Structural bracing of wooden roofs under the extreme winds

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Abstract. An essential element of every building is a roof that protects it against the influence of weather conditions - rainfall, wind, and temperature changes. The shape of the roof, the type of roof covering, and the slope of the roof have the greatest impact on the type and material solutions. The roof structures are made of wooden, steel, or reinforced concrete. Especially in single-family residential buildings, wooden roof structures are most often used. Wood is perceived by many as the oldest and best building material, valued for its low weight, good strength, elasticity, and high thermal and insulation values. Traditional roof has been used over the centuries. The more common roof in wood framing roof is gable and hip roof which is consist of rafter, ridge, hip, collar tie and joist. The common slop for hip roof is 3/12 to 12/12. By increasing the slop, the length of the hip element in roof increases and needs to brace closely. The aim of the study is to analyse the location of roof braces in hip roof structures, due to the ultimate and serviceability limit states, under dead, live and wind loads based on finite element method model. Two wind speeds of 22 m/s and 40 m/s is taken into consideration. Elements with the different spans, cross-sections and slope of the roof are analysed.

1. Introduction
Wood framing is the most popular structural framing for residential, commercial building in north America and part of Europe [1-3]. Stick framing is the most common wood framing which is consist of several element such as hip, ridge and rafter [4]. Roof in stick framing is usually sloped from 3 inches of rise per 12 inches of rafter length (3/12), to steep slopes of more than 12 inches per 12 inches of rafter length (12/12) to provide a sloping surface intended to shed snow or rain. Hip is structural member in the roof where two rafter areas join and it is 2 inches deeper than adjoining rafter [3], [5]. Due to IRC, IBC 2018, and NDSWC 2019, hip shall be braced at the ridge point [5-7]. The light wood framed houses are highly vulnerable to damage under the tornado and hurricanes [8-10]. Long unsupported structural member lengths are the reason of the damage among stick frame roofs based on prescriptive design requirements and visual inspection of the damage photos [11], [12]. In recent study, it was recommended to brace the hip closely [13].

Each time the wind load requires the analysis, according to design codes, e.g. [14]. There are cases when there is a need to individually determine the airflow parameters [15-21].

Since last years, the most attention has been focused on the phenomena and effects of strong winds [22]. The results of such load consist in destroying building structures, their elements and infrastructure.
The aim of the study is to analyze the location of roof braces for hip element in the roof due to the ultimate and serviceability limit states. Elements with the following different spans and cross-sections are analyzed for different slope of the roof. The effect of standard and extreme wind speeds acting on the roof structure is analyzed.

2. Model and numerical analysis
The multi-slope roof model presented in Figure 1 is analyzed. The work focuses on the corner element which is called HIP.

Figure 1. Multi-hipped roof 3D model. The hip under consideration is marked with a red circle.

In this way, the skeleton of the roof truss was created, consisting of two ridge tiles, six corner rafters and two valley rafters. The roof structure is based on the wall, placed on the wreath above the walls. The main design data include: the type of roofing material influencing the permanent load, cross-sections of elements - the cross-sections of wooden beams typical for a roof truss, the length of the corner rafter, and the angle of the roof slope.

Then, rafters with a cross-section of 38 x 154 mm were inserted into the model, at different spacing, to determine the maximal unsupported hip element. The example of a spacing is shown in Figure 2. The construction timber is the C-24 class according to [23].

Figure 2. Roof rafters inclined at an angle of 45° at 30 cm distance, as an example distance, adjacent to the corner rafter

In the next part, the analysis of the wind load is presented. Walls are added to the model to correctly apply the loads. The model is shown in Figure 3.
In the study, the analysis of the location of roof braces in hip roof structures, due to the ultimate and serviceability limit states, under dead, live and wind loads based on finite element method model is performed. Numerical simulations were made for two wind speeds of 22 m/s and 40 m/s. Elements with the different spans, cross-sections and slope of the roof are analyzed. The structure is loaded as for a concrete tiled and composite shingle roof, presented in Table 1.

Table 1. Load on the roof

| Covering | Dead [kN/m²] | Live [kN/m²] |
|----------|--------------|--------------|
| Concrete tile | 0.96 | 0.96 |
| Composite shingles | 0.48 | 0.96 |

Various ways of applying the load were considered: surface and point. Details are shown in Figure 4.

Figure 4. Methods of load application: a) distributed over the rafters - surface, b) concentrated, transferred from the rafters to the HIP - point.

The following models with the variables are created: the span of the hip beam, the sections, the angle of the roof slope. The individual values are shown in Table 2.
**Table 2.** Decision variables that defined individual models.

| Decision variables | Cases |
|--------------------|-------|
| Span [m]           | 2.67  3.27 7.35 14.7 |
| Cross-sections [mm] | 38x184 38x140 51x152 |
| Angle of the roof slope [°] | 35.26 45 |

2.1. Dead load and live load effects

The main criterion considered when selecting solutions were the values of forces and displacements, in particular: stresses, moments, shear forces, deflection. The comparison of the results depending on the variables is presented in Table 3. Load types are as shown in Figure 3.

Case 1-3 were achieved for the hip span supported on the ridge and wall directly, cases 4 to 17 were received for hip supported on the ridge and wall with additional rafters that reduces the unsupported span, as shown in figure 7.

**Table 3.** Calculation results of different models depending on decision variables.

| Case (gravity) | bxh [mm] | HIP length [m] | Length in projection [m] | α - roof angle [°] | β - HIP angle [°] | HIP type | σ [Mpa] | M [kNm] | T [kN] | u [mm] |
|----------------|----------|----------------|------------------------|-------------------|-----------------|----------|---------|---------|--------|--------|
| 1              | 38x140   | 2.67           | 1.54                   | 54.78             | 45              | Surface  | 10.85   | 1.31    | 2.15   | 4.6    |
| 2              | 51x152   | 2.67           | 1.54                   | 54.78             | 45              | Surface  | 6.89    | 1.31    | 2.16   | 2.6    |
| 3              | 38x184   | 2.67           | 1.54                   | 54.78             | 45              | Surface  | 6.35    | 1.31    | 2.15   | 2      |
| 4              | 38x184   | 2.67           | 2.18                   | 45                | 35.26           | Surface  | 6.99    | 1.46    | 2.54   | 2.2    |
| 5              | 38x184   | 2.26           | 1.85                   | 45                | 35.26           | Surface  | 3.95    | 0.82    | 1.76   | 0.9    |
| 6              | 38x184   | 2.35           | 1.92                   | 45                | 35.26           | Surface  | 4.82    | 1       | 1.95   | 1.2    |
| 7              | 38x184   | 3.78           | 2.67                   | 54.78             | 45              | Surface  | 17.42   | 3.63    | 4.53   | 10.6   |
| 8              | 38x184   | 3.27           | 2.67                   | 45                | 35.26           | Surface  | 14.38   | 2.74    | 3.35   | 8.5    |
| 9              | 38x184   | 7.35           | 6                      | 45                | 35.26           | Point    | 90.16   | 18.74   | 12.11  | 438    |
| 10             | 38x184   | 7.35           | 6                      | 45                | 35.26           | Point    | 6.34    | 0.7     | 2.28   | 3.3    |
| 11             | 38x184   | 14.7           | 12                     | 45                | 35.26           | Point    | 725.1   | 149.83  | 50.34  | 15617.3|
| 12             | 38x184   | 14.7           | 12                     | 45                | 35.26           | Point    | 23.08   | 2.01    | 8.15   | 18.5   |
| 13             | 38x184   | 14.7           | 12                     | 45                | 35.26           | Point    | 20.39   | 1.38    | 5.66   | 14.7   |
| 14             | 38x184   | 2.26           | 1.85                   | 45                | 35.26           | Surface  | 2.75    | 0.58    | 1.44   | 0.7    |
| 15             | 38x184   | 2.26           | 1.85                   | 45                | 35.26           | Surface  | 4.17    | 0.83    | 2.19   | 1.5    |
| 16             | 38x184   | 2.26           | 1.85                   | 45                | 35.26           | Surface  | 3.3     | 0.69    | 1.6    | 0.7    |
| 17             | 38x184   | 2.60           | 2.12                   | 45                | 35.26           | Surface  | 4.71    | 0.99    | 2.09   | 2.9    |

In the first group of results (cases 1-3), HIP beams with a 45.0° inclination were analyzed, which corresponds to a roof slope of 54.78°, for comparable internal forces - moment 1.31 kNm, shear force 2.16 kN. The load was transferred as an evenly distributed surface over the roof plane (surface). The maximum unsupported span of the element is 2.67 m. Due to the lower value of the cross-sectional height than the others in this group, a greater displacement of 4.6 mm was obtained for case no.1. Comparable results are also obtained for the roof slope of 35.26° (case 4).

Case 5 and 6 is a continuation of the analysis resulting from cases 4 and earlier relating to the 38x184 cross-section and the 45° angle. The analysis concerns the optimization of internal forces in the element in relation to the constant and variable gravitational load as well as the wind load for cases 2 and 4.
The second group of analysis consists of the hips from cases 7 and 8, where the elements with the same cross-section, load type - surface and the same length in the projection (2.67 m), but with a different slope of the roof, respectively 54.78° (case 7) and 45° (case 8), that gives the actual lengths of the elements of 3.78 (case 7) and 3.27 m (case 8). The obtained results confirm the need for additional support of the structural element due to the increase in internal forces and displacements, confirming the correctness of the results from the first group. The maximum stress value is for these cases are 17.42 MPa and 14.38 MPa, respectively.

The third group is the analysis of elements with a span of 7.35 m and a slope of 45.0°. To limit the internal forces and displacements (case 9), additional rafters were introduced at 60 cm intervals (case 10). The stresses have decreased by more than fourteen times, while the displacements have decreased by 132 times.

The fourth group is the analysis of elements with a span of 14.7 m and a slope of 45.0°. To limit the internal forces and displacements (case 11), additional rafters were introduced at a distance of 60 cm (case 12).

Case 13 concerns roof analysis when hip is braced by rafters at 30cm spacing.

One example of the results of individual models is presented in Figure 5.

![Figure 5](image)

**Figure 5.** Results for case 1, a) stress [kPa], b) bending moments [kNm], c) shear forces [kN], d) deflections [mm]

### 2.2 Wind load effects

In the analysis the base wind speed of 22 m/s and 40 m/s is taken into consideration. One example of the results is presented in Figure 6.
Figure 6. Results for wind load, HIP, case A, a) stress [kPa], b) bending moments [kNm], c) shear forces [kN], d) deflections [mm], V=22 m/s

Results from wind load analysis are presented in the Table 4. This table concerns the analysis of the impact of the wind speed 22 m/s and the speed 40 m/s. Case groups A, C, E concern optimization of internal forces in an element with a cross-section of 38 x 184 and an angle of 45°, under a total vertical total constant and variable load and wind v = 22 m/ s. The purpose of the analysis is to find an element with a maximum unsupported span and a stress not exceeding 7.2 MPa. This condition is fulfilled for a span of 2.26 m (6.1 MPa). For a span of 2.35 m, the total stress is 7.64 MPa. The sum of the results is summarized in the table 5.

Table 4. Calculation results for wind loads of various models depending on decision variables

| Case (wind) | b x h [mm] | HIP length [m] | Length in projection [m] | α - roof angle [°] | β - HIP angle [°] | Load type | σ [MPa] | M [kNm] | T [kN] | u [mm] |
|-------------|------------|----------------|-------------------------|-------------------|------------------|-----------|---------|---------|-------|-------|
| A           | 38x184     | 2.26           | 1.85                    | 45                | 35,26            | Wind 22   | 2.15    | 0.18    | 0.39   | 2.6   |
| B           | 38x184     | 2.26           | 1.85                    | 45                | 35,26            | Wind 40   | 6.72    | 0.49    | 1.04   | 8.2   |
| C           | 38x184     | 2.35           | 1.92                    | 45                | 35,26            | Wind 22   | 2.82    | 0.22    | 0.43   | 2.9   |
| D           | 38x184     | 2.35           | 1.92                    | 45                | 35,26            | Wind 40   | 9.6     | 0.74    | 1.46   | 9.6   |
| E           | 38x184     | 2.67           | 2.18                    | 45                | 35,26            | Wind 22   | 3.79    | 0.32    | 0.56   | 4.7   |
| F           | 38x184     | 2.67           | 2.18                    | 45                | 35,26            | Wind 40   | 12.68   | 1.08    | 1.89   | 15.4  |
| G           | 38x184     | 2.26           | 1.85                    | 45                | 35,26            | Wind 22   | 2.48    | 0.14    | 0.28   | 3     |
| H           | 38x184     | 2.26           | 1.85                    | 45                | 35,26            | Wind 22   | 2.59    | 0.19    | 0.5    | 3.1   |
| J           | 38x184     | 2.26           | 1.85                    | 45                | 35,26            | Wind 22   | 1.85    | 0.15    | 0.35   | 2.2   |
| J           | 38x184     | 2.60           | 2.12                    | 45                | 35,26            | Wind 22   | 2.32    | 0.21    | 0.44   | 2.1   |
Table 5. Sum of the results.

| wind load | dead+live loads | HIP length [m] | Load type | σ [Mpa] | M [kNm] | T [kN] | u [mm] |
|-----------|-----------------|----------------|-----------|---------|---------|--------|-------|
| 5         | 2.26            | Surface        | 3.95      | 0.82    | 1.76    | 0.9    |
| A         | 2.26            | Wind 22        | 2.15      | 0.18    | 0.39    | 2.6    |
| B         | 2.26            | Wind 40        | 6.72      | 0.49    | 1.04    | 8.2    |
|           | Σ for 22:       | 6.1            | 1.21      | 2.15    | 3.5    |
|           | Σ for 40:       | 10.67          | 1.31      | 2.8    | 9.1    |
| 6         | 2.35            | Surface        | 4.82      | 1.16    | 1.85    | 1.2    |
| C         | 2.35            | Wind 22        | 2.82      | 0.22    | 0.43    | 2.9    |
| D         | 2.35            | Wind 40        | 9.6       | 0.74    | 1.46    | 9.6    |
|           | Σ for 22:       | 7.64           | 1.22      | 2.38    | 4.1    |
|           | Σ for 40:       | 14.42          | 1.74      | 3.41    | 10.8   |
| 4         | 2.67            | Surface        | 6.99      | 1.46    | 2.54    | 2.2    |
| E         | 2.67            | Wind 22        | 3.79      | 0.32    | 0.56    | 4.7    |
| F         | 2.67            | Wind 40        | 12.68     | 1.08    | 1.89    | 15.4   |
|           | Σ for 22:       | 10.78          | 1.78      | 3.1    | 6.9    |
|           | Σ for 40:       | 19.67          | 2.54      | 4.43    | 17.6   |

2.3. Unsupported length
In the last part of the analysis, the effect of introducing additional rafters, reducing the total unsupported length of the element, was checked. The rafters were introduced in various ways, as shown in Figures 7. Table 6 shows the stress results for the models without additional support and with support.

![Figure 7. Bracing model](image)

Figure 7 a, b, c show different ways of supporting the HIP using additional rafter elements. The obtained results were compared with models of the corresponding unsupported total length. Cases 14, G refer to the diagrams shown in figure 7a for vertical loads and wind loads, respectively, while cases 15 and H refer to the diagrams shown in figure 7b for vertical loads and wind loads, respectively. Cases 16, 17, I and J refer to the diagrams shown in figure 7c, for vertical loads and wind loads, respectively. The analyses are presented for hip. Smaller internal forces and displacements were obtained for the schemes shown in figure 7a due to the support of the hip in the place of the highest loads. The summary results are shown in table 6.
The final purpose of the analysis is to find an element with a maximum unsupported span and a stress not exceeding 7.2 MPa with application of additional rafters that brace the hip. Besides case I, this condition is fulfilled for the cases III, IV, V – unsupported hip length of 2.26, maximum stresses of 5.23 MPa, 6.76 MPa and 5.15 MPa respectively, and for the case VI - unsupported hip length of 2.60, maximum stresses of 5.03 MPa (table 6).

Table 6. The results held were compared with models of the corresponding unsupported length

| Summary | Wind load | Dead-live loads | HIP length [m] | Total unsupported length | Load type | σ [Mpa] | M [kNm] | T [kN] | u [mm] |
|---------|-----------|-----------------|----------------|--------------------------|-----------|---------|---------|--------|--------|
| I       | A         | 5               | 2,26           | 2,26                     | Surface   | 3.95    | 0.82    | 1.76   | 0.9    |
|         |           |                 |                |                          | Wind 22   | 2.15    | 0.18    | 0.39   | 2.6    |
|         |           |                 |                |                          | Σ         | 6.1     | 1       | 2.15   | 3.5    |
| II      | E         | 4               | 2,67           | 2,67                     | Surface   | 6.99    | 1.46    | 2.54   | 2.2    |
|         |           |                 |                |                          | Wind 22   | 3.79    | 0.32    | 0.56   | 4.7    |
|         |           |                 |                |                          | Σ         | 10.78   | 1.78    | 3.1    | 6.9    |
| III     | G         | 14              | 2,26           | 2,26                     | Surface   | 2.75    | 0.58    | 1.44   | 0.7    |
|         |           |                 |                |                          | Wind 22   | 2.48    | 0.14    | 0.28   | 3      |
|         |           |                 |                |                          | Σ         | 5.23    | 0.72    | 1.72   | 3.7    |
| IV      | H         | 15              | 2,26           | 2,26                     | Surface   | 4.17    | 0.83    | 2.19   | 1.5    |
|         |           |                 |                |                          | Wind 22   | 2.59    | 0.19    | 0.5    | 3.1    |
|         |           |                 |                |                          | Σ         | 6.76    | 1.02    | 2.69   | 4.6    |
| V       | I         | 16              | 2,26           | 2,26                     | Surface   | 3.3     | 0.69    | 1.6    | 0.7    |
|         |           |                 |                |                          | Wind 22   | 1.85    | 0.15    | 0.35   | 2.2    |
|         |           |                 |                |                          | Σ         | 5.15    | 0.84    | 1.95   | 2.9    |
| VI      | J         | 17              | 2,60           | 2,60                     | Surface   | 4.71    | 0.99    | 2.09   | 2.9    |
|         |           |                 |                |                          | Wind 22   | 2.32    | 0.21    | 0.44   | 2.1    |
|         |           |                 |                |                          | Σ         | 7.03    | 1.2     | 2.53   | 5      |

3. Conclusions
The obtained results were compared with models of the corresponding unsupported total length. Cases 14, G (table 4 - wind load) refer to the diagrams shown in figure 7a for vertical loads and wind loads, respectively, while cases 15 and H (table 4 - wind load) refer to the diagrams shown in figure 7b for vertical loads and wind loads, respectively. Cases 16, 17, I and J (I and J, table 4 - wind load) refer to the diagrams shown in figure 7c, for vertical loads and wind loads, respectively. The analyzes are presented for hip and valley elements. For hip, smaller internal forces and displacements were obtained for the schemes shown in figure 7 due to the support of the hip in the place of the highest loads. The comparable internal forces and deflections for the valley result from the comparable values of the loads acting on the valley.

The conducted analysis shows that it is necessary to support the hips, apart from the ridge and the support on the wall, in the case of roof slope of 45°, the length of the element longer than 2.26 m and for the tile roofs, under dead, live and wind loads. In the case of extreme wind load of 40 m/s the bracing in the distance of 2.26 is insufficient and will be the subject of further analysis, the results of which will be presented in the next article.
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