit plot for *No.2* 2x10 Lognormal Distribution.

c. Gumbel Smallest Distribution

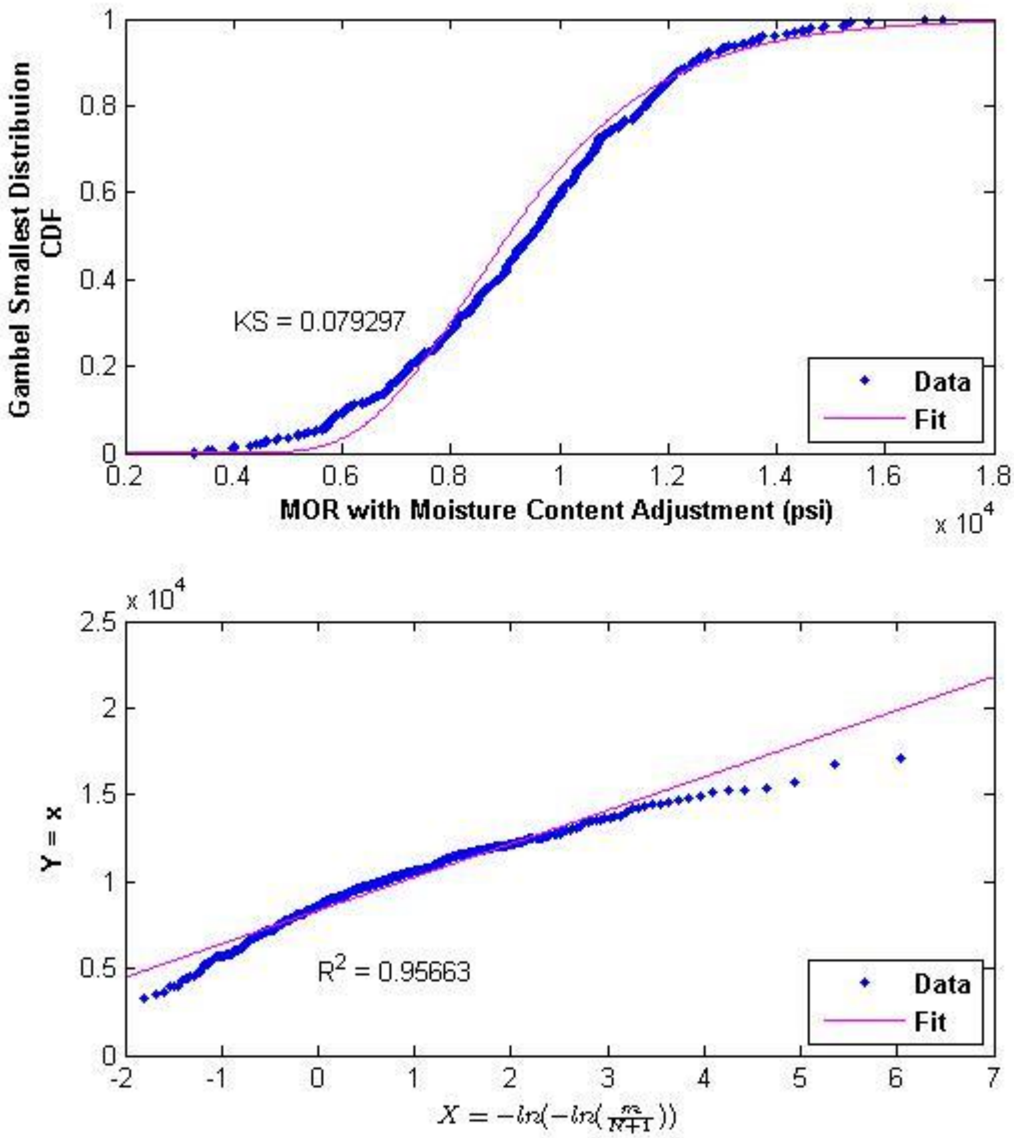
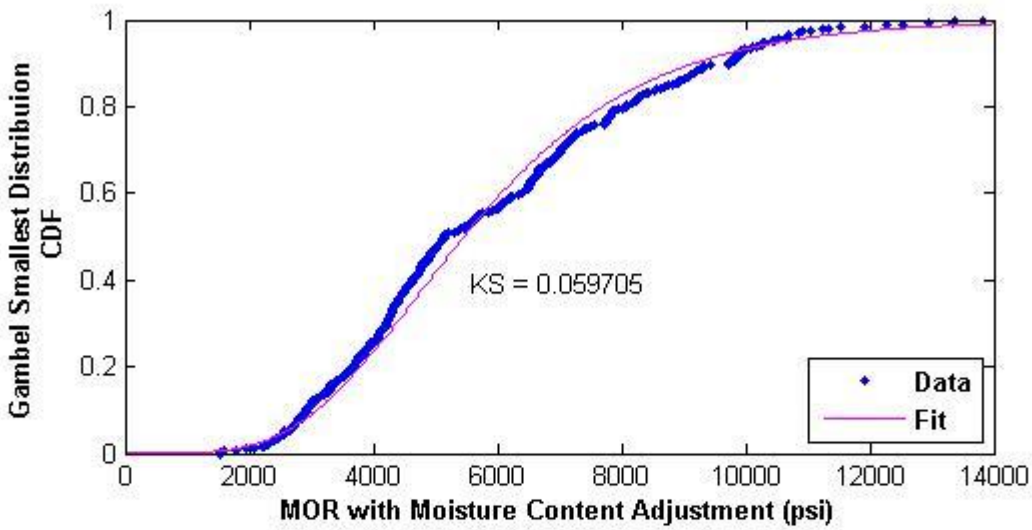


Figure A.25: K-S fitness and probability fit plot for *SS* 2x4 Gumbel Smallest Distribution.



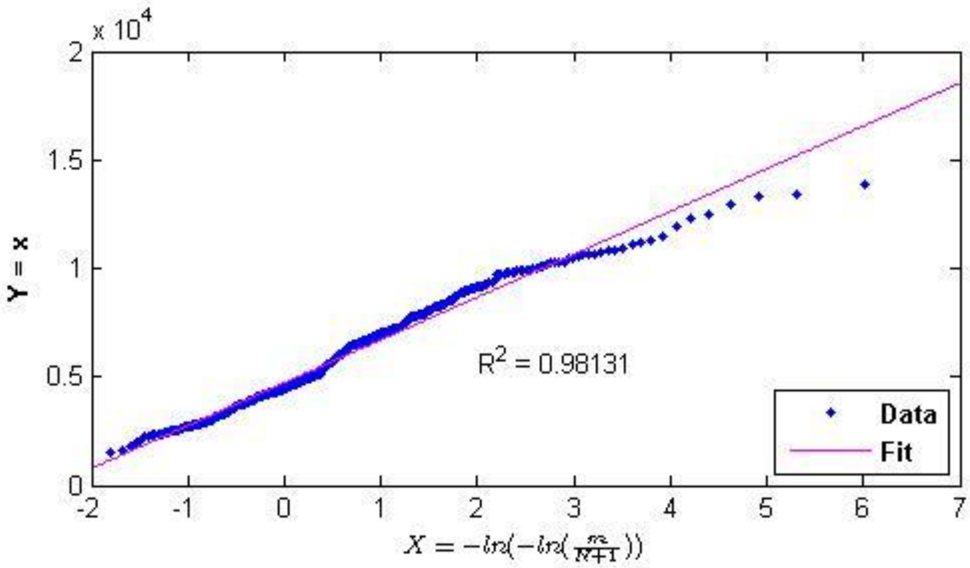
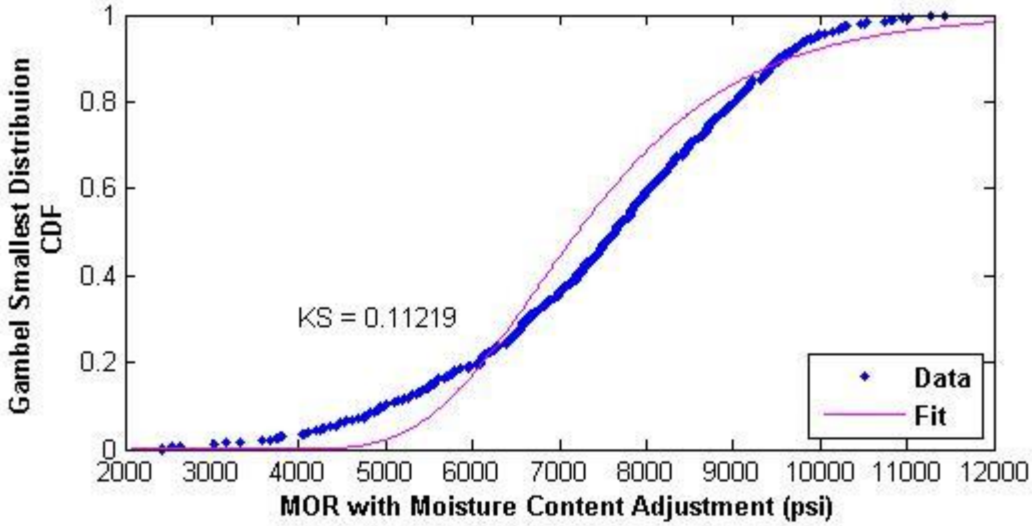


Figure A.26: K-S fitness and probability fit plot for *No.2* 2x4 Gumbel Smallest Distribution.



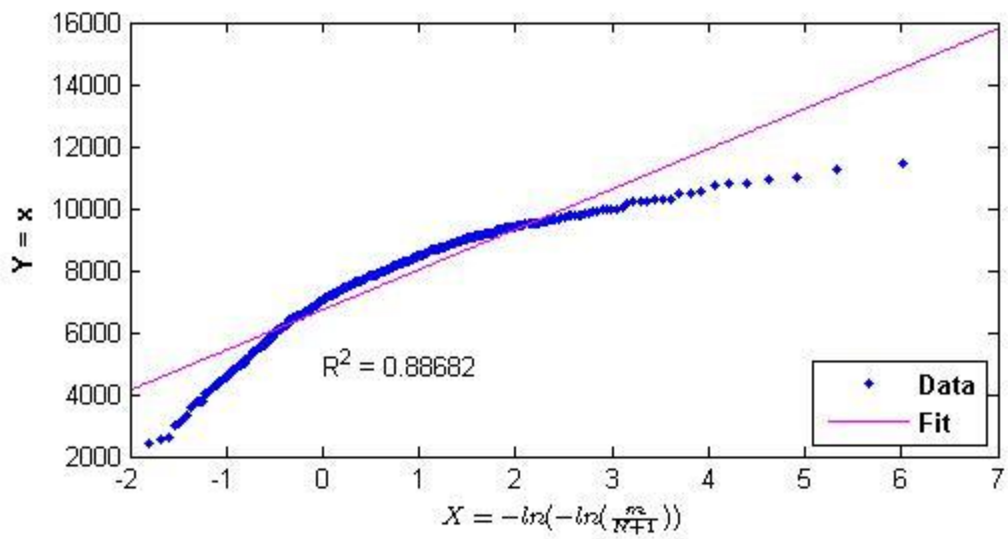


Figure A.27: K-S fitness and probability fit plot for *SS* 2x8 Gumbel Smallest Distribution.

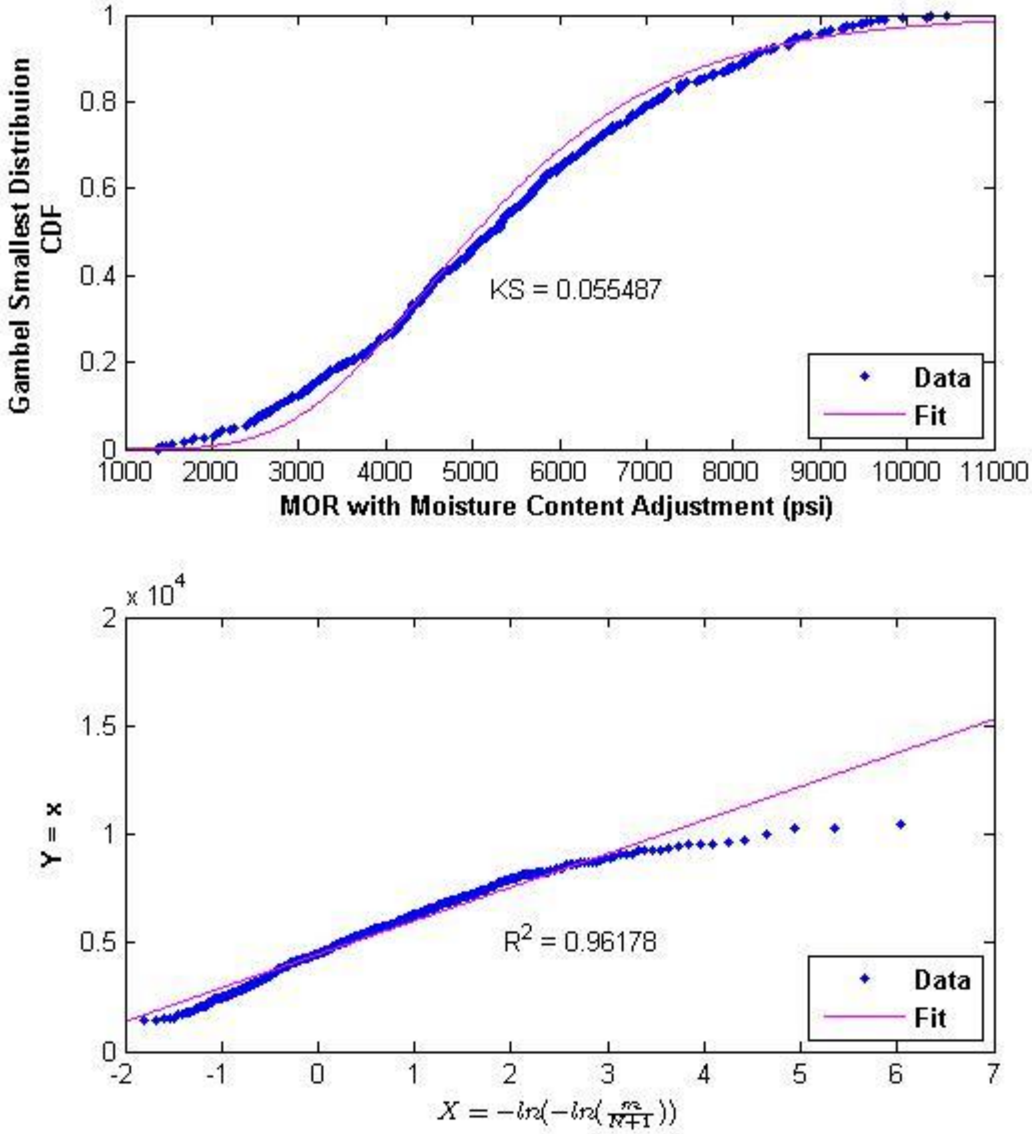


Figure A.28: K-S fitness and probability fit plot for *No.2* 2x8 Gumbel Smallest Distribution.

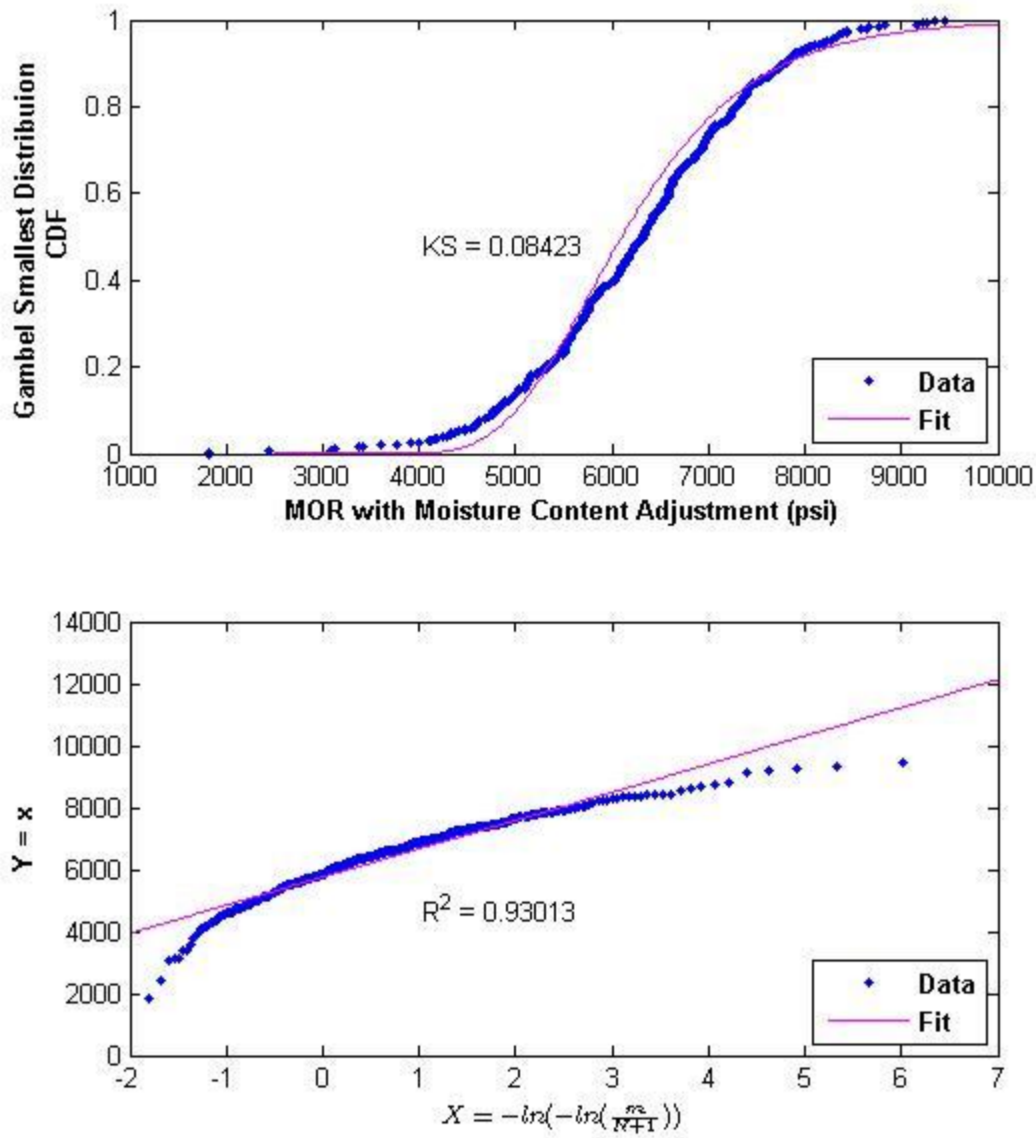


Figure A.29: K-S fitness and probability fit plot for *SS* 2x10 Gumbel Smallest Distribution.

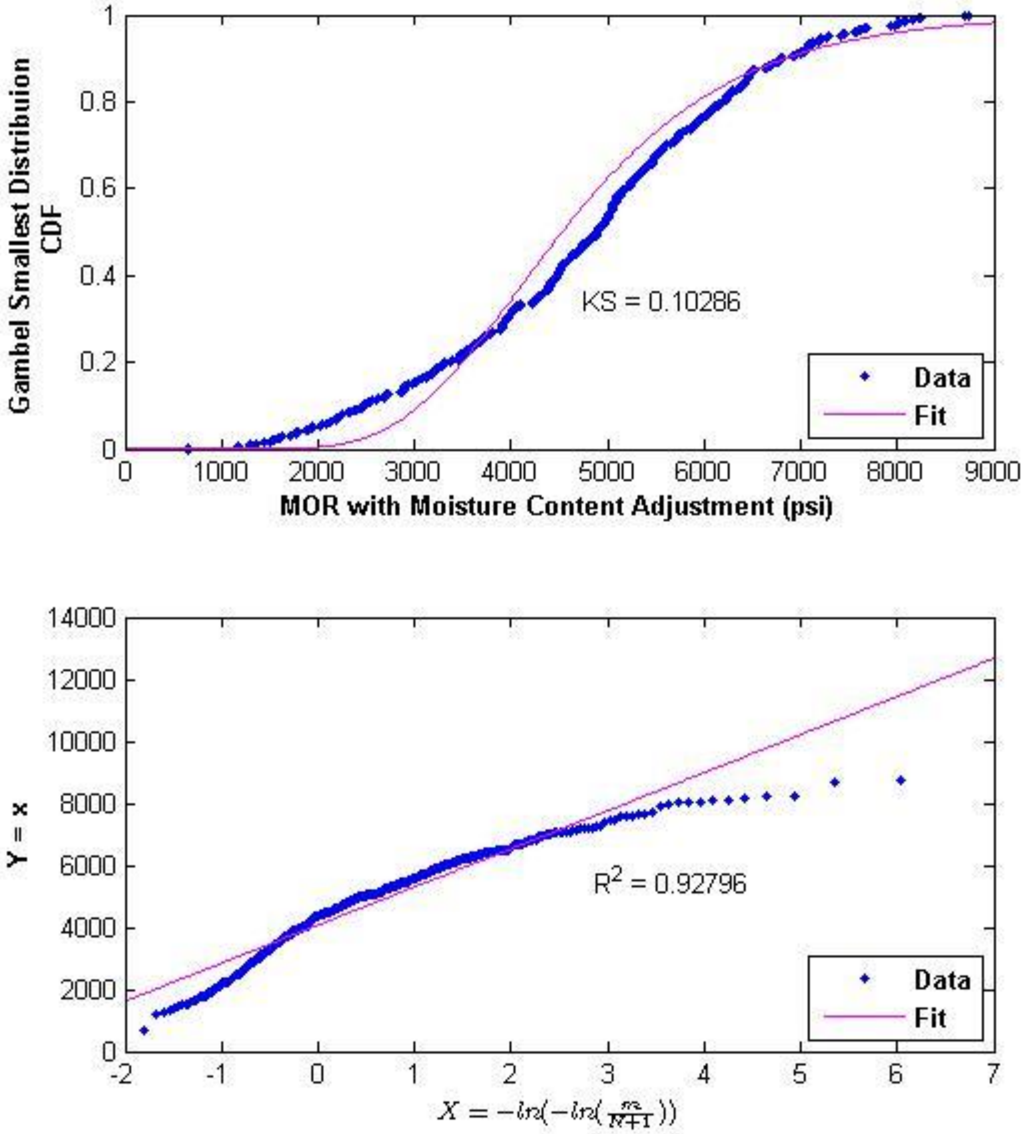


Figure A.30: K-S fitness and probability fit plot for *No.2* 2x10 Gumbel Smallest Distribution.

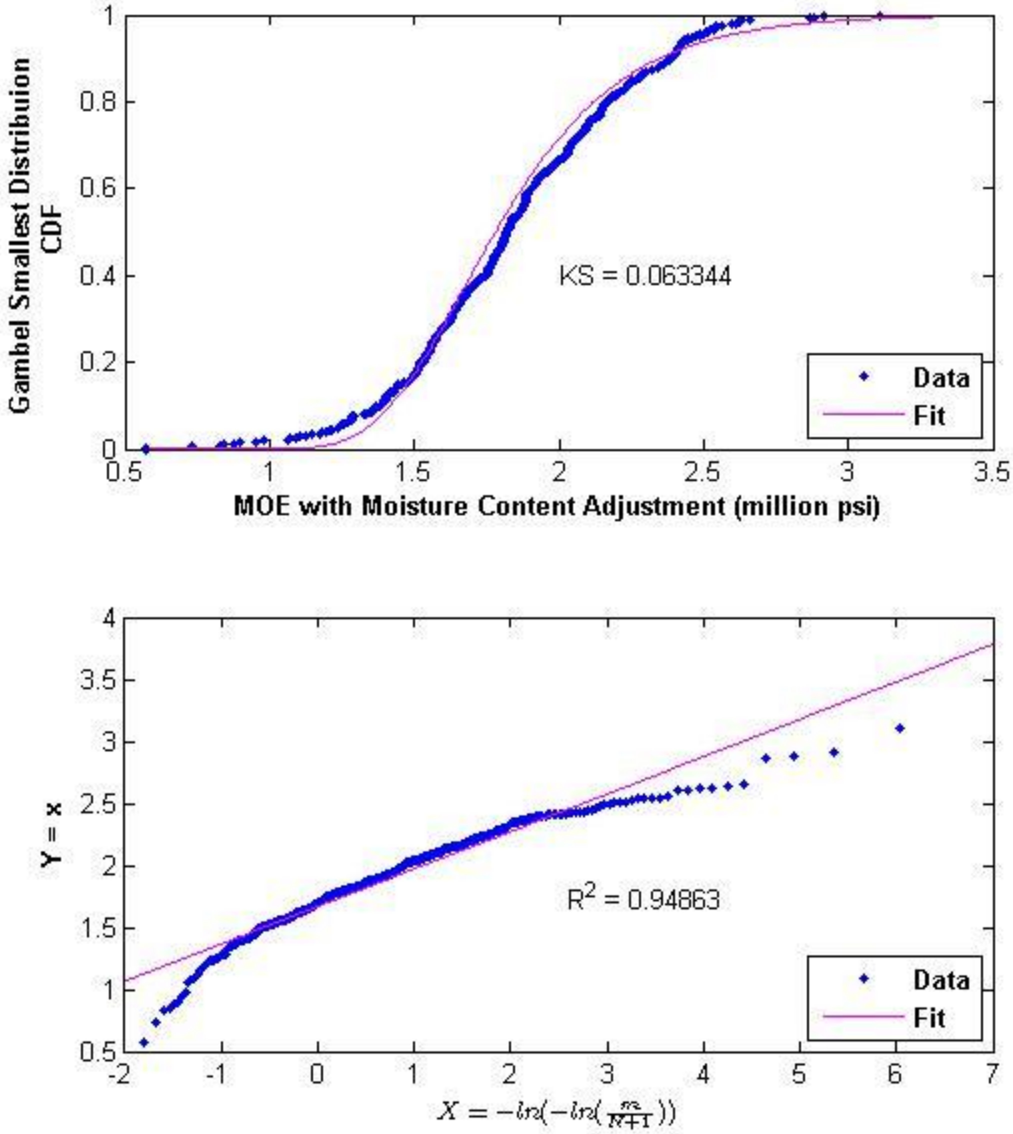


Figure A.31: K-S fitness and probability fit plot for *SS* 2x4 Gumbel Smallest Distribution.

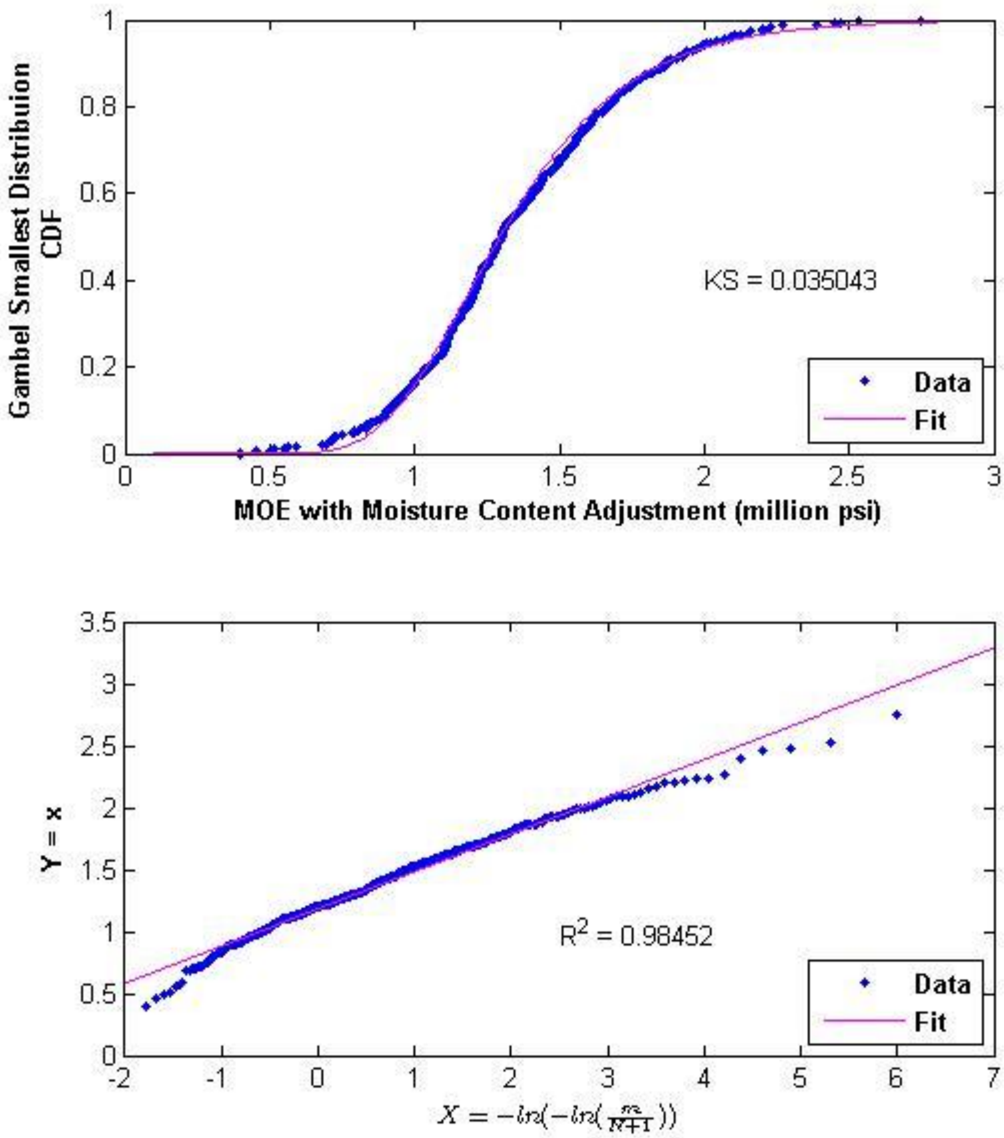
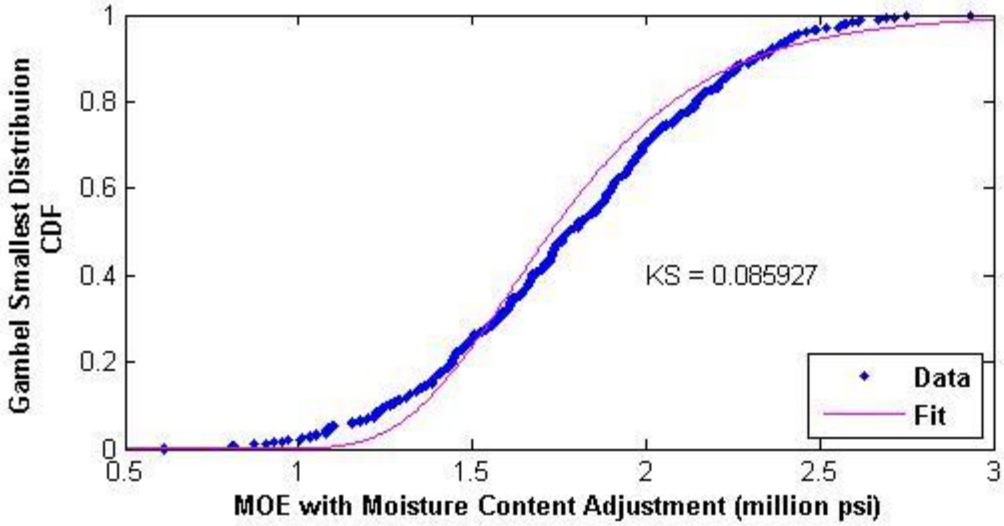


Figure A.32: K-S fitness and probability fit plot for *No.2* 2x4 Gumbel Smallest Distribution.



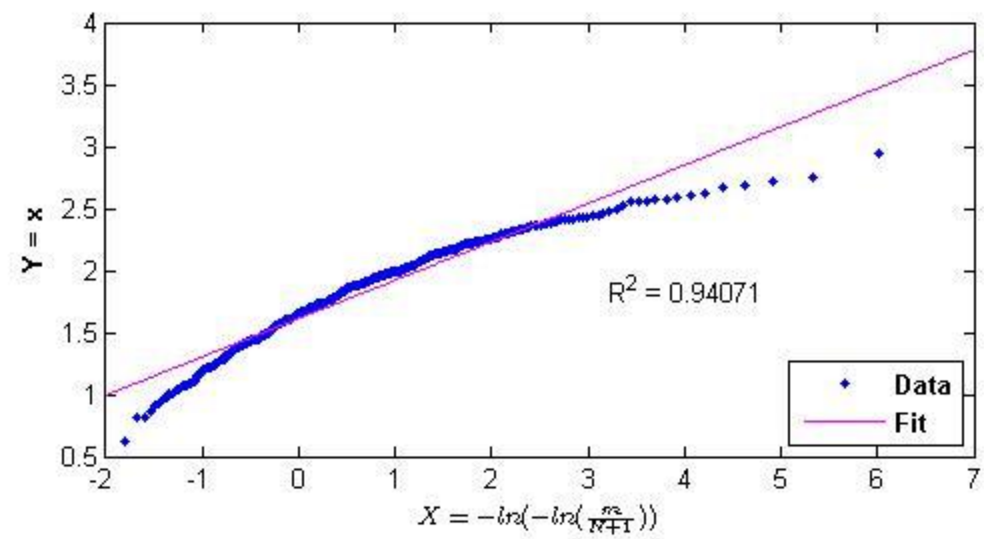
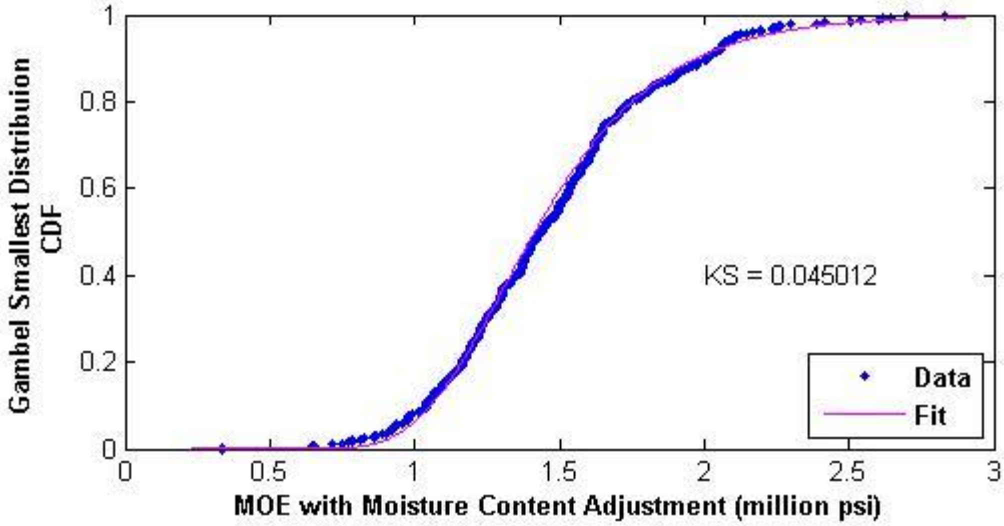


Figure A.33: K-S fitness and probability fit plot for *SS* 2x8 Gumbel Smallest Distribution.



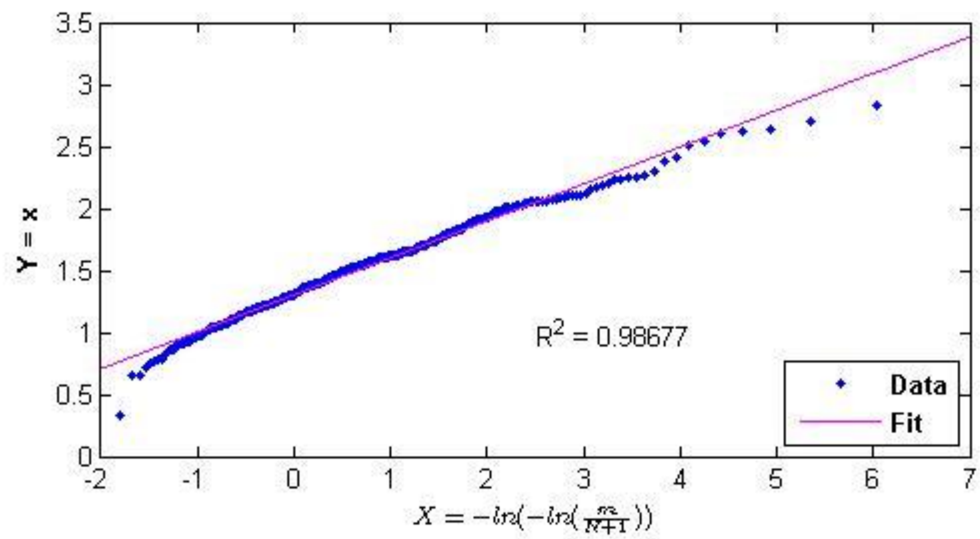


Figure A.34: K-S fitness and probability fit plot for *No.2* 2x8 Gumbel Smallest Distribution.

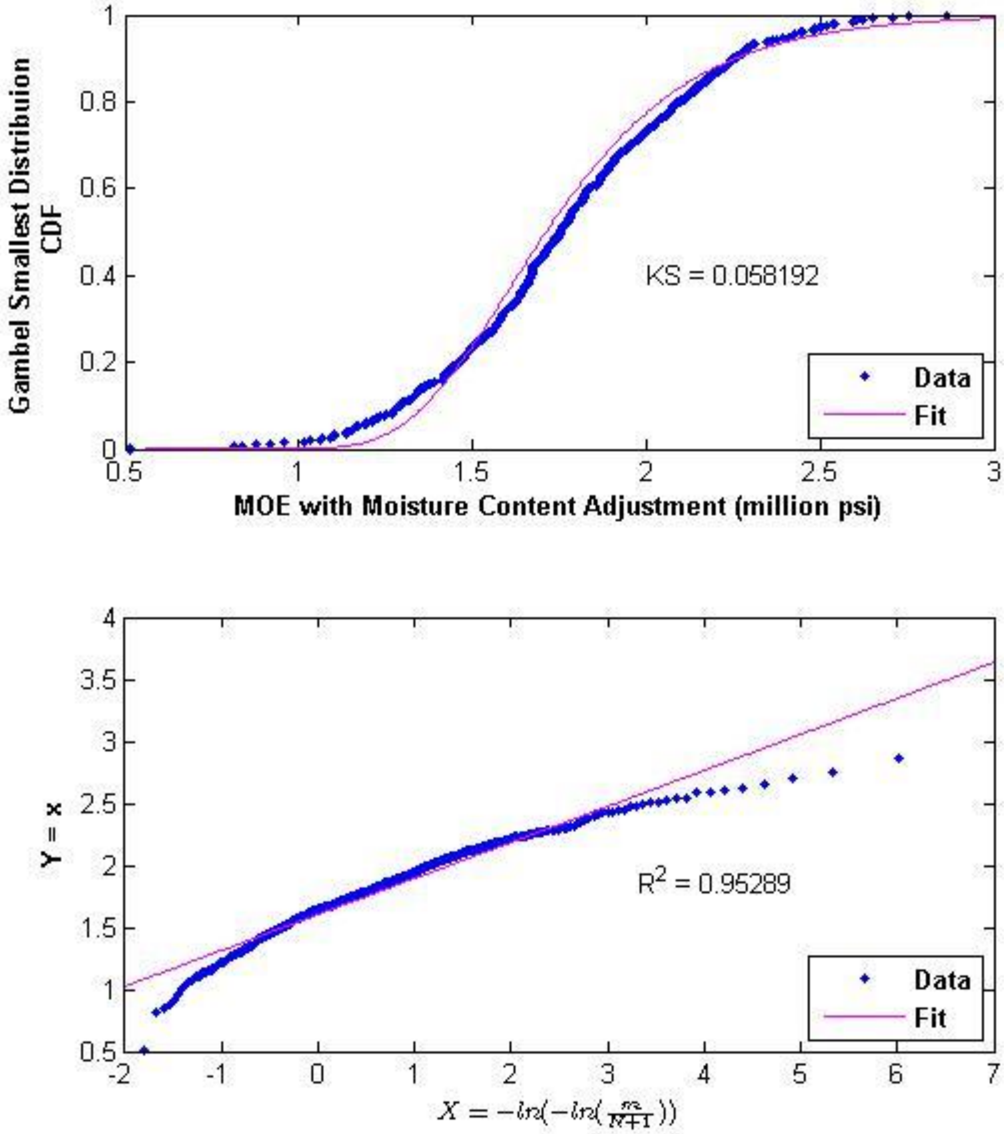


Figure A.35: K-S fitness and probability fit plot for *SS* 2x10 Gumbel Smallest Distribution.

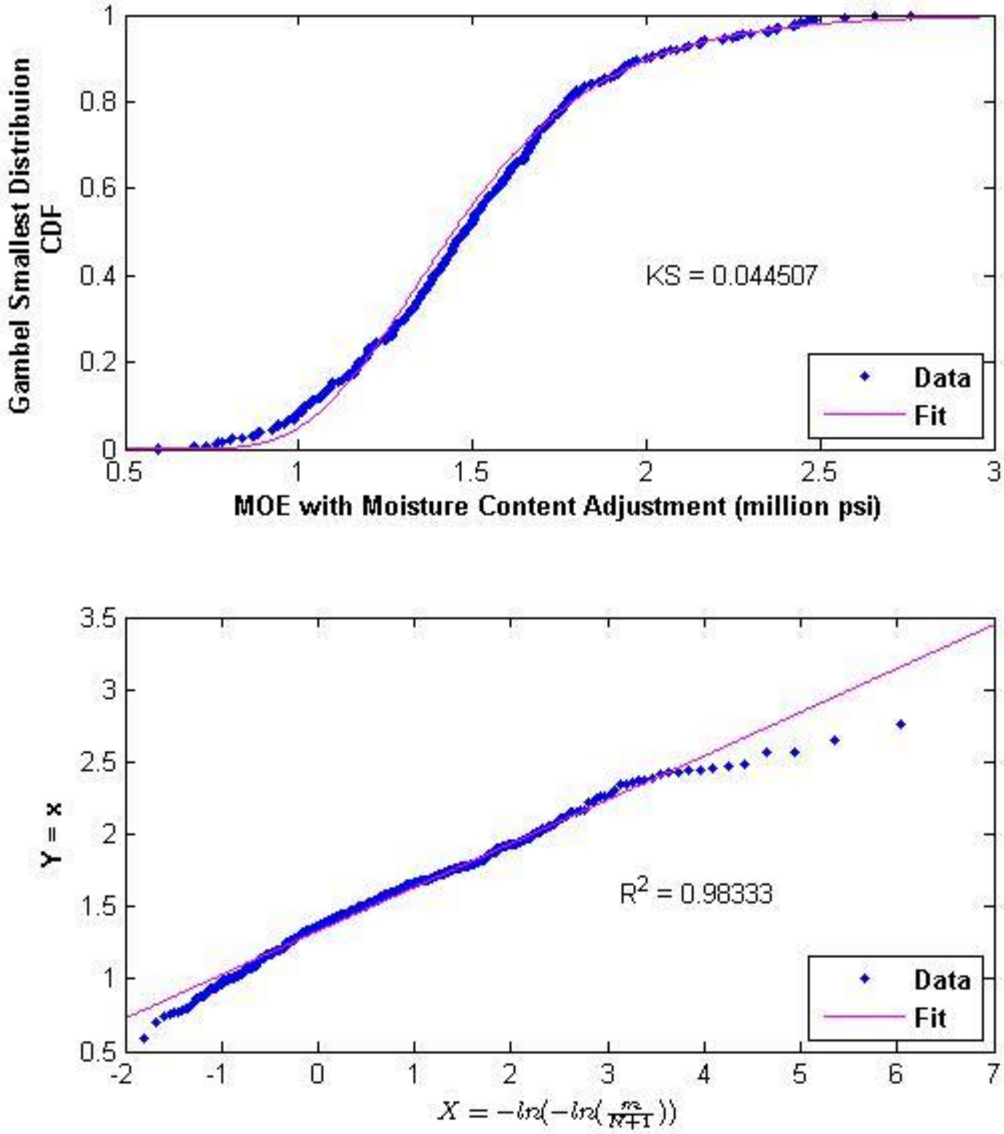


Figure A.36: K-S fitness and probability fit plot for *No.2* 2x10 Gumbel Smallest Distribution.

d. Frechet Smallest Distribution

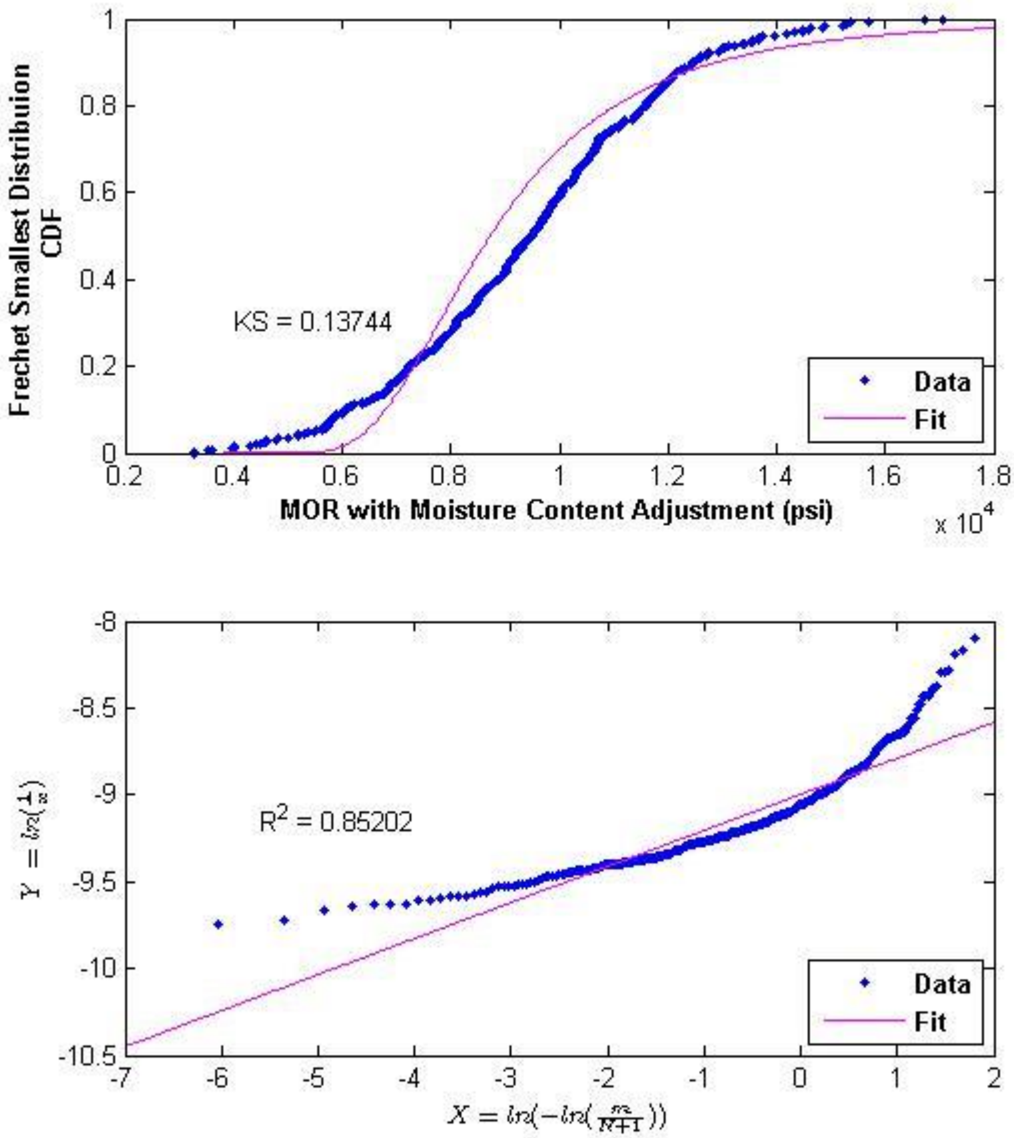


Figure A.37: K-S fitness and probability fit plot for *SS* 2x4 Frechet Smallest Distribution.

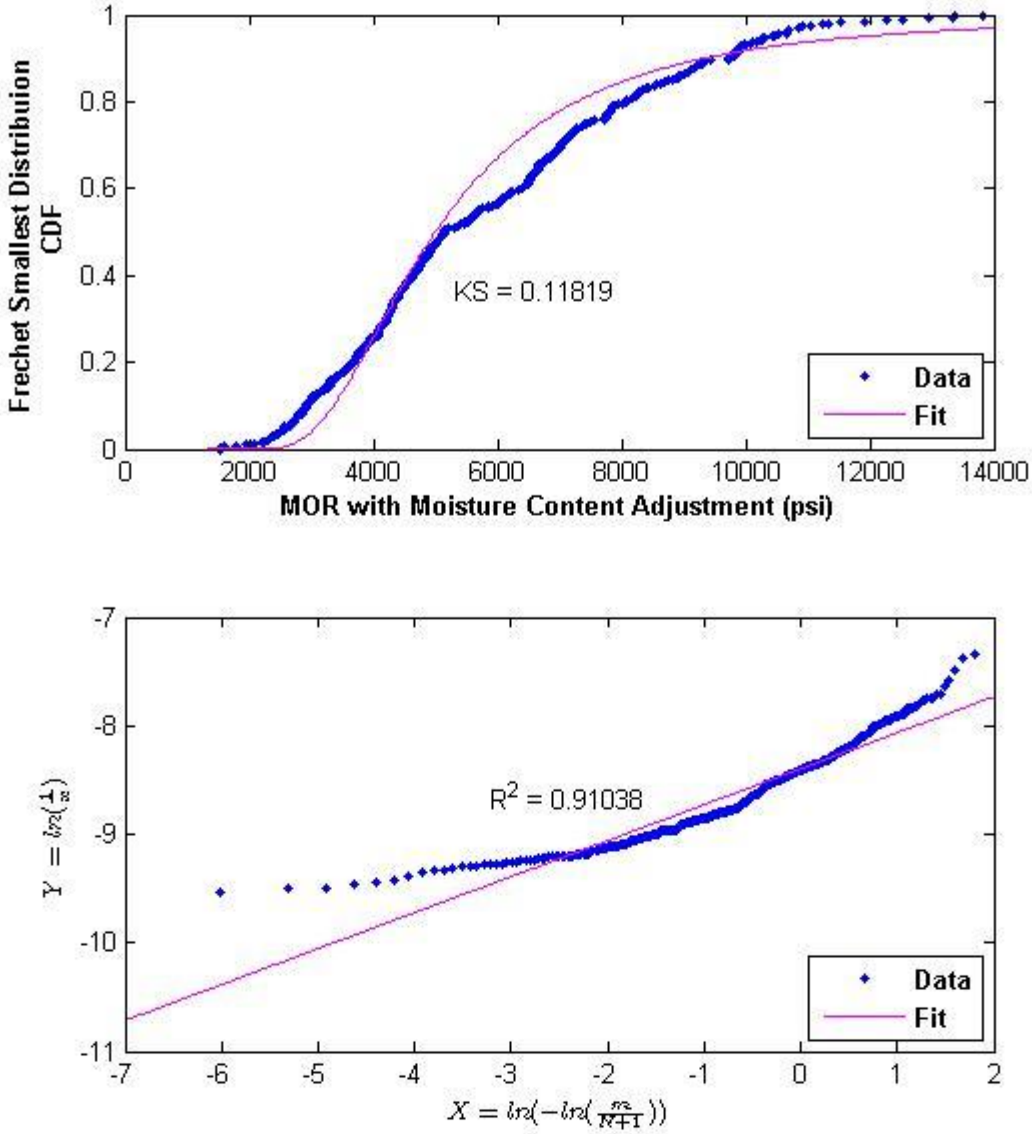
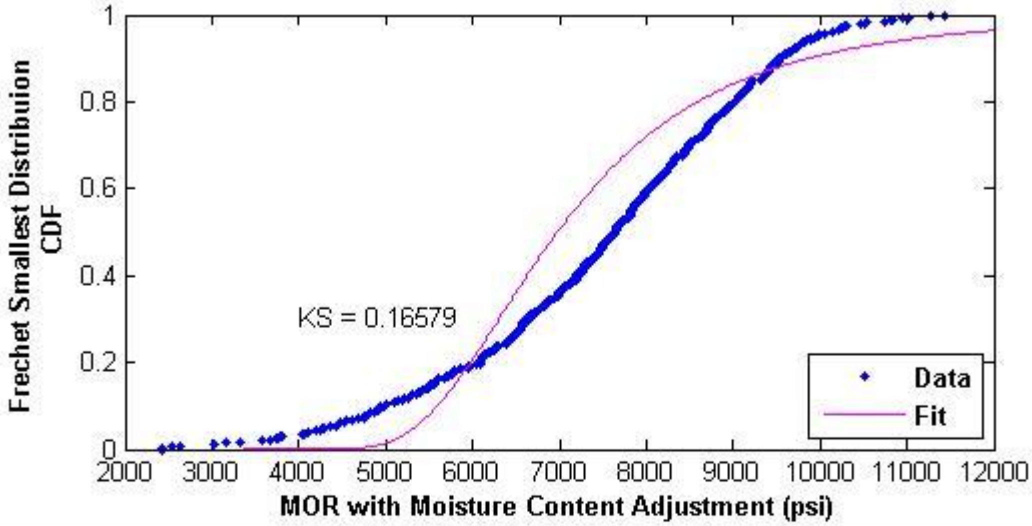


Figure A.38: K-S fitness and probability fit plot for *No.2* 2x4 Frechet Smallest Distribution.



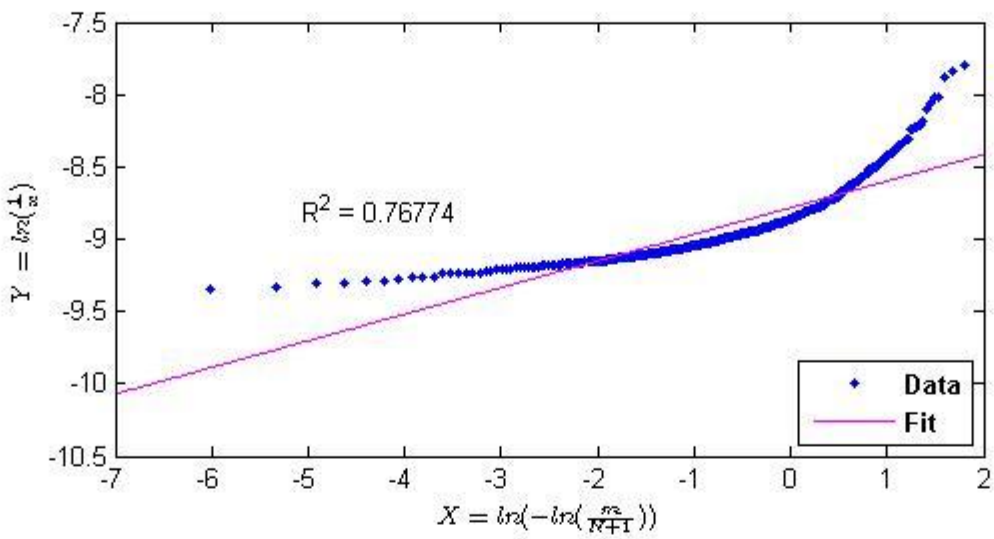


Figure A.39: K-S fitness and probability fit plot for *SS* 2x8 Frechet Smallest Distribution.

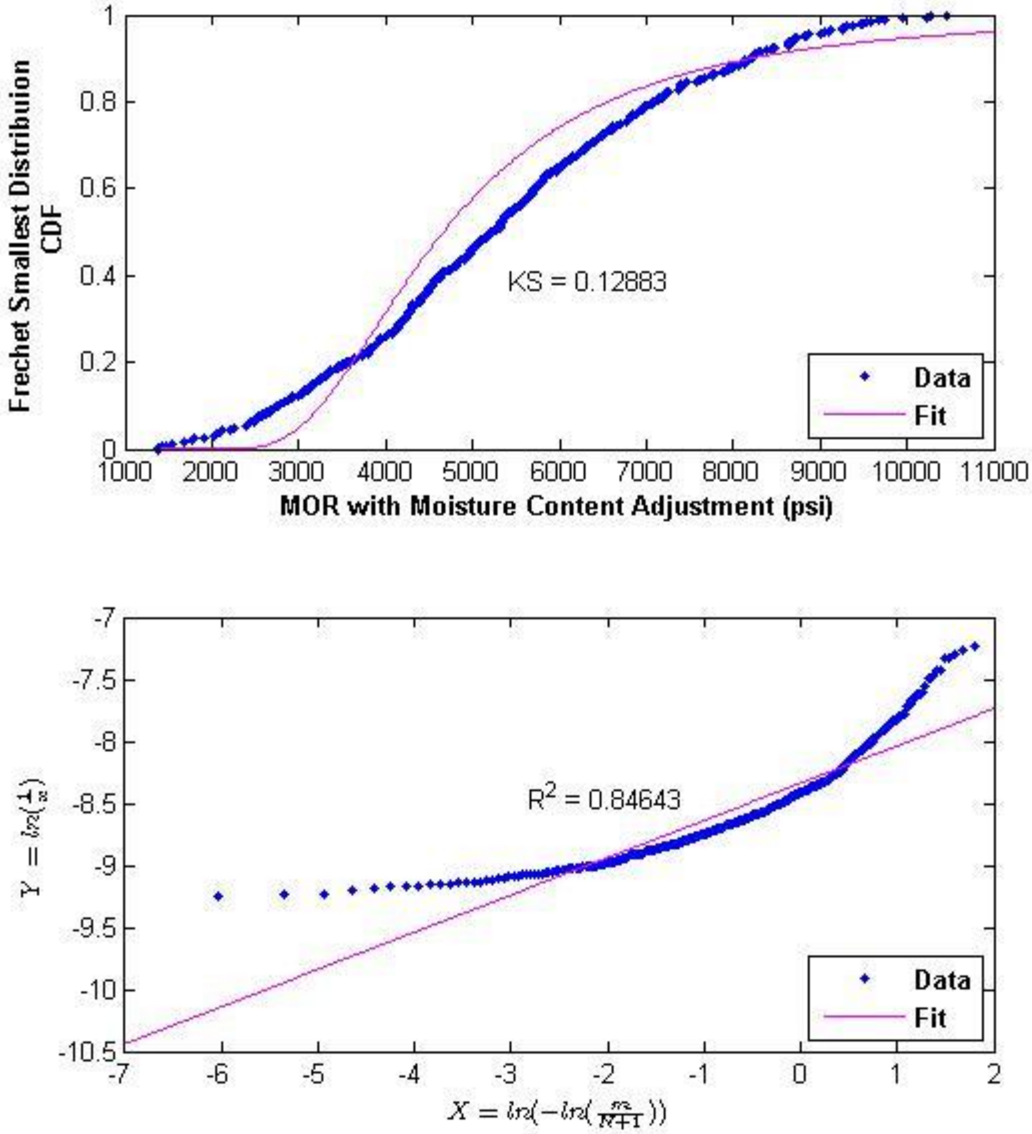
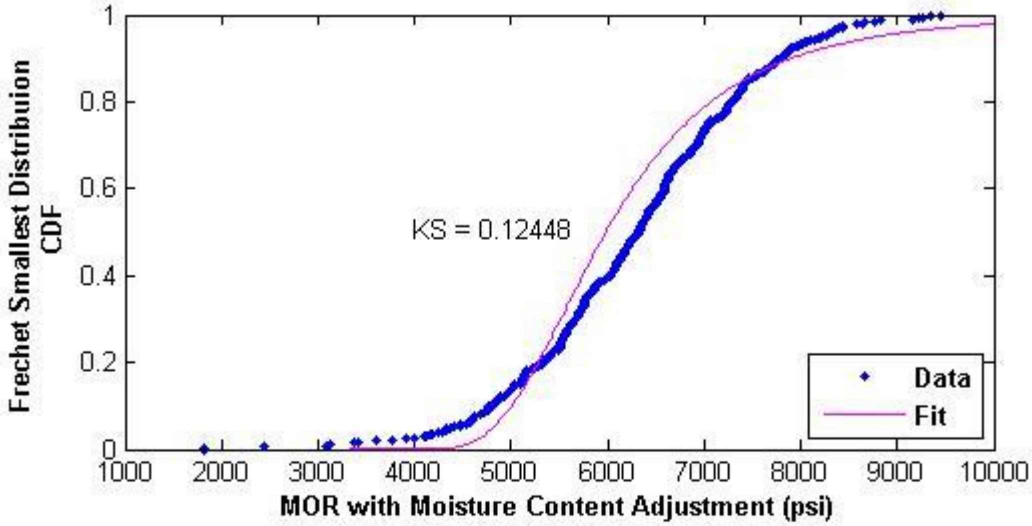


Figure A.40: K-S fitness and probability fit plot for *No.2* 2x8 Frechet Smallest Distribution.



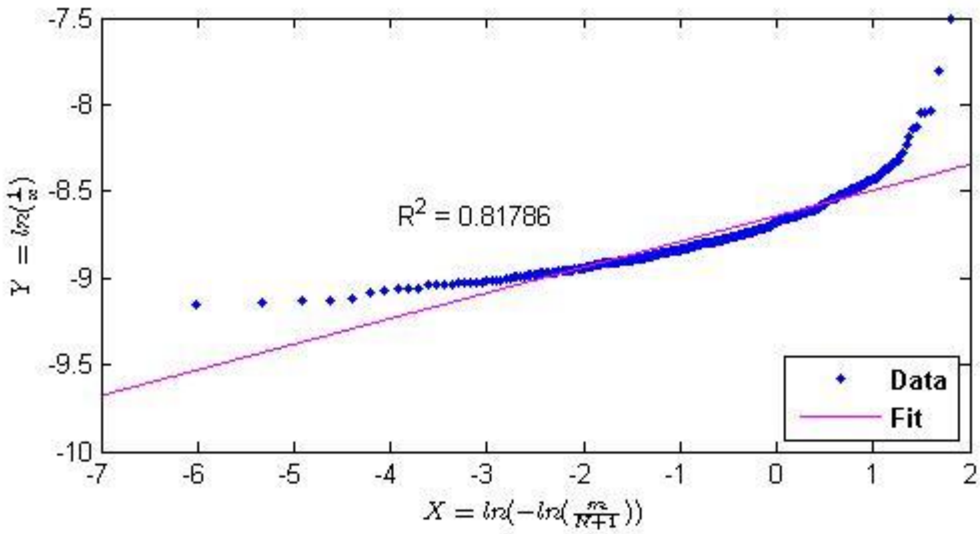


Figure A.41: K-S fitness and probability fit plot for *SS* 2x10 Frechet Smallest Distribution.

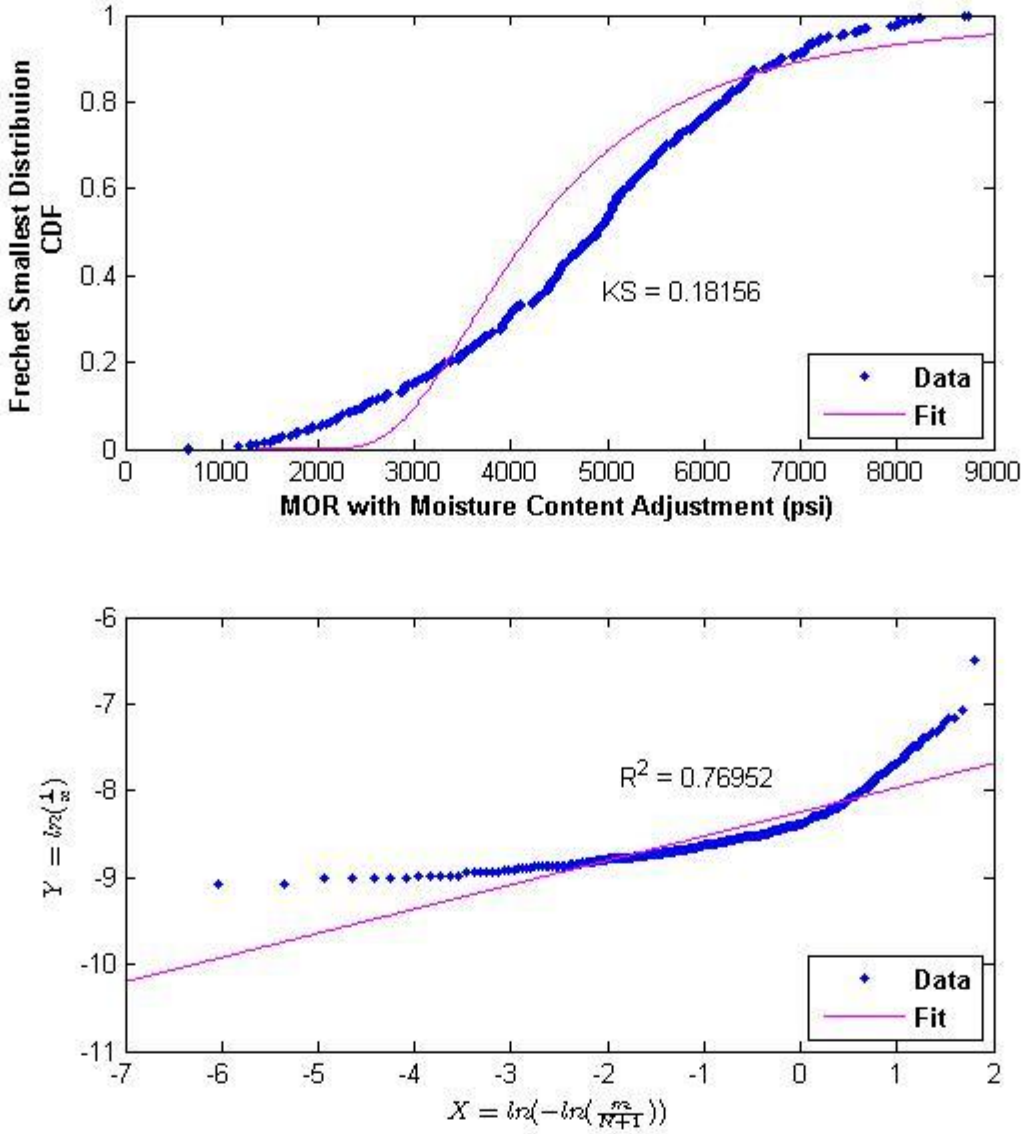


Figure A.42: K-S fitness and probability fit plot for *No.2* 2x10 Frechet Smallest Distribution.

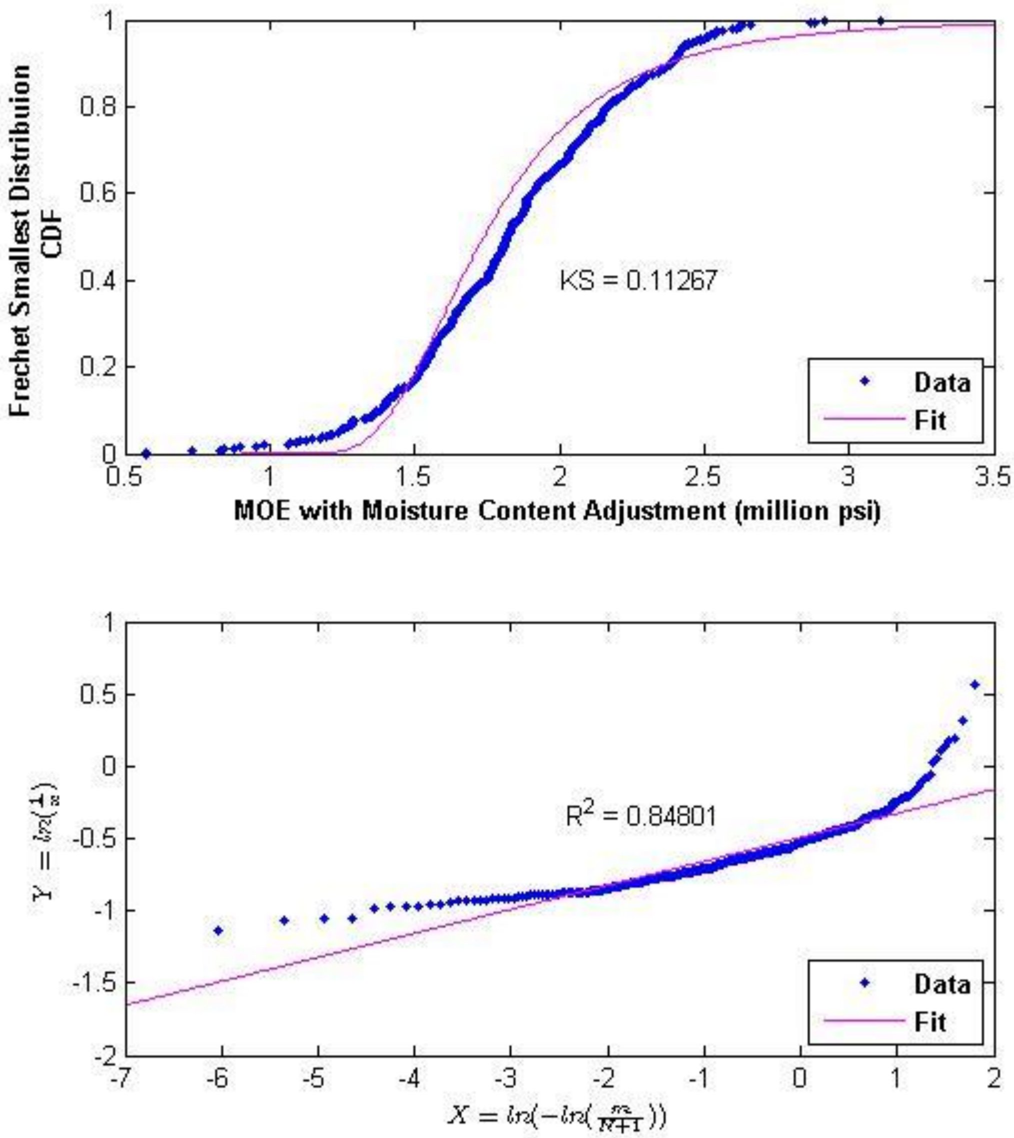


Figure A.43: K-S fitness and probability fit plot for *SS* 2x4 Frechet Smallest Distribution.

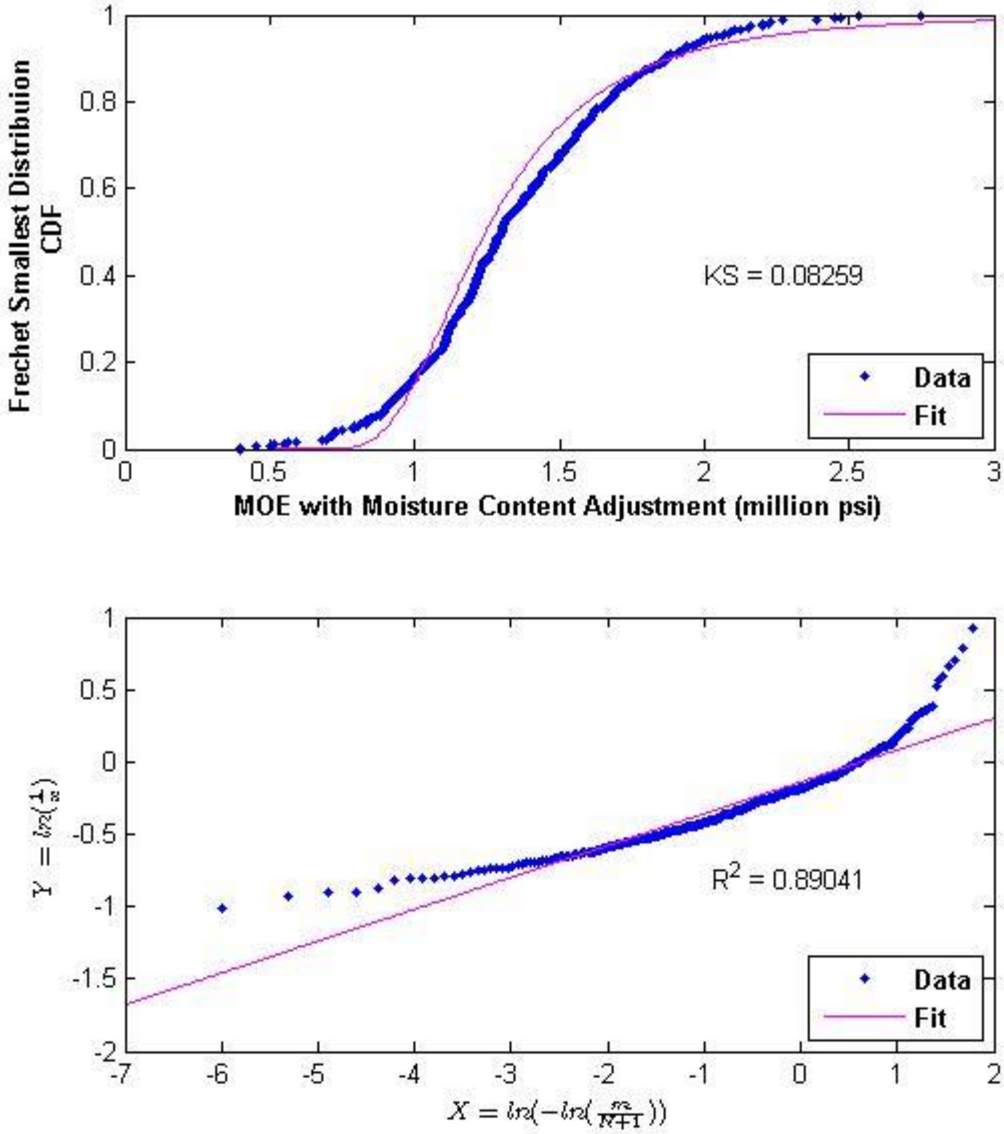


Figure A.44: K-S fitness and probability fit plot for *No.2* 2x4 Frechet Smallest Distribution.

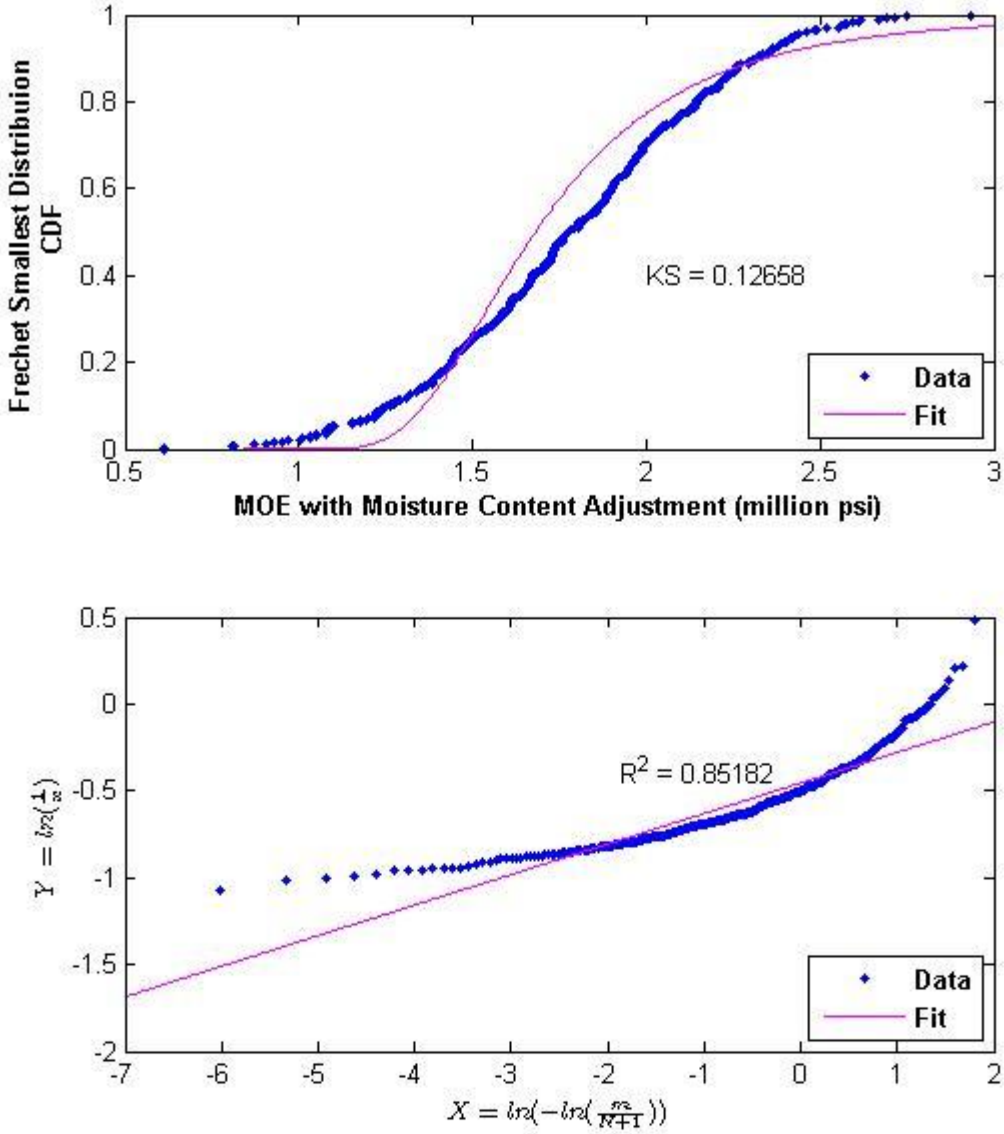


Figure A.45: K-S fitness and probability fit plot for *SS* 2x8 Frechet Smallest Distribution.

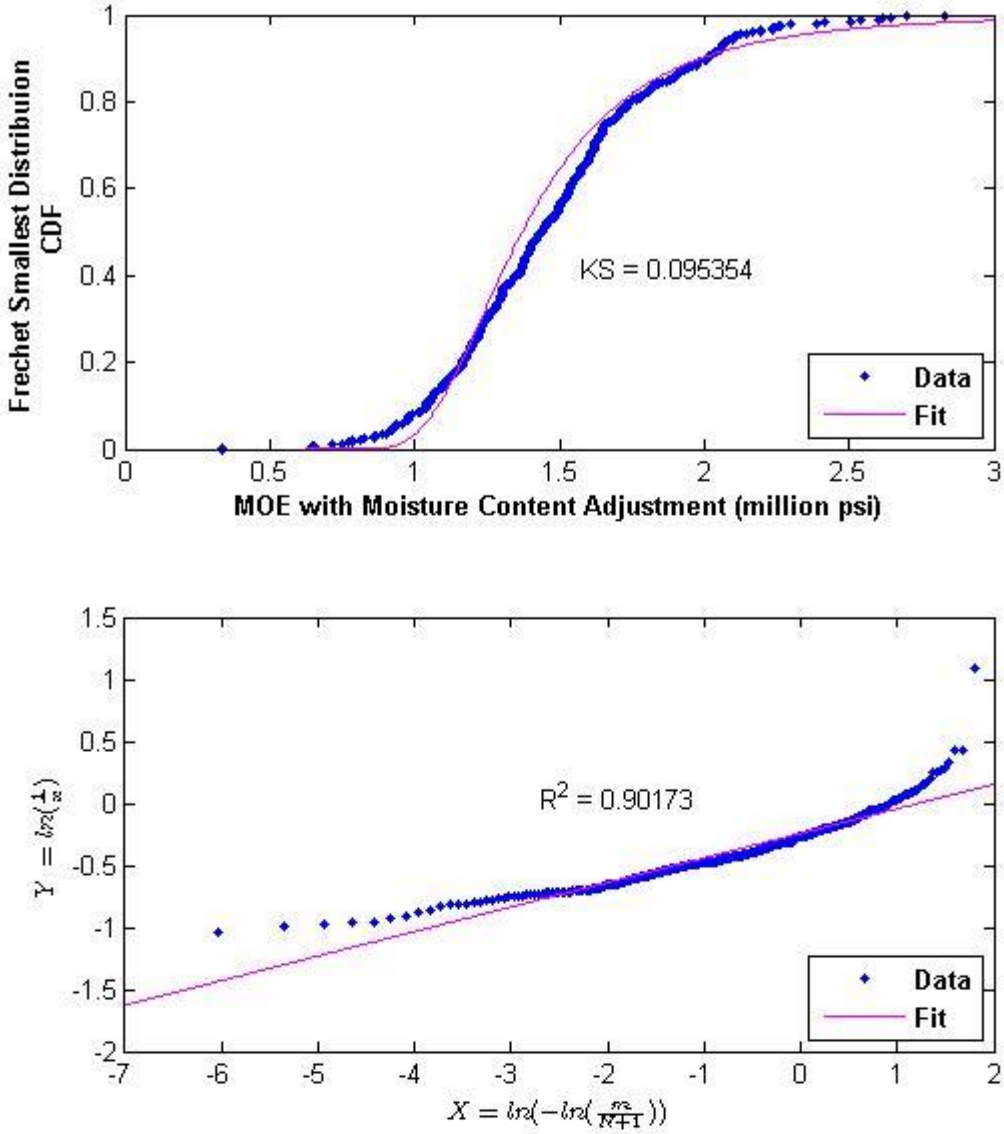


Figure A.46: K-S fitness and probability fit plot for *No.2* 2x8 Frechet Smallest Distribution.

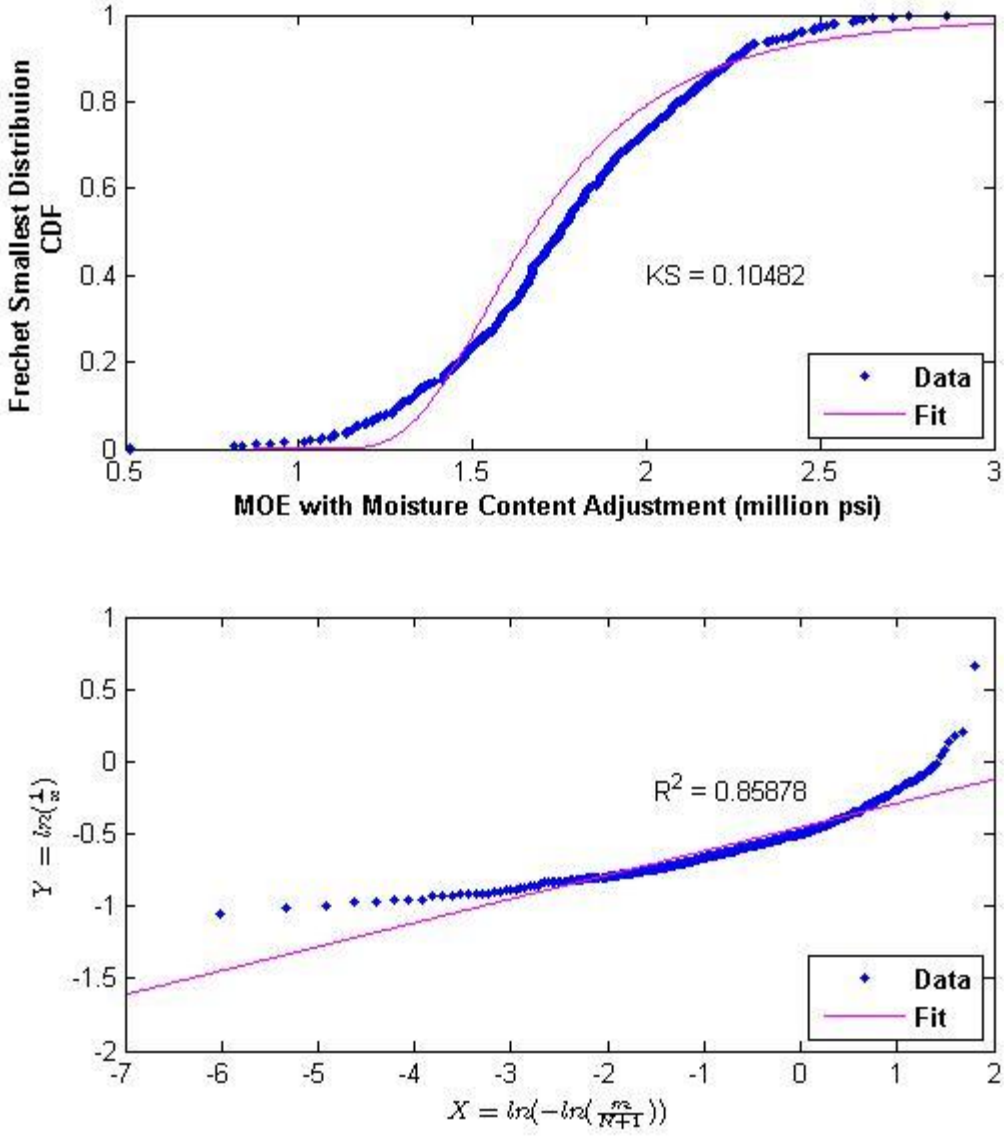


Figure A.47: K-S fitness and probability fit plot for *SS* 2x10 Frechet Smallest Distribution.

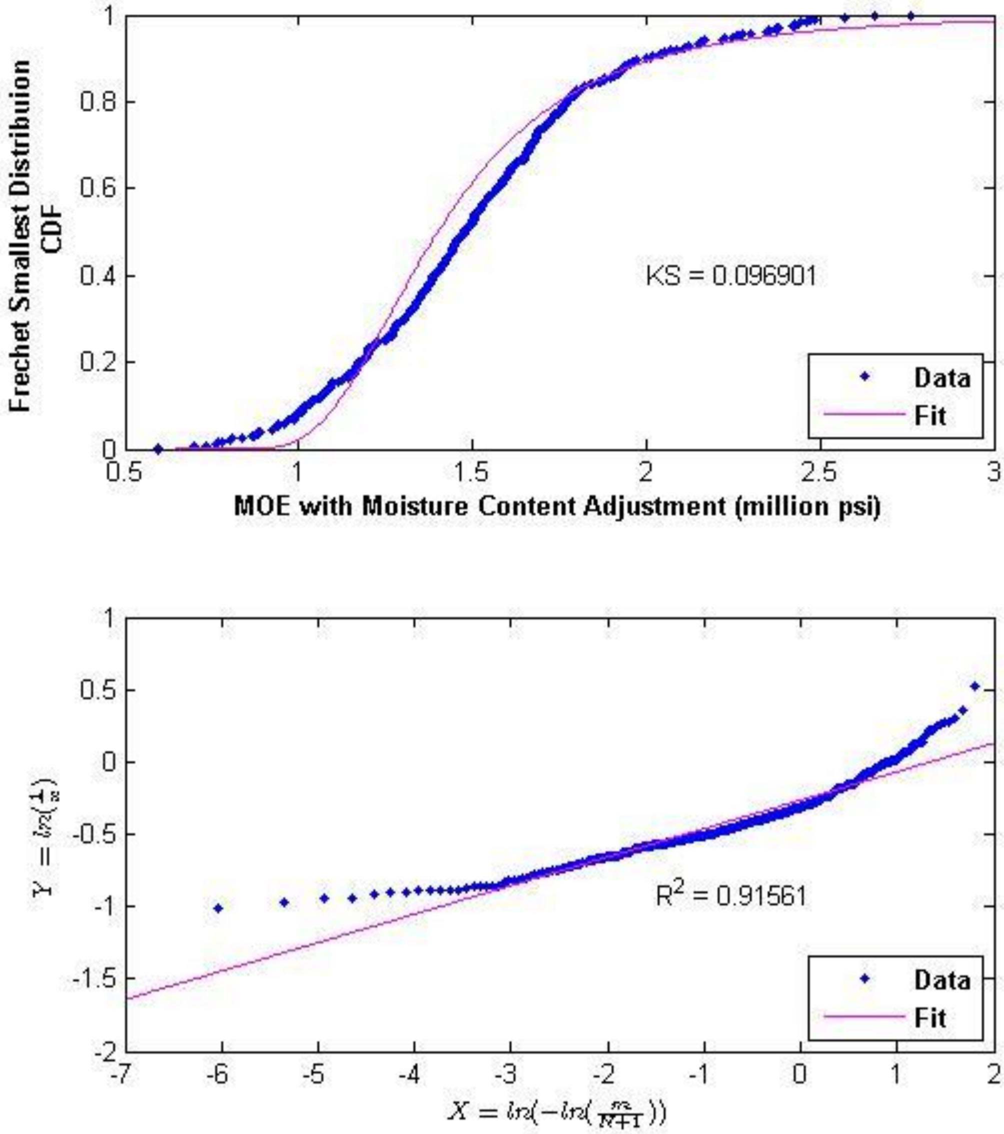


Figure A.48: K-S fitness and probability fit plot for *No.2* 2x10 Frechet Smallest Distribution.

e. Weibull Smallest Distribution

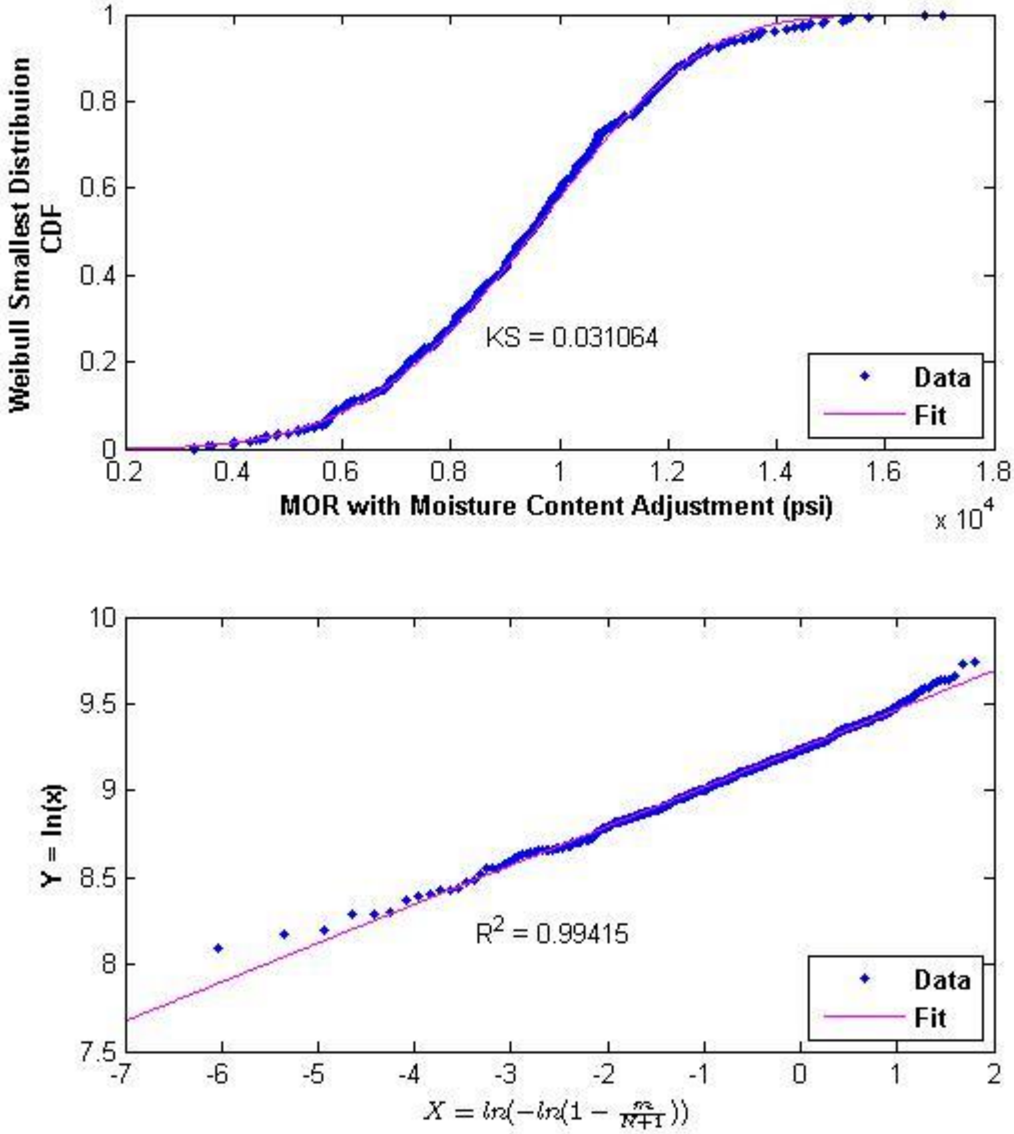
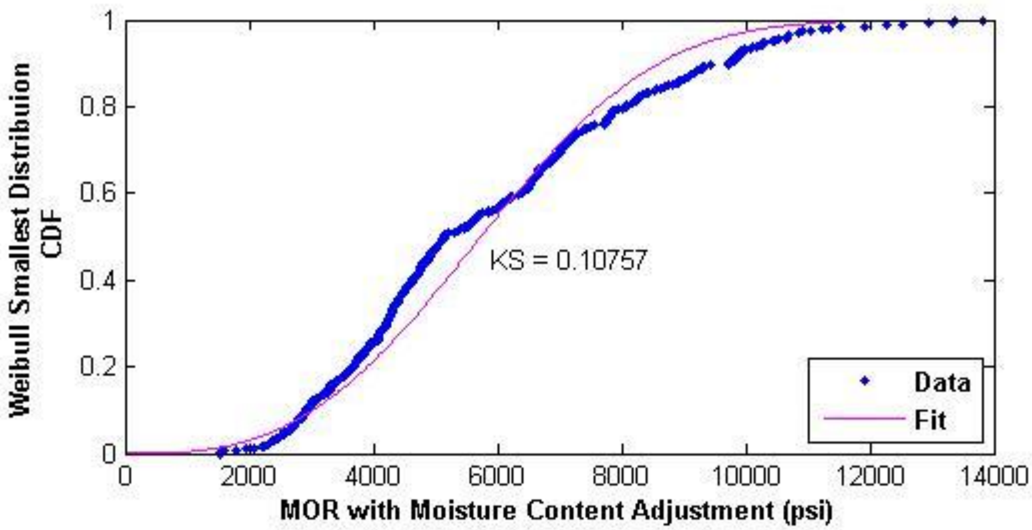


Figure A.49: K-S fitness and probability fit plot for *SS* 2x4 Weibull Smallest Distribution.



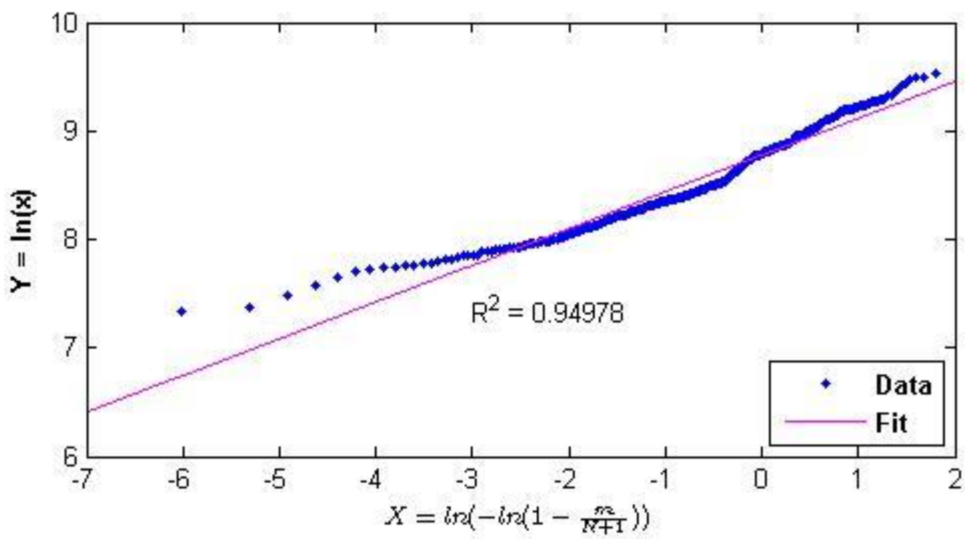


Figure A.50: K-S fitness and probability fit plot for *No.2* 2x4 Weibull Smallest Distribution.

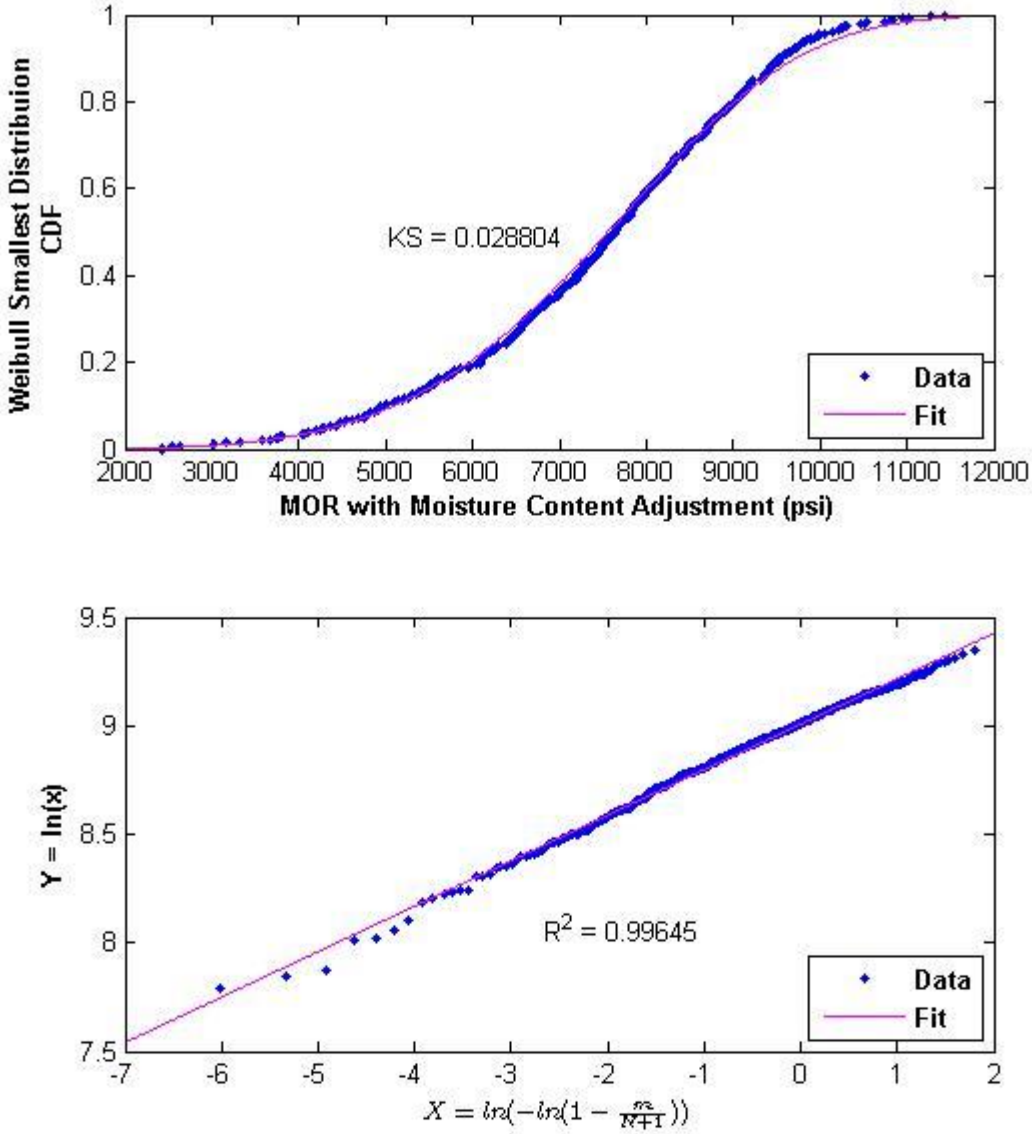


Figure A.51: K-S fitness and probability fit plot for *SS* 2x8 Weibull Smallest Distribution.

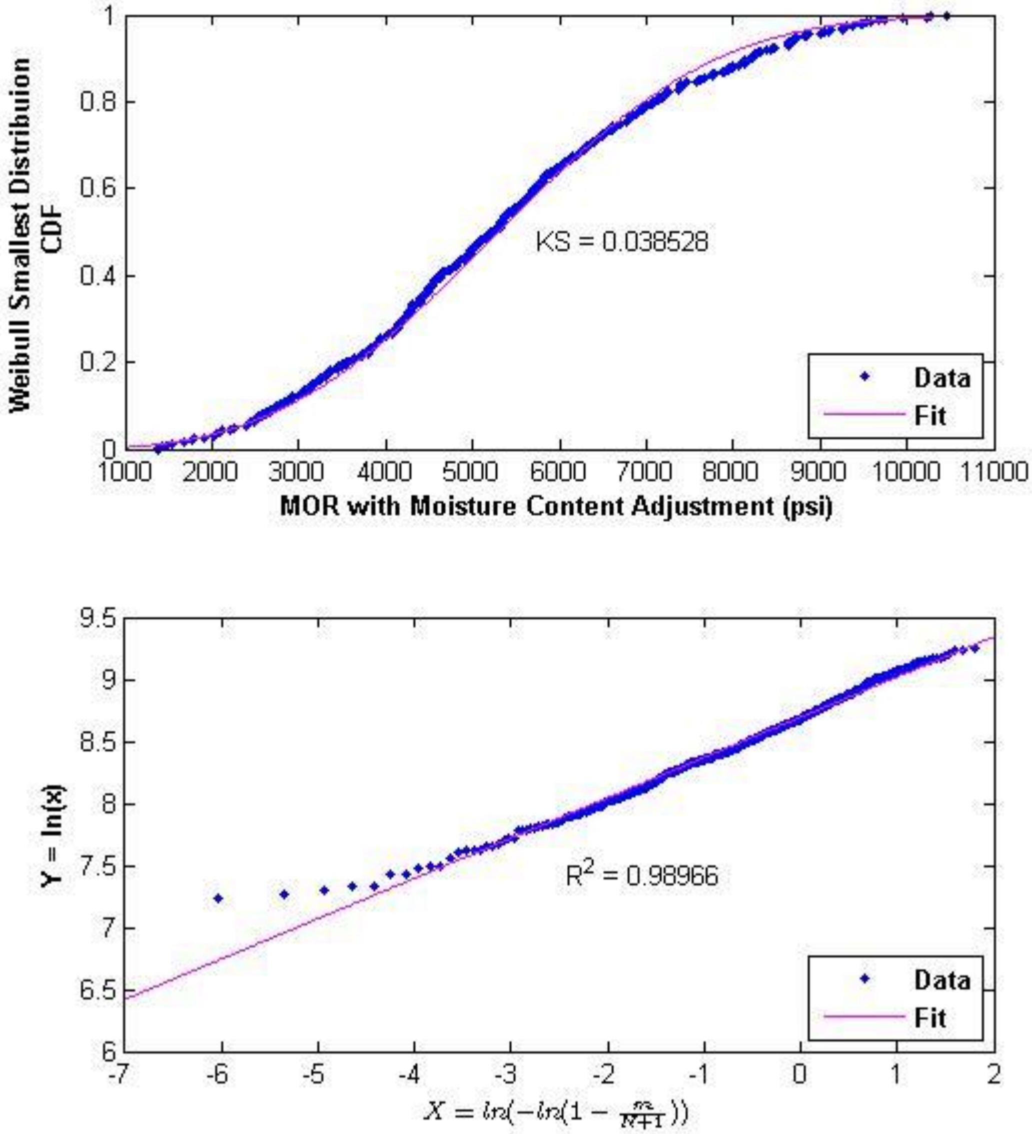


Figure A.52: K-S fitness and probability fit plot for *No.2* 2x8 Weibull Smallest Distribution.

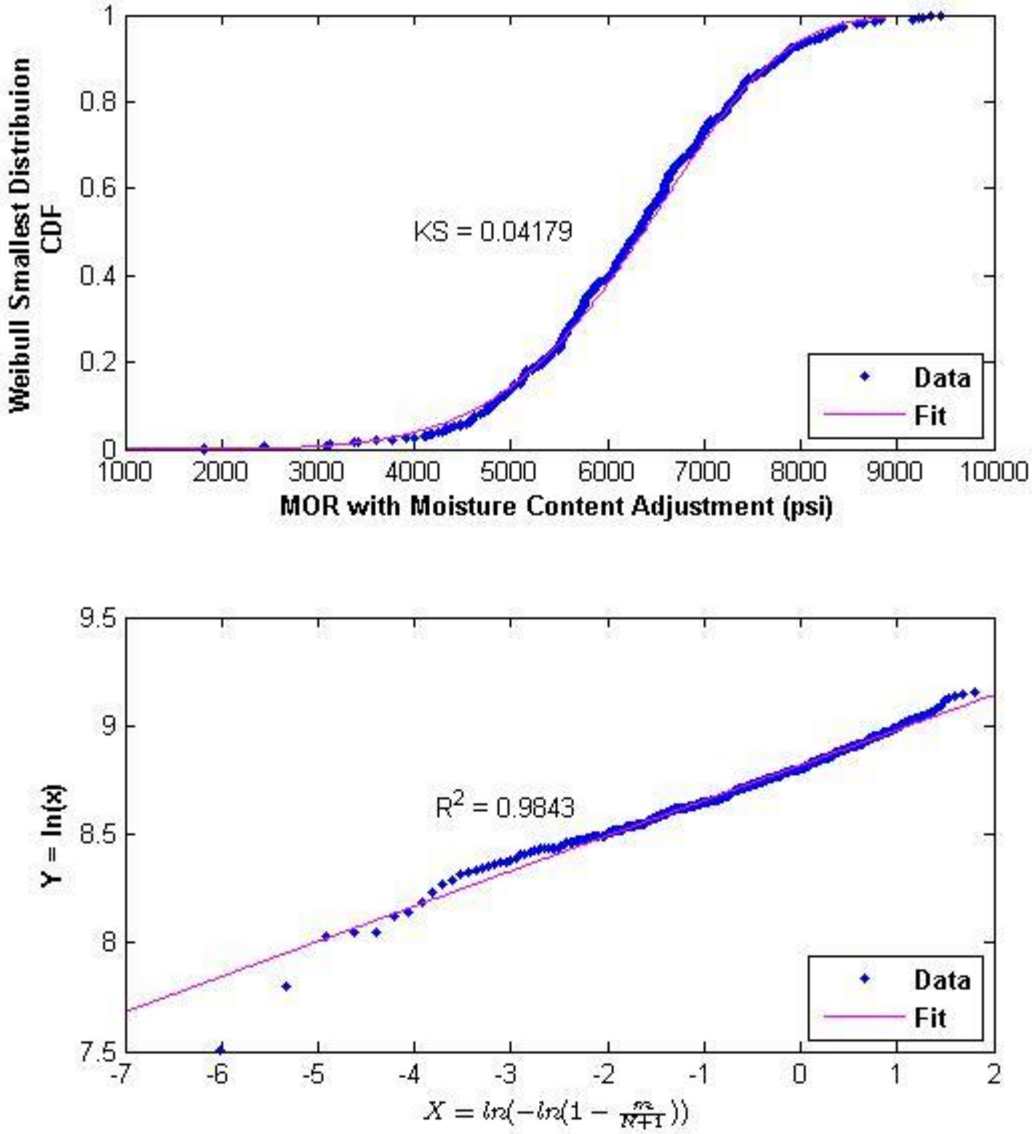


Figure A.53: K-S fitness and probability fit plot for *SS* 2x10 Weibull Smallest Distribution.

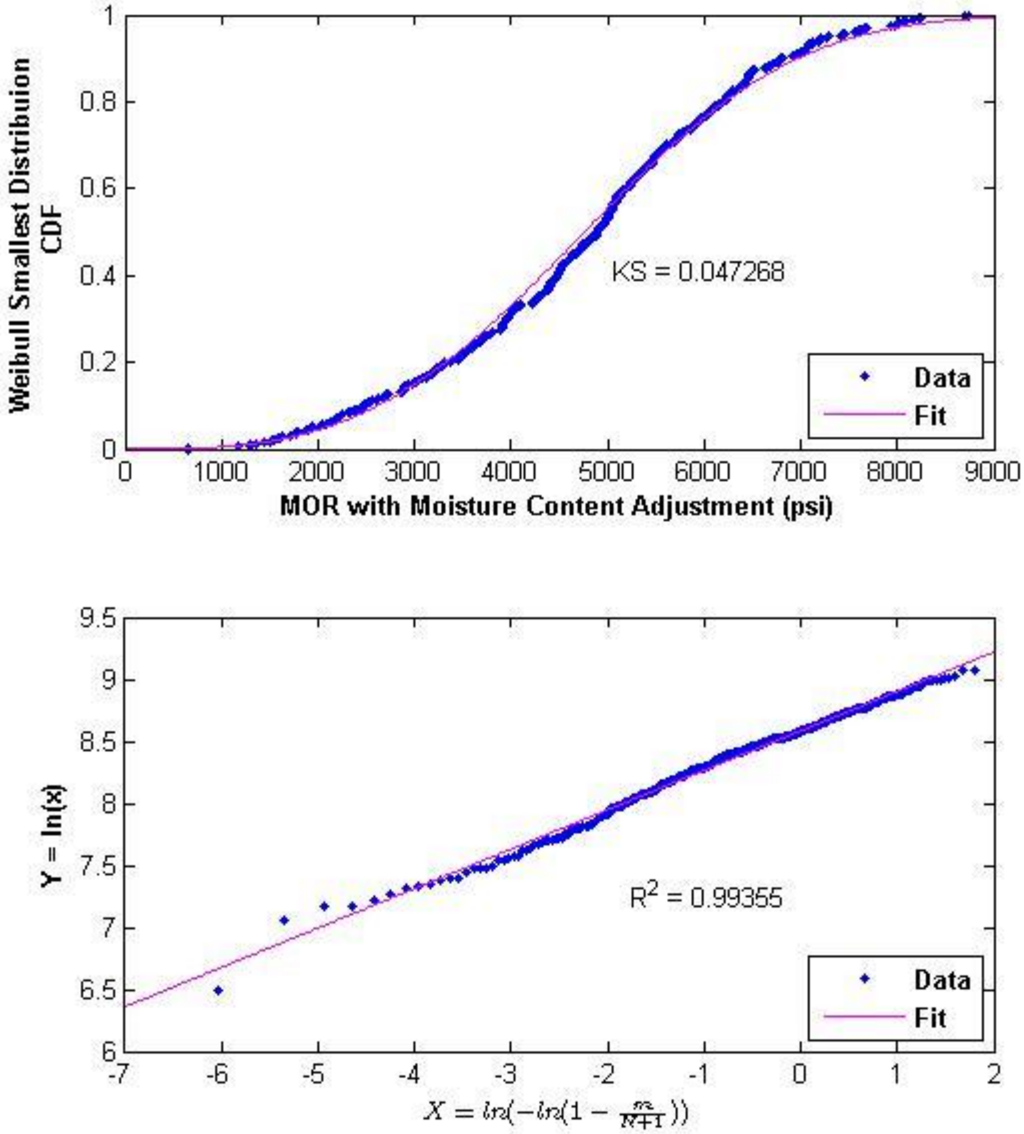
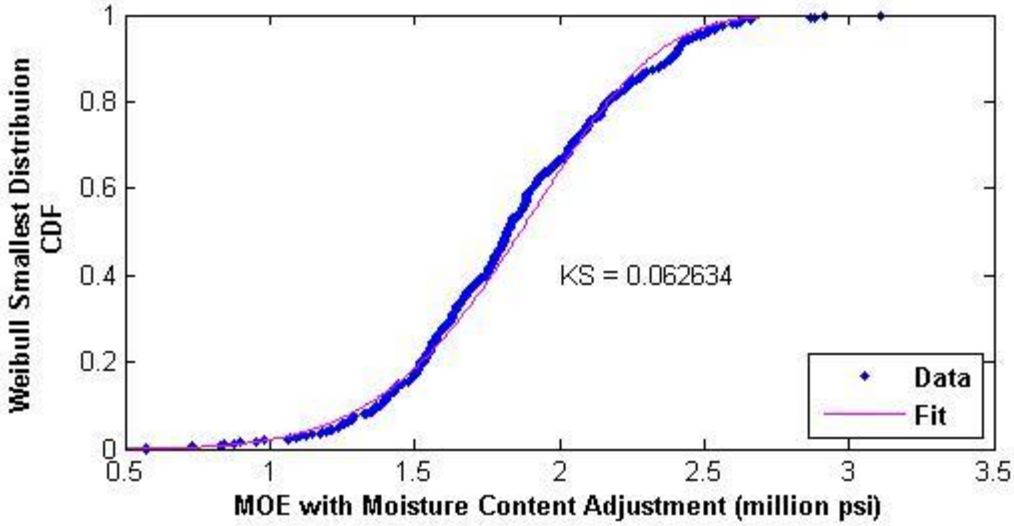


Figure A.54: K-S fitness and probability fit plot for *No.2* 2x10 Weibull Smallest Distribution.



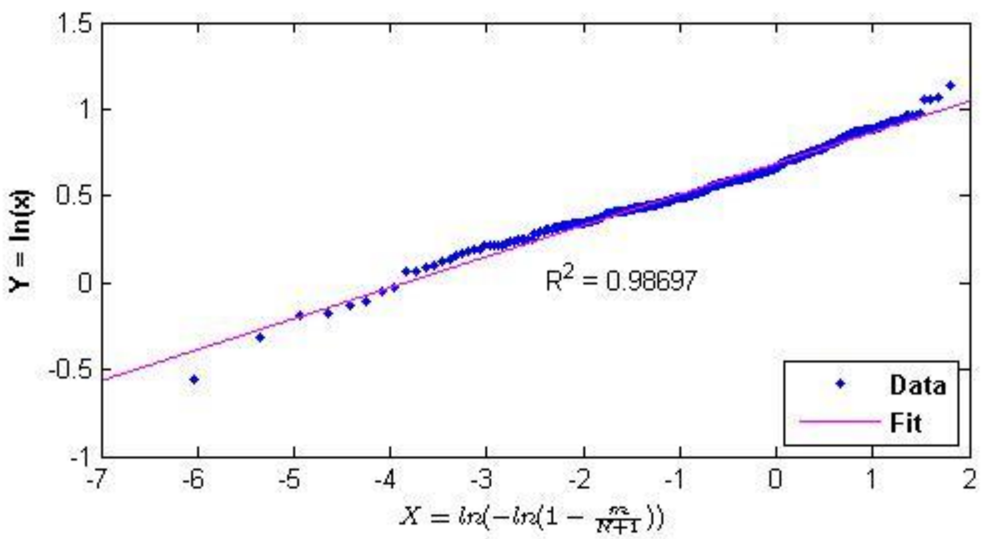


Figure A.55: K-S fitness and probability fit plot for *SS* 2x4 Weibull Smallest Distribution.

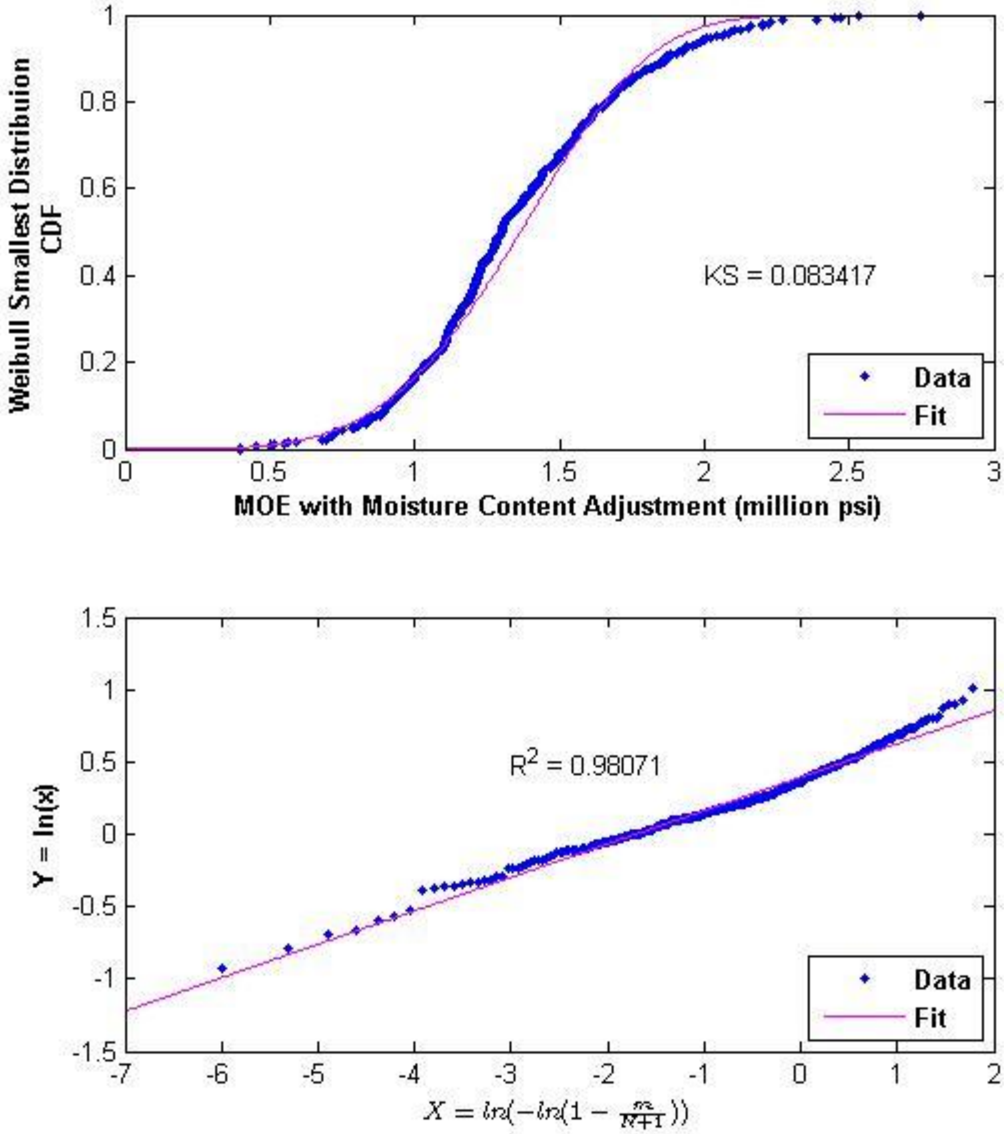


Figure A.56: K-S fitness and probability fit plot for *No.2* 2x4 Weibull Smallest Distribution.

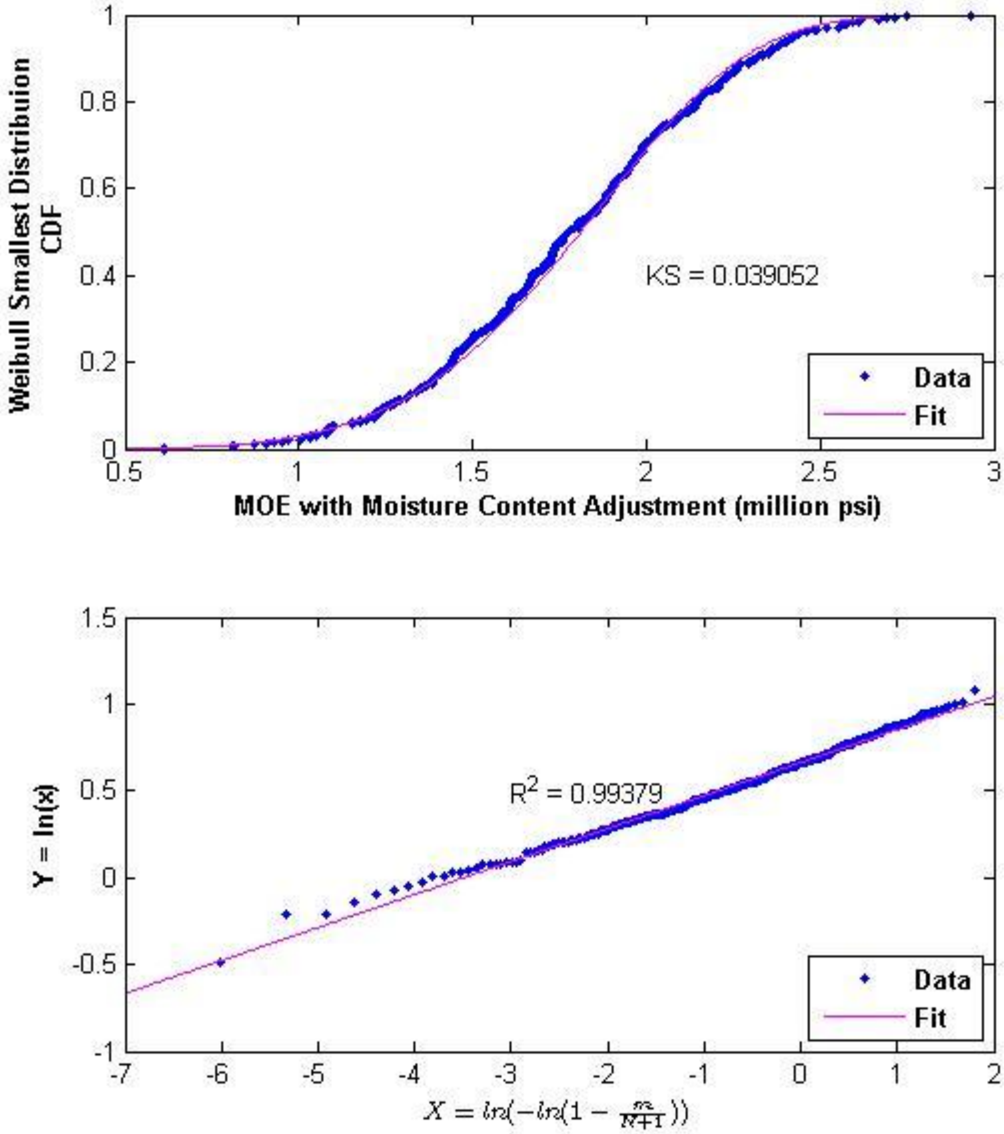
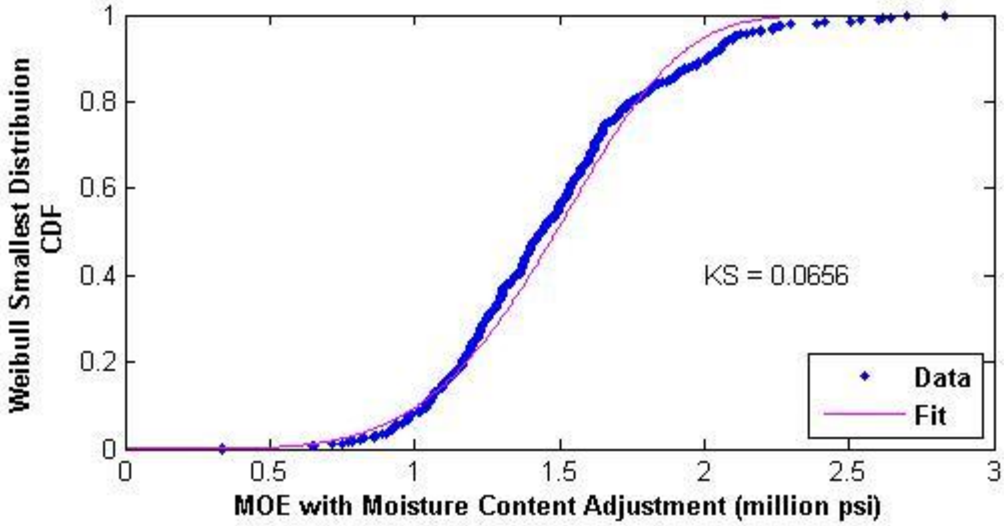


Figure A.57: K-S fitness and probability fit plot for *SS* 2x8 Weibull Smallest Distribution.



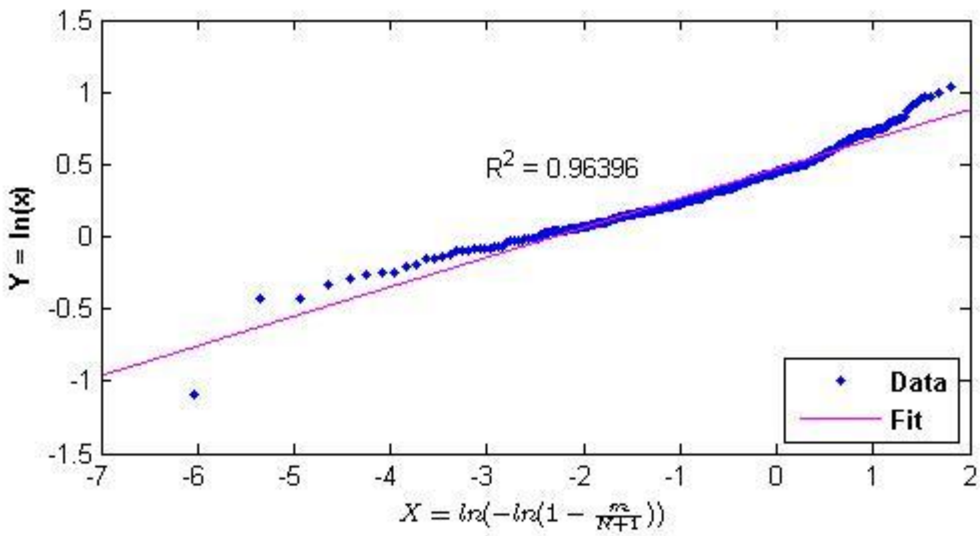


Figure A.58: K-S fitness and probability fit plot for *No.2* 2x8 Weibull Smallest Distribution.

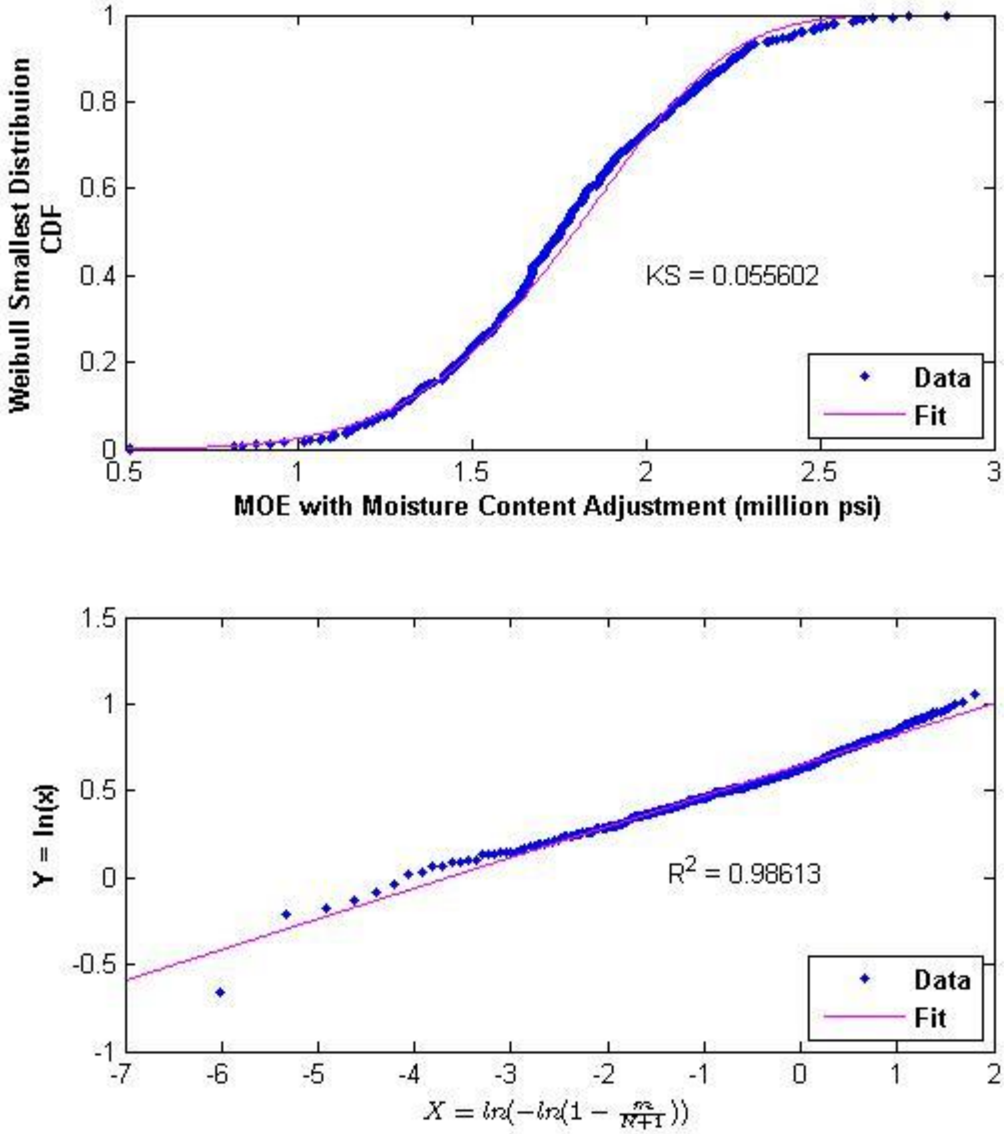


Figure A.59: K-S fitness and probability fit plot for *SS* 2x10 Weibull Smallest Distribution.

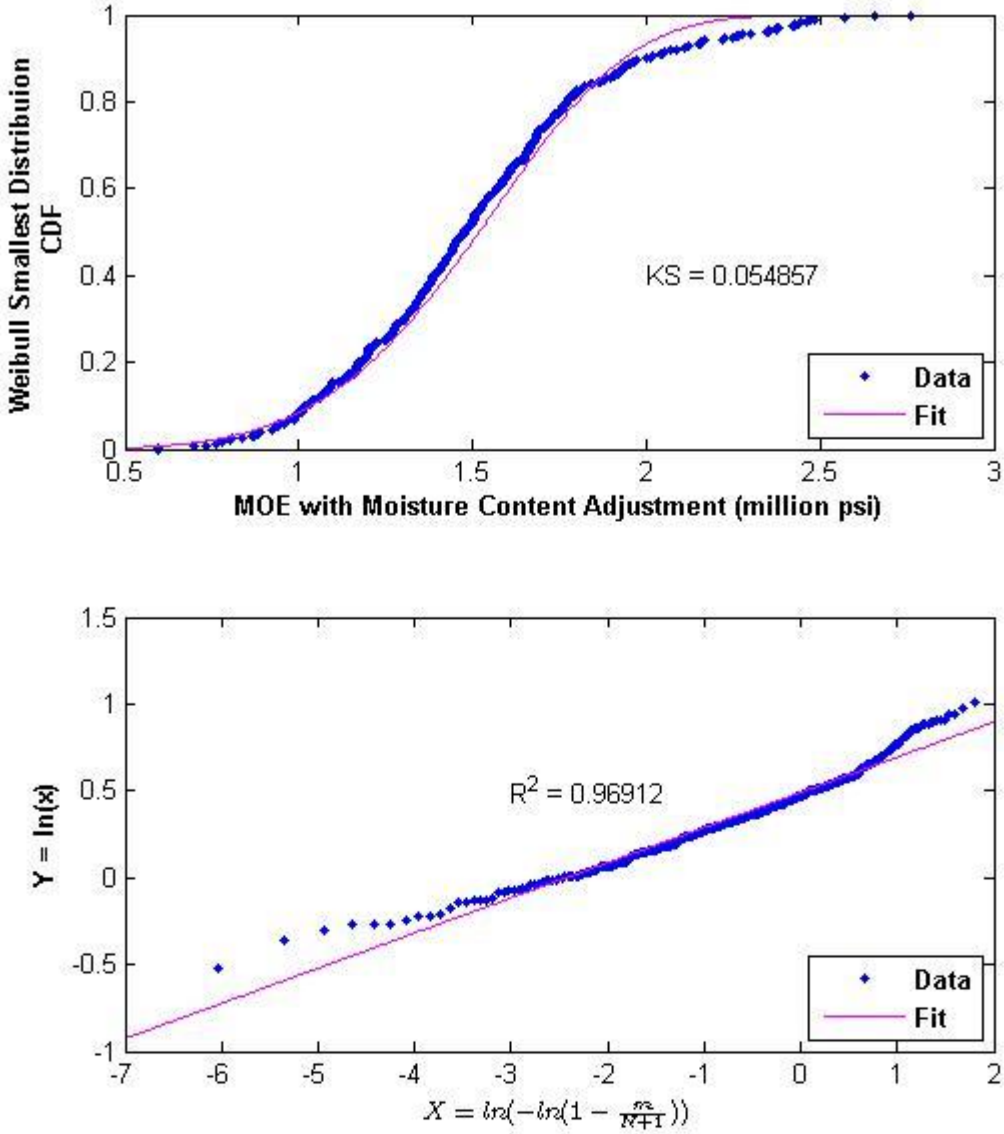


Figure A.60: K-S fitness and probability fit plot for *No.2* 2x10 Weibull Smallest Distribution.

Appendix B

Compared Weibull probability density function for MOR and MOE derived from the 1978 and 2010 IGTP tests.

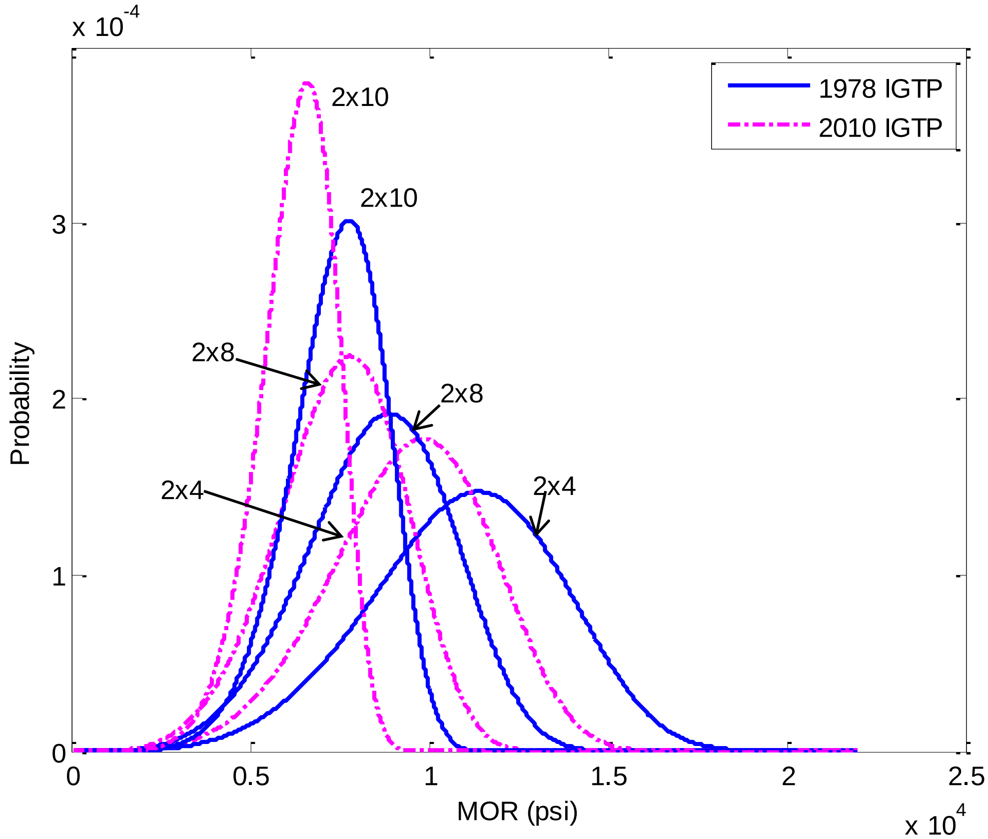


Figure B.1: MOR *Select Structural*.

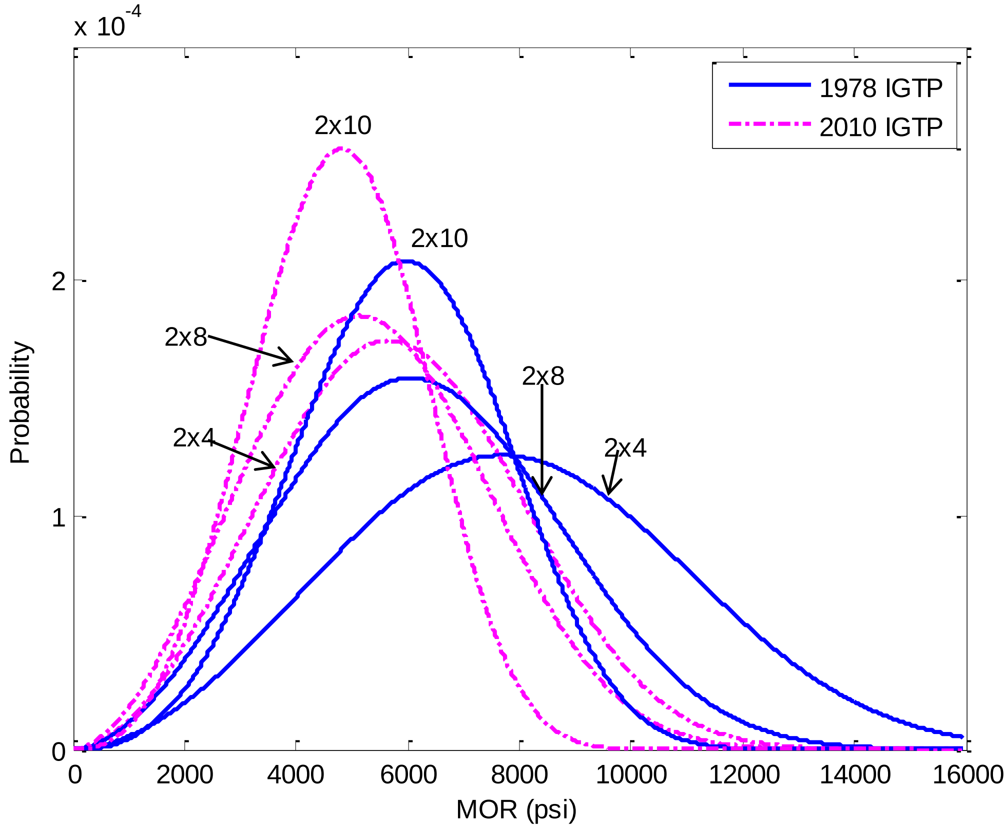


Figure B.2: MOR *No.2*.

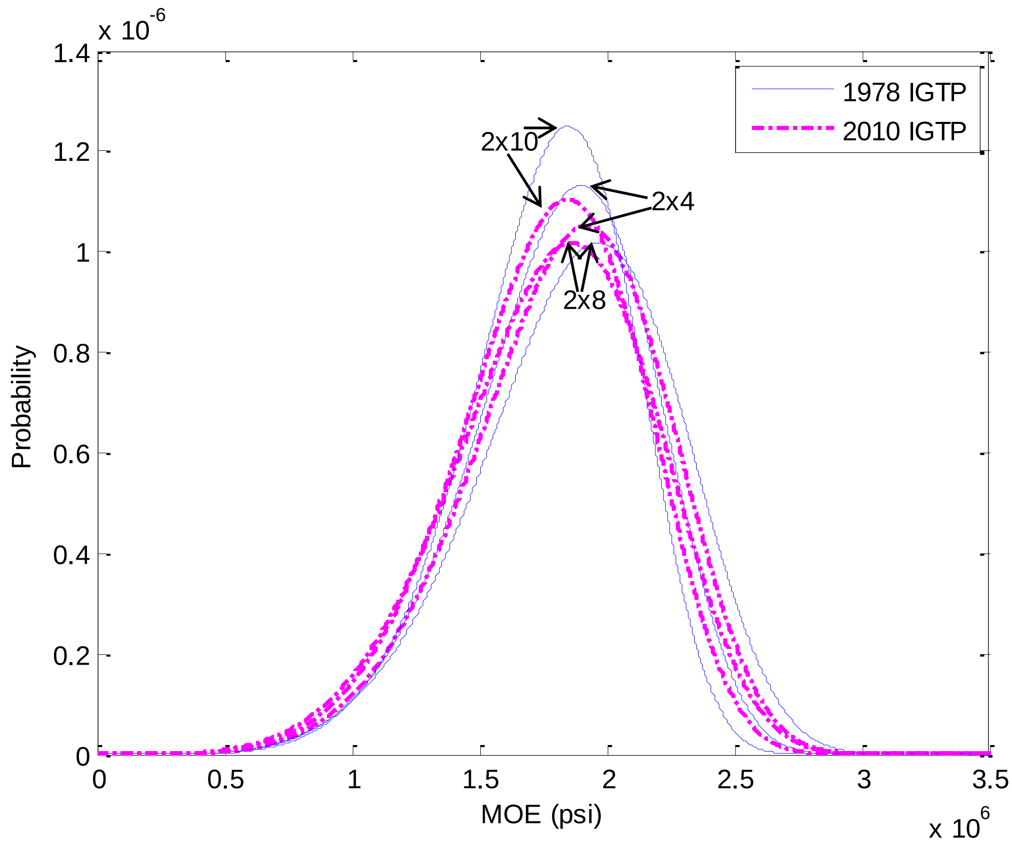


Figure B.3: MOE *Select Structural* (2010 IGTP and 1978 IGTP MOE probability from top to boot each is 2x10 2x4 and 2x8).

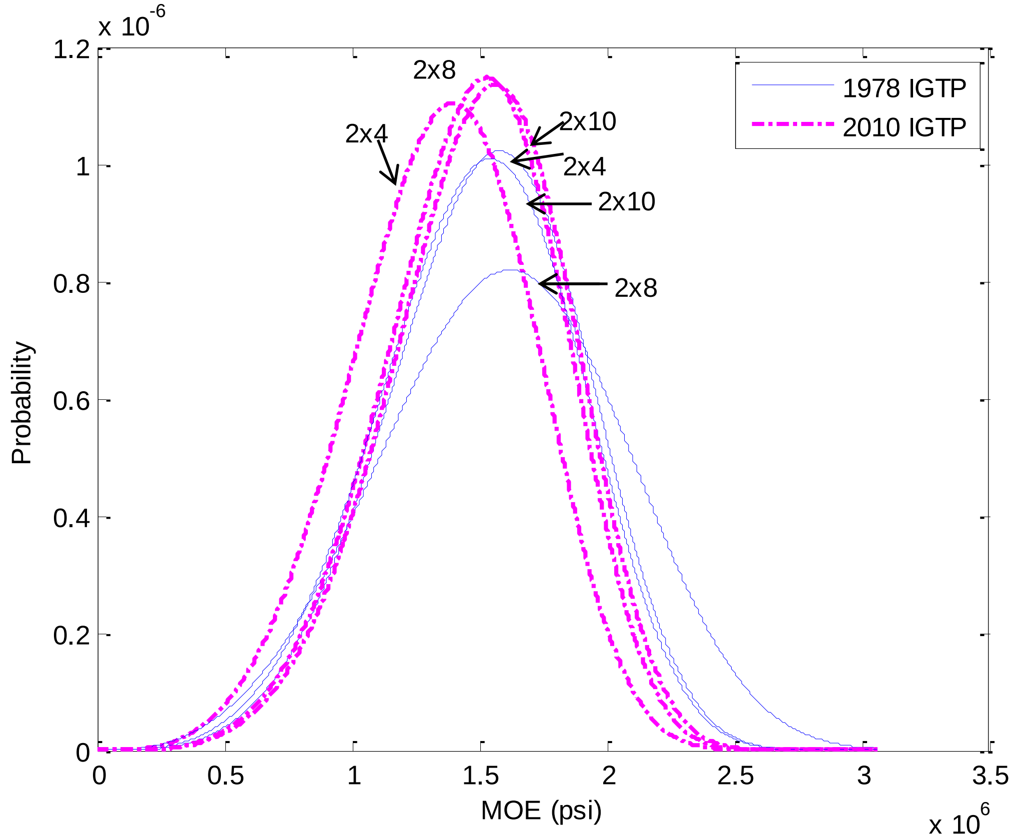


Figure B.4: MOE *No.2*

Appendix C

Effect of Joist Dimension

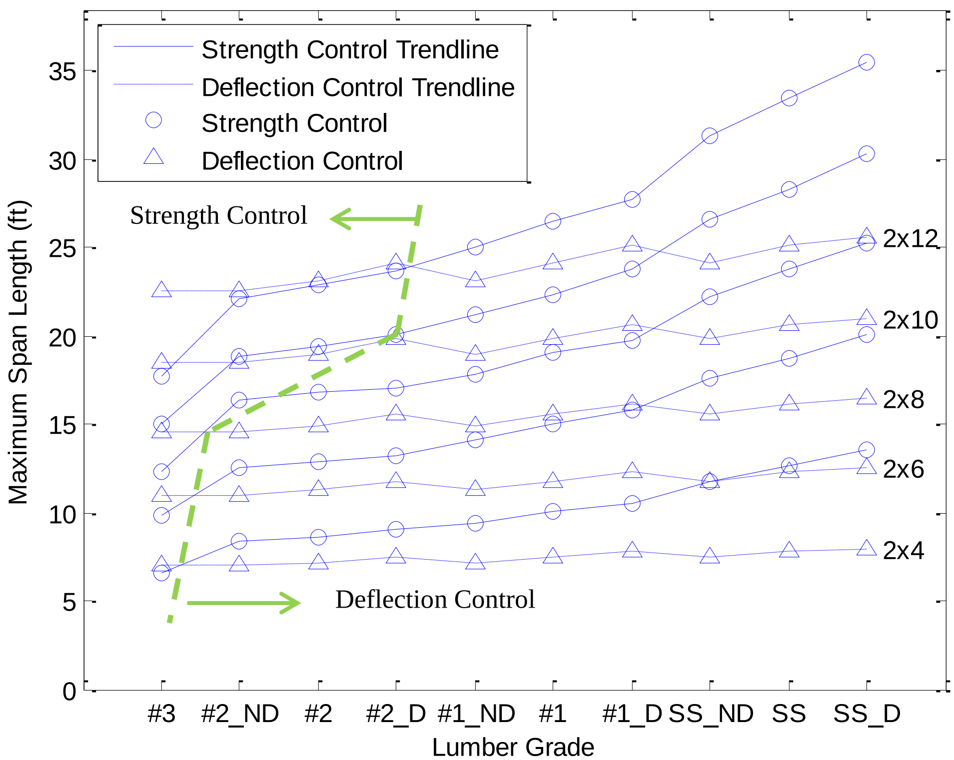


Figure C.1: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 12 in. on-center and *LL/DL* ratio of 3 (2012 NDS).

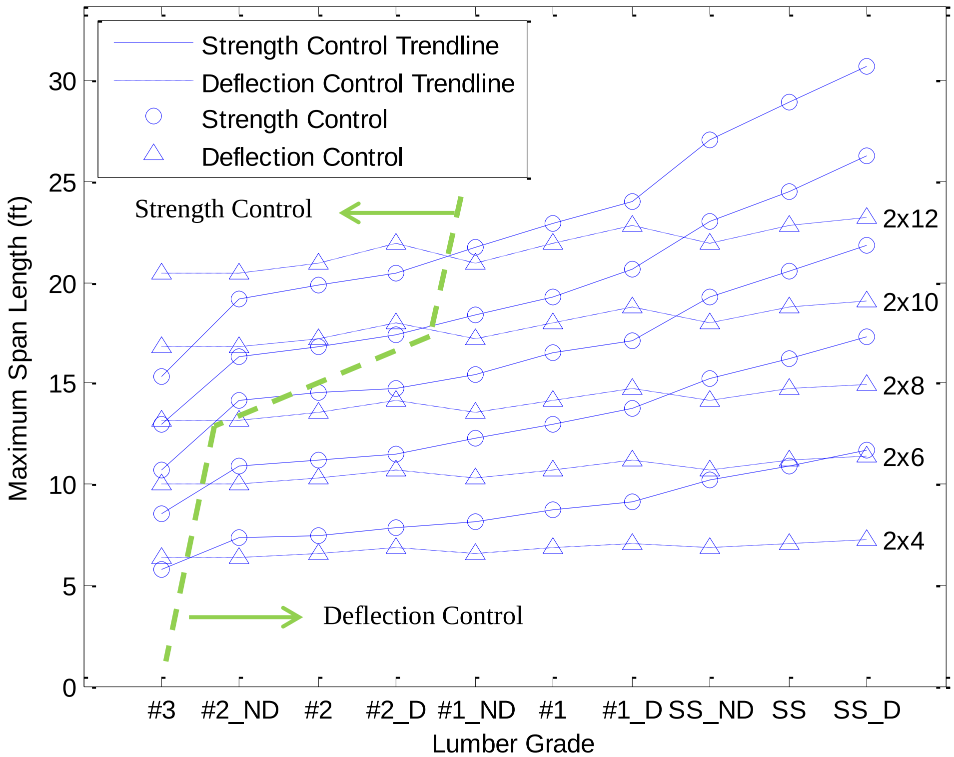


Figure C.2: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 16 in. on-center and *LL/DL* ratio of 3 (2012 NDS).

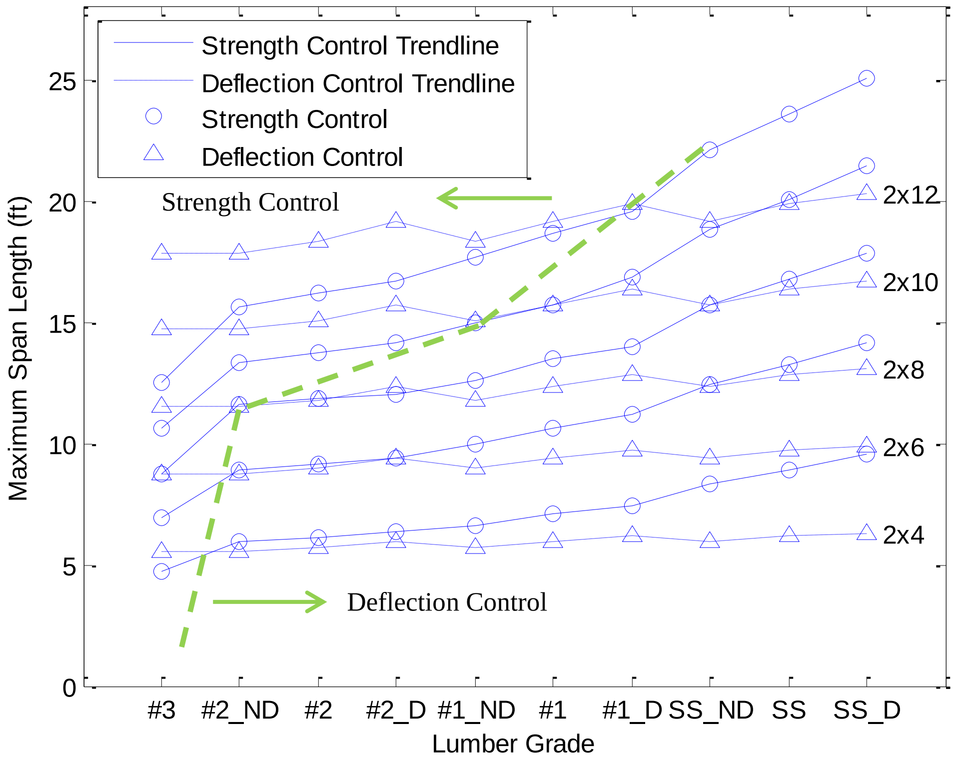


Figure C.3: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 24 in. on-center and *LL/DL* ratio of 3 (2012 NDS).

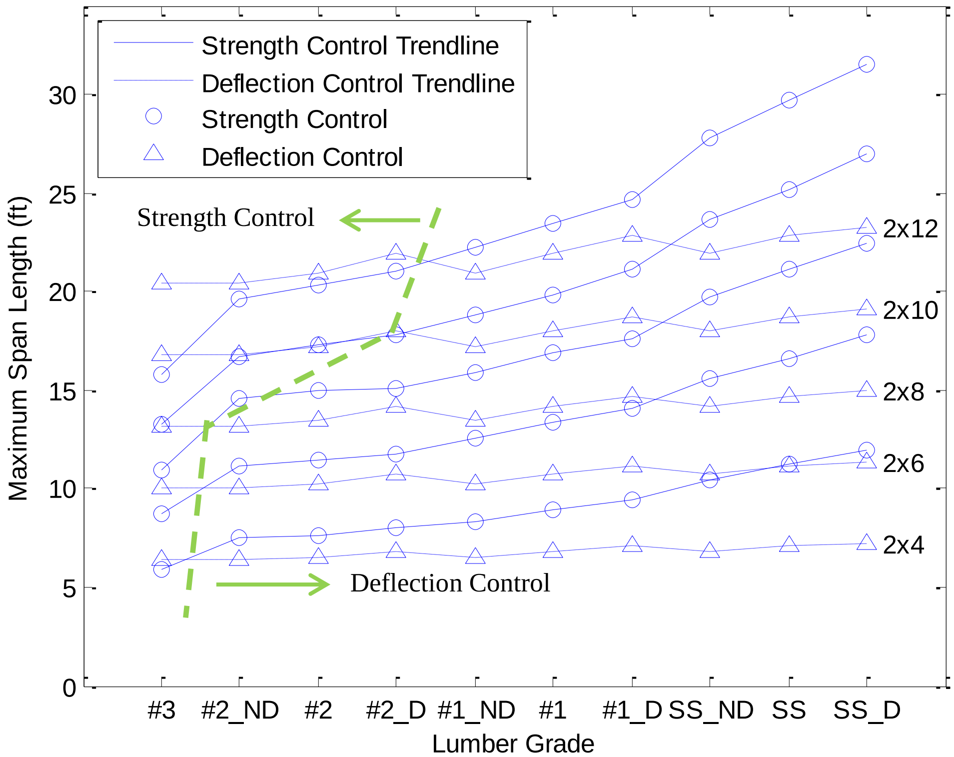


Figure C.4: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 12 in. on-center and *LL/DL* ratio of 4 (2012 NDS).

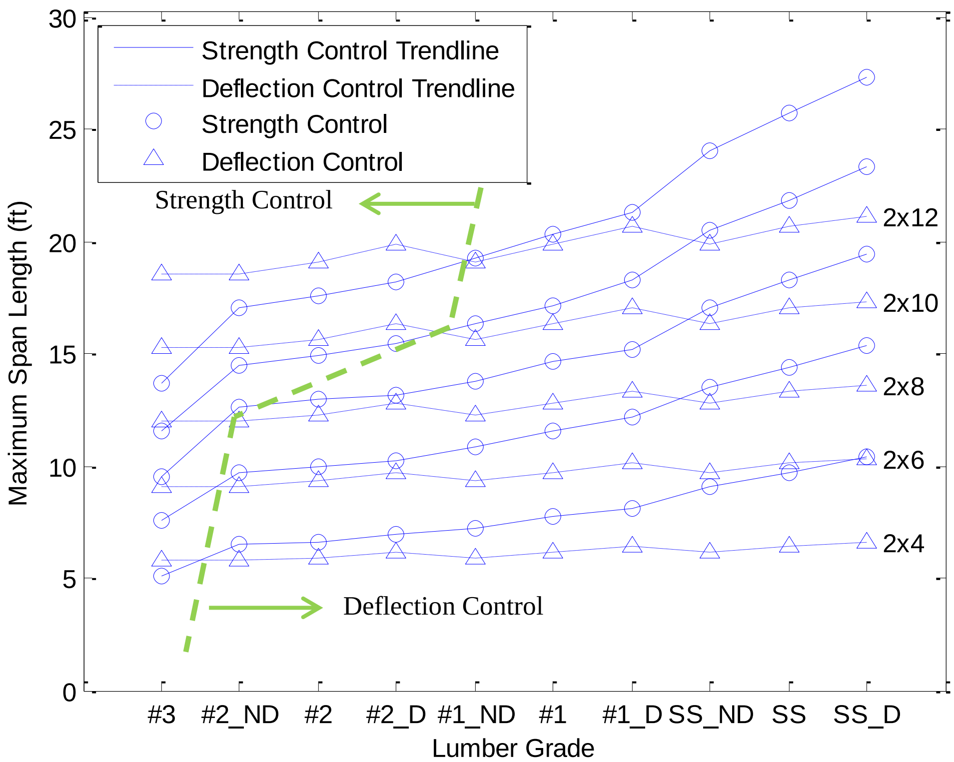


Figure C.5: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 16 in. on-center and *LL/DL* ratio of 4 (2012 NDS).

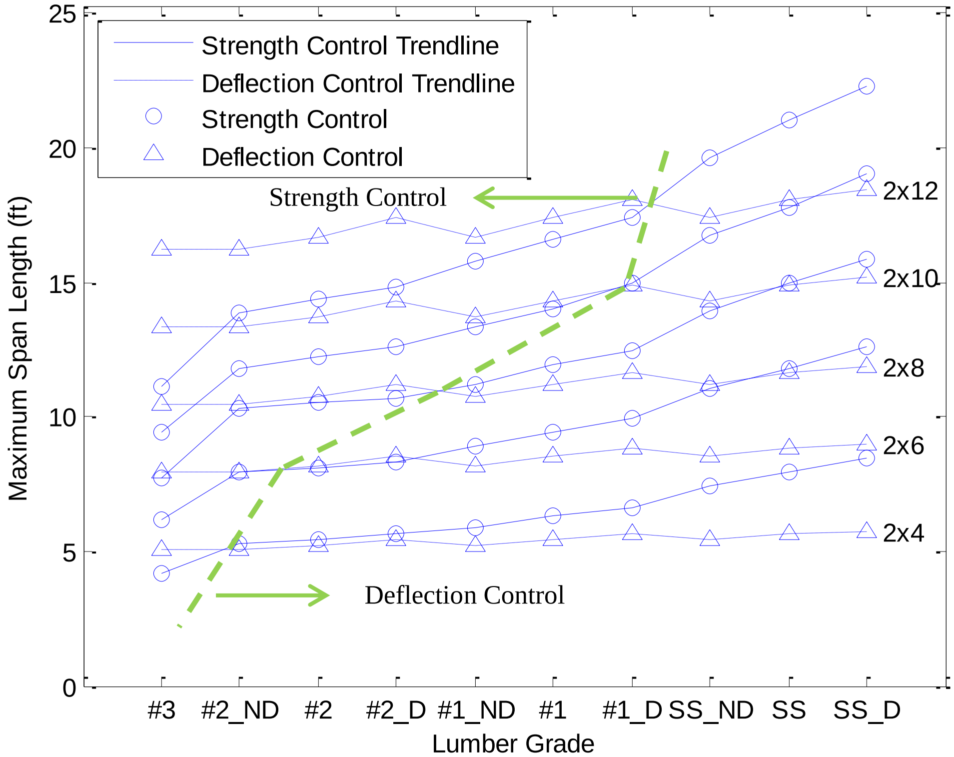


Figure C.6: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 24 in. on-center and *LL/DL* ratio of 4 (2012 NDS).

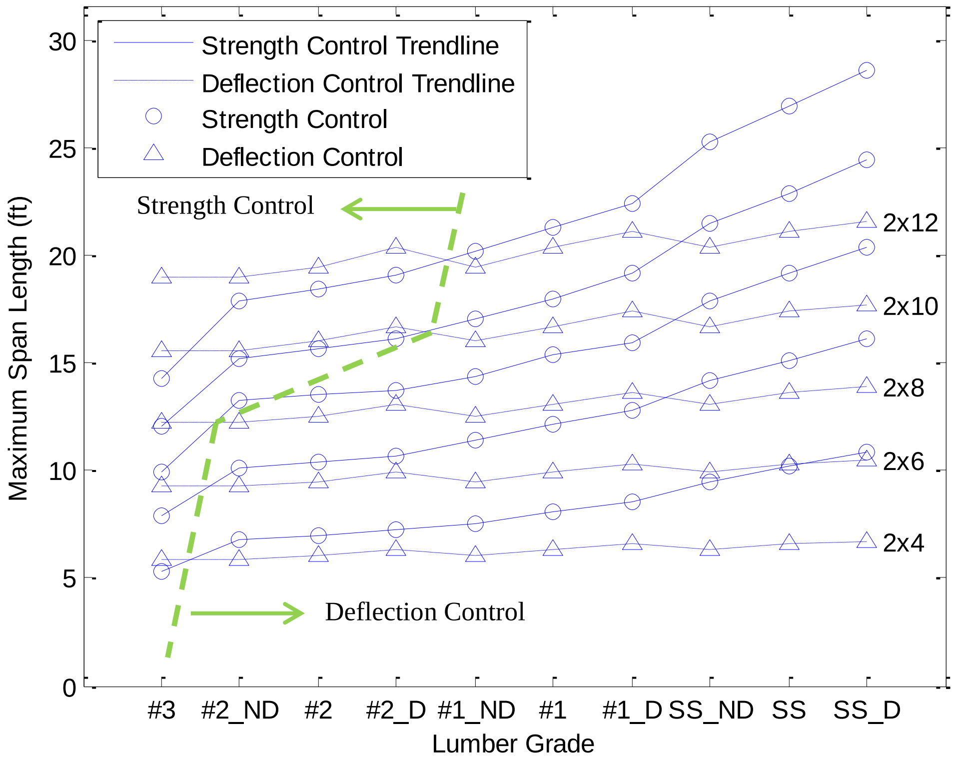


Figure C.7: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 12 in. on-center and *LL/DL* ratio of 5 (2012 NDS).

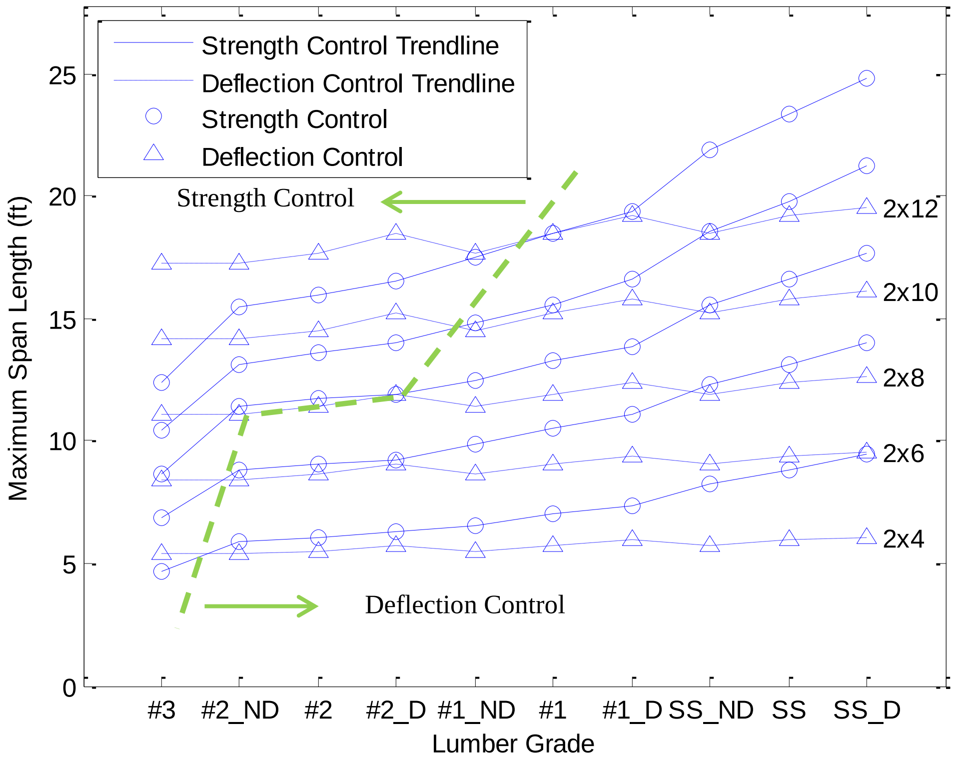


Figure C.8: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 16 in. on-center and *LL/DL* ratio of 5 (2012 NDS).

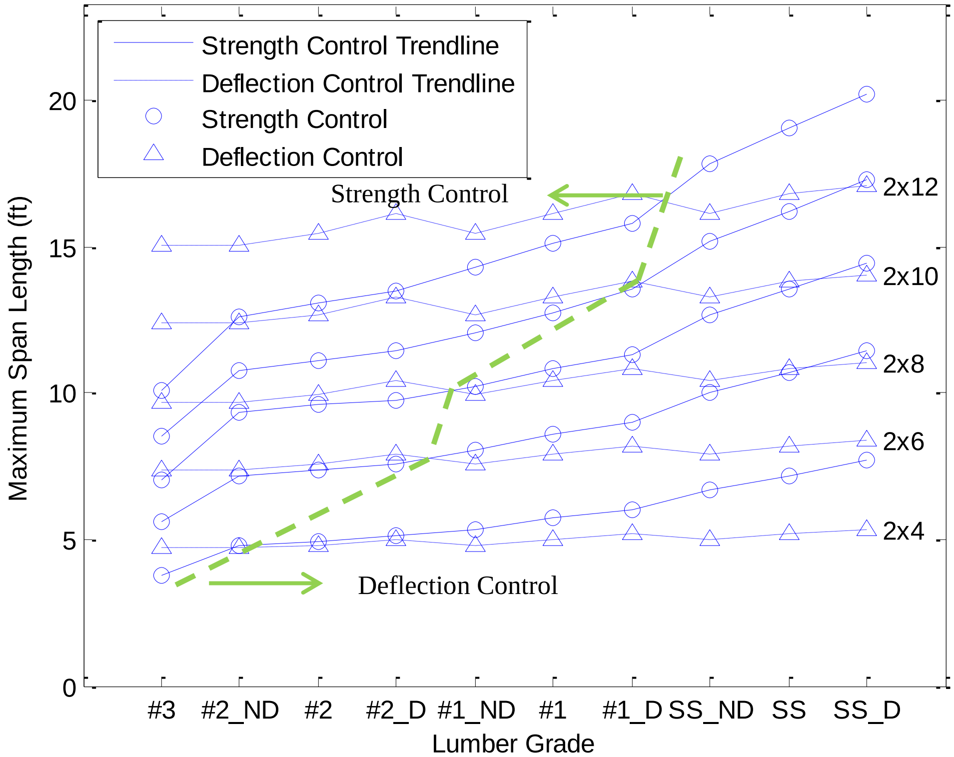


Figure C.9: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 24 in. on-center and *LL/DL* ratio of 5 (2012 NDS).

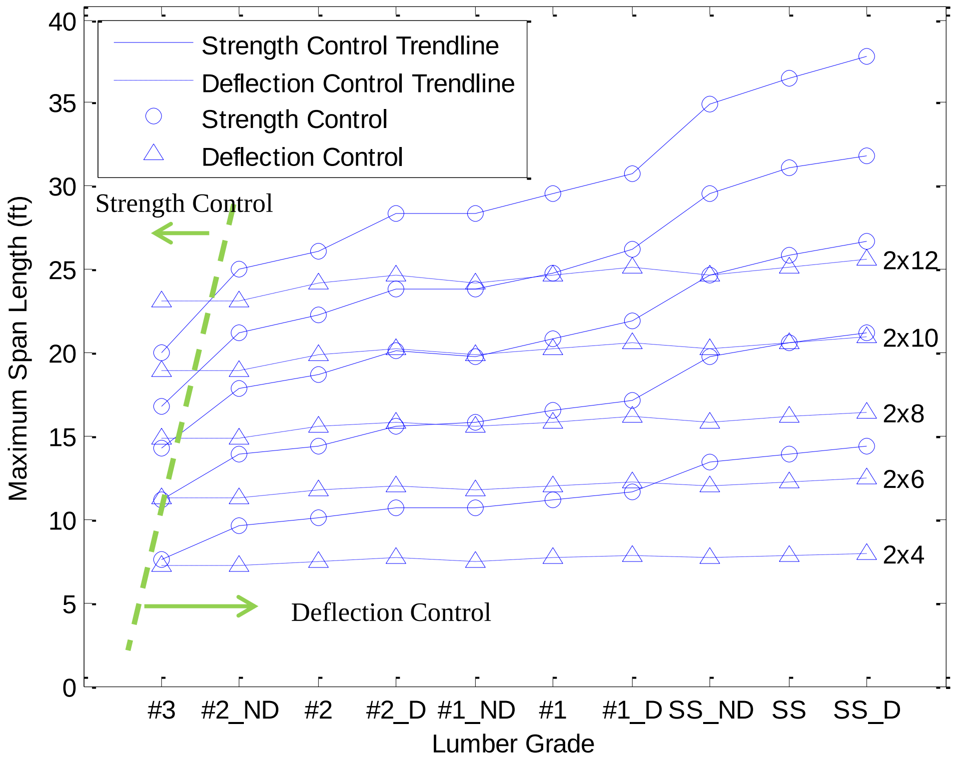


Figure C.10: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 12 in. on-center and *LL/DL* ratio of 3 (2005 NDS).

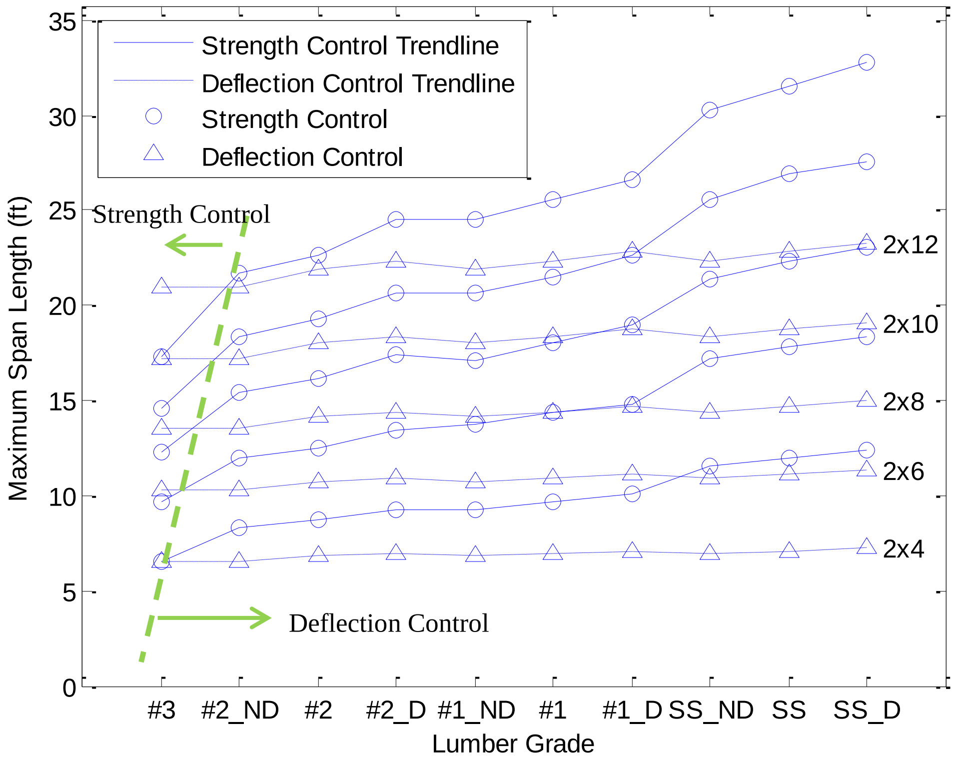


Figure C.11: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 16 in. on-center and *LL/DL* ratio of 3 (2005 NDS).

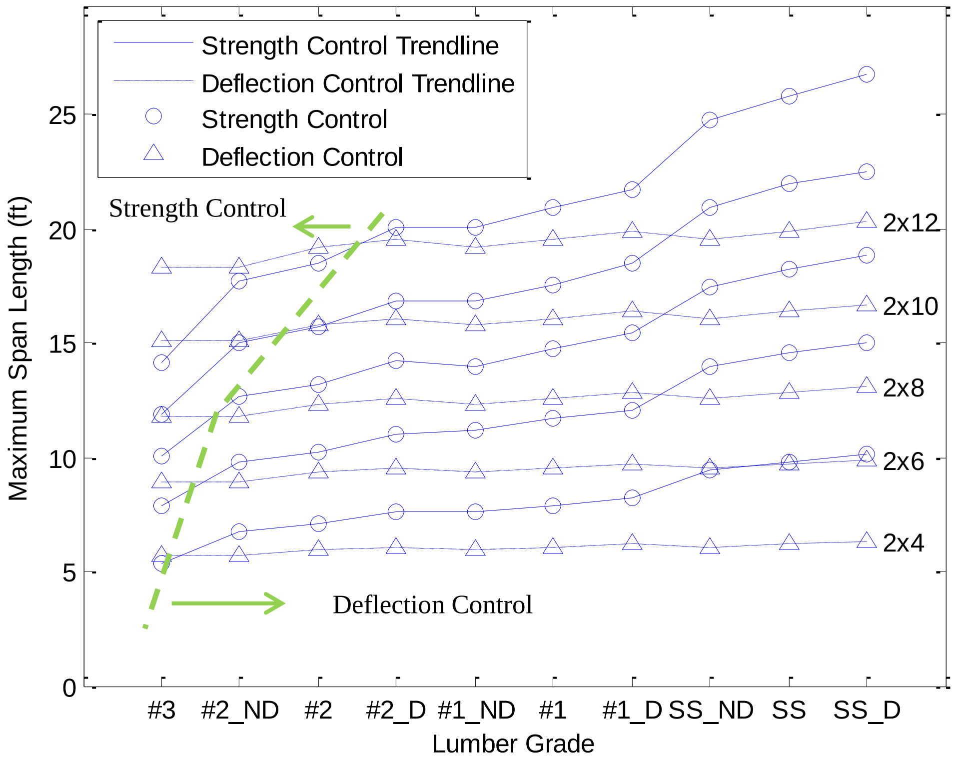


Figure C.12: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 24 in. on-center and *LL/DL* ratio of 3 (2005 NDS).

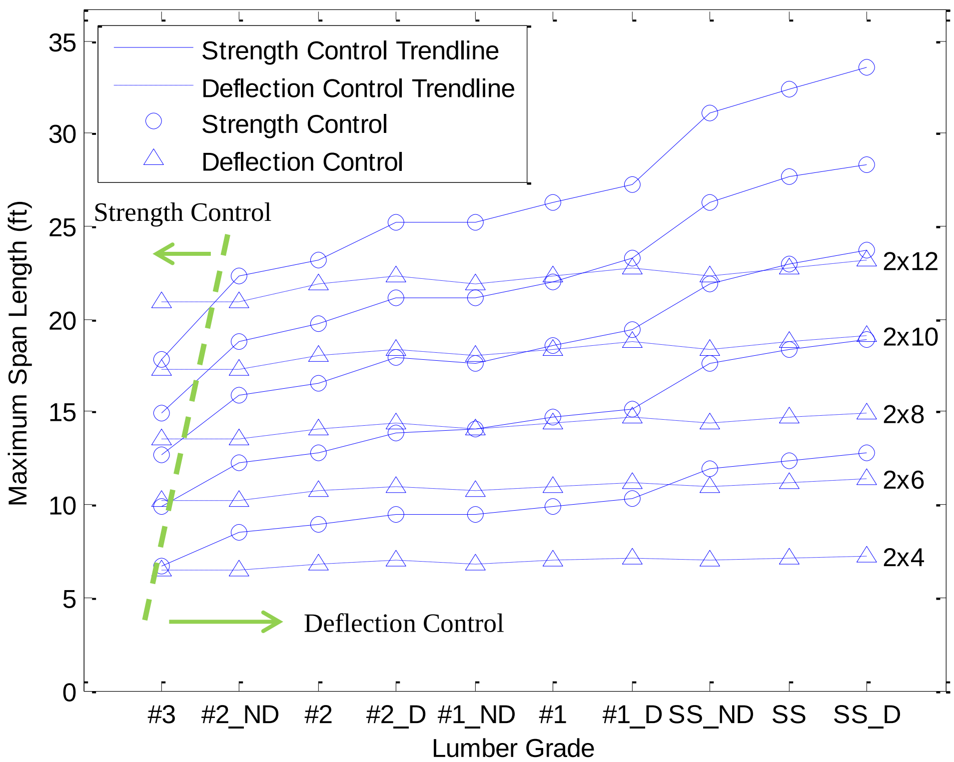


Figure C.13: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 12 in. on-center and *LL/DL* ratio of 4 (2005 NDS).

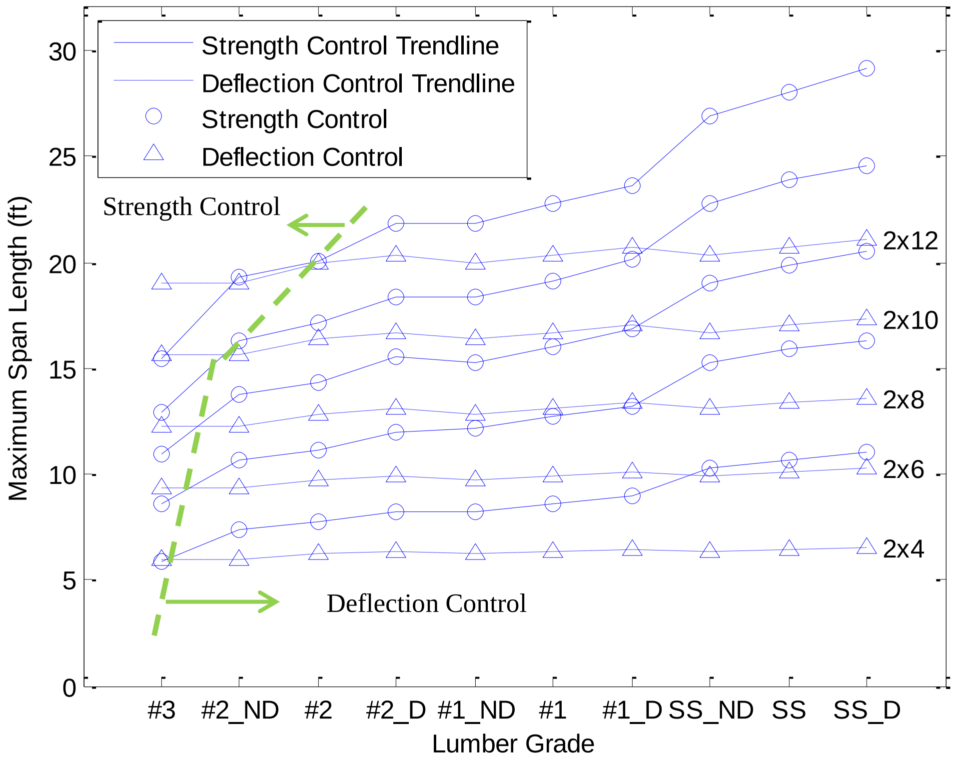


Figure C.14: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 16 in. on-center and *LL/DL* ratio of 4 (2005 NDS).

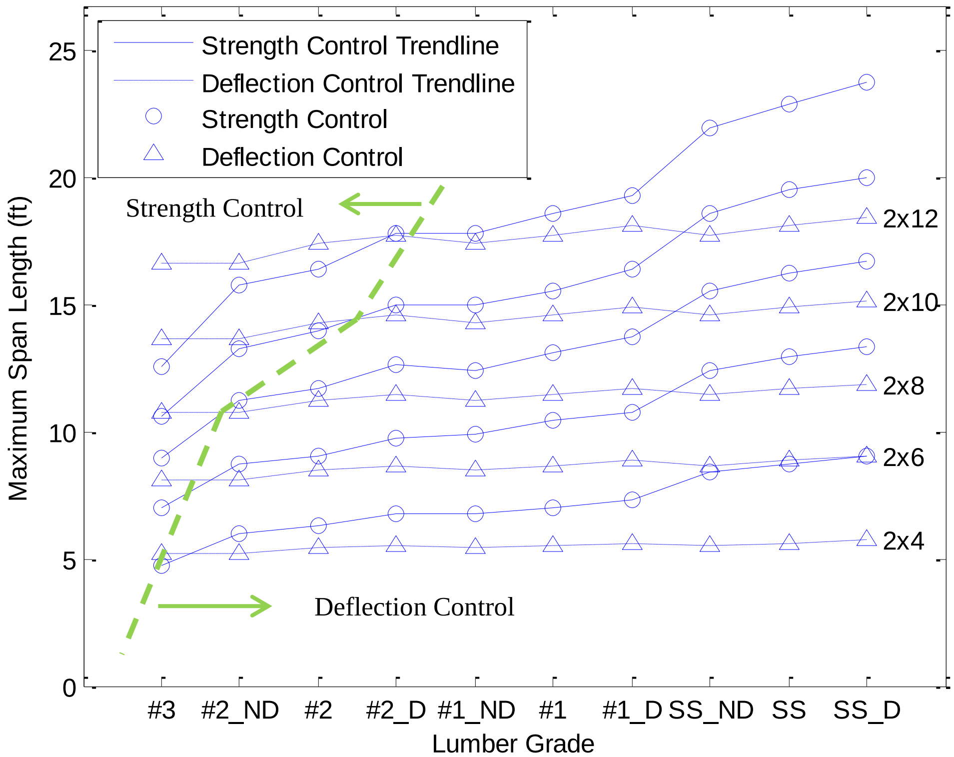


Figure C.15: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 24 in. on-center and *LL/DL* ratio of 4 (2005 NDS).

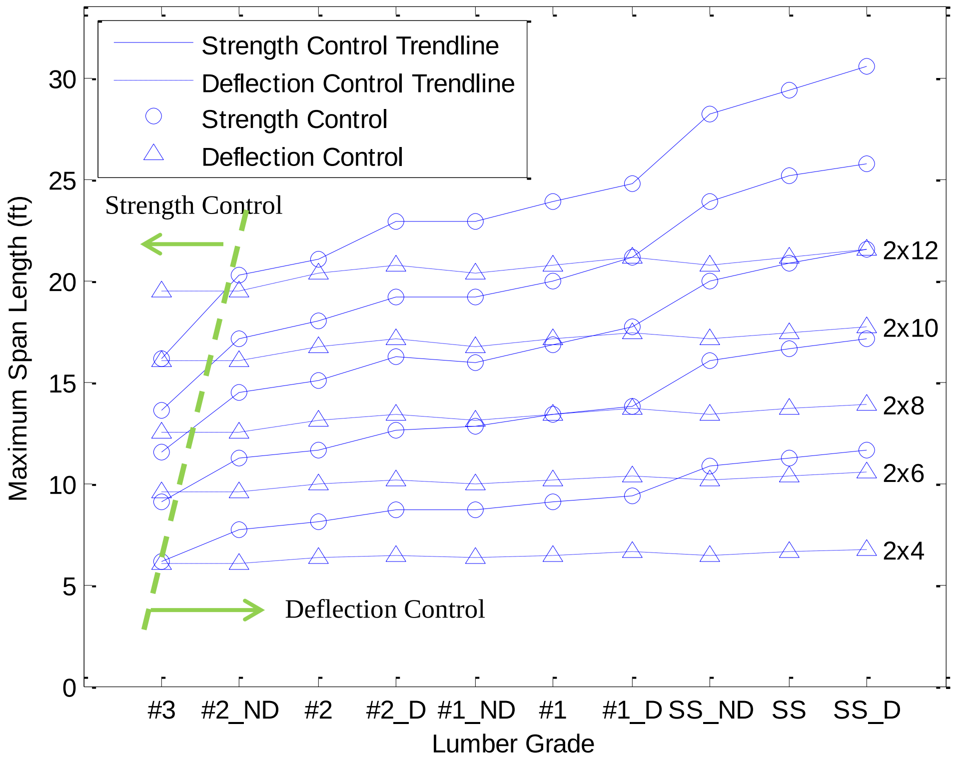


Figure C.16: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 12 in. on-center and *LL/DL* ratio of 5 (2005 NDS).

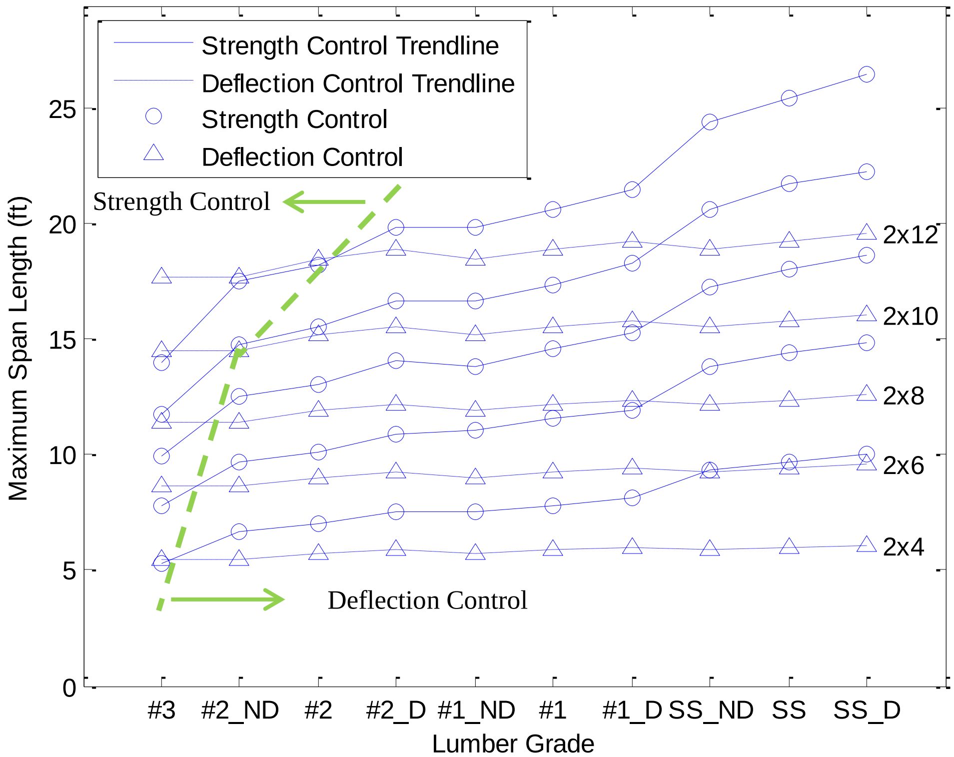


Figure C.17: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 16 in. on-center and *LL/DL* ratio of 5 (2005 NDS).

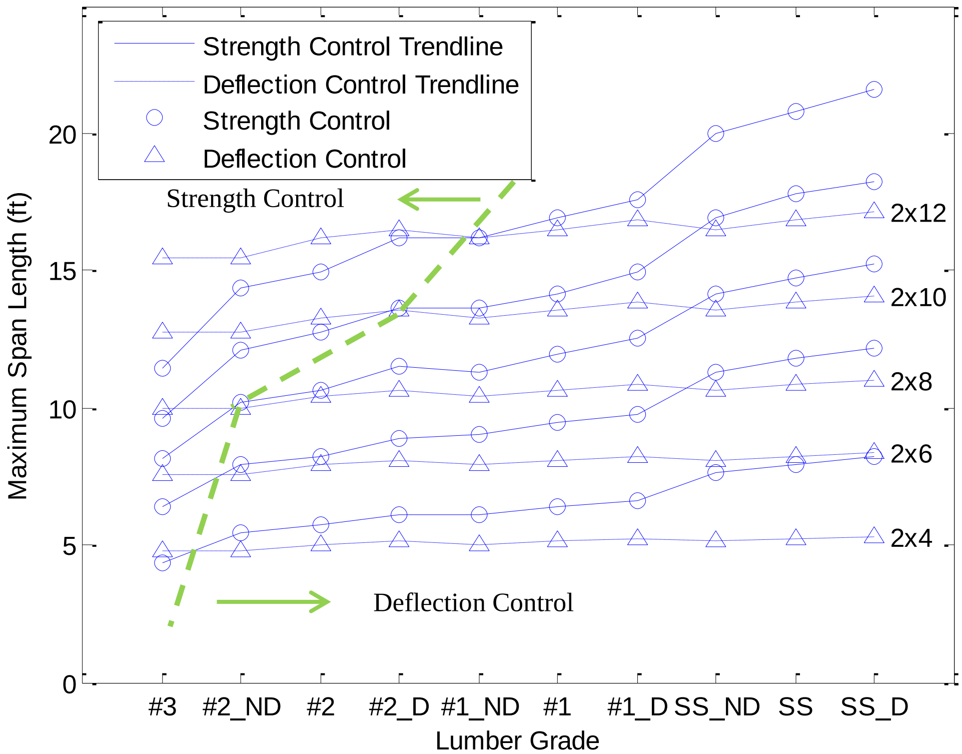


Figure C.18: Maximum span length versus lumber grade for Southern Pine floor joists spaced at 24 in. on-center and *LL/DL* ratio of 5 (2005 NDS).

Appendix D

Effect of Live Load to Dead Load Ratio

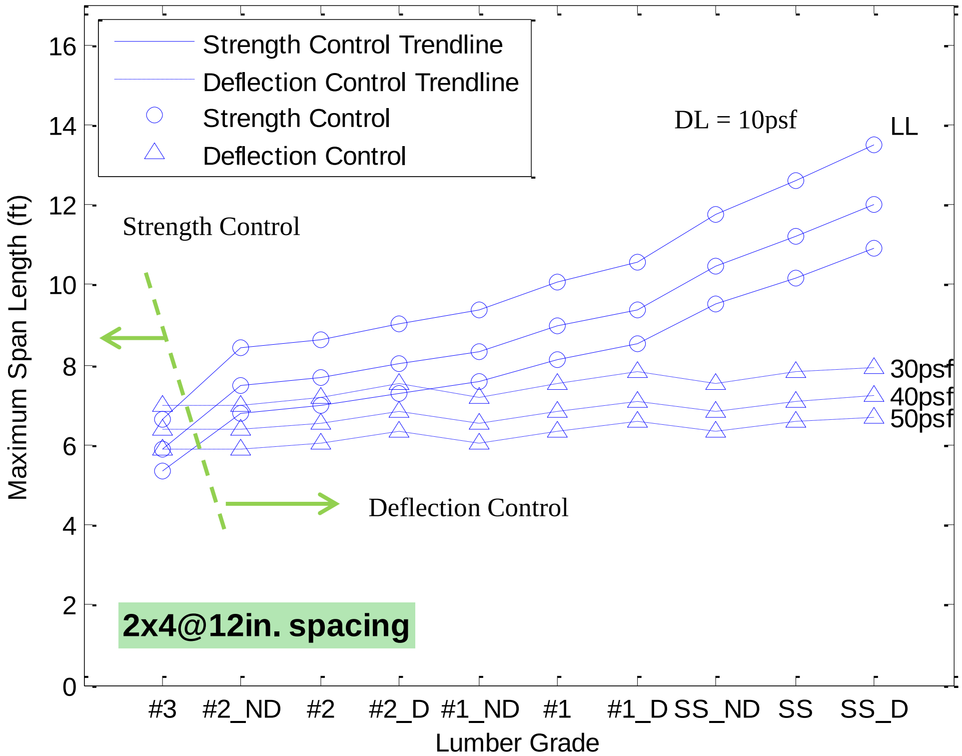


Figure D.1: Effects of live load on maximum span length for 2x4 Southern Pine floor joists at 12 inch on center (2012 NDS).

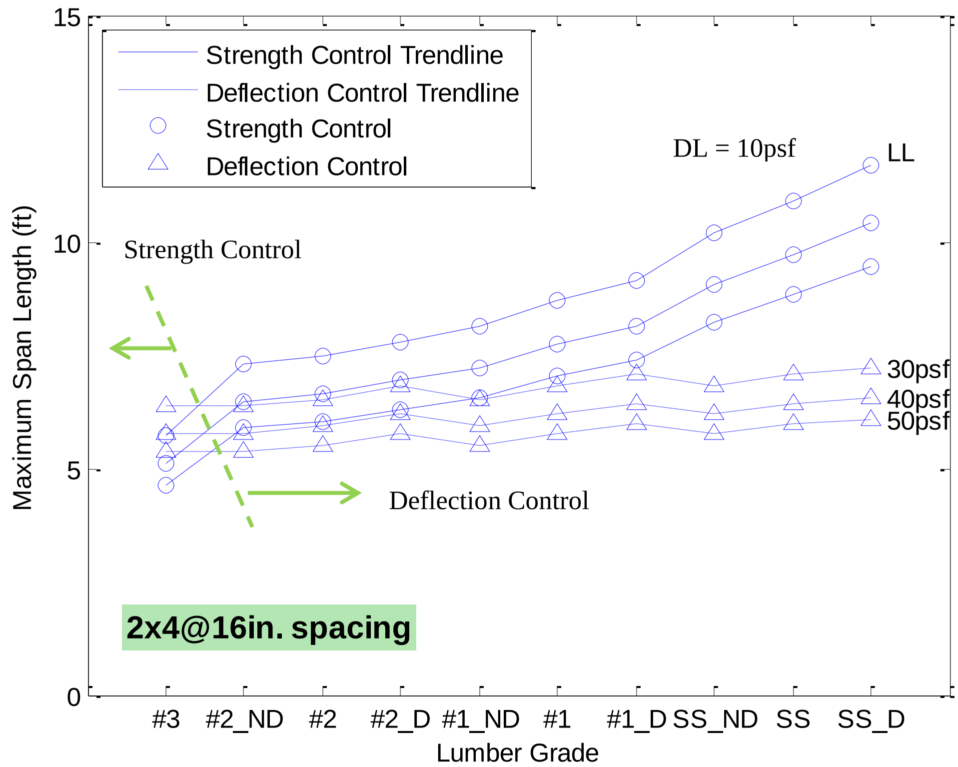


Figure D.2: Effects of live load on maximum span length for 2x4 Southern Pine floor joists at 16 inch on center (2012 NDS).

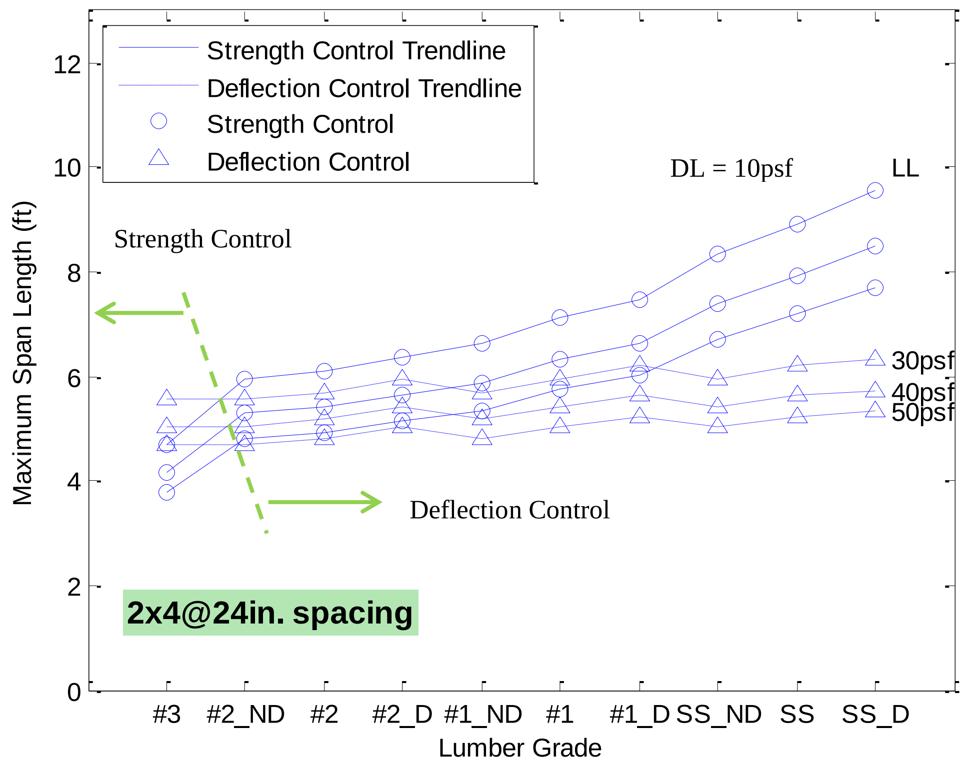


Figure D.3: Effects of live load on maximum span length for 2x4 Southern Pine floor joists at 24 inch on center (2012 NDS).

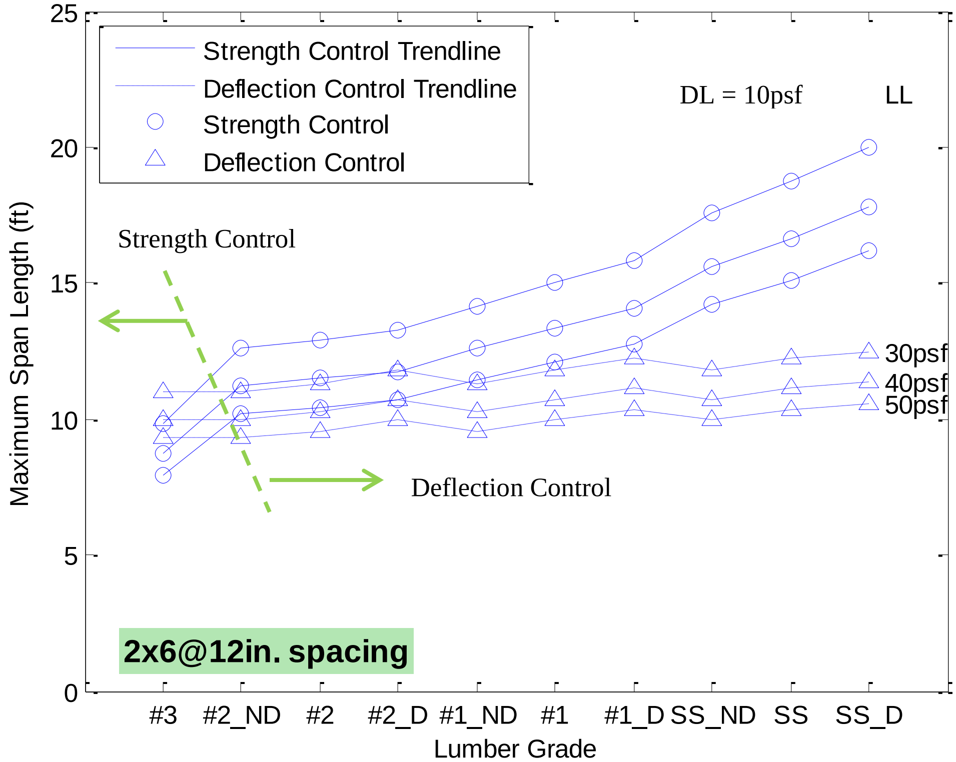


Figure D.4: Effects of live load on maximum span length for 2x6 Southern Pine floor joists at 12 inch on center (2012 NDS).

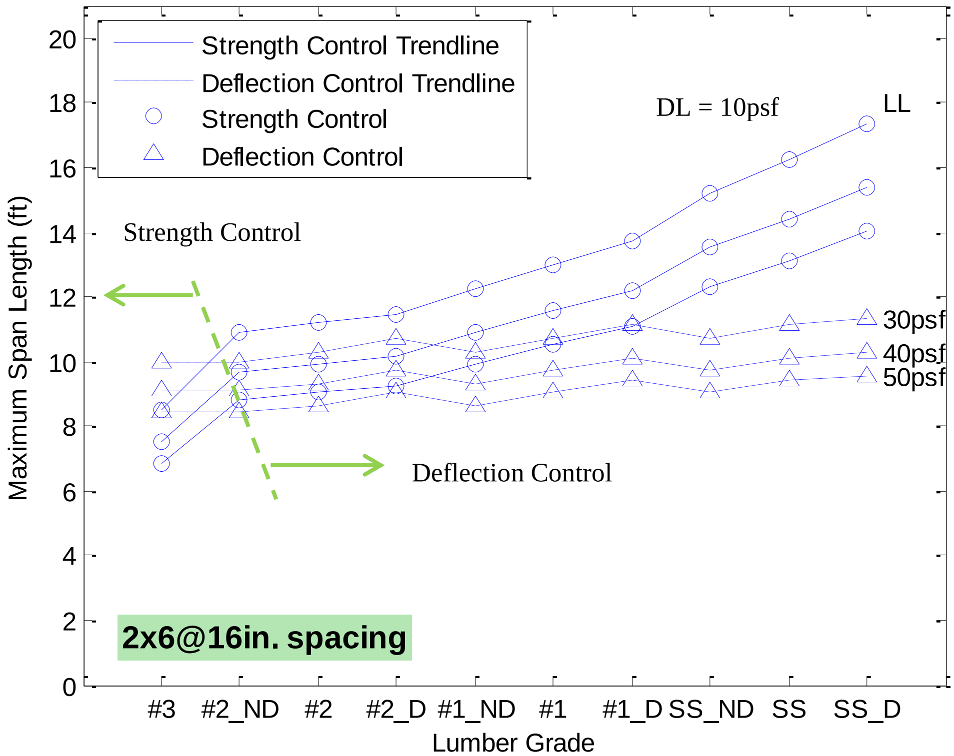


Figure D.5: Effects of live load on maximum span length for 2x6 Southern Pine floor joists at 16 inch on center (2012 NDS).

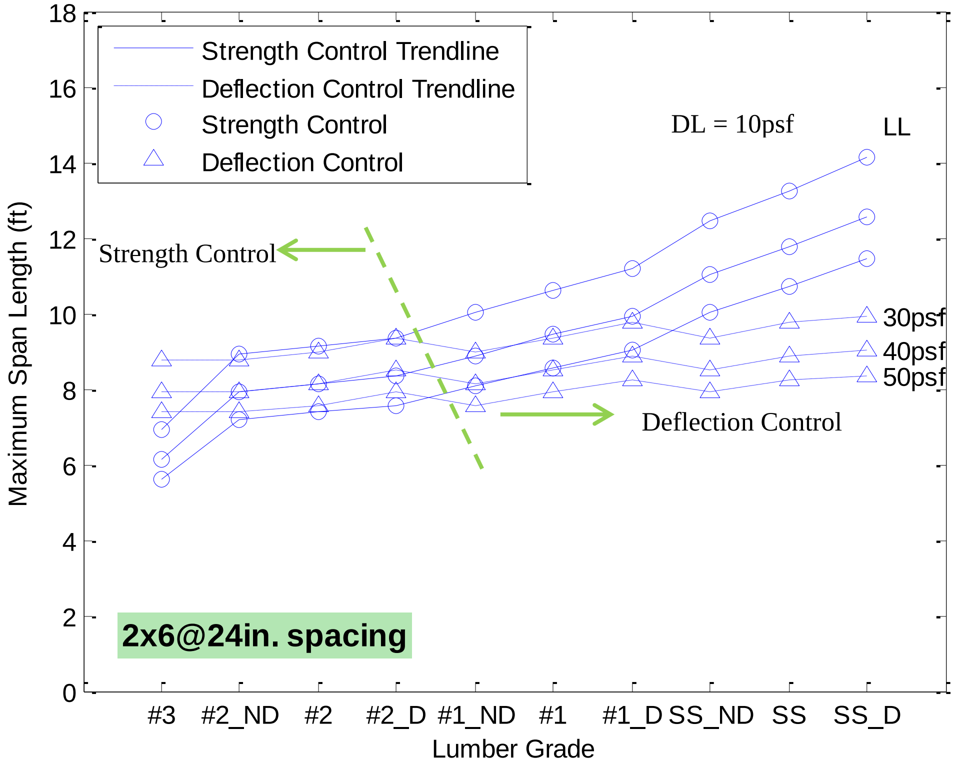


Figure D.6: Effects of live load on maximum span length for 2x6 Southern Pine floor joists at 24 inch on center (2012 NDS).

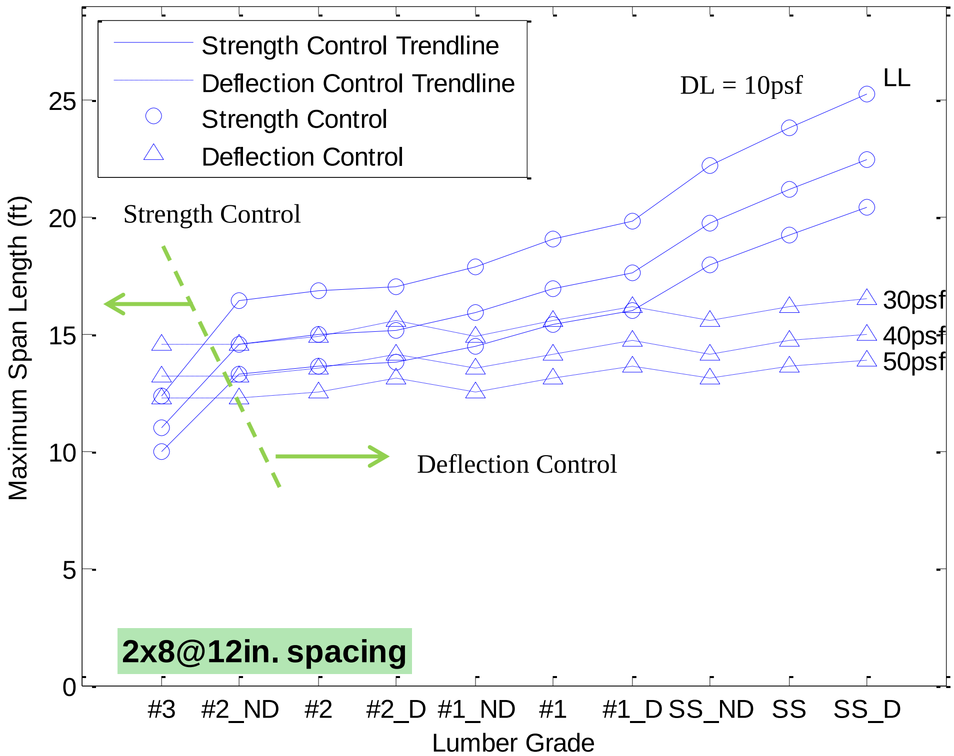


Figure D.7: Effects of live load on maximum span length for 2x8 Southern Pine floor joists at 12 inch on center (2012 NDS).

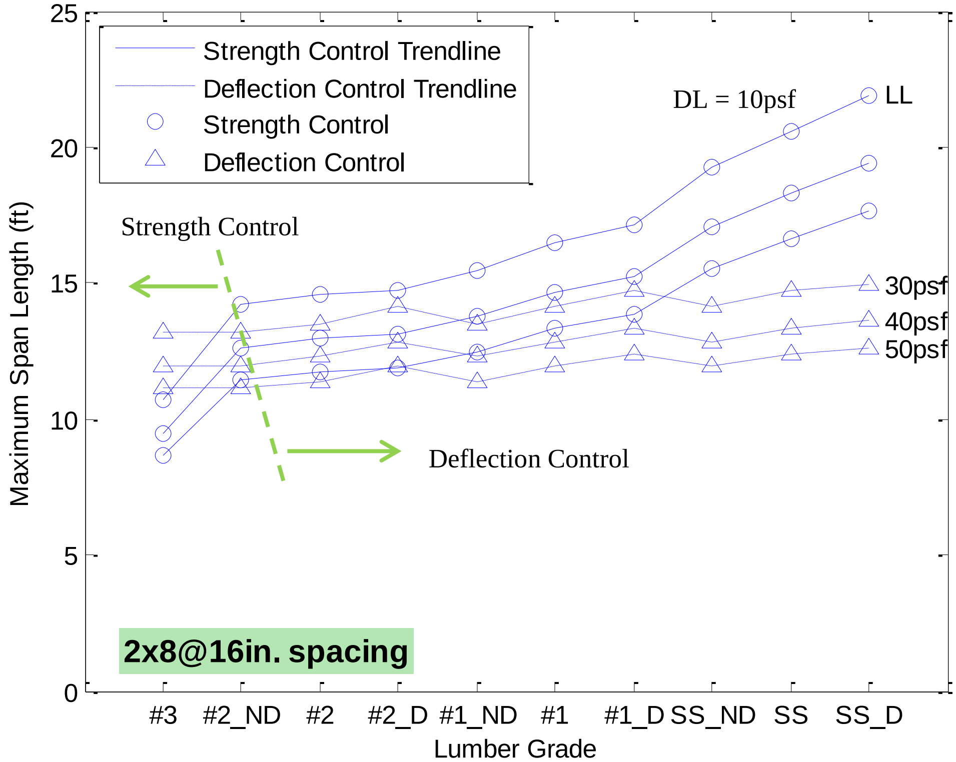


Figure D.8: Effects of live load on maximum span length for 2x8 Southern Pine floor joists at 16 inch on center (2012 NDS).

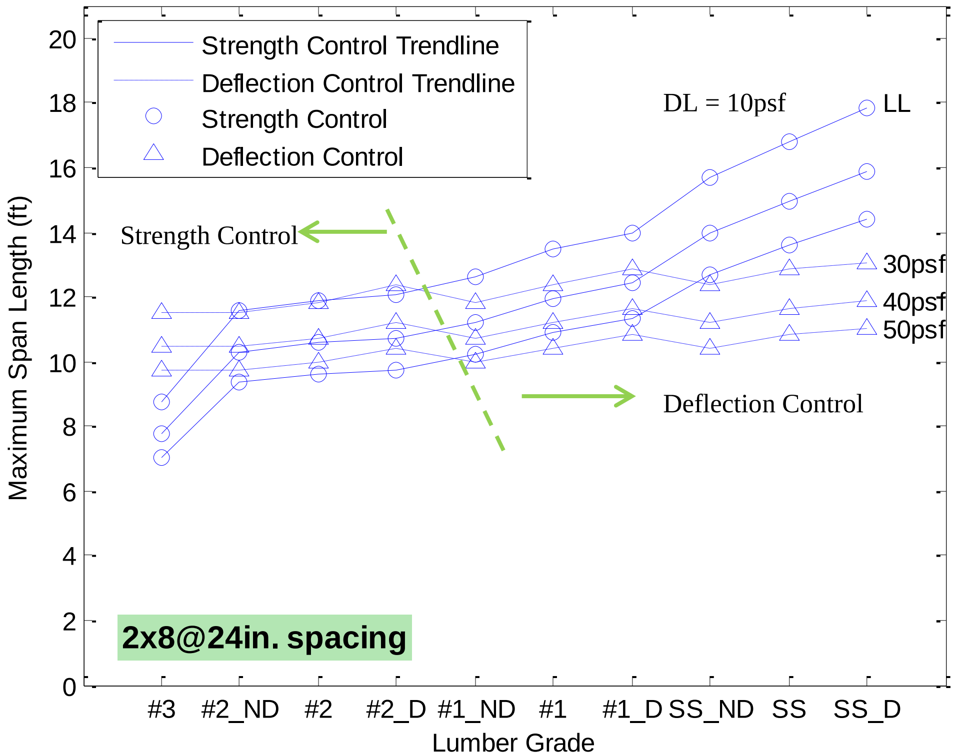


Figure D.9: Effects of live load on maximum span length for 2x8 Southern Pine floor joists at 24 inch on center (2012 NDS).

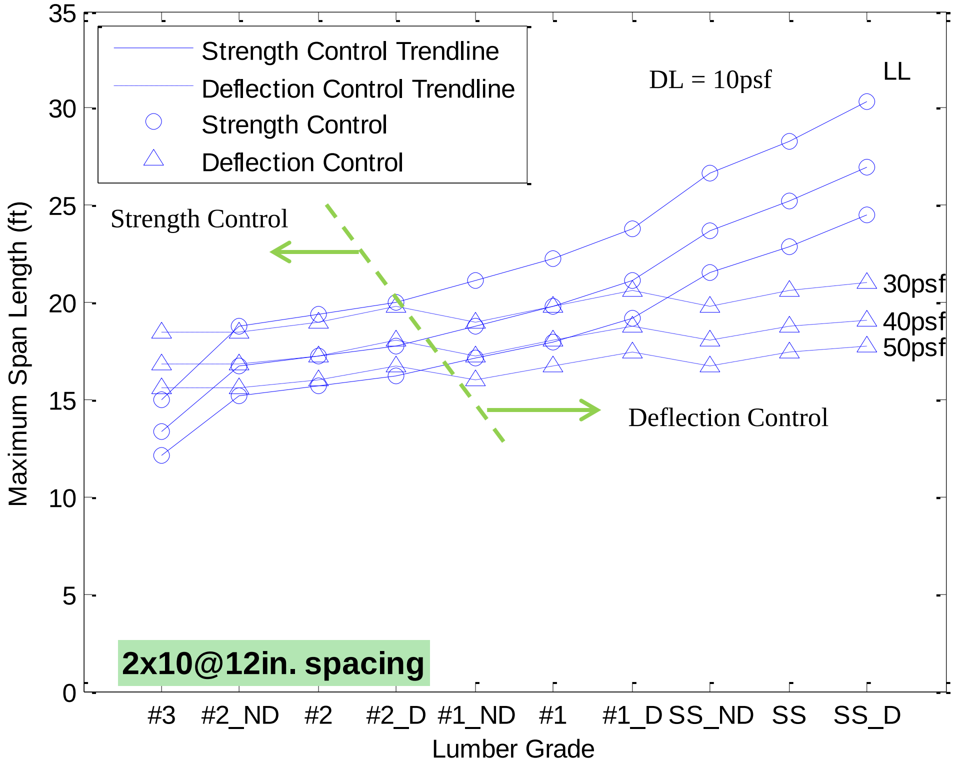


Figure D.10: Effects of live load on maximum span length for 2x10 Southern Pine floor joists at 12 inch on center (2012 NDS).

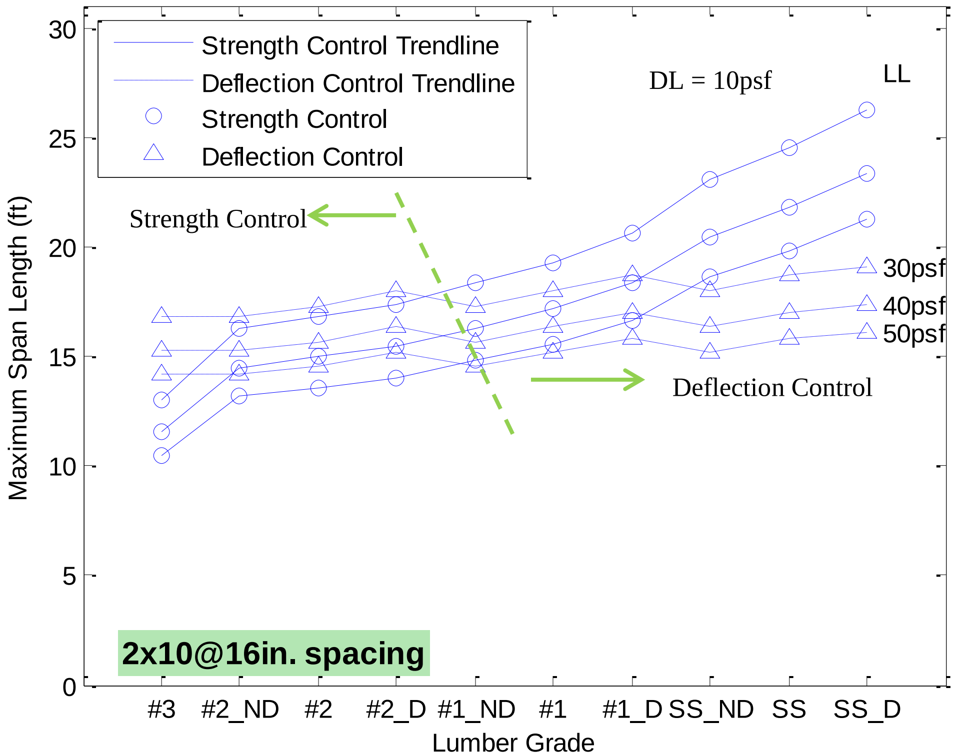


Figure D.11: Effects of live load on maximum span length for 2x10 Southern Pine floor joists at 16 inch on center (2012 NDS).

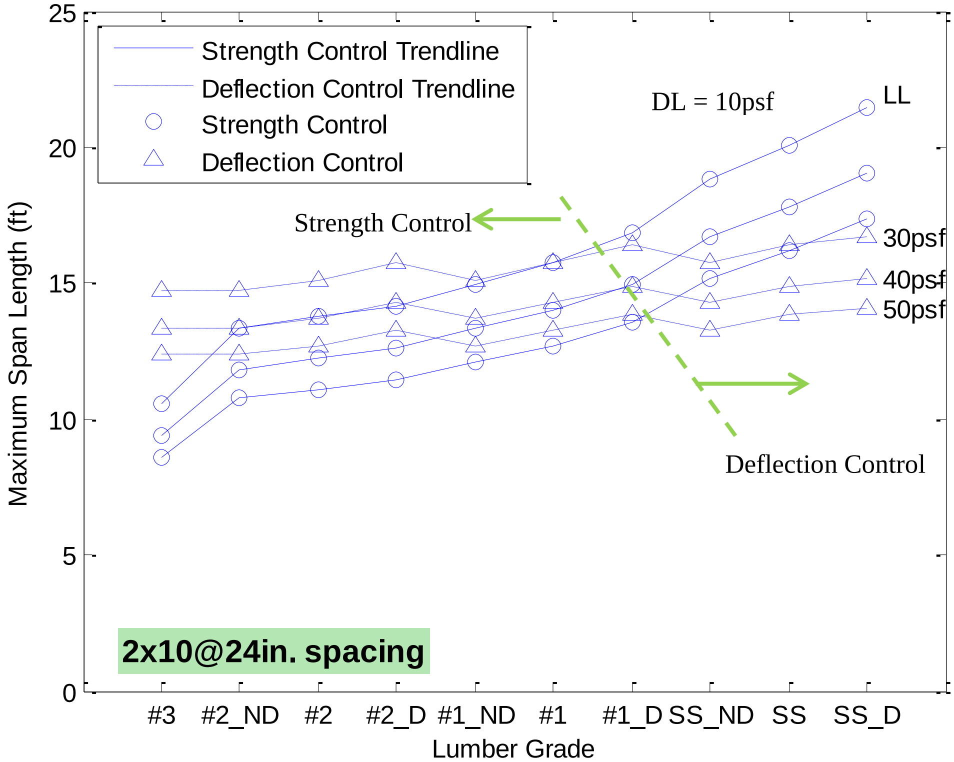


Figure D.12: Effects of live load on maximum span length for 2x10 Southern Pine floor joists at 24 inch on center (2012 NDS).

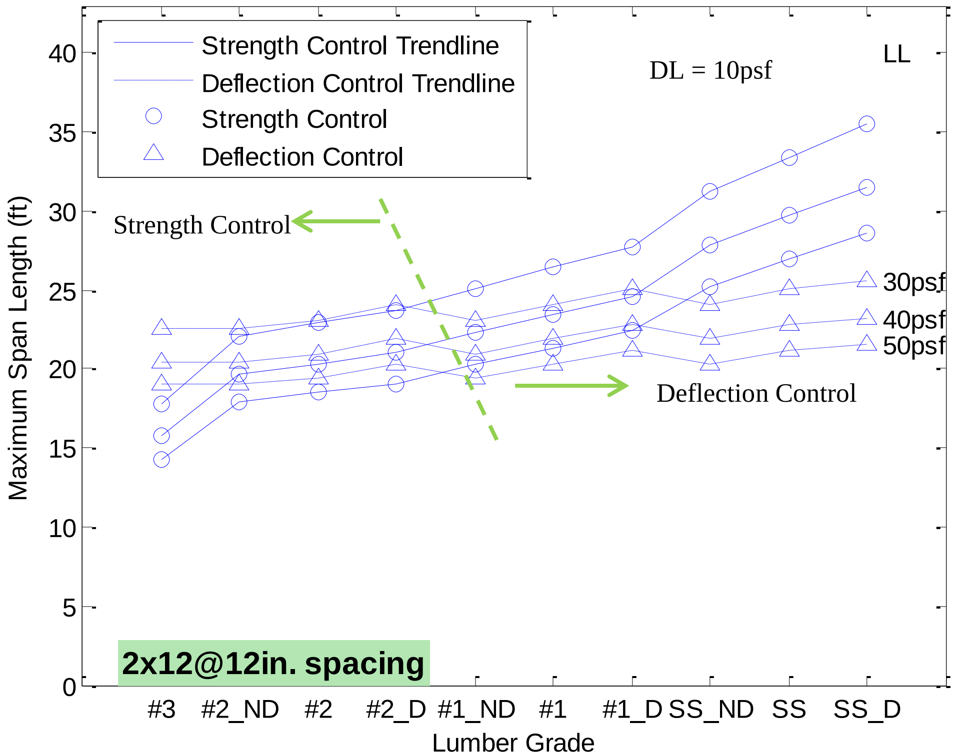


Figure D.13: Effects of live load on maximum span length for 2x12 Southern Pine floor joists at 12 inch on center (2012 NDS).

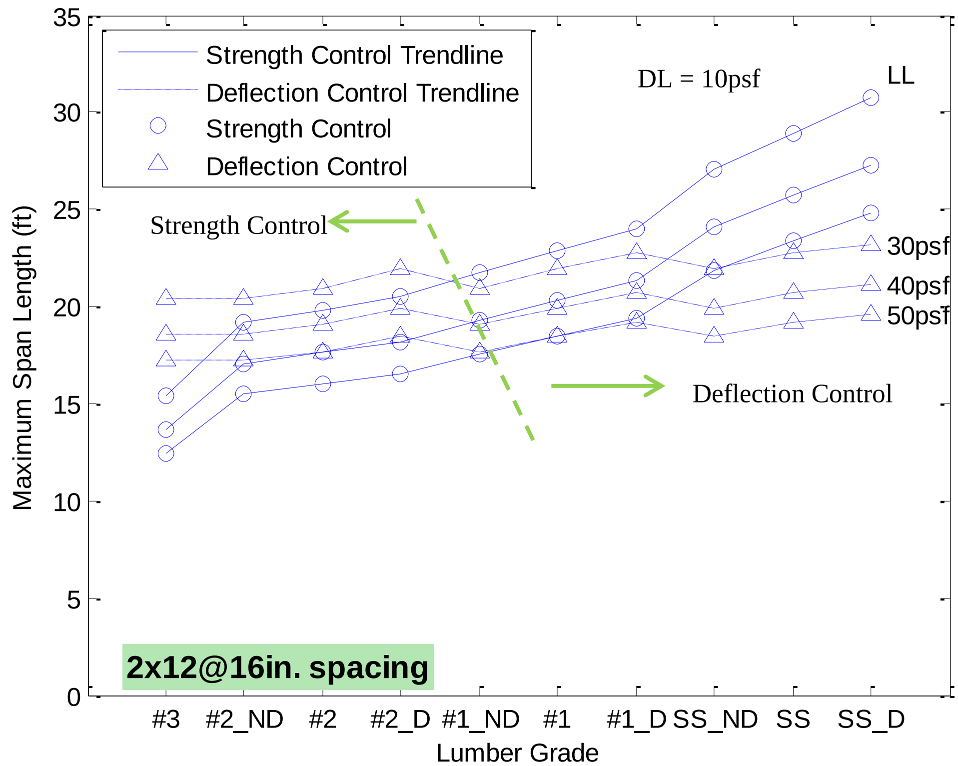


Figure D.14: Effects of live load on maximum span length for 2x12 Southern Pine floor joists at 16 inch on center (2012 NDS).

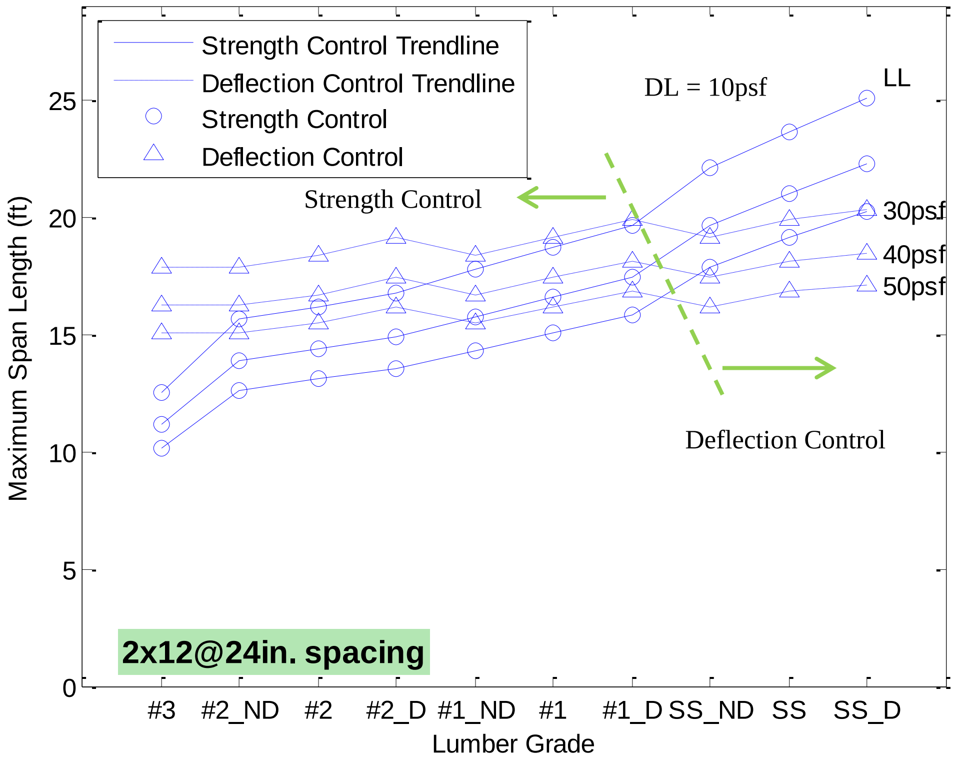


Figure D.15: Effects of live load on maximum span length for 2x12 Southern Pine floor joists at 24 inch on center (2012 NDS).

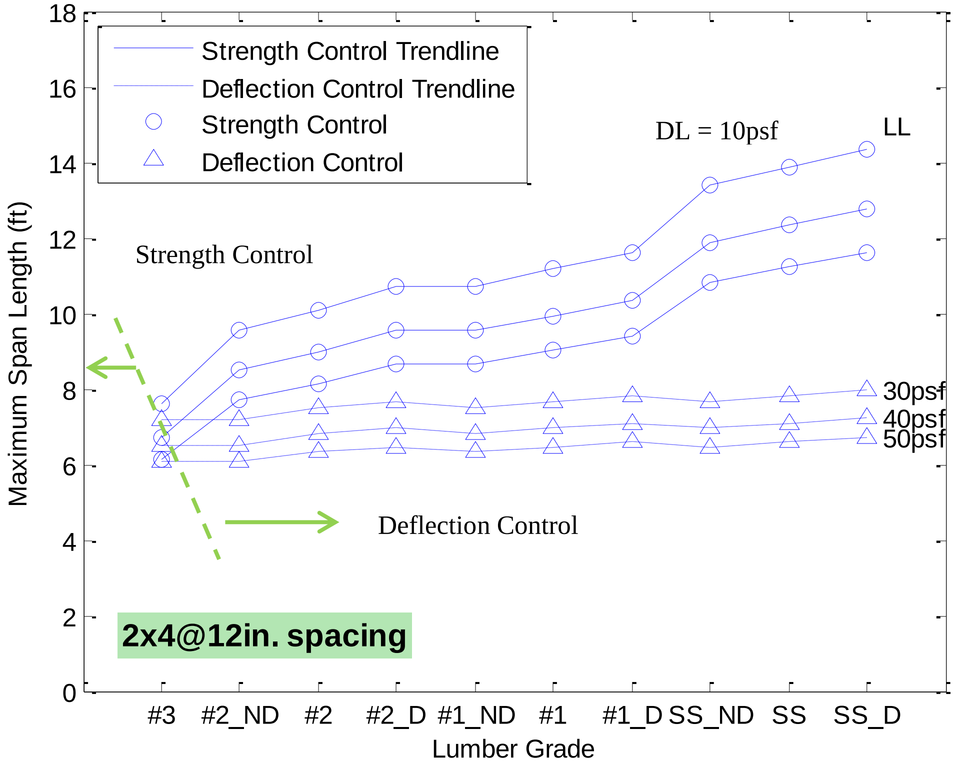


Figure D.16: Effects of live load on maximum span length for 2x4 Southern Pine floor joists at 12 inch on center (2005 NDS).

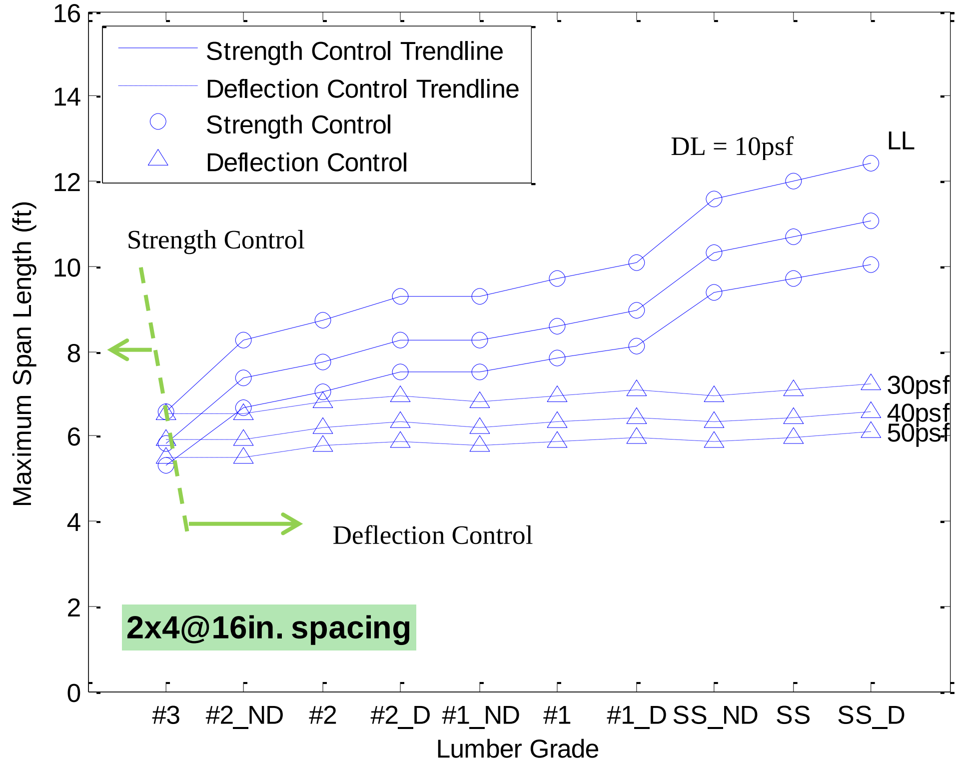


Figure D.17: Effects of live load on maximum span length for 2x4 Southern Pine floor joists at 16 inch on center (2005 NDS).

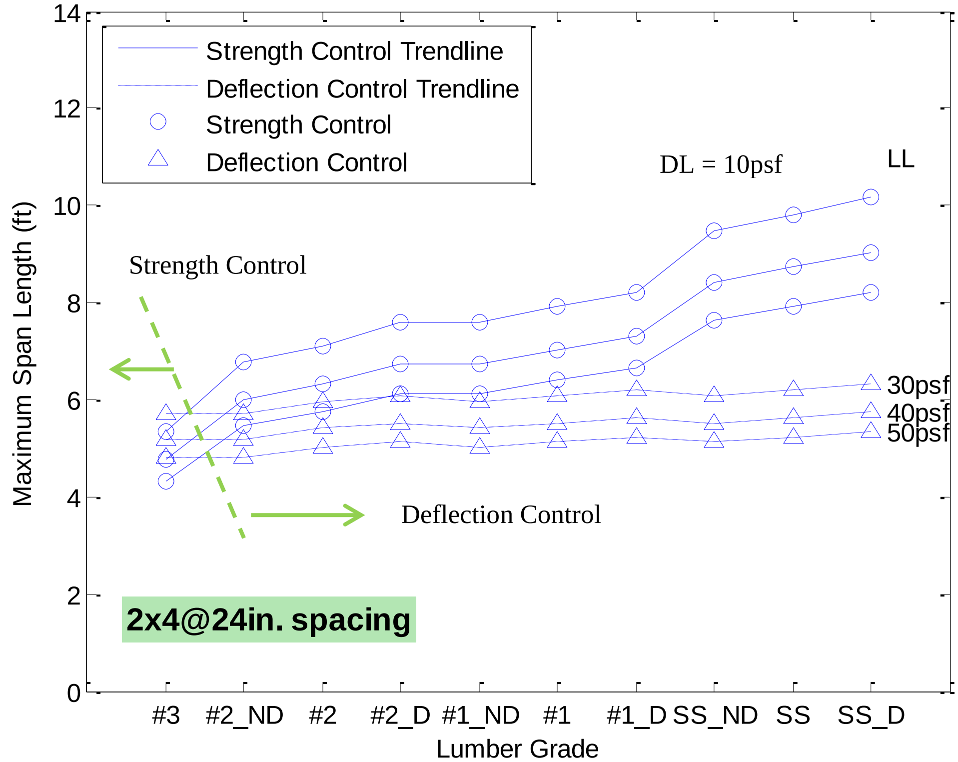


Figure D.18: Effects of live load on maximum span length for 2x4 Southern Pine floor joists at 24 inch on center (2005 NDS).

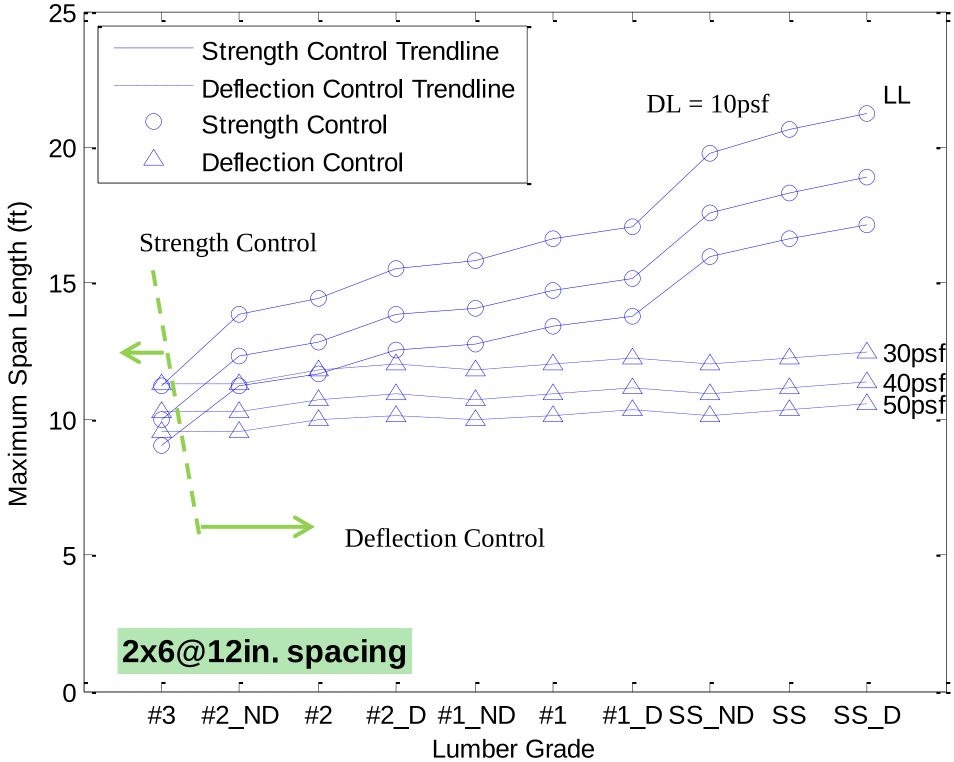


Figure D.19: Effects of live load on maximum span length for 2x6 Southern Pine floor joists at 12 inch on center (2005 NDS).

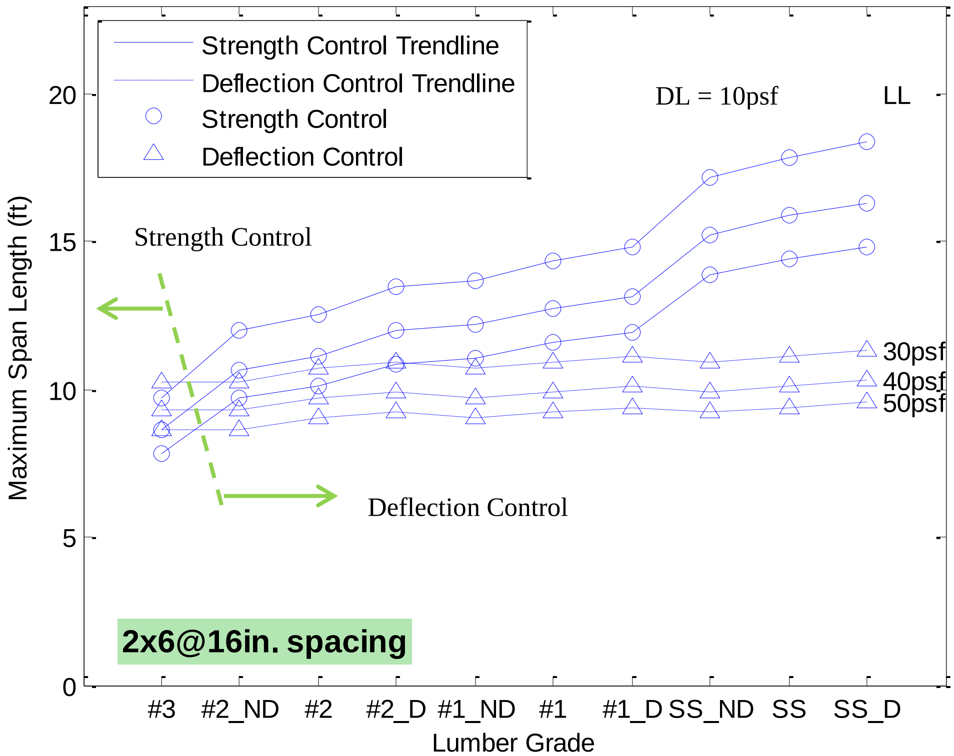


Figure D.20: Effects of live load on maximum span length for 2x6 Southern Pine floor joists at 16 inch on center (2005 NDS).

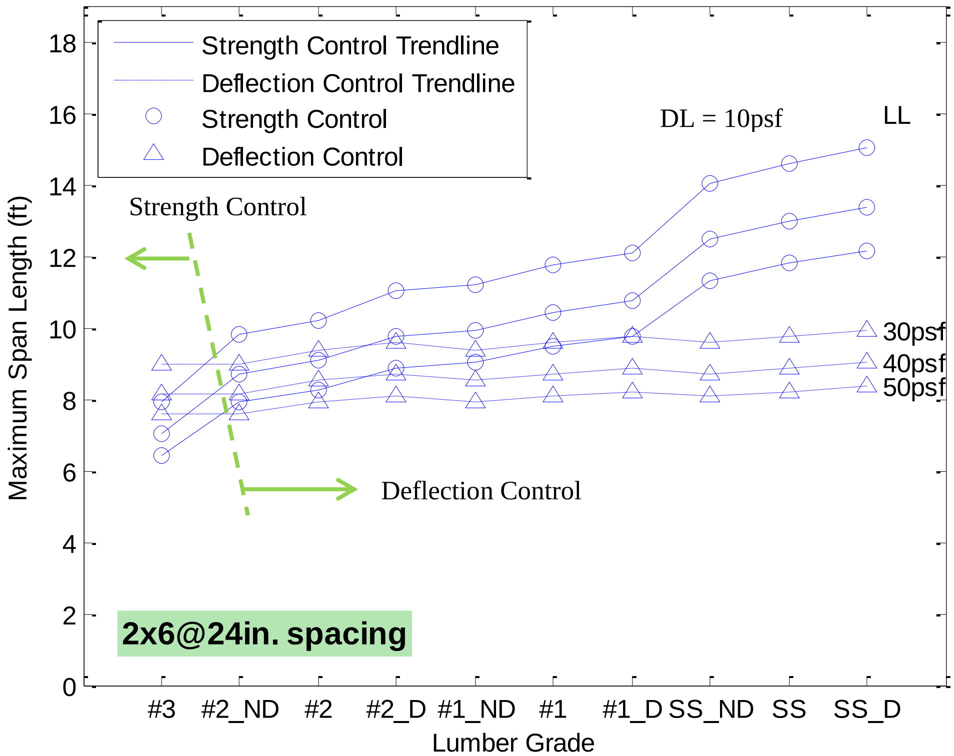


Figure D.21: Effects of live load on maximum span length for 2x6 Southern Pine floor joists at 24 inch on center (2005 NDS).

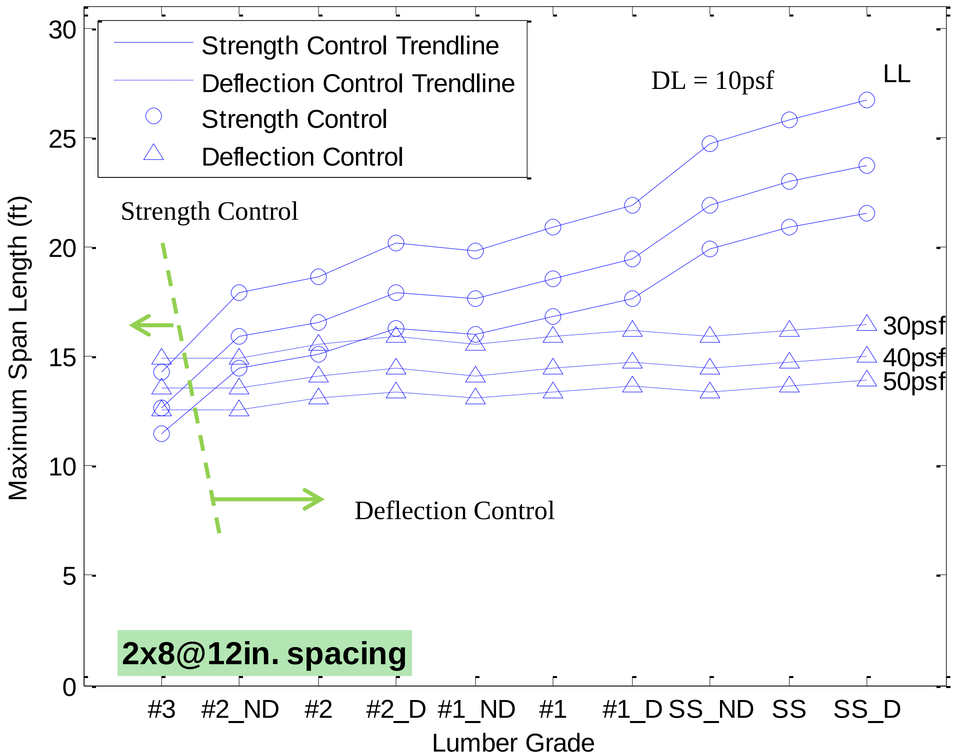


Figure D.22: Effects of live load on maximum span length for 2x8 Southern Pine floor joists at 12 inch on center (2005 NDS).

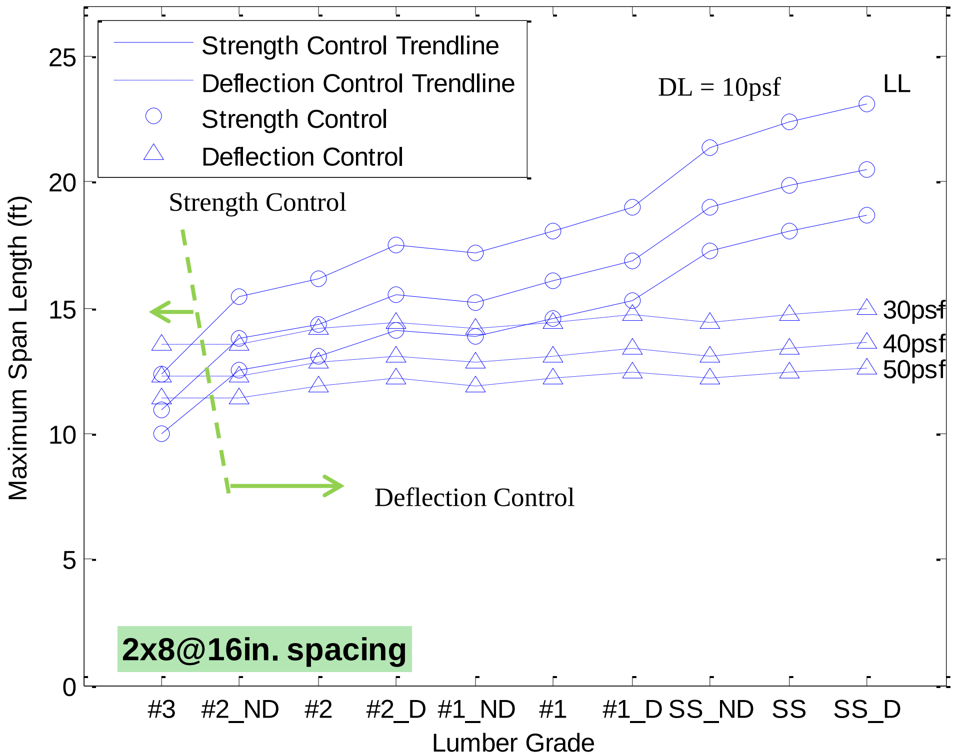


Figure D.23: Effects of live load on maximum span length for 2x8 Southern Pine floor joists at 16 inch on center (2005 NDS).

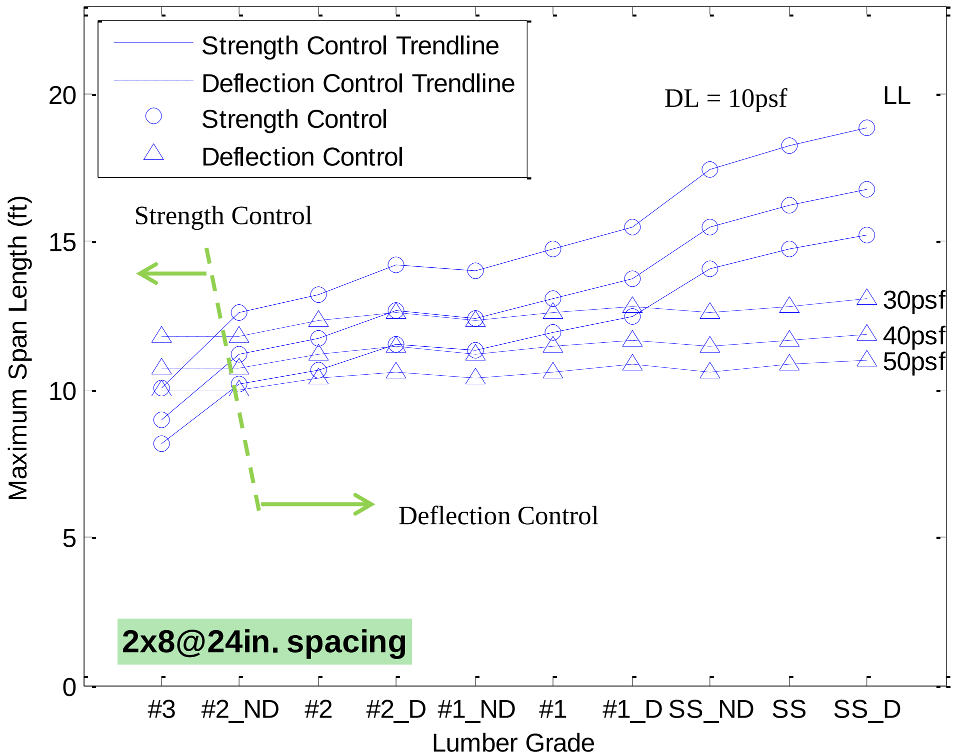


Figure D.24: Effects of live load on maximum span length for 2x8 Southern Pine floor joists at 24 inch on center (2005 NDS).

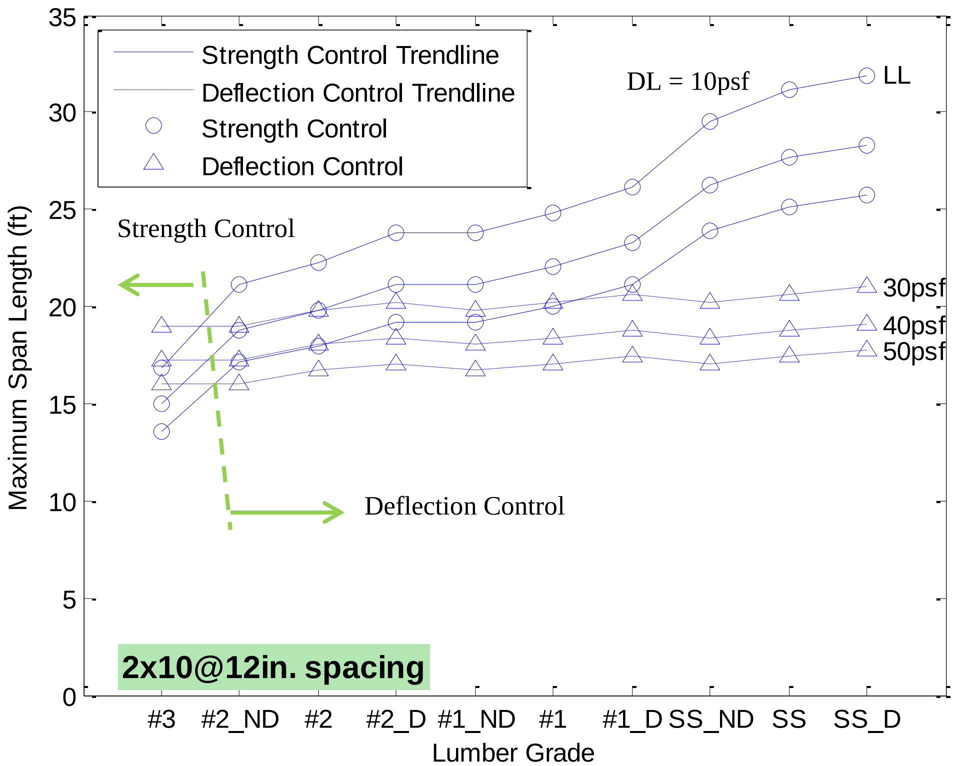


Figure D.25: Effects of live load on maximum span length for 2x10 Southern Pine floor joists at 12 inch on center (2005 NDS).

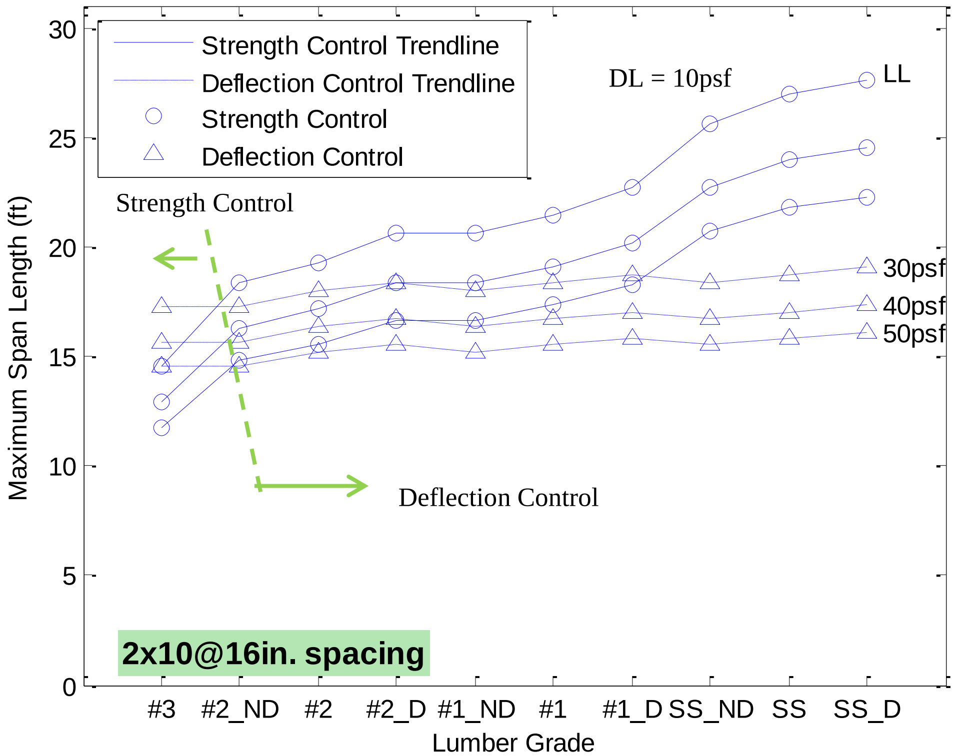


Figure D.26: Effects of live load on maximum span length for 2x10 Southern Pine floor joists at 16 inch on center (2005 NDS).

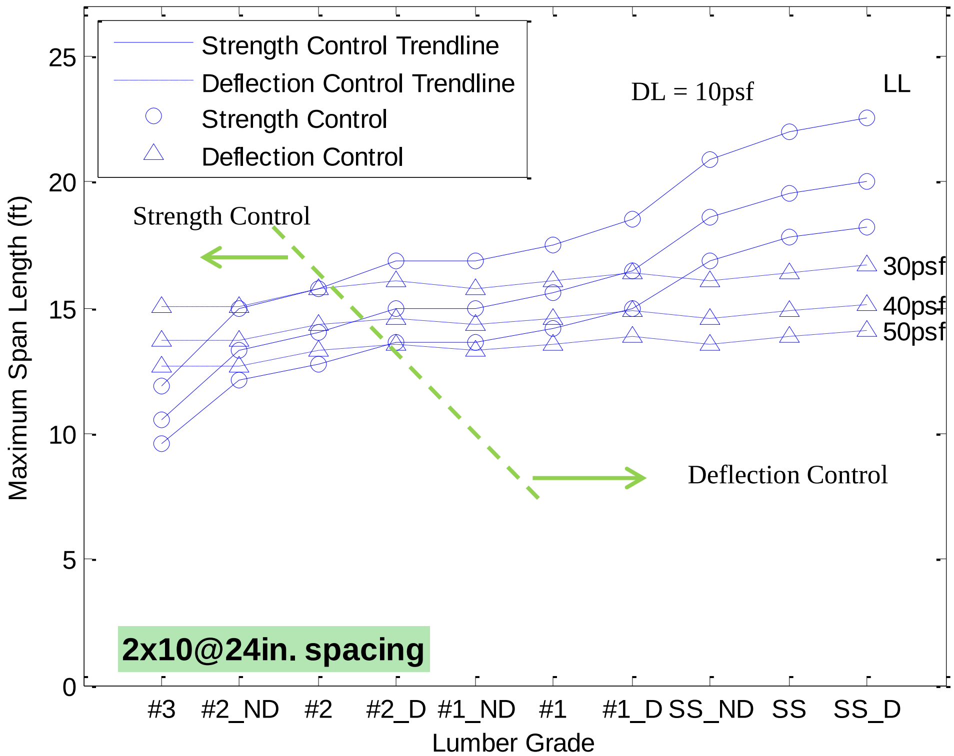


Figure D.27: Effects of live load on maximum span length for 2x10 Southern Pine floor joists at 24 inch on center (2005 NDS).

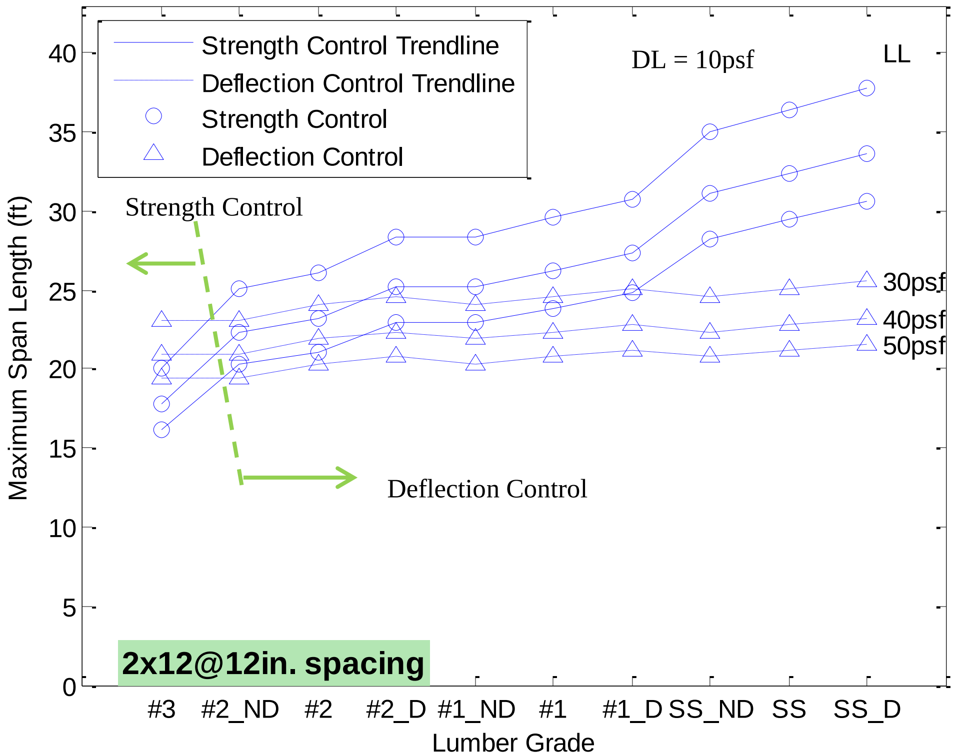


Figure D.28: Effects of live load on maximum span length for 2x12 Southern Pine floor joists at 12 inch on center (2005 NDS).

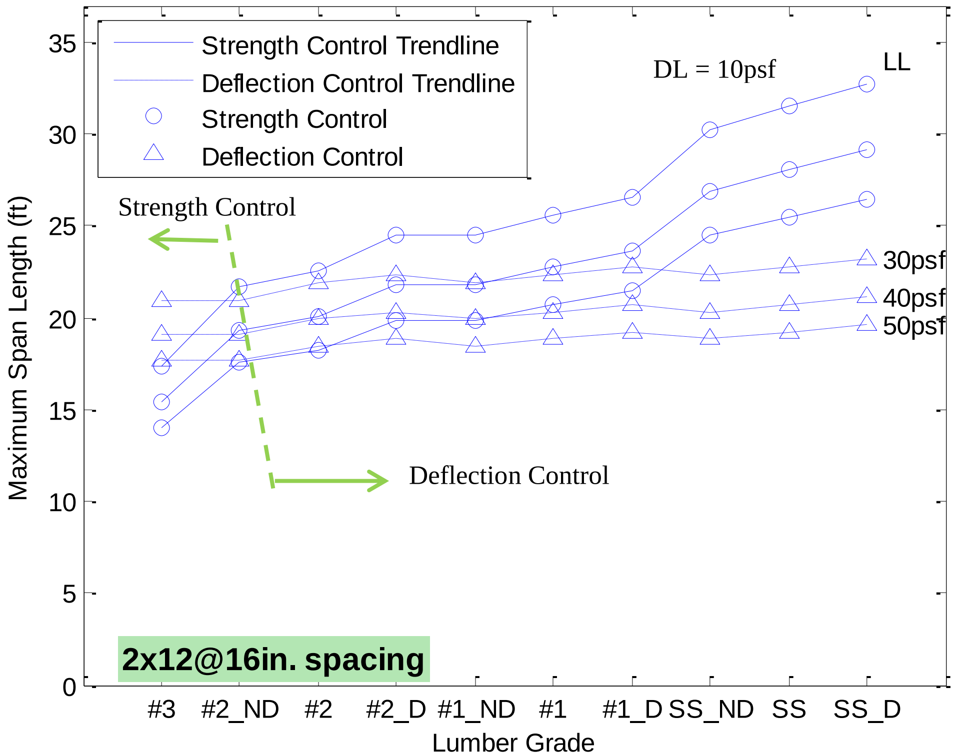


Figure D.29: Effects of live load on maximum span length for 2x12 Southern Pine floor joists at 16 inch on center (2005 NDS).

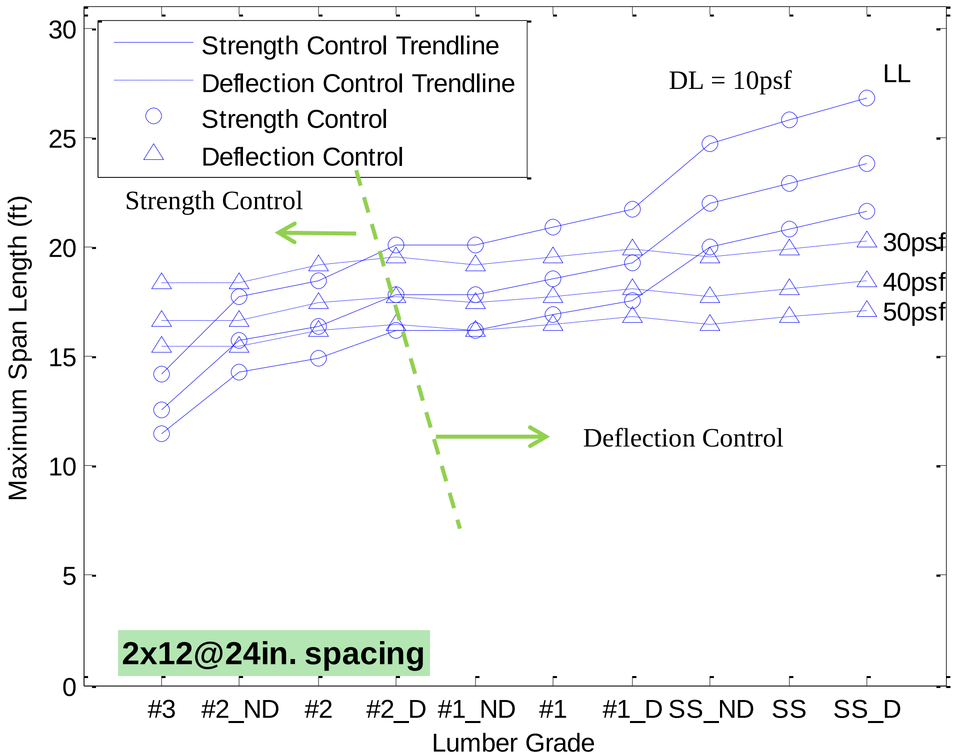


Figure D.30: Effects of live load on maximum span length for 2x12 Southern Pine floor joists at 24 inch on center (2005 NDS).

Appendix E

Effect of Spacing

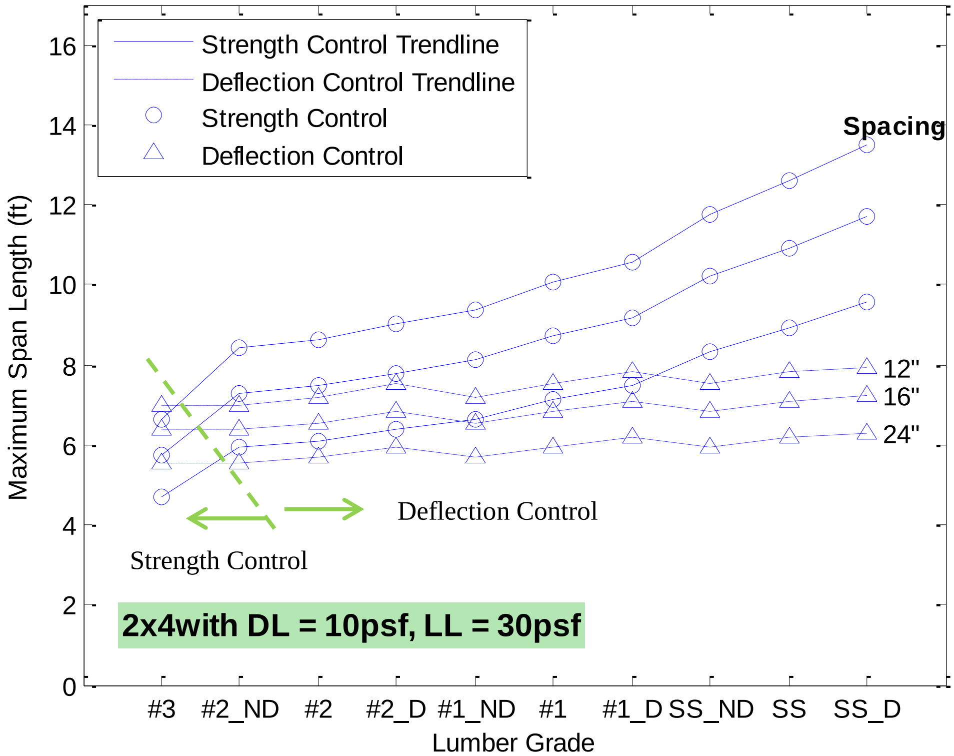


Figure E.1: Effect of joist spacing on maximum span length for 2x4 Southern Pine floor joists with *LL/DL* equal to 3 (2012 NDS).

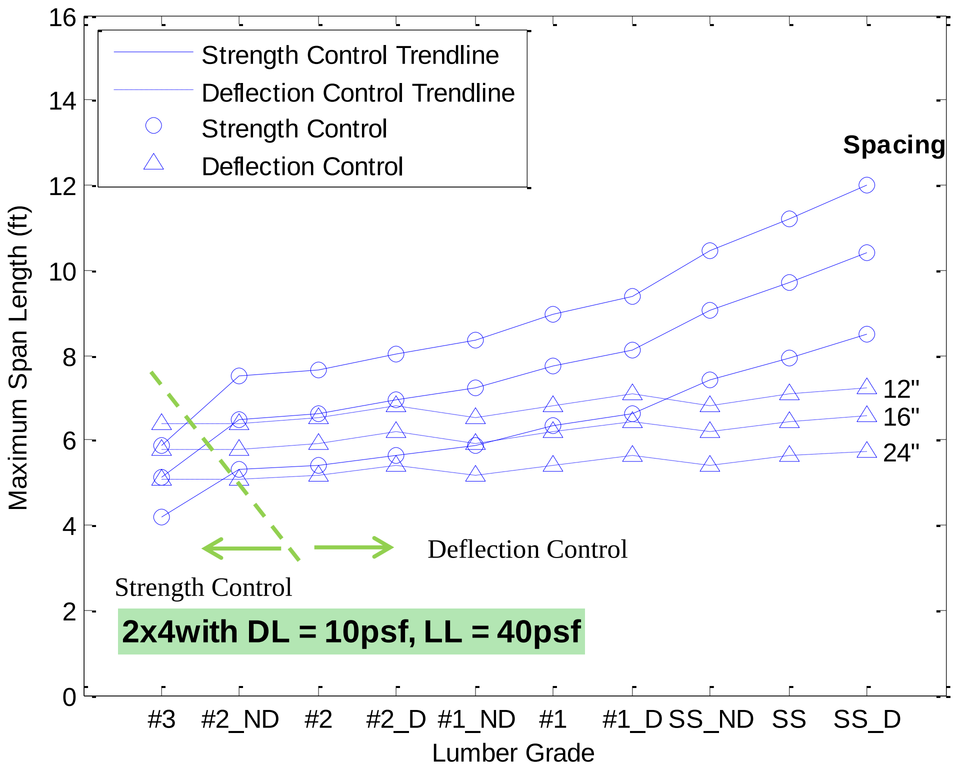


Figure E.2: Effect of joist spacing on maximum span length for 2x4 Southern Pine floor joists with *LL/DL* equal to 4 (2012 NDS).

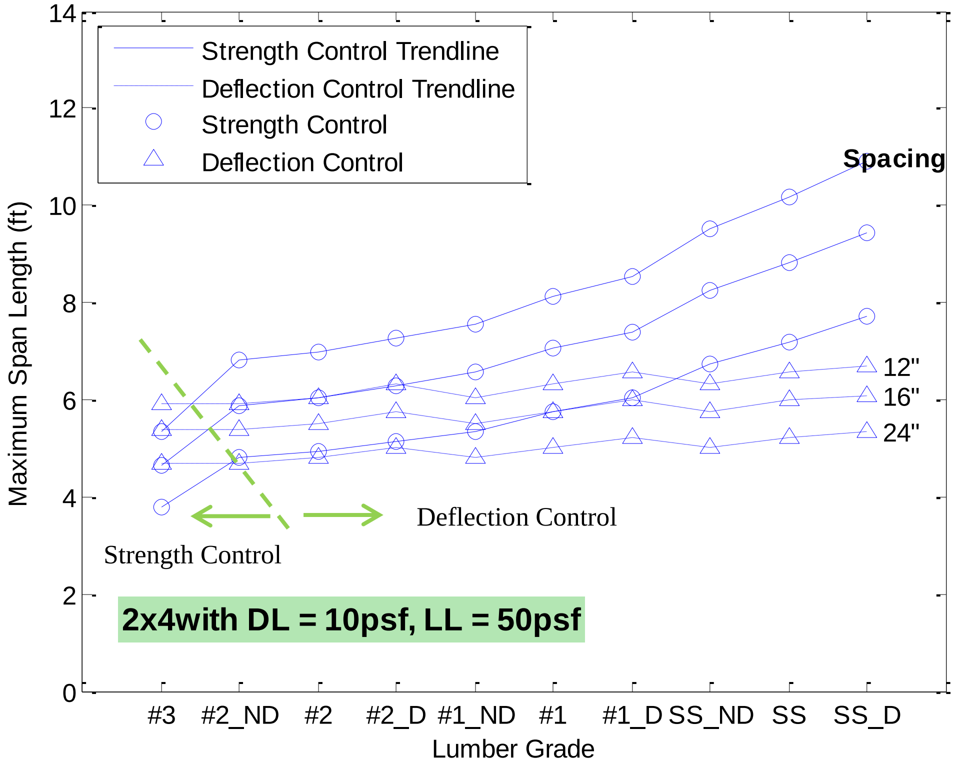


Figure E.3: Effect of joist spacing on maximum span length for 2x4 Southern Pine floor joists with *LL/DL* equal to 5 (2012 NDS).

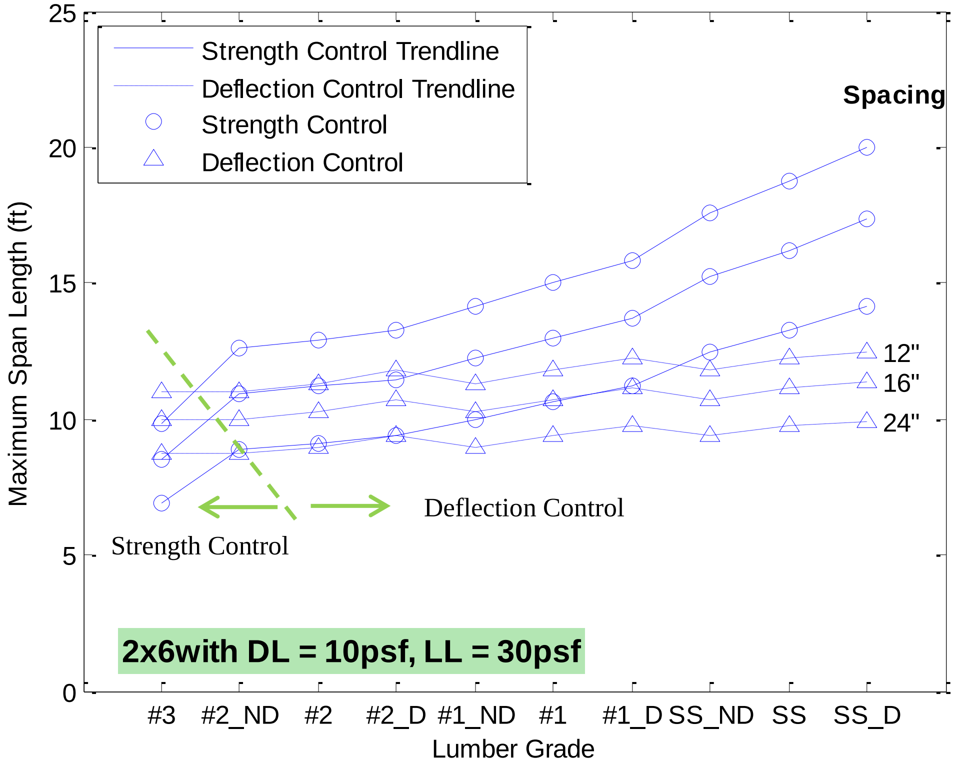


Figure E.4: Effect of joist spacing on maximum span length for 2x6 Southern Pine floor joists with *LL/DL* equal to 3 (2012 NDS).

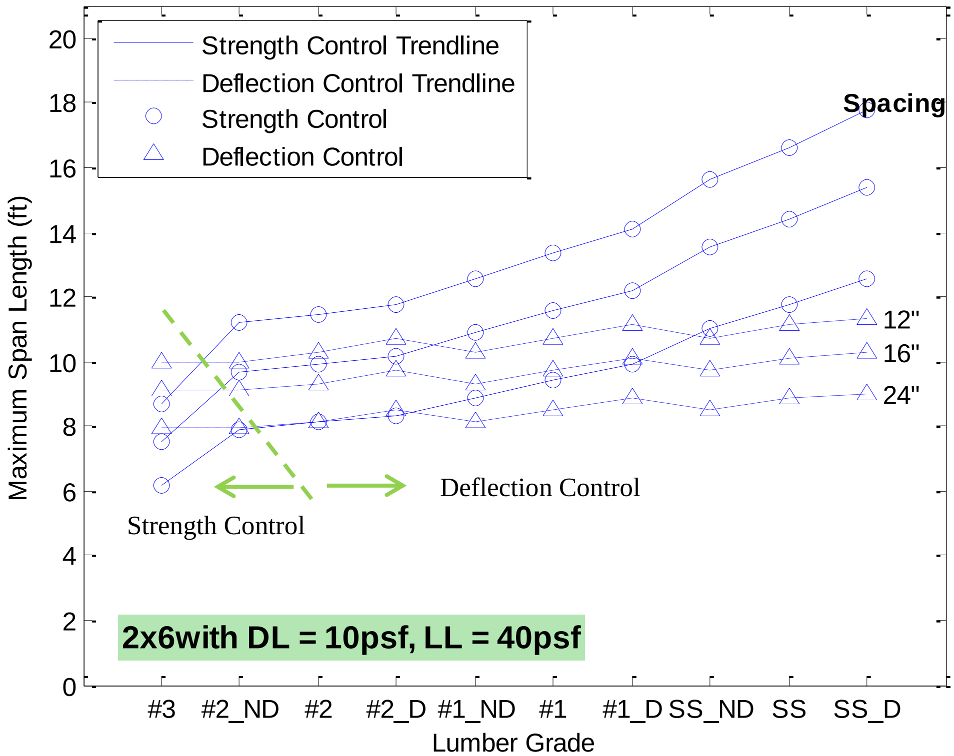


Figure E.5: Effect of joist spacing on maximum span length for 2x6 Southern Pine floor joists with *LL/DL* equal to 4 (2012 NDS).

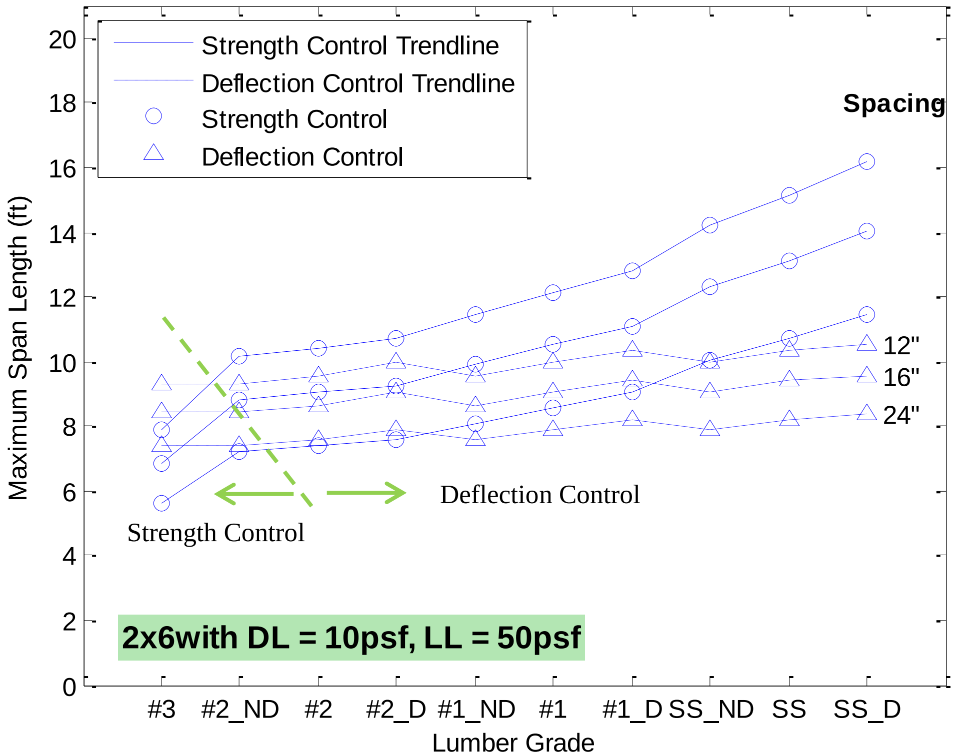


Figure E.6: Effect of joist spacing on maximum span length for 2x6 Southern Pine floor joists with *LL/DL* equal to 5 (2012 NDS).

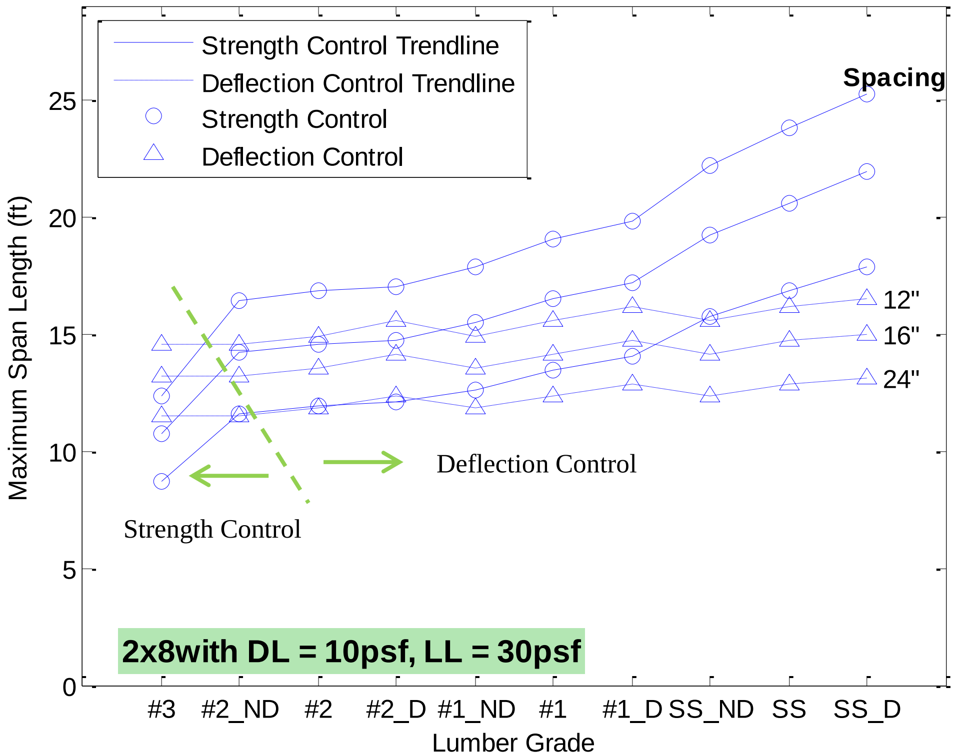


Figure E.7: Effect of joist spacing on maximum span length for 2x8 Southern Pine floor joists with *LL/DL* equal to 3 (2012 NDS).

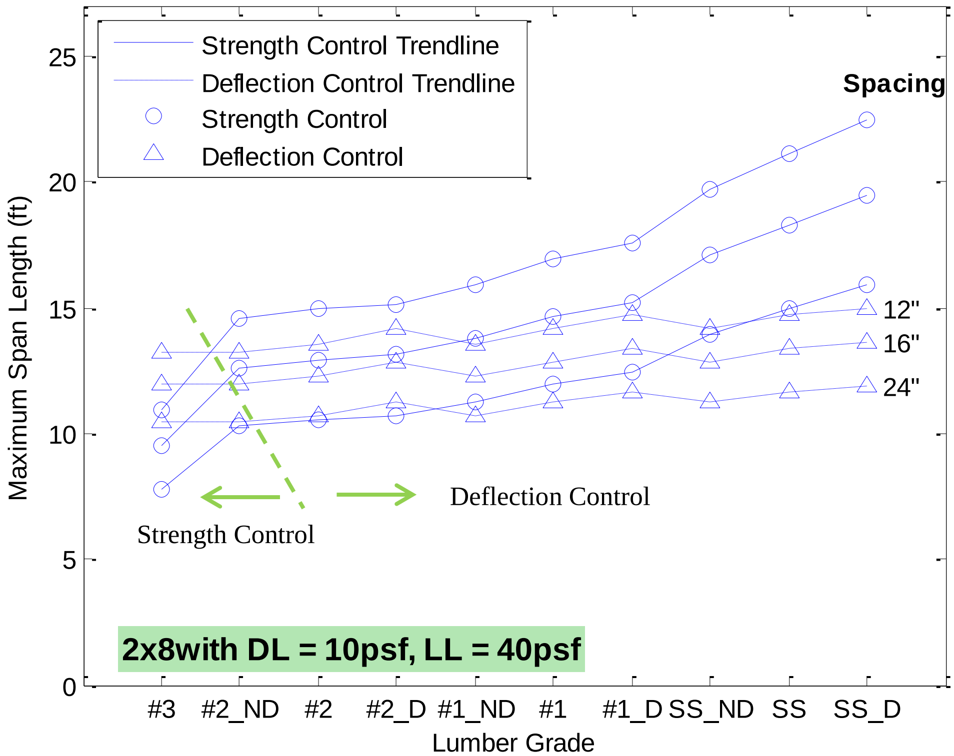


Figure E.8: Effect of joist spacing on maximum span length for 2x8 Southern Pine floor joists with *LL/DL* equal to 4 (2012 NDS).

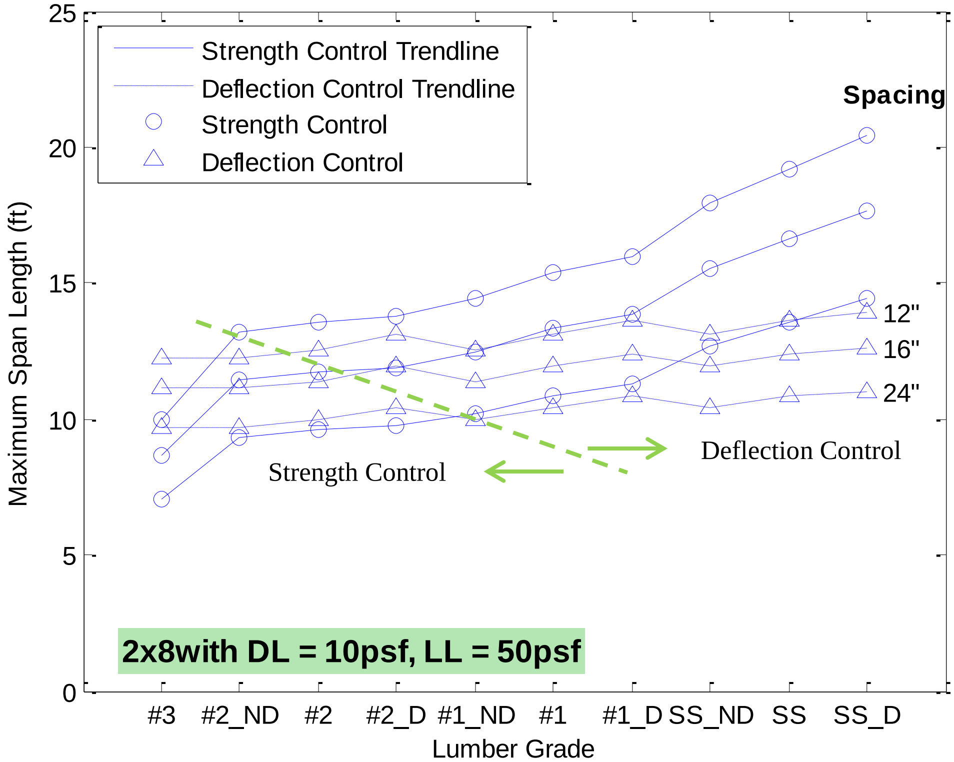


Figure E.9: Effect of joist spacing on maximum span length for 2x8 Southern Pine floor joists with *LL/DL* equal to 5 (2012 NDS).

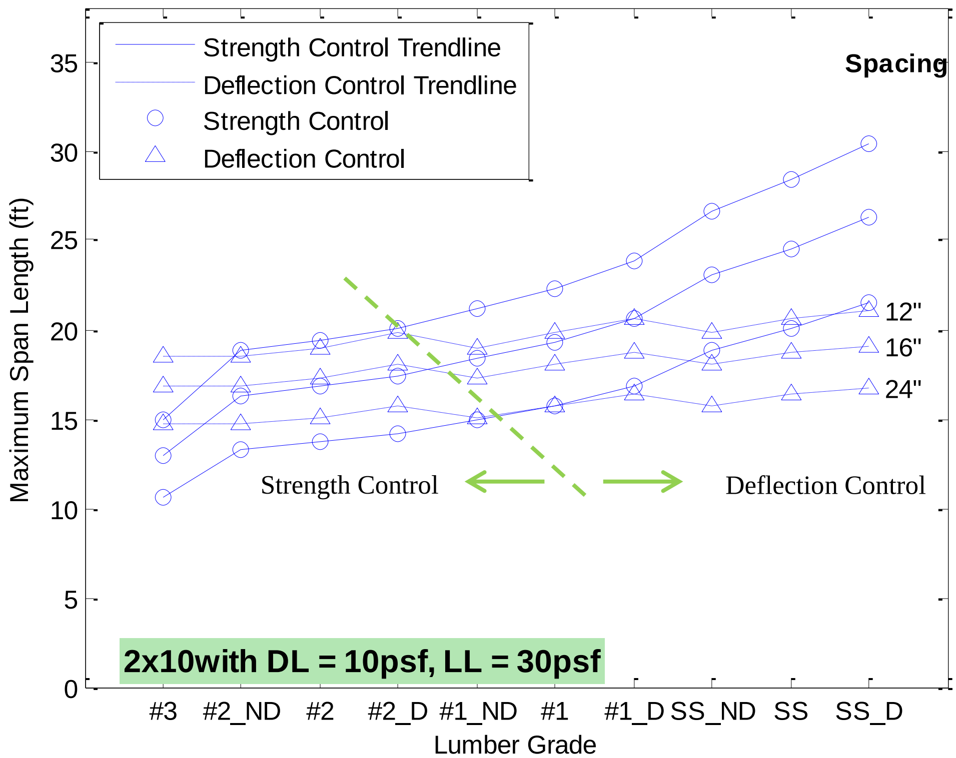


Figure E.10: Effect of joist spacing on maximum span length for 2x10 Southern Pine floor joists with *LL/DL* equal to 3 (2012 NDS).

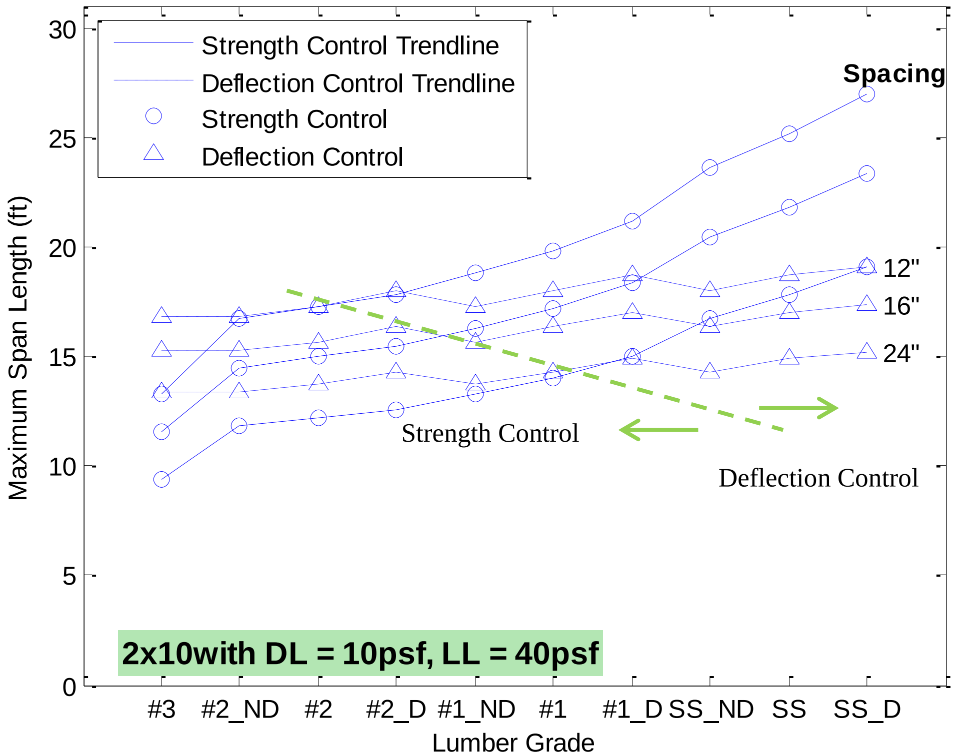


Figure E.11: Effect of joist spacing on maximum span length for 2x10 Southern Pine floor joists with *LL/DL* equal to 4 (2012 NDS).

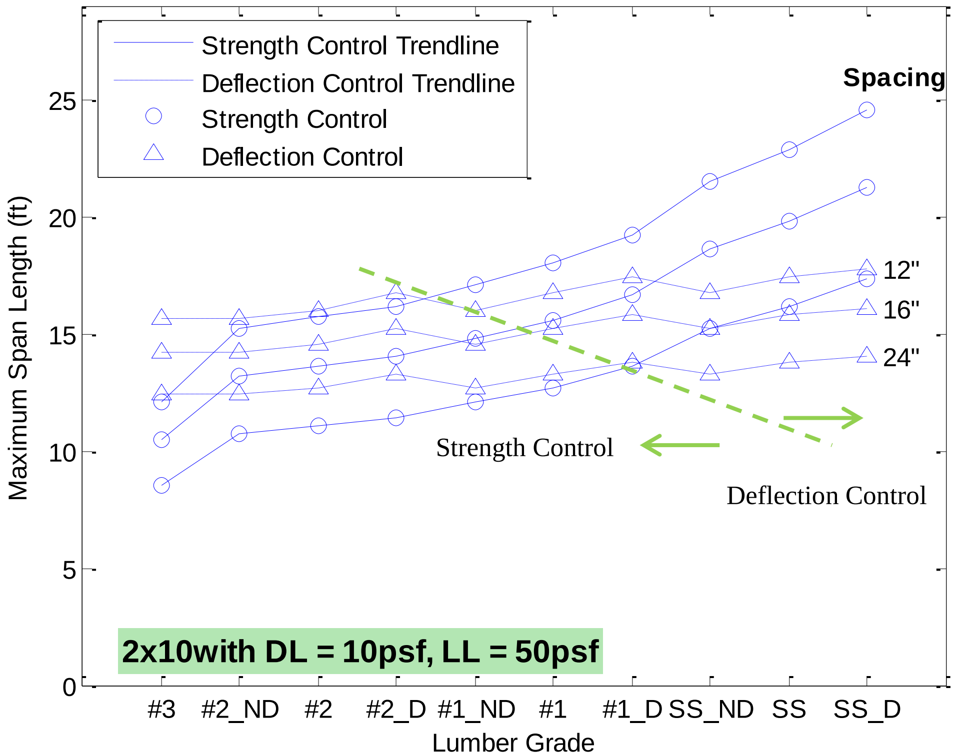


Figure E.12: Effect of joist spacing on maximum span length for 2x10 Southern Pine floor joists with *LL/DL* equal to 5 (2012 NDS).

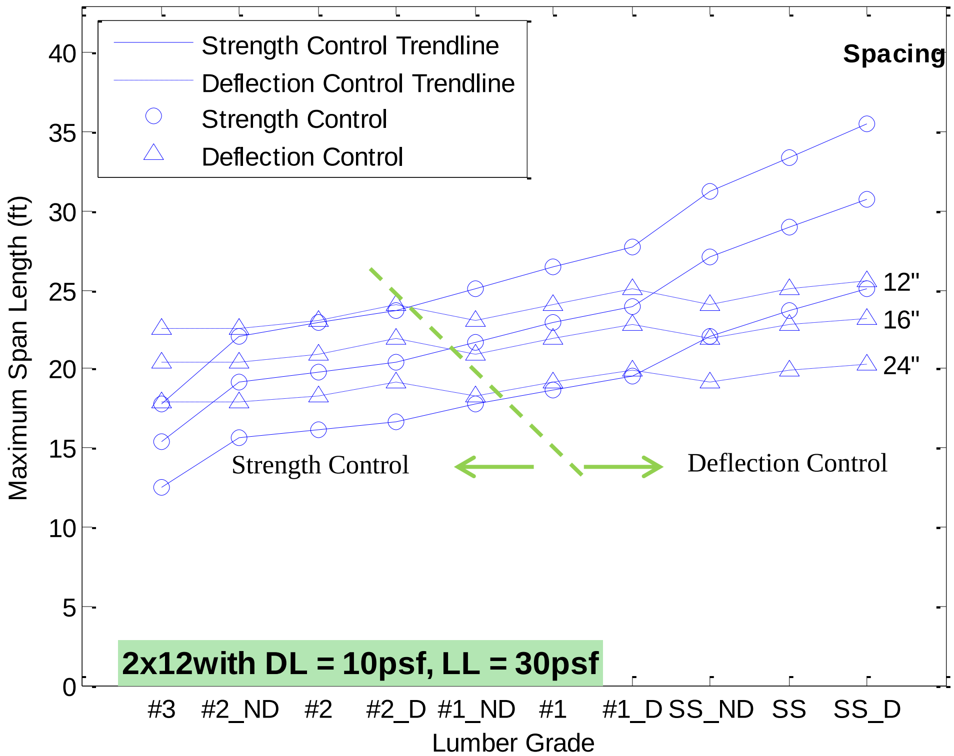


Figure E.13: Effect of joist spacing on maximum span length for 2x12 Southern Pine floor joists with *LL/DL* equal to 3 (2012 NDS).

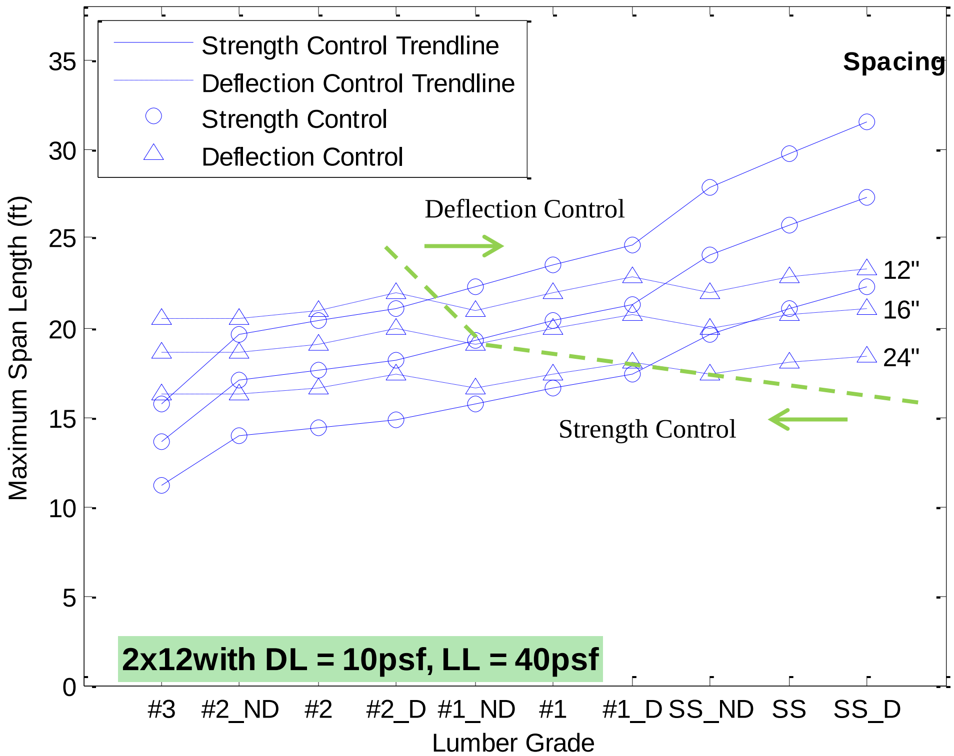


Figure E.14: Effect of joist spacing on maximum span length for 2x12 Southern Pine floor joists with *LL/DL* equal to 4 (2012 NDS).

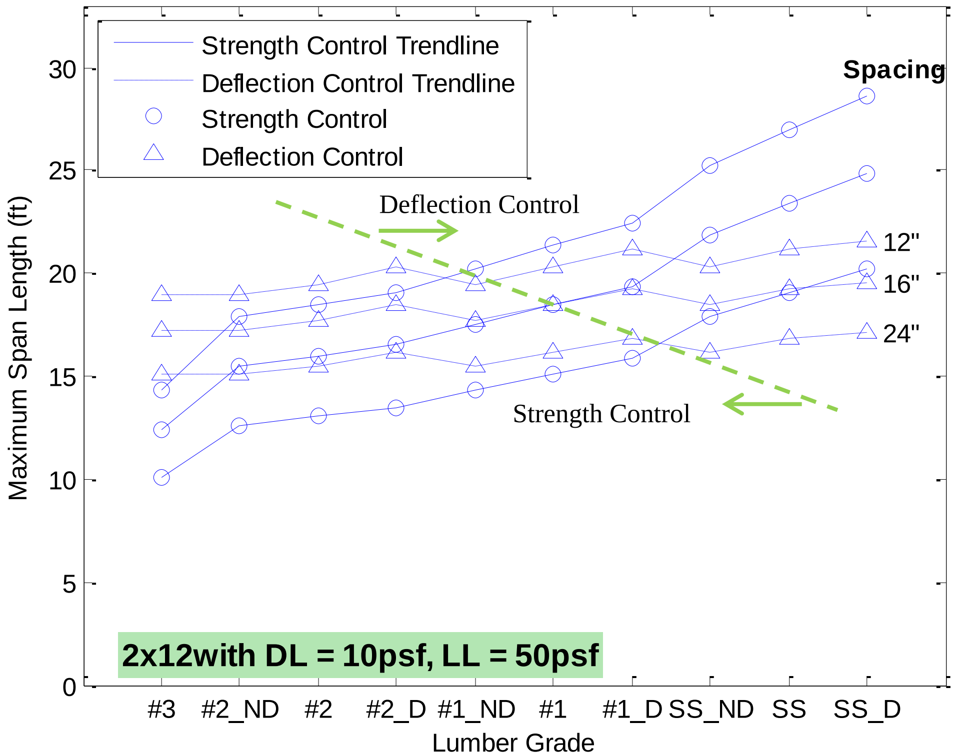


Figure E.15: Effect of joist spacing on maximum span length for 2x12 Southern Pine floor joists with *LL/DL* equal to 5 (2012 NDS).

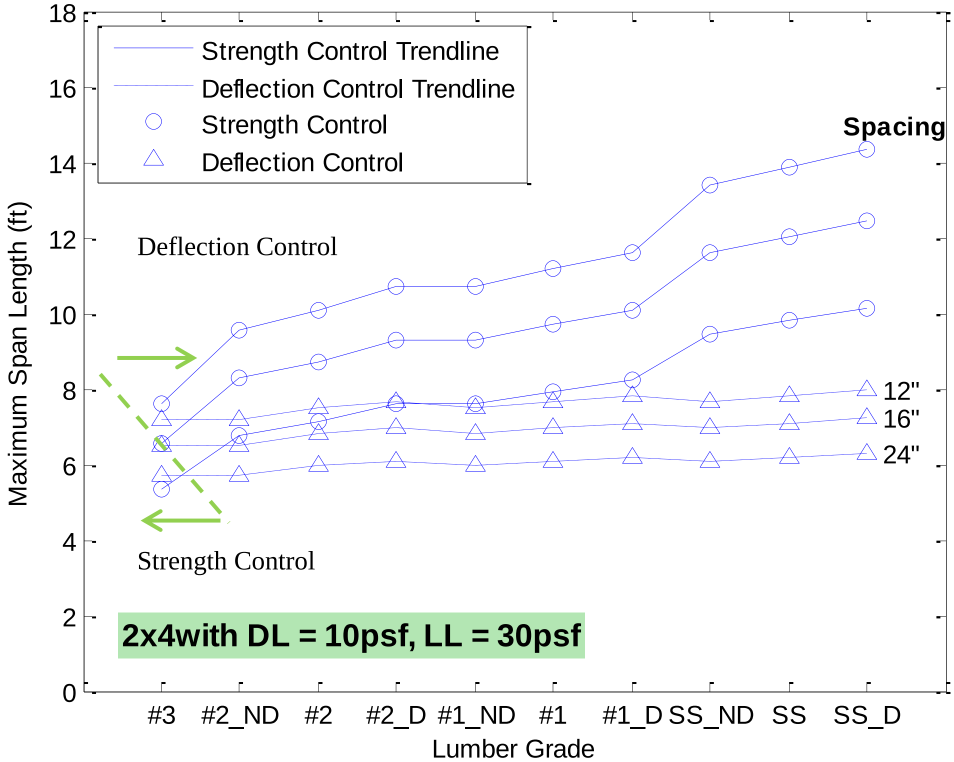


Figure E.16: Effect of joist spacing on maximum span length for 2x4 Southern Pine floor joists with *LL/DL* equal to 3 (2005 NDS).

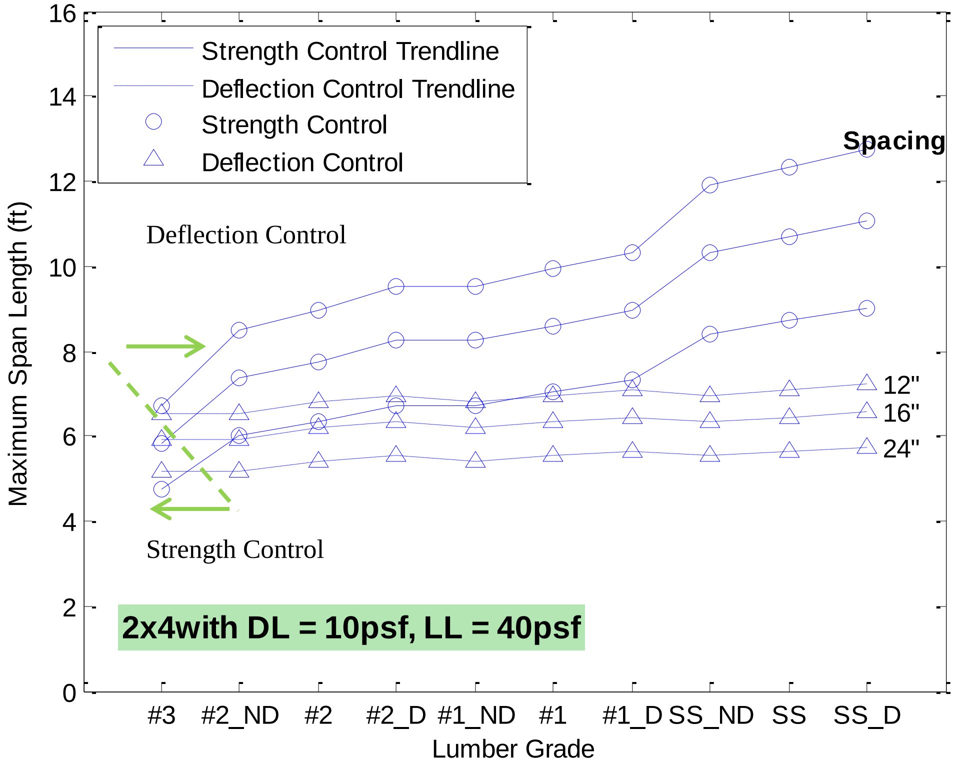


Figure E.17: Effect of joist spacing on maximum span length for 2x4 Southern Pine floor joists with *LL/DL* equal to 4 (2005 NDS).

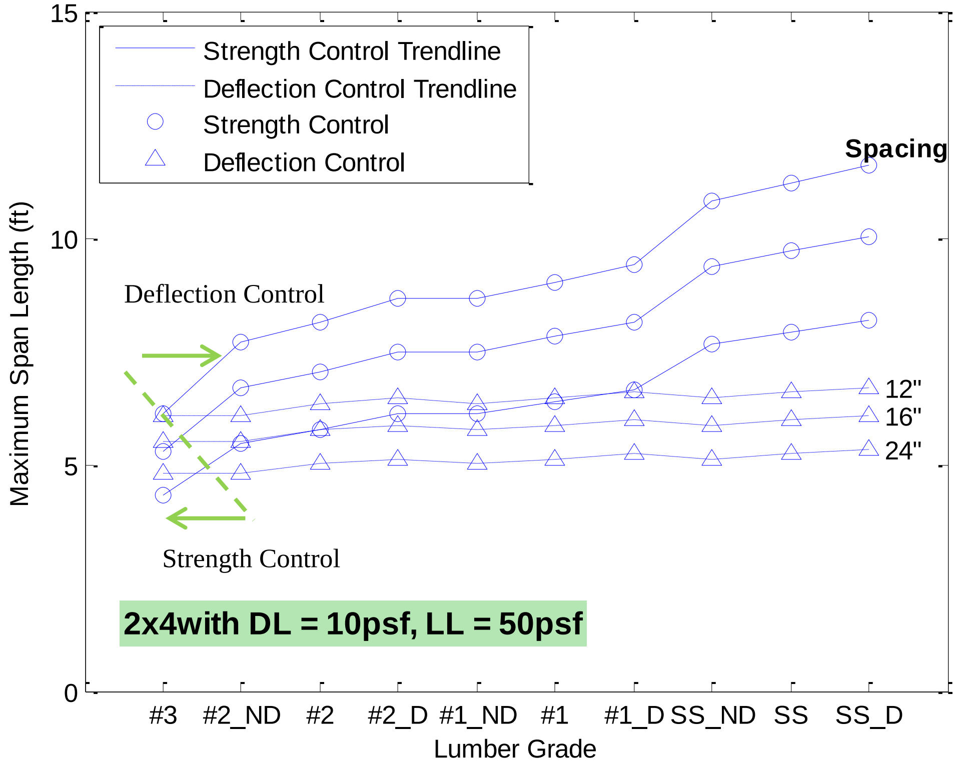


Figure E.18: Effect of joist spacing on maximum span length for 2x4 Southern Pine floor joists with *LL/DL* equal to 5 (2005 NDS).

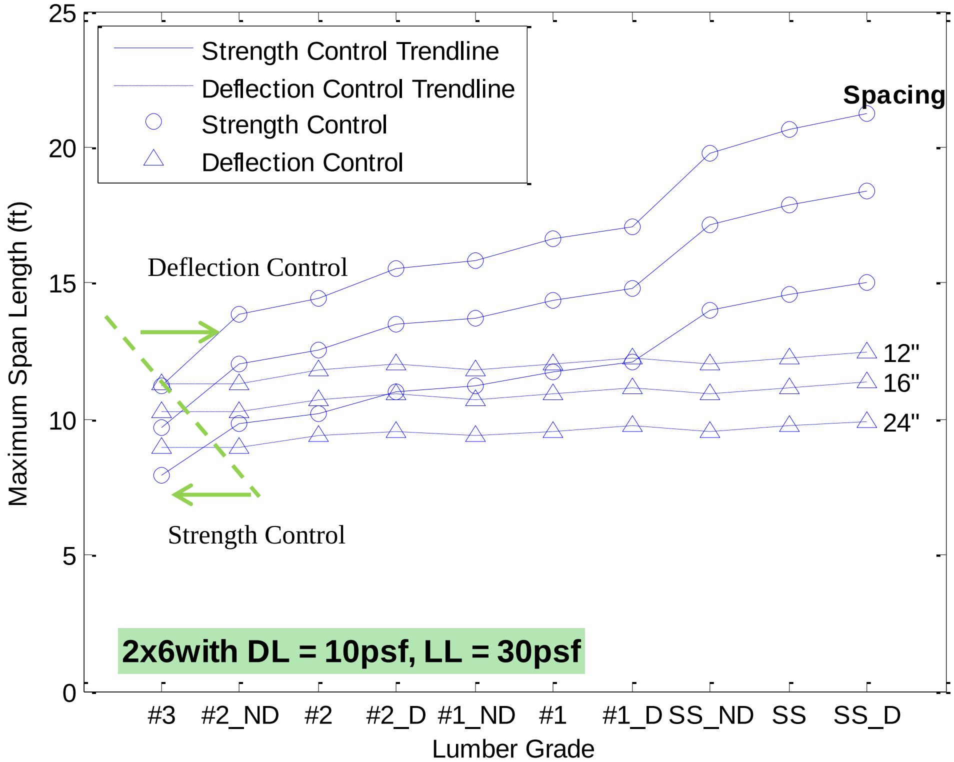


Figure E.19: Effect of joist spacing on maximum span length for 2x6 Southern Pine floor joists with *LL/DL* equal to 3 (2005 NDS).

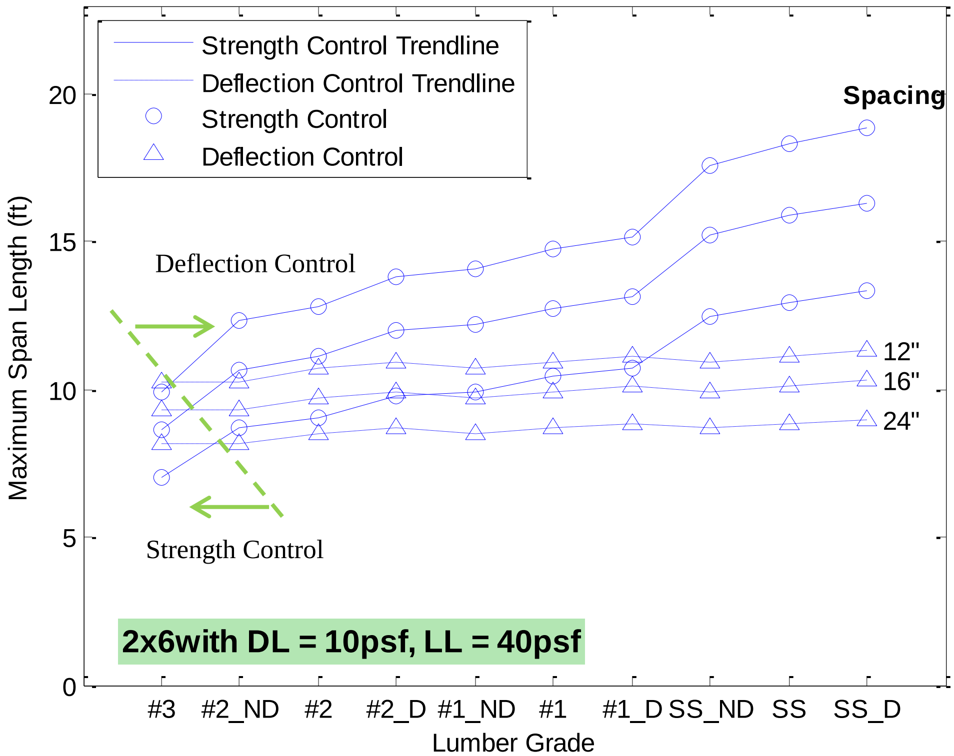


Figure E.20: Effect of joist spacing on maximum span length for 2x6 Southern Pine floor joists with *LL/DL* equal to 4 (2005 NDS).

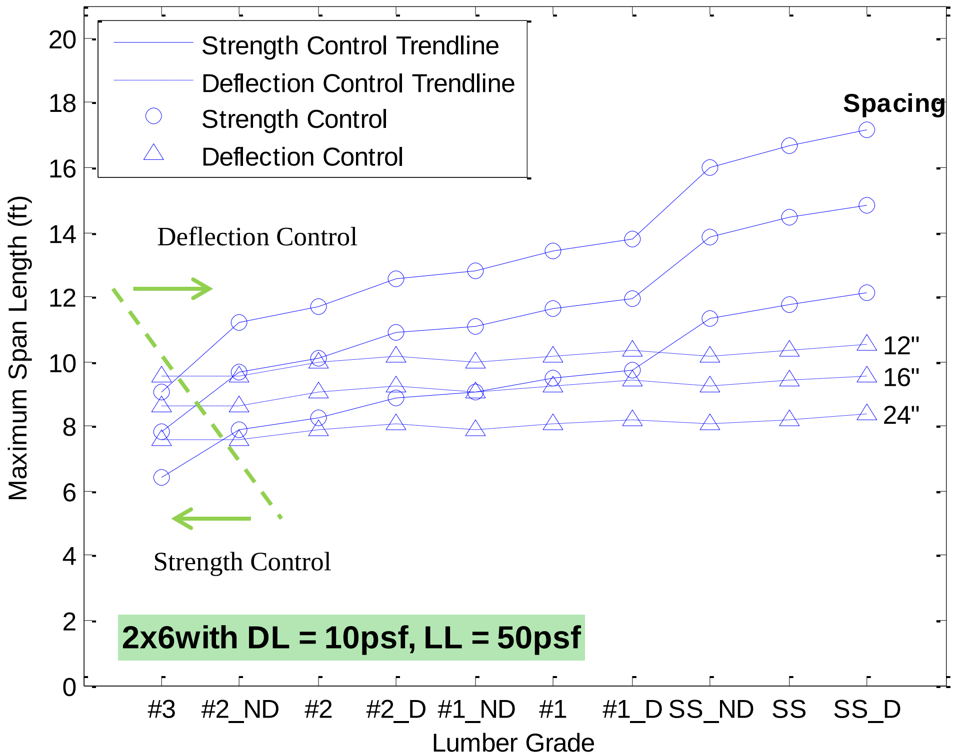


Figure E.21: Effect of joist spacing on maximum span length for 2x6 Southern Pine floor joists with *LL/DL* equal to 5 (2005 NDS).

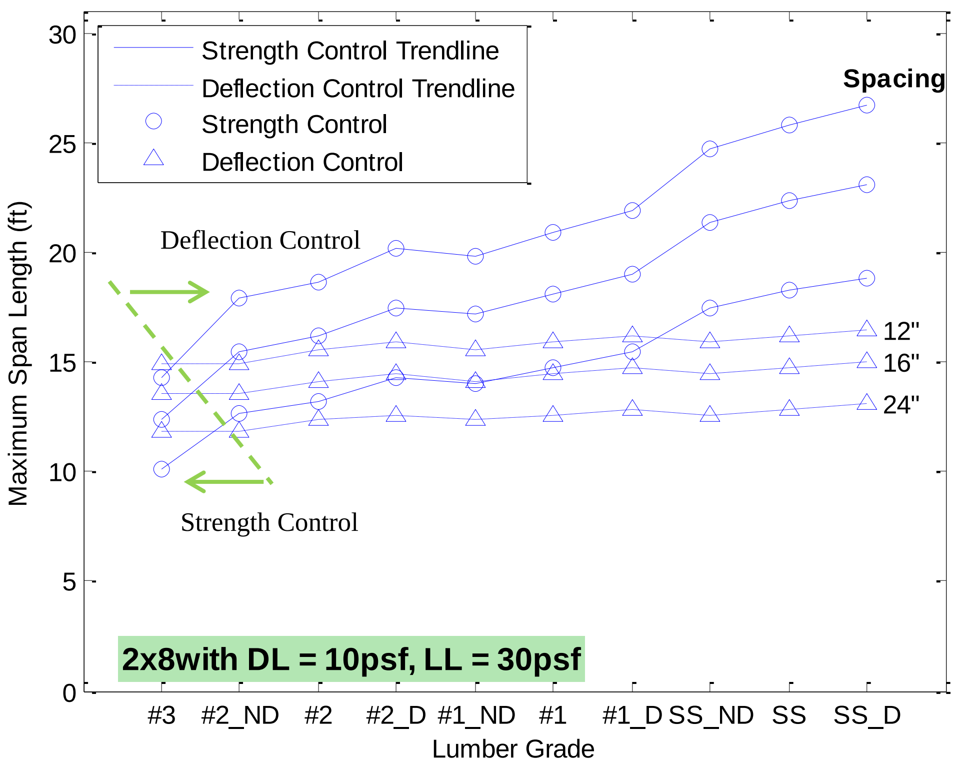


Figure E.22: Effect of joist spacing on maximum span length for 2x8 Southern Pine floor joists with *LL/DL* equal to 3 (2005 NDS).

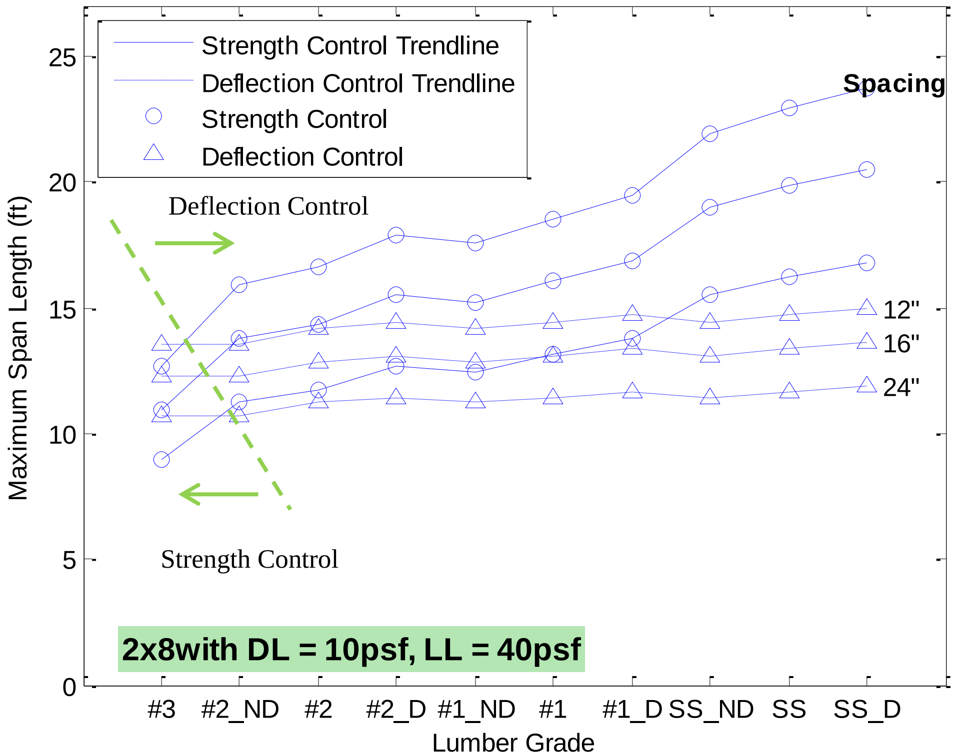


Figure E.23: Effect of joist spacing on maximum span length for 2x8 Southern Pine floor joists with *LL/DL* equal to 4 (2005 NDS).

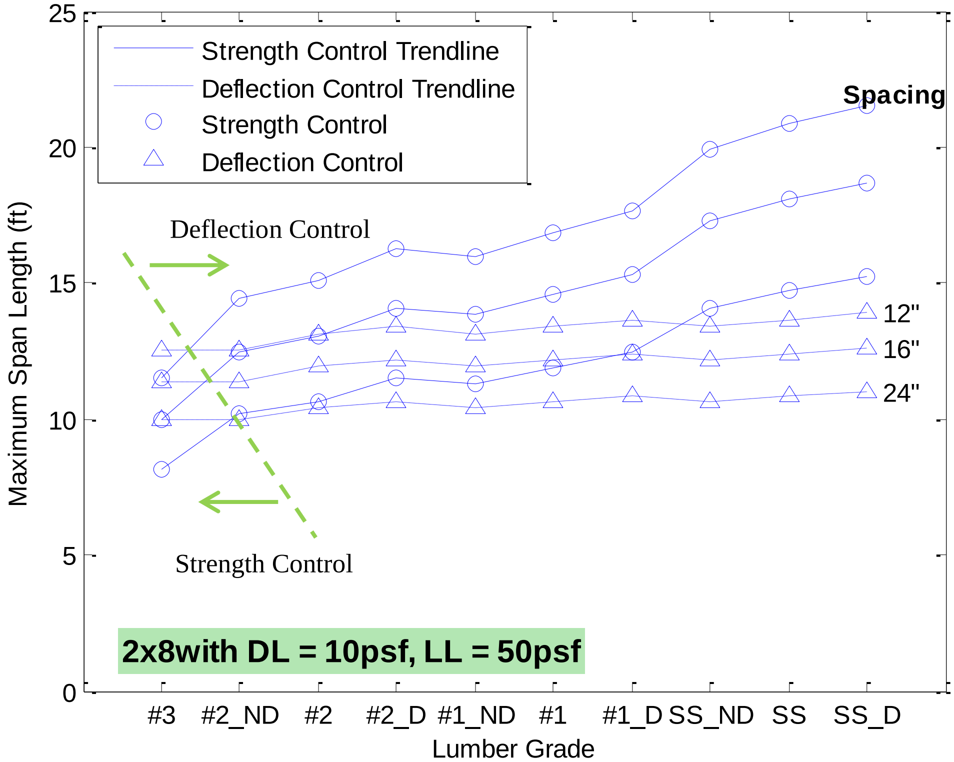


Figure E.24: Effect of joist spacing on maximum span length for 2x8 Southern Pine floor joists with *LL/DL* equal to 5 (2005 NDS).

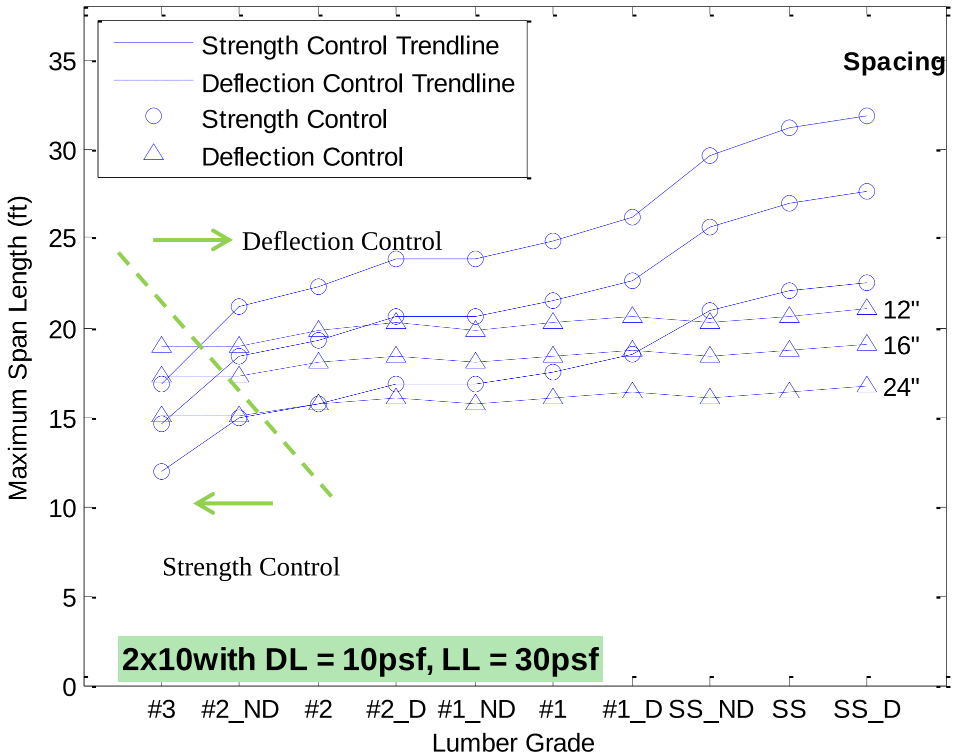


Figure E.25: Effect of joist spacing on maximum span length for 2x10 Southern Pine floor joists with *LL/DL* equal to 3 (2005 NDS).

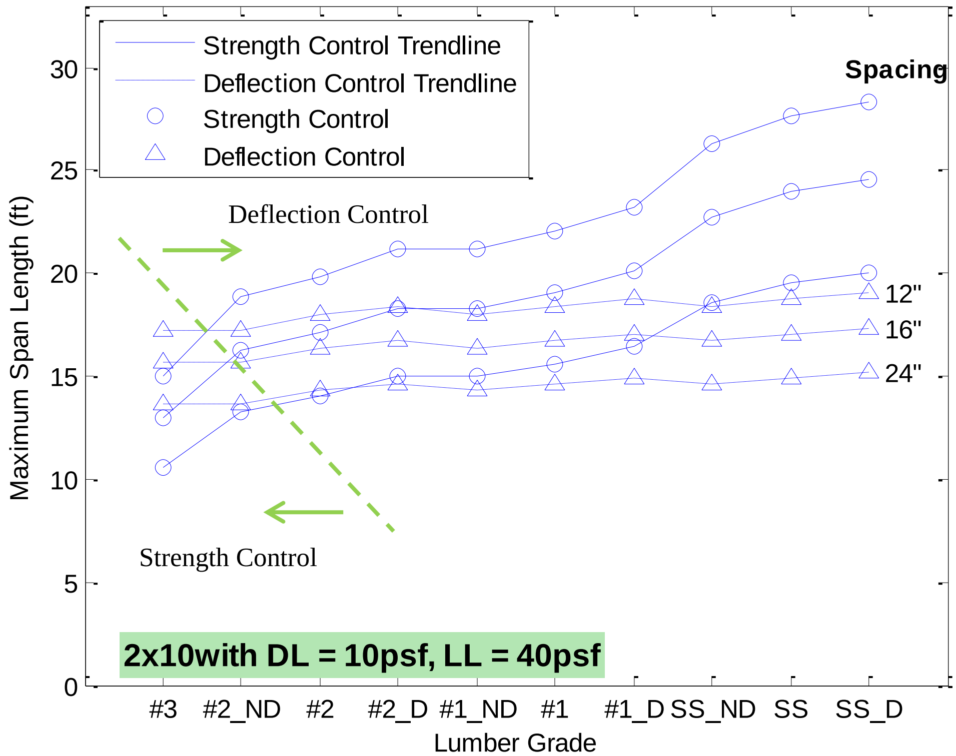


Figure E.26: Effect of joist spacing on maximum span length for 2x10 Southern Pine floor joists with *LL/DL* equal to 4 (2005 NDS).

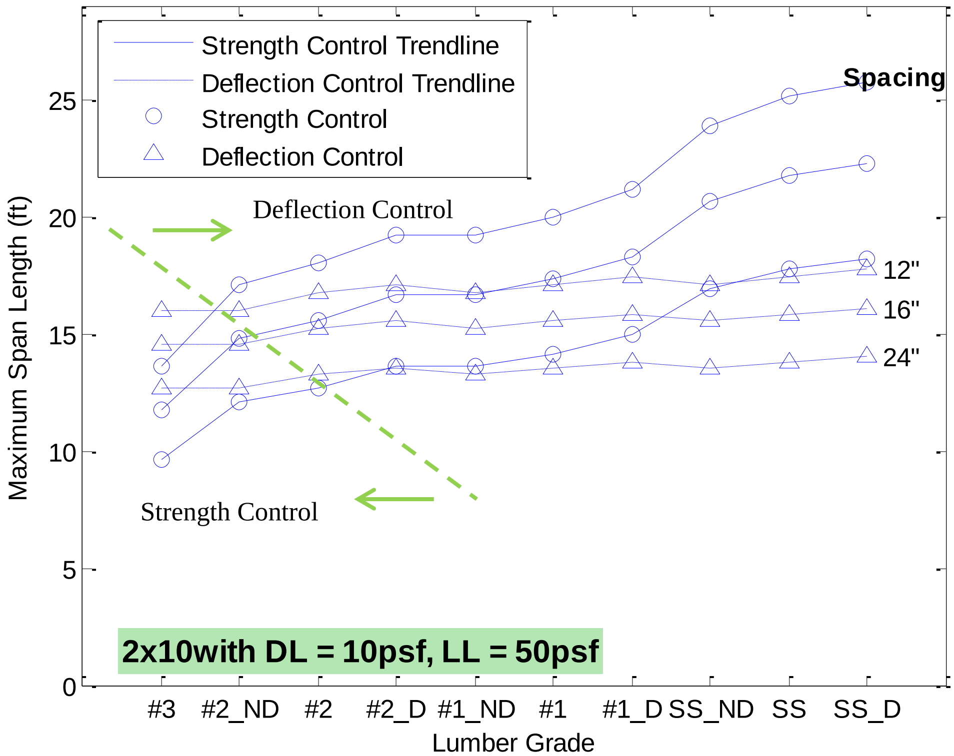


Figure E.27: Effect of joist spacing on maximum span length for 2x10 Southern Pine floor joists with *LL/DL* equal to 5 (2005 NDS).

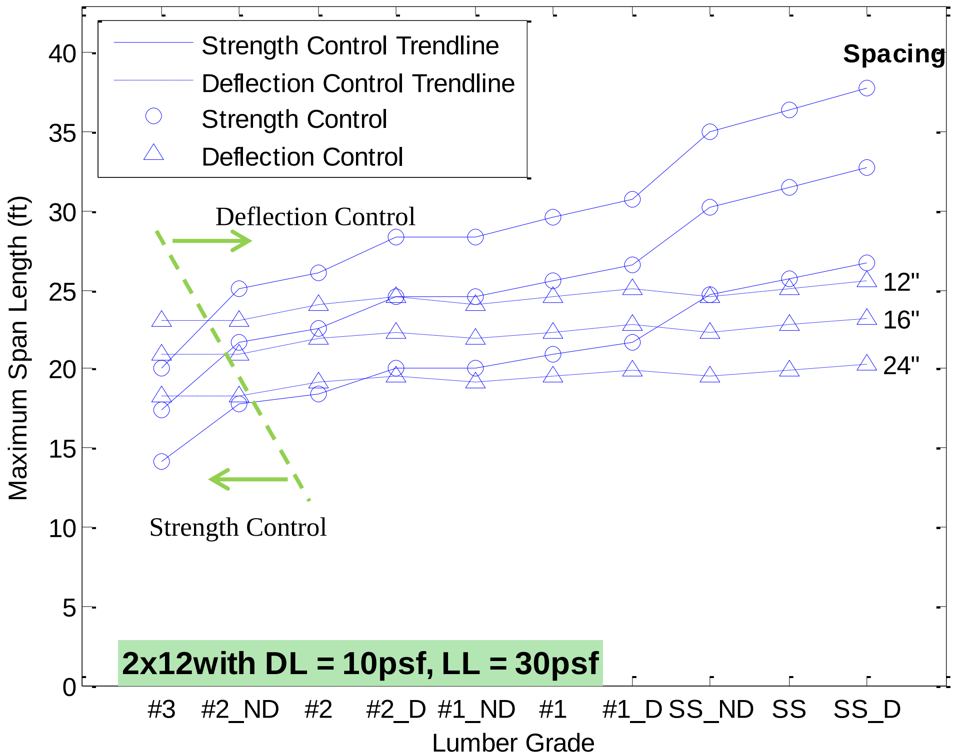


Figure E.28: Effect of joist spacing on maximum span length for 2x12 Southern Pine floor joists with *LL/DL* equal to 3 (2005 NDS).

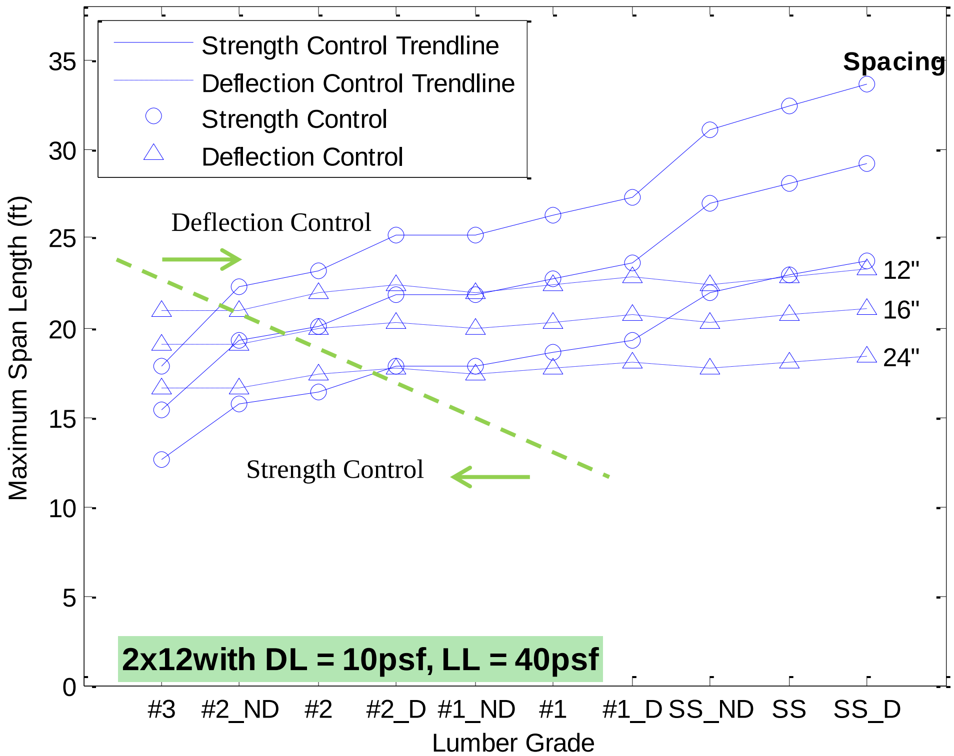


Figure E.29: Effect of joist spacing on maximum span length for 2x12 Southern Pine floor joists with *LL/DL* equal to 4 (2005 NDS).

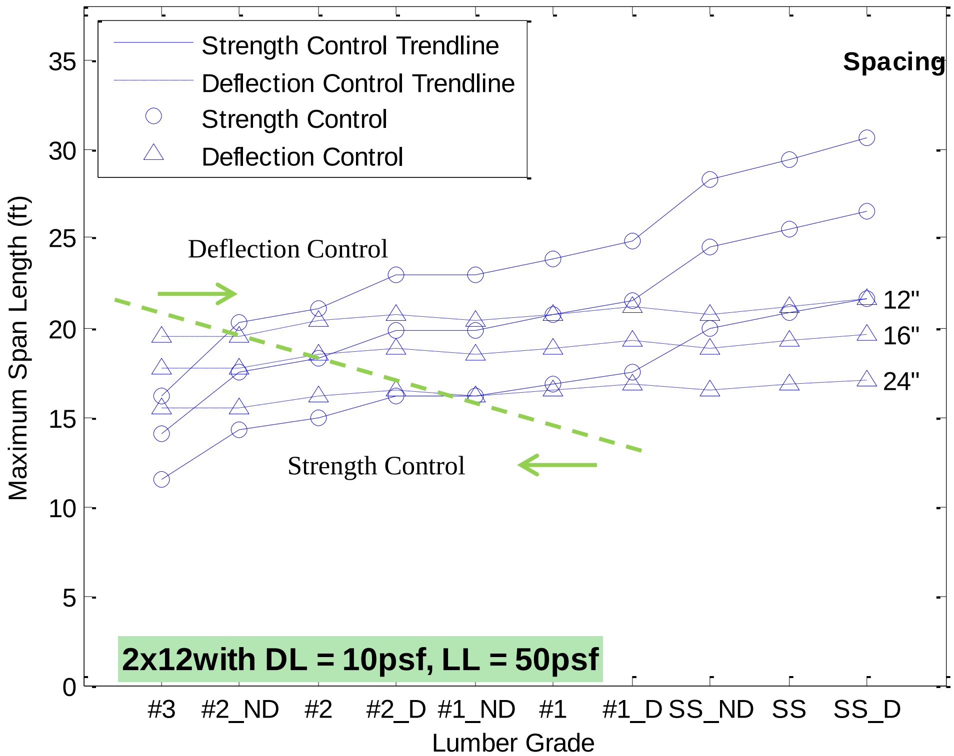


Figure E.30: Effect of joist spacing on maximum span length for 2x12 Southern Pine floor joists with *LL/DL* equal to 5 (2005 NDS).

Appendix F

Effect of Design Capacity

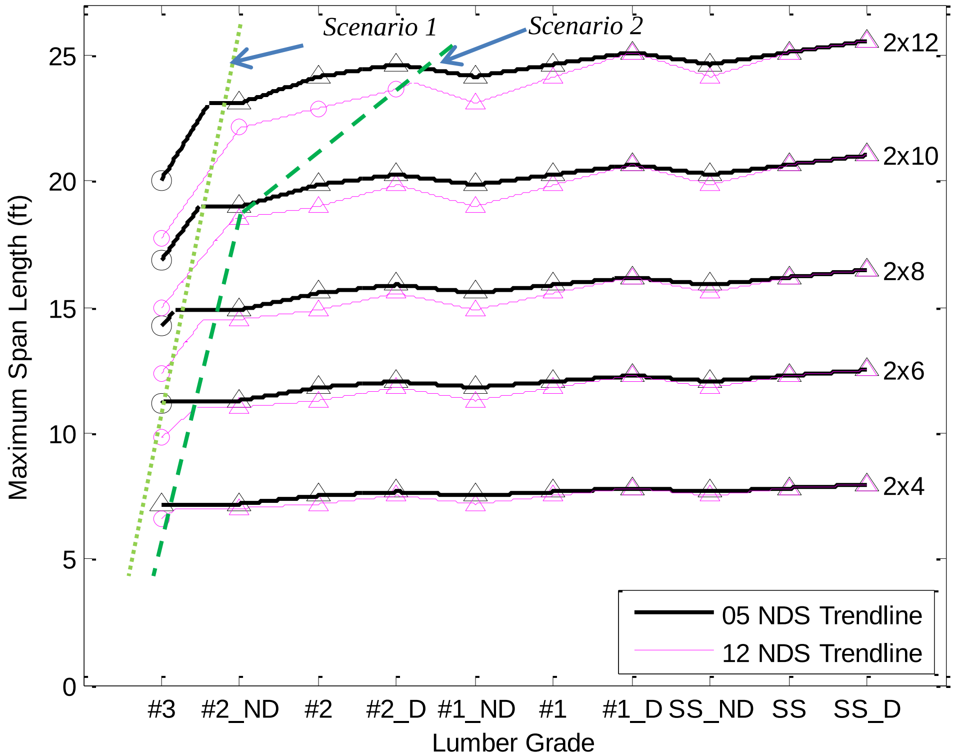


Figure F.1: Comparison between the maximum span lengths of 2005 NDS and 2012 NDS for Southern Pine floor joists spaced at 12 inches on center with *LL/DL* ratio at 3.

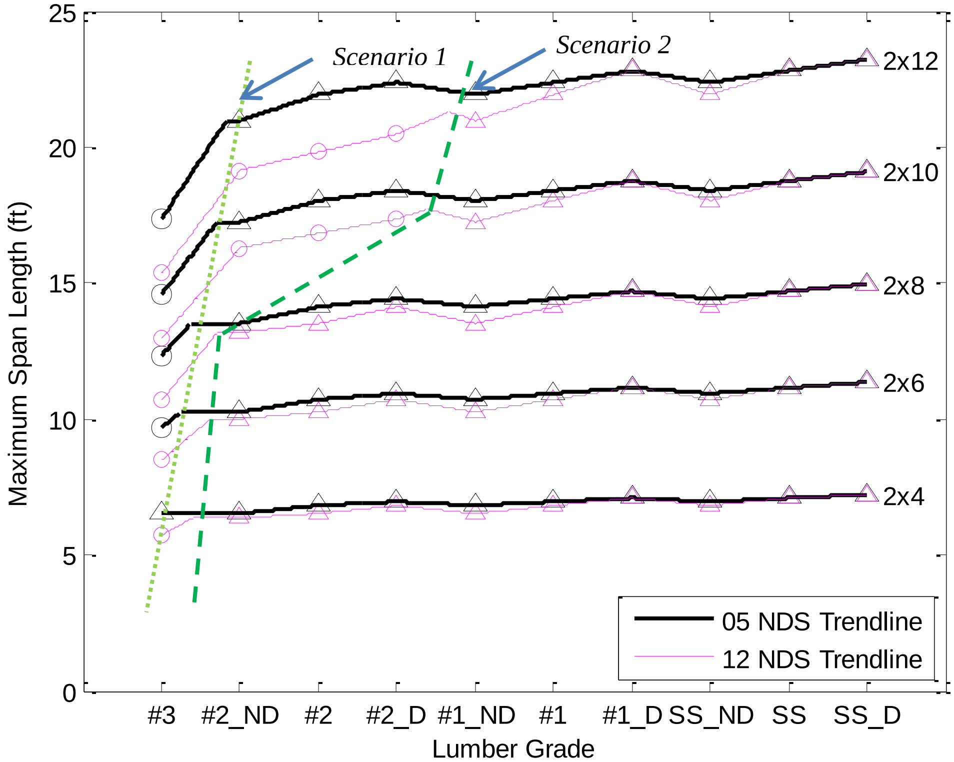


Figure F.2: Comparison between the maximum span lengths of 2005 NDS and 2012 NDS for Southern Pine floor joists spaced at 16 inches on center with *LL/DL* ratio at 3.

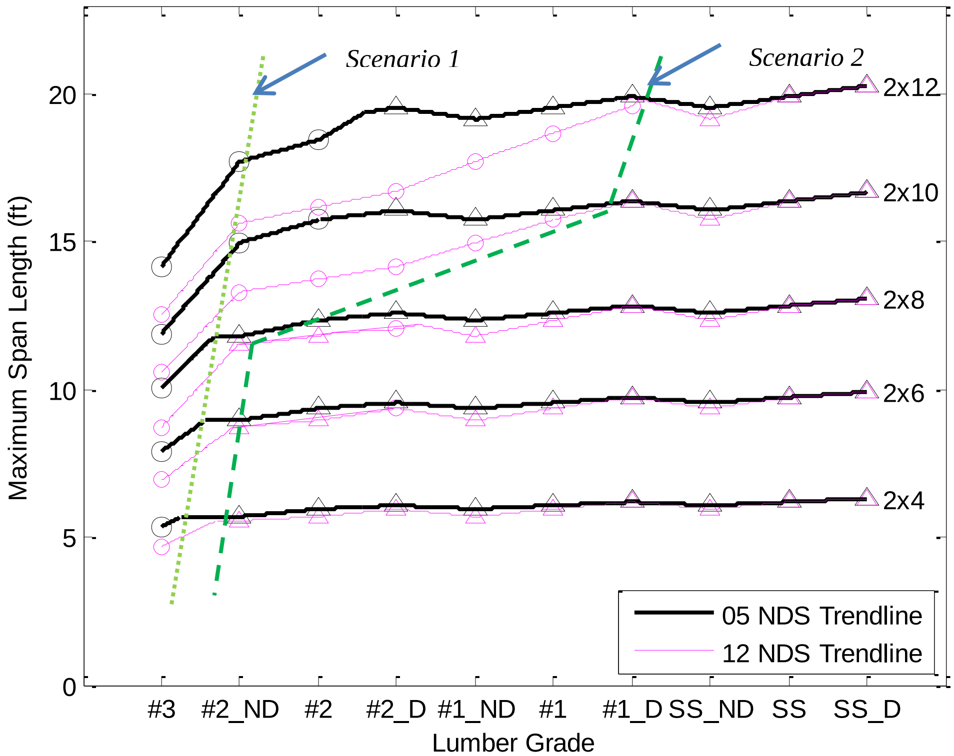


Figure F.3: Comparison between the maximum span lengths of 2005 NDS and 2012 NDS for Southern Pine floor joists spaced at 24 inches on center with *LL/DL* ratio at 3.

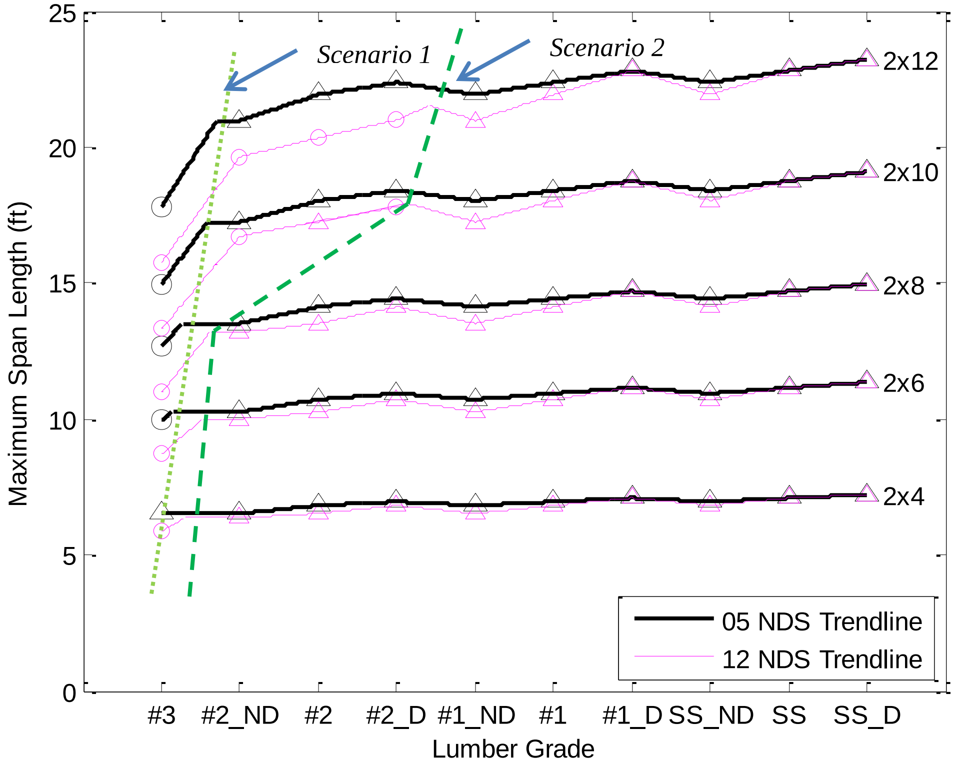


Figure F.4: Comparison between the maximum span lengths of 2005 NDS and 2012 NDS for Southern Pine floor joists spaced at 12 inches on center with *LL/DL* ratio at 4.

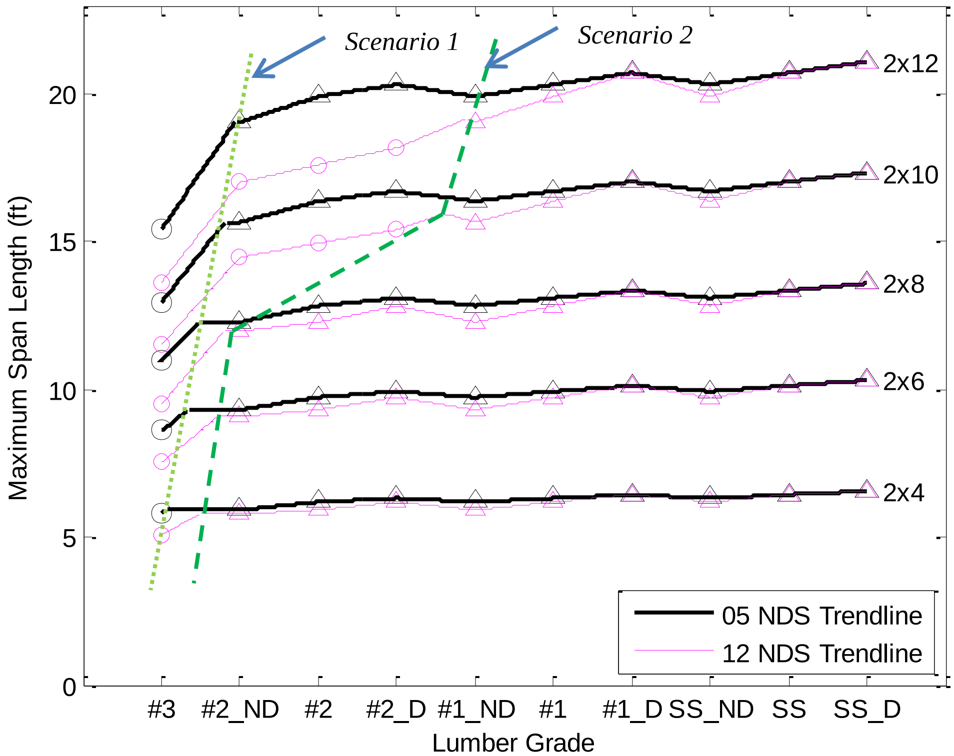


Figure F.5: Comparison between the maximum span lengths of 2005 NDS and 2012 NDS for Southern Pine floor joists spaced at 16 inches on center with *LL/DL* ratio at 4.

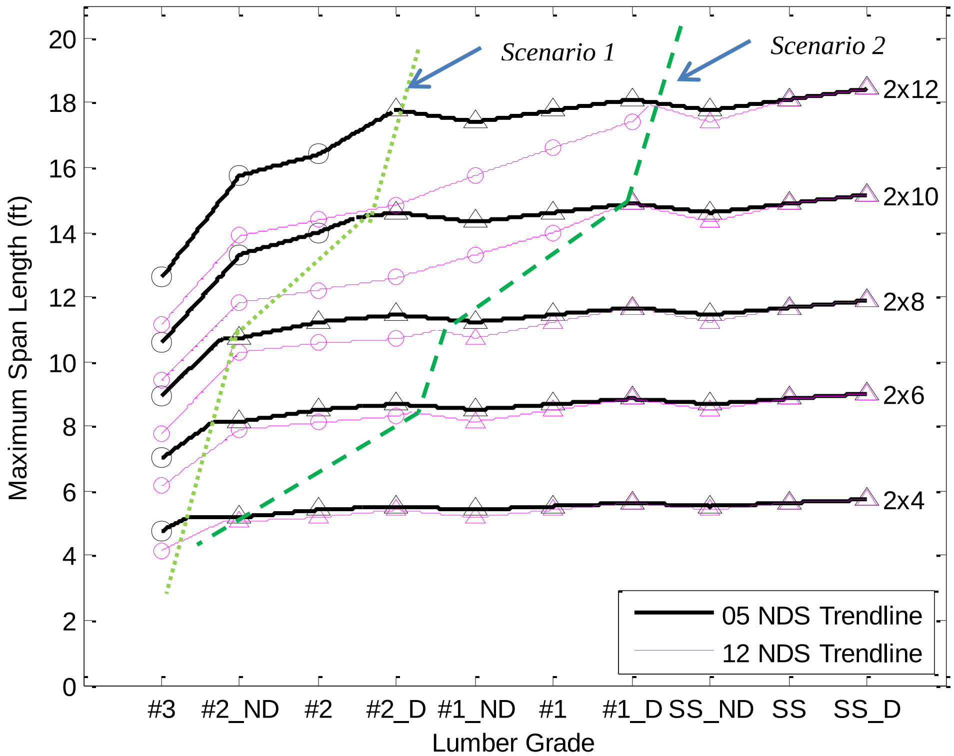


Figure F.6: Comparison between the maximum span lengths of 2005 NDS and 2012 NDS for Southern Pine floor joists spaced at 24 inches on center with *LL/DL* ratio at 4.

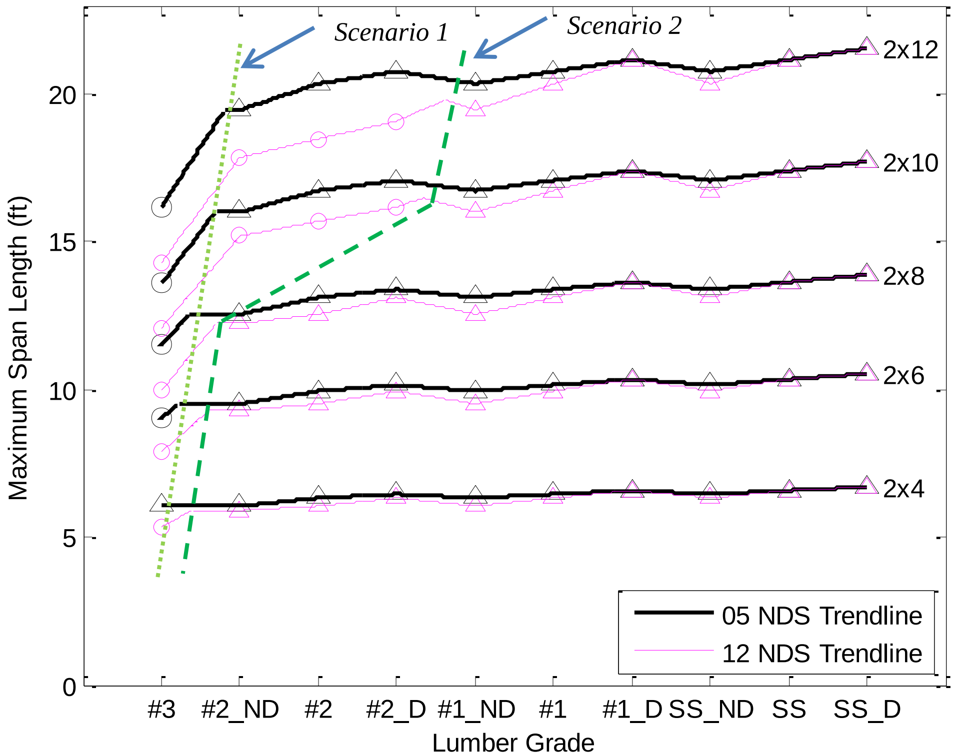


Figure F.7: Comparison between the maximum span lengths of 2005 NDS and 2012 NDS for Southern Pine floor joists spaced at 12 inches on center with *LL/DL* ratio at 5.

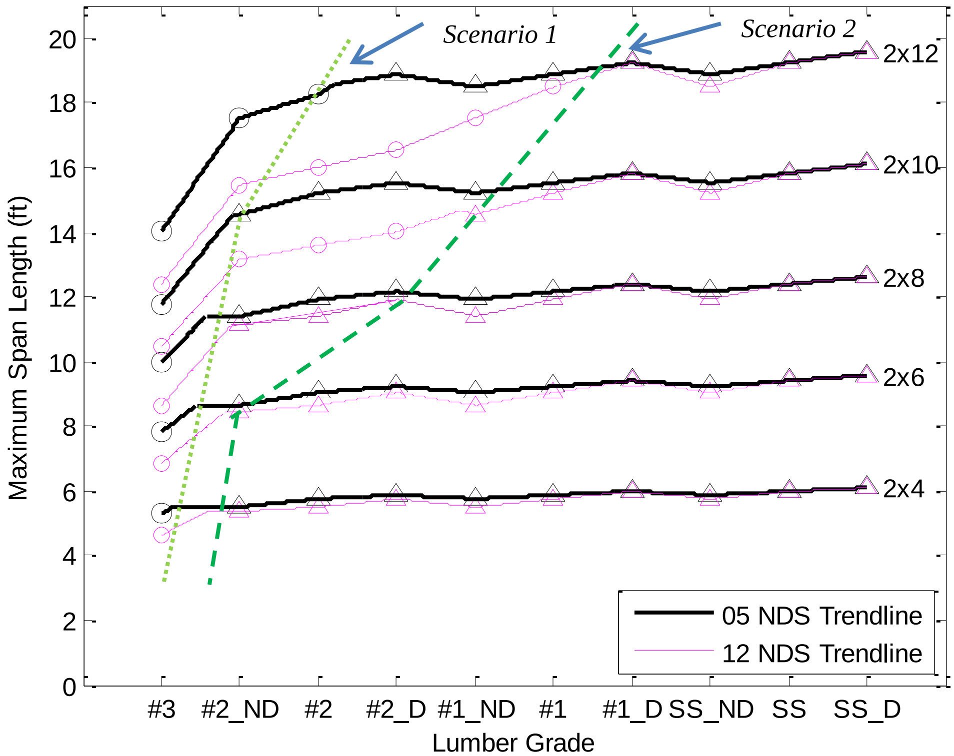


Figure F.8: Comparison between the maximum span lengths of 2005 NDS and 2012 NDS for Southern Pine floor joists spaced at 16 inches on center with *LL/DL* ratio at 5.

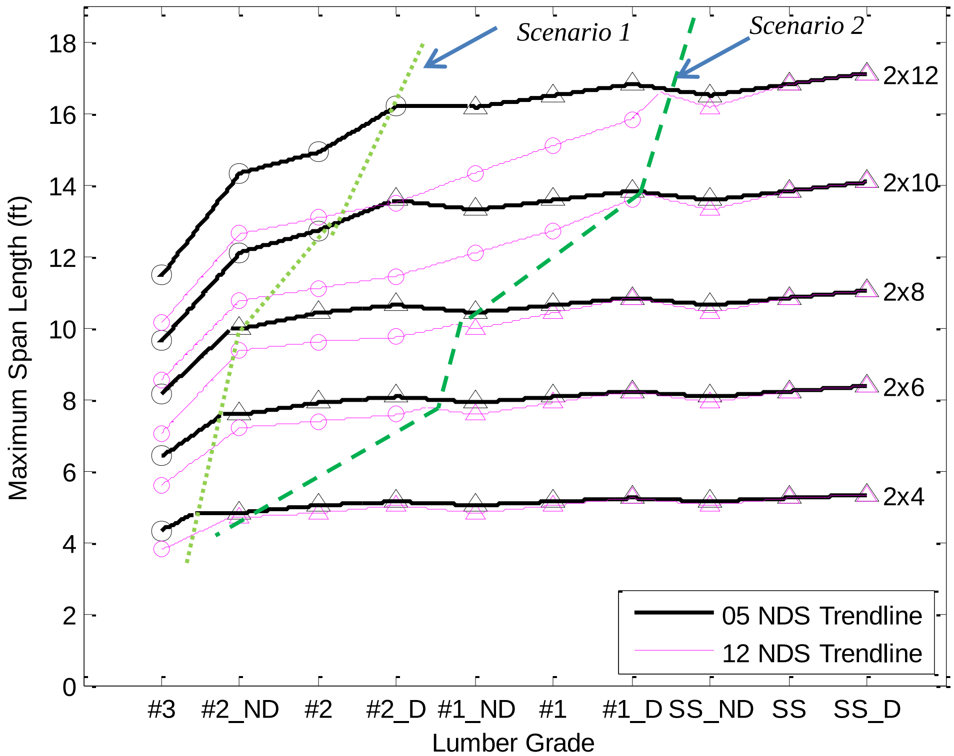


Figure F.9: Comparison between the maximum span lengths of 2005 NDS and 2012 NDS for Southern Pine floor joists spaced at 24 inches on center with *LL/DL* ratio at 5.

Table F.1: 2005 NDS design maximum span length with *LL/DL* ratio at 3.

2005 NDS Maximum Span length for DL = 10 psf LL = 30 psf (ft)											
Dimension	Spacing	Grade									
		D SS	SS	N-D SS	No.1 D	No.1	No.1 N-D	No.2 D	No.2	No.2 N-D	No.3 & Stud
2x4	12"	8.0 (d)	7.8 (d)	7.7 (d)	7.8 (d)	7.7 (d)	7.5 (d)	7.7 (d)	7.5 (d)	7.2 (d)	7.2 (d)
	16"	7.2 (d)	7.1 (d)	7.0 (d)	7.1 (d)	7.0 (d)	6.8 (d)	7.0 (d)	6.8 (d)	6.5 (d)	6.5 (d)
	24"	6.3 (d)	6.2 (d)	6.1 (d)	6.2 (d)	6.1 (d)	6.0 (d)	6.1 (d)	6.0 (d)	5.7 (d)	5.4 (b)
2x6	12"	12.5 (d)	12.3 (d)	12.0 (d)	12.3 (d)	12.0 (d)	11.8 (d)	12.0 (d)	11.8 (d)	11.3 (d)	11.2 (b)
	16"	11.4 (d)	11.2 (d)	10.9 (d)	11.2 (d)	10.9 (d)	10.7 (d)	10.9 (d)	10.7 (d)	10.3 (d)	9.7 (b)
	24"	9.9 (d)	9.7 (d)	9.6 (d)	9.7 (d)	9.6 (d)	9.4 (d)	9.6 (d)	9.4 (d)	9.0 (d)	7.9 (b)
2x8	12"	16.5 (d)	16.2 (d)	15.9 (d)	16.2 (d)	15.9 (d)	15.6 (d)	15.9 (d)	15.6 (d)	14.9 (d)	14.3 (b)
	16"	15.0 (d)	14.7 (d)	14.4 (d)	14.7 (d)	14.4 (d)	14.1 (d)	14.4 (d)	14.1 (d)	13.5 (d)	12.3 (b)
	24"	13.1 (d)	12.8 (d)	12.6 (d)	12.8 (d)	12.6 (d)	12.3 (d)	12.6 (d)	12.3 (d)	11.8 (d)	10.1 (b)
2x10	12"	21.0 (d)	20.6 (d)	20.3 (d)	20.6 (d)	20.3 (d)	19.8 (d)	20.3 (d)	19.8 (d)	19.0 (d)	16.8 (b)
	16"	19.1 (d)	18.8 (d)	18.4 (d)	18.8 (d)	18.4 (d)	18.0 (d)	18.4 (d)	18.0 (d)	17.2 (d)	14.6 (b)
	24"	16.7 (d)	16.4 (d)	16.1 (d)	16.4 (d)	16.1 (d)	15.8 (d)	16.1 (d)	15.7 (b)	15.0 (b)	11.9 (b)
2x12	12"	25.6 (d)	25.1 (d)	24.6 (d)	25.1 (d)	24.6 (d)	24.1 (d)	24.6 (d)	24.1 (d)	23.1 (d)	20.0 (b)
	16"	23.2 (d)	22.8 (d)	22.4 (d)	22.8 (d)	22.4 (d)	21.9 (d)	22.4 (d)	21.9 (d)	21.0 (d)	17.4 (b)
	24"	20.3 (d)	19.9 (d)	19.5 (d)	19.9 (d)	19.5 (d)	19.2 (d)	19.5 (d)	18.5 (b)	17.7 (b)	14.2 (b)

*Highlighted cells indicate bending limit state controls. The “(d)” and “(b)” indicate the respective designs are controlled by deflection and bending (strength) limit states, respectively.

Table F.2: 2012 NDS design maximum span length with *LL/DL* ratio at 3.

2013 NDS Maximum Span length for DL = 10 psf LL = 30 psf (ft)											
Dimension	Spacing	Grade									
		D SS	SS	N-D SS	No.1 D	No.1	No.1 N-D	No.2 D	No.2	No.2 N-D	No.3 & Stud
2x4	12"	8.0 (d)	7.8 (d)	7.5 (d)	7.8 (d)	7.5 (d)	7.2 (d)	7.5 (d)	7.2 (d)	7.0 (d)	6.6 (b)
	16"	7.2 (d)	7.1 (d)	6.8 (d)	7.1 (d)	6.8 (d)	6.5 (d)	6.8 (d)	6.5 (d)	6.4 (d)	5.7 (b)
	24"	6.3 (d)	6.2 (d)	6.0 (d)	6.2 (d)	6.0 (d)	5.7 (d)	6.0 (d)	5.7 (d)	5.6 (d)	4.7 (b)
2x6	12"	12.5 (d)	12.3 (d)	11.8 (d)	12.3 (d)	11.8 (d)	11.3 (d)	11.8 (d)	11.3 (d)	11.0 (d)	9.8 (b)
	16"	11.4 (d)	11.2 (d)	10.7 (d)	11.2 (d)	10.7 (d)	10.3 (d)	10.7 (d)	10.3 (d)	10.0 (d)	8.5 (b)
	24"	9.9 (d)	9.7 (d)	9.4 (d)	9.7 (d)	9.4 (d)	9.0 (d)	9.4 (b)	9.0 (b)	8.7 (b)	6.9 (b)
2x8	12"	16.5 (d)	16.2 (d)	15.6 (d)	16.2 (d)	15.6 (d)	14.9 (d)	15.6 (d)	14.9 (d)	14.5 (d)	12.3 (b)
	16"	15.0 (d)	14.7 (d)	14.1 (d)	14.7 (d)	14.1 (d)	13.5 (d)	14.1 (d)	13.5 (d)	13.2 (d)	10.7 (b)
	24"	13.1 (d)	12.8 (d)	12.3 (d)	12.8 (d)	12.3 (d)	11.8 (d)	12.0 (b)	11.8 (b)	11.5 (b)	8.7 (b)
2x10	12"	21.0 (d)	20.6 (d)	19.8 (d)	20.6 (d)	19.8 (d)	19.0 (d)	19.8 (d)	19.0 (d)	18.5 (b)	15.0 (b)
	16"	19.1 (d)	18.8 (d)	18.0 (d)	18.8 (d)	18.0 (d)	17.2 (d)	17.4 (b)	16.8 (b)	16.3 (b)	13.0 (b)
	24"	16.7 (d)	16.4 (d)	15.8 (d)	16.4 (d)	15.7 (b)	15.0 (b)	14.2 (b)	13.7 (b)	13.3 (b)	10.6 (b)
2x12	12"	25.6 (d)	25.1 (d)	24.1 (d)	25.1 (d)	24.1 (d)	23.1 (d)	23.6 (b)	22.9 (b)	22.1 (b)	17.7 (b)
	16"	23.2 (d)	22.8 (d)	21.9 (d)	22.8 (d)	21.9 (d)	21.0 (d)	20.5 (b)	19.8 (b)	19.2 (b)	15.4 (b)
	24"	20.3 (d)	19.9 (d)	19.2 (d)	19.6 (b)	18.7 (b)	17.7 (b)	16.7 (b)	16.2 (b)	15.6 (b)	12.5 (b)

*Highlighted cells indicate bending limit state controls. The “(d)” and “(b)” indicate the respective designs are controlled by deflection and bending (strength) limit states, respectively.

Table F.3: Percent reductions in maximum span lengths (2005 NDS versus 2012 NDS) for *DL*=10psf and *LL*=30psf.

Maximum Span length for DL = 10 psf LL = 30 psf (ft)											
		Grade									
Dimension	**Spacing**	D SS	SS	N-D SS	No.1 D	No.1	No.1 N-D	No.2 D	No.2	No.2 N-D	No.3 & Stud
2x4	12"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	7.7
	16"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.0
	24"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.6
2x6	12"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.4
	16"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.4
	24"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.4
2x8	12"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	13.4
	16"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	13.4
	24"	0.0	0.0	2.0	0.0	2.0	4.4	4.4	4.4	2.4	13.4
2x10	12"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	11.0
	16"	0.0	0.0	2.0	0.0	2.0	4.4	5.7	6.6	5.5	11.0
	24"	0.0	0.0	2.0	0.0	2.0	4.9	11.9	12.7	11.1	11.0
2x12	12"	0.0	0.0	2.0	0.0	2.0	4.4	4.0	5.2	4.2	11.5
	16"	0.0	0.0	2.0	0.0	2.0	4.4	8.5	9.6	8.7	11.5
	24"	0.0	0.0	2.0	1.6	4.4	7.4	14.5	12.3	11.8	11.5

Table F.4: 2005 NDS design maximum span length with *LL/DL* ratio at 4.

2005 NDS Maximum Span length for DL = 10 psf LL = 40 psf (ft)											
		Grade									
Dimension	Spacing	D SS	SS	N-D SS	No.1 D	No.1	No.1 N-D	No.2 D	No.2	No.2 N-D	No.3 & Stud
2x4	12"	7.2 (d)	7.1 (d)	7.0 (d)	7.1 (d)	7.0 (d)	6.8 (d)	7.0 (d)	6.8 (d)	6.5 (d)	6.5 (d)
	16"	6.6 (d)	6.4 (d)	6.3 (d)	6.4 (d)	6.3 (d)	6.2 (d)	6.3 (d)	6.2 (d)	5.9 (d)	5.8 (b)
	24"	5.7 (d)	5.6 (d)	5.5 (d)	5.6 (d)	5.5 (d)	5.4 (d)	5.5 (d)	5.4 (d)	5.2 (d)	4.8 (b)
2x6	12"	11.4 (d)	11.2 (d)	10.9 (d)	11.2 (d)	10.9 (d)	10.7 (d)	10.9 (d)	10.7 (d)	10.3 (d)	9.9 (b)
	16"	10.3 (d)	10.1 (d)	9.9 (d)	10.1 (d)	9.9 (d)	9.7 (d)	9.9 (d)	9.7 (d)	9.3 (d)	8.6 (b)
	24"	9.0 (d)	8.9 (d)	8.7 (d)	8.9 (d)	8.7 (d)	8.5 (d)	8.7 (d)	8.5 (d)	8.1 (d)	7.0 (b)
2x8	12"	15.0 (d)	14.7 (d)	14.4 (d)	14.7 (d)	14.4 (d)	14.1 (d)	14.4 (d)	14.1 (d)	13.5 (d)	12.7 (b)
	16"	13.6 (d)	13.4 (d)	13.1 (d)	13.4 (d)	13.1 (d)	12.8 (d)	13.1 (d)	12.8 (d)	12.3 (d)	11.0 (b)
	24"	11.9 (d)	11.7 (d)	11.4 (d)	11.7 (d)	11.4 (d)	11.2 (d)	11.4 (d)	11.2 (d)	10.7 (d)	9.0 (b)
2x10	12"	19.1 (d)	18.8 (d)	18.4 (d)	18.8 (d)	18.4 (d)	18.0 (d)	18.4 (d)	18.0 (d)	17.2 (d)	15.0 (b)
	16"	17.3 (d)	17.0 (d)	16.7 (d)	17.0 (d)	16.7 (d)	16.4 (d)	16.7 (d)	16.4 (d)	15.7 (d)	13.0 (b)
	24"	15.2 (d)	14.9 (d)	14.6 (d)	14.9 (d)	14.6 (d)	14.3 (d)	14.6 (d)	14.0 (d)	13.3 (b)	10.6 (b)
2x12	12"	23.2 (d)	22.8 (d)	22.4 (d)	22.8 (d)	22.4 (d)	21.9 (d)	22.4 (d)	21.9 (d)	21.0 (d)	17.8 (b)
	16"	21.1 (d)	20.7 (d)	20.3 (d)	20.7 (d)	20.3 (d)	19.9 (d)	20.3 (d)	19.9 (d)	19.1 (d)	15.4 (b)
	24"	18.4 (d)	18.1 (d)	17.8 (d)	18.1 (d)	17.8 (d)	17.4 (d)	17.8 (d)	16.4 (b)	15.8 (b)	12.6 (b)

*Highlighted cells indicate bending limit state controls. The “(d)” and “(b)” indicate the respective designs are controlled by deflection and bending (strength) limit states, respectively.

Table F.5: 2012 NDS design maximum span length with *LL/DL* ratio at 4.

2013 NDS Maximum Span length for DL = 10 psf LL = 40 psf (ft)																					
Dimension	Spacing	Grade																			
		D SS		SS		N-D SS		No.1 D		No.1		No.1 N-D		No.2 D		No.2		No.2 N-D		No.3 & Stud	
2x4	12"	7.2	(d)	7.1	(d)	6.8	(d)	7.1	(d)	6.8	(d)	6.5	(d)	6.8	(d)	6.5	(d)	6.4	(d)	5.9	(b)
	16"	6.6	(d)	6.4	(d)	6.2	(d)	6.4	(d)	6.2	(d)	5.9	(d)	6.2	(d)	5.9	(d)	5.8	(d)	5.1	(b)
	24"	5.7	(d)	5.6	(d)	5.4	(d)	5.6	(d)	5.4	(d)	5.2	(d)	5.4	(d)	5.2	(d)	5.1	(d)	4.2	(b)
2x6	12"	11.4	(d)	11.2	(d)	10.7	(d)	11.2	(d)	10.7	(d)	10.3	(d)	10.7	(d)	10.3	(d)	10.0	(d)	8.7	(b)
	16"	10.3	(d)	10.1	(d)	9.7	(d)	10.1	(d)	9.7	(d)	9.3	(d)	9.7	(d)	9.3	(d)	9.1	(d)	7.5	(b)
	24"	9.0	(d)	8.9	(d)	8.5	(d)	8.9	(d)	8.5	(d)	8.1	(d)	8.3	(b)	8.1	(b)	7.9	(b)	6.2	(b)
2x8	12"	15.0	(d)	14.7	(d)	14.1	(d)	14.7	(d)	14.1	(d)	13.5	(d)	14.1	(d)	13.5	(d)	13.2	(d)	11.0	(b)
	16"	13.6	(d)	13.4	(d)	12.8	(d)	13.4	(d)	12.8	(d)	12.3	(d)	12.8	(d)	12.3	(d)	12.0	(d)	9.5	(b)
	24"	11.9	(d)	11.7	(d)	11.2	(d)	11.7	(d)	11.2	(d)	10.7	(d)	10.7	(b)	10.6	(b)	10.3	(b)	7.8	(b)
2x10	12"	19.1	(d)	18.8	(d)	18.0	(d)	18.8	(d)	18.0	(d)	17.2	(d)	17.8	(b)	17.2	(b)	16.7	(b)	13.3	(b)
	16"	17.3	(d)	17.0	(d)	16.4	(d)	17.0	(d)	16.4	(d)	15.7	(d)	15.4	(b)	15.0	(b)	14.5	(b)	11.5	(b)
	24"	15.2	(d)	14.9	(d)	14.3	(d)	14.9	(b)	14.0	(b)	13.3	(b)	12.6	(b)	12.2	(b)	11.8	(b)	9.4	(b)
2x12	12"	23.2	(d)	22.8	(d)	21.9	(d)	22.8	(d)	21.9	(d)	21.0	(d)	21.0	(b)	20.3	(b)	19.6	(b)	15.8	(b)
	16"	21.1	(d)	20.7	(d)	19.9	(d)	20.7	(d)	19.9	(d)	19.1	(d)	18.2	(b)	17.6	(b)	17.0	(b)	13.6	(b)
	24"	18.4	(d)	18.1	(d)	17.4	(d)	17.4	(b)	16.6	(b)	15.8	(b)	14.9	(b)	14.4	(b)	13.9	(b)	11.1	(b)

*Highlighted cells indicate bending limit state controls. The "(d)" and "(b)" indicate the respective designs are controlled by deflection and bending (strength) limit states, respectively.

Table F.6: Percent reductions in maximum span lengths (2005 NDS versus 2012 NDS) for *DL*=10psf and *LL*=40psf.

Maximum Span length for DL = 10 psf LL = 40 psf (ft)											
		Grade									
Dimension	Spacing	D SS	SS	N-D SS	No.1 D	No.1	No.1 N-D	No.2 D	No.2	No.2 N-D	No.3 & Stud
2x4	12"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	9.7
	16"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.6
	24"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.6
2x6	12"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.4
	16"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.4
	24"	0.0	0.0	2.0	0.0	2.0	4.4	4.2	4.6	2.8	12.4
2x8	12"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	13.4
	16"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	13.4
	24"	0.0	0.0	2.0	0.0	2.0	4.4	6.5	5.8	4.1	13.4
2x10	12"	0.0	0.0	2.0	0.0	2.0	4.4	3.2	4.4	3.0	11.0
	16"	0.0	0.0	2.0	0.0	2.0	4.4	7.8	8.7	7.6	11.0
	24"	0.0	0.0	2.0	0.0	4.2	7.0	13.8	12.7	11.1	11.0
2x12	12"	0.0	0.0	2.0	0.0	2.0	4.4	6.1	7.3	6.3	11.5
	16"	0.0	0.0	2.0	0.0	2.0	4.4	10.5	11.6	10.7	11.5
	24"	0.0	0.0	2.0	3.8	6.5	9.5	16.4	12.3	11.8	11.5

Table F.7: 2005 NDS design maximum span length with *LL/DL* ratio at 5.

2005 NDS Maximum Span length for DL = 10 psf LL = 50 psf (ft)											
Dimension	Spacing	Grade									
		D SS	SS	N-D SS	No.1 D	No.1	No.1 N-D	No.2 D	No.2	No.2 N-D	No.3 & Stud
2x4	12"	6.7 (d)	6.6 (d)	6.5 (d)	6.6 (d)	6.5 (d)	6.3 (d)	6.5 (d)	6.3 (d)	6.1 (d)	6.1 (d)
	16"	6.1 (d)	6.0 (d)	5.9 (d)	6.0 (d)	5.9 (d)	5.8 (d)	5.9 (d)	5.8 (d)	5.5 (d)	5.3 (b)
	24"	5.3 (d)	5.2 (d)	5.1 (d)	5.2 (d)	5.1 (d)	5.0 (d)	5.1 (d)	5.0 (d)	4.8 (d)	4.3 (b)
2x6	12"	10.5 (d)	10.4 (d)	10.2 (d)	10.4 (d)	10.2 (d)	10.0 (d)	10.2 (d)	10.0 (d)	9.5 (d)	9.0 (b)
	16"	9.6 (d)	9.4 (d)	9.2 (d)	9.4 (d)	9.2 (d)	9.0 (d)	9.2 (d)	9.0 (d)	8.6 (d)	7.8 (b)
	24"	8.4 (d)	8.2 (d)	8.1 (d)	8.2 (d)	8.1 (d)	7.9 (d)	8.1 (d)	7.9 (d)	7.6 (d)	6.4 (b)
2x8	12"	13.9 (d)	13.6 (d)	13.4 (d)	13.6 (d)	13.4 (d)	13.1 (d)	13.4 (d)	13.1 (d)	12.5 (d)	11.5 (b)
	16"	12.6 (d)	12.4 (d)	12.2 (d)	12.4 (d)	12.2 (d)	11.9 (d)	12.2 (d)	11.9 (d)	11.4 (d)	10.0 (b)
	24"	11.0 (d)	10.8 (d)	10.6 (d)	10.8 (d)	10.6 (d)	10.4 (d)	10.6 (d)	10.4 (d)	10.0 (d)	8.1 (b)
2x10	12"	17.7 (d)	17.4 (d)	17.1 (d)	17.4 (d)	17.1 (d)	16.7 (d)	17.1 (d)	16.7 (d)	16.0 (d)	13.6 (b)
	16"	16.1 (d)	15.8 (d)	15.5 (d)	15.8 (d)	15.5 (d)	15.2 (d)	15.5 (d)	15.2 (d)	14.5 (d)	11.8 (b)
	24"	14.1 (d)	13.8 (d)	13.6 (d)	13.8 (d)	13.6 (d)	13.3 (d)	13.6 (d)	12.7 (b)	12.1 (b)	9.6 (b)
2x12	12"	21.6 (d)	21.2 (d)	20.8 (d)	21.2 (d)	20.8 (d)	20.4 (d)	20.8 (d)	20.4 (d)	19.5 (d)	16.2 (b)
	16"	19.6 (d)	19.2 (d)	18.9 (d)	19.2 (d)	18.9 (d)	18.5 (d)	18.9 (d)	18.3 (b)	17.5 (b)	14.0 (b)
	24"	17.1 (d)	16.8 (d)	16.5 (d)	16.8 (d)	16.5 (d)	16.2 (d)	16.2 (b)	14.9 (b)	14.3 (b)	11.4 (b)

*Highlighted cells indicate bending limit state controls. The “(d)” and “(b)” indicate the respective designs are controlled by deflection and bending (strength) limit states, respectively.

Table F.8: 2012 NDS design maximum span length with *LL/DL* ratio at 5.

2013 NDS Maximum Span length for DL = 10 psf LL = 50 psf (ft)											
Dimension	Spacing	Grade									
		D SS	SS	N-D SS	No.1 D	No.1	No.1 N-D	No.2 D	No.2	No.2 N-D	No.3 & Stud
2x4	12"	6.7 (d)	6.6 (d)	6.3 (d)	6.6 (d)	6.3 (d)	6.1 (d)	6.3 (d)	6.1 (d)	5.9 (d)	5.4 (b)
	16"	6.1 (d)	6.0 (d)	5.8 (d)	6.0 (d)	5.8 (d)	5.5 (d)	5.8 (d)	5.5 (d)	5.4 (d)	4.6 (b)
	24"	5.3 (d)	5.2 (d)	5.0 (d)	5.2 (d)	5.0 (d)	4.8 (d)	5.0 (d)	4.8 (d)	4.7 (d)	3.8 (b)
2x6	12"	10.5 (d)	10.4 (d)	10.0 (d)	10.4 (d)	10.0 (d)	9.5 (d)	10.0 (d)	9.5 (d)	9.3 (d)	7.9 (b)
	16"	9.6 (d)	9.4 (d)	9.0 (d)	9.4 (d)	9.0 (d)	8.6 (d)	9.0 (d)	8.6 (d)	8.4 (d)	6.9 (b)
	24"	8.4 (d)	8.2 (d)	7.9 (d)	8.2 (d)	7.9 (d)	7.6 (d)	7.6 (b)	7.4 (b)	7.2 (b)	5.6 (b)
2x8	12"	13.9 (d)	13.6 (d)	13.1 (d)	13.6 (d)	13.1 (d)	12.5 (d)	13.1 (d)	12.5 (d)	12.2 (d)	10.0 (b)
	16"	12.6 (d)	12.4 (d)	11.9 (d)	12.4 (d)	11.9 (d)	11.4 (d)	11.9 (b)	11.4 (b)	11.1 (b)	8.6 (b)
	24"	11.0 (d)	10.8 (d)	10.4 (d)	10.8 (d)	10.4 (d)	10.0 (d)	9.7 (b)	9.6 (b)	9.4 (b)	7.0 (b)
2x10	12"	17.7 (d)	17.4 (d)	16.7 (d)	17.4 (d)	16.7 (d)	16.0 (d)	16.2 (b)	15.7 (b)	15.2 (b)	12.1 (b)
	16"	16.1 (d)	15.8 (d)	15.2 (d)	15.8 (d)	15.2 (d)	14.5 (d)	14.0 (b)	13.6 (b)	13.2 (b)	10.5 (b)
	24"	14.1 (d)	13.8 (d)	13.3 (d)	13.6 (b)	12.7 (b)	12.1 (b)	11.4 (b)	11.1 (b)	10.7 (b)	8.6 (b)
2x12	12"	21.6 (d)	21.2 (d)	20.4 (d)	21.2 (d)	20.4 (d)	19.5 (d)	19.1 (b)	18.5 (b)	17.9 (b)	14.3 (b)
	16"	19.6 (d)	19.2 (d)	18.5 (d)	19.2 (d)	18.5 (b)	17.5 (b)	16.5 (b)	16.0 (b)	15.5 (b)	12.4 (b)
	24"	17.1 (d)	16.8 (d)	16.2 (d)	15.8 (b)	15.1 (b)	14.3 (b)	13.5 (b)	13.1 (b)	12.6 (b)	10.1 (b)

*Highlighted cells indicate bending limit state controls. The "(d)" and "(b)" indicate the respective designs are controlled by deflection and bending (strength) limit states, respectively.

Table F.9: Percent reductions in maximum span lengths (2005 NDS versus 2012 NDS) for *DL*=10psf and *LL*=50psf.

Maximum Span length for DL = 10 psf LL = 50 psf (ft)											
Dimension	**Spacing**	**Grade**									
		D SS	SS	N-D SS	No.1 D	No.1	No.1 N-D	No.2 D	No.2	No.2 N-D	No.3 & Stud
2x4	12"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	11.6
	16"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.6
	24"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.6
2x6	12"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.4
	16"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	12.4
	24"	0.0	0.0	2.0	0.0	2.0	4.4	6.2	6.6	4.8	12.4
2x8	12"	0.0	0.0	2.0	0.0	2.0	4.4	2.0	4.4	2.4	13.4
	16"	0.0	0.0	2.0	0.0	2.0	4.4	2.1	4.4	2.4	13.4
	24"	0.0	0.0	2.0	0.0	2.0	4.4	8.5	7.8	6.1	13.4
2x10	12"	0.0	0.0	2.0	0.0	2.0	4.4	5.3	6.2	5.1	11.0
	16"	0.0	0.0	2.0	0.0	2.0	4.4	9.7	10.6	9.5	11.0
	24"	0.0	0.0	2.0	1.6	6.2	9.0	15.6	12.7	11.1	11.0
2x12	12"	0.0	0.0	2.0	0.0	2.0	4.4	8.1	9.2	8.3	11.5
	16"	0.0	0.0	2.0	0.0	2.1	5.2	12.4	12.3	11.8	11.5
	24"	0.0	0.0	2.0	5.8	8.5	11.4	16.6	12.3	11.8	11.5

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