A Simplified Approach for Joist Girder Moment Frame Design Using Equivalent Beam Theory

PHILLIP A. KNODEL, ANDREA E. SUROVEK and JOSEPH J. POTE

ABSTRACT

The design of building structures has become a highly automated, computer-based process in which designers depend on the capabilities of commercial software for member strength checks and determination of deflections, drifts and member weights. Most commercial structural design software packages allow the user to build custom beam tables. The use of custom beam tables for joist girders requires the application of equivalent beam theory (EBT). Using EBT, section properties are determined in such a way that joist girder limit states are appropriately captured by strength checks employed by the software. By building custom beam tables, representing approximations of joist girders based on typical available chord sizes and typical ratios of weights, appropriate joist girder section properties can be estimated from almost any commercial structural software program. This paper presents the methodology for developing approximate section properties for steel joist girders that allow commercial software results to closely compare to joist manufacturers' designs.

Keywords: joist girder, beam theory, steel joist design.

INTRODUCTION

The design of building structures has become a highly automated, computer-based process in which designers depend on the capabilities of commercial software for member strength checks and determination of deflections, drifts and member/system weights. Currently available structural design software packages do not have the capabilities to estimate joist girder weight or section properties in an automated design process. For joist girders in moment frames, this is particularly critical because the stiffness of the joist girder affects the distribution of loads throughout the structure and the design of adjoining members, connections, etc. Consequently, selection of open-web steel joists and joist girders, as specified by the Steel Joist Institute (SJI), by commercially available software is typically limited to tabulated load tables for simply supported beams; estimates of joist girder properties and weights are unavailable. In particular, for complex loading, whether unequal loads at unequal spacing or lateral load-resisting frames with end moments and axial loads, the specifying professional has no automated tools for working with joist girders.

Joists and joist girders are custom designed for specific applications. Specific panel layouts and component sizes vary among manufacturers and may even vary among different plants or different design engineers for the same manufacturer. For this reason, it would be virtually impossible to provide accurate estimates of material sizes, weights and section properties in advance of the final joist or joist girder design. It is much more feasible to create a table of approximate joist girder material sizes, weights and section properties that can be used with commercial software programs.

The current design practice used for the design of joist girder moment frames (JGMFs) is detailed in *Technical Digest 11, Design of Lateral Load Resisting Frames Using Steel Joists and Joists Girders* (SJI, 2007). Additional discussion of JGMFs is provided in Green et al. (2009). There are two modeling issues in the approach that can cause problems in the design process:

- Computer software programs require the design engineer to input approximate values for moment of inertia, I_{eff}, and area, A, based on estimated top and bottom chord sizes and joist girder depth. The estimation process is somewhat tedious and time-consuming, and the estimated properties must be checked and updated with each design iteration. Because the design engineer must estimate joist girder section properties without knowledge of the final joist girder design, the estimates for the moment of inertia used in the frame design may differ from the final joist girder design section property values by well over 20%, based on SJI anecdotal evidence.
- If the discrepancies between the properties determined from the final design by the joist engineer and those used in the analysis by the engineer of record (EOR)

Phillip A. Knodel, Design Engineer, New Millennium Building Systems, Butler, IN. E-mail: phillip.knodel@newmill.com

Andrea E. Surovek, Ph.D., P.E., Associate Professor, Civil and Environmental Engineering, South Dakota School of Mines and Technology, Rapid City, SD (corresponding). E-mail: surovek@sdsmt.edu

Joseph J. Pote, Director of Research and Development, New Millennium Building Systems, Hope, AR. E-mail: joe.pote@newmill.com

are large enough, redesign of multiple structural elements may be necessary based on the joist girder sizes determined by the joist engineer.

Most commercial structural design software allows the user to build custom beam tables with custom section properties. Custom beam tables for selection of virtual joist girders were developed for use in the design software STAAD.Pro (Bentley, 2007). The properties in these custom tables do not represent any specific joist girder or the exact properties of the final girder design. The properties are intended to be approximations, based on typical available chord sizes and some typical ratios of weights. The tables could be used in a wide range of applied design loads, including lateral-load-resisting moment frames. If an equivalent beam table for use in commercial software yields relatively close approximations of joist girder section properties and weights designed by the manufacturer, this tool would allow the EOR to easily include joist girders in their building design models in the same automated approach used for wide-flange beams.

The primary objective of this study was to validate a procedure to improve the ability of specifying engineers to accurately select joist girders for building design projects using commercially available design software. The research process was as follows:

- Testing and, where necessary, improvement of user input design tables that allow the EOR to select preliminary joist girders with estimates of moment of inertia values and member weights that have low variance from those designed using the proprietary joist design software.
- Computation of estimates of $I_{zz,}$ shear area and member weight used in equivalent beam models in analysis software that closely match those provided by the joist manufacturer's software.
- Validation of the approach using realistic JGMF to show proof of concept.

BACKGROUND

Standard Joist Girder Design Procedure

Current methods for estimating sizes of joist girders in JGMFs can be tedious. In gravity frames, a joist girder and its equivalent properties can be input into a computer model of a structure by inputting data selected from a joist manufacturer's design catalog. While this method is not complex, it can become cumbersome with structures with a range of loading conditions or for in-progress projects that see changes to the load requirements being made as the structure is being designed.

The method for designing with joist girders in a moment-resisting load frame becomes much more complex because the stiffness of the joist girder affects the required strength and stiffness of the adjoined columns in the structural system. The method to accurately design a moment-resisting load frame with the use of joist girders is outlined in *SJI Technical Digest 11* (SJI, 2007) as follows:

1. Determine the loading (dead, live, wind, seismic) for every unique frame combination.

2. Make a preliminary selection of a joist girder of appropriate depth using the vertical loading only.

3. Approximate the moment of inertia using the following equation:

$$I_{eq} = 0.027NP_{npp}S_{jp}d \text{ (LRFD)} \tag{1a}$$

$$I_{eq} = 0.018NP_{npp}S_{jp}d \text{ (ASD)} \tag{1b}$$

where
I_{eq} = equivalent moment of inertia, in.^{4}
N = number of spaces between attached joists
P_{npp} = panel point load, kips
S_{jg} = joist girder span, ft
d_{jg} = effective joist girder depth, in.

4. Conduct a preliminary frame design to find the moments, shears and loadings in the frame, using the approximate joist girder moment of inertia. It is suggested to start with pinned base columns, with fixed rotation connections at the column–joist girder connection.

5. Use the lateral shear (the greater of the wind or seismic) per column value to calculate the maximum column moment, which is located at the bottom of the joist girder.

6. Select the load combinations that result in the worst loading, using the loads to select sufficient exterior and interior column sections.

7. Perform a computer analysis to determine forces, moments and deflections (both first- and second-order) for the load combinations prescribed by the applicable building code. The effects of leaning columns (if any) should be addressed in this analysis.

8. Use the end moments output by the analysis to calculate the maximum chord force in the joist girder. The chord force is the end moment divided by the depth of the girder, measured in between the centroids of the chords. It is assumed that the centroids of the chords are 1 in. from the top and bottom of the girder.

9. Use Table 2-1 in *SJI Technical Digest 11* (SJI, 2007) to choose a chord angle combination for the top and bottom of the joist girder. Calculate a new approximate joist girder moment of inertia, based on the chosen approximate chord angle section properties at the chosen joist girder depth.

10. Re-enter the new approximate moment of inertia into the model and re-analyze the model. If the new model fails to perform within the chosen drift and deflection parameters, the columns and chords must be approximated again.

Once a suitable design has been chosen for the columns and joist girders, the connections also need to be designed, and checks for local failures of the chords and webbing need to be completed. These last two steps would normally be the purview of the joist manufacturer unless special conditions need to be met.

As described, the method for joist girder design in moment frames is not automated, and the multistep process is iterative. Use of equivalent beam user tables allows this tedious manual approach to be replaced by an automated system of approximation that would yield similar, and potentially improved, results. The user table in this method is created using the entire practical range of chord sizes and a large range of depths. The equivalent beam properties of the joist girder are approximated using the properties from the top and bottom chords along with the selected joist girder depth.

Equivalent Beam Theory

Using equivalent beam theory (EBT), a complex flexural component such as a joist girder or other truss system is modeled as a single beam element with approximate equivalent beam properties. The use of an EBT model dramatically decreases the computational time of the software and the time required to input the joist girder into the structural model. As previously described, SJI provides the moment of inertia approximation given in Eq. 1 (SJI, 2007). As can be seen in Equations 1a and 1b, the approved EBT model is not applicable to joists or joist girders with uneven loading or unequally spaced loading.

Another method of utilizing equivalent beam theory explored by Giltner and Kassimali (2000) involves the direct modeling of a truss. The method involves designing a truss as one normally would for a structure. The loading and design configurations of the structure are considered, which are followed by a complete set of computer modeling under the applicable load cases. After the models are complete, the deflections of the truss are recorded. These deflections are then used to back-calculate the equivalent moment of inertia of a simple span beam with applied end moments. Once the equivalent moment of inertia is calculated, the equivalent beam can be used in the computer model for the entire structure wherever the comparative truss would have been placed. This method works well for a structure using custom trusses that are repeated often through a structure. The main benefit of using EBT is the reduction in processing time because the number of elements is reduced, as well as the time to enter the elements into the program. The method validates that the use of an equivalent beam model has the utility of decreasing the complexity of structural models while maintaining a good approximation of their behavior.

EQUIVALENT BEAM PROPERTY TABLES

In order to implement equivalent beam theory in a design program, a property table was developed for use in STAAD.Pro. Figure 1 presents a representation of the general configuration of a joist girder. The top and bottom chords are composed of two angles while the webbing can be either round or angle sections.

The properties included are typical of those required for user tables in commercial software, and the tables can be easily modified for use with other commercial software programs. Table 1 lists, in order, the properties included in the user table. A description of these properties and their approximations can be found in Appendix A.

Figure 2 displays a portion of the resultant virtual joist girder table. The file is simply a space-delineated text file. It is worth noting that in the virtual joist girder tables, the identifiers (e.g., 20GS1) call out the depth of the girders (e.g., the 20GS1 is 20 inches deep), but they otherwise do not have any significance other than to uniquely identify each data set.

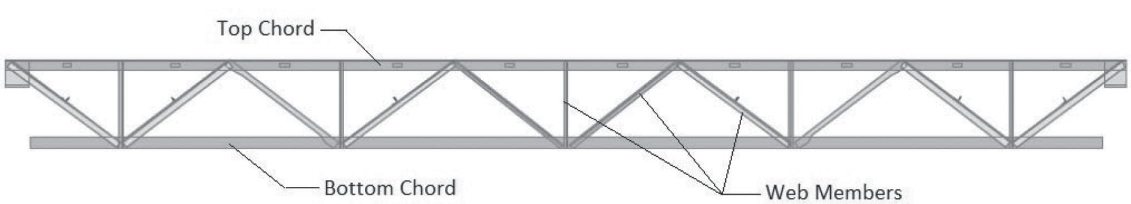

Fig. 1. Joist girder configuration.

The two properties of the most interest to the EOR and the joist designer are the moment of inertia, $I_{zz,}$ and the weight, the latter being approximately proportional to the chords area, A_x. The moment of inertia of a virtual joist girder is calculated using only the chords of the joist girder in the classical fashion. This value is then divided by 1.15 to account for shear deformation in the webbing. The webbing does not contribute any significant flexural stiffness.

The weight is calculated by using the cross-sectional area of the top and bottom chords, but the calculation does not explicitly consider the size of the webbing due to the large variation in webbing members used by joist manufacturers. The density of the virtual joist girder material is set to be the density of steel divided by 0.85 to account for the weight of the webbing. Joist girders with higher span-to-depth ratios will have more weight attributed to the chords, while joist girders with lower span-to-depth ratios will have more webbing and will therefore have less weight attributed to the chords. However, the 0.85 multiplier provides a simple method that represents an approximate average case, where 85% of the total joist girder weight is made up of the chord members.

STAAD.Pro calculates the member weight as a function of the member cross-sectional area and the material density. In order to correctly account for axial stresses in the STAAD.Pro code checks and material selections, it is essential to retain an accurate member cross-sectional area as the sum of the areas of the top and bottom chords. Therefore, the weight of the webs must be accounted for by adjusting the material density. Properties associated with out-of-plane limit states are not calculated in the tables but are set to unity. Lateral torsional buckling and weak-axis bending are not controlling limit states in joist girders due to industry standards for bracing; in instances where the design

Pseudo_Girder_Table - Notepad

File Edit Format View Help

```
UNITS INCHES
GENERAL
20GS1
3.548 20.000 0.667 6.000 0.224 271.802 7.315 1.000 32.730 2.438 0.887 0.887 32.730 1.000 1.000 2.500
22GS1
3.548 22.000 0.733 6.000 0.224 332.638 7.315 1.000 36.227 2.438 0.887 0.887 36.227 1.000 1.000 2.500
24GS1
3.548 24.000 0.800 6.000 0.224 399.644 7.315 1.000 39.724 2.438 0.887 0.887 39.724 1.000 1.000 2.500
26GS1
3.548 26.000 0.867 6.000 0.224 472.820 7.315 1.000 43.220 2.438 0.887 0.887 43.220 1.000 1.000 2.500
28GS1
3.548 28.000 0.933 6.000 0.224 552.166 7.315 1.000 46.717 2.438 0.887 0.887 46.717 1.000 1.000 2.500
30GS1
3.548 30.000 1.000 6.000 0.224 637.682 7.315 1.000 50.214 2.438 0.887 0.887 50.214 1.000 1.000 2.500
32GS1
3.548 32.000 1.067 6.000 0.224 729.368 7.315 1.000 53.710 2.438 0.887 0.887 53.710 1.000 1.000 2.500
34GS1
3.548 34.000 1.133 6.000 0.224 827.223 7.315 1.000 57.207 2.438 0.887 0.887 57.207 1.000 1.000 2.500
36GS1
3.548 36.000 1.200 6.000 0.224 931.249 7.315 1.000 60.704 2.438 0.887 0.887 60.704 1.000 1.000 2.500
38GS1
3.548 38.000 1.267 6.000 0.224 1041.444 7.315 1.000 64.200 2.438 0.887 0.887 64.200 1.000 1.000 2.500
40GS1
3.548 40.000 1.333 6.000 0.224 1157.809 7.315 1.000 67.697 2.438 0.887 0.887 67.697 1.000 1.000 2.500
42GS1
3.548 42.000 1.400 6.000 0.224 1280.344 7.315 1.000 71.194 2.438 0.887 0.887 71.194 1.000 1.000 2.500
44GS1
3.548 44.000 1.467 6.000 0.224 1409.048 7.315 1.000 74.691 2.438 0.887 0.887 74.691 1.000 1.000 2.500
46GS1
3.548 46.000 1.533 6.000 0.224 1543.923 7.315 1.000 78.187 2.438 0.887 0.887 78.187 1.000 1.000 2.500
48GS1
3.548 48.000 1.600 6.000 0.224 1684.967 7.315 1.000 81.684 2.438 0.887 0.887 81.684 1.000 1.000 2.500
50GS1
3.548 50.000 1.667 6.000 0.224 1832.181 7.315 1.000 85.181 2.438 0.887 0.887 85.181 1.000 1.000 2.500
52GS1
3.548 52.000 1.733 6.000 0.224 1985.566 7.315 1.000 88.677 2.438 0.887 0.887 88.677 1.000 1.000 2.500
54GS1
3.548 54.000 1.800 6.000 0.224 2145.119 7.315 1.000 92.174 2.438 0.887 0.887 92.174 1.000 1.000 2.500
56GS1
3.548 56.000 1.867 6.000 0.224 2310.843 7.315 1.000 95.671 2.438 0.887 0.887 95.671 1.000 1.000 2.500
58GS1
3.548 58.000 1.933 6.000 0.224 2482.737 7.315 1.000 99.168 2.438 0.887 0.887 99.168 1.000 1.000 2.500
60GS1
3.548 60.000 2.000 6.000 0.224 2660.800 7.315 1.000 102.664 2.438 0.887 0.887 102.664 1.000 1.000 2.500
62GS1
3.548 62.000 2.067 6.000 0.224 2845.034 7.315 1.000 106.161 2.438 0.887 0.887 106.161 1.000 1.000 2.500
64GS1
3.548 64.000 2.133 6.000 0.224 3035.437 7.315 1.000 109.658 2.438 0.887 0.887 109.658 1.000 1.000 2.500
```

Fig. 2. Excerpt of user table file.

Table 1. Equivalent Beam Properties			
A_x	Total area of the chords	S_z	Elastic section modulus about strong axis
D	Girder depth	S_y	Elastic section modulus about weak axis
TD	Web thickness	A_y	Shear area in *y* direction
B	Flange width	A_z	Shear area in *z* direction
TB	Flange thickness	P_z	Plastic section modulus about strong axis
I_{zz}	Joist girder strong-axis moment of inertia	P_y	Plastic section modulus about weak axis
I_{yy}	Joist girder weak-axis moment of inertia	HSS	Warping constant
I_{xx}	Torsional constant	DEE	Depth of web

requirements require out-of-plane limit states to be considered, this method is not recommended.

VALIDATION STUDIES

A three-stage process was used to establish the validity of the equivalent beam user tables for commercial design use. First, simply supported isolated joist girder designs were considered, eliminating the effect of support conditions or adjoining members on the results, to establish if the user tables were effective in the most fundamental design case. Next, isolated fixed-end joist girders were considered to include the effect of end moment. Finally, simple frames were designed to establish proof of concept, including the effects of adjoining beam-columns and leaning columns.

Because final joist girder design is always performed by the joist manufacturer, the objective was to determine if the moment of inertia and weight of the design software selected virtual joist girders were within an acceptable range of error from the joist girders designed by the robust proprietary joist design software. The primary difference in the two design processes is that the general commercial design software chooses a single-member equivalent beam with approximate property values, whereas the proprietary design software utilizes the actual joist girder truss configuration with multiple members.

Parameters for the isolated joist girder studies (simply supported and fixed) were chosen to represent a reasonably comprehensive, yet practical, range of design conditions. The intent was not to consider every possible permutation, but rather a representation of the practical values in design. The range of parameters was suggested by an advisory group consisting of members of the SJI Research Committee and Engineering Practice Committee based on their years of experience in joist and joist girder design. The ranges for the parameters considered in the single beam studies were as follows:

- Span: 20 ft to 80 ft at 10 ft intervals.
- Panel-point loads: 10 kips to 90 kips at 20-kip intervals.
- Panel-point spacing: 4, 5, 6 and 8 ft.

The joist depth was not an independent parameter, but was determined by design. Span-to-depth ratios were limited to between 12 and 24.

Based on the chosen parameters, there were 105 possible practical permutations of the span, spacing and loading. Combinations that cause overstressed members in the proprietary design program were removed from consideration, as were panel point spacings that did not equally divide the joist length, and joist girders using chords with leg lengths greater than 6 in.

The user table created to provide STAAD.Pro with equivalent beams includes a reasonably comprehensive selection of realistic combinations of chords and depths in joist girders. The two most relevant properties are computed based on SJI suggested values as follows:

$$I_{zz} = \frac{I_{chords}}{1.15} = \frac{\sum (I_{chord} + A_{chord} d^2)}{1.15} \tag{2}$$

$$\text{Material density} = \frac{\text{Density of steel}}{0.85} \tag{3}$$

where

I_{zz} = moment of inertia of the joist to be used in calculations

I_{chords} = moment of inertia calculated from the joist chords not considering web deformation

I_{chord} = moment of inertia of the chord members

A_{chord} = area of chord members

d = distance from the centroid of the chord to the centroid of the joist

The following procedure was used in the verification of the equivalent beam model:

1. Span, spacing and load configuration are chosen. The design is entered into STAAD.Pro, and the program is allowed to choose a joist girder with a depth that is within range of span-to-depth ratios from 12 to 24.

2. The unique identifier, total weight, moment of inertia

Table 2. Pinned-End Virtual Joist Girders with Partial Bracing			
Acceptable variance (±)	10%	15%	20%
Number considered	76	76	76
I acceptable	76%	80%	84%
Weight acceptable	63%	72%	83%
Both acceptable	62%	71%	82%

and end moments (if fixed ends) of the joist girder selected by STAAD.Pro are recorded.

3. The depth of the selected joist girder, along with the same span and loading configuration, is entered into the proprietary joist girder design software.

4. The corresponding results are compared and the variation in results is calculated.

To provide a full set of test permutations, the same procedure was run for joist girders of the same span, spacing and loading configuration, except a depth was specified in STAAD.Pro. This produced values that might be encountered in situations where architectural constraints might affect allowable joist depth.

Simply Supported Joist Girders

The model used for the simply supported joist girder studies is shown in Figure 3. Here, S_{pp} is equal to the panel point spacing; the other variables are defined in Equations 1a and 1b.

The first set of simply supported beam studies were run according to the previously described equivalent beam testing procedure. At the end of the study, 76 cases produced designs with an angle leg of 6 in. or smaller; this limit was recommended by the SJI advisory group and imposed in these studies. The results are summarized in Table 2. Complete results are reported in Knodel (2011). Results of a single beam test were deemed "acceptable" if the value of Equation 4 was within a designated variance from the proprietary software values and given by:

$$\frac{\text{STAAD\_value} - \text{P.Software\_value}}{\text{P.Software\_value}} \times 100\% \tag{4}$$

where

STAAD_value = moment of inertia or weight of joist girder selected by STAAD.Pro

P.Software_value = moment of inertia or weight of joist girder designed by SJI proprietary software

The initial set of simply supported beam studies presented a practical limitation of the virtual joist girder tables. After completing 102 tests on pinned-end joist girders, 76 were included in the results. These did not exceed a 6-in. maximum chord leg, an upper limit suggested by SJI for this study.

Initial examination of the results determined that a number of the joist girders were failing in STAAD.Pro due to lateral torsional buckling (LTB). The parametric study was then re-run with the bracing in STAAD.Pro changed from panel point bracing to continuous lateral support. While the equivalent beam theory works well for in-plane bending of joist girders, the equivalent beam section properties that control lateral torsional buckling—including C_W, I_y and J—have not been well defined for steel joists and are consequently not correctly modeled in the user tables. Additionally, typical steel joists designs have adequate lateral bracing, so LTB

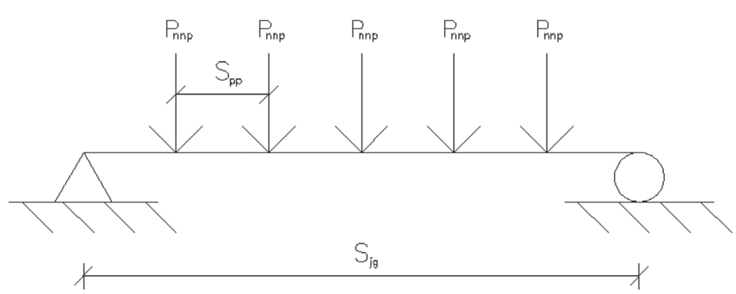

Fig. 3. Simply supported isolated joist girder.

Table 3. Pinned-End Virtual Joist Girders			
Acceptable variance (±)	10%	15%	20%
Number considered	78	78	78
I acceptable	97%	99%	99%
Weight acceptable	72%	86%	97%
Both acceptable	72%	86%	97%

Table 4. Fixed-End Virtual Joist Girders			
Acceptable variance (±)	10%	15%	20%
Number considered	82	82	82
I acceptable	91%	100%	100%
Weight acceptable	71%	91%	99%
Both acceptable	70%	91%	99%

is typically not considered to be a limit state in joist girder design. Changing the lateral support condition changed the controlling limit state to in-plane bending; this represented the joist behavior and allowed for direct comparison with the proprietary joist girder design software results.

Once tests were re-run with continuous lateral bracing, a significant improvement was noted in agreement between the designs of the two programs. With continuous lateral bracing, STAAD.Pro selected lighter joist girders in many instances, resulting in 78 joist girders within the 6-in. maximum chord size limit. These results are summarized in Table 3.

As can be seen in Table 3, the acceptability of the moment of inertia approximation for pinned-end virtual joist girders is close to complete acceptability at a ±10% acceptable variance. It can be seen that increasing the acceptability criteria to ±20% increased the weight approximations acceptability by 25%. It is clearly demonstrated in the overall results that the decision to use a completely braced model results in a much more accurate approximation of actual joist girder behavior.

Fixed-End Joist Girders

The trials on fixed-end joist girders utilized the same virtual joist girder user table as the pinned-end, single beam trials. Out of the 105 joist girders designed, 82 of the designs were at or below the 6-in. maximum chord size limit. A summary of the results is given in Table 4.

As can be seen in Table 4, the acceptability of the moment of inertia approximation for fixed-end virtual joist girders is acceptable 91% of the time when considering ±10% variance. Increasing the acceptability criteria to ±15% increased the weight approximations acceptability from 71 to 91% and the moment of inertia approximation to complete acceptability (100%).

Trends in Variance of Isolated Joist Girder Designs

The results of the beam studies were examined to determine if improvements could be made to the approximate properties typically used by SJI to provide for better estimates in the virtual joist girder user table, particularly with respect to weight. Variance was plotted with respect to depth and length/depth ratios to establish any trends in error that could lead to better estimates for the properties. Figures 4 and 5 show representative plots of the variance data for the fixed-end joist girders comparing moment of inertia and weight to depth, respectively.

As expected, a minor correlation was seen in the variance when considering weight versus span/depth ratio. On average, 85% of a joist girder's weight is from the top and bottom chords. In a more shallow joist girder (span-to-depth ratio of 24), 90% of the joist girder weight will typically come from the chords. In a deeper joist girder (span-to-depth ratio of 12), typically only 80% of the total weight may come from the chords, and the equivalent beam will typically underestimate the weight of deep joist girders. Because the span-to-depth ratio is not a known parameter prior to preliminary design, it was not considered a practical parameter for any possible adjustments to the weight approximation for use in the tables.

Based on the scatter of the data, no significant correlation was established that would provide a means to adjust the weight or moment of inertia approximation. The SJI recommended approach of increasing density by dividing the value of steel by 0.85 was not changed for the remainder of the study nor was the moment of inertia approximation of $I_{chords}/1.15$.

MOMENT FRAME STUDY

To study the behavior of the virtual joist girder method in a system where the effects of adjoining members are considered, a series of frames were run in the same manner as the single beam studies. The parameters of the tests can be seen in Figure 6 and include bay width, L; frame height, H; and leaning column load, αP. Specifically, the value αP represents the destabilizing effect of leaning columns on the frame, where P is an equivalent one-bay load applied as a point load to the column and α is the number of columns "leaning" on the moment frame. The parameters were chosen to represent a typical joist girder design. The parameters of the frame study resulted in 24 unique frames, each with three virtual joist girder spans. Frames with 40-ft spans were designed with a joist spacing of 8 ft. Frames with 50-ft spans were designed with a joist spacing of 5 ft. The frame studies followed the same procedure as the isolated joist girder studies, with one additional step. Once the proprietary software design was complete, the specific properties of that design were input in STAAD.Pro, and the resulting frame designed was analyzed. A comparison of the interaction value of the controlling limit state was made between the preliminary design and the proprietary design to determine the impact of the variation in joist girder properties on the beam-column designs.

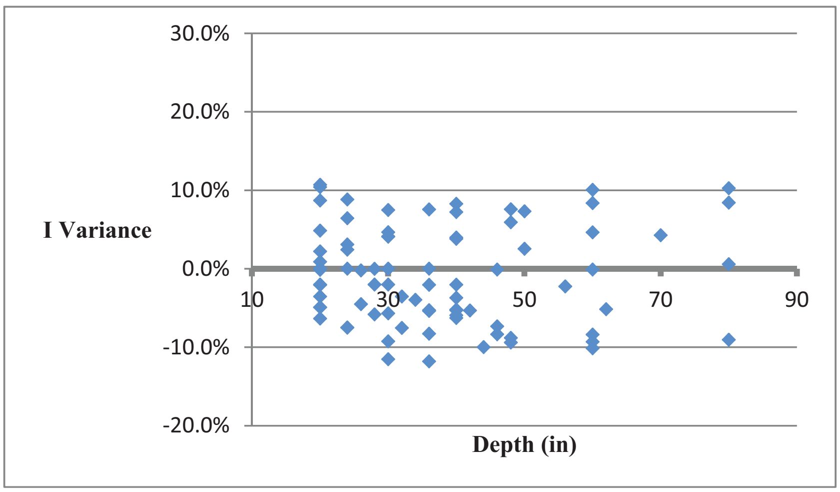

Fig. 4. Fixed-end condition moment of inertia variance versus joist girder depth.

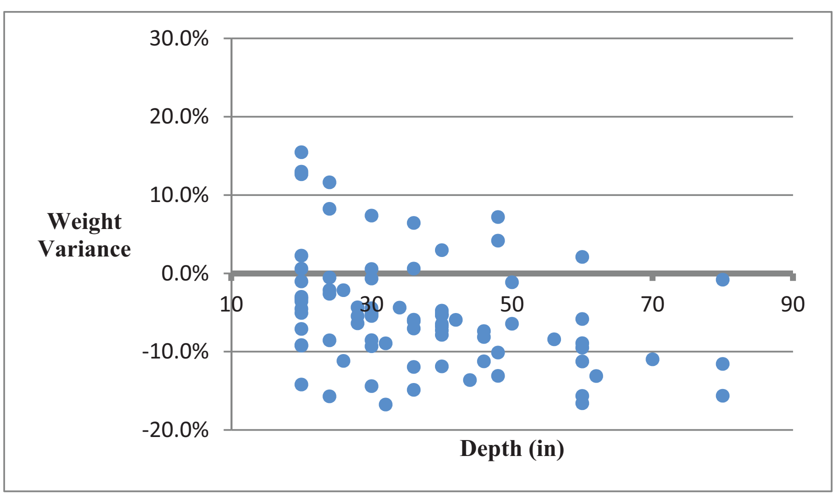

Fig. 5. Fixed-end condition weight variance versus joist girder depth.

Table 5. Fixed-End Virtual Joist Girders in Frames			
Acceptable variance (±)	10%	12.5%	15%
Number considered	72	72	72
I acceptable	88%	96%	100%
Weight acceptable	90%	100%	100%

Frame Study Results

The results from the frame study resulted in a total of 72 tested virtual joist girders. The virtual joist girders selected by STAAD.Pro included no overstressed joists girders or designs with chord sizes with legs longer than 6 in. Table 5 provides a summary of the variances. A summary of all results from the parametric studies is presented in Knodel (2011).

As in the fixed-beam study, the virtual joist girder study results show a high level of acceptability when considering the initial ±10% variance with 100% acceptable variance when considering a ±15% variance. Over the course of the frame study, the column stress ratios and story drifts were recorded. As reported in Knodel (2011), the story drift for all 24 frames never exceeded $H/100$, and 17 of the 24 frames did not exceed an $H/200$ story drift. It can also be seen that the stress ratios for columns never changed more than 5% between the first and second design iterations with the average difference being insignificant (0.2%).

OUTLIER INVESTIGATION

A review was performed of the individual cases in which the variance exceeded 10% in order to establish the specific reasons for the design variations. The review looked at five individual cases and resulted in four different design situations. The reader should note that the five cases examined were above 10% variance when comparing the proprietary software data to the STAAD.Pro data. The final results of the virtual joist girder study are reported using the proprietary software as the baseline.

The first two cases with the greatest variance examined showed that STAAD.Pro picked a virtual joist girder with larger chord sizes than the proprietary software. It was found that when STAAD.Pro picked an initial member size, there was a small overstress that resulted in STAAD.Pro choosing a new, larger section size. Coincidently, the next larger size was a chord with a longer leg length, which dramatically changed the properties. This relatively large change in size pushed the variance over the 10% limit. With further investigation, it was found that the initial small overstress in STAAD.Pro was caused by the approximately 2% increase in loading due to self-weight of the virtual joist girder. Because the self-weight is neglected in the proprietary joist design software settings, the extra stress was not detected and the chords were not upsized. It can be noted that the initial pick by STAAD.Pro—before self-weight calculation—was the same as the proprietary software. It was noticed after the project had been completed that this inconsistency in self-weight inclusion had occurred. While introducing error into the overall results, that error renders the results an upper bound of variance between EOR and joist designer results.

The other three cases examined were very close to the 10% variance limit. In all cases, the STAAD.Pro chord pick

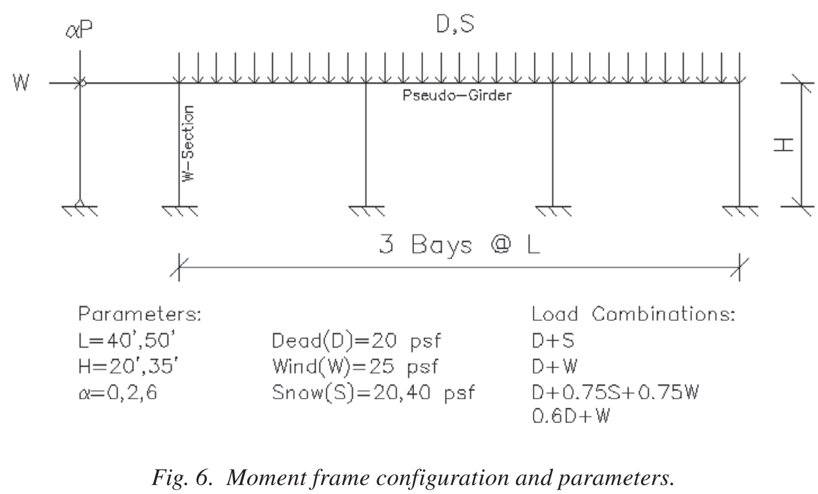

Fig. 6. Moment frame configuration and parameters.

was smaller than the pick from the proprietary joist design software. In two of the cases, clear reasons could be identified for the discrepancies in the designs, as follows:

- In the first case, the joist girder had a localized failure on the chord angle under the high 30-kip loading, which controlled the top chord selection in the proprietary software. If stiffeners were used to support the horizontal leg of the top chord, or some other means were used to minimize the localized bending stress effects, then the STAAD.Pro chord choice would be acceptable.
- The next case suffered in-plane buckling of the four panels nearest the mid-span, which controlled the design of the top chord in the proprietary software. If two panels were added to either side of the midspan, halving the effective panel length, the STAAD.Pro pick would be suitable.

Overall, it is concluded that the outlier conditions found in the study were no different than the typical variance found between the designs of different SJI member companies for the same loading and geometric configuration.

CONCLUSIONS AND RECOMMENDATIONS

Designing with steel joist girders is currently a labor-intensive task, especially when considering design timetables that force early assumptions or designs with complex loadings. An automated design process utilizing a pseudo–joist girder section table allows for changing and complex projects to consider joist girders more readily. The virtual joist girder method provided designs within 10% of the joist girder manufacturer's design approximately 90% of the time, when considering the design moment of inertia, and weight approximations were within 20% variance more than 90% of the time. The single beam studies provide a wide range of possible design configurations. The frame studies showed particularly good results with 100% of the frame designs falling within 15% variance levels; in addition, there was little to no effect on the column response to the variance in the joist girder selections.

Overall, this study suggests that the virtual joist girder user tables provide a straightforward and user-friendly approach for automated preliminary design of joist girders by the specifying engineer. The method for using the tables STAAD.Pro is included in Appendix B, although the tables are easily adaptable for other commercial design programs. Also, although no seismic load conditions were run in the frame studies, there appears to be no reason the approach could not be used for seismic designs utilizing equivalent static seismic loads; design examples with seismic loading will be developed as part of an upcoming SJI research project to determine if any specific limitations are required.

The virtual joist girder tables are available as of this writing (2012) from SJI for use by design engineers, and may be downloaded by visiting http://steeljoist.org/virtual-joist-girder-table. SJI is currently examining extension of the tables to include all open web joists (including K-, LH-, and DLH-series joists) to facilitate improved selection and weight estimation of joists by the EOR when using commercially available structural design software.

ACKNOWLEDGMENTS

This research was sponsored by the Steel Joist Institute. The opinions presented are solely those of the authors and not of SJI or any other organizations. Bentley Systems Inc. provided a seat license for STAAD.Pro for this project, and Phil Hodge provided the HABCO joist design software package currently in use by several SJI member companies.

The authors wish to acknowledge the input and assistance offered by members of the SJI Research Committee, in particular David Samuelson of Nucor Research and Development for Downstream Products and Walter Worthley of Valley Joist Inc.

REFERENCES

Bentley (2007), Staad.Pro Software V7, Bentley Systems Inc., Exton, PA.

Giltner, Brian and Kassimali, Aslam (2000), "Equivalent Beam Method for Trusses," *Practice Periodical on Structural Design and Construction,* ASCE, Vol. 5, No. 2, pp. 70–77.

Green, Perry S., Fisher, James M. and Pote, Joe (2009), "Design of Lateral Load Resisting Frames Using Steel Joists and Joist Girders," *Don't Mess with Structural Engineers: Expanding Our Role, Proceedings of the 2009 Structures Congress,* April 29–May 2, ASCE.

Knodel, Phillip (2011), *Development of an Improved Design Method for Joist Girder Selection in a Generalized Structural Design Program*, M.S. Thesis, South Dakota School of Mines and Technology, Rapid City, SD.

SJI (2007), *Technical Digest 11, Design of Lateral Load Resisting Frames Using Steel Joists and Joist Girders,* Steel Joist Institute, Myrtle Beach, SC.

APPENDIX A

Virtual Joist Girder Properties

A_x Total area of top and bottom chords: Sum of top and bottom chord areas.

D Total joist girder depth.

TD Web thickness: Total depth/30; ensures that the section is treated as compact when considering web shear.

B Flange width: 2 × Chord angle leg + 1 in. chord gap.

TB Flange thickness: (Chord angle thickness/Chord angle leg) × $B/2$; this value results in the correct width-to-thickness ratio when STAAD.Pro checks $(B/2)/TB$.

I_{zz} Joist girder strong-axis moment of inertia: Classically calculated moment of inertial then divided by 1.15 to reduce to obtain an effective I.

I_{yy} Joist girder weak-axis moment of inertia: 2 × Top chord moment of inertia; based on flange (chord) that would typically be in compression; not required in open web joist design.

S_z Elastic section modulus about strong axis: Minimum chord area × Joist effective; reduces the overestimation of chord (flange) stresses. The method substitutes an effective section modulus based on a stress distribution used in classis truss theory of uniform stress distribution across the cross section of the member.

S_y Elastic section modulus about weak axis: Section modulus of top chord; a reasonable conservative value used when joist girder is used in out-of-plane bending.

A_y Shear area in y direction: $A_x \times 0.25$; based on an approximation of the shear area used by SJI for chord shear checks.

A_z Shear area in z direction: $A_x \times 0.25$; based on an approximation of the shear area used by SJI for chord shear checks.

P_z Plastic section modulus about strong axis: Equals S_z; stress distribution is always uniform across the chord in classical truss analysis, whether in a plastic or elastic state.

P_y Plastic section modulus about weak axis: Unity; not required in open web joist design.

HSS Warping constant: Unity; not required in open web joist design.

DEE Depth of web: Equals top chord angle leg length.

APPENDIX B

User Manual

The following instructions are applicable for the use of the virtual joist girder user table in STAAD.Pro.

Installing User Table File

1. Create directory (folder) for STAAD.Pro design files that will be using the virtual joist girder user table.
2. Place a copy of the user table file into the same directory.
3. Any design files saved in a directory without the user table file will not be able to access the user table data.

Activating User Table

1. In modeling mode select *Tools*.
2. Select *Create User Table*.
3. In the pop-up window select the *New Table* button.
4. Checkmark the *External Table* box and select the *Browse* button.
5. Select the user table file and click *Open*.
6. In the *Select Section Type* drop down menu, choose *General* and press *OK*.
7. The user table should automatically be given a number. Press *Close*.

Assigning User Table Data

1. In modeling mode, select the *General* tab.
2. In the Properties–Whole Structure window, select the *User Table* button.
3. Choose the previously assigned user table number.
4. Select a section and assign the appropriate material.
5. Select *Add* and close the window.
6. Assign virtual joist girder sections from the Properties–Whole Structure window in the same manner as with ordinary sections.

Virtual Joist Girder Material Properties

Virtual joist girders use the same material properties as steel, except with a higher density. Then density modification is required to accurately approximate the weight of a steel joist girder.

To create a new material in STAAD.Pro:

1. In modeling mode, select the *General* tab.
2. Select the *Material* tab.
3. Select the *Create* button in the pop-up window.
4. Name the new material and enter the following data:
   Young's modulus, E = 2.9e+007 lb/in.^{2}
   Poisson's ratio, ν = 0.3
   Density = 0.333 lb/in.^{3}
   Thermal coefficient, α = 6e–006
   Critical damping = 0.03
   Shear modulus, G = 1.1154e+007 lb/in.^{2}

Notes on Using the Virtual Joist Girder User Table

1. All virtual joist girders must be modeled as having an unbraced length of zero.
2. Virtual joist girder designations shown in STAAD.Pro and in the .txt user table file do not correspond to specific joist girders. The virtual joist girders user table is for initial design approximation only.