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Finite element modeling of open web steel joists comprised of nonsymmetric shapes

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Abstract
Open web steel joists are flexural members that are often used in long-span roof and floor systems. Although their truss geometry is quite efficient, as they can provide excellent strength and stiffness with relatively small self-weight, stability is a major design consideration given that they tend to be slender in their out-of-plane direction. To further complicate their stability analyses, such joists are fabricated from single and double angles, which are nonsymmetric shapes with their shear center and centroid at different locations. In most finite element analysis programs, this difference in location of centroid and shear center is neglected – in other words, all sections are treated as doubly symmetric during the structural analysis. This research provides various methods of modeling joists and assesses the impact of treating nonsymmetric shapes as symmetric. Two joist configurations (30K12 and 32LH06), which were recommended for investigation by the Steel Joist Institute, are examined. Based on models that range from all shell elements to all line elements, with combination models also included, recommendations are given for modeling open web steel joists for a stability analysis, and comments on those factors that can influence behavior are presented.

1. Introduction
Open web steel joists are often used in place of steel I-beams in floor and roof systems due to their efficient truss structure. Such joists include top and bottom chords, which are constructed from back-to-back double angles, and diagonal web members, which are typically made up of single angles (Fig. 1). The geometries of these joists result in a relatively high in-plane moment of inertia for the entire joist, while the cross-section areas of the individual members remain small, thereby creating a light-weight structure that is efficient under flexure (Geschwindner et al., 2017). While these joists are effective under flexure, the slender sections can decrease the resistance to out-of-plane buckling, and as a result, they are often braced laterally at various locations along the span.

Similar to practically all structures built today, open web steel joists are designed and analyzed using finite element analysis (FEA) programs. With safety as their top priority, structural engineers strive to find the most efficient and accurate way of performing these analyses. Currently, members of open web steel joists are often modeled with single line elements due to the computational

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efficiency and ease of modeling these long span structures. When members are modeled as line elements, most FEA software treat nonsymmetric shapes as doubly symmetric, and thereby assume the shear center and centroid are located at the same point. As a result, they may neglect a substantial twist component that could significantly change the member forces and moments within the joist. The objective of this paper is to assess the significance of this assumption and make recommendations to alleviate any related concerns (Rojahn 2020).

Figure 1. Open web steel joists in a roof system.

2. Background

2.1 Shear center

The shear center of a cross section identifies the point where transverse loading on a beam results in only flexural displacements aligned with the axis of the loading – no other twisting or displacement actions occur. To locate the shear center, the shear flow along the section is calculated based on an arbitrary shear force, and then the moments are summed to find the lever arm that satisfies moment equilibrium (Hibbeler 2011). For doubly symmetric shapes, it is in the same location as the centroid, and for nonsymmetric (single and point symmetric) shapes, the centroid and shear center are at different locations (Fig. 2). Of significance to this research is the relative location of the shear center and centroid for the single and double back-to-back angles shown.

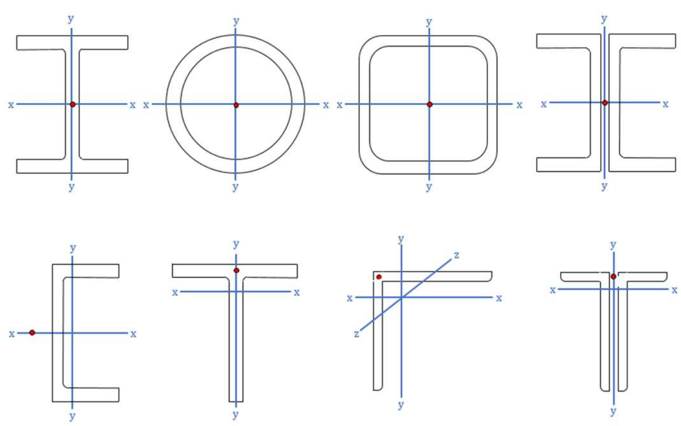


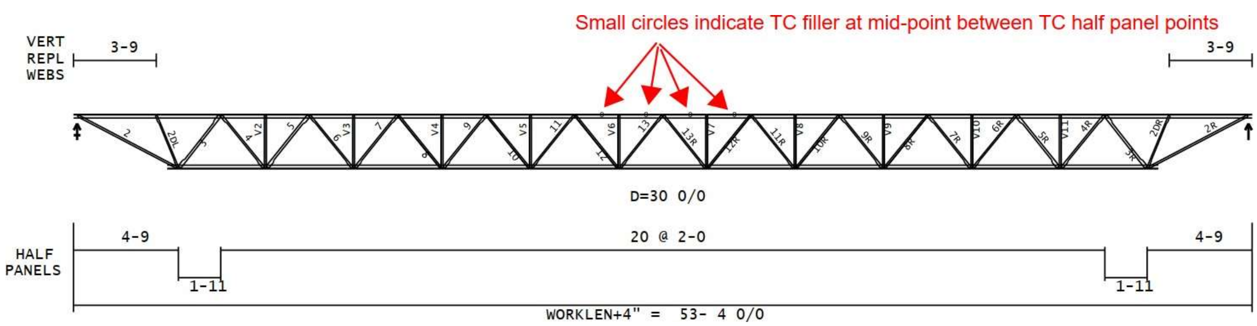
Figure 2. Shear center (point in red) versus centroid (intersection point of axes) of several common symmetric and nonsymmetric sections.

2.2 Joist geometry

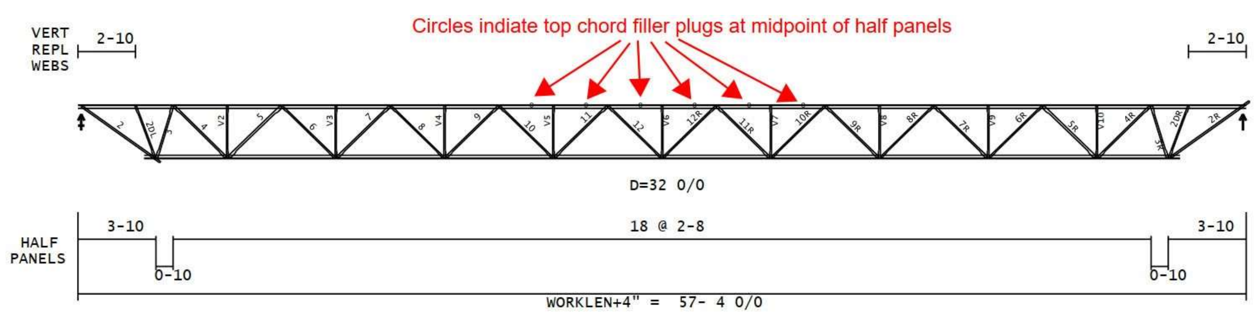
The top and bottom chords of open web steel joists are double back-to-back angles, and the diagonal members are often single angles (Fig. 3).

Figure 3. Geometry of open web steel joist (Vulcraft 2020).

In this study, two joist configurations (30K12 and 32LH06) are computationally modeled and analyzed under gravity and wind uplift loadings. Details of these joist geometries were provided by Vulcraft, a member of the Steel Joist Institute, and are provided in Figure 4 (Vulcraft 2020).



a. 30K12



b. 32LH06

Figure 4. Joist geometries investigated.

2.3 Finite element analysis programs

Several features of two analysis programs, including MASTAN2 (Ziemian et al., 2019) and Strand7 (2020), are used in this research. MASTAN2 is an educational structural analysis program that can model cross-sections within line elements as either symmetric or nonsymmetric (Liu et al., 2018, 2019).

Strand7 is commercial finite element analysis software that provides for modeling with line and/or shell elements. When line elements are used to model nonsymmetric shapes in Strand7, the behavior associated with the difference in location between the shear center and centroid is approximated by simply offsetting the element ends from their connecting nodes. When Strand7 shell element models are employed, the behavior of nonsymmetric sections is directly modeled in the analysis.

2.4 Preliminary Background Study

Before preparing detailed models of the relatively complex long span joists, a small study on the global buckling behavior of single members comprised of T-sections was completed. A T-shape was used because the shear center is offset from its centroid and it is a geometrical simplification of closely spaced back-to-back angles.

Four different T-shape cross sections (WT12x81 WT9x87.5, WT7x96.5, and WT6x68) were studied. To gain insight on the impact of the distance between the shear center and centroid, the stem of each of the T-shapes was artificially extended (Fig. 5). Four different types of models were created, including (1) a Strand7 shell element model; (2) Strand7 line element model; (3) MASTAN2 line element model with cross section assumed doubly symmetric; and (4) MASTAN2 line element model with the cross section properly modeled as singly symmetric. In all cases linear buckling analyses (LBA) were performed on 40-ft members with both ends restrained from rotation and lateral displacement. The fixed-fixed end conditions were employed to provide a comparison between analysis results that are not hampered by strategies for modeling end conditions in the shell element models. Members were compressed by a prescribed axial displacement and the strain corresponding to member buckling was calculated by critical load analyses (LBA). Such displacement-controlled analyses were performed instead of load-controlled analysis in order to be consistent in modeling the end conditions for the shell element and line element models.

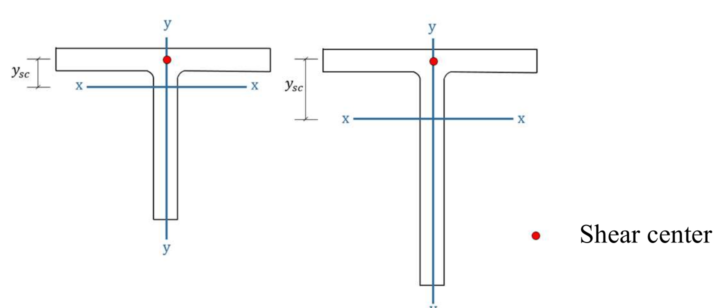


Figure 5. Impact of artificial elongation of T-shape stem.

The theoretical solution for this problem is used as the basis for comparison when computing percent error values. As expected, when the distance y_{sc} between the shear center and centroid increased, the error produced by employing a line element that assumes the section is doubly symmetric significantly increases (Fig. 6). For the specific cases of a WT9x87.5 with varying artificially extended stem lengths, Table 1 provides the errors associated with each of the four analysis models explored. Similar results were obtained for the other T-shapes investigated. The observations from this study suggest the potential shortcomings of modeling nonsymmetric shapes as symmetric in finite element analyses.

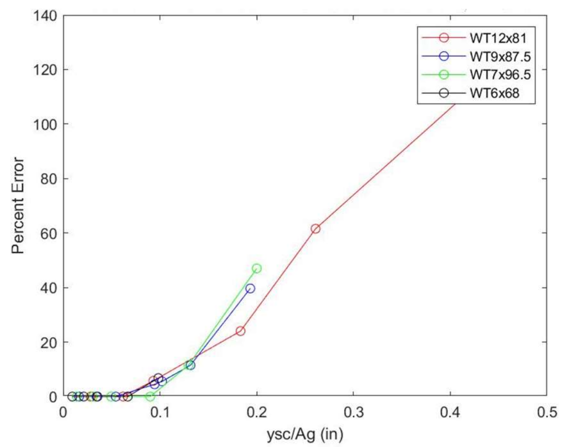


Figure 6. Percent error of analyses assuming T-shapes a doubly symmetric.

Table 1. Percent errors for analyses of WT9x87.5.

Depth (in.)	y_{sc} (in.)	Strand7 (shell elements)	Strand7 (line elements with offset)	Mastan2 (symmetric cross section)	Mastan2 (nonsymmetric cross section)
5	0.359	0.495	3.00	0.001	0.001
7.5	0.829	0.770	2.26	0.001	0.001
10	1.429	1.31	1.12	0.001	0.001
15	2.906	0.764	6.29	4.48	0.018
16	3.235	0.810	7.31	5.55	0.022
20	4.634	1.08	13.1	11.45	0.050

3. Joist study

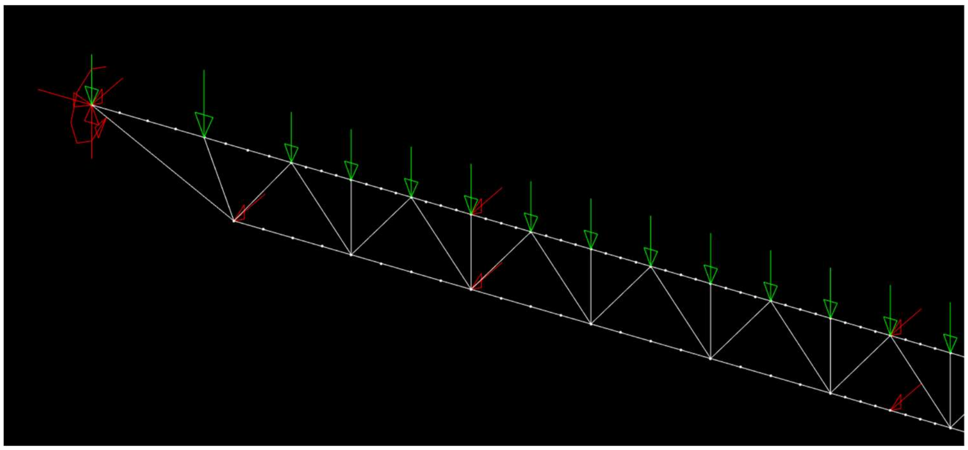
3.1 Models

A summary of the different variations of the computational models used to study the joists is provided in Table 2. These variations include combinations of modeling section properties as symmetric or nonsymmetric, and the manner in which the top and bottom chords are modeled, including single line elements (Fig. 7a), double line elements (Fig. 7b), or shell elements.

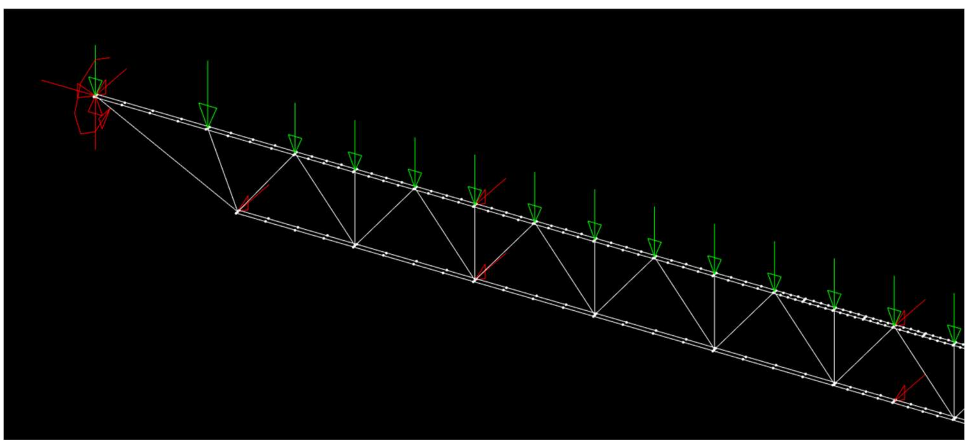
Table 2. Summary of models for both 30K12 and 32LH06 joist geometries.

Model Type	Description
Strand7 or MASTAN2 single line element - symmetric	Strand7 or MASTAN2 with all joist members modeled with single line elements and only doubly symmetric properties used.
Strand 7 or MASTAN2 single line element - nonsymmetric	Strand7 or MASTAN2 with all joist members modeled with single line elements, and advanced nonsymmetric properties used in MASTAN2 and an equivalent offset approximation used in Strand7.

Strand7 or MASTAN2 double line element - symmetric	Strand7 or MASTAN2 with the joist's top and bottom chord members modeled with two parallel line elements and only doubly symmetric properties used.
Strand7 or MASTAN2 double line element - nonsymmetric	Strand7 or MASTAN2 with the joist's top and bottom chord members modeled with two parallel line elements, and advanced nonsymmetric properties used in MASTAN2 and an equivalent offset approximation used in Strand7.
Strand7 hybrid shell and line-symmetric	Top and bottom chords are modeled with shell elements, web members are modeled with line elements using doubly symmetric properties.
Strand7 hybrid shell and line-nonsymmetric	Top and bottom chords are modeled with shell elements, web members are modeled with line elements using an Strand7's equivalent offset approximation.
Strand7 all shell elements (30K12 only)	All joist members are modeled with shell elements.



a. Single line element



b. Double line element

Figure 7. MASTAN2 models (30K12).

When single line elements are used to model the top and bottom chords, MASTAN2 and Strand7 differ in their approach to defining and modeling the cross-sections of the back-to-back double angles. Given that MASTAN2 only provides the opportunity to compute section properties (e.g. Wagner constants, etc.) for nonsymmetric shapes in which all components are connected, a segment with a negligible thickness (0.0001-in.) is used to connect the chord's back-to-back double angles with a 1-in. spacing (Fig. 8).

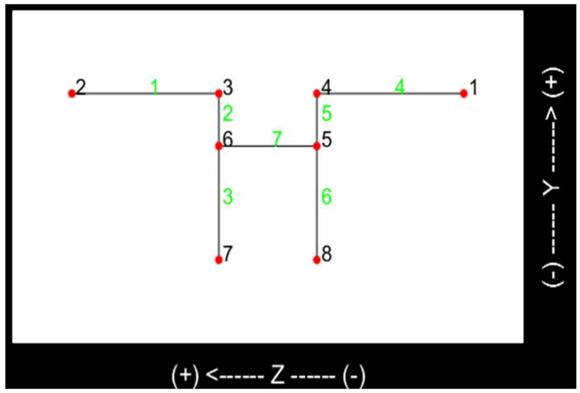


Figure 8. MASTAN2 cross-section used in single line models.

Although Strand7 does not require this thin connecting segment (Fig. 9), only doubly symmetric section properties (e.g. A, I_{11}, I_{22}, and J) are computed for line elements. As previously indicated, Strand7 uses an element end offset to approximate the effects related to differing locations of the shear center and centroid. In this study, Strand7 models that incorporate this offset are defined as with nonsymmetric sections, and those in which the offset is purposely set to zero are defined as with symmetric properties.

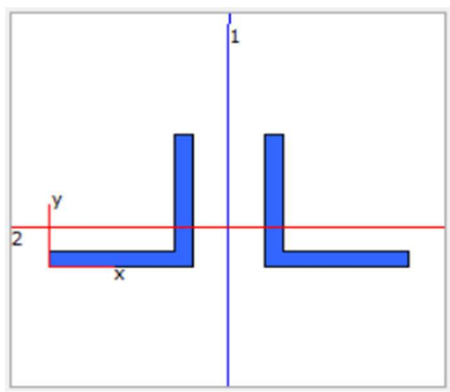


Figure 9. Strand7 cross-section used in single line models.

Two types of models with shell elements were analyzed with Strand7, including a full shell element model, and a model with the top and bottom chords comprised of shell elements and all web members represented with line elements. Given that web member buckling may not control the failure mode of either of these joists, modeling them with line elements is felt to be a compromise between accuracy and analysis efficiency. It is further noted that the ends of the angle web members are crimped to fit within the 1-inch gap provided between the angles defining the top and bottom chords. When using full shell element models, it is quite time consuming to represent such crimping.

In all cases in which two parallel line elements or shell elements are used, short line elements are used to connect the double angles defining the chords (Figs. 7b and 10). These elements were defined at all chord-to-web intersections as well as at the given filler plug locations along the span lengths (Fig. 4). The section properties of these connecting elements were taken as those of a 1-in. diameter steel rod. The impact of the stiffness of these elements is further discussed below.

In all analysis models, the joists are braced out-of-plane at the span length quarter points. This was implemented by restraining displacement translation at such points on the top and bottom chords.

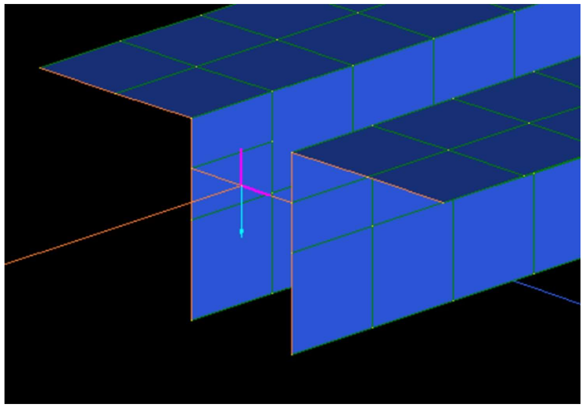


Figure 10. Strand7 shell element model of chord's double angles.

3.2 Loading conditions

The joists were subject to uniformly distributed gravity loads or uplift loads due to wind. Such loads were applied as concentrated loads (computed using tributary length) at the joist panel points (e.g., Fig. 7).

4. Results and Observations

4.1 30K12 and 32LH06

As a means for comparison, three-dimensional elastic liner buckling analyses (LBA) were employed for all model types and joists investigated. In all cases, a failure mode of lateral torsional buckling moving between the brace points of the joist was observed (Figs. 11 and 12). Results for gravity loading and wind uplift loading are provided in Tables 3 to 6. In addition to providing the buckling load, relative capacity and percent error values are indicated. The relative capacity uses the simpler single element model, which assumes all sections as doubly symmetric, as a basis for comparison. Percent error is computed using shell element results as the "exact" solution.

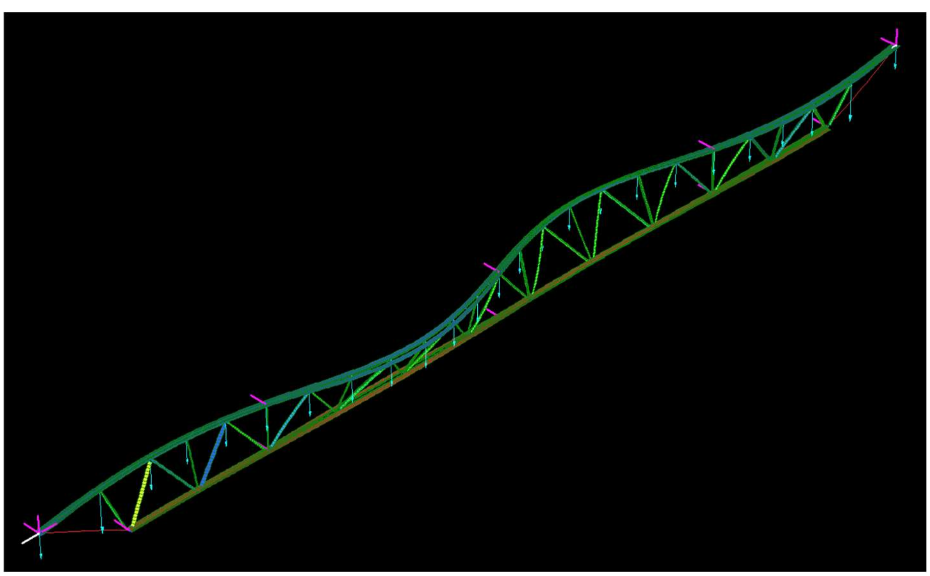


Figure 11. Strand7 all shell element model (30K12 – gravity loading).

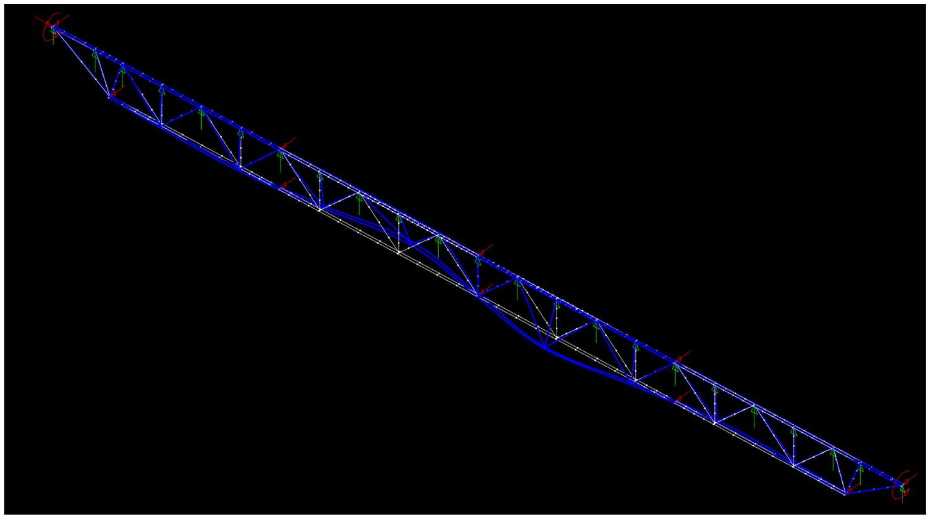


Figure 12. MASTAN2 double line element model (32LH06 – uplift wind loading).

Table 3. 30K12 subject to gravity loading.

Model Type	Buckling Load (plf)	Relative Capacity	% Error
Strand7 single line element - symmetric	312.7	1.00	17.03
MASTAN2 single line element - symmetric	312.9	1.00	17.12
Strand7 single line element - nonsymmetric	312.2	1.00	16.86
MASTAN2 single line element - nonsymmetric	303.7	0.97	13.66
Strand7 double line element - symmetric	272.6	0.87	2.04
MASTAN2 double line element - symmetric	280.7	0.90	5.05
Strand7 double line element - nonsymmetric	273.8	0.88	2.48
MASTAN2 double line element - nonsymmetric	264.4	0.85	-1.03
Strand7 hybrid shell and line-symmetric	272.5	0.87	1.99
Strand7 hybrid shell and line-nonsymmetric	272.5	0.87	1.98
Strand7 all shell elements	267.2	0.85	0.00

Table 4. 32LH06 subject to gravity loading.

Model Type	Buckling Load (plf)	Relative Capacity	% Error
Strand7 single line element - symmetric	260.1	1.00	19.65
MASTAN2 single line element - symmetric	259.8	1.00	19.52
Strand7 single line element - nonsymmetric	259.5	1.00	19.38
MASTAN2 single line element - nonsymmetric	258.1	0.99	18.71
Strand7 double line element - symmetric	221.9	0.85	2.06
MASTAN2 double line element - symmetric	228.1	0.88	4.92
Strand7 double line element - nonsymmetric	222.7	0.86	2.46
MASTAN2 double line element - nonsymmetric	214.1	0.82	-1.50
Strand7 hybrid shell and line-symmetric	217.4	0.84	0.00
Strand7 hybrid shell and line-nonsymmetric	217.4	0.84	0.00

Table 5. 30K12 subject to wind uplift loading.

Model Type	Buckling Load (plf)	Relative Capacity	% Error
Strand7 single line element - symmetric	339.5	1.00	47.27
MASTAN2 single line element - symmetric	339.0	1.00	47.06
Strand7 single line element - nonsymmetric	336.3	0.99	45.87
MASTAN2 single line element - nonsymmetric	336.3	0.99	45.87
Strand7 double line element - symmetric	235.7	0.69	2.25
MASTAN2 double line element - symmetric	247.1	0.73	7.17
Strand7 double line element - nonsymmetric	236.6	0.70	2.61
MASTAN2 double line element - nonsymmetric	226.2	0.67	-1.88
Strand7 hybrid shell and line-symmetric	234.5	0.69	1.70
Strand7 hybrid shell and line-nonsymmetric	234.5	0.69	1.70
Strand7 all shell elements	230.6	0.68	0.00

Table 6. 32LH06 subject to wind uplift loading.

Model Type	Buckling Load (plf)	Relative Capacity	% Error
Strand7 single line element - symmetric	262.3	1.00	60.01
MASTAN2 single line element - symmetric	261.7	1.00	59.60
Strand7 single line element - nonsymmetric	261.1	1.00	59.25
MASTAN2 single line element - nonsymmetric	259.7	0.99	58.38
Strand7 double line element - symmetric	166.3	0.63	1.44
MASTAN2 double line element - symmetric	172.8	0.66	5.39
Strand7 double line element - nonsymmetric	167.3	0.64	2.03
MASTAN2 double line element - nonsymmetric	157.8	0.60	-3.75
Strand7 hybrid shell and line-symmetric	164.0	0.63	0.01
Strand7 hybrid shell and line-nonsymmetric	164.0	0.62	0.00

4.2 Observations

Based on the results given in the above tables for the various FEA models, the following observations are made.

- Both Strand7 and MASTAN2 indicate that the use of two parallel line elements to model the top and bottom chords of the joists can provide remarkably accurate results with much less computational demands when compared to the Strand7 shell element models.
- Both Strand7 and MASTAN2 suggest that modeling all members of a joist with single line elements may overpredict the out-of-plane flexural stiffness of the top and bottom chords, and thereby indicate elastic buckling capacities that are 14% to 20% unconservative for the gravity loading condition. For the wind uplift loading condition, the unconservative percent error is significantly higher and ranges from 46% to 60%.
- Both of Strand7's double line element models agree quite well with shell element results. The use of an element end offset to represent the effects of nonconcentric locations of the shear center and centroid appears to have only changed the results by less than 0.5%.
- For the double line element models, MASTAN2's nonsymmetric cross section algorithm does indicate a more significant reduction in buckling load capacity of approximately 5% to 10% when compared to employing its symmetric element results.

- MASTAN2's equivalent double line element model that accounts nonsymmetric cross sections appears slightly conservative given that it consistently underpredicted the capacity of that determined by the shell element models by 3% to 4%.

4.3 Impact of connecting elements

Short line elements with properties of a 1-in. diameter steel rod are used in the double line and shell element models to connect the two back-to-back angles comprising the top and bottom chords. Such connections are located at all chord-to-web and filler plug locations. As may be expected, an artificial increase in the number of these connector locations (Fig. 13) increases the buckling capacities of the double line and shell element models. Indeed, such capacities approached the results reported in Tables 3 to 6 for the single line models. This indicates that the limited number of connection points between the angles defining the chords in actual open web steel joists reduces the opportunity for shear flow in these composite sections, and may most likely explain why the single line models tend to significantly overpredict the elastic buckling capacities reported for the more realistic double line and shell element models. This conclusion is further supported by the wind uplift loading results, in which there are fewer connectors in the bottom chords at the midspan (Fig. 4).

Although the use of more rigid flexural properties (moments of inertia) for these connectors was determined to have an insignificant effect on the results reported herein, the use of a more rigid torsional property (Saint-Venant torsion constant) was found to provide capacities that far exceeded the capacities reported by the single line element models. This finding may be useful in guiding future studies that may have otherwise employed fully rigid elements as connectors.

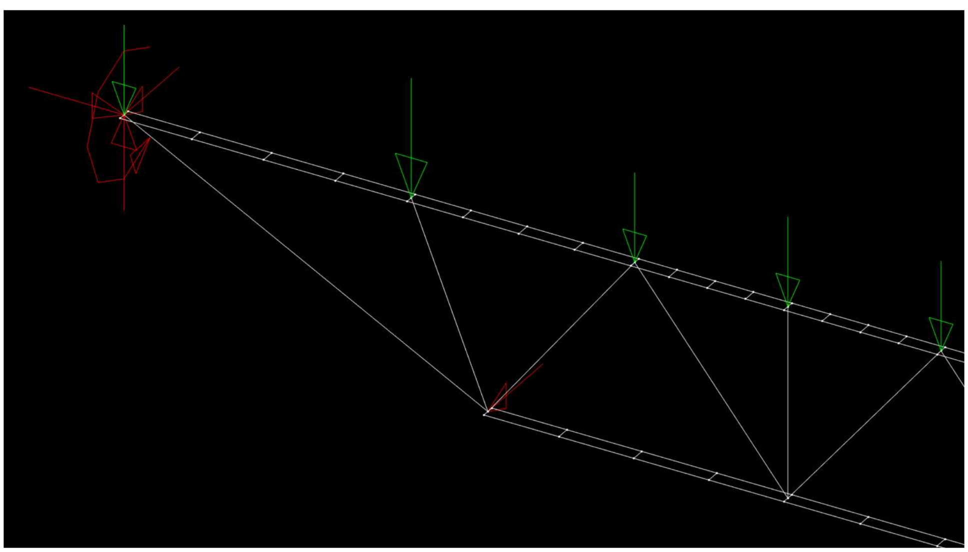


Figure 13. Model with an artificial increase in the number of connector locations.

5. Summary and conclusions

Using the commercial structural analysis software Strand7 and the academic software MASTAN2, a study is presented that aims to investigate the accuracy of three-dimensional finite element models of open web steel joists. Using two joist configurations and exploring both gravity loading and wind uplift loading, the need for advanced line elements and/or shell elements is explored. Results from elastic linear buckling analyses (eigenvalue critical load analyses) are used as a means for making comparisons.

The results from this study suggest that two parallel line elements should be considered when modeling a joist's top and bottom chords when they are comprised of back-to-back spaced double angles. It was not clear as to whether the use of Strand7's element end offset feature to model the impact of different locations of the shear center and centroid is needed for capturing the behavior of nonsymmetric sections within open web steel joists. In contrast, MASTAN2's line element, which models nonsymmetric cross sections, did have a more significant impact on results. Regardless, both the Strand7 and MASTAN2 double line element models performed quite well when compared to results of shell element models. It is important to note that only the global failure mode of lateral torsional buckling was observed in all analyses. It is not known from this study if similar conclusions would be observed if flexural-torsional buckling of the angles were to control.

Any observations or conclusions made in this paper are based only on a very limited study; one which was completed with the objective of providing insight to potential issues with three-dimensional nonlinear analyses of open web steel joists. Additional studies are encouraged before significant changes are made to industry practices.

Acknowledgments
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