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PROBABILISTIC ANALYSIS OF WOOD FLOOR VIBRATIONS CONSIDERING SHEATHING DISCONTINUITIES

by

Mubarak O. Adesina

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Committee Approval

To the Graduate Faculty:

The members of the committee appointed to examine the thesis of MUBARAK O. ADESINA find it satisfactory and recommend that it be accepted.

Major Advisor:

Dr. Arya Ebrahimpour

Committee Member:

Dr. Andrew Sorensen

Graduate Faculty Representative:

Dr. Marco Schoen

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ABSTRACT

Probabilistic analysis of wood floor vibrations under occupant induced loads is presented. The project adopts the finite element analysis approach using the Opensees© simulation framework with Microsoft Excel© used as the user interface. The Opensees© results were imported into the user interface and compared against multiple vibration perception criteria. Analyses included the effect of sheathing continuity on the floor response. Extensive literature search was performed to obtain the relevant statistical data on sawn lumber joists and engineered I-joists. An automatic process was developed based on appropriate probability distribution functions, and the Excel© interface simulated random values for the parameters considered. Limit state functions are developed based on the current serviceability criteria. Combinations of random and deterministic parameters are used in the limit state equations. With availability of statistical data on loading, reliability analyses were performed for a single joist as well the full floor for static deflection under a uniform live load. Using Monte Carlo simulation, probability of failure values were obtained for two floor systems of same dimensions. The first floor had continuous sheathing and the other had discontinuous sheathing. Furthermore, results are discussed, followed by summary and conclusions. The results show a large range of probability of failure for the vibration serviceability as well as satisfying the limit states for both floors investigated.

Keywords: Reliability analysis, limit state, probability of failure, wood floors, sawn lumber, wood floor sheathing, vibrations, OpenSees©, finite element analysis.

CHAPTER ONE

INTRODUCTION

1.1 Background

Among the major structural systems in buildings, floors are the only systems with which human occupants are in constant physical contact. As such, any failure in performance can be a source of inconvenience to the occupants. Failure in performance can be characterized in terms of strength limit state, serviceability limit state, and fatigue limit state.

Historically, in the United States, floors in wood structures have been designed according to strength and deflection criteria under static uniform loads. This method was used to develop maximum span tables which are currently used in practice. An essential part in the determination of maximum span has been the well-known deflection criterion of SPAN/360 under a live load; where, SPAN is the length of the floor joist. This ratio was determined by designer experience to ensure a certain level of serviceability under static loads. However, research has suggested that this criterion does not ensure vibrational serviceability. Vibrational serviceability is defined as a situation where occupants or users of a structure in this case floors, feel uncomfortable due to excitations on the floor. These excitations could be mechanical or human.

Assessment from a structural perspective, a wood floor can be treated as a two dimensional thin plate reinforced with a series of beams. Typically, this two dimensional system is simplified as a one dimensional beam structure for design under specified dead and live loads. The performance of the floor has been known to be influenced by stiffness, mass, damping and the two-way action of the floor structure. Sometimes, the static stiffness properties of the wood floor are adequate to ensure satisfactory vibration performance. In some cases however, floors designed to meet traditional deflection criterion under uniformly distributed loads have been found to exhibit vibration problems.

Recently, new construction practices have had a profound impact on the vibration characteristics of wood floors. Amongst these is the use of prefabricated engineered wood joist and concrete toppings. The availability of engineered wood joist and trusses has led to longer span and continuous multi-span floor systems while the use of a concrete topping has ultimately altered the mass characteristics of wood floors. The implication of this change is that previous empirical and semi-empirical vibration performance criteria and conventional calculation procedures are no longer appropriate for a large number of floors employing these construction methods.

Generally, a number of researchers from various countries have dwelled over the subject for a period of time (Ellingwood & Talin (1984), Foschi & Gupta (1987), Smith & Chui (1988), Folz & Foschi (1991, 1995), Philpot et al (1995), Dolan et al (1999), Al-Foqaha'a et al (1999), Lin J. Hu (1997, 2001, 2012). Significant progress has been made in understanding vibration parameters influencing human perception, development of design approaches for control of floor vibration, modeling floor responses to static and dynamic loads, and understanding the role each floor component plays in controlling wood floor vibrations.

1.2 Problem Definition And Scope

The prevalent use of wood floor systems has made it important to understand their behavior when subjected to occupant-induced vibrations. A number of researchers have developed deterministic relations to quantify the vibration acceptability of floors under human-induced activities. Generally, the dynamic response of a wood floor system is a complex problem. Each joist has a different modulus of elasticity and connections between joists and sheathing are non-rigid (Foschi and Gupta 1987).

In recent years, there have been frequent cases where the deflection criterion has been insufficient to guarantee acceptable vibrational serviceability due to normal human activities. Unacceptable floors have been particularly evident in long span lightweight designs regardless of material – steel, concrete, or wood (Kalkert et al, 1995).

Static deflection criterion has been used consistently in the past to define the serviceability limit state of floor system but this criterion does not reflect the dynamic effect experienced by the floor system due to human activities such as running, walking, jumping and other domestic activities. In the last three decades, researchers have developed empirical ways of defining acceptability criteria for wood floor system in terms of natural frequency, floor damping and root mean square (rms) of floor response acceleration.

This research focuses on the uncertainties and variations present in the floor structural components from a statistical view point. The probabilistic analysis will investigate the effect of uncertainties in material and geometric properties of the floor structure and thus the probability of failure will be determined. Much research has been done on the topic, yet there remains to be a code-implemented method of vibration serviceability control for residential floor systems in the United States.

1.3 Objectives

This research project has two goals:

I. To compare the probability of failure of current vibration acceptability criteria; and

II. To study the effect of sheathing continuity on probabilistic serviceability analysis of wood floor system.

The criteria used consider the natural frequency of the floor, the static deflection, and the root-mean-square value of response acceleration.

1.4 Methodology

The study focuses on vibration serviceability criterion on wood floors caused by occupant's activities (running and walking) of residential apartment. The effects of these vibrations are evaluated with respect to discontinuities present in the sheathing material and also the probability of failure of the entire floor system under certain defined limit states. Also, the results presented are obtained by a simulation process based on experimental values from other literature and references.

The probabilistic analysis is carried out with a constant live load of forty pounds per square foot (40 psf) on the wood floor because the program was setup this way (Burch, 2013). Here, a single joist static deflection and natural frequency is compared with the full floor static deflection and natural frequency.

Furthermore, a reliability analysis is carried out with varying live load with known mean and standard deviation. This analysis is done on a single joist and on the full floor but it's limited to the static deflection criterion (SPAN/360) only. Reliability index of both conditions is then compared bearing in mind the composite action between the sheathings and joists under the full floor static deflection.

1.5 Thesis Overview

The thesis follows a chronological sequence broken down into five chapters. Chapter One provides a general background on the subject, problem definition, scope, objective(s), and limitations. Chapter Two presents a review of literature pertaining to the current study is presented. Chapter Three presents a detailed methodology for carrying out the analyses, stating all conditions considered and tools used in process of decision making. Chapter Four presents the limit state considered for the probabilistic study. The last chapter concludes the study with available results, discussion of results, conclusions, and recommendations for future studies.

CHAPTER TWO

LITERATURE REVIEW

2.1 Serviceability Limit State

In many design situations, particularly in civil engineering structures, acceptability is defined by both ultimate and serviceability limit states. Serviceability refers to the satisfactory function of a structure.

Currently the criteria used in design for serviceability are essentially prescriptive and cannot be translated between structural elements using different structural materials or even between different types of elements using the same building material. As a designer one has to presume not only the circumstances for the building when it is erected and shortly after, but for the entire service duration of the structure. The designer also has to decide what structural system will be used in co-operation with architects, contractors and stakeholders. The normal manner to perform a serviceability analysis is to use code values for the material properties and for the loads applicable to the situation. In many codes, performance criteria are limit values for deflection, while other codes only state that the structure should function in a satisfactory manner during its service life. Serviceability requirements in current standards and specification which are rules of thumb, based on experience with traditional construction often are not sufficient for minimizing objectionable motion in modern structures (Ellingwood and Talin 1984). Detailed loading and resistance criteria have been developed for the ultimate or safety related limit states. However, serviceability requirements determine the degree to which limit states design lead to a feasible and economical structure. The rules, irrespective if they are given in regulations or are given as recommendations, differ however between countries, materials and structural systems.

To date, the National Design Specification (NDS) for Wood Construction does not provide any specific guidance regarding floor vibrations because it is serviceability not safety related. It is common knowledge that serviceability criteria used to control vibrations, limits deflection under uniform design live load to L/360 (where L is length of joist or beam). This is found to be acceptable and adequate for shorter spans. However, the emergence of pre-engineered joists combined with longer spans and more wide-open areas has shown floors to have poor performance with respect to floor vibrations. Therefore, designers tend to use higher deflection limits usually between L/480 and L/720 to control floor vibrations (Aghayere, 2007).

Generally, serviceability limit state in terms of static deflection for floor systems is limited to midspan deflection usually defined as a fraction of the floor span. However, there is yet to be a standard for limiting the dynamic response of floor systems.

2.2 Wood Floor Vibration

Structural vibrations arise from normal human activity (walking, running or rhythmic activity), operation of mechanical equipment within buildings, external traffic or wind storms and earthquakes. Methods of structural analysis and design are growing more refined, the systems are better integrated and use of high strength construction material is now common.

Numerous studies have been conducted in attempts to relate levels of floor vibration to human discomfort or tolerance levels. Specific findings in these studies are not always consistent due to diverse methods and purposes in the course of conducting the experiment or modeling the floor systems.

Ellingwood and Talin (1984) found that vibration is more likely to be a problem when caused by a single person walking than by a group of people. They showed that a single person walking on the floor provides an appropriate dynamic model for developing serviceability criteria. They concluded that frequent floor vibration problems can be minimized by requiring only a simple static deflection check. This deflection limit depends on occupancy but independent of span which conflicts with the existing specification of serviceability limit state that is dependent on span and independent of occupancy. Also, acceptability of floor vibrations is a function of occupants sensitivity to floor vibrations which is quite subjective and variable (Aghayere, 2007).

Limits on excitation and floor acceleration are usually expressed as a percentage of acceleration due to gravity *g*. Generally accepted limits on acceleration of floor vibration are shown in Table 2.1.

Table 2.1: Acceleration Limits for Floor Vibrations (Aghayere, 2007)

Activity	**Acceleration Limit, (a_0/g x 100%)**
Hospital (operating rooms)	0.25
Office, residential, church	0.50
Shopping malls	1.50
Dining, weight lifting	2
Rhythmic activity (aerobics, dancing)	5

In Table 2.1, a_0 is the measured acceleration response of the floor, and g is acceleration due to gravity.

Also, the natural frequency of the floor needs to be higher than the forcing frequency of the highest harmonic due to the rhythmic activity. Table 2.2 lists typical minimum floor frequencies.

Table 2.2: Typical Minimum Floor Frequencies (Hertz) (Aghayere, 2007)

Activity	Steel/Concrete Floor	Light-frame Floor
Dancing and dining	5	10
Rhythmic activity	9	13

Researchers have estimated the natural frequency of the floor as follows (Aghayere, 2007):

$$f_n = 0.18\sqrt{\frac{g}{\Delta_T}} \tag{2.1}$$

where: f_n is the natural frequency of floor system, (Hz), g is the acceleration due to gravity (386 in/s^2), and Δ_T is the total floor deflection at the mid-span (in).

A study by Foschi and Gupta (1987) used the finite strip method to study floor vibration induced by footfall impact loading. It was observed that the dynamic response analysis of wood floor systems was quite challenging due to variation in individual joist modulus of elasticity and the fact that the connection between joists and sheathing is non-rigid. Similarly, Folz and Foschi (1991) used the finite-strip method to simulate a footfall impact on a one-way stiffened floor system and the dynamic response due to occupants using dynamic floor analysis program (DYFAP). Its accuracy was tested numerically considering the combined free-vibration response of a plate-oscillator system. Humans were idealized as lumped oscillators that included masses, springs and dashpots in the vertical direction varying from a simple two degree of freedom system to a detailed eleven degree of freedom system. They assumed that nails exhibit linear load-slip characteristics, allowing slip parallel to the joist, slip perpendicular to the joist and rotational slip. They considered two kinds of floor systems: a lightweight residential wooden floor and a longer spanning, heavier, composite steel beam concrete slab floor. Results obtained from the simulation agreed with experimental result of the idealized two Degree of Freedom (DOF) composite steel beam floor but did not agree with 11 Degree of Freedom human model on the same floor. A better result could be achieved by calibrating the model's damping and stiffness parameters. Similarly, the lightweight wooden floor model did not agree with experimental result from composite floors as its frequency response due to excitation coincides with the frequency of the human body. This is problematic as it causes discomfort to the occupants. This clearly implies that dynamic floor evaluation adopted for composite floors cannot always be applied in the same way to lightweight residential wooden floors due to difference in material properties.

Designing a lightweight wooden floor to prevent human discomfort, Smith and Chui (1988) proposed a model, as shown in Figure 2.1, for predicting dynamic response of wood-joist floors in terms of natural frequencies and root mean square acceleration under a defined forcing function. The root mean square acceleration is the criterion for judging user perception tolerance of wooden floors used in residential buildings. The research stated that the range of frequencies to which humans are most sensitive is from 4 Hz to 8 Hz. In order to avoid excessive vibrations in this range, the natural frequency of the floor system must be greater than 8 Hz. Experimental work by Chui (1986) on both laboratory-built and on site floors concluded that acceptable root mean square acceleration (a_{rms}) should be less than $1.48ft/s^2(0.45m/s^2)$ for domestic structures. The acceleration response refers to excitation observed when a human is standing at the center of the floor and produces a rapid heel-drop impact through an approximate distance of 2.56 in (65 mm).

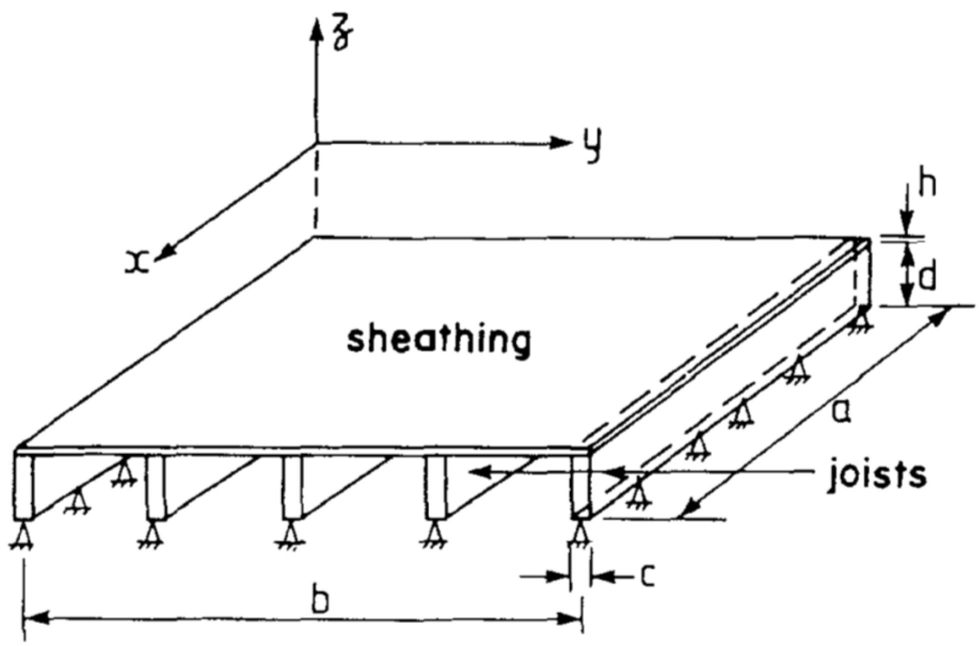

Figure 2.1: Smith and Chui standard floor (Smith and Chui, 1988)

The authors also provided suggested inputs for analysis such as a forcing function for the heel-drop test with recommended force and mass representative of a human initiating the heel-drop. As shown in Figure 2.2, the shape of the actual forcing function for a heel-drop would be quite complicated to reproduce. However, the shape of the assumed forcing function of a heel-drop test would be quite easily reproduced. The authors assure that this simplification of the forcing function leads to "only a small conservative error in the solution." The recommended values of P_0 and t_1 are 500 N (154 lbs) and 0.05 s - 0.07 s, respectively (Smith and Chui, 1988).

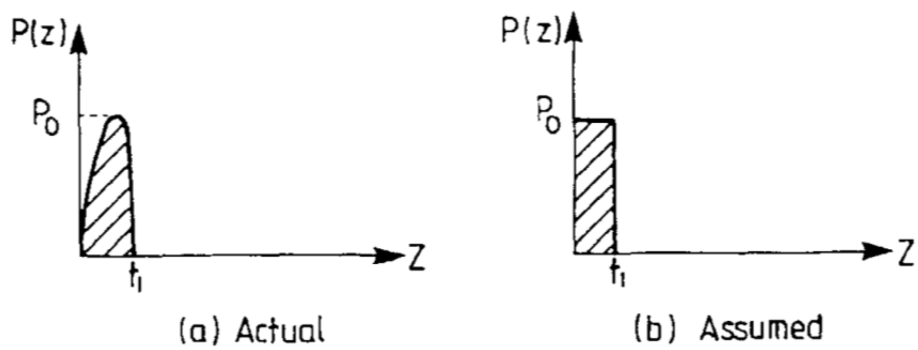

Figure 2.2: Shape of forcing function of heel-drop impact (Smith and Chui, 1988)

Experimental work by Chui (1986) shows that root mean square acceleration is a function of viscous damping ratio, natural frequency of the floor, and period of design impact. This root mean square acceleration should be further frequency weighted by an appropriate factor of $8/f_o$ because human bodies can tolerate higher vibration magnitudes at high frequencies than at low frequencies (Smith and Chui, 1988) where f_o is the floor fundamental frequency, for floor frequencies between 8 and 80Hz. Root mean square acceleration can be calculated using Equation (2.2):

$$A_{rms} = \frac{P_0 K_{\delta w_n t_1}}{m w_n} \tag{2.2}$$

where, $w_n = 2\pi f_0$ is angular fundamental natural frequency, f_0 is fundamental natural frequency, P_0 is amplitude of design impact, m is mass, $K_{\delta w_n t_1}$ is a floor factor to be taken from a lookup table developed by Smith and Chui (1988). Smith and Chui stated that quality floor performance can be achieved by supporting all four edges of the floor, insertion of adequate members between joist strutting, and use of flooring materials with high bending stiffness in the across joists direction. However, this criterion affects the building costs of some floors with greater span than the width, although overall economic cost of production of floors with acceptable serviceability is likely to be small as generally, wood floors in the United States are designed according to strength and serviceability criteria under static uniformly distributed load.

Kalkert, Dolan and Woeste (1995) examined different criteria: [Onysko (1985, 1988), Foschi and Gupta (1987), Ohlsson (1991), and Canadian Wood Council (1990)] with an experimental floor of 4.88m x 4.88m. Varying joist types were used: solid-sawn southern pine, parallel chord trusses and I-joist. The aim of the research was to develop a deflection factor based on floor dimensions and material properties. All floors considered using SPAN/360 (i.e., deflection factor of 360) failed with respect to vibration serviceability. Therefore, an increase in allowable deflection factor may be necessary. Deflection factors ranging between 701 – 1448 showed to be acceptable but this will eliminate solid sawn material from many design considerations because of decrease in allowable span. Also, it will be more expensive to design a structure using the proposed deflection factors. For acceptability, the experimental floor would be designed using SPAN/701 deflection criteria as proposed by the Canadian Wood Council (1990). The other criteria produced acceptable floor with an allowable deflection factor ranging from 935 to 1465. The deflection factors here excluded any direct structural interaction effects. It is best if structural interaction effects are considered as the allowable deflection for a single joist would be reduced there by considering the entire floor system rather than a single member approach.

In an effort to prevent annoying wood floor vibration, considering human perception, Dolan et al. (1999) developed a vibration-limiting criterion that does not require any knowledge of the damping associated with a floor system. Their criterion is based solely on the calculated or predicted natural frequency of a floor system. Dolan et al adopted a simple method of estimating the natural frequency of a floor as shown in Equation (2.3).

$$f = \frac{\pi}{2}\sqrt{\frac{gEI}{WL^3}} \tag{2.3}$$

where: g is the acceleration of gravity, E is the modulus of elasticity, I is the moment of inertia of the joist alone, W is the weight of floor system supported by joist, and L is the span length.

After calculation, the estimated natural frequency of the floor system is compared to the acceptability criteria. Based on results of 126 floors tested in the unoccupied condition and 54 floors in the occupied condition, wood floor acceptability criterion is as follows. The natural frequency of an unoccupied floor system, based on Eq. (2.2) must be higher than 15 Hz to be considered acceptable. Likewise, in the case of an occupied floor system, the natural frequency must be higher than 14 Hz. The occupancy loads considered in the analysis of Dolan et al range from 2 psf (45 MPa) to 4 psf (90 MPa). This criterion is very effective in disqualifying floors with unacceptable vibrations. All floors classified as unacceptable and marginal were disqualified using this criterion.

While previous researchers did not consider the mass of the entire floor system, Al-Foqaha'a, et al. (1999) developed a vibration design criterion for wood floors under human activities. Their work employed ABAQUS finite element analysis program to model wood floor under dynamic loading. Figure 2.3 shows the floor root mean square acceleration, fundamental frequency and mass of floor system, serves as a standard used to describe the floor behavior for the study. Similar to other researchers, the dynamic analysis involved determination of the floor response to a heel-drop test where an individual (impactor) drops his heels through an estimated distance of 65 mm applying an excitation to the floor similar to a person walking or running. The individual was modeled numerically as a mass-spring-dashpot single degree of freedom system with an initial velocity of the heel as it drops on the floor. Results from this study were compared to experimental results and the two sets of results were found to be in concord. Current vibration criteria based upon static properties or fundamental natural frequency has been found to be insufficient to prevent annoying floor vibration. Al-Foqaha'a design curves predicted that for a wood floor subjected to dynamic loading an acceptable frequency range was between 8 – 40 Hz based on a simplified equation for a simply supported beam. However, the floor vibration is only acceptable when natural frequency is approximately greater than 20 Hz depending on floor mass and acceleration root mean square, (a_{rms}) criterion. It is best that wood floors be designed to have combinations of stiffness and mass that yield acceptable a_{rms} values ($a_{rms} \leqslant 0.45$ m/s^2) (Al-Foqaha'a, A., et al. 1999).

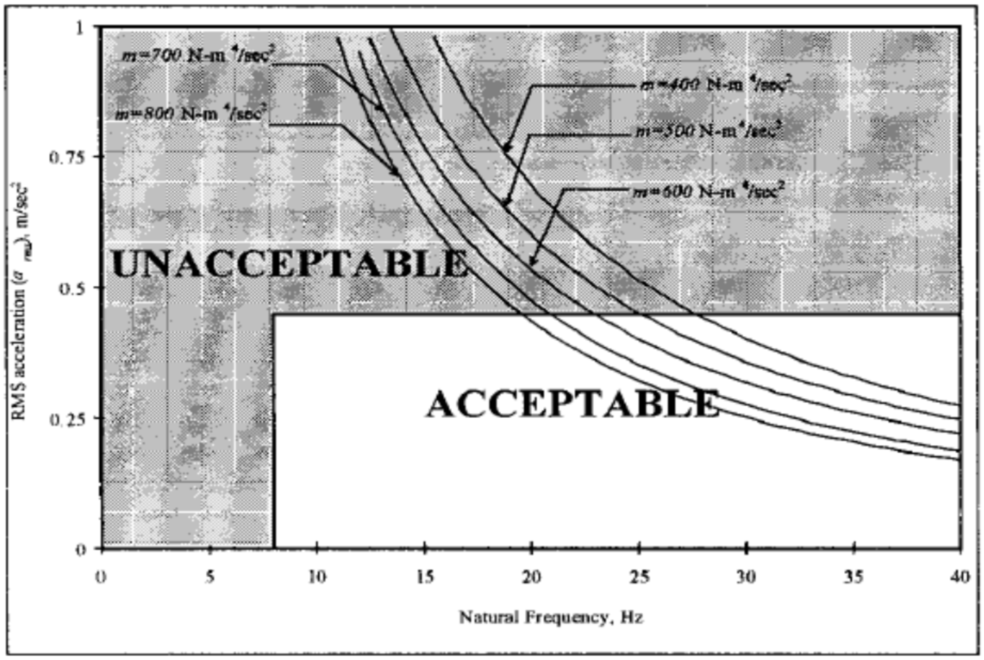

Figure 2.3: Proposed design curves (Al-Foqaha'a, A., et al. 1999)

Hu, Chui and Onysko (2001) reviewed the progress made on vibration serviceability of timber floors in the 1990s. It was found that despite the amount of experimental and simulated result available on the subject, none of the methods have fully considered the effect of construction methods as well as the variations in material property of individual structural members of wood floors. Therefore, raising the question of which approach is best suitable to minimize vibration serviceability problems in wood floors to prevent human discomfort. It was recommended by Hu, Chui and Onysko (2001) that a universally applicable design approach be adopted in the building codes for vibration serviceability of wood floors other than the known criteria (uniformly distributed live load deflection, concentrated load deflection, fundamental natural frequency and frequency-weighted root mean square (rms) acceleration). The authors concluded that any reliable design approach should be derived from predictable and measurable parameters, and also reflect the nature of occupancy for which it is designed.

Hu (2007) furthered her 2001 study and developed a criterion. The criterion developed by Hu deals with a combination of natural frequency and static displacement. The decision to include these two metrics instead of other dynamic methods is based on the ease of field measurements and predictive calculation of the static displacement and natural frequency. Hu's combination of natural frequency and static deflection compared well with other combinations such as natural frequency with peak velocity, natural frequency with peak acceleration, and natural frequency with root-mean-square acceleration. The results were similar with occupant perceptions of floor vibration acceptability.

Hu's criterion is designed for measurements on unoccupied floors without partitions, finishing, or furniture. The static deflection is measured after application of a 225 lbs. (1-kN) load at mid-span. The allowed deflection can be determined using either Equation (2.4) or (2.5).

$$\left(\frac{f}{\delta^{0.44}}\right) > 18.7 \tag{2.4}$$

$$\delta < \left(\frac{f}{18.7}\right)^{2.27} \tag{2.5}$$

where: f is fundamental natural frequency, δ is 225 lbs. static deflection

This criterion was compared to a database of 106 floors which had been rated by occupants as to their vibration acceptability in order to determine accuracy of the criterion in prediction of acceptability.

Hu and Gagnon (2012) studied the fundamentals and methodology required to control cross-laminated timber (CLT) floor vibrations. CLT floors have been known to have a mass varying between 6 pounds per square foot to 31 pounds per square foot and fundamental natural frequency greater than 9 Hz. The laboratory testing focused on performance parameters such as natural frequencies, modal damping ratios, static deflection under 225 pounds load, velocity and accelerations. This was done to determine the construction and design parameters that greatly affected the CLT floor vibration. Also the CLT floors were subjected to subjective evaluation to assess the maximum annoying vibration level that is permissible to the majority of occupants of residential floors. Other tests performed include static concentrated load test, modal test, and forced vibration test. Laboratory results show that the CLT stiffness along longitudinal axis and mass greatly controlled the vibration performance of CLT floors. The design criterion uses the stiffness and mass of CLT floors to control the vibration through a combination of fundamental natural frequency and 225 pounds static deflection.

Burch (2013) study was based on the assumption that wood floor sheathing discontinuities play a key role in the finite element vibration analysis of wood floors. This observation has been made in an earlier study by Al-Foqaha'a (1999) as a result of the difference in natural frequency of a wood floor subjected to excitation over a continuous sheathing and a discontinued sheathing. The continuous sheathing is found to behave relatively better under vibration as compared to discontinued sheathing but this simplification is not valid as the sheathing is always discontinuous when used for wood floor construction. Burch created a computer program that would aid designers and engineers in design wood floor system and also use this program to perform finite element analysis comparing the effect of sheathing discontinuities on a wood floor system subjected to vibration. His program utilized OpenSees© (an open source code developed by University of California, Berkeley), Microsoft Excel© and Visual Basic program to perform the finite element vibration analysis. All material setup and design criterion was done in Excel© leaving OpenSees© to perform the analysis with varying mesh size. The program is user friendly as the user can input various floor sizes, standard I-joist and regular lumber joist sizes of different species, joist modulus of elasticity, sheathing properties, fastener spacing, advanced fastener inputs, sheathing connectivity, edge support conditions, occupancy load, and dynamic input which are already embedded in the Excel© workbook. He performed the analysis on over 100 floors with slight variations in sizes and floor properties. The results obtained showed that continuous sheathed floor produced deflections approximately 11% to 22% lower than a floor system with discontinued sheathing. These floors also achieved a natural frequency that was 7% to 12% higher than floors with discontinued sheathing. It can be said that great care should be taken in over simplifying the sheathing set up on a wood floor model since the results of the model create an implication of better serviceability performance than actual installed floors will achieve.

The British Standard (Guide to evaluation, 1992) states the general guidance on how to assess floor vibrations and how to predict human response to vibrations. Basic requirement for floor vibration assessment is that it must cover all important parameters affecting human response. The parameters include amplitude, damping and frequency of vibration. Frequency weighted root mean square acceleration of vibration caused by a footfall impact satisfies this requirement (Chui 1986). Humans tend to tolerate higher vibration magnitude at higher frequencies than lower frequencies; thus, the calculated root-mean-square acceleration is frequency weighted. International Standards Organization 2631-2 (Evaluation, 1989) states only frequencies between 8 and 80 Hz should be included scaled by a factor equal to $8/f_o$, where f_o is the floor fundamental natural frequency in Hertz (Hz). Smith and Chui (1988) introduced a design criterion based on the requirement that fundamental frequency of vibration for the floor be greater than 8 Hz and that the root mean square acceleration value for the first one-second of vibration be less than 0.45 m/s^2.

The previous literature has not been able to state clearly a standard for performing a dynamic analysis of wood floor system subjected to human activities. Due to the uncertainties and randomness involved in developing such a standard, a structural reliability analysis will be utilized to develop a safety level which can be defined or used as a standard. The ability to predict an acceptable dynamic response in a floor occupant system is central to the estimation of reliability in serviceability limit states.

2.3 Structural Reliability Analysis

The aim of any structural design is to ensure safety and economy of the structure operating under a given environment for a given period of life. As a result, designers always check whether the resistance or capacity of the structure exceeds the applied load or demand on the structure. Mathematically,

$$Resistance\ (R) > Applied\ Load\ (Q)$$

So long as this condition is satisfied, the safety of the structure is ensured for the intended purpose for which the structure is built. Besides this, designers also ensure that there is an optimal use of the materials which, in turn, ensures economy. In this process, the designer uses some pre-fixed values of different design parameters like geometry, material property, boundary conditions and loads. However, experience shows that there is a significance difference between these fixed design parameters and their actual values during operations. The reason behind this phenomenon is that the design parameters are not deterministic, but random in nature (Nowak and Collins, 2000). Similarly, code requirements have evolved to include design criteria that take into cognizance the sources of uncertainty in design. Criterion such as this is referred to as reliability-based design criterion.

Therefore, the reliability analysis of a structure may be described as the procedure to incorporate the uncertainty in a systematic manner to ensure safety and economy or the ability of a structure to fulfill its design purpose for a specific design lifetime. It has been defined that reliability equals the probability that a structure will not fail to perform its intended function. Failure does not mean catastrophic failure but is used to indicate that the structure does not perform as desired (Nowak and Collins, 2000).

Structural reliability helps to answer the following questions: How can we measure the safety of structures?; How safe is safe enough?; and How does a designer implement the optimum safety level?

2.3.1 Random Variables

A random variable is a variable whose values are always associated with a probability of occurrence, (i.e. the numerical value of the random variable cannot be predicted with certainty before experiment). Random variable ‘X’ in sample space ‘S’ is a set of real number. It may be discrete or continuous. A discrete random variable is a variable that can only assume a limited number of entities in the sample space while a continuous random variable can assume any value within the sample space.

Basic parameters of a random variable include: expected value, variance, standard deviation and coefficient of variation. Every random variable has the fore mentioned parameters which enables a reliability study to be possible.

2.3.2 Simulation Techniques

There are multiple ways to solve structural reliability problems. Simulation technique is a possible way to solve this problem and is employed in this research. It should be noted that simulation is used when a closed-form solution is not possible. The idea of simulation involves the numerical experimentation of a certain phenomenon then observing the frequency of occurrence of a certain event of interest. Simulation is somewhat straight forward but the process is computationally complex.

A common technique used is called the Monte Carlo simulation. Monte Carlo simulation helps to generate numerical results without actually performing any physical experiment or test. Sometimes, it uses result from previous tests to establish the probability distributions of important variables in the problem. According to Nowak and Collins (2000), it is often applied in the following situations:

1. It is used to solve complex problems for which closed-form solutions are either not possible or extremely difficult. For instance, probabilistic problems involving complicated nonlinear finite element models.

2. It is used to solve complex problems that can be solved in closed form if many simplifying assumptions are made.
3. It can be used to check results of other solution techniques and also make predictions.

Basis of all Monte Carlo simulation is the generation of random numbers that are uniformly distributed between 0 and 1.

2.3.3 Limit States and Reliability Index

Design constraints are frequently referred to as limit states. Limit states are conditions of potential structural failure. Structural failure can be defined as a situation when the structure cannot perform its intended purpose. This definition is general as the purpose of the structure is not specified. Depending on the structural material, structures can fail by yielding, rupture, buckling, excessive deflection or excessive vibrations.

Limit state helps define failure as observed within structural reliability analyses. It is a region between desired and undesired performance of a structural system. This region is usually represented by a limit state function or performance function.

In structural reliability analyses three types of limit states are considered:

1. Ultimate limit states
2. Serviceability limit states
3. Fatigue limit states (common with tension members).

A performance function or limit state function for a mode of failure can be written as

$$g\ (R, Q) = R - Q \tag{2.6}$$

where: R is resistance or capacity and Q is the applied load.

If $g \geq 0$, the structure is safe (desired performance); if $g < 0$, the structure is not safe (undesired performance).

The probability of failure P_f is the occurrence of undesired performance and it is expressed mathematically in terms of limit state function as:

$$P_f = P(R - Q < 0) = P(g < 0) \tag{2.7}$$

where: P_f is probability of failure, R is resistance or capacity, Q is the applied load, g is the limit state function.

Reliability index on the other hand is simply defined as the inverse of coefficient of variation. In terms of performance function, as shown in Figure 2.4, it is the shortest distance from the origin of reduced variables to the line g (Z_R, Z_Q) = 0.

This can be graphically defined as shown in figure 2.4.

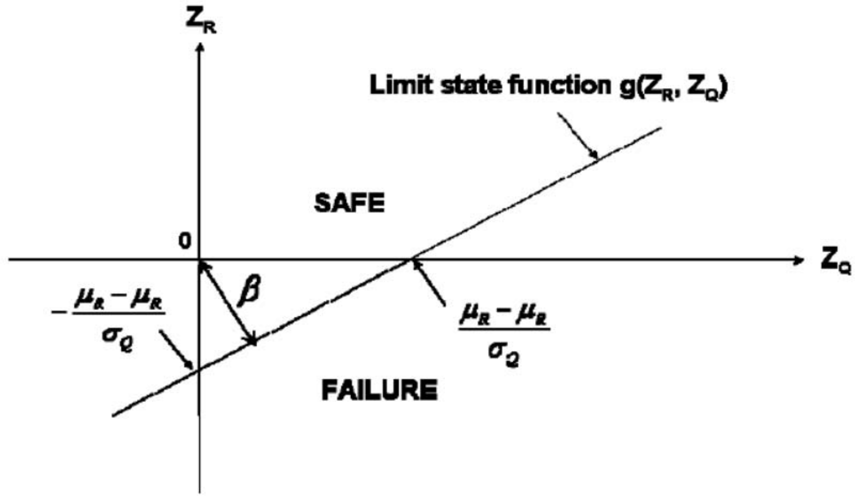

Figure 2.4: Reliability index defined as the shortest distance. (Nowak and Collins, 2000)

By geometry, reliability index can be calculated using Equation (2.8)

$$\beta = \frac{\mu_R-\mu_Q}{\sqrt{\sigma_R^2+\sigma_Q^2}} \tag{2.8}$$

where: β is the reliability index of the function when R and Q are uncorrelated.

For normally distributed random variables R and Q, it can be shown that reliability index is related to probability of failure by:

$$\beta = -\phi^{-1}(P_f) \; or \; P_f = \phi(-\beta) \tag{2.9}$$

where: ϕ is standard normal cumulative distribution function and ϕ^{-1} is the inverse.

2.4 Reliability Analysis of Wood Floors

Recent studies have shown that static analysis is insufficient to measure the safety or serviceability of a wood floor structure. As a result, a probabilistic study is necessary to ensure all uncertainties needed to achieve a safe and economical wood floor system are within appropriate limit as specified by designer or standard building codes. These uncertainties include the variation in mechanical and physical properties of wood due to its orthotropic nature, variations in floor geometry, stiffness of fastener used, and the load applied on the floor system.

Most wood floors are now subjected to vibrations caused by occupants or mechanical devices which cause discomfort to occupants. Foschi and Gupta (1988) conducted a reliability study on wood floors with torsional restraints, varying joist size as random variables under impact vibration but the floor span was an independent variable. Their outcome considered a target reliability index of 2.0 as satisfactory for serviceability limit state. Philpot et al., 1995 used Monte Carlo simulation to investigate reliability of wood-joist floor system with attention to effects of creep deformations on overall system performance. The system is said to have failed when the first member fails which provides a conservative estimate of system reliability. A rigid deck model was used to analyze each floor as it assumes one way bending action. A total of 20,000 floor system was analyzed. Since creep deformation is as a result of continuous deformation due to applied load, size of the floor was very important as it affected the reliability of the wood floor system.

On the subject of reliability based design on wood floor serviceability criteria, Al-Foqaha'a (1997) used five criteria to investigate the acceptability of a wood floor under static and dynamic loading using reliability analysis (static deflection criterion, Frequency criterion, modified Reiher-Meister criterion, root mean square acceleration based on design curves and Root mean square acceleration based on direct analysis). Parameter such as partial safety factor (ϕ) was obtained based on a target reliability index (β) of 2.0 which is a common standard for serviceability.

The deflection and modified Reiher-Meister criteria was achievable so long as the floor is designed for nominal values given the statistical distributions that have been assumed for random variables. However, for dynamic criteria to be achieved, higher floor stiffness is desired with appropriate partial safety factor (ϕ) value (ϕ=0.61) because more random variables were considered in the direct a_{rms} criterion yielding a conservative result (Al-Foqaha'a, 1997). Standard practice has shown that static criteria are met but floor vibration continues to be a challenge as static design criteria are not adequate for dynamic serviceability issues.

In 2001, Rosowsky in conjunction with National Association of Home Builders (NAHB) prepared a report on probability based design for residential construction. The study focused on wood-frame structures built using nominal 2-by framing lumber, structural sheathing, and nail fasteners—the most common materials used today. Various efforts have been made to consider a representative range of conditions so that many of the results can be generalized. The report represents an initial effort and is exploratory rather than conclusive in many instances. The results obtained can be used (along with other information) as the basis for calibration of new design provisions or improvements to existing design provisions (e.g., partial factors). However, more work is needed and additional lumber grades, load combinations, and limit states (e.g., tension, compression), for both members and systems (assemblies), must be considered before a full set of target reliabilities can be recommended (Rosowsky, 2001). The time is certainly right for a re-evaluation of partial safety factors in standards (such as the LRFD Standard for Engineered Wood Construction). It is hoped that efforts will continue and that the move toward probability-based design of residential structures, particularly those located in high hazard regions, can be fully realized. Table 2.3 shows statistical parameters of some random variables relevant to conducting a probability based design in terms of serviceability limit state.

Table 2.3: Serviceability Load and Resistance Statistics for Floor Joist Analysis (Rosowsky, 2001)

		HB			SB		
		Mean to Nominal	*Coefficient of Variation*	*Distribution*	*Mean to Nominal*	*Coefficient of Variation*	*Distribution*
Load	Live (L_s only)	0.24	0.9	Gamma	0.24	0.9	Gamma
Modulus of Elasticity	1906, High	1.79	0.207	Lognormal	Nil	Nil	Nil
	1906, Low	1.06	0.197	Lognormal	Nil	Nil	Nil
	1931, High	1.153	0.211	Lognormal	0.959	0.205	Lognormal
	1931, Low	1.086	0.207	Lognormal	0.962	0.212	Lognormal
	1997, High	0.916	0.185	Lognormal	0.949	0.246	Lognormal
	1997, Low	0.919	0.192	Lognormal	0.932	0.254	Lognormal

*HB – honor built member of higher quality but less widely use
*SB – standard built member of common (lower) quality but more widely use

2.5 Summary

Earlier research [Ellingwood and Talin (1984), Chui (1986), Smith and Chui (1988), Hu et al (2001, 2007)] have only treated wood floor as a continuous system ignoring the sheathing discontinuities. Al-Foqaha'a et al (1997) did observe the difference between a continuous floor system and a discontinuous system. Hence, this study investigates the effect of sheathing discontinuities on wood floors from a statistical view point due to the uncertainties present in wood. This, in essence would aid in controlling wood floor serviceability problems.

CHAPTER THREE

METHODOLOGY

The following is a description of the methods by which the probability of failure of a wood floor subjected to human induced vibration is obtained. It describes the finite element analysis performed by OpenSees© and also the iterative process carried out by Microsoft Excel©.

3.1 Methodology Overview

This research is based on the computer program developed by Burch (2013). The Program is intended to consider various scenarios of wood floors subjected to serviceability issues and also carry out design with a wide range of floor sizes. The results are compared to available standards to determine the acceptability of such floors in terms of static deflection, occupied natural frequency, unoccupied natural frequency, and root mean square acceleration. The Program is a very useful tool as it is able to simulate various floor sizes, specify joists and sheathing sizes. It requires no knowledge of OpenSees©, and it is suitable for what-if situations including reliability analysis. When used for probabilistic analyses, the program can be modified to take advantage of Excel© statistical functions.

To determine the probability of failure of a wood floor, five hundred (500) simulations were carried out using the Program. The OpenSees© is responsible for the finite element analysis considering a two-way floor system while Excel© serves as a user interface for inputting the properties of the floor and subsequently presenting the result (output) after the analysis is done by OpenSees©.

The study considers two major floor types; one floor type is supported by regular (sawn) lumber joists and the other uses engineered I-joists. For the lumber joists, sources of uncertainties include joist size, modulus of elasticity, and torsional rigidity. On the other hand, variation in the bending stiffness and torsional rigidity of the engineered I-joist was investigated. Also, variation of modulus of elasticity of the sheathing material was also considered.

3.2 Opensees© Software

Finite element modeling software can be a powerful tool for Engineers in all fields, but without proper calibration, comparison to real-world scenarios, and verification, finite element modeling software cannot be considered reliable. OpenSees©, an open source software created and maintained by University of California, Berkeley, has not undergone the level of verification that is attained through the commercialization process. OpenSees does, however, receive constant verification at an academic level through ongoing peer-review and has even been adopted by the Pacific Earthquake Engineering Research Center and the George E. Brown Jr. Network for Earthquake Engineering Simulation (www.opensees.berkeley.edu).

The level of verification involved in the creation of OpenSees© can be considered sufficient and it can be considered accurate in its basic programming and analysis. While OpenSees© is considered accurate as software, it must be recognized that the results achieved through any software can only be as correct as the inputs. In other words, for an analysis to be correct, it must be modeled correctly – representing the actual physical characteristics and setup of the structure being analyzed. Figure 3.1 represents a model set up of a wood floor using OpenSees©. Shell elements represents sheathing material, beam-column elements represents joist, and zero elements are used for fasteners.

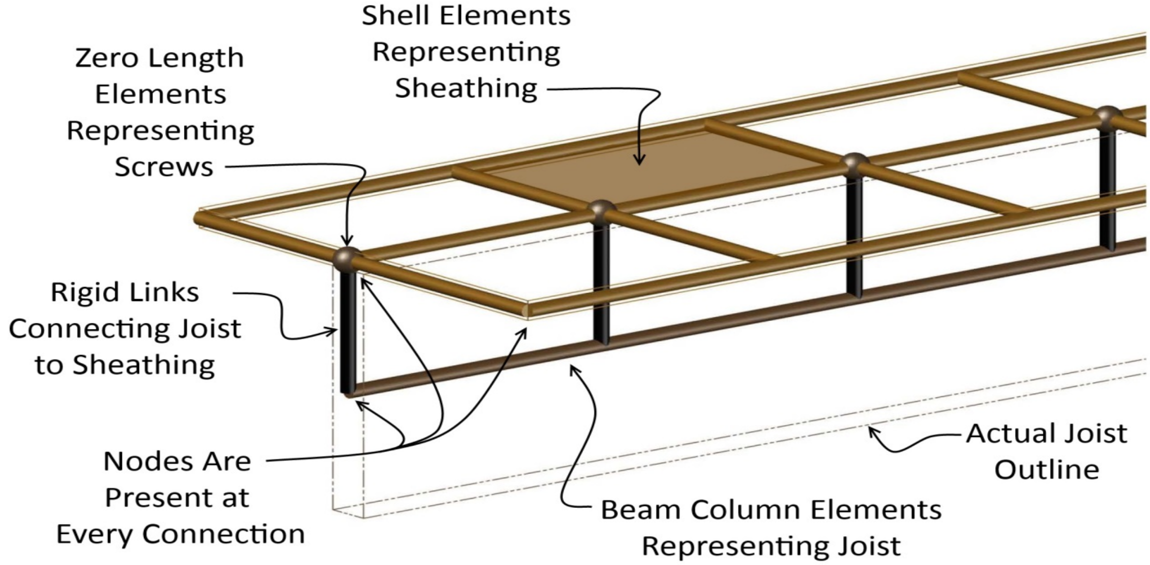

Figure 3.1: Model setup of a wood floor in OpenSees© (Burch, 2013)

3.3 Excel© User Interface

The Excel user interface created for this project was designed to facilitate the use of OpenSees in vibration serviceability analysis with floor systems. In summary, the Excel© interface contains various sections such as joist type and sizes, joist spacing, sheathing type and thickness, floor span, floor width, etc. required for a wood floor. Brief descriptions of the sections are explained below.

3.3.1 Joist Inputs

The joist inputs category is composed of the following inputs: Joist Type, Deflection Criteria, Joist Center-to-Center Spacing, Joist Depth, Joist Model/Material, Joist Span Length, and Floor Width (perpendicular (⊥) to Joist Span). Figure 3.2 shows the Excel user interface for joist inputs.

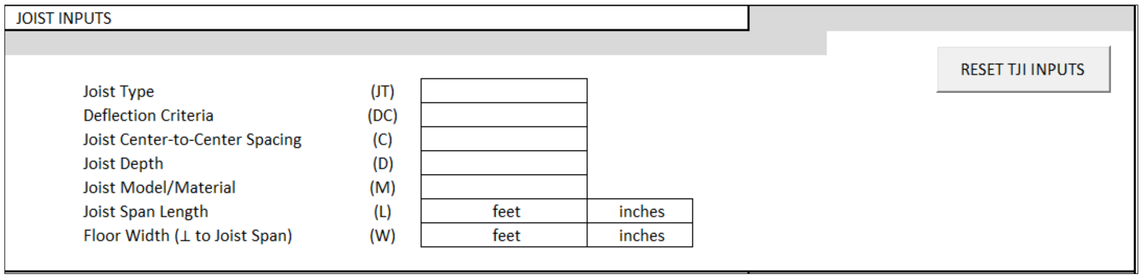

Figure 3.2: Joist input (Burch, 2013)

The Joist Type input allows the user to choose among three types of joists to use in the analysis. The three choices are Nominal Lumber (NOM. LUMBER), Trus Joist I-joist (TJI), and Boise Cascade I-joist (BCI).

Deflection Criteria is a restricted input that the system uses to give the user an estimate of the maximum estimated span which will appear to the right of the Joist Span Length input cell for certain TJI and BCI Joists. The Span Length input is able to be edited freely until the analysis is started.

Joist Center-to-Center Spacing is a restricted input variable that is used both as a variable for estimating maximum span as well as variable in the modeling procedure. The input is restricted to the following commonly used joist spacing: 12”, 16”, 19.2”, 24”, 32”, and 48”.

The Joist Depth input allows the user to choose from various joist depth which are specific to the Joist Type chosen previously. The available choices for each Joist Type are seen in Table 3.1.   The future input of Joist Model/Material is dependent upon the Joist Depth value.

Table 3.1: Joist Depth Options Based on Joist Type (Burch, 2013)

Nominal Lumber	Trus Joist (TJI)	Boise Cascade (BCI)
2 x 4	9-1/2”	9-1/2”
2 x 6	11-7/8”	11-7/8”
2 x 8	14”	14”
2 x 10	16”	16”
2 x 12		18”
2 x 14		20”
4 x 4		
4 x 6		
4 x 8		
4 x 10		
4 x 12		
4 x 14		

The Joist Model/Material input is intended to allow the user the option of I-Joist models in the case of a Joist Type of TJI or BCI and allow the option of materials in the case of a Joist Type of Nominal Lumber.

The Joist Span Length input is independent and unrestricted, however, in order to obtain favorable vibration serviceability results, the user should consider the estimated maximum span if it is provided. The user may enter the joist span length in feet or inches or a combination of both. Values should be entered only as numerical values, with no text or symbols in the cell.

The Floor Width input, like the Joist Span Length input is independent and unrestricted. Data input for Floor Width is also similar to Joist Span Length in that only numerical values should be used as inputs and “feet” and “inches” labels will appear automatically. The program is not designed to locate the outside joists directly on the edge of sheathing, so if a value is entered for the Floor Width which is a multiple of the joist center-to-center spacing, the system will automatically add 2 inches to the width.

3.3.2 Advanced Joist Inputs

The Advanced Joist Inputs category is composed of one input, Joist Torsional Rigidity as seen in Figure 3.3. Joist Torsional Rigidity represents the product of the shear modulus of elasticity (G) and the polar moment of inertia (J). Research has shown that joist twist is a notable contributor to the overall deflection of a floor system.

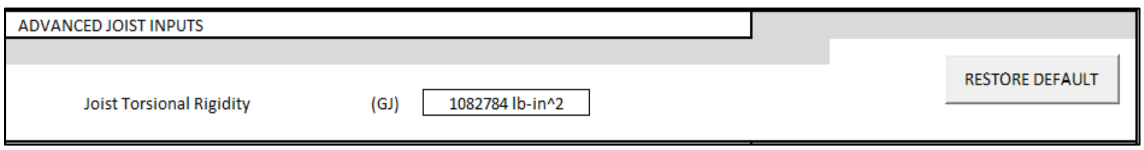

Figure 3.3: Advanced Joist Inputs (Burch, 2013)

3.3.3 Sheathing Inputs

The Sheathing Inputs category is made-up of variables which deal directly with sheathing properties. The inputs are Span Rating, Sheathing Thickness, Sheathing Modulus of Elasticity, Sheathing Poisson Ratio, Mesh Width, and Connectivity as shown in Figure 3.4.

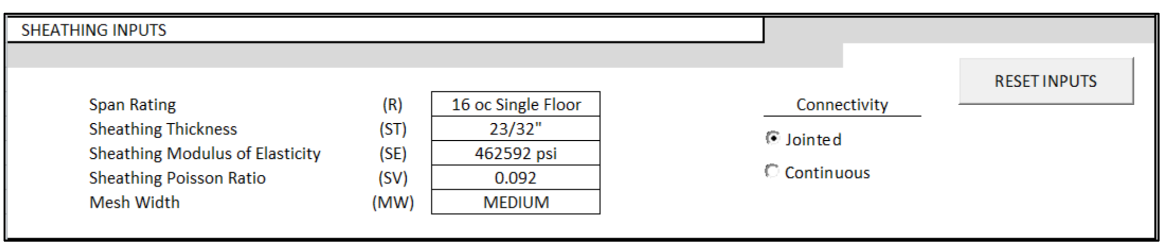

Figure 3.4: Sheathing inputs (Burch, 2013)

Span Rating is defined based on the Joist Center-to-Center Spacing chosen in Joist Inputs. The only values of Span Rating that will be available to select are the span ratings that are high enough for the spacing of the joists. Table 3.2 shows typical span ratings used in wood floor design.

Table 3.2: Typical Span Ratings (AWC, 2012)

Span Rating
24/0
24/16
32/16
16 oc Single Floor
40/20
20 oc Single Floor
48/24
24 oc Single Floor
32 oc Single Floor
48 oc Single Floor

Sheathing Thickness input is dependent on the Span Rating chosen. Table 3.3 illustrates the available sheathing thicknesses for the various Span Ratings. The Sheathing Thickness is used by the system as it assigns properties to shell elements in the OpenSees© code.

Span Rating	Nominal Thickness (in.)										
	3/8	7/16	15/32	1/2	19/32	5/8	23/32	3/4	7/8	1	1-1/8
SHEATHING											
24/0	**P**	A	A	A							
24/16		**P**	A	A							
32/16			**P**	A	A	A					
40/20					**P**	A	A	A			
48/24							**P**	A	A		
SINGLE FLOOR											
16 oc					**P**	A					
20 oc					**P**	A					
24 oc							**P**	A			
32 oc									**P**	A	
48 oc											**P**

P = Predominant nominal thickness for each span rating.
A = Alternative nominal thickness that may be available for each span rating. Check with suppliers regarding availability.

Table 3.3: Relationship Between Span Rating and Nominal Thickness (AWC, 2012)

The Sheathing Modulus of Elasticity input is independent and unrestricted. The value chosen for this input is used directly into the OpenSees© code as a property of the shell elements. Only a numerical value should be entered as input for this variable.

Sheathing Poisson Ratio input is independent and unrestricted. Like the Sheathing Modulus of Elasticity, the Sheathing Poisson ratio default value is based on the results of Wolfe’s mechanical tests on 23/32” OSB sheathing. The value chosen by the user for Sheathing Poisson Ratio is input directly into the OpenSees© code as a property of the shell elements.

The Mesh Width input gives the user the option of assigning a width to the mesh in the model. The Mesh Width input only affects the size of the mesh in the direction perpendicular to the joist span. The mesh width in the direction parallel to the joist span will always be determined by the Fastener Spacing input. The mesh width is a function of the joist spacing. The mathematical relationship is expressed in Equation (3.1):

$$NS = \frac{C}{MW} \tag{3.1}$$

where: NS is the actual node spacing (perpendicular to joist) applied to the OpenSees© model, C is joist center-to-center spacing, MW is mesh width input (Coarse =1, Medium = 2, Fine = 4).

It should be noted that the value chosen for mesh width will affect the size of the OpenSees© code file and will have an effect on the time required to complete the analysis in OpenSees©.

The Connectivity input allows the user to specify whether the sheathing is modeled with joints or without joints. In other words, if "Jointed" is chosen as the Connectivity input, then the sheathing will be modeled as 4'x8' sheets placed in the strong direction. If "Continuous" is chosen as the Connectivity input, the floor sheathing will be modeled as one continuous sheet covering the entire span and width of the floor. This input allows analysis to be performed comparing jointed sheathing to continuous sheathing.

3.3.4 Fastener Inputs

The Fastener Spacing input determines the spacing of the fasteners along the joist span. The smaller the spacing of the fasteners, the more the joist and sheathing will approximate a composite section. Figure 3.5 shows the Excel© user interface for specifying fastener spacing.

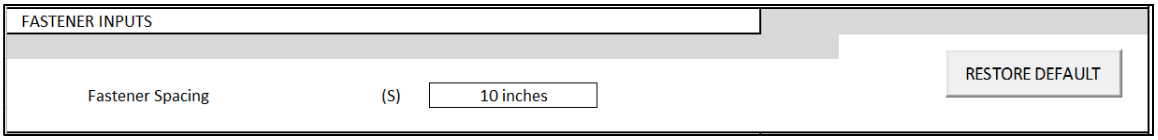

Figure 3.5: Fastener Inputs (Burch, 2013)

3.3.5 – Advanced Fastener Inputs

This category includes four inputs related to the properties of the fasteners as shown in Figure 3.6. The inputs are Fastener Stiffness in the Horizontal Plane, Fastener Stiffness in the Vertical Plane (Pullout), Fastener Stiffness about Horizontal Axes, and Fastener Stiffness about Vertical Axis. The value for each of these inputs is applied to the Zero Length Element connecting the joist to the sheathing in OpenSees©. Each of these inputs is independent and unrestricted.

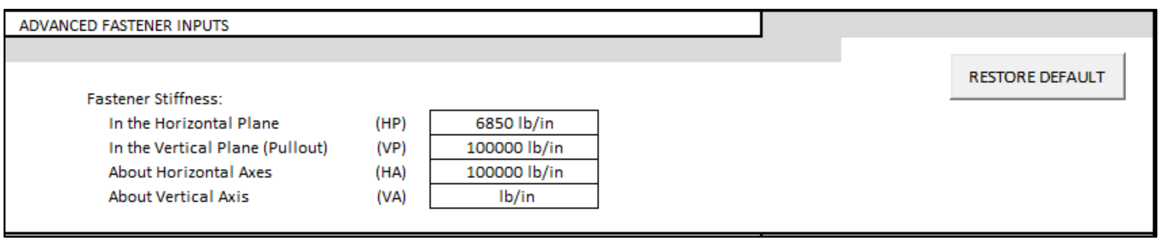

Figure 3.6: Advanced Fastener Inputs (Burch, 2013)

Fastener Stiffness in the Horizontal Plane input represents the property of a fastener connecting sheathing to a joist in its ability to restrict the sheathing from lateral movement with respect to the joist.

Fastener Stiffness in the Vertical Plane (Pullout) represents the pullout stiffness of the fastener. Since structural failure is not considered in this program, this default value is intentionally inflated, representing a fastener (nail or screw) that does not pull out of the joist or pull through the sheathing.

Fastener Stiffness about Horizontal Axes input represents the bending stiffness of the fastener. Bending is considered in the input for Fastener Stiffness in the Horizontal Plane, so the default value for this input is intentionally inflated.

Fastener Stiffness about Vertical Axis represents the property of a fastener to resist twist. In other words, this input will determine to what extent the nail or the screw prevents the sheathing from rotating about the shank of the fastener. The fastener is not considered to prevent the rotation of the sheathing about its axis, so the default value is intentionally zero.

3.3.6 Distributed Loading Inputs

The Distributed Loading Inputs category includes only one input: Occupancy Load as shown in Figure 3.7. The Occupancy Load input is unrestricted and independent of all other inputs. The default value is 2 psf and the recommended value range is from 2 to 4 psf as suggested by Dolan et al (1999). This input is only used by the system to calculate the natural frequency of an occupied floor and does so by converting the Occupancy Load input to mass and distributing it to various nodes. The dead weight of the floor structure is automatically applied in a similar manner without requiring user-input. A value of 2 psf for Occupancy Load represents a lightly loaded floor and 4 psf represents a heavily loaded floor (Dolan et al, 1999).

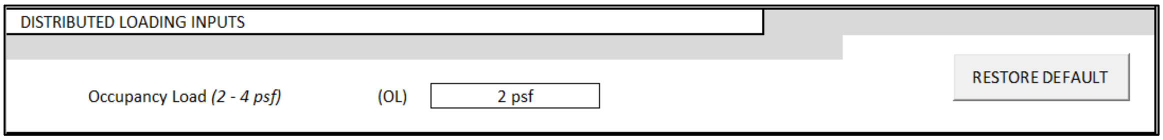

Figure 3.7: Distributed Loading Inputs (Burch, 2013)

3.3.7 Dynamic Inputs

The Dynamic Inputs Category includes Floor Damping as its sole input as seen in Figure 3.8 (though floor damping is not the only input which affects the dynamic properties of the floor). The Floor Damping input is independent and unrestricted and represents the damping ratio (δ) of the floor system. The default value is 3% and the recommended range for this input is 2-3% per Smith and Chui (1988). The value of 2% represents the damping of an unoccupied floor while the 3% damping ratio represents a floor occupied with human bodies (Smith and Chui, 1988). The value selected for this input will only affect the results of the root mean square acceleration analysis.

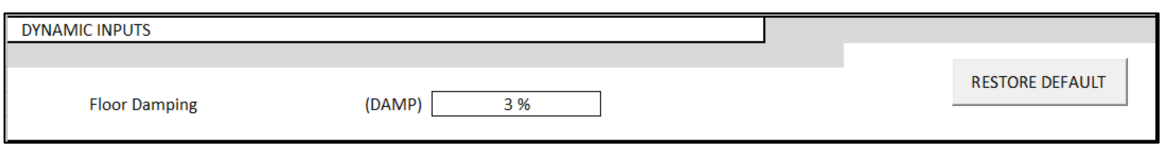

Figure 3.8: Dynamic Inputs (Burch, 2013)

3.3.8 Edge Conditions Inputs

The user is allowed two options in the Edge Conditions Inputs category as seen in Figure 3.9. The options are “2 Edges Supported” and “4 Edges Supported”. The “2 Edges Supported” option models the system with both ends of the joists supported with “pin” or “roller” connections. The “4 Edges Supported” option includes the support condition provided in “2 Edges Supported” but additionally provides “roller” supports along the outer extremes of the floor width (parallel to joist span).

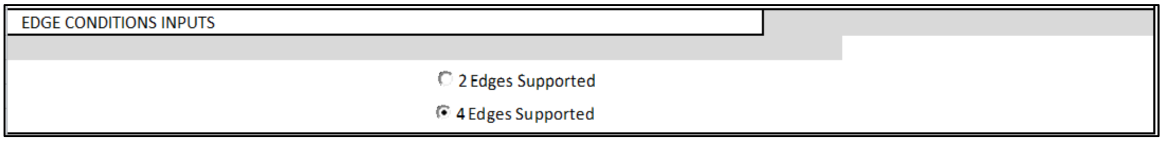

Figure 3.9: Edge Conditions Inputs (Burch, 2013)

3.4 Visual Basic Applications

Microsoft© Visual Basic for Applications (VBA) is where the majority of the code for this project was created. VBA is included with the Microsoft Excel© program and the code contained in VBA for a particular Excel© file can be accessed from within the Excel file. VBA can be accessed from within Excel by pressing the key combination ALT+F11.

VBA allows access to data and performs functions not only within Excel©, but can also call programs and functions outside of Excel©. The VBA code that is part of this program performs functions within Excel© as well as OpenSees©. The code covers the entire process of the analysis from initial setup to importing results.

3.5 Random Variables

There are many uncertainties associated with wood as a structural material. Therefore, some physical and mechanical properties of the joist and sheathing were treated as random variables.

The regular sawn lumber joist is prone to more uncertainties as it is manufactured directly from the natural log and then cut into sizes. As a result, the joist dimensions (depth and width), modulus of elasticity (MoE), and torsional rigidity (a function of both MoE and dimensions) are considered random variables in the probabilistic analysis.

A typical 2” x 10” Douglas Fir-larch No 1 is used as regular lumber joist. Variations in section properties and strength properties were obtained from Nowak and Collins (2000).

The shear modulus G_j for regular lumber joist is gotten from the relation:

$$\frac{G_j}{E_j} = 0.071 \tag{3.2}$$

where: E_j is the moment of elasticity of the joist.

The effective polar moment of inertia J_e is given as (Ugural, A. et al, 2011):

$$J_e = \beta a b^3 \tag{3.3}$$

where: β is a coefficient based on the aspect ratio of the joist $\left(\frac{a}{b}\right)$, a is the depth of the joist, and b is the width of the joist.

Two random variables were used for engineered I-joist, bending stiffness (EI) and torsional rigidity (GJ). There is little variation involved in these parameters since precision and quality are essential during manufacturing process. The torsional rigidity value for I-joist is obtained from experimental results published by Hindman et al., 2005. Bending stiffness on the other hand is obtained from Wolfe’s (2007) experimental measurement. The coefficient of variation was obtained via e-mail (Appendix D) from a representative of an I-joist manufacturing company.

The modulus of elasticity of floor sheathing is also considered a random variable. This material property increases the stiffness of the entire floor thereby allowing a composite action between the joist and the sheathing material.

The random variables have a mean value and standard deviation. These statistical parameters are used for the Monte Carlo simulation. Table 3.4 and 3.5 gives a summary of the random variables, mean values, standard deviations and statistical distribution. The mean value for moment of inertia is based on Excel© generated samples of mean width of 1.5 in. and a mean depth of 9.25 in.

Table 3.4: Random Variables for Lumber Joist

Parameter	Mean	Standard Deviation	Coeff. of Variation	Distribution
Modulus of Elasticity (DF-L No 1)	1.7×10^6 psi	340,000 psi	0.2	Lognormal
Modulus of Elasticity for Sheathing	700,000 psi	70,000 psi	0.1	Normal
Torsional Rigidity	1.1×10^6 lb-in^2	2.4×10^5 lb-in^2	0.223	Lognormal
Moment of Inertia	103.4 in^4	10.17 in^4	0.098	Normal

Table 3.5: Random Variable for Generic I-joist

Parameter	Mean	Standard Deviation	Coeff. of Variation	Distribution
Bending Stiffness (TJI 110)	1.38 x 10^8 psi	1.38 x 10^7 psi	0.1	Normal
Torsional Rigidity	2.22 x 10^5 lb-in^2	2.22 x 10^4 lb-in^2	0.1	Normal

3.6 Monte Carlo Simulation

Monte Carlo simulation helps to generate numerical results without actually performing any physical experiment or test. Sometimes, it uses result from previous tests to establish the probability distributions of important variables in the problem. Basis of all Monte Carlo simulation is the generation of random numbers that are uniformly distributed between 0 and 1.

The following steps were used to perform the Monte Carlo simulation in Microsoft Excel©:

1. A set of uniformly random numbers (U_i) between zero and one was generated using the function RAND().
2. The inverse of the standard normal cumulative function (Z) of the uniformly distributed random numbers was obtained using the function NORM.S.INV. These set of numbers had a mean of 0 and standard deviation of 1.
3. A set of numbers were obtained and standardized using the mean and standard deviation of the random variable say X. The formula for standardized X if normally distributed is given as

$$x_i = \mu_X + z_i \sigma_X \tag{3.4}$$

where: x_i is normally distributed variable X, μ_X is normally distributed mean of variable X, z_i is standard normal random number, σ_X is normally distributed standard deviation of variable X

If the variable is lognormally distributed, the standardized X is given as

$$x_i = \exp(\mu_{lnX} + z_i \sigma_{lnX}) \tag{3.5}$$

where: x_i is lognormally distributed variable X, μ_{lnX} is lognormally distributed mean of variable X, z_i is standard normal random number, σ_{lnX} is lognormally distributed standard deviation of variable X.

The above steps were carried out in Microsoft Excel© cell as shown below:

If the variable is normally distributed, Monte Carlo equation is:

$$x_i = \mu_X + \{Norm.S.Inv\big(RAND(U_i)\big)\}\sigma_X \tag{3.6}$$

where: x_i is normally distributed variable X, μ_X is normally distributed mean of variable X, U_i is uniformly generated random number, σ_X is normally distributed standard deviation of variable X

If the variable is lognormally distributed, Monte Carlo equation is:

$$x_i = exp\big[\mu_{lnX} + \{Norm.S.Inv\big(RAND(U_i)\big)\}\sigma_{lnX}\big] \tag{3.7}$$

where: x_i is lognormally distributed variable X, μ_{lnX} is lognormally distributed mean of variable X, U_i is uniformly generated random number, σ_{lnX} is lognormally distributed standard deviation of variable X.

The resulting x_i is then compared with the set limit state equation g.

A graph of limit state g against standard normal variate z is plotted to know the beta (β) value, hence determining the probability of failure.

3.7 Floor Parameters

Tables 3.6 and 3.7 show the floor parameters for the sawn lumber joist floor and I-joist floor used for the entire study. This floor has a 15 feet joist span length and 17.2 feet wide. It is a large floor system as there is a possibility to have such a floor system in some residential buildings. The reason for selecting such a large floor was to obtain a floor that barely satisfied the static deflection criterion based on hand calculations as performed in a design office.

It is common practice to assume the entire floor to be a continuous one way system without considering the effect of the sheathing on the floor. This allows the hand calculation to be quick and easy as compared to the true condition of the floor which is actually a discontinuous two way system. Furthermore, in design the uniformly distributed load is assumed to be resisted by a single joist rather than the entire floor system. The load effect is measured by an actual static deflection on the floor which is then compared to the allowable deflection defined by SPAN/360 to determine the serviceability adequacy of the floor system. This method only accounts for static loads on the floor without considering dynamic human activities.

In essence, it will prove that static deflection criterion is not sufficient under serviceability to design a floor subjected to both static and dynamic loadings. Also, the joist type will play a role in resisting such dynamic loads.

Table 3.6: Floor dimensions and properties (Sawn Lumber)

Floor Property	Dimension
Floor width	206 inches
Floor Span	180 inches
Joist Size (Douglas Fir-Larch No 1)	2 in x 10 in
Joist Spacing	16 in
Average Joist Modulus of Elasticity (E_j)	1.7 x 10^6 lb/in^2
Joist Torsional Rigidity (GJ)	1.1 x 10^6 lb-in^2
Sheathing Modulus of Elasticity (E_s)	0.7 x 10^6 lb/in^2
Sheathing Thickness	23/32”
Span rating	24 oc single floor
Fastener Type	Common 8d Nail
Fastener Spacing	10 inches
Fastener Horizontal Slip Stiffness	6852 lb.in/rad
Fastener Vertical Stiffness	100000 lb.in/rad
Fastener Rotational Stiffness	100000 lb.in/rad
Support Conditions	All four edges supported

Table 3.7: Floor dimensions and properties (Engineered I-Joist)

Floor Property	Dimension
Floor width	206 inches
Floor Span	180 inches
Joist Size (Generic I-joist)	1.75 in x 9.5 in
Joist Spacing	16 inches
Average Joist Bending Stiffness (EI_j)	138.5 x 10^6 lb-in^2
Joist Torsional Rigidity (GJ)	220,000 lb-in^2
Sheathing Modulus of Elasticity (E_s)	700000 lb/in^2
Sheathing Thickness	18 mm (23/32”)
Span rating	24 oc single floor
Fastener Type	Common 8d Nail
Fastener Spacing	10 in
Fastener Horizontal Slip Stiffness	6852 lb.in/rad
Fastener Vertical Stiffness	100000 lb.in/rad
Fastener Rotational Stiffness	100000 lb.in/rad
Support Conditions	All four edges supported

3.8 Reliability Analysis Under Uniformly Distributed Live Load

The applied uniformly distributed live load on a floor system is to be treated as a random variable if a reliability analysis is to be performed. This is only possible if the statistical parameters (mean, standard deviation, coefficient of variation) of such a random variable are known. Other random variables include the modulus of elasticity of the joist and the moment of inertia.

Every reliability analysis requires a limit state equation. In this case, the limit state is defined in terms of the static deflection criterion:

$$g = \frac{L}{360} - \frac{5wL^4}{384EI} \quad (3.8)$$

Where, L is the span of the floor system, E is the modulus of elasticity of the joist (sawn lumber), I is the moment of inertia of the joist (sawn lumber), EI is bending stiffness of the joist (engineered I-joist), w is the varying uniformly distributed live load on the floor

3.8.1 Reliability Analysis of a Single Joist

This approach is of common practice in design as it treats the floor as a continuous system ignoring the composite action between the joists and sheathing material. This approach also ignores the two-way action in the floor system. The limit state used is defined by Equation (3.8) above. The entire process is geared towards achieving a reliability index which is a measure of safety for the floor. As an approximate method, a line of best fit was used to determine the reliability index (β).

3.8.2 Reliability Analysis of Full Floor

For proper comparison to be achieved, reliability analysis must be conducted for the entire floor. This however can be a challenge as mathematical procedures do not take into account the two way floor system which happens to be the subject of discussion.

In the same vain, the program developed by Burch (2013) has the ability to determine the static deflection of the entire floor system under a constant live load of 40 psf.

The full floor deflection under varying load is determined by principle of similarity. Since, the program used for analysis has given the full floor static deflection under constant live load of 40 psf, the full floor deflection under varying live load can then be obtained easily. This is shown mathematically with Equation (3.9).

$$\delta_{\substack{Varied \\ Live\ Load}} = \delta_{\substack{Constant \\ Live\ Load}} \ x \ \frac{Varied\ Live\ Load}{40\ psf\ Load} \quad (3.9)$$

Where, $\delta_{\substack{Varied \\ Live\ Load}}$ is the full floor deflection under "varied" live load, $\delta_{\substack{Constant \\ Live\ Load}}$ is the full floor deflection under 40 psf.

Both joist type and sheathing conditions are considered as noted previously. As noted in Table 2.3, the "varied" live load has a Gamma distribution with a mean of 9.6 psf and a coefficient of variation of 0.24.

3.9 Comparison of Serviceability Limit States

The goal here is to compare proposed limit state functions for all cases under consideration, irrespective of the variability in the source of vibrations or dynamic activities. This is because not all the criteria considered specify the source of vibration and/or magnitude of the impact load.

3.9.1 Static Deflection Criteria (Full Floor)

The first criterion considers only static deflection. The maximum allowable deflection for floor members with the application of the required live load of 40 psf (1.92 kPa) is L/360. The limit state equation is defined as:

$$g_1 = \frac{L}{360} - \delta_{40\ \mathrm{psf}} \qquad (3.10)$$

where: $\delta_{40\ \mathrm{psf}}$ is the deflection under 40 psf (1.92 kPa) uniform load on the floor.

3.9.2 Bare Joist Static Deflection

Canadian researchers Foschi and Gupta (1987) proposed that a bare joist loaded at mid-span with 1 kN (225 lb) concentrated should not deflect more than 1 mm (0.039 in.) independent of the length of the joist. Limit state equation is defined as:

$$g_2 = 1\ \mathrm{mm} - \delta_{1\mathrm{kN}} \qquad (3.11)$$

where: δ_{1kN} is the deflection under 1 kN load.

3.9.3 Natural Frequency Criterion

In an effort to find a method of predicting acceptability of a floor during the design phase, Dolan, et al. (1999) created a vibration-limiting criterion that does not require any knowledge of the damping associated with a floor system. Their criterion is based solely on the calculated or predicted natural frequency of a floor system. The natural frequency of an unoccupied floor system must be higher than 15 Hz to be considered acceptable. Also, for an occupied floor system, the natural frequency must be higher than 14 Hz. The occupancy loads considered in the analysis of Dolan et al. range from 2 psf (96 Pa) to 4 psf (192 Pa). The limit state for an unoccupied floor system is defined as:

$$g_3 = f_u - 15 \text{ Hz} \tag{3.12}$$

where: f_u is the unoccupied floor natural frequency.

The limit state for an occupied floor system is defined as

$$g_4 = f_o - 14 \text{ Hz} \tag{3.13}$$

where: f_o is the occupied floor natural frequency.

3.9.4 Lin J. Hu Criterion

The criterion developed by Hu (2007) a Canadian researcher deals with a combination of natural frequency and static displacement. The criterion is designed for measurements on unoccupied floors without partitions, finishing, and furniture. The static deflection is measured after application of a 225 lb (1 kN) load at mid-span of the entire floor system.

The formula from which the limit state is derived:

$$\delta < \left(\frac{f}{18.7}\right)^{2.27} \tag{3.14}$$

Thus, the limit state equation is:

$$g_5 = \left(\frac{f_u}{18.7}\right)^{2.27} - \delta_{225\ lb} \tag{3.15}$$

where: f_u is the unoccupied floor natural frequency, $\delta_{225\ lb}$ is the deflection under 225 lb load.

3.9.5 Smith and Chui Root Mean Square Acceleration Criterion

This criterion includes limitations on the natural frequency of the floor system as well as the root-mean-square (RMS) acceleration for a one second period of time. Smith and Chui (1988) state that the range of frequencies to which humans are most sensitive in terms of floor vibrations is from 4 to 8 Hz (Smith and Chui, 1988). In order to avoid excessive vibrations in this range, the natural frequency of the floor system must be greater than 8 Hz. Also, based on experimental work of Chui, an acceptable limit for the frequency-weighted root-mean-square acceleration should be less than 0.45 m/s^2 or 0.046g.

Based on the above, the limit state is given as:

$$g_6 = 0.046g - a_{rms} \tag{3.16}$$

Where, a_{rms} is the frequency weighted RMS acceleration of the floor

3.10 Probability of Failure

Probability of failure of a structure is equal to the probability that the structural capacity is less than the load. The capacity is denoted as R and load as Q;

Probability of failure $P_f = (R < Q)$ or

$$P_f = \phi(-\beta) \tag{3.17}$$

Where, β is Hasofer-Lind reliability index, ϕ is standard normal variate.

In this project, we will obtain probabilities of failure in two cases: (1) as related to reliability analyses of single joists and floors under a uniformly distributed live load (a random variable – Section 3.8); and (2) as related to satisfying the various limit states considered (Section 3.9).

CHAPTER FOUR

RESULTS AND DISCUSSIONS

The reliability analysis for a single joist (sawn lumber and engineered I-joist) is performed under uniformly distributed varying live load. The results obtained are then transformed to determine the reliability index of a full floor using static deflection criterion for both continuous and discontinuous sheathing conditions.

Furthermore, 500 simulations were performed for one floor size with two different types of joist material. 500 simulations were concluded after a negligible difference in reliability index value was observed from 10,000 simulations for a single joist under uniformly distributed randomly varying live load. This floor was further categorized in terms of sheathing continuities (continuous and discontinuous) to determine the probability of failure under certain serviceability limit state condition.

All limit state results presented have been normalized, in the sense that, each limit state value for each simulation has been divided by the absolute average limit state value obtained for each criterion considered. For example, if the limit state corresponding to the static deflection under a uniform load of a single joist is considered, without normalization the limit state will have the form

$$g = \frac{L}{360} - \frac{5wL^4}{384EI} \tag{4.1}$$

The normalized limit state will be

$$g_n = \frac{\frac{L}{360} - \frac{5wL^4}{384EI}}{g_{avg}} \tag{4.2}$$

Where, g_{avg} is the absolute average value of the simulated g.

4.1 Reliability Analysis Under Uniformly Distributed Live Load

A reliability analysis was carried out considering a varying live load on the floor. This is usually the case in reality. Here, only static deflection criterion is been considered for reliability analysis as this is done for verification purpose.

Since, the program used for analysis has resulted in full floor static deflection under constant live load of 40 psf, the full floor deflection under varying live load can then be obtained easily. This is shown mathematically with Equation (3.9).

4.1.1 Reliability Analysis Result for Single Joist

Results presented compares a single lumber joist with an engineered I-joist.In the case of sawn lumber, the reliability index was approximately 2.6 and reliability index for I-joist was approximately 3.3. The disparity in the reliability indexes could be as a result of the simulated data were too far away from the failure point (g_n = 0). Figure 4.1 shows the reliability index plot for single joist (lumber and I-joist) under static deflection criterion.

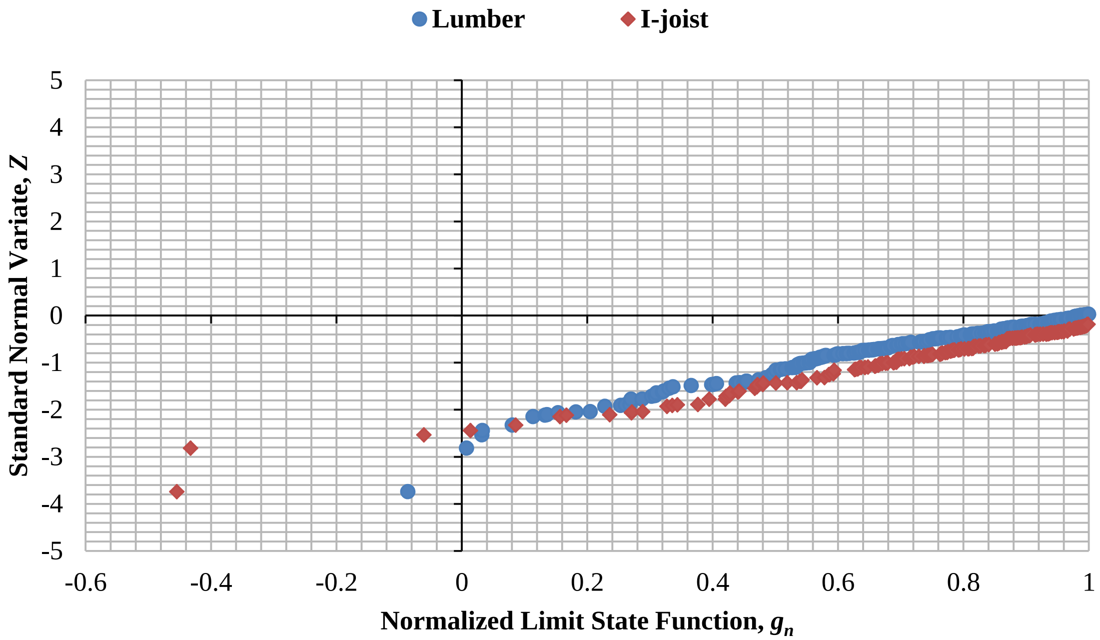

Figure 4.1: Reliability Index for Single Joist Under Static Deflection Criterion

Table 4.1 shows the tabulated result for single joist under static deflection for both joist types. Both joist type were adequate under static deflection criterion for the floor size since no composite action between the joist and sheathing was taking into consideration

Table 4.1: Reliability Index and Probability of Failure for Both Joist Type.

Joist Type	Reliability Index	Probability of Failure
Sawn lumber	2.55	0.005
Engineered I-joist	3.31	0.0005

4.1.2 Reliability Analysis Result for Full Floor

Figure 4.2 and 4.3 shows the reliability index plot for full floor deflection for sawn lumber floor and engineered I-joist floor for the continuous and discontinuous condition. The continuous sheathing scenario for both joist types shows a reliability index of 6.0 for lumber and 5.3 for engineered I-joist. The discontinuous sheathing scenario shows a reliability index of approximately 3.6 lumber joist and 3.4 for engineered I-joist. Comparing both sheathing conditions for this floor size, the difference in reliability index is a proof that the effect of discontinuity should not be disregarded. Disregarding it can lead to serviceability failure and/or uneconomical floor design as the common practice always treats the sheathing as a continuous system.

Table 4.2 presents the beta value and probability of failure under full floor static deflection for both continuous and discontinuous sheathing conditions.

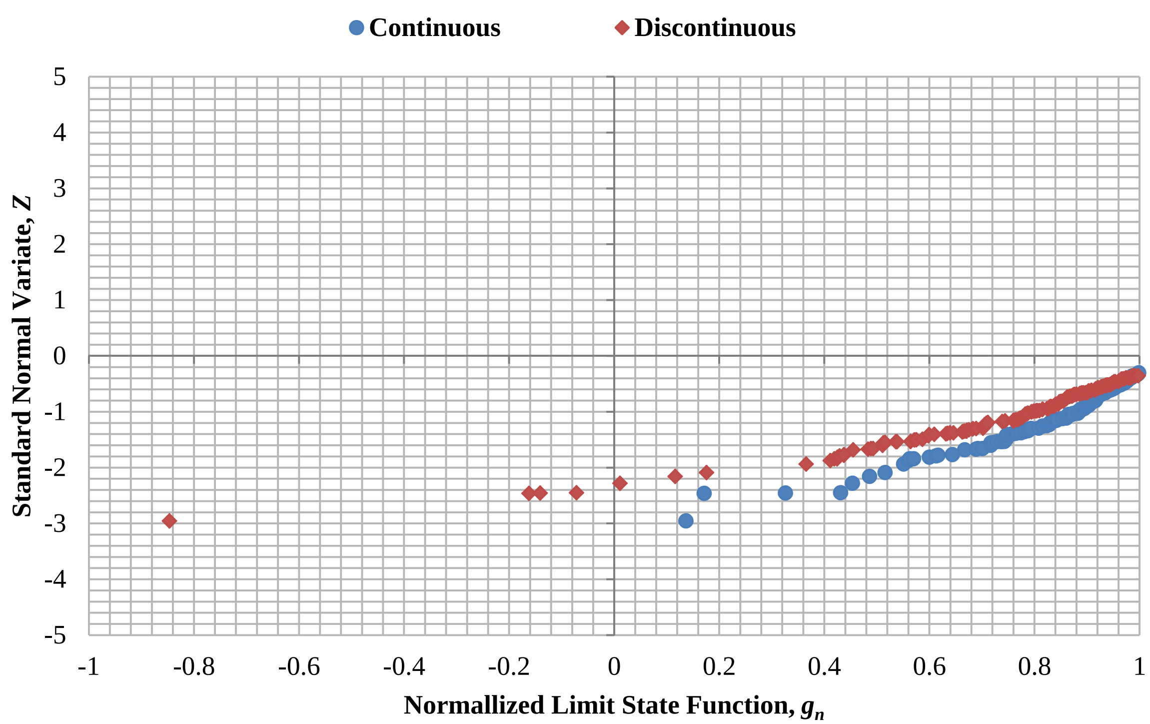

Figure 4.2: Normalized Full Floor Static Deflection for Sawn Lumber Joist

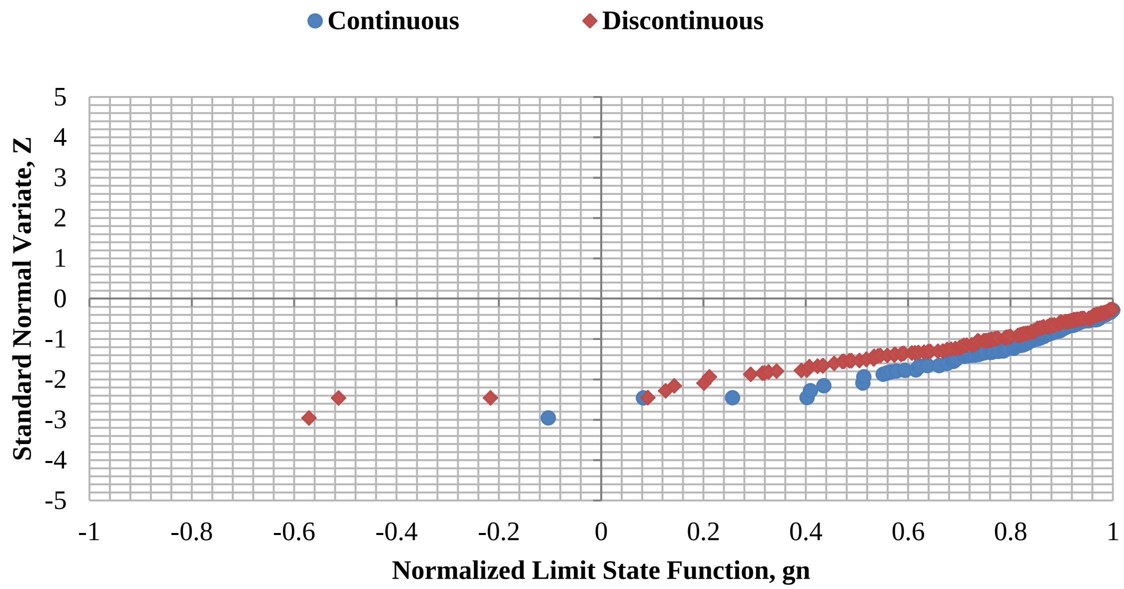

Figure 4.3: Normalized Full Floor Static Deflection for Engineered I-Joist.

Table 4.2: Reliability Index for Full Floor Static Deflection Criterion

Floor Type	Beta for Continuous Sheathing	P(failure)	Beta for Discontinuous Sheathing	P(failure)
Sawn Lumber Joist	6.04	7.71×10^{-10}	3.6	0.0002
Engineered I-Joist	5.33	4.91×10^{-8}	3.41	0.0003

4.2 Result of Limit State Analyses

4.2.1 Lumber Joists

Figures 4.4 and 4.5 show result of 500 simulations performed for a wood floor using 2 x 10 Douglas Fir-Larch No. 1 lumber joists with special consideration to the continuities present in the sheathing material. Table 4.3 shows comparison between various serviceability limit state criteria in terms of the probability of failure (i.e., not satisfying a particular criterion) and also the percentage difference between the standard normal variate which measures the amount of standard deviation the mean is away from the failure point.

The percentage difference is calculated as:

$$\% \, Difference = \frac{Z_{0_{discontinuous}} - Z_{0_{continuous}}}{Z_{0_{continuous}}} \, x \, 100\% \tag{4.3}$$

Where, Z_0 is the value of Z corresponding to linear best fit at $g_n = 0$

The floor used for the study was designed to be barely adequate in terms of static deflection as this is the most common criterion used to satisfy serviceability limit state design. This floor has an allowable deflection of 0.5 inch and an actual deflection of 0.465 inch. Appendix B shows the hand calculations for a narrow floor of same span length.

The static deflection criterion had a -73.5 percent difference for the standard normal variate between the discontinuous and continuous sheathing. The probability of failure for the floor with jointed sheathing was significantly greater than that of the continuous sheathing. Dolan et al. (1999) occupied natural frequency criterion also had a -72 percent difference for the standard normal variate.

Bare joist static deflection criterion has a 0 percent difference because this criterion does not take into consideration the composite action between joist and sheathing. It just considers a single joist under its own weight and a 225 lb concentrated force located at mid span of the joist.

Dolan et al (1999) unoccupied natural frequency and Lin J. Hu's (2007) criterion had percentage difference of -43.9 percent and -20.2 percent, respectively. This is because Hu's criterion uses Dolan et al unoccupied natural frequency and full floor static deflection in her criterion (see Chapter 3 for details). Under Dolan et al unoccupied natural frequency, the probability of failure was about 0.0008 percent for continuous and 0.04 percent for discontinuous sheathing. However, Hu's criterion had significantly small probability of failure.

Generally, the floor with continuous sheathing exhibits a higher degree of safety. In other words, it has a lower probability of failure as compared to the floor with discontinuous (jointed) sheathing for all criteria considered.

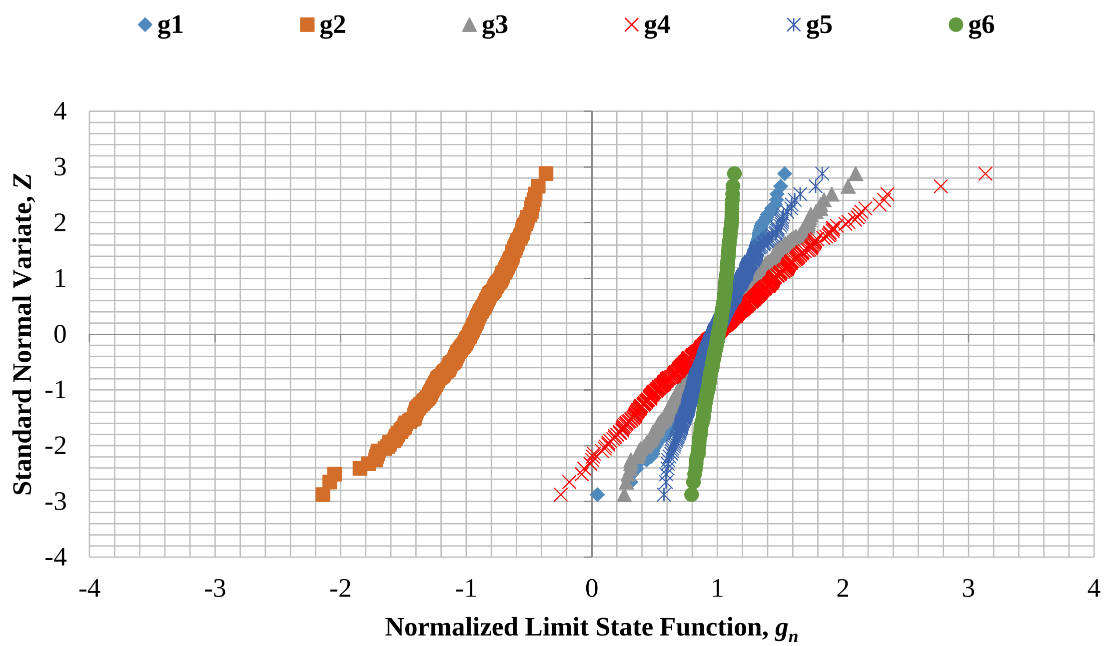

Figure 4.4: Normalized limit state for continuous sheathing using lumber joists.

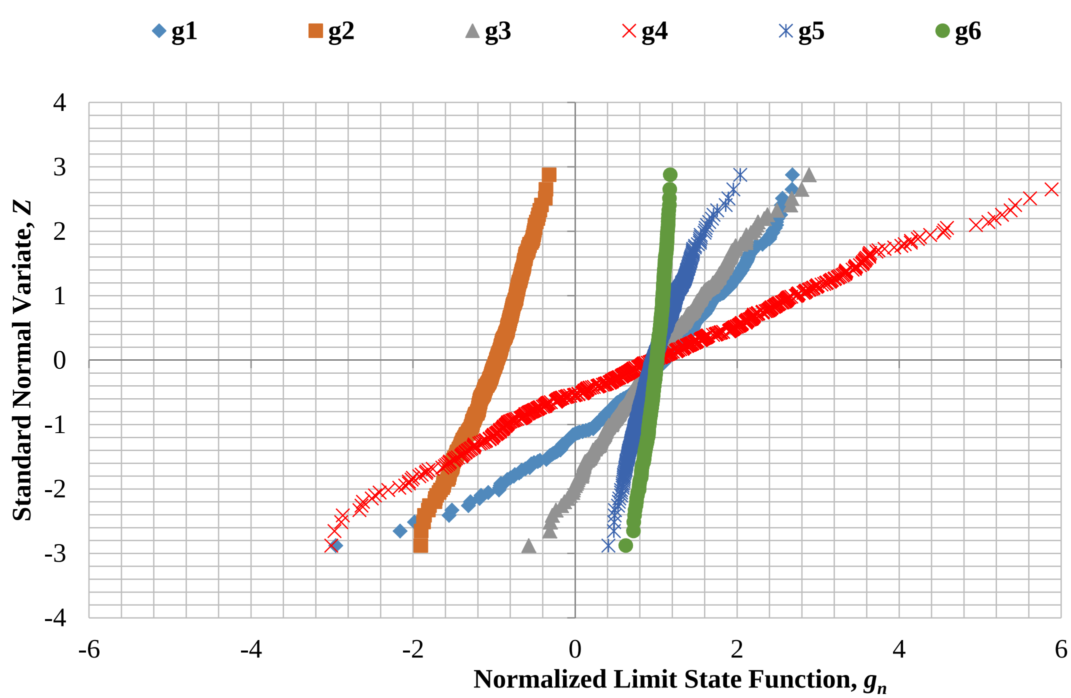

Figure 4.5: Normalized limit state for discontinuous sheathing using lumber joists

Table 4.3: Probability of Failure for Various Serviceability Limit State Criteria Using Sawn Lumber Joist

Limit State	Z_o for Continuous Sheathing	P(failure)	Z_o for Discontinuous Sheathing	P(failure)	% Difference (Z)
Static deflection(g_1)	-4.42	4.94×10^{-6}	-1.17	0.121	-73.5%
Bare joist static deflection (g_2)	3.55	Approx. 1	3.55	Approx. 1	0%
Unocc. Natural freq. (g_3)	-3.14	0.0008	-1.76	0.039	-43.9%
Occupied Nat. freq (g_4)	-2.07	0.02	-0.58	0.281	-72%
Hu's Criterion (g_5)	-4.75	1.02×10^{-6}	-3.79	7.53×10^{-5}	-20.2%
Smith and Chui a_{rms} (g_6)	-14.14	1.08×10^{-45}	-11.17	2.86×10^{-29}	-21%

4.2.2 Wood Floor Using Engineered I-Joist

Figures 4.6 and 4.7 show result of 500 simulations performed for a wood floor using a generic 9.5 inch deep engineered I-joist with special consideration to the continuities present in the sheathing. Table 4.6 shows comparison of various serviceability limit state criteria in terms of the probability of failure and also the percentage difference between the standard normal variate.

The I-joist floor used for the study was also designed to be barely adequate in terms static deflection. A -84 percent difference was observed for the standard normal variate between the discontinuous and continuous sheathing under the static deflection criterion. The probability of failure for the floor with jointed sheathing was significantly greater than that of the continuous sheathing showing that the discontinuity effect of sheathing should be taken into effect during the design phase of construction. Dolan et al. occupied natural frequency criterion also had -88.5 percent difference for the standard normal variate.

Dolan et al. (1999) unoccupied natural frequency and Lin J. Hu's (2007) criterion had the best result amongst the criteria considered. This is so because Hu's criterion uses Dolan et al. unoccupied natural frequency and full floor static deflection in her criterion. Dolan et al. unoccupied natural frequency and Hu's criterion had significantly small probability of failure.

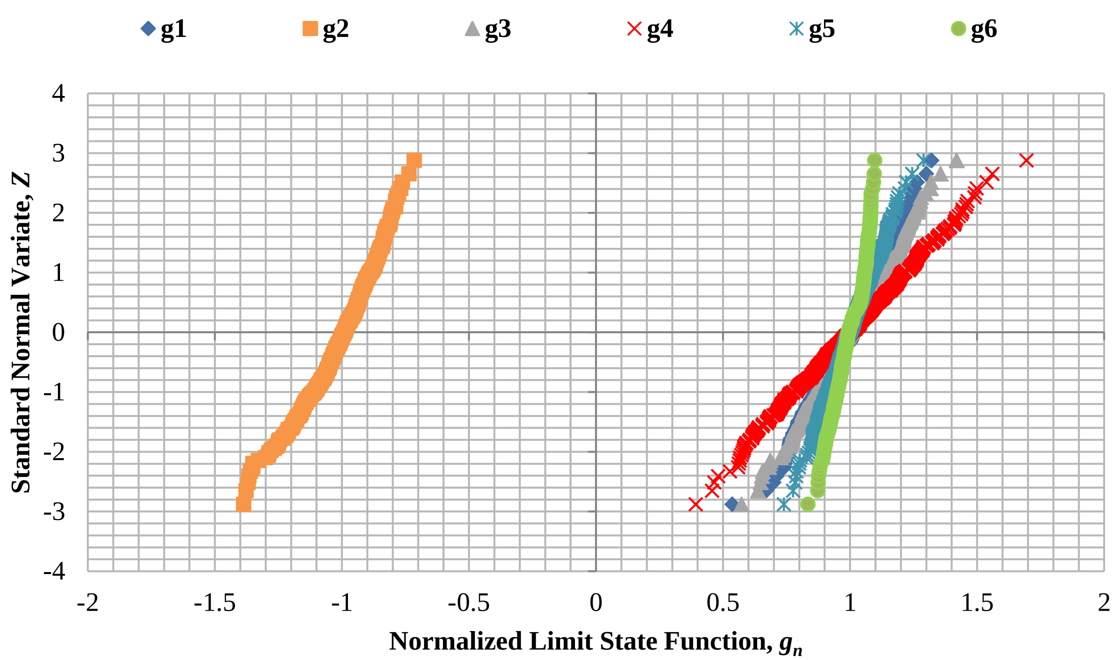

Figure 4.6: Normalized limit state for continuous sheathing using engineered I-joists.

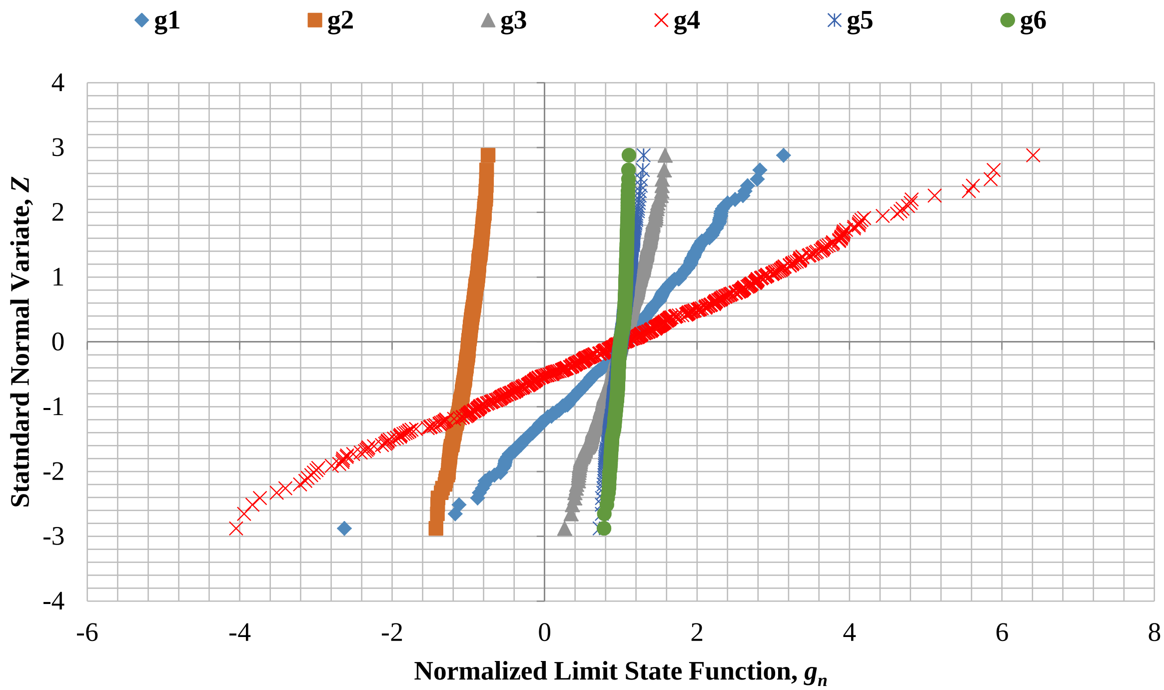

Figure 4.7: Normalized limit state for discontinuous sheathing using engineered I-joist.

Table 4.4: Probability of Failure for Various Serviceability Limit State Criteria Using Engineered I-Joist

Limit State	Z_o for Continuous Sheathing	P(failure)	Z_o for Discontinuous Sheathing	P(failure)	% Difference (Z)
Static deflection(g_1)	-8.1	2.75×10^{-16}	-1.29	0.099	-84.1%
Bare joist static deflection (g_2)	8.47	Approx. 1	8.47	Approx. 1	0%
Unocc. Natural freq. (g_3)	-7.52	2.74×10^{-14}	-3.95	3.91×10^{-5}	-47.5%
Occupied Nat. freq (g_4)	-4.61	2.01×10^{-6}	-0.53	0.298	-88.5%
Hu's Criterion (g_5)	-11.54	4.15×10^{-31}	-9.54	7.14×10^{-22}	-17.3%
Smith and Chui a_{rms} (g_6)	-19.31	2.12×10^{-83}	-14.99	4.27×10^{-51}	-22.4%

Comparison between the two types of floor considered shows that the floor with engineered I-joist behave better irrespective of the sheathing conditions. However, the continuous case was better than the discontinuous case. It should be noted that accounting for discontinuities within the sheathing will aid limiting the floor vibration but it is not likely to be a controlling factor. The size of the floor, joist type, floor stiffness, joist spacing, support conditions, applied load, type of structure all affect wood floor vibrations.

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATION

5.1 Summary

The research project in this thesis investigated the effect of sheathing discontinuities on wood floor vibrations caused by human activities in residential structures. The aim of the study was to determine the probability of failure under certain serviceability limit state criteria defined by previous researchers. The analyses were carried out using Microsoft Excel© and OpenSees© software. The Microsoft Excel© served as an interface where the floor parameters and conditions can be set up. This information serves as input which OpenSees© uses to perform finite element analysis for the floor system. Five hundred simulations were performed to accommodate the variations present in the properties of wood affecting its use as a structural material. Furthermore, reliability analysis was performed to determine the reliability of a floor system under the static deflection limit state criterion. Other limit states considered to determine the reliability of the floor system were Foschi et al (1987) bare joist deflection, Dolan et al (1999) unoccupied and occupied natural frequency, Lin J. Hu (2007) vibration criterion, and Smith & Chui's (1988) root mean square acceleration criterion.

5.2 Conclusions

Some of the conclusions drawn from the study include:

1. Generally, design of wood floors is carried out assuming the floor system to be continuous, ignoring the discontinuities present in the floor.
2. Probabilistic analyses showed that there is a distinct difference in the behavior of floors with discontinuous sheathing to those with continuous sheathing under serviceability limit state. Floors modeled with continuous sheathing consistently performed better than those modeled with discontinuous sheathing under the defined limit states. However, all residential floors have discontinuous sheathing. Results obtained from the simulations for both joist types considered, show the probability of failure for the discontinuous cases to be higher than those of the continuous cases. This implies that the simplified assumption of wood floors as continuous systems is inadequate for vibration serviceability issues. As such, new design protocols which take into consideration these floor discontinuities need to be defined to mitigate their effect on floor systems under vibration serviceability limit states.
3. Floors with engineered I-joists performed better than sawn lumber joists. This can be attributed to the fact that engineered I-joists are designed and produced to maximize the attractive structural properties of wood unlike with regular lumber joists. Many uncertainties remain present in regular lumber joist due to minimal modifications made to it before using in construction.
4. From research carried out, it can be inferred that there is no stand-alone criterion defining the general acceptability of wood floor vibrations. This is as a result of

various conditions considered by different researchers. Dolan et.al (1999) criterion defines serviceability from a natural frequency standpoint, Hu's (2007) criterion combines static deflection under 225 lbs. concentrated load at midspan with natural frequency, and Smith and Chui (1988) focused on the root mean square acceleration. For some situations, a floor acceptable under natural frequency criterion may be deemed unacceptable using the root mean square acceleration criterion and vice-versa.

5.3 Recommendations and Future Work

Based on the results and conclusions drawn in this study, some recommendations can be made as follows:

1. More in depth research should be done on the torsional rigidity (GJ) of engineered I-joist. This will further help to determine if blocking will be required for floors using this type of joist as a support system.
2. The program is a very useful tool for design engineer as it can handle most residential floor sizes. However, there are few things that can be revised and improved upon such as accommodating larger floor sizes, and reducing the computation time.

Suggestions for future work include:

1. The subroutine for root mean square acceleration criterion should be properly defined.
2. To improve the accuracy of probabilistic study, larger sample sizes should be considered in the Monte Carlo simulations.

3. Despite the amount of research that has been done on the subject of lightweight floor vibrations, the design code is yet to adopt a standard for measuring its acceptability criterion in the design of both residential and commercial lightweight floors. Subsequent research can help define the best approach to be adopted.

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APPENDIX A

DETERMINATION OF EFFECTIVE POLAR MOMENT OF INERTIA (J_e) FOR RECTANGULAR SECTION

Given a rectangular section as shown in Figure A-1;

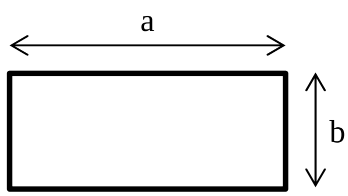

Figure A-1: Rectangular section

The effective polar moment of inertia is

$$J_e = \beta a b^3 \tag{A-1}$$

Where: a = depth of the section

b = width of the section

β = a coefficient determined by the aspect ratio of $\frac{a}{b}$

Table A-1 shows beta (β) values corresponding to aspect ratio of the section.

Table A-1: Beta Values for Rectangular Section (Ugural and Fenster, 2012)

a/b	β
1.0	0.141
1.5	0.196
2.0	0.229
2.5	0.249
3.0	0.263
4.0	0.281
5.0	0.291
10.0	0.312
∞	0.333

APPENDIX B

NARROW FLOOR STATIC DEFLECTION AND NATURAL FREQUENCY

The design of a narrow floor under 40 psf live load was done to compare hand calculation result with that produced by the program. Figure B-1 shows the plan view of the narrow floor

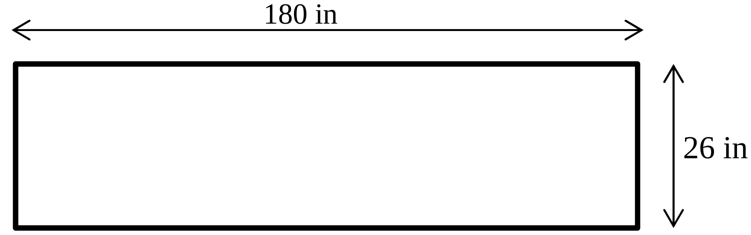

Figure B-1a: Plan view of Narrow Floor

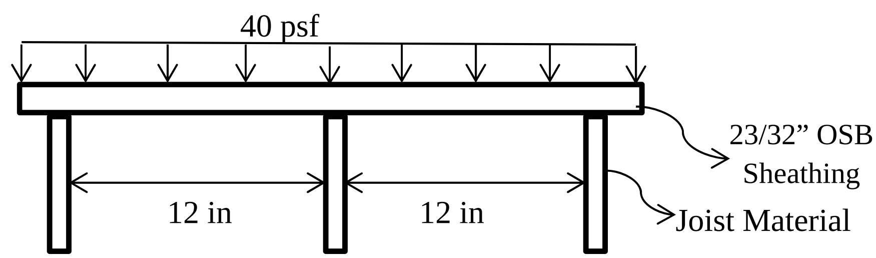

Figure B-1b: Section view of Narrow floor showing Joists, Sheathing material.

The floor system was treated as a continuous composite structure. This was done to account for the effect of the sheathing on the joist. Also, modulus of elasticity of the joist was assigned to the sheathing. Torsional rigidity on the other hand was high enough to make the floor very stiff and prevent any kind of joist rotation.

The major parameters solved for using the hand calculation was full floor static deflection under 40 psf and unoccupied natural frequency.

<u>Parameters Used for Calculation</u>

Given:

Length of floor = 180 inches; Floor width = 26 inches; Spacing = 12 inches

Modulus of elasticity of joist = modulus of elasticity of sheathing = 1.6 x 10^6 lb/in^2

Weight of 2" x 10" nominal lumber joist = 3.006 lb/ft

Weight of $9\frac{1}{2}$ TJI 110 I-joist = 2.3 lb/ft

Weight of sheathing material = 0.0199 lb/in^3

Moment of Inertia lumber floor (joist and sheathing) = 618.74 in^4

Equivalent moment of inertia for I-joist floor = 576.64 in^4

Live load = 40 lb/ft^2 = 0.2778 lb/in^2

Static Deflection Criterion

- Allowable deflection

$$\delta_{all} = \frac{L}{360} = \frac{180}{360} = 0.5\ in \qquad \text{(B-1)}$$

- Actual deflection lumber floor (hand solution)

$$\delta_{act} = \frac{5wL^4}{384EI} = \frac{5x0.2778x26x180^4}{384x1.6Ex618.74} = 0.0997\ in \qquad \text{(B-2)}$$

- Actual deflection lumber floor (program solution) = 0.112 in
- Actual deflection engineered I-joist floor (hand solution)

$$\delta_{act} = \frac{5wL^4}{384EI} = \frac{5x0.2778x26x180^4}{384x1.6Ex576.64} = 0.107\ in \qquad \text{(B-3)}$$

- Actual deflection engineered I-joist floor (program solution) = 0.137 in

Unoccupied Natural Frequency

$$f = \frac{\pi}{2}\sqrt{\frac{gEI}{WL^3}} \qquad \text{(B-4)}$$

Where g is acceleration due to gravity, E is modulus of elasticity of the floor, I is moment of inertia, W is weight of the floor system, L is floor span.

- Unoccupied natural frequency for lumber floor (hand solution)

$$f = \frac{\pi}{2}\sqrt{\frac{386.4x1.6Ex618.74}{202..21\ x\ 180^3}} = 28.28\ Hz \qquad \text{(B-5)}$$

- Unoccupied natural frequency for lumber floor (program solution) = 27.79 Hz

- Unoccupied natural frequency for engineered I-joist floor (hand solution)

$$f = \frac{\pi}{2}\sqrt{\frac{386.4x1.6E6x576.64}{170.44\ x\ 180^3}} = 29.73\ Hz \qquad \text{(B-6)}$$

- Unoccupied natural frequency for engineered I-joist floor (program solution) = 27.30 Hz

The next two pages show the program output file for both floor types.

INPUTS

Joist Type:	NOM. LUMBER	Span Rating:	24 oc Single Floor	Fastener Spacing:	4 in
Joist O.C. Spacing:	12"	Sheathing Thick.:	0.71875 in	Fast. Stiff. In Horiz. Plane:	1000000 lb/in
Joist Depth:	2 x 10	Sheathing E:	1600000 psi	Fast. Stiff. In Vert. Plane:	100000 lb/in
Joist Model/Mtl:	DF-L No. 2	Sheathing v:	0.092	Fast. Stiff. About Horiz. Axes:	100000 lb/in
Joist Span Length:	180 in	Mesh Width:	12 in	Fast. Stiff. About Vert. Axes:	0 lb/in
Floor Width:	26 in	Connectivity:	Continuous Sheathing	Occupancy Load *(2 - 4 psf)*:	2 psf
Torsional Rigidity:	20000000 lb-in^2	Edge Supports:	2 Edges Supported	Floor Damping *(2 - 3 %)*:	3%

CRITERION 1 - STATIC DISPLACEMENT with 40 psf Uniform Load (L/360)

CATEGORY	ALLOWED VALUES	ACHIEVED VALUES
40 psf BARE JOIST STATIC DEFLECTION	≤ 0.500 *in*	0.288 *in*
40 psf STATIC DEFLECTION FULL FLOOR	≤ 0.500 *in*	0.112 *in*

ACCEPTABLE

CRITERION 2 - STATIC DISPLACEMENT (Foschi and Gupta Method)

CATEGORY	ALLOWED VALUES	ACHIEVED VALUES
1 kN BARE JOIST STATIC DEFLECTION	≤ 0.039 *in*	0.173 *in*
	L/4572	L/1042

UNACCEPTABLE

CRITERION 3 - STATIC DISPLACEMENT (NBCC - National Building Code of Canada Method)

CATEGORY	ALLOWED VALUES	ACHIEVED VALUES
1 kN STATIC DEFLECTION (3.0 - 5.5 m)	≤ 0.044 *in*	0.030 *in*
40 psf BARE JOIST STATIC DEFLECTION	≤ 0.500 *in*	0.288 *in*

ACCEPTABLE

CRITERION 4 - NATURAL FREQUENCY (Dolan, Murray, Johnson, Runte, and Shue Method)

CATEGORY	ALLOWED VALUES	ACHIEVED VALUES
DOLAN ET AL NATURAL FREQUENCY	> 15 *Hz*	18.454 *Hz*
UNOCCUPIED NATURAL FREQUENCY	> 15 *Hz*	27.794 *Hz*
OCCUPIED NATURAL FREQUENCY	> 14 *Hz*	23.864 *Hz*

ACCEPTABLE

RESULTS

CATEGORY	ACHIEVED VALUES
40 psf BARE JOIST STATIC DEFLECTION:	0.2878 *in*
1 kN BARE JOIST STATIC DEFLECTION:	0.173 *in*
40 psf STATIC DEFLECTION FULL FLOOR:	0.112 *in*
1 kN STATIC DEFLECTION FULL FLOOR:	0.0301 *in*
DOLAN ET AL NATURAL FREQUENCY:	18.454 *Hz*
UNOCCUPIED NATURAL FREQUENCY:	27.794 *Hz*
OCCUPIED NATURAL FREQUENCY:	23.864 *Hz*

Figure B-2: Program Output File for Lumber Joist Floor

INPUTS

Joist Type:	TJI	Span Rating:	24 oc Single Floor	Fastener Spacing:	4 in
Joist O.C. Spacing:	12"	Sheathing Thick.:	0.71875 in	Fast. Stiff. In Horiz. Plane:	1000000 lb/in
Joist Depth:	9-1/2"	Sheathing E:	1600000 psi	Fast. Stiff. In Vert. Plane:	100000 lb/in
Joist Model/Mtl:	110	Sheathing v:	0.092	Fast. Stiff. About Horiz. Axes:	100000 lb/in
Joist Span Length:	180 in	Mesh Width:	12 in	Fast. Stiff. About Vert. Axes:	0 lb/in
Floor Width:	26 in	Connectivity:	Continuous Sheathing	Occupancy Load *(2 - 4 psf)*:	2 psf
Torsional Rigidity:	20000000 lb-in^2	Edge Supports:	2 Edges Supported	Floor Damping *(2 - 3 %)*:	3%

CRITERION 1 - STATIC DISPLACEMENT with 40 psf Uniform Load (L/360)

CATEGORY		ALLOWED VALUES		ACHIEVED VALUES	
40 psf BARE JOIST STATIC DEFLECTION	≤	0.500	*in*	0.329	*in*
40 psf STATIC DEFLECTION FULL FLOOR	≤	0.500	*in*	0.137	*in*

ACCEPTABLE

CRITERION 2 - STATIC DISPLACEMENT (Foschi and Gupta Method)

CATEGORY		ALLOWED VALUES		ACHIEVED VALUES	
1 kN BARE JOIST STATIC DEFLECTION	≤	0.039	*in*	0.197	*in*
		L/4572		L/912	

UNACCEPTABLE

CRITERION 3 - STATIC DISPLACEMENT (NBCC - National Building Code of Canada Method)

CATEGORY		ALLOWED VALUES		ACHIEVED VALUES	
1 kN STATIC DEFLECTION (3.0 - 5.5 m)	≤	0.044	*in*	0.036	*in*
40 psf BARE JOIST STATIC DEFLECTION	≤	0.500	*in*	0.329	*in*

ACCEPTABLE

CRITERION 4 - NATURAL FREQUENCY (Dolan, Murray, Johnson, Runte, and Shue Method)

CATEGORY		ALLOWED VALUES		ACHIEVED VALUES	
DOLAN ET AL NATURAL FREQUENCY	>	15	*Hz*	18.606	*Hz*
UNOCCUPIED NATURAL FREQUENCY	>	15	*Hz*	27.295	*Hz*
OCCUPIED NATURAL FREQUENCY	>	14	*Hz*	22.920	*Hz*

ACCEPTABLE

RESULTS

CATEGORY	ACHIEVED VALUES	
40 psf BARE JOIST STATIC DEFLECTION:	0.3290	*in*
1 kN BARE JOIST STATIC DEFLECTION:	0.197	*in*
40 psf STATIC DEFLECTION FULL FLOOR:	0.137	*in*
1 kN STATIC DEFLECTION FULL FLOOR:	0.0364	*in*
DOLAN ET AL NATURAL FREQUENCY:	18.606	*Hz*
UNOCCUPIED NATURAL FREQUENCY:	27.295	*Hz*
OCCUPIED NATURAL FREQUENCY:	22.920	*Hz*

Figure B-3: Program Output File for Engineered I-Joist Floor.

APPENDIX C

TORSIONAL RIGIDITY (GJ) OF LUMBER AS A LOGNORMAL VARIABLE

Defining the statistical distribution for torsional rigidity was a bit challenging as it is a product of two different variables having different statistical distribution.

The shear modulus G which has similar statistical properties with modulus of elasticity E is a lognormally distributed variable. Polar moment of inertia J is normally distributed as its dependent on dimensional properties of lumber joist which are also normally distributed.

1000 normal and lognormal values were simulated in excel and plotted on normal probability paper to determine the distribution of GJ. A straight line graph on a probability paper determines what distribution is most appropriate for a certain variable.

Figure C-1 and C-2 show the different plots.

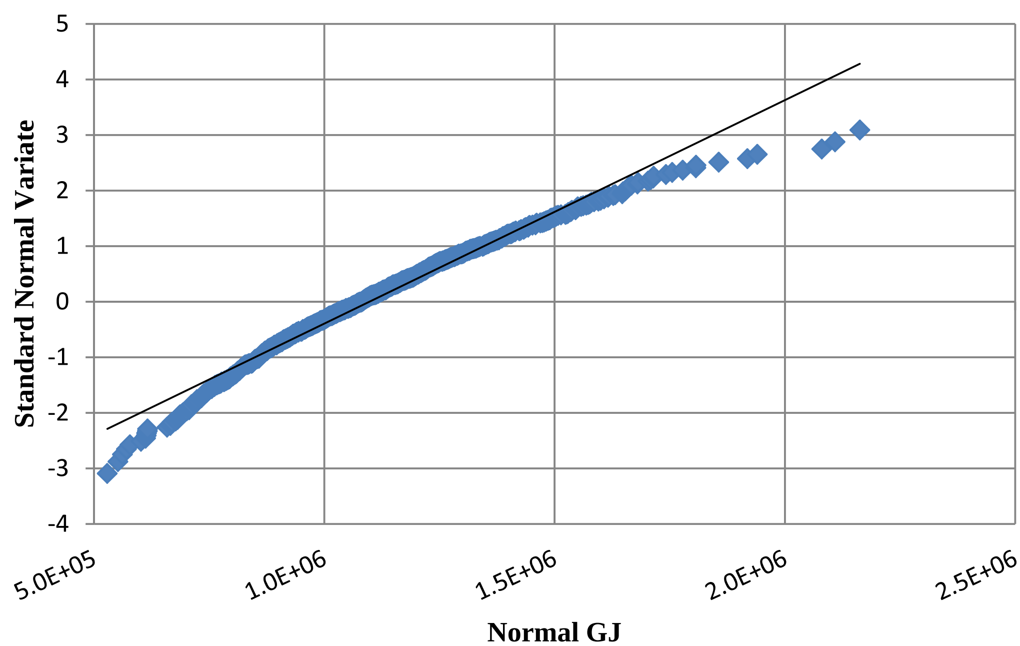

Figure C-1: Simulated Normal Values of Torsional Rigidity (GJ) on Probability Paper

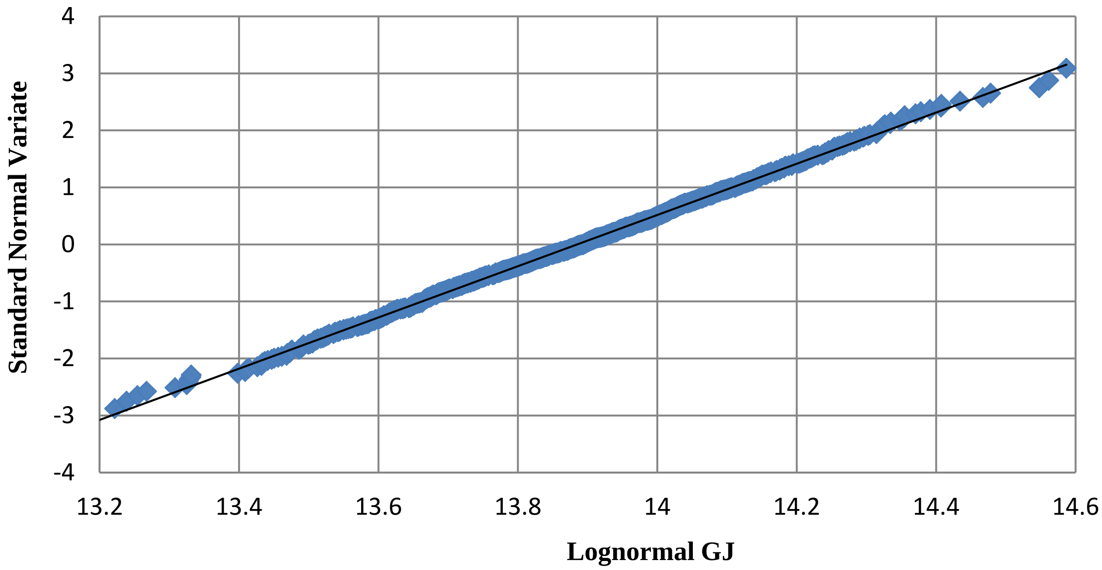

Figure C-2: Simulated Lognormal Values of Torsional Rigidity (GJ) on Probability Paper

APPENDIX D

COEFFICIENT OF VARIATION FOR ENGINEERED I-JOIST

This is an email sent to Dr. Ebrahimpour from a contact at Weyerhauser Trus Joist Company.

From: **Tsuda, Tomoyuki** <Tomoyuki.Tsuda@weyerhaeuser.com>
Date: Mon, Jun 1, 2015 at 2:53 PM
Subject: TJI 110
To: "ebraarya@isu.edu" <ebraarya@isu.edu>

Hi Dr. Ebrahimpour,

I was a pleasure talking with this morning about our products.

With regards to the stiffness variability of our TJI 110 joists, I would go with a COV of about 10%.
I would caution that if you are testing, it would be a good idea to do a control since we do have differences in stiffness between eastern and western species and there are cases where the flanges may be running high in stiffness.

Thanks
Tomo

Weyerhaeuser

Tomo Tsuda, P.Eng, P.E.
Product Engineering, Codes and Standards

Tel: (1) - 253-924-3636
Fax: (1) - 253-924-6603

Mobile: (1) - 208-598-1223
Tomo.Tsuda@weyerhaeuser.com
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APPENDIX E

RELIABILITY INDEX FOR 10,000 SIMULATIONS

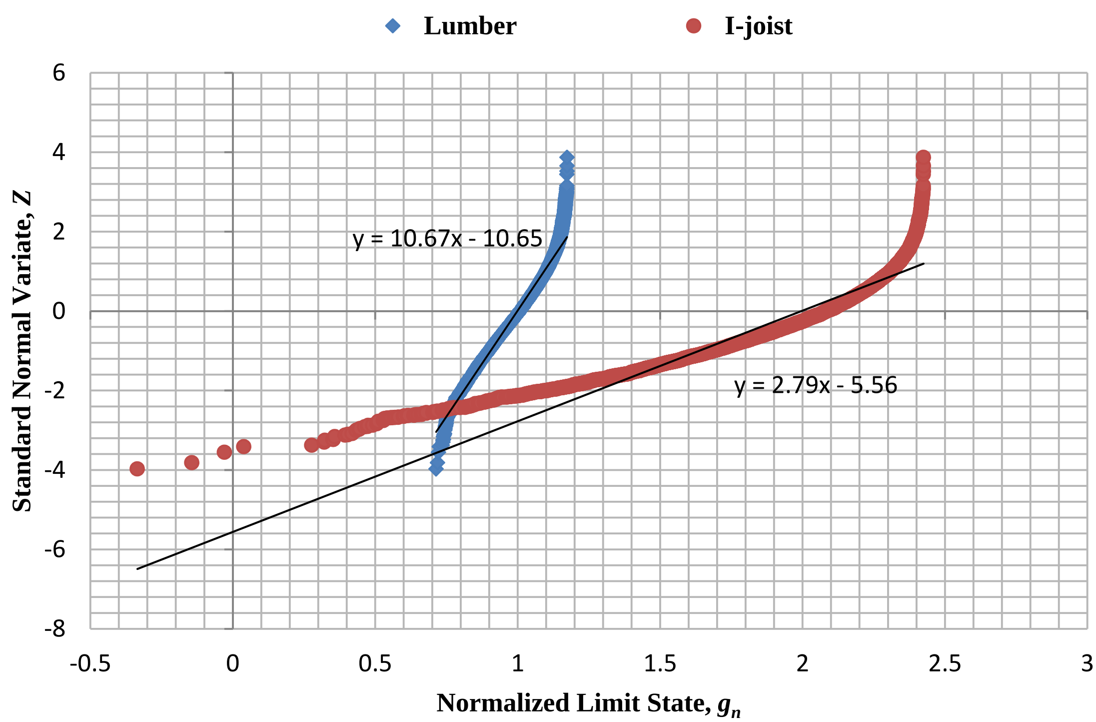

Figure E-1: Reliability Index (10000) for Single Joist Under Static Deflection Criterion