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Modeling Steel Deck Diaphragms Using Beam Element

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Abstract
This paper presents a study on modelling steel diaphragms using beam elements with the finite element software MASTAN2, in lieu of modelling with shell elements. The aim for this study was to (1) reduce computational resources; and (2) to model and analyse diaphragms using truss elements. Steel deck plays a critical role in structural stability through the ability of the deck to perform as a diaphragm. The goals of this study were to demonstrate the capability of truss elements for modelling steel deck diaphragms and to determine the minimum diaphragm stiffness to effectively brace joists against lateral buckling.

A prototype structure consisting of two bays of open-web steel joists with steel deck attached to the top chord was modelled. The joists are 50 feet (15.24 m) long and spaced 6 feet (1.83 m) apart. The steel deck is represented by pin-ended beam elements (truss elements) to simulate the in-plane stiffness of the deck. The effective stiffness of the diaphragm can be modelled by varying the cross sectional area of the beam elements. The methodology involved iterating stiffness values until reaching the threshold that prevented lateral buckling under gravity loading through a nonlinear elastic analysis. The analysis identified a minimum stiffness value of 0.45 kip/in per foot (0.55 kN/m) as sufficient to brace the steel joist and deck system against lateral buckling. This study highlights the practicality of using truss elements for modelling steel deck diaphragms, offering a fast and effective solution for both design and educational purposes.

1 Introduction

Open-web steel joist and deck systems are integral to the structural stability of buildings, providing a lightweight yet robust solution for spanning large distances. The steel deck acts as a diaphragm, resisting lateral loads and preventing buckling in the connected joists. Traditional approaches to modeling such systems often rely on shell elements for the diaphragm, which, while accurate, can be computationally intensive. This study investigates the feasibility of using beam elements as an efficient alternative for modeling steel deck diaphragms, aiming to reduce computational effort while maintaining accuracy.

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Some previous research has extensively explored stability requirements and bracing strategies for steel joist systems. For instance, Eberle et al. (2012) presented a computational study to optimize the stiffness requirements of bridging systems under various configurations, focusing on axial stiffness (β) and intermediate point bracing for individual joists. While their study examined discrete bracing points, this study emphasizes a continuous bracing system where the steel deck resists the total buckling demand of a three-joist layout through its shear stiffness (G).

In addition, research on continuous bracing systems for beams and columns provided foundational formulations for analyzing elastic and inelastic buckling behavior (Yura and Helwig, 2021). This framework informs the analytical solution in this study, allowing for comparison between computational and theoretical approaches. Unlike traditional point bracing, continuous bracing through the steel deck ensures uniform lateral stability across the system.

This paper demonstrates the practical advantages of using truss elements to model steel deck diaphragms and identifies the minimum effective stiffness required to brace the joists against lateral buckling. By combining computational analysis and analytical validation, this work highlights an efficient and accurate approach to modeling steel deck systems, reducing the need for high-fidelity finite element formulations such as shell or solid elements.

2 Finite element model Methodology

This section provides an in-depth exploration of the overall layout and modeling approach for the tested joist-deck steel system analyzed in MASTAN2. It begins with a description of the model set up, detailing the connection between the two primary system components. The modeling approach, utilizing line element formulation for both system members, is explained in detail. Inputs such as section types and distribution, material properties, boundary conditions, loading configuration, and key assumption are thoroughly illustrated. Finally, the analysis approach is outlined, emphasizing how the line element modeling captures the system's lateral buckling behavior and enables determination of the corresponding system stiffness.

2.1 Model Setup

The modeled system consists of two primary components: a hot-rolled open-web steel joist (OWSJ) and steel deck diaphragm. The system features three joists spaced 6 feet (1.83 m) apart, with the steel deck on top. A truss analogy was employed to represent the equivalent steel diaphragm layout. Details about each component are provided in Sections 2.1.1 and 2.1.2.

The model was created using nodes and line elements where nodes correspond to the centroid of the cross-sections. These nodes are connected by line elements to define the various system members. Fig. 1 illustrates the overall layout of the joist-deck system modeled in MASTAN2, highlighting its configuration at the final modeling stage.

The top chords of the joists are braced at every panel point provided by the line elements simulating continuous deck bracing on the joists. Vertical bracing (bridging) is provided at each end of the bottom chords. The system is simply supported, with one end of each joist having a pinned fixity and the other a roller fixity.

To simulate the diaphragm's behavior, truss elements are pin-connected to the joists top chord at every panel point, reflecting the equivalent connection type observed between joist and deck in real-world applications (Luttrell et al., 2015). A downward 300 plf (408 N/m) uniformly distributed load is applied along the top chord of each joist directed in the global vertical direction, simulating the transfer of load from the deck to the joists under real-world conditions.

A 150 lb (667 N) notional load, corresponding to one percent of the applied vertical distributed load, was applied at the mid panel point of each joist along the global Z-axis direction (lateral direction) to represent equivalent member imperfections.

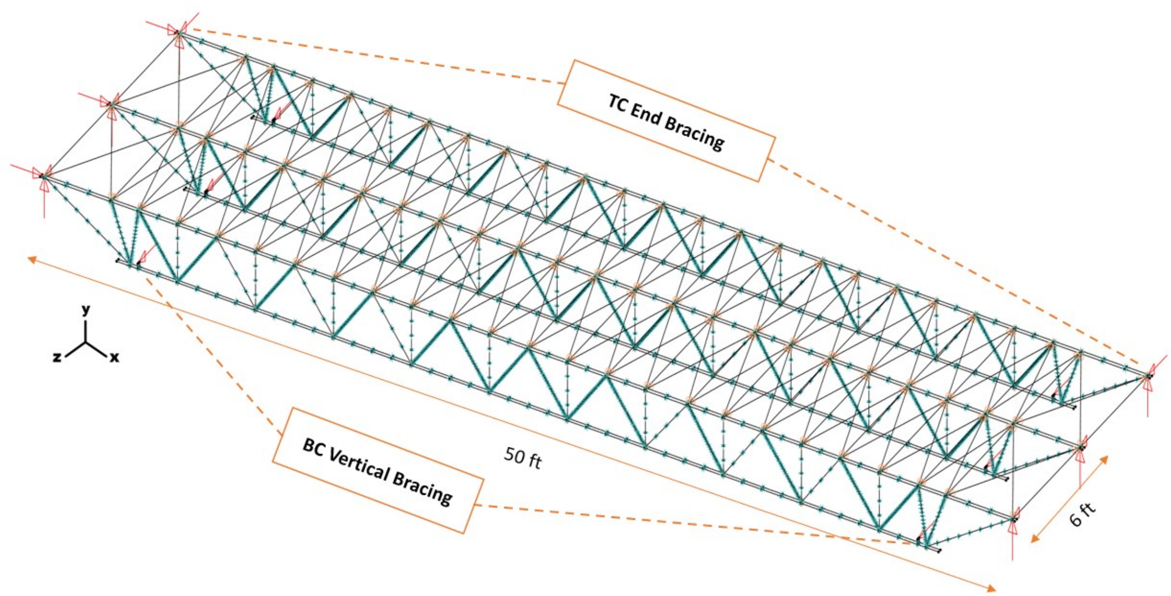

Figure 1: End model layout of the system (red is boundary conditions, orange is member ends fixity, and light blue is nodes meshing).

2.1.1 Joist

The joist layout used in this study was derived from a joist manufacturer's design sheet for a hot-rolled steel joist, targeting bottom chord yielding as the primary failure model. Fig. 2 illustrates the joist layout from the design sheet. The system includes three identical joists, each with an overall length of 50 feet (15.24 m) and spaced 6 feet (1.83 m) apart. To reflect detailing practices, a bearing length of 4 inches is provided at each end, which results in a bearing span of 596 inches (15.14 m) between centers of bearing, The length of the bottom chord is 490 inches (12.45 m).

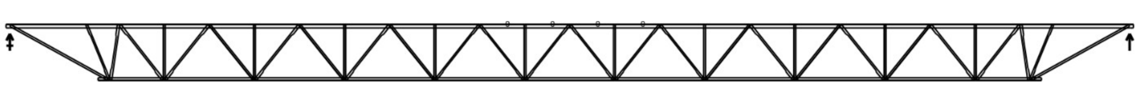

Figure 2: Joist Layout as per design sheet.

An individual joist in the system consists of 36 webs connected to the top and bottom chords, forming 24 panels in the top chord and 11 in the bottom chord. The top chord panels are divided into three types: two start/end panels (3 feet 5 inches or 1.04 m each), two initial panels (17 inches or 0.432 m each), and twenty intermediate panels (2 feet or 0.61 m each). For the bottom chord, there are two initial panels (2 feet 5 inches or 0.74 m each) and nine intermediate panels (4 feet or 1.22 m each). Fig. 3 details the joist dimensions.

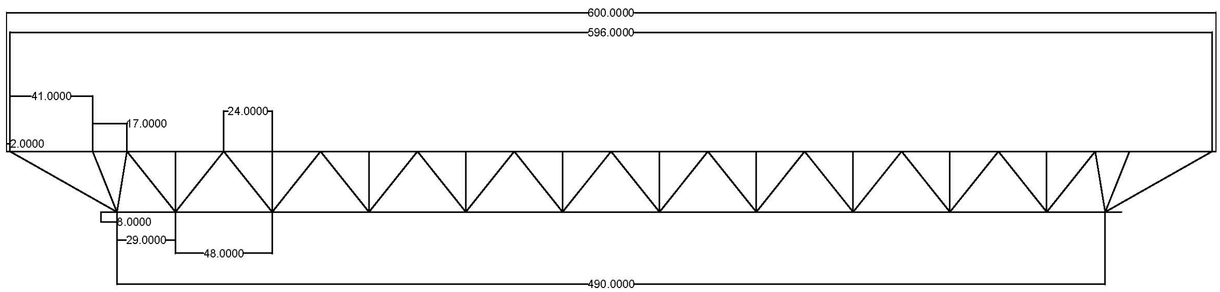

Figure 3: End model layout of the Joists (all dimensions are in inches).

The joist chords are constructed from back-to-back channel sections, spaced 1.125 inches (28.6 mm) apart to accommodate the web connections. The webs are primarily angle sections, except for the last webs (also referred to as "end bars"), which are solid rods. To accurately reflect the design sheet, varying web section sizes were applied to ensure proper load distribution and failure mode representation, as summarized in Table 1. A color-coded depiction of the web assignments is shown in Fig. 4.

Table 1: Joist Parts section input

Part	**Section Type (inches)**
Top Chord	L 2 × 2 × 0.163
Bottom Chord	L 1.5 × 1.5 × 0.17
End Webs	Circular 1-1/16 solid rod
Section 1	L 1-1/4 × 1-1/4 × 0.109
Section 2	L 1-1/2 × 1-1/2 × 0.170
Section 3	L 1 × 1 × 0.109
Section 4	L 1-1/2 × 1-1/2 × 0.123

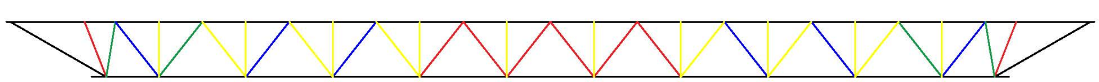

Figure 4: Joist colored webs for section assignment (Red = section 1, Green = section 2, Yellow = section 3, Blue = section 4).

The joist modeling approach in MASTAN2 follows recommended modeling practices (Sippel et al., 2020). The cross-sections were defined based on the three-dimensional coordinates of the cross-section centroids. Top and bottom chord nodes were categorized into three sets: (1) a single angle in the positive z-direction, (2) a corresponding single angle in the negative z-direction, and (3) connecting panel points. The designed joist depth is 30 inches (0.762 m), but the effective depth, accounting for centroid locations, is 28.9 inches (0.734 m).

Two material types were defined: a general steel with a yield strength of 50 ksi (345 MPa) and a modulus of elasticity of 29,000 ksi (200 GPa), and a rigid material with a significantly higher modulus to represent welding and bracing components. Using MASTAN2's MSASect tool, eight sections were defined: seven representing the various chord and web components and one for rigid elements using a 2 in.×2 in. (50.8 mm×50.8 mm) solid square section. This rigid section replicates the welded connections and fillers in the actual joist. Additionally, crimped web ends, modeled as separate sections, account for space constraints between the chords. Fig. 5 illustrates the crimped sections, and transition sections between the crimped and uncrimped sections were also defined with dimensions averaging the leg length of the crimped and angle sections to replicate the design accurately.

Mesh refinement was applied strategically across the model. Top and bottom chords were meshed with 12-inch (30.5 cm) elements. Webs were divided into four segments, with finer meshing at the web ends to capture the 6-inch (15.25 cm) crimping sections accurately. Transition regions were meshed with sizes ranging from 4 to 5 inches (10.2 to 12.7 cm), depending on the web length, ensuring a uniform and precise mesh pattern.

To replicate design sheet joist orientation, each member's local axis was adjusted. In MASTAN2, local axes define member orientation; therefore, the top chords were rotated to 135 degrees and the bottom chords to 45 degrees, ensuring proper vertical leg orientation. Fig. 6 shows a YZ-plane side view with blue tick marks indicating local y-axis orientation. Webs were reoriented between 0 and 180 degrees to match their angle openings as depicted in the design sheet, with webs on the left side facing left and those on the right facing right.

Additional member fixity was incorporated to account for torsional effects. Continuous torsional connections were applied throughout the model, with web ends fixed to ensure isolated web behavior. The joist ends were left free to define the start and end of torsional effects. Typically, joist systems should have a semi-rigid fixity at their ends to ensure resistance against out-plane movement while keeping in-plane movement free (Committee on Specifications for the Design of Cold-Formed Steel Structural Members, 2021). To resist out-of-plane movement while allowing in-plane flexibility, semi-rigid end fixity was applied. Following recommended guidelines (Sippel et al., 2020), a rotational stiffness of 0.001 kip/in (0.175 kN/m) was assigned to the end webs to meet this requirement. Fig. 7 shows the completed joist layout in MASTAN2.

2.1.2 Steel Deck Diaphragm

For modeling the steel deck using beam element formulation in MASTAN2, the procedure outlined in the Steel Deck Institute (SDI) technical notes was followed (Luttrell et al., 2015). The selected deck profile was a 22-gauge B deck with a width of 3 feet (0.915 m), as shown in Fig. 8. In the model, the deck ribs were oriented perpendicular to the joist span. The modeling process categorized the beam elements representing the deck diaphragm into two types: straight and cross-diagonal elements (Fig. 9).

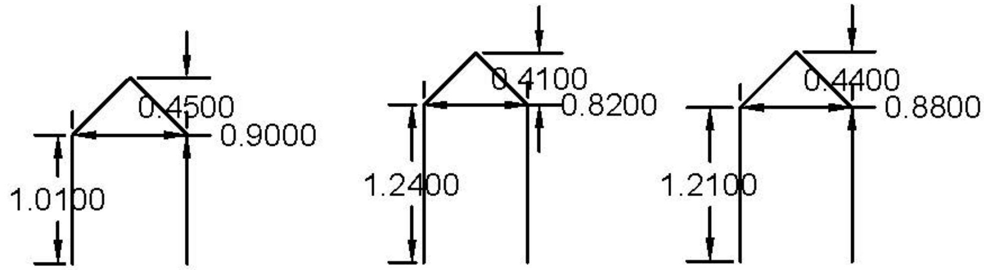

Figure 5: Modeled crimping section, from left to right, represent crimping for L 1.25 × 1.25 × 0.109, L 1.5 × 1.5 × 0.17, and L 1.5 × 1.5 × 0.123, respectively (all dimensions are in inches).

According to the SDI technical notes, two primary dimensions are required to represent deck diaphragms with line elements: b and h (Fig. 10). Here, b denotes the distance between the straight-line elements, while h represents the length of the of the straight-line element. In the model, b corresponds to the distance between adjacent panel points. Since the top chord panels were categorized into three types in the joist subsection, three distinct b values were used. On the other hand, h corresponds to the spacing between adjacent joists, which was set to 6 feet (1.83 m).

The sectional properties of the actual 22-gauge B deck profile (3 feet wide) were pre-calculated using the Cold-Formed Steel Design (CFS 14) software (RSG Software, Inc., 2025). Fig. 11 shows the sectional property output of the modeled deck profile. In MASTAN2, the straight-line elements were assigned equivalent sectional properties scaled to represent a 6-foot (1.83 m) wide deck, as utilized in this study.

For the cross-diagonal elements, the sectional properties were calculated under the assumption that they represented solid steel rods. To emphasize the study's focus on the lateral buckling of the system, the input moment of inertia (I) for both principal axes of the cross-diagonal elements was artificially set to $100\,\text{in}^4$. This ensured that these elements were sufficiently stiff to prevent flexural buckling, thereby allowing the system's overall lateral behavior to dominate the analysis.

2.2 Analysis Approach

The primary focus of the analysis was determining the minimum effective shear stiffness (G) of the deck required to brace the system against lateral deflection. This was achieved through an iterative process, assigning calculated sectional properties and performing a geometric nonlinear (second-order elastic) analysis to monitor the system's stability.

The analysis began by assuming a high lateral stiffness value of 10 kip/in per foot in the longitudinal direction. Next, the the cross-sectional area of the diagonal brace, A_d, was calculated. To determine the area, first the applied point load P needed to deform the truss system (as shown in Fig. 10) was calculated using Eq. 1. Subsequently, the axial tensile force (T) in the diagonal element was determined using similar triangles as given in Eq. 2. Finally, the required input area of the diagonal element (A_d) was computed using Eq. 3 which is given in Luttrell et al. (2015):

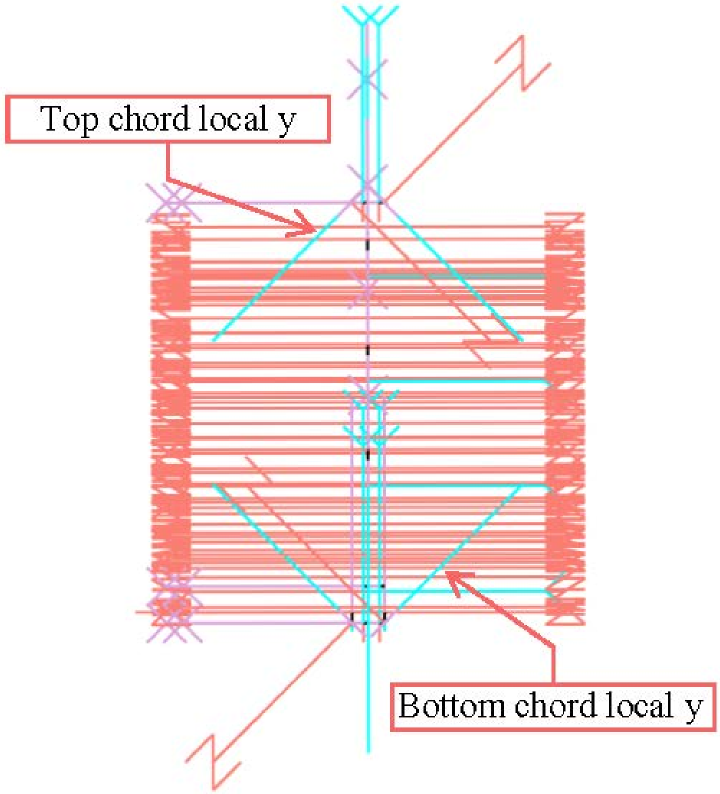

Figure 6: Side view of the joist indicating chords orientation (Red = Local z axis, Cyan = Local y axis, Purple = Local x axis).

$$P = G \cdot b \tag{1}$$

$$T = P \cdot \frac{L_d}{b} \tag{2}$$

$$A_d = \frac{L_d^2 T}{\Delta b E} \tag{3}$$

where:

- A_d = Cross-sectional area of the steel rod
- L_d = Length of the cross-diagonal element
- Δ = shear deflection (1 inch)

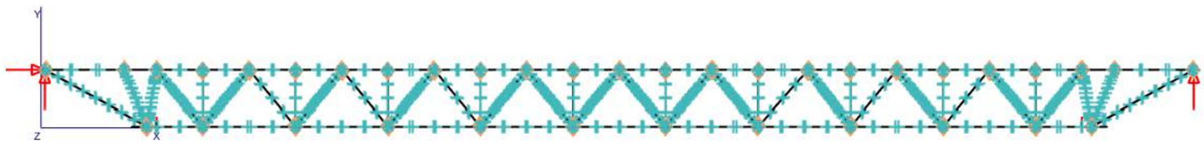

Figure 7: Joist Layout at the end of the modeling stage in MASTAN2.

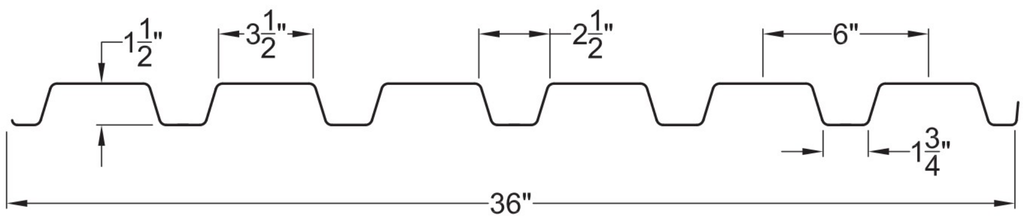

Figure 8: Deck profile utilized in the model (D-MAC-Industries, 2023).

- T = Axial tensile force in the cross-diagonal element (assuming Δ = 1 inch)
- b = Distance between adjacent panel points (three distinct values were used in this study)
- E = Young's modulus for steel ($29,000\,\text{ksi}$)

After calculating A_d, additional sectional properties, such as the plastic section modulus (Z) and the polar moment of inertia (J), were determined based on the diameter of the corresponding solid steel rod section. These properties provided the necessary input information for the cross-diagonal members prior to running the analysis.

The iterative process commenced with a high assumed shear stiffness value ($G = 10\,\text{kip/in}$ per foot), which resulted in a completed full analysis (reached an applied load ratio = 1) indicating a stiffness value sufficient to sustain the full design load. The stiffness increment was then iteratively reduced, the cross-sectional properties of the diagonal brace was recalculated, and the analysis was repeated until the analysis output yielded an applied load ratio of less than 1, indicating a brace stiffness value insufficient to sustain the full design load. The iterative value before this threshold was then considered the effective stiffness value.

Ultimately, the analysis produced at a threshold stiffness value of $G = 0.45\,\text{kip/in}$ per foot, which was identified as the minimum effective stiffness required to brace the three-joist parallel system with a deck on top against lateral buckling.

3 Analytical Calculation

To validate the results obtained from the computational analysis, an analytical investigation was conducted using the known parameters of this study. While the equivalent truss system modeled

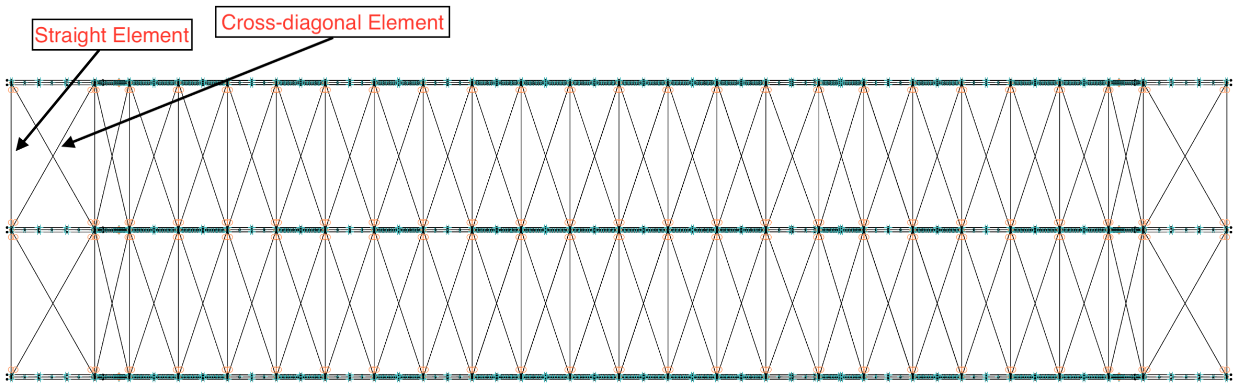

Figure 9: Deck diaphragm truss elements modeled in MASTAN2.

in the analysis represents the deck-joist system with the top chord braced at discrete intermediate points, in reality, the steel deck provides continuous bracing to the joists in the system. Therefore, to determine the analytical effective stiffness value of the deck, the joists are treated as beams continuously braced by the deck.

According to Yura and Helwig (2021), the lateral stiffness of a beam with continuous point lateral bracing can be calculated using the following equation:

$$G = \left(\frac{M_{cr}}{H_o C_b}\right)^2 \cdot \left(\frac{1}{\tau_b E I_y}\right) \cdot \frac{L}{n} \tag{4}$$

where:

- G: Lateral stiffness of the beam with continuous point lateral bracing.
- M_{cr}: Required compression strength of the joist, calculated to be 1110 kip-in for this study ($M_{cr} = \frac{wL^2}{8}$, where $w = 300$ plf in this study).
- C_b: Moment gradient factor. Since the deck provides continuous bracing, the unbraced length (L_b) is zero, resulting in $C_b = 1$.
- H_o: Distance between the centroids of the joist's flanges, equal to the effective depth between the top and bottom chords (28.9 inches).
- τ_b: Stiffness reduction factor. For elastic analysis, $\tau_b = 1$.
- E: Elastic modulus of the material ($29,000$ ksi).
- I_y: Weak-axis moment of inertia for the top chord's back-to-back angles ($I_y = 3.76$ in^4 accounting for both top chords in this study).

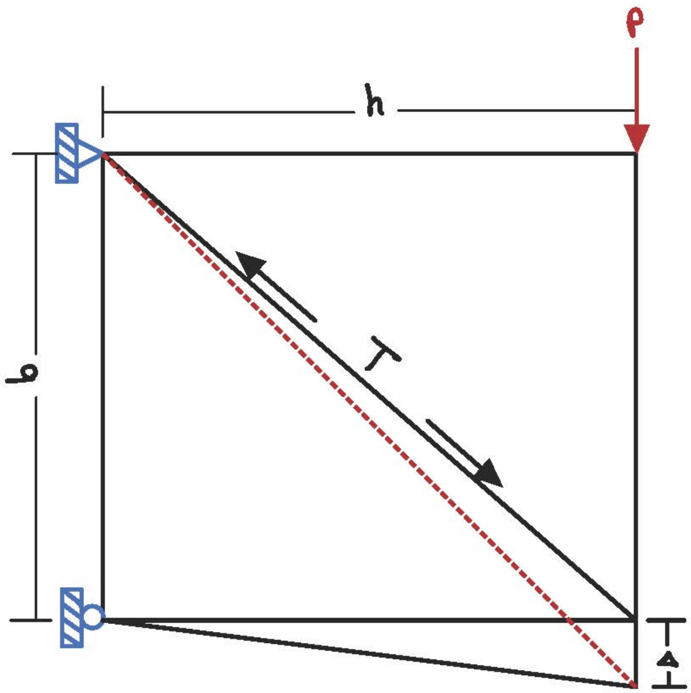

Figure 10: Truss sample highlighting the main dimensions utilized in deck modeling truss elements method .

- L: Working length of the joist.
- n: Number of braces along the beam. For continuous bracing, $L/n = 1$.

Substituting the known values into the equation yields the lateral stiffness for a single joist. Considering this to be a "lean-on" system, the system will not buckle until the total load which causes all the joists to buckle is applied to the system. Therefore, to determine the stiffness demand to brace the entire system, this value for a single joist is multiplied by the number of joists.

The analytical approach results in a lateral stiffness value of:

$$G = 0.473 \, \text{kip/in per foot}$$

This result closely aligns with the computational findings, validating the effectiveness of the modeling approach and analysis techniques used in this study.

4 Results and Discussion

The computational analysis conducted in this study determined that the minimum lateral stiffness (G) required to adequately brace the deck-joist system against lateral buckling was approximately 0.45 kip/in per foot. In contrast, the analytical solution yielded a stiffness value of 0.473 kip/in per foot, resulting in a difference of about 5%. This discrepancy is within an acceptable range, further validating the accuracy of the adopted modeling and analysis methods.

Ix	0.55 in^4	rx	0.619 in	Ixy	-0.62 in^4
Sx(t)	0.860 in^3	y(t)	0.639 in	α	89.785 deg
Sx(b)	0.631 in^3	y(b)	0.871 in		
Zx	0.813 in^3	Height	1.510 in		
Iy	165.54 in^4	ry	10.738 in	x_o	0.086 in
Sy(l)	8.916 in^3	x(l)	18.567 in	y_o	0.188 in
Sy(r)	8.944 in^3	x(r)	18.508 in	jx	-0.108 in
Zy	13.338 in^3	Width	37.076 in	jy	-7.765 in
I_1	165.54 in^4	r_1	10.738 in	Cw	66.004 in^6
I_2	0.55 in^4	r_2	0.617 in	J	0.0004165 in^4
Ic	166.09 in^4	rc	10.756 in		
I_o	166.15 in^4	r_o	10.758 in		

Figure 11: CFS calculated section properties for 3-foot (0.915 m) wide deck (RSG Software, Inc., 2025).

The close agreement between the computational and analytical results demonstrates the potential of utilizing the truss analogy in combination with beam element finite element formulations. Despite the differing approaches, the outcomes align closely: the computational model treated the deck as a truss system and included the entire joist to calculate the required stiffness, while the analytical method analyzed the joist as a beam with continuous bracing provided by the deck.

The slight differences in the results can be attributed to variations in the approach considerations between the two methods. The computational approach focused on the effect of the entire system in restraining the structure braced at specific locations. In contrast, the analytical solution assumes a single beam that is continuously braced, yielding results for one joist in the system. To obtain the overall effect, this result is then multiplied by the number of joists.

This study highlights the efficiency and practicality of the adopted modeling approach. The truss analogy and beam element formulations offer a fast and straightforward method for analyzing deck-joist system stability. Compared to higher-fidelity finite element formulations, such as shell or solid elements, this method is significantly less time-intensive. The computational analysis in this study was completed within a few minutes, whereas advanced modeling techniques could require several hours or even longer to achieve comparable results.

The results reinforce the effectiveness of this method as a practical tool for structural analysis, offering a balance between accuracy and computational efficiency.

5 Conclusions

This study highlights the viability of using beam element formulations to model steel deck diaphragms in finite element software such as MASTAN2. Through computational analysis, the minimum shear stiffness (G) required to prevent lateral buckling in a three-joist deck system was determined to be 0.45 kip/in per foot. An analytical solution, based on continuous bracing formulations, yielded a comparable stiffness value of 0.473 kip/in per foot, with a difference of only 5%. The close agreement between the two methods validates the accuracy of the computational modeling approach and the truss analogy for representing the deck's in-plane stiffness.

Beam element models are typically computationally less demanding than their shell or solid element model counterparts. Therefore, the methodology presented herein provides engineers with a reliable, fast, and accessible tool for evaluating the stability of steel deck-joist systems, offering a balanced trade-off between precision and efficiency. Future work could expand this methodology to investigate other joist configurations, deck profiles, and loading scenarios.

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