Proceedings of the
Annual Stability Conference
Structural Stability Research Council
Pittsburgh, Pennsylvania, May 10-14, 2011

Improved Joist Girder Moment Frame Design Using Equivalent Beam Theory

P.A. Knodel[1], A.E. Surovek[2], J.J. Pote[3]

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/system weights. Currently commercially available structural design software packages do not have the capabilities to estimate joist girder weight or section properties correctly, if at all, due to the proprietary nature of joist girder design. For joist girders in moment frames, this is particularly critical, since correct estimation of properties is critical for accurate distribution of forces in the analysis.

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, 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 manufacturer's designs as well as examples that illustrate the practical application of the approach.

1. Background and Motivation

Joist girders are widely used in design of industrial and retail buildings. The long spans provided by joists allow for large, purpose-flexible areas for its occupants. However, joist girders, which support other framing members, pose challenges to the engineer of record. Selection of simply supported steel joists is straightforward using supplied tables, assuming typical loading and detailing. The design of joist girder moment frames is complicated by the iterative nature of the process; a change in the moment of inertia of the joist girder can significantly affect the distribution of moments and forces in the framing system, and selection of the joist girder cannot

[1]Graduate Research Assistant, Civil and Environmental Engineering, South Dakota School of Mines and Technology, Rapid City, SD, phillip.knodel@mines.sdsmt.edu
[2]Associate Professor, Civil and Environmental Engineering South Dakota School of Mines and Technology, Rapid City, SD, Surovek@sdsmt.edu
[3] Director of Research & Development, New Millennium Building Systems, LLC, Joe.Pote@newmill.com

be determined simply from initial load and deflection requirements. Consequently, proper estimates of joist girder properties are necessary for correct modeling and communication between the engineer of record and the joist engineer regarding the design.

The current design practice used for the design of joist girder moment frames (JGMF's) 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). In the methodology presented, a model of the frame is developed for computer based analysis using equivalent beam theory to model the joist girder, with an additional model required for seismic categories D – F. Equivalent beam theory (EBT) is used to model the joist girder with a prismatic beam section. This requires a reasonable estimate of the equivalent section properties by the design engineer. There are three 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 I_{eff} and 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. Since 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%.
- If the discrepancies between the properties determined from the final design by the joist engineer and those used in the analysis by the EOR are large enough, redesign may be necessary based on sizes determined by the joist engineer.

Unlike standard rolled shapes, joists and joist girders are custom designed for specific applications. Specific panel layouts and material sizes vary between manufacturers and may even vary between different plants or different design engineers for the same manufacturer. It is for that reason that it is 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.

Most commercial structural design software allows the user to build custom beam tables with custom section properties. For pseudo-girder tables developed for this project to be used in commercial software, the properties in the custom tables do not represent any specific joist girder or the exact properties of the final girder design. Instead, they are approximations based on typical available chord sizes and some typical ratios of weights. If the user table approach is successful, appropriate joist girder section properties could be estimated for use with any commercial structural software system. The created tables could be used in a wide range of applied design loads, including lateral load resisting moment frames. The objective is to be able to define a pseudo-girder equivalent beam table that will yield relatively close approximations of joist girder section properties and weights. This tool would allow specifying professionals to easily include joist girders in their building design models, in the same automated approach used for wide flange beams.

2. Equivalent Beam Theory

To simplify the structural analysis of a lateral load resisting frame utilizing a joist girder, the joist girder is modeled as one a single element as an alternative to the intricate modeling of every piece making up the joist girder. This is an equivalent beam theory (EBT) model. The use of an EBT model dramatically decreases the computational time of the software and the time required inputting the joist girder into the structural model. In the traditional EBT model, an equivalent moment of inertia, I_{eq}, is assigned to the joist girder. The equivalent moment of inertia is approximated by

$$I_{eq} = 0.027 N P_{npp} S_{jg} d \tag{1}$$

where

- I_{eq} is the equivalent moment of inertia (in^4),
- N is the number of joist spaces,
- P_{npp} is the panel point load (kips),
- S_{jg} is the joist girder span (ft), and
- d_{jg} is the effective joist girder depth (in).

As can be seen in Eq. 1 (SJI 2002), in the traditional EBT model there is no consideration for uneven loading or unequally spaced loading. There are also no approximations for other properties of a joist girder that would influence their performance in a lateral load resisting moment frame. Because joist girders require sufficient bridging and lateral support to prevent lateral torsional buckling, pseudo-joist girders are modeled with continuous lateral support to preventing global lateral torsional buckling of the member. Lateral and torsional forces produced by joists connected at panel points are not considered as the joists are laterally supported by bridging at the bottom chord and by the roof deck-plate at the top chord, essentially limiting their effect to negligible. The user table approach requires that there be approximate values for all the general section properties of a structural member.

3. Pseudo-Girder Table

The user table created to provide equivalent beam properties is based on a list provided by industry professionals that includes a comprehensive selection of realistic combinations of chords and depths in joist girders. The current table was developed for use with STAAD.Pro, but the process is adaptable to other commercial software applications. The properties of the joist girders are modified to better simulate their performance as an equivalent beam. In Table 1 the pseudo-girder section properties are listed along with how their modified values were derived.

After the pseudo-girder combinations are created, the sections are sorted by equivalent moment of inertia, cross-sectional area, and depth. The sorted list of sections is then converted into a .txt file that is readable as a user table by STAAD.Pro, as seen in Fig. 1. The values in the user table file are column delineated. The corresponding property labels correspond to the order of the section properties as listed in Table 1.

Table 1: Pseudo-Girder Table 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" Chord Gap
TB:	Flange Thickness - (Chord angle thickness)/(chord angle leg)*B/2; This value results in the correct width/thickness ratio when STAAD checks (B/2)/TB
I_{zz}:	*Joist Girder Strong-Axis Moment of Inertia* - Classically calculated then divided by 1.15 to reduce for "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.
S_z:	*Section Modulus About Strong-Axis* - Minimum Chord Area*Joist Effective Depth; Reduces the over-estimation 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:	*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 (out-of-plane bending is not recommended)
A_y:	*Shear Area in Y Direction* - Ax*.25; Based on an approximation of the shear area used in SJI spec's for chord shear checks.
A_z:	*Shear Area in Z Direction* - Ax*.25; Based on an approximation of the shear area used in SJI spec's for chord shear checks.
P_z:	*Plastic Modulus About Strong-Axis* - Equals Sz; Stress distribution is always uniform across the chord in classic truss analysis, whether in a plastic or elastic state.
P_y:	*Plastic Modulus About Weak-Axis* - Unity; is not a significant factor in current analysis.
HSS:	*Warping Constant* - Unity; torsion is not a significant factor
DEE:	*Depth of Web* - Equals top chord angle leg length

```
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
```

Figure 1: Excerpt of Pseudo-Girder User Table Text File

4. Parametric Study

To prove that joist girder could be accurately modeled using EBT, a wide range of joist girder loading situations were run in STAAD.Pro and the results were compared against the joist girders chosen by the SJI-approved joist design program. The parameters considered in the study included:

Span length: 20 – 80 feet in ten foot increments

Panel spacing: evenly spaced panels at 4, 5, 6, and 8 ft

Panel Loading: 10 – 150 kips at 20 kip increments

Span/depth ratio: 12 – 24

These parametric limits, which represent the most common orders placed in the industry, were established based on recommendation of members of the SJI research committee. All possible combinations of span, loading, and spacing were examined, with each combination examined at multiple non-specific depths. All single beam permutations were run in a pinned-pinned scenario and then a fixed-fixed scenario to represent a joist girder in a lateral load resisting moment frame. The initial study considered simply supported and fixed end joists to validate the selection process. Only joists that are constructed of joists with chords of 6”x6”x3/4” angle or smaller are considered in the overall results.

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

1) A span, spacing, and load configuration are chosen. The model is entered into STAAD.Prowhich then chooses a joist girder with a depth that is within the span/depth ratio of 12 to 24.
2) The designation, total weight, and moment of inertia value of the joist girder selected by STAAD are recorded.
3) The depth of the selected joist girder, along with the same span and loading configuration, is entered into the SJI-approved joist and joist girder design program.
4) The corresponding results are compared for equivalency of design parameters.

The results returned by the proprietary software were compared to the results returned by STAAD.Pro using the pseudo-girder user table in the manner shown in Eq. 2.

$$\%_{diff} = \frac{PS_{value} - STAAD\_value}{STAAD\_value} \times 100 \qquad (2)$$

where PS_{value} is the result generated from the SJI-approved proprietary software and STAAD_value is the result returned by STAAD after picking a suitable pseudo-joist girder. The overall results of the fixed-end and pinned-end pseudo-girder tests can be seen in Table 2 and Table 3, respectively.

The initial acceptance criteria set for the comparisons for the pseudo-girder approximations to be within +/- 10% of the SJI approved software’s results. The approximate section properties were within the 10% limit for the moment of inertia over 90% of the time. The weight approximation, however, was within the limit 66% of the time for fixed-end pseudo-girders and 71% of the time for pinned-end pseudo-girders. As can be seen in Table 2 and Table 3, the number of acceptable tests increased significantly with a small increase in acceptable error. The data generally trended evenly across the positive and negative error regions, as displayed in Fig. 2. No major trends were observed in the data from the weight results or when comparing to span or panel point loading.

Table 2: Fixed-End Pseudo-Joist Girders

Acceptable Difference (+/-)	10%	15%	20%
Cases Considered	82	82	82
Moment of Inertia Acceptable	91%	100%	100%
Weight Acceptable	66%	85%	98%
Both Acceptable	65%	85%	98%

Table 3: Pinned-End Pseudo-Joist Girders

Acceptable Difference (+/-)	10%	15%	20%
Cases Considered	78	78	78
Moment of Inertia Acceptable	94%	99%	99%
Weight Acceptable	71%	85%	91%
Both Acceptable	68%	85%	91%

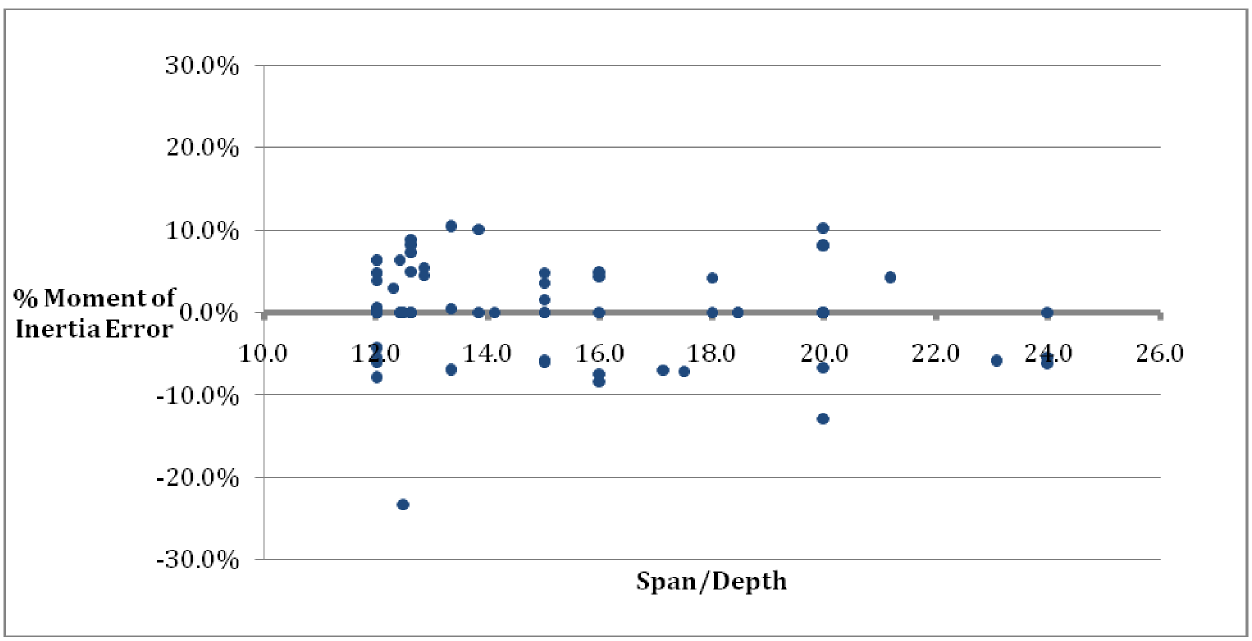

Figure 2: % Moment of Inertia Error vs Pinned-End Joist GirderSpan/Depth

5. Frame Example

To demonstrate the effectiveness of the equivalent beam method in more complex frames, a design example is presented. Fig. 3 shows a model of a three bay, single story frame.The columns are composed of W-sections and are topped with joist girders with moment connections. The panel point loading on the pseudo-girders are products of the per-square-foot gravity loads and the tributary areas of the connecting joist system. Connection flexibility effects were ignored.The loading is intended to mimic that of a typical retail outlet that sees a low amount of equipment being fitted to the roof or ceiling.The frame is resisting dead, snow, and wind loadings. The joistgirder is connected as a lateral load resisting load frame and the columns are fixed at the supports. With the equivalent beam method, the joists are modeled as a single element in the frame with continuous lateral support. The design considered the wind loading in separate iterations of the design to account for the wind approaching in either direction. The model used initial guess sizesfor all members, which were run through three design iterations to optimize the sections for the columns and the joist girders.Once the pseudo-joist girder sizes were chosen, the corresponding gravity loading and end moments were inputted into the SJI-approved joist girder design software. The overall results of the design example can be viewed in Table 4. All results in Table 4 were calculated using Eq. 2.

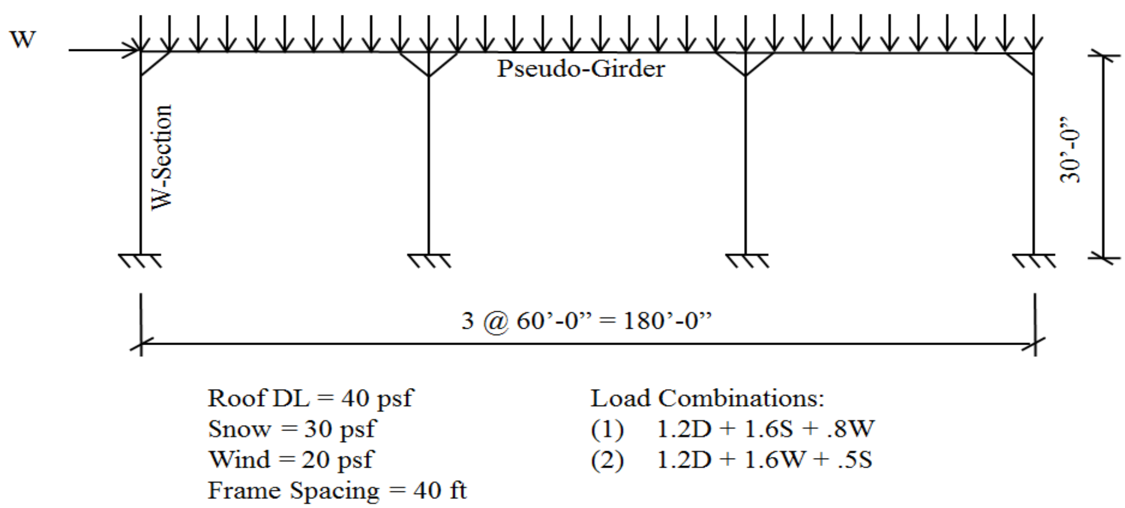

Figure 3: Representation of 3-Bay Lateral Load Resisting Frame Example

Table 4: Differences in Outputs for Joist Girders Between STAAD and SJI-Approved Joist Girder Software for Design Example

	Load Case 1		Load Case 2	
Bay (Left to Right)	% Moment of Inertia Difference	% Weight Difference	% Moment of Inertia Difference	% Weight Difference
1	10.4%	10.5%	0.1%	3.3%
2	-1.9%	0.2%	-4.3%	1.9%
3	10.4%	10.5%	0.1%	3.3%

The frame design example returned results that were similar to the results obtained from the parametric study of single, pinned-pinned and single, fixed-fixed beams. The joist girders chosen using the equivalent beam user table were completely within the +/- 10% acceptability criteria for load case 2, while the results for load case 1 were close to +/- 10% limit.From this example it can be expected that one can successfully use EBT to approximate joist girder sizes in large structures. The sections chosen from the pseudo-girder user table will give the engineer of record a good approximation of the depths and moments of inertia of joists required for joist girder, which are an important deliverable to the joist girder manufacturer.

6. Seismic Design/Future Work

Seismic loading is the dominant failure mode for many areas. For the pseudo-girder method to applicable to the engineer of record, it must be able to work in the complex models used to design for the behavior of buildings under seismic loading conditions.The next step for the research is to validate the use of EBT in planar frames and in three-dimensional structural design when undergoing seismic loading.

7. Conclusions

Designing with steel joist girders in mind 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 would allow for changing and complex projects to consider joist girders more readily. This paper has shown that the pseudo-girder process provides good approximations of necessary moment of inertia and weight values for pinned and fixed joist-girders. Future research will be in regard to the applicability of the process to seismic design and the applicability in three-dimensional models.

Acknowledgments

This research is 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 Delta Joist, East Coast Steel, Gooder-Henrichsen, & Valley Joist

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

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*, American Society of Civil Engineers,

Kim, U.S. (2003), “Seismic Behavior of Steel Joist Girder Structures,” Ph.D. Dissertation, School of Civil and Environmental engineering, Georgia Institute of technology, Atlanta, GA.

Kim, U., Leon, R.T., Galambos, T.V. (2007). “Seismic Design of Steel Joist Girder Structures.”*Engineering Journal,* AISC, Vol. 44 No. 3, pp. 233 – 242.

Pote, J. J. (2009). “Design of Lateral Load Resisting Frames Using Steel Joists and Joist Girders.” *Proceedings of the ASCE Structures Congress*,Austin. TX. 1431-1446.

SJI (2002), *Standard Specifications – Load Tables and Weight Tables for Steel Joists and Joists Girders,* 41st Ed., Steel Joist Institute, Myrtle Beach, SC.

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