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S. Clayton

S. F. Stephens

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FEASIBILITY STUDY FOR A REPETITIVE MEMBER FACTOR FOR COLD-FORMED STEEL FRAMING SYSTEMS

By
S. Clayton[1] and S.F. Stephens[2]

Abstract

Cold-formed steel has become a preferred building material for structural framing in many different types of structures, commonly used as 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 connected by a load distributing element. The behavior of the individual members, then, is affected by inclusion into this system. The effects of both composite action and load-sharing in a repetitive system increase the bending capacity of bending members. The same general principles of repetitive use should apply to cold-formed steel due to its similarity to wood construction. Based upon a preliminary analytical study of the effects of both composite action and load-sharing in cold-formed steel assemblies it has been concluded that a repetitive member factor for cold-formed steel members is feasible and should be further investigated.

[1] Graduate Student, Department of Architectural Engineering and Construction Science, Kansas State University, Manhattan, Kansas
[2] Associate Professor, Department of Architectural Engineering and Construction Science, Kansas State University, Manhattan, Kansas

1.0 Introduction

Cold-formed steel has become a preferred building material for structural framing 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 (305 mm) to 24-inches (610mm) 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. 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. For sawn lumber construction, the repetitive member factor is 1.15. 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 (610 mm). 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.

The main goal of this study was to determine if a repetitive member factor is feasible for 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.

2.0 Repetitive Assemblies and System Effects

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).

Bending strength of individual wood members is allowed to be increased when part of a repetitive assembly, due to assembly action. Assembly action is primarily composed of three effects: composite action, load-sharing, and residual capacity. The conservative reference design values for bending stress provided 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 reference design values for bending stress. The strength of sawn 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. The coefficient of variation (COV) for stiffness or strength is relatively high for visually graded lumber, while the COV of machine graded lumber is somewhat less (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 reference design values for bending stress is found by statistically analyzing test data and calculating the 5% exclusion value (ASTM, 2006).

This means that most members in a system will have a higher strength than the strength calculated using the NDS reference design values. The load-sharing effect, which is discussed later, is able to take advantage of these 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 in wood systems, 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. Sheathing also comes in panels, and therefore many gaps occur between sheathing panels along the length of the "T-Beam." These gaps cause a discontinuity of the effective flange and 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 sawn lumber members are conservative. Load-sharing is able to take advantage of both of these concepts by transferring load from 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 shows an assembly made of three members connected by sheathing, which is acting as a load-distributing element.

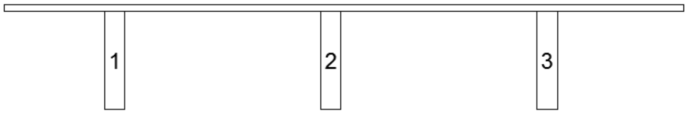

Figure 1 - Load Sharing Assembly

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 deflect more than members 1 and 3. However, due to its stiffness, the sheathing is assumed to transfer 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 carry additional load, 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 a 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:

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

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:

$$\bar{X} = \frac{F_b}{\left(1 - \frac{(1.645)(0.25)}{\sqrt{3}}\right)} = 1.31F_b \qquad \text{(Equation 2)}$$

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. This is referred to as residual capacity and is based upon both composite action and load sharing. 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 factors affect an assembly's residual capacity 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.

3.0 Literature Review

Since the establishment 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 previous studies that are centered on the effects of both partial composite action and load-sharing.

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 partial composite sections. This calculation took into account the reduction of composite action because of connection slippage and sheathing gaps. To test the equations developed in this study, seven floors were constructed with nine 2x8 (51mm x 204 mm) 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 measured 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.

4.0 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.

4.1 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. An analytical study of a cold-formed steel stud with attached sheathing was used to find the contribution of composite action in a cold-formed steel assembly. The section, shown in Figure 2, consists of an ASTM A1003 Structural Grade 33 Type H, 600S-162-33 cold-formed steel stud with 7/16-inch (11 mm) thick oriented strand board (OSB) with a 24/0 span rating.

The stud spacing was based on several assumptions. First, if the stud-spacing limitation used for wood is assumed for cold-formed steel, the maximum member spacing would be 24-inches (610 mm). 16-inch (407 mm) stud spacing is commonly used in walls; therefore a 16-inches (407 mm) spacing was used. The width of flange that can be used in composite calculations is limited in the design of both concrete T-Beams and steel composite construction, but no literature was found on the limitations of the effective flange width for wood sheathing. For simplicity, the full flange width was used for the calculations.

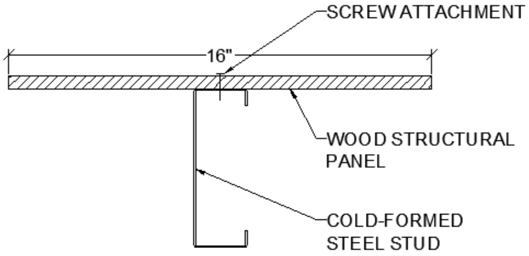

Figure 2 – Composite Section of CFS Stud and Wood Structural Panel

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. The properties and the Allowable Stress Design (ASD) allowable 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 1.

Table 1: Cold-Formed Steel Stud Properties

Depth:	6	in	(152.4	mm)
Width:	1.625	in	(41.275	mm)
Thickness:	0.0346	in	(0.8788	mm)
Return Lip:	0.5	in	(12.7	mm)
F_y:	33	ksi	(228	MPa)
M_a:	11282	lb*in	(1274	Nm)
A:	0.343	in^2	(221.3	mm^2)
I_x:	1.784	in^4	(742557	mm^4)
S_x:	0.595	in^3	(9750	mm^3)
E:	29500	ksi	(203395	MPa)

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.

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_x), 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.

Using these methods, the composite factor is calculated to be 1.24, which as previously stated, 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. Fastener capacity calculations determine whether the screws provide a connection that can transfer shear forces at the maximum moment. In order to calculate the shear force, an equivalent distributed load on an assumed 10-foot (3.05 m) span is found from the maximum moment. Using this shear force, the maximum shear force is checked against the fastener capacity.

The full shear force is found to be transferable across the connection at a screw spacing no more than 6-inches (152 mm) when the maximum moment is applied. 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 allow for slippage.

These calculations were performed on a 6-inch (152 mm) deep member, but cold-formed steel sections are available in depths that commonly range from 3.625-inches (102 mm) to 16-inches (406 mm). To find the possible composite action for a deeper member as might be used in a roof or floor system, the same calculations on a 1200S162-68 member were performed. The composite factor for this 12-inch (305 mm) deep member was found to be 1.12.

4.2 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. The result of that test is shown in Table 2:

Table 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 as follows.

Load Sharing Factor (LSF) $= \left(1 - k\Omega/\sqrt{n}\right)^{-1}$ (Equation 3)

$k = 1.645$ (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 COV for cold-formed steel is only 0.046, compared to 0.3 to 0.4 for sawn lumber.

4.3 Cold-Formed Steel 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 the sheathing is in tension is dependent only on load-sharing. For these assemblies, such as walls, a repetitive member factor of 1.02 was determined.

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 1.12 to 1.24, 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 1.14 to 1.26. 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 limitations:

- Only 600S162-33 and 1200S162-68 sections without punchouts were investigated
- $F_y = 33$ ksi (228 MPa)
- Full composite action was assumed

- Flange width of sheathing 16-inches (40.64 cm) was assumed
- ½-in (12.7 mm) OSB sheathing

5.0 Conclusion

This study shows that the effects of partial composite action, load sharing, and residual capacity can all have positive effects on the flexural 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, this study investigated the feasibility of a repetitive member factor for cold-formed steel members using the same principles that apply to wood. When the sheathing is used in flexural compression, composite action resulted in an increase of member bending strength from 12 to 24 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 used, a load-sharing factor for repetitive cold-formed steel members was calculated to be 1.02.

Therefore, when compression in the sheathing can be assured, the repetitive member factor for the limited scope of this study can range from 1.14 to 1.26, depending on the depth of the member. However, for applications where the sheathing is in tension, a repetitive member factor is limited to1.02.

This study has found that a repetitive member factor is feasible for cold-formed steel when the values are based only on load-sharing and full composite action. To determine a reliable factor for design however, research will need to be conducted to establish a number of items including but not limited to the effective flange width of sheathing, the type of sheathing, the effect of slippage in the connection, and the effect of gaps in the sheathing.

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Appendix. – Notation

Ω : Coefficient of variation
A : Cross-sectional area
COV : Coefficient of variation
E : Modulus of elasticity
f : Stress
F_b : Allowable bending stress
F_c : Axial compressive strength
F_y : Yielding stress of steel
I_x : Moment of inertia about x-axis
k : Distance from the mean to the lower percentile in terms of standard deviates
M_a : Allowable moment
n : Number of members in the system
n : Transformed area conversion factor
P : Fastener capacity
Q : First moment of area about x-axis
S_x : Section modulus about x-axis
V : Shear force
w : Distributed load
$\bar{X}$: Allowable bending stress using averaging model