Chapter 2 – Literature Review

2.1 – Durability

A material's resistance to deteriorating elements can be referred to as its durability or more specifically, "…its capacity to perform for a specified period of time the function for which it was intended, whether it be structural safety, serviceability, amenity, or aesthetic," as stated by Foliente and others (2002).

The development of a holistic durability-design method for wood-frame construction has become a recent goal for designers and builders. Recent unforeseen failures of apparently sound structures demonstrate the consequences of poor structural durability. Consequently, regulatory agencies are strongly considering incorporating durability guidelines into regional building codes. The primary objective of integrating durability prediction protocols into design regulations is to prevent decay issues, shorten maintenance intervals, and extend the reliable service-life.

New Zealand was the first country to order durability requirements for construction materials in 1992. In 1998, the United States government launched the Partnership for Advancing Technology in Housing (PATH) in an attempt to educate builders and designers in methods that improve the quality, durability, efficiency, and overall affordability of residential structures in the United States. This partnership is composed of all federal, state, and local agencies that are involved in housing research (e.g., Departments of Housing and Urban Development, Agriculture, Federal Emergency Management Agency, etc.). Also included are participants from the private sector such as manufacturers, builders, designers, and insurance companies. One of four goals of PATH is to improve durability and reduce maintenance costs of building products and housing technologies by fifty percent by the year 2010 (Burdock et al. 2001).

In cooperation with PATH, the National Association of Home Builders (NAHB) and its subsidiary, the NAHB Research Center, conducted a study among thousands of houses to evaluate construction practices and assess durability issues (NAHB Research Center 2001). Based on this survey, the NAHB published a manual for the benefit of home designers and contractors (NAHB Research Center 2002). This document identified the major sources of wood deterioration and outlined design and building techniques for improving the long-term performance of residential structures.

2.2 – Durability Issues

In regards to wood connections, the major factor controlling durability is moisture management. Wood materials are at great risk for deterioration because of wood's unique characteristic of being hygroscopic (i.e., an affinity for water). Wood placed in an environment at a stable temperature and constant relative humidity will eventually reach a moisture content that yields no vapor pressure difference between the wood and the surrounding air. This is called the equilibrium moisture content (EMC) and is approximated by the following formula.

$$M = \frac{1800}{W}\left[\frac{Kh}{1-Kh} + \frac{K_1Kh + 2K_1K_2K^2h^2}{1 + K_1Kh + K_1K_2K^2h^2}\right]$$

Where:

h = relative humidity (%/100)

M = moisture content (%)

$W = 349 + 1.29T + 0.0135T^2$

$K = 0.805 + 0.000736T - 0.00000273T^2$

$K_1 = 6.27 - 0.00938T - 0.000303T^2$

$K_2 = 1.91 + 0.0407T - 0.000293T^2$

T = temperature in Celsius

Wood's inherit ability to absorb and desorb water encourages colonization of moisture thriving organisms such as insects and fungi. An examination of fungal degradation in oriented strand board (OSB) concluded that brown-rot was the primary decay agent rather than white-rot fungi (Yang et al. 2000). Explanations of the deterioration mechanisms of wood by moisture cycling, fungi attack, and insect infestation have been provided in past research by Verrall and Amburgey (1975), Smulski (1992, 1993), and Loferski (2000).

Another significant durability issue related to moisture infiltration is the corrosion of metal fasteners. Exposure to moisture by either direct contact (e.g., rain and snow) or indirect contact (e.g., moisture diffusion) can substantially influence the useful life of a metal fastener. In a wall system, the movement of moist air and the relative location of vapor barriers, insulation, and voids can cause moisture to condense on colder surfaces, such as the metal fasteners. This concentration of liquid moisture in the wood/fastener zone can promote the growth of fungus on the wood surface and initiate corrosion of the metal fastener.

Moisture accumulation on unprotected steel surfaces will initiate a loss in cross-section of a fastener. This is called galvanic corrosion and is known to have a deteriorating effect on adjacent wood materials (Marian and Wissing 1960). Pinion (1970) described how an exposed end of an iron fastener in wet wood will develop hydroxyl ion formation and therefore, become a cathode. Conversely, the shank will form the anode of ferrous ions (Fe^{++}), become unstable, and then react with ferric ions (Fe^{+++}). This produces rust. Iron ions are absorbed into the surrounding wood and the exposure to air produces ferric hydroxide. As a result of the change from ferrous to ferric states, a reaction catalyzes in which oxygen joins with cellulose molecules and forms oxycellulose. This is a mechanically weak and brittle material, which explains why wood softens near corroding fasteners. Another galvanic process affects wet, or submerged, wood in close proximity to metal fasteners. A galvanic cell forms between separate fasteners of dissimilar metals and consequently, the least corrosive-resistant metal will corrode initially followed by the more corrosive-resistant fastener (Farber 1954; Baker 1974). Galvanic corrosion is well documented in boats and other equipment utilizing different fasteners in harsh marine environments (Fink and Boyd 1970).

2.3 – Evaluation of Durability

Estimating the durability of solid wood and wood-based composites has been largely limited to the testing of new construction employing virgin materials. These procedures utilize short-term loading schedules while sustaining constant environmental conditions. Particular attention is given to maintaining consistent moisture contents and specific gravities of the wood materials because the purpose of the tests is to observe changes in strengths and stiffnesses of joints and shear walls as influenced by different design treatments only, without the effect of moisture (Arima et al. 1981). Examinations of nailed connections often center on applying prediction models to observed load-slip responses to quantify behavior and performance (Ocloo and Potter 1988; Jang et al. 1993; Kalkert and Dolan 1997). Other investigations of unweathered construction elements have involved evaluating head pull-through resistance and withdrawal of fasteners (Chow et al. 1988; Chui and Craft 2002).

Behavior of nailed connections in response to natural features of solid wood lumber has received thorough investigation. The differences in specific gravities of latewood and earlywood regions are known for each species group. Specific gravity ratios of latewood to earlywood range from 2.0 to 3.0 in softwoods (Forest Products Laboratory 1999). Accordingly, Wilkinson (1991) reported a positive correlation between dowel-bearing resistance and specific gravity in clear, straight-grained samples. Winistorfer (1995) found no differences between bearing strengths afforded by either radial or tangential surfaces in relation to annular ring orientation. This test was based on the idea that a nail, driven into solid wood, will bear its load upon different amounts of latewood and earlywood and consequently, influence the overall connection strength. When a nail penetrates a knot, maximum load has been determined to increase by twenty percent in comparison to defect-free connections (Blass 1994).

The studies of nailed connections in which moisture content *was* an experimental factor have often been long-term endeavors. Mohammad and Smith (1994) reported strong influences of moisture content change (between fabrication and testing) on connection stiffness. Flake orientation and direction of load dissipation were found to hold less dominant roles in influencing the stiffness characteristics. In another case, observations by Feldborg (1989) of nail-plate connections, placed in an environment of cyclically changing relative humidly (between 85% and 50% relative humidity) and under long-term tensile loading, have shown significant increases in joint slippage. This resulted from accumulating deformations occurring during each of the drying cycles. Furthermore, Feldborg examined nail withdrawal performance in loaded and non-loaded samples with identical moisture loading histories. In the group receiving long-term axial withdrawal loading, nail movement was significant in comparison to the non-loaded group. However small, the nail withdrawal movements within the non-loaded group were noticeable and resulted from nail popping. Caused by the repeated shrinkage and swelling of wood materials, Stern (1956) researched the nail popping phenomena and suggested threaded nails as a solution. Similarly, short-term investigations of moisture effects have targeted the truss-plate back-out behavior as a function of moisture content changes. Cyclic moisture loading contributed to more severe back-out movements (Groom 1994). The effects of real-time exposure to environmental conditions have also been examined in wood-based panels (River 1994), laminated veneer lumber (Hayashi et al. 2002), and glulam beams (Arima and Hong 1996). The long-term method of durability evaluation is the most direct in providing trustworthy information, but require long-term time commitments lasting several months or years.

Most durability studies simulate long-term exposure to environmental factors by means of accelerated aging (ASTM 2003f; McNatt and Link 1989; McNatt and McDonald 1993). In reality, homes and building materials are rarely, if ever, subjected to such intense conditions (e.g., complete submersion in boiling water). These laboratory procedures are subjective and often extreme in nature, but can provide useful information without the commitment of lengthy testing periods. Soundness of laboratory procedures have been demonstrated by Okkonen and River (1996) wherein the modulus of rupture (MOR) values for wood-based panel samples after one year of outdoor exposures were compared to the MOR of samples receiving the standard accelerated-aging simulation of repeated boil-dry treatments (ASTM 2003f). Their results indicated a correlation coefficient of 0.98 between real-time aging and the laboratory simulation.

Short-term studies have received skepticism as to their validity in predicting long-term events. A lengthy study of fungal colonization rates and resulting strength reductions in wood discovered negligible results (Morrell et al. 2000). Their conclusion stated that actual rates of colonization occurred at much slower rates than in short-term laboratory procedures. In addition, inadequacies of a short-term standard test, ISO 6891 (1983), were observed in regards to stiffness assessment (Feldborg 1989).

A novel approach for assessing thickness swell within wood-based composite panels was developed. The method involves cutting a series of specifically spaced slots on the edge of a sample using a special cutterhead. Then, the composite sample is subjected to the common water soak test, ASTM D 1037. The measured changes of slot and space dimensions can indicate localized regions of low or high thickness swell and therefore, identify low and high densities across the thickness of a panel (Wang and Winistorfer 2003). A nondestructive technique of measuring the density gradient across the thickness of a panel product is described by Winistorfer and others (1986) in which gamma ray radiation is used to detect changes in material density. Additionally, density variation can be detected by precisely measuring the differences in electrical resistance of a drill motor as a hole is made through the thickness (Winistorfer et al. 1995). Evaluating tendencies for significant thickness swelling and delaminations within a composite provides insight into the material's actual resistance to environmental risks.

The pick test is a simple technique for detecting fungal decay in lumber appearing sound from a visual surface inspection. A pointed tool is driven into the wood - driving out a splinter. Differences in penetration force and splinter breakage are noted in respect to observations at known sound regions and those suspected of decay within an individual timber (Anderson et al. 2002).

A quantitative index system was developed to describe how certain areas of the United States are more prone to aboveground wood decay (Scheffer 1971). The formula, below, is based on rainfall and temperature measurements.

$$\text{Decay - potential index} = \frac{\sum_{January}^{December}\left[(T-35)(D-3)\right]}{30}$$

In the above equation, T equals the average monthly temperature (°F) and D is the number of days each month with a rainfall total of 0.01 in. or more. The resulting index value allows for normalized comparisons among different regions. For example, Miami = 131.3, Seattle = 49.7, and Las Vegas = 0.0. Miami's moderate number of rainy days and above average temperatures throughout the year equates to a high index value. Alternatively, Las Vegas has the lowest value possible index at zero. This region experiences some of the highest temperatures in the country, but very few days of rainfall. Seattle, an area with nearly constant periods of rainfall and moderate temperatures, is given an intermediate index value and thus, is at a level of wood decay vulnerability between the two extremes.

In an attempt to overcome the obstacle of extensive testing periods, engineers and scientists designed weathering chambers to simulate actual conditions in abbreviated time periods (Stockwell and Goodell 1990). The International Conference of Building Officials (ICBO) publishes one of three regional building codes (Uniform Building Code) used in the United States. In addition, the ICBO also publishes "acceptance criteria" for an array of building products and systems. One set of acceptance criteria, entitled *Acceptance Criteria for Special Roofing Systems*, describes durability test procedures for synthetic roofing systems (International Conference of Building Officials 2002). Tests include an evaluation of resistance to water, UV radiation, freeze-thaw, and temperature cycling. This ICBO standard references the use of a weather-o-meter device that automatically controls temperature, humidity, light, and water spray according to user inputs as described in ASTM G 151 (ASTM 2003a). This device is common in the research and development areas of the paint, plastic, and textile industries.

In 2000, the National Evaluation Service (NES), which is now part of the International Code Council Evaluation Service, Inc. (ICC-ES), released a guide for conducting durability assessments on building products and systems (NES 2000). The protocol provides the accepted procedures for determining estimates of expected service life of an entire structure and individual materials. While the protocol does prescribe an extensive description of the system and potential factors that affect its service life, it does not provide guidance on how service conditions are determined or how service conditions are influenced by other factors, such as building maintenance or the effect of building and site design elements (e.g., roof overhangs, site drainage, etc.). The protocol also requires that installation and maintenance procedures be taken into account when estimating service life, but provides no clear guidance on how this is accomplished. Both moisture engineering analysis and the NES protocol have been used to verify a structure's susceptibility to moisture-related decay with success (TenWolde 2000).

Another valuable tool for predicting moisture contents in wall systems is MOIST version 3.0, a building energy simulation program. MOIST is able to predict the potential mass transfer of heat and moisture flow through a wall system as seasonal climate changes occur. This allows for simulations of temperatures and moisture contents in wall systems with any given configuration of layering sequences and material specifications. The software utilizes Weather Year for Energy Calculation (WYEC) climate data for seventy-seven metropolitan areas in the United States and Canada. The user chooses the geographical location prior to running the simulation, which provides accurate estimates for housing exposed to location-specific climate conditions. The theory for the software was developed by Burch and Thomas (1993) at the National Institute of Standards and Technology and further described by Burch and Chi (1997). The software and reference documentation is available in the public domain at http://www.bfrl.nist.gov/863/moist.html. The limitations of the MOIST software include its one-dimensional analysis of heat and moisture transfer in a wall system. The model does not include the effect of thermal bridges and framing members. It is only able to evaluate mass transfer in the direction of the exterior to interior surface. In addition, this software is not capable of incorporating the effects of direct wetting by rainfall (i.e., moisture absorption) or the influence of freezing liquid on the material properties of the wall components. Although limited, Burch and others (1995) and TenWolde (2000) have successfully verified and validated the results from the MOIST program by actual experimental results.

2.4 – Reliability-Based Design

The development of engineered design models for wood construction has seen much less research attention in comparison to other building materials (e.g., steel and concrete). Knowledge related to deterioration of wood construction by environmental factors is in the early stages and many degradation models have been developed (Leicester and Foliente 1999); however, few design procedures employ the use of decay models. The design procedures are entirely based on probabilistic prediction models of degradation, which include consideration for natural variability. With the use of these models, performance can be a decisive factor for developing an engineered durability design method.

Describing a distribution of random variables with a known mean and standard deviation can lead to more complex questions regarding other attributes specific to a certain data set. Several commonly used functions incorporate various input parameters in an effort to better explain the spread of a dataset. The familiar bell curve shape represents the distribution of normal random variability ($\mu = 0$, $\sigma = 1$), which is called a normal, or Gaussian, distribution. Weibull distributions use measures of shape, scale, and location to describe a dataset. Figure 2.1 illustrates both Gaussian and Weibull probability density functions using identical data. Weibull reports an increased concentration in the lower tail and therefore, is considered a better fit, in this case. Of course, the distribution of any unknown set of random variables is debatable, but Weibull has been used extensively to model the performance characteristics of solid structural lumber and engineered wood composites (Green and Evans 1987, Durrans et al. 1998, Sharp et al. 2000). Weibull's appeal is credited to its ability to fit data with significant modal skewness about the mean. The original Weibull (1939) formula included three-parameters (i.e., scale, shape, location), but is commonly reduced to a two-parameter version by setting the location value to zero. Goodness-of-fit tests have analyzed the correlation of the abridged two-parameter distribution with favorable results (Littell et al. 1979, Wozinak and Warren 1984). In addition, the three-parameter formula was investigated for goodness-of-fit by Woodruff and others (1983). In terms of wood products, the lower tail of a performance distribution is of primary interest and receives significant attention. This is because wood design criteria are based on this region of the loading curve. Allowable stress design (ASD) is based on the lower fifth percentile of a performance distribution. ASTM D 5457, *Standard specification for computing the reference resistance of wood-based materials and structural connections for load and resistance factor design*, endorses the use of the two-parameter Weibull method for tail fitting (ASTM 2003b). Load and resistance factor design (LRFD) uses performance parameters for scale, but otherwise functions with a reliability-based design to model for uncertainty (Ellingwood 1994). Table 2.1 further explains the Gaussian and Weibull distributions.

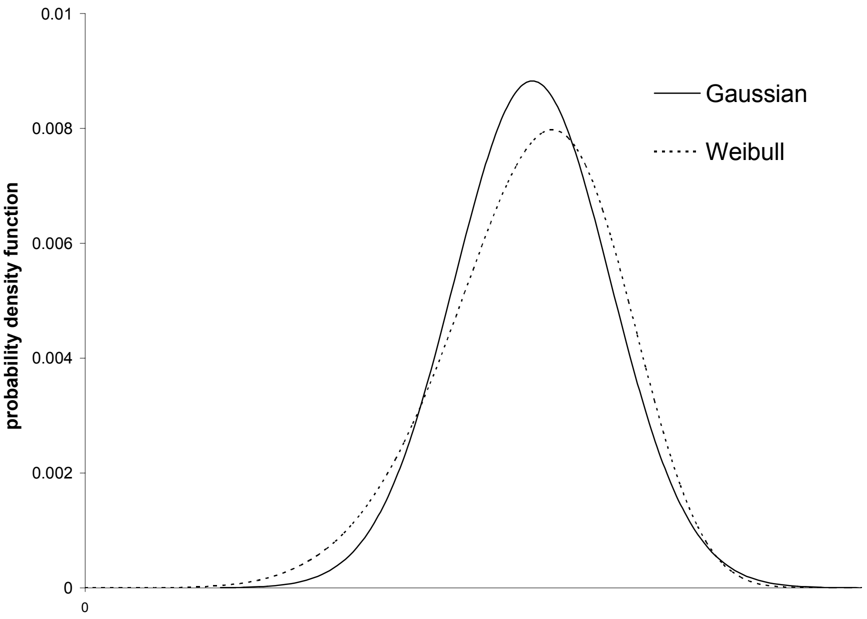

Figure 2.1: Gaussian and Weibull distributions.

Table 2.1: Distribution descriptions.

	Gaussian	Weibull
Density *f(x)*	$\frac{1}{\sqrt{2\pi\sigma^2}}\exp\left[\frac{-(x-\mu)^2}{2\sigma^2}\right]$	$ba^{-b}(x-c)^{b-1}\exp\left[-\left(\frac{x-c}{a}\right)^b\right]$
Parameters	location, μ scale, σ	scale, a shape, b location, c

Modeling reliability of systems relies heavily on the use of the cumulative distribution function. Figure 2.2 is a plot of the survival probability over time for two independent systems and was created using the cumulative distribution function for a Weibull distribution. The graph depicts an initial increase in the chance for failure of ‘System B’, but ‘System A’ quickly declines in reliability and proves to have a shorter service-life overall.

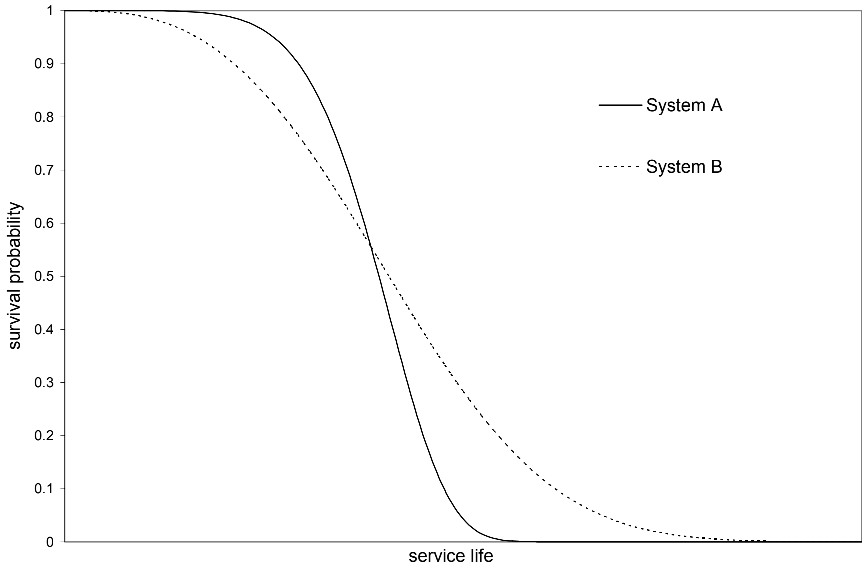

Figure 2.2: Survival graph.

The basis for evaluating durability as a time-dependent function is used in the model proposed by Kameda and Koike wherein, degradation of in-service structural members was analyzed (1975). Their model utilizes a probability density function for the load and resistance effect, which can involve any of the deterioration factors acting on a material. As a rule, survival requires the resistance to be greater than the load effect; otherwise, failure occurs. This is graphically represented in Figure 2.3. In order to simulate a large population (n=1,000,000+) based on the parameters of an observed event, a statistical procedure called a Monte Carlo simulation is utilized. This tool can generate incredibly large sample sizes with the same statistical attributes of a small, observed population and therefore, provide for a very high order of certainty in the final predictions. More specifically, the Monte Carlo application produces a large distribution, which is then evaluated using the probability density function to predict, within an extremely narrow confidence interval, the likelihood of a specific occurrence. Researchers use Monte Carlo simulation methods to deal with the large variability of wood properties when working with related wood engineering problems (Pellicane 1978).

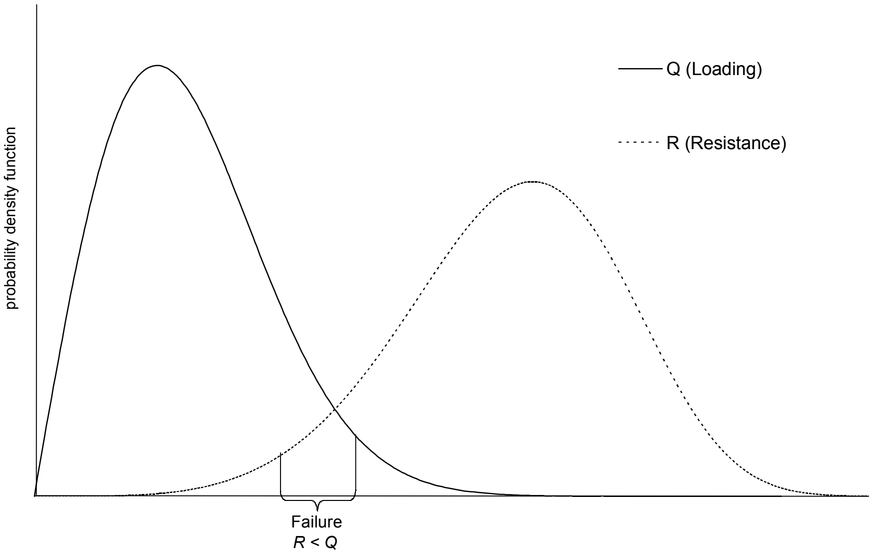

Figure 2.3: Probability density functions of loading, resistance, and failure region.

2.5 – Design of Wood Connections

Stated simply, “A structure is a constructed assembly of joints separated by members” (McLain 1998). Joints, or connections, unify structural elements so loads are transferred from one member to another until the load path terminates at the foundation. In comparison to the structural elements found in light-frame construction, the connections possess relatively low strengths and stiffnesses and therefore, are a limiting factor in designing for structural stability, reliability, and safety.

Initial investigations into the behavior and performance of laterally-loaded wood connections were directed toward aircraft design for the United States Navy (Grenoble 1925). This research investigated the influence of material variability on the performance of framing connections within airplanes where lightweight components are essential. The USDA Forest Products Laboratory performed a more expansive study involving lateral connections of several different commercial species (Trayer 1932). This research established a relation among member thickness, dowel diameter, and normalized stress parameters. In this manner, safe design loads were postulated on an empirical basis, which consequently, restricted the number of applicable connection designs. Nevertheless, Trayer’s work did describe a more significant finding. His load-slip curves of monotonically stressed connections indicated non- linearity in deformation beyond the original departure from the linear portion of the line, or the proportional limit.

In 1949, K. W. Johansen published his European Yield Model (EYM), which was a set of equations derived from experimental data (Johansen 1949). He investigated the bearing resistances of connection components and categorized failures into specific modes. Figure 2.4 illustrates the single-shear connection failure modes. The EYM selects the failure yield that performs the worst when all possible modes are calculated and compared. The theory incorporates the bearing resistances and dimensions of the main and side members and the dowel fastener. Mode I occurs when one member is compressed, or crushed, but the dowel is free of deformation. Mode II is distinguished by crushing within the main and side member, but again, no deformation of the dowel. Mode III is observed in connections where one member is crushed and the dowel deforms. When crushing takes place in both members and the dowel is also deformed, Mode IV failure is demonstrated. Modes $\mathrm{I_m}$ and II are not exhibited in nailed connections because nails have relatively low bearing stiffness in comparison to wood materials. Furthermore, Mode $\mathrm{I_s}$ is only applicable to configurations involving side member materials with low bearing resistances (e.g., gypsum wallboard and fiberboard). Modes $\mathrm{III_m}$, $\mathrm{III_s}$, and IV are most commonly observed in single-shear connections with side member materials of OSB or plywood.

Prior to 1991, Trayer's approach was used for connection design in the United States, while Europe used Johansen's yield model. The flexibility and validity of the EYM was repeatedly proven in many studies, including those by Moller (1950), Siimes and others (1954), and Aune and Patton-Mallory (1986). In 1991, the theory of the EYM was adopted as the foundation of connection design in the United States. This design method is accomplished using a set of revised yield model formulas (for applicability to U. S. building practices) to predict the limiting mode of failure (AF&PA 1999). Referred to as *general dowel equations*, their accuracy in accounting for dowel moment resistance and gaps between members is documented (Showalter et al. 1999). Table 2.2 presents the specific formulas.

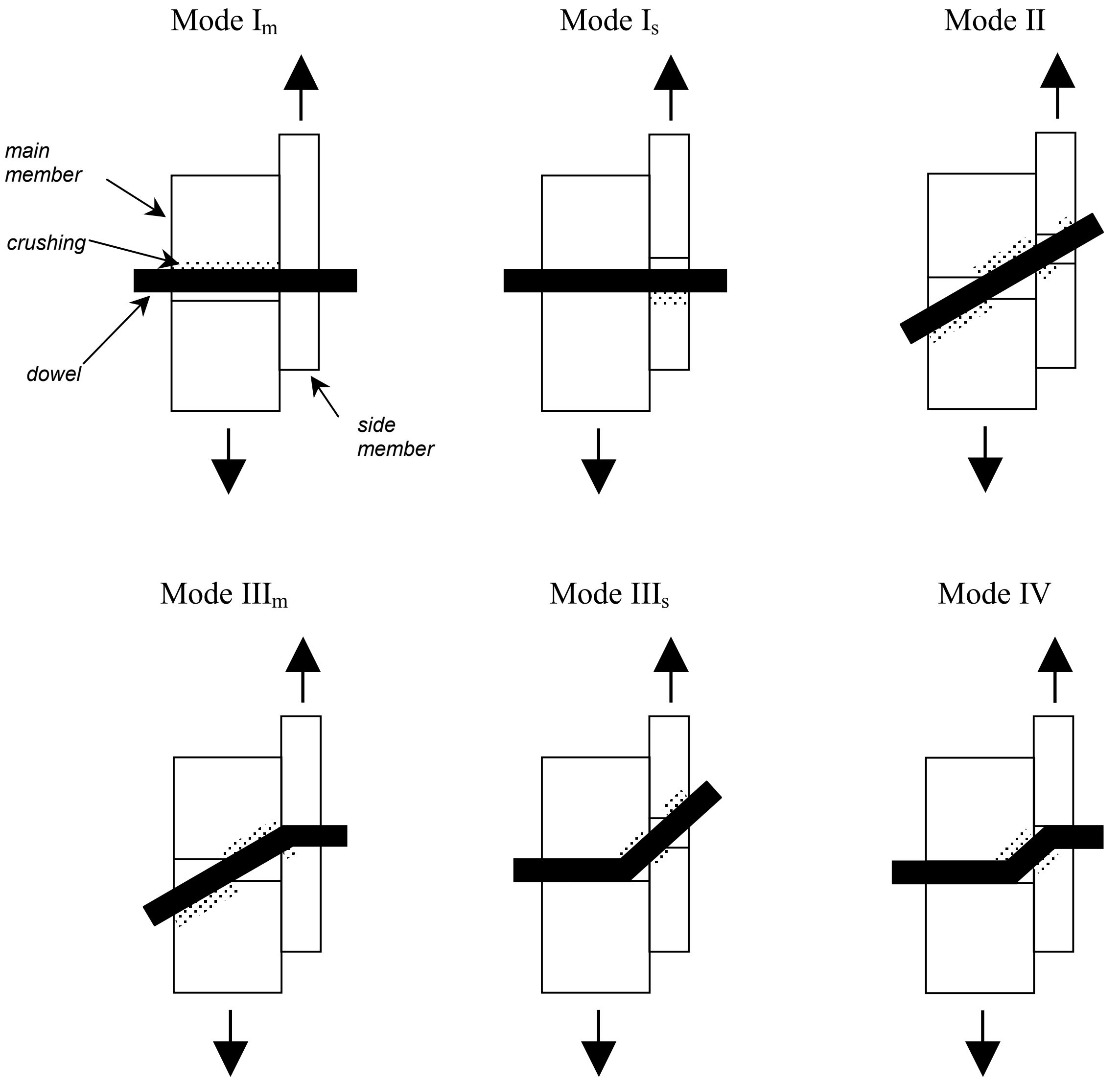

Figure 2.4: Single-shear connection yield modes (from AF&PA 1999).

Table 2.2: General dowel equations for single-shear connections (from AF&PA 1999).

Mode I_m	Mode I_s	Modes II - IV
$P = q_m l_m$	$P = q_s l_s$	$P = \frac{-B+\sqrt{B^2-4AC}}{2A}$

Inputs A, B, and C for Yield Modes II - IV

Mode II	$A = \frac{1}{4q_s} + \frac{1}{4q_m}$	$B = \frac{l_s}{2} + g + \frac{l_m}{2}$	$C = -\frac{q_s l_s^2}{4} - \frac{q_m l_m^2}{4}$
Mode III_m	$A = \frac{1}{2q_s} + \frac{1}{4q_m}$	$B = g + \frac{l_m}{2}$	$C = -M_p - \frac{q_m l_m^2}{4}$
Mode III_s	$A = \frac{1}{4q_s} + \frac{1}{2q_m}$	$B = \frac{l_s}{2} + g$	$C = -\frac{q_s l_s^2}{4} - M_p$
Mode IV	$A = \frac{1}{2q_s} + \frac{1}{2q_m}$	$B = g$	$C = -2M_p$

Where:

P = nominal lateral connection value, lbs

l_s = side member dowel bearing length, in

l_m = main member dowel bearing length, in

l_b = span length used with dowel bending tests, in

D = dowel diameter, in

g = gap between members, in

$P_{5\%}$ = 5% offset load as measured from bearing tests, lbs

$q_s = F_{es}D$ = side member dowel bearing resistance, $^{\mathrm{lb}}/_{\mathrm{in}}$

$q_m = F_{em}D$ = main member dowel bearing resistance, $^{\mathrm{lb}}/_{\mathrm{in}}$

$M_p = (F_b D^3)/6$ = dowel plastic moment, in-lbs

$F_{es} = \frac{P_{5\%}}{l_s D}$ = side member bearing strength, psi

$F_{em} = \frac{P_{5\%}}{l_m D}$ = main member bearing strength, psi

$F_b = \frac{8P_{5\%} l_b}{\pi D^3}$ = dowel bending strength, psi

2.6 – Conclusion

The review of the current state of the performance concept in building design of wood structures indicates that the general philosophy is well accepted and various levels of applications exist in all the areas relevant to the building process. Full utilization of durability-based design depends strongly on continuing research on the factors affecting wood durability during its in-service life. In particular, the validity of the current yield model is questionable when estimating yields of cyclically conditioned connections.