REPETITIVE MEMBER FACTOR STUDY FOR COLD-FORMED STEEL FRAMING SYSTEMS

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Abstract

Cold-formed steel has become a preferred building material for structural farming in many different types of structures, commonly for repetitive members such as floor joists, roof rafters, roof trusses and wall studs. For wood framed structures with repetitive members, a repetitive member factor increases the allowable bending stress from 1.00 to 1.50 times the reference design value, depending on both the type of material and the type of load. Currently, however, the bending strength of cold-formed steel repetitive members is not permitted to be increased, even though the method of framing is quite similar to that of wood except for the material properties.

Typical light-frame wood construction consists of floor, roof, and wall systems, each with repetitive members connected by sheathing. A repetitive system is one of at least three members that are spaced not farther apart than 24-inches. These members must also be joined by a load distributing element adequate to support the design load. The behavior of the individual members, then, is affected by inclusion into this system. Additionally, the connected sheathing increases the bending capacity of bending members due to both composite action and load sharing. Composite action is a result of T-beam-like action between the repetitive member and connected sheathing, but is limited by nail slippage in the connection. Secondly, due to differential deflection between the members, sheathing is also able to distribute loads from weaker, more flexible members to the more rigid and stronger members. This effect is known as load-sharing.

The same general principles of repetitive use should apply to cold-formed steel due to its similarity to wood construction. Accordingly, this paper conducts a preliminary study of the effects of both composite action and load-sharing in cold-formed steel assemblies and subsequently recommends using a repetitive member factor for cold-formed steel members.

Table of Contents

List of Figures

List of Tables

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CHAPTER 1 - Introduction

Cold-formed steel has become a preferred building material for structural farming in many different types of structures, commonly for structural systems such as floor joists, ceiling joists, roof rafters, and wall studs. For each of these systems, the cold-formed steel members are repetitive in nature; that is they are usually spaced at regular intervals of 12-inches to 24-inches apart, which is very similar to conventional light frame wood construction. For wood framed structures with repetitive members, a repetitive member factor is permitted for individual members as long as they meet specific criteria. This adjustment factor has the effect of increasing the allowable bending stress for the member and ranges anywhere from 1.00 to 1.50, depending mainly on the member material properties. Currently, no repetitive member factor for cold-formed steel repetitive members exists, even though the method of framing is quite similar to that of wood.

The National Design Specification (AF&PA, 2005) allows the use of a repetitive member factor for members such as joists, truss chords, rafters, studs, planks, decking and other similar members. The required criteria are that there must be at least three members joined by a load distributing element such as sheathing, and they must be spaced no further apart than 24-inches. Moreover, the repetitive member factor is only for bending and is applied as an adjustment factor to the reference design value for allowable bending stress. For sawn lumber construction, the repetitive member factor is 1.15.

This factor is permitted in the design of individual members because a member behaves differently when it is part of a system, due to interactions with the sheathing and the surrounding members, assuming that sheathing increases the bending strength of repetitive members from both composite action and load sharing. First, composite action is a result of T-beam like action between the repetitive member and connected sheathing but is limited by nail slippage in the connection. Next, wood members typically are quite variable in their mechanical properties from one member to another; therefore, sheathing is also assumed to distribute loads from weaker, more flexible members to the more rigid and stronger members. This effect is known as load-sharing.

The main purpose of this paper is to determine if a repetitive member factor can be applied to cold-formed steel members that meet the same criteria as sawn lumber repetitive members. The following sections discuss the factors that were used to develop repetitive member factor for wood systems, review relevant literature, and also review current repetitive member factors for different types of wood materials. The study also performs an analytical study of both composite action and load-sharing for a cold-formed steel assembly, and calculates a repetitive member factor.

CHAPTER 2 - Repetitive Assemblies and System Effects

Before repetitive-member systems can be discussed, the term must first be defined. The *Standard Guide for Evaluating System Effects in Repetitive-Member Wood Assemblies* (ASTM, 2003), which establishes the guidelines for evaluating repetitive wood assemblies, defines a repetitive-member wood assembly as a system in which three or more members are joined using a transverse load-distributing element. Also, the National Design Specification (AF&PA, 2005) defines a load-distributing element as "any adequate system that is designed or has been proven by experience to transmit load to adjacent members without displaying structural weakness or unacceptable deflection." Sheathing, which includes plywood, oriented strand board (OSB), and gypsum wall board, is the most commonly used load-distributing element for most structures (Rosowsky, Yu, & Bulleit, 2005).

Load carrying capacity of individual wood members increases when part of a repetitive assembly, due to assembly action. Assembly action comprises three primary effects: composite action, load-sharing, and residual capacity. The conservative allowable stresses given in the *National Design Specification* (NDS) also have an effect on the increased assembly strength.

2.1 Wood Design Values

It is important to understand the conservatism built into the NDS design strengths. The strength of wood products is highly variable because of inconsistencies in the material, such as knots, shakes, and slope of grain. To account for the effect that the material characteristics will have on the member's strength and stiffness, grading rules have been established. The most common method is to visually inspect each piece and sort them into grades based on their characteristics. The other method is to utilize machine grading, which uses non-destructive tests to sort the members into strength and stiffness classes. Neither of these grading methods eliminates the coefficient of variation (COV) of stiffness or strength, but the COV of machine graded lumber is less than that of visually graded lumber (WCLIB, 2009).

Current design methods specified in the NDS are based on individual member design. To assure adequately safe design strength for any single member requires a conservative member strength design value. The design bending stress is found by statistically analyzing test data and calculating the 5% exclusion value (ASTM, 2006). To better illustrate this concept, Figure 1 shows an idealized standard distribution curve and the 5% exclusion value. The area of the graph that is not shaded represents the 95% of wood members that have a greater strength than the 5% code given value (ASTM, 2006).

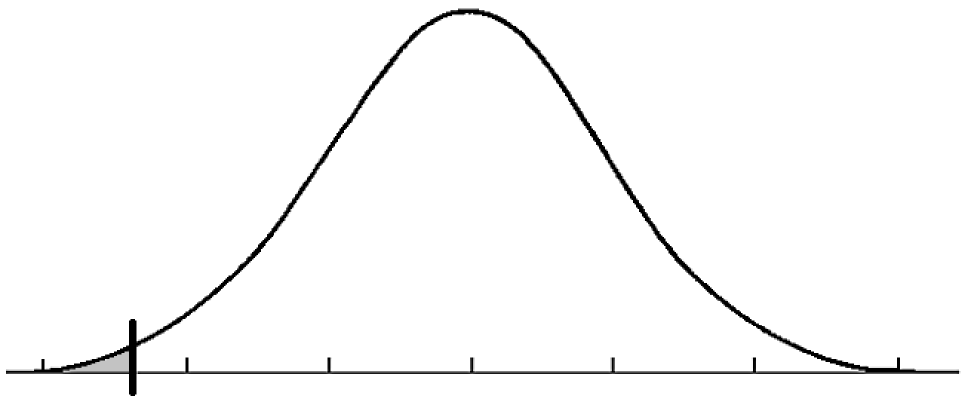

Figure 1- Standard Distribution Curve

As the graph illustrates, most members in a system will have a higher strength than the code design strength. The load-sharing effect, which is discussed later, is able to take advantage of the stronger members.

2.2 Composite Action

Composite action is the interaction of the sheathing and the bending member that creates T-Beam-like action, effectively increasing the moment of inertia of the bending member by moving the neutral axes of the components toward each other (Wolfe, 1990). Typically, the sheathing and the bending member are connected by nails, glue, or both. However, nails do not provide fully rigid connections between the member and the sheathing because of slippage due to shear, resulting in only partial composite action. Because sheathing comes in panels, many gaps occur between sheathing panels along the length of the "T-Beam." These gaps cause a discontinuity of the effective flange and will therefore have an adverse effect on the amount of partial composite action that can occur (McCutcheon, 1977). Partial composite action is important because it can provide a significant amount of increased capacity. For example, for sawn lumber, it accounts for approximately 2/3 of the increased capacity (ASTM, 2007).

2.3 Load-Sharing

Load-sharing between members is another main component of assembly action. As was discussed previously, the strength of a wood member can be highly variable, and the design strengths of the members are conservative. Load-sharing is able to take advantage of both of these concepts by transferring load on a weaker member to the surrounding stronger members. Transfer of load is possible mainly due to differential deflections between members, as stiffer members will deflect less than less rigid members (Wolfe, 1990). Figure 2 shows an assembly made of three members connected by sheathing, which is acting as a load-distributing element.

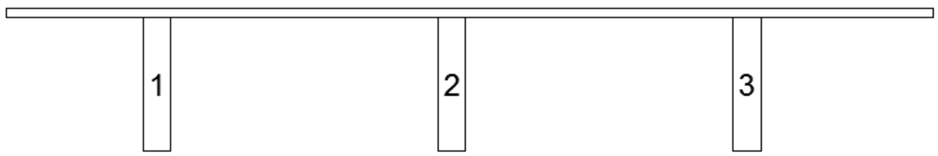

Figure 2 - Load Sharing Assembly

To illustrate load-sharing, assume that member 2 is a weak member surrounded by stronger members 1 and 3. If uniform load was applied to the assembly, the weaker member 2 would try to deflect more than members 1 and 3. The sheathing would effectively span member 2, transferring more load to 1 and 3 until their deflections reach that of member 2. In this way, the load-distributing element is able to transfer load away from weaker members to stronger ones. Because the stronger members are able to effectively reinforce the weaker members, the strength of the assembly is greater than that of the weakest member. The amount of load that is able to be transferred to the surrounding members depends on many factors, including the effects of size and mutual restraint (Wolfe, 1990).

2.3.1 Effects of Size on Assembly Capacity

The size effect is dependent on the number of members in the assembly and the dimensions of the individual members (Wolfe, 1990). The failure of an assembly is defined as the point at which the first member in the assembly fails (ASTM, 2003). Load-sharing is dependent on having multiple members in the system, though the chances of including a weak member increase with increasing number or length of members (Rosowsky & Yu, 2004). Because the capacity of the assembly is dependent on first member failure, the higher chance of including a weak member will cause the assembly capacity to decrease. Thus, the calculation of the load-sharing factor, which will be discussed in Section 2.3.3, is highly dependent on the number of members in the assembly. For example, the load sharing factor for a 5-member assembly with a COV of 25% is 1.22, but decreases to 1.06 for a 50-member assembly.

2.3.2 Mutual Restraint

Mutual restraint is a measure of the stiffness of the load distributing element that will cause all of the members in the assembly to deflect together. It is the main component of load-sharing. Two theoretical systems can be used to illustrate the effects of mutual restraint.

The first theoretical system is known as a brittlest-link system. It has an infinitely rigid deck, and therefore the highest amount of mutual restraint (Zahn, 1970). Because the deck is infinitely rigid, all members in the assembly would be constrained to have the same deflection. In this system, the member with the least deflection capacity (brittlest-link) will fail first (Zahn, 1970). Members in a brittlest-link system will act as described previously, where load will be transferred from less stiff members to stiffer ones. This will lead to an increase in assembly capacity in wood products because a positive relationship between rigidity and strength exists. Alternatively, if the most rigid member is also the weakest, mutual restraint would have a detrimental effect on the assembly capacity because the weakest member would take the most load.

The other hypothetical system is one with an infinitely flexible deck, known as a weakest-link system (Zahn, 1970). This system would have no mutual restraint, as the members could deflect independently of each other. Here, the capacity of the assembly would be controlled by the weakest member in the system. A weakest-link system does not take advantage of the stronger members because no load is shared through the sheathing.

Realistically, repetitive assemblies fall somewhere between these two theoretical systems. Ultimately, the amount of mutual restraint that can occur is dependent on the difference in deflections between adjacent members and stiffness of the sheathing. For this reason, the effects of mutual restraint increase with material variability.

2.3.3 Calculation of Load-Sharing Factor

The load-sharing factor is defined as the ratio of load at first member failure in an assembly to that of first member failure not in an assembly. A load-sharing factor can be found either analytically or empirically utilizing the guidelines given in ASTM D 6555 (ASTM, 2003).

The concept of repetitive member factor was based primarily on the effects of load-sharing (ASTM, 1970), a concept originally introduced in 1962 in *Tentative Recommended Practice for Determining Design Stresses for Load-Sharing Lumber Member*s (ASTM, 1962). The standard was discontinued in 1968, but a 1.15 factor was adopted in 1970 in *Standard Methods for Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber* (ASTM, 1970). This load sharing factor was based on a simplified statistical analysis of three parallel bending members, known as an averaging model (ASTM, 1970). The allowable bending stress of a member in a load sharing system is found by using the following equation:

$$\bar{X} = \frac{F_b}{(1 - k\Omega/\sqrt{n})} \qquad \text{(Equation 2-1)}$$

where F_b is the 5% exclusion limit of the allowable bending stress of an individual member**,** *k* is the distance from the mean to the lower percentile in terms of standard deviates, Ω is the coefficient of variation (COV), n is the number of members in the assembly, and $\bar{X}$ is the allowable bending stress of a member as a result of load-sharing (Wolfe, 1990). Based on a 95% inclusion value, k is found on a standard normal distribution chart to be 1.645. Typical visually graded sawn lumber has a COV of modulus of rupture (MOR) of 25% to 30% (Wolfe, 1990). If an assembly had three members and a COV of 25%, the calculation would be:

$$\bar{X} = \frac{F_b}{\left(1 - \frac{(1.645)(0.25)}{\sqrt{3}}\right)} = 1.31F_b$$

The same calculation with a COV of 30% yields a factor of 1.40. ASTM Committee D07, which has jurisdiction of most wood standards, proposed a conservative factor of 1.15, which coincides with a COV of approximately 16%. The committee also placed conservative guidelines for usage of the repetitive member, including limits of spacing, number of members, and the size of lumber (ASTM, 2003).

2.4 Residual Capacity

Though one member in a system may fail, the whole assembly will not collapse in most cases. Because of both composite action and load sharing, the assembly has added capacity after first member failure, which is defined as residual capacity. For sawn lumber, the residual capacity has been found to be as much as two to five times greater than the capacity of the weakest member in the system (ASTM, 2003). An assembly is an indeterminate system, and so many unforeseen factors affect an assembly's residual capacity that are not always obvious without detailed analysis. In deciding how to address residual capacity as it applies to member design, ASTM Committee D07 on Wood wrote the following:

> "The committee chose to discourage the use of residual capacity in system factor calculations based on the premise that traditional "safety factors" are calibrated to a member-based design system. The committee believes that is inappropriate to extend the same factors to entire systems. In other words, engineers should not design entire systems that have the same computed probability of failure as individual members in today's designs." (ASTM, 2003)

Even though an assembly can have a significant residual capacity, that capacity is not currently permitted in member design.

CHAPTER 3 - Literature Review

Since the inception of the repetitive member factor, many studies and tests have been conducted to better understand the repetitive member behavior and how it should be calculated. The following sections review literature that is centered on the effects of both partial composite action and load-sharing, as well as development of repetitive member factors.

3.1 Studies of Partial Composite Action

Sheathing attached to a joist or stud creates a T-Beam-like effect that increases the effective moment of inertia of the bending member (Wolfe, 1990). The relationship between loading, connection slippage, and gaps in the sheathing has been the focus of many studies.

For instance, McCutcheon (1977) presented a simplified method to calculate the deflection in these partial composite sections. This calculation took into account the reduction of composite action because of connection slippage and sheathing gaps. The equation for partial composite deflection McCutcheon developed follows:

$$\Delta = \Delta_R \left[1 + f_\Delta \left(\frac{EI_R}{EI_U} - 1\right)\right] \qquad \text{(Equation 3-1)}$$

where Δ is deflection of the beam element due to partial composite action, Δ_R is the deflection if the components are rigidly connected, EI_R is the bending stiffness if the components are rigidly connected, EI_U is the bending stiffness if the components are not connected, and f_Δ is equal to:

$$f_\Delta = \frac{10}{(L\propto)^2 + 10} \qquad \text{(Equation 3-2)}$$

where α^2 is equal to:

$$\propto^2 = \frac{h^2 S}{EI_R - EI_U}\left(\frac{EI_R}{EI_U}\right) \qquad \text{(Equation 3-3)}$$

In equation 3-3, h is the distance between the centroidal axes of the joist and sheathing, and S is the load per unit length that causes a unit slip in the nail or adhesive joint. If sheathing gaps are considered in the calculation, L in Equation 3-2 is replaced by the gap spacing.

To test the equations developed in this study, seven floors were constructed with nine 2x8 joists sheathed with tongue-in-groove plywood. Four of the floors were connected with 8d common nail fasteners, and the other three were nail-glued using rigid adhesive. The stiffness of each joist was found prior to construction using non-destructive bending tests. The floors were non-destructively tested with both concentrated and uniform loads, and the mid-span deflections were compared to the calculated values. Results showed 22 of 29 floors tested were within 5 percent of the calculated deflections, which suggests that the composite stiffness could be approximated by these simplified equations.

3.2 Load-Sharing Studies

Load sharing between members is a main component of the current repetitive member factor, but the amount of load that can be transferred to the surrounding members is dependent on many factors, including the effects of size, mutual restraint, and bridging (Wolfe, 1990): The size effect is dependent on the number of members in the assembly, the length, and the dimensions of the individual members; mutual restraint is a measure of the rigidity of the load distributing element; bridging is the ability of the components to transfer load around defects within an element (Wolfe, 1990).

Zahn (1970) conducted a statistical analysis of both brittlest-link and weakest-link systems to investigate the size effect and mutual restraint. He also utilized computer modeling to confirm that weakest-link and brittlest-link systems represent the lower and upper bounds of system capacity. For the statistical analysis of the weakest-link system, Zahn assumed load was equal on all members and concluded that increasing the number of members in a weakest-link system decreases the capacity of the system. Then, he modeled a brittlest-link system by constraining the mid-span deflections of all members to be equal. The statistical analysis of this system yielded a maximum load-sharing increase of 12.8 percent. Because a brittlest-link system is the upper bound of load-sharing, Zahn concluded the maximum load sharing increase should be 12% for sawn lumber systems. The study did not investigate bridging or partial composite action.

McCutcheon (1984) analyzed floor systems by assuming the sheathing to be a partially composite beam on elastic springs. Specifically, he studied the deflection in a floor system by modeling joists as springs. This method represents the effect of joist stiffness on the system more effectively than assuming the joists to be simple beams. Figure 3 illustrates the analysis method, with sheathing being supported by joist "springs."

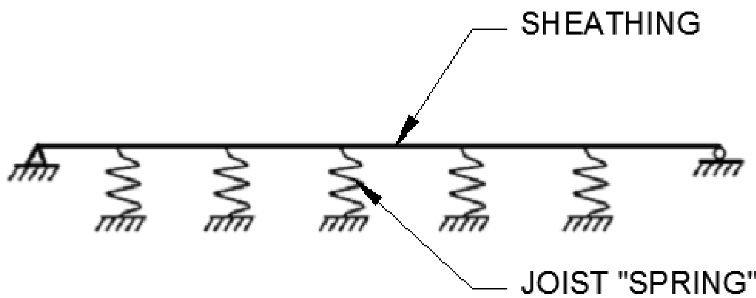

Figure 3 – Beam on Elastic Springs

This study expands on *Method for Predicting the Stiffness of Wood-Joist Floor Systems with Partial Composite Action* (McCutcheon, 1977), which was discussed previously. The equations previously outlined take into account the slippage in the joist-sheathing connection. The deflection of each joist is converted to a spring constant that is applied to the sheathing "beam." Differential stiffness from joist variability can be taken into account using the spring constants. Because both joist variability and nail slippage are taken into account, the calculations were very accurate when compared to finite-element analysis (McCutcheon, 1984). McCutcheon concluded that these calculation methods are an adequate simplified method for calculating system deflections.

3.3 Continued Development of System Factors

Folz and Foschi (1989) introduced a modification factor, K_s, that would encompass all the aspects of load-sharing in multiple member floor and roof systems. The reliability of a system of members was studied in two ways: failure of the complete structural system defined by the failure of any member in the system, and the reliability of a single member within the system. The first method takes into account the effect that a single member failure will have on the reliability of the system, but the second assumes that the failures are independent. Using statistical analysis, the authors found the system factors for both types of study were 1.38 and 1.63, respectively (Folz & Foschi, 1989).

Rosowsky and Ellingwood (1991) conducted a study hypothesizing that duration of loading would have an effect on the repetitive system factor. According to the report, actual failures of wood assemblies generally occur due to creep in wood, as opposed to short term overloading. Using software, the authors analyzed the reliability of floor 3 floor systems including the effects of load duration. A comparison of system factors with and without the duration of load is shown in Table 3-1.

Table 3-1 - System Factors for Duration of Load Study

Lumber Type	ψ (Duration of Load Included)	ψ (Duration of Load Not Included)
Douglas Fir-Larch (2 x 10, No. 2)	1.11	1.37
Southern Pine (2 x 10, No. 2)	1.33	1.67
Hem-Fir (2 x 8, No. 2)	1.53	1.88

As Table 3-1 shows, not considering the duration of load can cause overestimation of repetitive factors. For this reason, they concluded that more conservative factors, in the range of 1.2 to 1.3, would be more appropriate than the factors proposed by Folz and Foschi.

Bulleit and Liu (1995) used computer analysis to model the effects of partial composite action between the sheathing and the member, the random mechanical properties of the members, the load duration effects, and post-yield properties of the partial composite members. Post-yield behavior is synonymous with residual capacity, which was discussed earlier. The system consisted of simply supported Douglas-fir lumber members connected to sheathing by 8d common nails 8-inches on centers. A Monte Carlo simulation was conducted on the system that included over 500,000 runs. From the simulations, the authors concluded that system factors are heavily dependent on the coefficient of variation of the modulus of rupture (bending strength) and the post-yield behavior of partial composite members. They suggested that the current 1.15 factor is sufficient if the post-yield behavior of the partial composite members was unknown (Bulleit & Liu, 1995). They also concluded that the system factor could be as high as 1.4 if the post-yield behavior is known, but suggested 1.25 as a conservative value.

Wolfe (1990) conducted an in depth study of both load-sharing and composite action. He observed that the effects of composite action are more likely to increase the load capacity of an assembly than would load sharing. Composite action both reduces member stresses and increases system stiffness. Wolfe also stated that the amount of load sharing is highly dependent on many conditions, including boundary conditions, the correlation between strength and stiffness, and whether the design is controlled by strength or deflection. Because sheathing increases the stiffness of the members, Wolfe stated that repetitive factors are better suited for designs controlled by deflection (Wolfe, 1990). The study concluded that the current 1.15 factor is adequate.

Yu and Rosowsky (2003) performed an analytical study of system factors in wood assemblies using the equations developed by McCutcheon (1977, 1984) and compared the results to results of wall tests by Polensek (1976). They then proposed a different method of analytically solving for the repetitive member factor. The factor was split into four ratios that better accounted for the variety of effects: post-yield, partial composite action, load sharing, and number of members (Yu, 2003). The partial composite action factor can be calculated using the following equation:

$$K_{PCA} = \frac{6(EI)h}{6(EI_S)+h_S[EI-(EI_S+EI_C)]} \qquad \text{(Equation 3-4)}$$

where EI, EI_s, and EI_c are the stiffness of the partial composite member, the stud, and the sheathing, respectively. h is the distance from the centroid of the member to the sheathing, and h_s is the height of the stud. The size effect factor, K_{NMEM}, accounts for the negative effect of the number of members in the system. It is equal to the ratio of the strength of the weakest member to the wall member strength. For systems with a large number of members, this factor can be well below 1. The load sharing factor, K_{LS}, is defined as the ratio of 5th-percentiles of system strength of first-member failure to system strength of weakest member strength. The last factor is the post-yield factor, K_{PY}, which is defined as the ratio of ultimate system strength to system strength defined by first-member failure. The post-yield ratio, or residual capacity, was found to be the largest, but it is not allowed in the repetitive member calculations. Without the post-yield effects, the authors found that many times the repetitive factor was less than 1. One assembly discussed in the study decreased from a total system factor of 1.33 with 4-members, down to 0.87 when the number of members was increased to 22.

Rosowsky and Yu (2004) used the analysis from their previous study (Yu, 2003) and concluded the overall system factor is significantly influenced by system size. Because of the adverse effects of system size, they proposed that a system factor should be greater than 1.0 if an assembly has as up to 7 members and less than 1.0 for a wall assembly with greater than 10 members.

3.4 Objections to Current Factor

As was discussed in the previous sections, the repetitive member factor is dependent on many effects. The current standard for calculating repetitive member factors considers only composite action and load sharing (ASTM, 2003). Some studies argue that this method is too simplified and is not adequately conservative for all situations and loading types.

Verrill and Kretschmann (2009) studied the load sharing factor and concluded that in some cases, the repetitive member factor should be less than 1. The report claims that the current methods of calculating the load sharing factor are backwards, and so the load sharing contribution should in fact decrease with increasing COV of Modulus of Rupture (MOR) of the material (Verrill & Kretschmann, 2009). Whether a high COV of MOR should increase or decrease the amount of load sharing is dependent on the definition of failure. If failure is defined as the load at which the first member fails, a high COV of MOR should decrease the contribution of load sharing, in some cases to below 1 (Verrill & Kretschmann, 2009). Though the high amount of COV of MOR is advantageous for load sharing due to differential deflection, the chances of including a weak member are increased as well, which can cancel out the other load sharing contributions. They noted that using the current 1.15 factor has not caused any notable failures, but they proposed some ideas as to why that is:

- "Solid sawn 2 by's have load capacity correlated with stiffness. Floor and roof systems must meet both serviceability and strength requirements. Solid sawn products sized to meet serviceability requirements usually oversatisfy strength requirements. Also, depending on span, a solid sawn product of intermediate size might satisfy the serviceability requirement, but because solid sawn products are produced in fixed increments, the specifier must select the next larger size, resulting in even higher reliability."
- "Actual loads are often much lower than allowable loads."

- "…if we believe that assembly failures are only noted if two or more members fail or if two adjacent members fail, then the probability of perceived assembly failure declines even further."

These ideas can account for the lack of failures due to using the repetitive member factor.

The load sharing effects are most closely related to the differential deflection of members in an assembly, which is due to inconsistencies of the material. Since the inception of the factor, machine stress rated (MSR) has become an option for grading sawn lumber. As opposed to visually graded lumber, MSR lumber is non-destructively tested and graded according to modulus of elasticity and strength. Though this method of grading greatly reduces the variation in the material, neither the NDS (AF&PA, 2005) nor ASTM D 6555 (2003) discuss the effect of grading on the repetitive member factor.

CHAPTER 4 - NDS Repetitive Member Factors

Repetitive member factors have been developed for many different types of wood materials, ranging from 1.04 in structural composite lumber to 1.5 in some sawn lumber applications. The following sections explain the repetitive member factors that have been assigned to types of wood materials and applications.

4.1 Wood I-Joist Systems

Wood I-joists consist of sawn lumber of structural composite lumber flanges connected by an adhesive to a wood structural panel web. These sections are commonly used for joists in floor systems and rafters or joists in roof systems.

Wood I-Joist repetitive systems are currently one of the few wood materials where no repetitive member factor is allowed. Previously, the 2001 NDS allowed a 1.07 factor for I-joists with sawn lumber flanges, and a 1.04 factor for structural composite flanges, but removed the factor due to multiple reasons given in the *Standard Specification for Establishing and Monitoring Structural Capacities of Prefabricated Wood I-Joists* (ASTM, 2007) as discussed below.

Partial composite action is most influenced by the relative stiffness of the sheathing to both the framing member and the connection. The stiffness of an I-joist is mainly dependent on the area of the flanges and depth of the section. Because the stiffness of the I-joist varies with depth, so will the amount of achievable partial composite action. To apply a repetitive member factor that could work conservatively for all I-joists, the D 5055 Specification task group decided on a factor near 1.0 (ASTM, 2007).

Stiffness variability of the framing members has the greatest impact on load sharing in a repetitive member system. Compared to sawn lumber, wood I-joists have a much more consistent stiffness from member to member. As previously discussed, in a load sharing assembly, the stiffest member will take the most load. For this reason, the stiffness of the member must have a positive correlation to its strength. In data collected by the committee from many I-joist manufacturers, this relationship was not always consistent (ASTM, 2007). If the stiffest member has the least moment capacity, the most load will be taken by the weakest member, resulting in a load-sharing effect that is detrimental to the system. Because the stiffness to strength relationship was not consistent for I-joists of all manufacturers, only a limited amount of load sharing effects could be applied to all I-joists.

Even with the minimal benefits of both partial composite action and load sharing, the committee had found that a 1.05 repetitive member factor could be safely applied (ASTM, 2007), but decided that removing the repetitive member factor would make for a more simplified design. For this reason, the committee revised the repetitive member factor to 1.0.

4.2 Sawn Lumber

Sawn lumber is commonly used for repetitive assemblies in walls, floors, and roofs. The NDS (AF&PA, 2005) specifies a 1.15 factor for sawn lumber systems that meet the repetitive member criteria. However, the International Building Code (ICC, 2006) allows a larger factor for sawn lumber wall studs resisting wind loads based on the depth of the member. The factors are shown in Table 4-1.

Table 4-1 – Wall Stud Bending Stress Factors

Stud Size	System Factor
2 x 4	1.5
2 x 6	1.35
2 x 8	1.25
2 x 10	1.2
2 x 12	1.15

The requirements to use these values are more stringent than those given in the NDS: The members must be spaced no more than 16-inches apart, sheathed on the inside with a minimum of ½-inches of gypsum board, and sheathed on the outside with a minimum of 3/8-inch thick wood structural panel sheathing; and, both the gypsum board and wood sheathing must meet connection standards set in Table 2306.4.5 of the IBC 2006. If these criteria are met, the repetitive member factor ranges from 1.50 for a 2x4 to 1.15 for a 2x12 (ICC, 2006). The higher factors are available for members designed for wind loads due to the behavior of both composite action and load-sharing under high wind conditions (American Wood Council, 2006)

4.3 Structural Composite Lumber

Standard Terminology Relating to Wood and Wood-Based Products (ASTM, 2005) defines structural composite lumber as a composite of wood elements bonded with an exterior grade adhesive and intended for structural use. The wood elements can include wood strands, strips, veneer sheets, or a combination of any of these. Typical structural composite lumber products are laminated veneer and parallel strand lumber, and such lumber is used in most of the same applications as sawn lumber, except for high moisture applications.

The NDS (AF&PA, 2005) specifies a 1.04 repetitive member factor for structural composite lumber. Additionally, there must be at least three parallel members in contact or spaced a maximum of 24" on center, and they must be joined by a load distributing element.

Because structural composite lumber is a manufactured product, its properties are much more consistent than those of sawn lumber. Therefore, the stiffness coefficient of variation ranges from 10 to 20 percent (ASTM, 2007), compared to 30 to 40 percent for sawn lumber. The decreased variability causes the repetitive member factor to be limited to 1.04 for this material (AF&PA, 2005).

4.4 Pre-engineered Trusses

Pre-engineered trusses are commonly used as the main structural system for both floors and roofs in many residences and wood framed commercial structures. They are usually composed of sawn lumber or structural composite lumber elements connected by metal plates. The behavior and applicability of the repetitive member factor is not inherently obvious for trusses. Most truss elements are designed assuming only tension or compression forces, except for chord elements, which must also be designed for bending due to uniform loads applied to the truss. The important clarification in the case of a truss is the definition of a bending member. According to ASTM D 6555 (2003), the entire truss is considered a bending member because the assembly of elements acts like a flexural member. Consequently, if a truss can be considered a bending member, a repetitive member factor can be applied for truss design if the assembly meets the spacing and connection limitations set for sawn lumber members.

According to the IBC (ICC, 2006), the *National Design Standard for Metal Plate Connected Wood Truss Construction* (TPI, 2008) governs the design of pre-engineered trusses. According to this standard, bending members in the truss are allowed to apply the standard 1.15 repetitive factor. Though repetitive factors cannot be applied to F_c or F_t for standard member design, a limited factor is allowed when a compression or tension member is part of a truss.

Through testing of pre-engineered trusses, the National Design Standard for Metal Plate Connected Wood Truss Construction (TPI, 2008) allows the following repetitive factors:

- "Those listed in the recognized lumber grading rules and consisting of a 15 percent increase to F_b for solid sawn lumber."
- "A 15 percent increase to F_b and ten percent increase to F_c and F_t for solid sawn lumber members to which structural wood sheathing is mechanically attached."
- "A ten percent increase to F_b, F_c and F_t for solid sawn lumber members to which structural wood sheathing is not mechanically attached. These increases apply to Chord members where three or more Trusses are positioned side by side, are in contact, or are spaced no more than 24 in. on center and are joined by roof sheathing, flooring, gypsum, or other load distributing elements attached directly to the Chords."

These factors apply only to sawn lumber trusses; trusses composed of structural composite lumber are allowed only the 1.04 factor for bending members, but no increases for F_t or F_c (TPI, 2008).

CHAPTER 5 - Investigation of a Repetitive Member Factor for Cold-Formed Steel Framing

Cold-formed steel is commonly used as repetitive members in similar applications to wood. The following sections discuss the application of the same principles used for establishing wood repetitive member factors to cold-formed steel.

5.1 Composite Action Effect

In wood assemblies, composite action accounts for approximately 2/3 of the repetitive member factor, while load-sharing accounts for the other 1/3. To find the contribution of composite action in a cold-formed steel assembly required an analytical analysis of a cold-formed steel stud with sheathing attached. The section, shown in Figure 5.1, consists of an A653 SS Grade 33, 600S-162-33 cold-formed steel stud with 1/2-inch thick oriented strand board (OSB) with a 24/0 span rating.

The width of the OSB was based on several assumptions. If the stud-spacing limitation used for wood is assumed for cold-formed steel, the maximum member spacing would be 24-inches. 16-inch spacing is commonly used, and to provide a more conservative composite calculation by limiting the flange width, the spacing of the studs was assumed to be 16-inches. The amount of flange that can be used in composite calculations is limited in the design of both concrete T-Beams and steel composite beams, but no literature was found on the limitations of the effective flange width for wood sheathing. Because of the lack of research on the subject, the full flange width was used for the calculations.

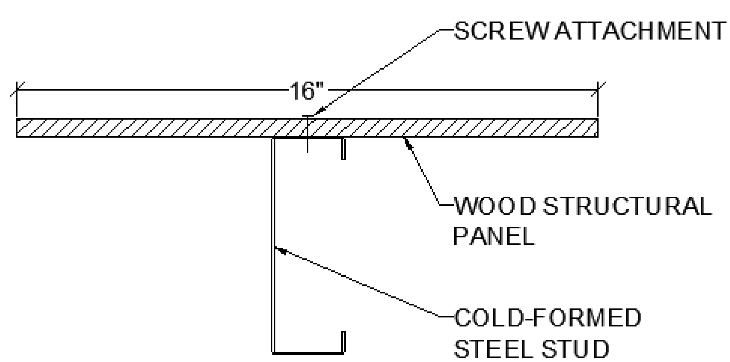

Figure 4 - Composite Section of CFS Stud and Wood Structural Panel

To simplify the calculations, the screw connection between the sheathing and stud was assumed to provide full composite action. Also, the cold-formed steel stud is assumed to be a solid section, with no holes punched in the web; however, punched holes would have little effect on the bending properties of the member. The properties and the ASD (Allowable Stress Design) design strength of the cold-formed steel stud were found by utilizing a cold-formed steel analysis program, CFS (RSG Software, 2006). The results of the analysis are shown in Table 5-1.

Table 5-1: Cold-Formed Steel Stud Properties

Depth:	6.0	in
Width:	1.625	in
Thickness:	0.0346	in
Return Lip:	0.50	in
F_y:	33	ksi
M_a:	11282	lb*in
A:	0.343	in^2
I_x:	1.784	in^4
S_x:	0.595	in^3
E:	29500	ksi

Several assumptions were made in the selection of the rating of the sheathing and its properties. The OSB with the least modulus of elasticity was chosen because it would result in the least transformed area. Also, the study sought and found properties of sheathing in the weak direction with stress perpendicular to the strength axis to generate a conservative composite calculation.

The axial compressive strength of OSB with stress perpendicular to the strength axis is much stronger than the tensile strength. Due to the limited tensile strength, the composite effect was found to be negligible when composite action was calculated with tension assumed in the sheathing. As the following calculations show, the effect of composite action can provide notable strength increase when compression is assumed in the sheathing.

Some properties of both the sheathing and the cold-formed steel stud were not specifically given, and required calculations to find them. The modulus of elasticity (E) and the axial compressive strength (F_c) of the OSB sheathing, found in the *Panel Design Specification* (APA, 2004), were each given per unit area. Also, the maximum allowable stress of the cold-formed steel was not given by the analysis program, but the maximum moment was. The stress in the steel at maximum moment, found by dividing the moment by the section modulus (S), was set as the maximum allowable stress in the cold-formed steel member.

To find the effect of composite action, the transformed area method is used. First, the area of the OSB is transformed to an equivalent area of cold-formed steel so the section can be analyzed like one material. Next, the neutral axis and moment of inertia of the composite section are calculated. The maximum moment of the composite section is found by checking the maximum stresses at three critical locations in the composite section: the top of the sheathing, and the top and bottom of the cold-formed steel member. For this calculation, it is assumed the maximum allowable stress of the composite cold-formed steel member cannot surpass the maximum allowable stress from the non-composite analysis. The composite factor is the ratio of the maximum moment of the composite section to that of the non-composite member.

1/2-inch OSB (24/0 Span Rating)

EA: 2900 ksi/ft width (APA, 2004)

I_x: $\frac{(16\ in)(0.5\ in)^3}{12} = 0.167\ \text{in}^4$

Axial Compression (F_cA): 2500 lb/ft (APA, 2004)

Cold-Formed Steel Maximum Stress at Maximum Moment:

$$\boldsymbol{f_{steel} = {}^{M}/_{S_x} = \frac{11282^{lb*in}}{0.595\ in^3} = 18960\ psi}$$

OSB Mechanical Properties:

$$\boldsymbol{E = {}^{EA}/_{A} = \frac{2900000\ psi/ft}{(.5\ in)(12\frac{in}{ft})} = 483333\ psi = 483.3\ ksi}$$

$$\boldsymbol{f_{max} = \frac{F_cA}{A} = \frac{2500\ lb/ft}{\left(\frac{1}{2}\ in\right)\left(12\frac{in}{ft}\right)} = 417\ psi}$$

Transform OSB to Steel

$$\boldsymbol{n = \frac{E_{sheathing}}{E_{steel}} = \frac{483.3\ ksi}{29500\ ksi} = \frac{1}{61.03}}$$

Calculate Neutral Axis

$$N.A. = \frac{(0.343\ in^2)(3\ in)+\left(\frac{16\ in}{61.03}\right)\left(\frac{1}{2}\ in\right)(6.25\ in)}{0.343\ in^2+\left(\frac{16\ in}{61.03}\right)\left(\frac{1}{2}\ in\right)} = 3.899\ in$$

Calculate $I_{composite}$

$$I_{comp} = 1.784\ in^4 + (0.343\ in^2)(3.899 - 3\ in)^2 + (0.131\ in^2)(6.25 - 3.899\ in)^2 + 0.167\ in^4$$

$$=2.953\ in^4$$

Check Maximum Allowable Stresses

$$f = \frac{My}{I}$$

$$f_{OSB} = 417\ psi = \frac{M(6.5-3.899\ in)}{61.03(2.953\ in^4)} \quad \Rightarrow \quad M = 28894\ lb * in$$

$$f_{steel,top} = 18960\ psi = \frac{M(6.0-3.899\ in)}{(2.953\ in^4)} \quad \Rightarrow \quad M = 26648\ lb * in$$

$$f_{steel,bot} = 18960\ psi = \frac{M(3.899\ in)}{(2.953\ in^4)} \quad \Rightarrow \quad M = 14360\ lb * in$$

$$\therefore \quad M_{composite} = 14360\ lb * in$$

Find Ratio of Moments

$$\frac{\boldsymbol{M_{comp.}}}{\boldsymbol{Ma}} = \frac{\mathbf{14360\ lb*in}}{\mathbf{11282\ lb*in}} = \mathbf{1.27}$$

The 1.27 factor assumes that full composite action can be developed between the cold-formed steel member and the sheathing. For full composite action to be possible, the screws must be able to transfer the shear across the connection. The following calculations determine that the screws provide a connection that is able to handle the shear forces at the maximum moment. For the purpose of these calculations, the stud is assumed to span 10-ft with a uniform distributed load.

Calculate Approximate Equivalent Distributed Load:

$$M = \frac{wl^2}{8} \Rightarrow w = \frac{8M}{l^2}$$

M = 14360 lb*in = 1197 lb*ft

$$w = \frac{8(1197\ lb * ft)}{(10\ ft)^2} = 96\ plf$$

Calculate Maximum Shear:

$$V_{max} = \frac{wl}{2} = \frac{(96\ plf)(10\ ft)}{2} = 480\ lb$$

Calculate Shear Stress at Screws:

$$f_{shear} = \frac{VQ}{I}$$

$$Q = \left(\frac{16\ in}{61.03}\right)(0.5\ in)(6.25 - 3.899\ in) = 0.308\ in^3$$

$$f_{shear} = \frac{(480\ lb)(0.308\ in^3)}{2.953\ in^4} = 50\ lb/in$$

8 Screw Lateral Load Capacity (APA, 1995):

P = 350 lb (1/2-inch plywood into 14-guage galvanized steel)

Calculate Required Fastener Spacing

$$s_{max} = \frac{350\ lb/screw}{50\ lb/in} = 7.0\ in$$

As the calculations show, the full amount of shear force is transferable across the connection when the maximum moment is applied as long as the screw spacing is no larger than 7-inches. It is important to note that because of the size of the load, the deflection would likely govern the design of the member. Additionally, composite action results in an increase of stiffness due to the increase of the moment of inertia of the section. Also, due to slippage in the connection, the actual deflection of the section will be higher than the deflection that could be calculated for the fully composite section. Finally, because there has been limited research into the slippage occurring between cold-formed steel studs and sheathing, this study does not calculate for slippage.

These calculations were performed on a 6-inch deep member, but cold-formed steel studs are available in depths that commonly range from 4-inches to 16-inches. To find the possible composite action for a deeper member, the study performed the same calculations on a 1200S162-68 stud. The composite factor for this 12-inch deep member was found to be 1.14.

5.2 Load Sharing Effect

The other effect to be considered is the load-sharing capabilities of the system. The effects of load-sharing are directly related to the differential deflection between system members. In general, steel has much more consistent material properties than wood products. Pekoz (1987) performed bending tests that can be applied to this study. The test used was of a beam with a stiffened compression flange, similar to that provided by sheathing. The result of that test is shown in the Table below:

Table 5-2 - Beam Test Results

Number Tested	Mean	C.O.V.
8	1.146	0.046

A load sharing factor can be calculated using this data.

Load Sharing Factor (LSF) $= \left(1 - k\Omega/\sqrt{n}\right)^{-1}$

k = 1.645 (5th Percentile)

$\Omega = 0.046$

n = 8

LSF = 1.027

Though steel has relatively little variation of stiffness when compared to wood, the variation is high enough that some load-sharing can occur. The coefficient of variation for cold-formed steel is only 0.046, compared to 0.3 to 0.4 for sawn lumber.

5.3 Recommendation of Repetitive Member Factor

The calculations performed in the previous sections yield only preliminary results to support the feasibility of a repetitive member factor for cold-formed steel members. Though more rigorous testing is required, this study showed that a repetitive member factor can likely be applied to cold-formed steel in some applications. Because composite action is negligible when the sheathing is in tension, a repetitive member factor for applications where tension in the sheathing could result is dependent only on load-sharing. For these assemblies, such as walls, a repetitive member factor of 1.02 can be recommended.

For assemblies where compression in the sheathing can be assured, both composite action and load-sharing can be considered. The preliminary calculations showed that strength increase due to composite action ranged from 1.14 to 1.27, depending on the depth of the cold-formed steel member. Combined with the load-sharing factor of 1.02, the repetitive member factor could be as high as 1.16 to 1.29. These numbers are based on full composite action and do not take into account gaps in the sheathing or slippage in the connections.

The calculations performed were based on several assumptions, and therefore have limitations to their use:

- Can only be applied to stiffened channel cold-formed steel sections
- Cold-formed steel sections must be connected to sheathing with screws
- Sheathing must be plywood or OSB, not gypsum board

CHAPTER 6 - Conclusion

This study reviewed the current repetitive member factors for many wood products, including sawn lumber, wood I-joists, pre-engineered trusses, and structural composite lumber. Subsequent investigation determined that the effects of partial composite action, load sharing, and residual capacity all can have positive effects on the capacity of a repetitive system. Currently, the methods used in the NDS (AF&PA, 2005) permit only partial composite action and load sharing to be used in the calculation of a repetitive member factor for wood products.

Given the similarities between wood and cold-formed steel, a preliminary study investigated the possibility of a repetitive member factor for cold-formed steel members using the same principles that apply to wood. In particular, the effect of composite action was calculated on a range of member depths, and results showed composite action was small for applications where tension occurs in the sheathing, such as walls. When the sheathing was in compression, composite action resulted in an increase of member capacity from 14 to 27 percent, depending on the depth of the member.

Next, though the variability of stiffness in cold-formed steel members is relatively small when compared to wood, it can still yield a positive effect on the capacity of an assembly. Based on test data, a load-sharing factor for repetitive cold-formed steel members was calculated to be 1.02.

For applications where the sheathing is in tension, a repetitive member factor of 1.02 can be recommended; however, when compression in the sheathing can be assured, the repetitive member factor can range from 1.16 to 1.29, depending on the depth of the member.

This report is only a preliminary study, and the numbers for the suggested factors are based on the maximum possible amount of composite action and load-sharing. To determine a factor for design, research needs to be conducted on the effective flange width of plywood and OSB sheathing, the effect of slippage in the connection, and the effect of gaps in the sheathing.

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