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RAFTER STRUCTURE ANALYSIS USING WEB-TAPERED STEEL MEMBERS WITH THE FINITE ELEMENT METHOD

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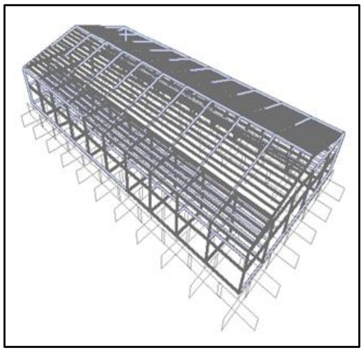
Graphical Abstract



Abstract
Building design using steel materials that generally use prismatic cross-sections can be modified with a modified cross-section with the aim of cutting costs. This research was conducted with the aim of modifying an existing structure of the building, which are in the form of a steel construction with prismatic members, to replace it with a modified web-tapered steel members. Design analysis is conducted based on the results of modeling output on SAP2000 and numerical analysis based on SNI standards and applicable AISC's Steel Design Guide books. This paper will show the stages of analysis, calculation, section capacity, and the cross-sectional size of the design results of the structure.

Keywords: Modified Design, SAP2000, Web-Tapered Steel, SNI, AISC

1. INTRODUCTION

In recent decades, the application of tapered steel members—also known as non-prismatic sections—has gained significant attention in structural engineering, especially for portal frames. These members are characterized by varying cross-sectional dimensions along their length, allowing designers to match structural capacity more closely to internal force demands. This results in more efficient material usage, improved aesthetic appeal, and optimized stress distribution compared to conventional prismatic members. Such benefits make tapered members particularly suitable for long-span, single-story structures such as warehouses, workshops, and hangars, where reducing self-weight and cost is critical without compromising strength or stability.

Despite these advantages, the structural behavior of tapered steel members is more complex than that of uniform sections. Their geometric variability introduces additional challenges in design and analysis, particularly under combined loading scenarios. Many existing design codes and traditional calculation methods assume prismatic sections and are not directly applicable to tapered members. As a result, structural engineers must rely on advanced computational tools and accurate modeling techniques to predict their behavior effectively. This creates a gap between practical application and theoretical understanding, especially in regions or practices where simplified assumptions are still widely used.

Several studies have explored the use of tapered members in portal frames, focusing on optimization, stress distribution, and performance under various loading conditions. Researchers have shown that finite element analysis (FEA) is an effective method for capturing the non-linear and non-uniform responses of tapered structures. As Quan et al. (2020) highlight, "a consistent design approach, performed by second-order inelastic analysis using beam finite elements with strain limits, is proposed for web-tapered steel members… [where] the ultimate strength of the member is signified by reaching either the strain limit defined according to the Continuous Strength Method (CSM) or the peak load factor, whichever occurs first." [1]. Software like SAP2000 enables the modeling of such effects by incorporating geometric nonlinearity, second-order analysis, and material variation, offering a more realistic simulation of structural performance. However, there remains limited focus specifically on the detailed analysis of rafter components within such systems using web-tapered profiles, despite their critical role in resisting bending and ensuring frame stability.

This research addresses the need for a more in-depth investigation into rafter structures utilizing web-tapered steel members. By employing finite element methods via SAP2000, the study aims to simulate realistic loading scenarios and evaluate structural performance with greater accuracy. The focus is placed on how tapered geometry influences stress distribution, deflection behavior, and overall structural efficiency, particularly in the rafter segments of portal frames. The use of computational tools also allows the study to explore variations in cross-sectional geometry and span configurations systematically.

The primary innovation of this research lies in its focused analysis of web-tapered rafter structures using finite element modeling, which bridges the gap between generalized portal frame studies and the specific structural role of rafters. While tapered elements are not a new concept, applying them with precision modeling in critical frame components such as rafters provides novel insights into optimizing both material usage and structural performance. This work contributes to the broader field by enhancing design recommendations and encouraging the practical application of tapered steel members in industrial-scale buildings where cost-efficiency and spatial clarity are paramount.

2. METHOD

This research was conducted by modeling a steel portal frame structure using the SAP2000 structural analysis software to evaluate the performance of rafter elements designed with web-tapered steel members. The object of the study is an industrial-type building with a portal frame system modeled after the workshop-warehouse building at Jakabaring Sports City. The modeling was based on architectural working drawings and applied standards for materials, section properties, and loading requirements. As noted by Lamkhade et al. (2019), “web tapered portal frames are on average 30% lighter through efficient use of steel… designed as per the bending moment diagram obtained.” [2] This aligns with this study's approach in optimizing material efficiency through tapered geometry. Additionally, as highlighted by Kamesh & Prabha (2020), “Web-tapered members are widely advocated as a cost-effective alternative to conventional structural sections for portal frames,” [3] further justifying their use in this project.

The building layout used in the model includes a span of 60 meters (10 × 6 m modules), a width of 30 meters (5 × 6 m modules), a ground floor height of 4 meters, a clearance height of 8 meters, and a total height of 13.03 meters. The roof has a pitch angle of 18°32’16.87”. Two types of steel materials were applied in the model: ASTM A572 Grade 50 for built-up sections (with yield strength Fy = 345 MPa and tensile strength Fu = 490 MPa), and ASTM A653 SQ Grade 33 for cold-formed sections (Fy = 228 MPa, Fu = 310 MPa). The cross-sections were selected from the Sections8.Pro database for built-up profiles and the AISI Cold-Formed Steel Properties database for cold-formed elements.

The structural loads applied include dead loads, live loads, wind loads, and seismic loads. Dead loads consisted of the self-weight of structural members (automatically calculated by SAP2000), roofing (14.85 kg/m^2), walls (300 kg/m), and the second-floor slab (372 kg/m^2). Live loads were applied as 100 kg for the roof and 11.97 kN/m^2 for the second-floor slab. Wind loads were analyzed based on SNI 1727:2013 with a basic wind speed of 15 m/s (based on BMKG data for Palembang), exposure category B, and a roof slope of 18°32’16.87”. Pressure coefficients and velocity pressures were calculated using the standard procedure, and interpolated values were used where necessary. As demonstrated by Green & Chan (2021), “It was found that wind load has a significant effect on the optimisation compared to just the gravity load combination. Tapered sections were found to allow for additional weight savings (2–10% extra) compared to fabricated sections.” [4] This reinforces the need to evaluate the structural performance under wind conditions in this study.

Seismic loading was modeled using a response spectrum analysis based on SNI 1726:2019. The site is located in Palembang with coordinates 104.793177°E, -3.018589°S, classified as Site Class SE (soft soil). Seismic parameters were derived from the RSA software output provided by PUSKIM, resulting in values such as PGA = 0.149780g, Ss = 0.294535g, S1 = 0.249730g, and design spectrum parameters Sds = 0.446770g and Sd1 = 0.508009g. A total of 25 load combinations were used in accordance with SNI 1727:2013, covering dead, live, wind, and earthquake actions in various directions and combinations. As highlighted by Quan et al. (2020), an accurate structural performance assessment “is signified by reaching either the strain limit defined according to the Continuous Strength Method (CSM) or the peak load factor,” [1] validating the need for detailed and rigorous load case definitions in tapered frame analysis.

After modeling and applying the loads, SAP2000 was used to perform structural analysis and extract internal force results. These results were used to carry out design calculations for the rafter and column elements. The rafter analysis specifically focused on web-tapered steel profiles, assessing their structural efficiency, stress distribution, and deflection performance under combined loading. As supported by Shahmohammadi & Lim (2022), “beam elements are used to idealize the column and rafter members… deflections predicted using the beam idealization are shown to be comparable to deflections obtained from … full-scale laboratory tests," [5] which supports the element modeling strategy used in SAP2000. Advanced modeling concepts such as Timoshenko–Euler beam representation, as proposed by Chan & Yu (2018), [6] enable refined simulation of the tapered frame behavior.

Connection designs were developed based on member forces, followed by evaluation of overall system behavior. Final conclusions and design recommendations were derived from the performance of the proposed tapered rafter system under realistic building conditions.

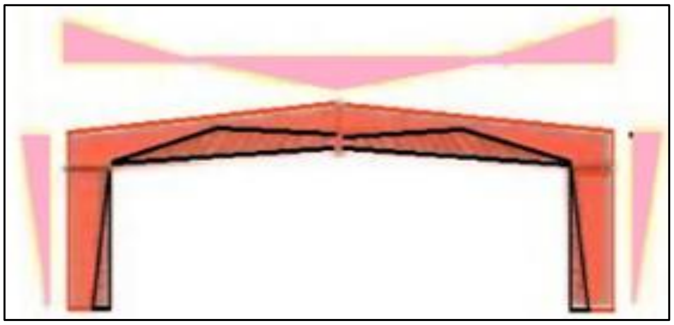


Figure 1. Use of Non-Prismatic Steel Member on bending moment (Firoz, 2012)

Data Koordinat

Lokasi: Palembang (P)

Bujur: 104.793177

Lintang: -3.018589

Results at Bedrock:

PGA: 0.149780

PGAm: 0.322191

Ss: 0.294535

S1: 0.249730

TL: 20.000000

Kelas: SE - Tanah Lunak

Figure 2. Building location for wind and seismic load analysis

3. RESULTS AND DISCUSSION

The analysis and design in this study were carried out following the procedures and equations recommended in the AISC Design Guide 25 [9] for tapered steel members. The rafter, modeled as a web-tapered steel beam, was divided into three distinct segments based on the moment envelope—two tapered sections (sections a and c) located near the supports, and one prismatic section (b) positioned at midspan, where the bending moment is relatively lower.

Based on the SAP2000 maximum and minimum moment envelopes, the internal force demands on each segment were obtained as follows:

Tapered sections (a & c): Mu = 554.59 kip-in, Pu = 13.78 kips, Vu = 3.88 kips

Prismatic section (b): Mu = 150.27 kip-in, Pu = 13.14 kips, Vu = 2.60 kips

Initial sizing from SAP2000 yielded a W14X34 section (depth = 14 in) for the tapered ends and a reduced W14X34-T section (depth = 8 in) for the prismatic midspan. Taper geometry verification showed a taper angle of 3°03′88″, which is well within the AISC-allowed maximum of 15°, confirming that the web-tapered configuration is acceptable for further strength evaluation.

The structural adequacy of each segment was evaluated through detailed checks of axial strength, flexural capacity, shear resistance, lateral-torsional buckling, and interaction effects using force-based criteria. Material compactness and slenderness ratios were also assessed. The properties of each section and the critical stress ratios were tabulated to confirm compliance. Calculations showed that all strength checks—including axial compression, flexure, and combined loading—were satisfied, with unity ratios well below the allowable limit (φPn, φMn, and φVn).

In addition to strength verification, deflection criteria were also evaluated. SAP2000 output indicated a maximum vertical deflection at midspan of 1.72 inches, which is less than the allowable deflection of 2.595 inches, calculated as L/240 based on total span length. This confirms that the structural system not only meets strength requirements but also serviceability limits. As emphasized by Clancy & Broderick (2007), "The portal frames should be pre-set carefully to ensure that all dead load deflections result in frames that line up with the gable frame under dead load only." [8] This reinforces the importance of satisfying deflection criteria in portal frame design.

The results demonstrate that the selected web-tapered rafter configuration is structurally safe and efficient for the applied loading combinations. A comprehensive summary of axial, flexural, shear, and combined interaction ratios is provided in the final recap table, validating the use of tapered steel members for industrial portal frames.

Table 1. Summary of Ultimate Load-to-Section Capacity Ratios

Member	Axial Strength Ratio	Flexural Strength Ratio	Combined Axial-Flexural Strength Ratio	Shear Strength Ratio
a & c	0.0399	0.311	0.351	0.036
b	0.347	0.328	0.639	0.042

4. CONCLUSION

This research has successfully conducted a comprehensive structural analysis and design evaluation of a steel portal frame system utilizing web-tapered steel members, with a particular focus on rafter behavior under multi-directional loading conditions. The modeling was performed using SAP2000, incorporating realistic material properties, cross-sectional configurations, and loading criteria in accordance with Indonesian national standards (SNI 1726:2019 and SNI 1727:2013) [10] [11] and the AISC Design Guide 25 [9] for tapered steel members.

The analysis results indicated that all critical sections met or exceeded strength requirements. The maximum axial strength ratio was 0.347, the maximum flexural strength ratio was 0.328, and the maximum combined axial-flexure strength ratio was 0.639—each well below the unity threshold of 1.0. Shear capacity was also satisfied with the highest ratio recorded at 0.042. In addition, the maximum midspan deflection of 1.72 inches was found to be within the allowable limit of 2.595 inches, thereby fulfilling the serviceability criteria for vertical displacement.

From the perspective of structural efficiency, the use of web-tapered members allowed material optimization by adapting section geometry to internal force variations, leading to a potentially lighter structure without compromising safety or stability. This aligns with findings in recent literature, where tapered sections were shown to improve performance by concentrating material where it is most structurally effective.

In conclusion, the application of web-tapered steel members in portal frame rafters—analyzed through finite element modeling using SAP2000 and designed in compliance with modern steel design provisions—has proven to be a structurally sound and materially efficient solution for long-span, single-story industrial buildings. The study validates the feasibility of using tapered geometries to reduce steel consumption while maintaining compliance with strength and deflection criteria, thus offering a viable alternative to conventional prismatic systems in similar architectural and structural contexts.

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