

Residential Hip Roof Framing Using Cold-Formed Steel Members

RESEARCH REPORT RP06-2

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PREFACE

The objectives of this project were to investigate a more rational rafter design methodology for both gable and hip roofs and develop all the necessary tables, details and specification requirements for hip roof framing members and connections for addition to the *AISI Standard for Cold-Formed Steel framing – Prescriptive Method for One and Two Family Dwellings [Prescriptive Method]*. This report accomplishes these objectives, provides useful insight and suggests future study topics that should assist in identifying and prioritizing future research needs.

It is expected that portions of this report will indeed be incorporated in the *Prescriptive Method*. As such, the results of this work will have a lasting and beneficial impact on the steel-framed residential construction industry.

Research Team
Steel Framing Alliance

Final Report

**RESIDENTIAL HIP ROOF FRAMING USING COLD-FORMED STEEL
MEMBERS**

by

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PREFACE

Cold-formed steel is continuing to increase in popularity in the residential construction market and is gaining an increasing market share compared with other construction materials. Conventionally framed roof construction uses rafters, ridge members, and ceiling joists and does not include any supplemental interior ridge member supports or collar ties between rafters although ceiling joists may be supported by an interior bearing wall. At hip ends, conventionally framed construction uses hip members and jack rafters, and ridge member support braces are also commonly used. Section R802.3 of the International Residential Code (ICC 2003) states “Hip and valley rafters shall be supported at the ridge by a brace to a bearing partition or be designed to carry and distribute the specific load at that point.” Conventional framing has traditionally been used in light framed wood structures and more recently in roofs framed with cold-formed steel members.

The American Iron and Steel Institute developed the *Standard for Cold-Formed Steel Framing – Prescriptive Method for One and Two Family Dwellings* (AISI 2002). This Standard is useful for the design of residential projects because it allows standard one and two story residential structures to be designed without the services of an architect or structural engineer. The current edition of the *Prescriptive Method*, however, does not address the design of the members necessary to construct hip roofs. Accordingly, the AISI Committee on Framing Standards (COFS) determined that research should be carried out to develop all the information necessary to allow for the construction of hip roofs using the *Prescriptive Method*. One of the objectives of this study was to investigate a more rational rafter design methodology for both gable and hip roofs. A second objective was to develop all the necessary tables, details and specification requirements for additions to the *Prescriptive Method*, and the *Commentary to the Prescriptive Method* for hip roof framing members and connections.

This report is based mainly on a thesis submitted to the Faculty of the Graduate School of the Kansas State University in partial fulfillment of the requirements for the degree of Masters of Science in Architectural Engineering.

Technical guidance for this study was provided by the Steel Framing Alliance's Project Monitoring Task Group (Bill Babich, Nader Elhajj, Steve Fox, Dick Layding, and Steve Walker), and the American Iron and Steel Institute's Prescriptive Method Subcommittee (Steve Fox, Chairperson). The Project Monitoring Task Group and the Subcommittee's guidance is gratefully acknowledged. Appreciation is also extended to Jay Larson, AISI for his guidance and assistance. Partial funding for this study was provided by the American Iron and Steel Institutes. The authors extend their appreciation to AISI for the financial support.

1.0 Analysis of Hip Roof System

1.1 Analysis Procedure

The purpose of this portion of the report is to provide details of a finite element analysis that was conducted to investigate the interaction of plywood sheathing with a typical rafter. The goal was to determine what contribution the sheathing makes in the distribution of forces to other members in the framing system. The current method of analysis for conventionally framed roof rafters, whether of wood or cold-formed steel, is to ignore compressive forces and design the rafter for bending only (AFPA 2001a, AISI 2003). Rafters are designed as individual pieces, neglecting any strength and stiffness contribution of the sheathing other than to provide restraint against lateral-torsional buckling. However, a simple two dimensional analysis of the rafter in combination with the ceiling joist and the rafter on the opposite side of the ridge to form a truss type framing system, as show in Figure 1.2, shows that a compression force is developed in the rafters. It should also be noted that the lower the slope of the rafter, the greater the axial compression in the rafters.

An unsupported hip roof system does not provide direct support, via either columns or bracing, for the hip and ridge members. Because of this, the structural support for these members is provided by the rafters that frame into them, the ridge member being supported by the side rafters, and the hip rafters being supported by the jack rafters.

1.1.1 Model Development

Computer models of two different sloped hip roofs were developed for analysis utilizing RISA-3D (RISA 2005) analysis and design software. Both sheathed and unsheathed models were built. All hip roof systems were analyzed assuming a 32 ft. x 60 ft. rectangular building with a 2 ft. roof overhang around the perimeter of the roof (Figures 1.1 and 1.2). The horizontal rafter span was 16 ft. from the centerline of the ridge to the outside face of the wall. The rafters were spaced at 24-

inches on center, the most common spacing for roof rafters. The ceiling joists were also spaced at 24-inches and were pinned to the rafter at the top of the wall. Roof slopes of 3:12 and 10:12 were analyzed. A 3:12 roof slope is the minimum allowed when using the *Prescriptive Method* (AISI 2003) and 12:12 is the greatest slope allowed. The 10:12 slope model was selected for analysis since it was assumed to be more common for high sloped roofs.

All members were modeled with simple pin-pin connections. The hip members and ridge members were modeled as a built-up section consisting of a C-shape and a track section (Figure 1.3). The hip members and ridge were assumed continuous for their full length. The ceiling joists were supported at mid-span by an interior bearing wall and were assumed continuous over the interior support. Table 1.1 lists the different member sizes used for analysis of all roof models. The member designations used in the table are in accordance with the *Standard for Cold-Formed Steel Framing – General Provisions* (AISI, 2004).

The perimeter walls were assumed to provide vertical support for gravity load from the roof rafters and ceiling joists. They also were assumed to have sufficient in-plane stiffness to provide lateral restraint for the roof and ceiling members in the plane of the wall. The walls were not assumed to provide any lateral support in the out-of-plane direction at the top of the wall for the roof and ceiling framing members. The wall itself was not included in the model for analysis; however, the continuous top track of the wall was included in the model (Figure 1.4). This member provided a tie in what would be the plane of the wall, just as in an actual structure.

The loading applied to all roof framing models were dead and snow loads. The dead loads applied were those currently assumed in the *Prescriptive Method* and taken from Table A1-1. The *Prescriptive Method* can be used for snow loads up to 70 psf ground snow load. For this study, a 30 psf ground snow load was assumed since it represents a practical maximum for many portions of the

United States. Wind loads were not considered for this study. Figure 1.5 shows the method used for load application to the rafters. A description of the loads used for this study is given as follows:

Roof Dead Load	7 psf
Ceiling Dead Load	5 psf
Ground Snow Load	30 psf (21 psf roof snow load on the projected area)

1.1.1.1 Unsheathed Model

The first set of models with 3:12, and 10:12 roof slopes, were analyzed without including structural sheathing. As previously stated, it is common practice to neglect any contribution of roof sheathing when designing the framing members except to prevent lateral-torsional buckling of the rafter. This is usually done to simplify analysis and design and is assumed not to add undue conservatism.

1.1.1.2 Sheathed Model

The *Prescriptive Method* requires the use of wood structural panel for roof sheathing applied directly to the top of the rafters. Wood structural panel sheathing was modeled as plate elements in RISA3D. The individual plate elements were applied as ½-inch thick 4 ft. by 8 ft. sheets which is the actual size of panels used for roof sheathing. It was assumed the sheathing layout would begin at the eaves, with the long direction of the sheet perpendicular to the rafters and continue along the slope up to the ridge. The properties of the structural panel sheathing used in the model are given in Table 1.2. The attachment of the sheathing was assumed to be in accordance with Table F2-10 in the *Prescriptive Method*.

The 4 x 8 foot rectangular plate elements were initially sub-meshed into 2 ft. x 1 ft. rectangular sub-plate elements but then later reduced to 1 ft. x 1 ft. sub-plate elements. After analyzing a number of models, it was determined that by using 1 ft. square sub-plate elements, some

of the inconsistencies experienced with the larger mesh were reduced. The areas at the hips were completed with triangular and non-regular quadrilateral plates as shown in Figure 1.6.

The sub-plate elements themselves were attached at their corners. They were connected to provide continuity, thereby transferring all shear forces, axial forces, and bending moments between adjacent sub-plate elements. The sub-plate elements were directly attached to the rafters, and were considered to be attached at the mid-height centerline of the rafters. This prevented any unintentional composite action between the sheathing and the rafters in bending, even though the sub-plate elements were also connected to provide continuity at all joints along the rafters. The connections to the hip and ridge members, however, did require a different approach.

It was determined the plate elements could not be attached directly to the hip members or the ridge member because RISA-3D was treating the connection between the plate elements on either side of the ridge or hip as fixed. This configuration caused the rafters to act as if they were continuous over the support and thereby producing moment in the rafter at the supports. The solution to this problem was to use very short but very stiff beams to connect the plate element to the hip members and ridge at the same locations where the rafters also connected to the hip and ridge members. These stiff beams were connected to the plate elements to provide continuity, while being pin connected to the hip or ridge members. This configuration approximated a pinned connection from the plate to the hip or ridge, allowing a transfer of shear and axial force without producing moment in the rafter. These additional stiff beam members were 0.02 ft. long (RISA-3D's smallest increment of noticeable change between nodes), and connected in-plane with the plate elements (Figure 1.7). This was done to prevent coplanar errors within the solution. Figure 1.8 shows the final model of the 1 x 1 foot plate mesh layout.

1.1.2 Results of RISA-3D Analysis

The primary focus of this study was to assess the effect sheathing has on forces for typical rafters. A typical rafter in these models is defined as one which frames into the ridge member on one end and is supported at the other on one of the 60-foot long walls. This rafter in combination with the ceiling joist and the rafter on the opposite side of the ridge form a truss type framing system as shown in Figure 1.2. Forces in the typical rafter include axial compression, bending and shear. The hip members are supported at the building corners and span to the ridge at 45 degrees to the typical rafters. The hip members support the jack rafters both along the end and the side walls.

1.1.2.1 Unsheathed Model Results

The results from the 3:12 and 10:12 unsheathed models are summarized in Table 1.3 and provide axial force and bending moments for six of the typical hip roof framing members as shown in Figures 1.9.and 1.10.

1.1.2.1.1 3:12 Model

For this roof slope, there were significant axial forces developed within all structural members investigated. The typical rafter M42 had an axial compression force of 2.60 kips at 1.9 feet from the cantilevered (lower) end. Its maximum moment was 31.99 kip-inches at 10.63 feet from the cantilevered end. The axial compressive force to be used for design is at the section of maximum moment. Because the maximum axial force in the member decreases from the wall support to the ridge connection, the maximum moment does not occur at the same cross-section as the maximum axial force. The axial compression force at the point of maximum moment was 2.43 kips. The hip member had significant bending of 192.48 kip-inches combined with an axial compressive force of 6.62 kips.

1.1.2.1.2 10:12 Model

The 10:12 model results also showed significant axial force present in all structural members investigated. As expected, the axial force present in the typical rafter was reduced by more than 40% from 2.60 kips to 1.57 kips due to the increase in slope. The hip had significant bending moment combined with axial compression but these forces were reduced by about 25% in bending and over 50% in axial compression from the 3:12 model. The typical rafter, M113, had a maximum axial compression of 1.56 kips at 2.7 ft. past the cantilevered end. The maximum moment was 33.71 kip-inches at 13.42 ft. from the cantilevered end, with a concurrent axial force of 1.10 kips. The typical hip member, M35, had a bending moment of 147.18 kip-inches at 17.2 ft. from its cantilevered end, with an axial force of 1.93 kips.

1.1.2.2 Sheathed Model Results

The results from the 3:12 and 10:12 sheathed models are summarized in Table 1.4 and provide axial force and bending data for six of the typical framing members shown in Figures 1.11 and 1.12. The typical rafter was of primary concern in this analysis; however other members are included to show the effect sheathing has on the entire roof system.

1.1.2.2.1 3:12 Model

For this roof slope, bending moments in the rafters (typical and jack) were essentially unchanged from the unsheathed models, however, axial compression was significantly reduced. Member forces are shown in Table 1.4. The maximum moment in the hip members was only about 7 kip-inches combined with an axial compression force of 2.5 kip.

1.1.2.2.2 10:12 Model

Similar to the unsheathed model, moment in the rafters did not change appreciably between the 3:12 and 10:12 models; however, axial compression was reduced significantly as expected. For the hip member both moment and axial compression was reduced by well over 50%.

1.2 Comparison of Unsheathed and Sheathed Roof Framing Systems

1.2.1 Analysis Summary and Comparison

Table 1.5 summarizes the results between the sheathed and unsheathed models. The results indicate the inclusion of sheathing greatly reduces the axial compression in the typical rafters. Including the sheathing in the analysis also significantly reduces bending moment in the hip and ridge members, while also reducing the axial compression.

Comparison of the unsheathed and sheathed roof systems shows that the roof system acts more as a stiffened shell, rather than as individual members acting independently. Rafters and the hip members share the axial forces with the sheathing. In general, the sheathing acts to distribute axial forces more evenly between the rafters and hip members. Both roof slopes showed over 50% reduction in axial compression in the side rafters at the point of maximum bending due to the contribution of the structural sheathing. There was also a 35-40% reduction in the maximum axial compression in the side rafters. Figures 1.13 through 1.16 are provided as a graphical representation of the relative axial force and moment distributions for the 3:12 slope model for both the unsheathed and sheathed conditions. There is no correlation of relative magnitude between figures, only between members of each figure.

1.3 Conclusions

It is apparent from the results of this preliminary study there is an interaction between the wood structural panel sheathing and the cold-formed steel framing members of the hip roof system. Through the inclusion of sheathing in the analysis of the roof framing system, axial forces are distributed between the sheathing, rafters and hip members. The result is a lower axial force present in the rafters and lower axial and bending forces in the hip members. The main advantage for considering sheathing to act together with the framing members is that the rafters and hip members

can be designed as much smaller members, thereby reducing the cost of construction. Current design methodologies for both wood and cold-formed steel roofs framed with rafters do not consider any contribution of the roof sheathing. These roofs are shown to be typically unconservative when a rational analysis approach is used. Since current design methodologies are simplified and unconservative, it is apparent that in reality, the sheathing is acting with the framing members to provide the additional margin of safety and prevent a wide spread failures of this type of roof framing system.

1.4 Recommendations for Further Research

Based on the conclusions drawn from the results of this study, it is apparent the sheathing in conventionally framed roof systems works in conjunction with the rafters as a structural system to resist applied loads. The results indicate that the sheathing has the effect of reducing axial forces in rafters and hip members. Further investigation is required to fully quantify the contribution and of the sheathing and derive a design methodology that accurately models the system behavior and can be easily used for design. Items for further research should include:

- Additional analysis for models with different roof slopes, building widths and load combinations. This is needed to develop a clearer understanding of force distribution and the effect of different slopes, spans and loads on force distribution.
- Develop models for gable roofs to determine if the sheathing provides the same advantage as it appears to for hip roofs.
- Determine connection requirements between the wood structural panel sheathing and the cold-formed steel rafters.
- Determine minimum wood structural panel sheathing material properties required.

- Develop the design methodology that correctly predicts the behavior of the sheathing and the cold-formed steel members for the hip roof framing system. The design methodology should cover design of the sheathing, rafters, hip members, ridge member and connections between the sheathing and supporting members.

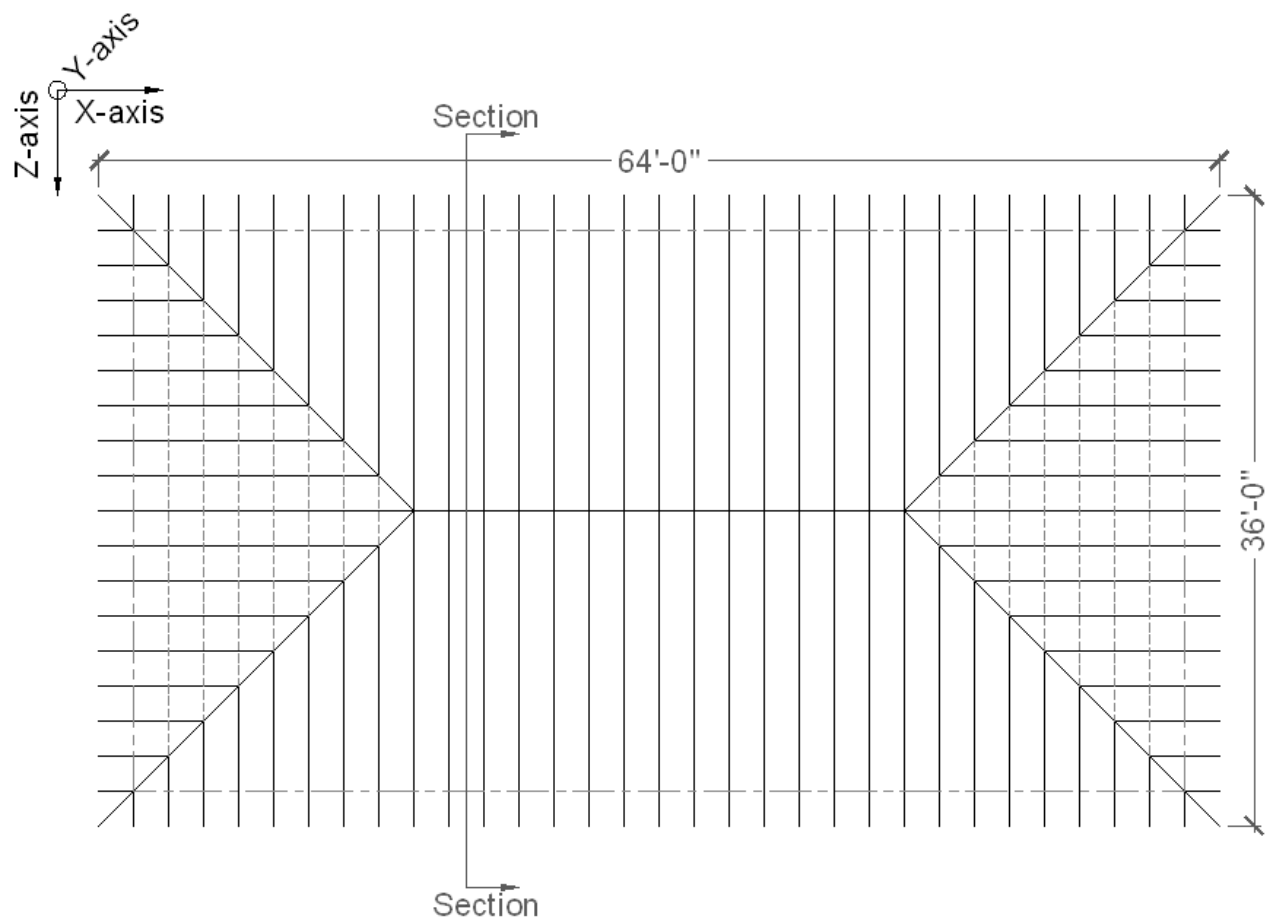


Figure 1.1: Study model roof framing plan

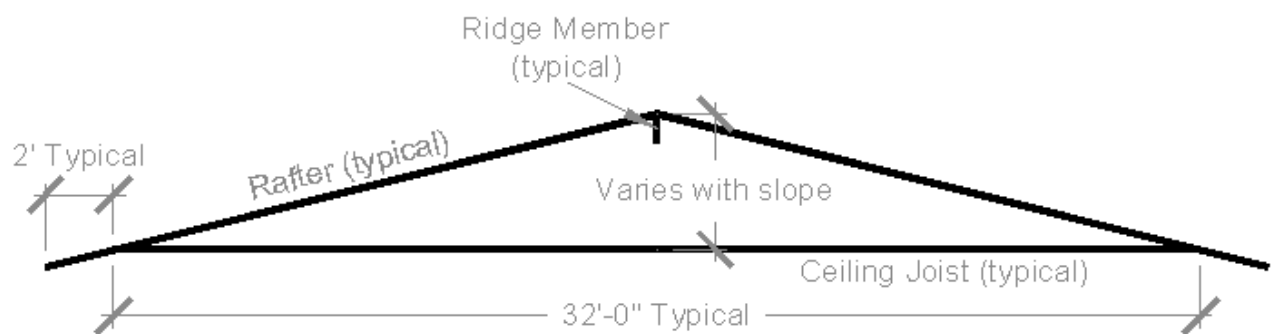


Figure 1.2: Section through roof of study model

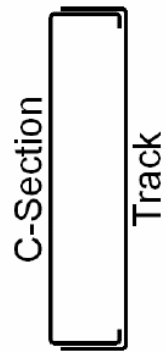


Figure 1.3: Typical hip and ridge member configuration

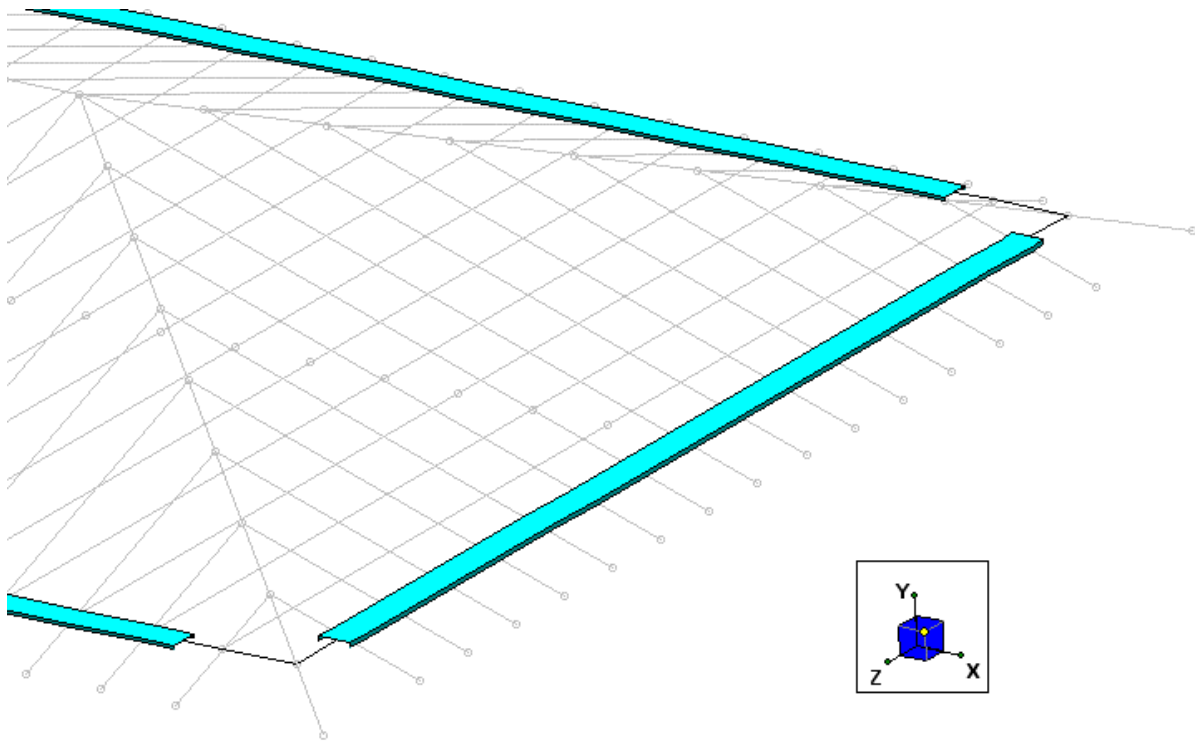


Figure 1.4: Configuration of wall track for computer model