Data Article

Steel benchmark frames for structural analysis and validation studies: Finite element models and numerical simulation data

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\textbf{A B S T R A C T}

A sample of twenty-two steel benchmark frames was formed and used to investigate the accuracy of a single increment predictor-corrector (SIPC) solution scheme; an approximate method of second-order elastic analysis. Each of the frames is based on a structure from the literature and, as a collection, the set includes a diverse assortment of practical planar geometries and a wide range of sensitivities to second-order effects. This data article presents the details of these frames, including finite element models, relevant nodal coordinates and element connectivity, and detailed information regarding member sizes, support conditions, and applied loading. In addition, this article presents simulation data obtained from testing the SIPC method using the benchmark frames, and assessing its accuracy and precision. Error analysis results, based on comparisons of joint displacements and member design moments simulated using the SIPC method with those obtained using the more exact and computationally expensive work-control (WC) method, are summarized. The finite element modelling and subsequent structural analysis utilized the software package MASTAN2, which provides user-friendly features to execute both SIPC and WC methods. A detailed description of these analysis methods and the algorithms used to generate data is provided in “Efficient geometric nonlinear elastic analysis for design of steel structures: Benchmark studies” Ziemian and

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Ziemian [1]. The benchmark frame models are more generally useful for any researcher interested in testing and validating structural analysis and design methods, and the simulation data allow for comparisons with the results of other proposed solution schemes.

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### Specifications Table

| Subject | Structural Engineering, Structural Stability |
|---------|---------------------------------------------|
| Specific subject area | Finite element analysis of steel benchmark frames; simulation of second-order elastic response to applied loading. |
| Type of data | Table, Figure, Graph |
| How data were acquired | Software: MASTAN2 (www.mastan2.com); Finite element models and numerical simulation of frame analysis |
| Data format | Raw; Source files: MASTAN2 Finite element models |
| Parameters for data collection | Finite element models of benchmark frames were created using MASTAN2 structural analysis software. |
| Description of data collection | Frames were analysed using the proposed approximate method (Single Increment Predictor-Corrector or SIPC), the more exact work-control (WC) method, and a first-order linear analysis (LA) [1]. The geometric nonlinear elastic response of each frame was simulated using SIPC and WC methods, by applying features provided within MASTAN2. Data comparisons and error analysis were performed using MATLAB. |
| Data source location | Bucknell University, Lewisburg, Pennsylvania, USA. |
| Data accessibility | Repository name: Mendeley Data |
| Related research article | C.W. Ziemian, R.D. Ziemian, (2021). Efficient geometric nonlinear elastic analysis for design of steel structures: Benchmark studies, Journal of Constructional Steel Research, 186, https://doi.org/10.1016/j.jcsr.2021.106870. |

### Value of the Data

- The data provides a variety of useful resources for investigating structural behaviour and analysis methods using finite element software. The set of twenty-two benchmark frame models is important for testing/validating computational analysis methods and comparing results with those from commercial software and/or other works in the literature.
- Researchers and practicing engineers interested in studying or validating structural design and analysis methods and/or newly proposed solution schemes can use the developed set of benchmark frame models, which includes a variety of structural systems with a range of sensitivities to second order effects, realistic geometries, and boundary conditions that satisfy current design codes. Researchers and practicing engineers can also use the provided frame models/data and the associated analysis results to compare the performance of other proposed solution schemes to that of the SIPC method.
• The finite element models of the perfect and/or imperfect frames can be directly opened in MASTAN2 and further studied using any of the analyses and graphical visualization features available in the software. The frame nodal and connectivity data can be used to create the same benchmark structures (perfect and/or imperfect geometries) with other finite element software packages. The numerical simulation data can be used and/or reproduced as a basis for comparison with the results of other second-order elastic analysis methods or different approximate solution schemes.

1. Data Description

This data article presents the computational models and details associated with a collection of twenty-two planar steel frames, as well as the numerical simulation data produced by elastic analyses performed on the frames.

The benchmark frames are introduced in Fig. 1, which displays the structure’s geometry, load case investigated, and critical buckling load ratio \( \alpha_{cr} \). For each frame in Fig. 1, the following data are provided in the Mendeley data repository [3]:

• Description of principal characteristics, including geometry, member sizes, and loading details (PDF file). A sample of this data is presented in Fig. 2.
• Finite element models of both perfect and imperfect (with global sway) geometries (MASTAN2 [2] files).
• Finite element model data for both perfect and imperfect geometries (Excel file), including nodal coordinates and element connectivity, useful for creating the same frame models with other analysis programs.

Fig. 2 illustrates the detailed descriptive information that is provided as supplementary data [3] for each frame.

This set of benchmark frames has been used to test and validate a proposed solution scheme for the approximate second-order elastic analysis of structures; the single increment predictor-corrector (SIPC) method [1]. Table 1 presents a summary of the error analyses completed to assess the accuracy and precision of the SIPC method, including comparisons of simulation data produced using SIPC with those produced using the more exact and computationally expensive work-control (WC) method [13].

Table 1 also includes two indicators used to assess each frame’s sensitivity to instability. The first is an amplification factor proposed by Merchant [14] to estimate second-order forces from first-order LA results. Merchant’s amplifier is based on a frame’s critical buckling load factor, \( \alpha_{cr} \), as follows:

\[
A_{F_{\alpha_{cr}}} = \frac{1}{1 - \frac{1}{\alpha_{cr}}}
\]  

(1)

The second indicator is the maximum ratio of second-order (WC) to first-order (LA) lateral joint displacements at any joint in the frame, or \( \frac{\delta_{\text{WC}}}{\delta_{\text{LA}}} \). A comparison of the two indicators is presented in Fig. 3.

The Mendeley data repository [3] includes an Excel data file with a tab for each benchmark frame. Each tab lists the lateral displacements of every joint and the design moments (maximum moment) in every member in the frame, as simulated by WC, SIPC, and LA analyses for both imperfection (and lateral loading) directions; for the load cases investigated. This file also provides the critical buckling load ratio, \( \alpha_{cr} \), for each frame, corresponding to the lowest sway buckling mode of the structure, as determined in an elastic eigenvalue buckling analysis (LBA) within MASTAN2.
Fig. 1. Overview of benchmark frames, including geometry, dimensions, load combination investigated, and critical buckling load ratio ($\alpha_{cr}$). Global imperfections are in the direction of lateral loading, unless otherwise noted. (a) Frame 1; (b) Frame 2 [4]; (c) Frame 3 [5]; (d) Frame 4 [6]; (e) Frame 5 [7]; (f) Frame 6 [7]; (g) Frame 7 [7]; (h) Frame 8 [7]; (i) Frame 9 [8]; (j) Frame 10 [9]; (k) Frame 11 [4]; (l) Frame 12 [10]; (m) Frames 13-16 ($n = 0, 4, 8, 12$ lean-ons) [11]; (n) Frame 17 [12]; (o) Frame 18 [12]; (p) Frame 19 [12]; (q) Frames 20-22 [12].
Fig. 1. Continued
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Fig. 2. Sample of the detailed information available for each benchmark frame.
Table 1
Percent errors from comparisons of SIPC and WC results for benchmark frames (conservative (+) and un-conservative (-)). Frames sorted by indicators of stability sensitivity, $A_F'\text{cr}$, and $(\delta_{\text{wc}}' / \delta_{\text{cr}})_{\text{cr}}$, from least to most sensitive.

| No. | $A_F'\text{cr}$ | $\delta_{\text{wc}}' / \delta_{\text{cr}}$ | Lateral joint displacements | Member design moments |
|-----|-----------------|-------------------------------|-----------------------------|-----------------------|
|     |                 |                               | Min | Median | Max | Range | Min | Median | Max | Range |
| 1   | 1.14            | 1.15                          | −0.82 | −0.82 | −0.81 | 0.01 | −0.83 | −0.68 | −0.68 | 0.16 |
| 12  | 1.16            | 1.17                          | −1.14 | −1.12 | −1.05 | 0.09 | −1.20 | −0.36 | −0.01 | 1.19 |
| 18  | 1.15            | 1.17                          | −1.12 | −1.04 | −0.61 | 0.51 | −0.90 | −0.52 | −0.02 | 0.88 |
| 21  | 1.17            | 1.18                          | −1.22 | −1.18 | −0.61 | 0.61 | −1.33 | −0.87 | −0.04 | 1.29 |
| 22  | 1.18            | 1.19                          | −1.33 | −1.23 | −0.52 | 0.82 | −1.56 | −0.92 | 0.07  | 1.48 |
| 7   | 1.18            | 1.19                          | −1.20 | −0.71 | −0.21 | 1.00 | −1.04 | −0.01 | −0.01 | 1.03 |
| 13  | 1.17            | 1.19                          | −1.37 | −1.27 | −0.86 | 0.51 | −1.59 | −0.63 | 0.00  | 1.59 |
| 2   | 1.16            | 1.20                          | −1.64 | −1.27 | −1.24 | 0.40 | −0.65 | −0.63 | −0.61 | 0.04 |
| 20  | 1.20            | 1.21                          | −1.60 | −1.56 | −0.88 | 0.71 | −1.74 | −1.03 | −0.02 | 1.71 |
| 11  | 1.24            | 1.30                          | −2.96 | −2.73 | −2.43 | 0.53 | −2.35 | −0.41 | 0.00  | 2.35 |
| 14  | 1.33            | 1.37                          | −4.08 | −3.79 | −2.47 | 1.61 | −4.76 | −2.19 | −0.01 | 4.75 |
| 8   | 1.38            | 1.41                          | −4.54 | −2.71 | −0.88 | 3.66 | −3.98 | −0.01 | −0.01 | 3.97 |
| 5   | 1.36            | 1.42                          | −5.50 | −4.97 | −4.49 | 1.01 | −2.07 | −0.82 | −0.04 | 2.03 |
| 15  | 1.52            | 1.60                          | −8.31 | −7.73 | −5.06 | 3.25 | −9.65 | −4.65 | −0.01 | 9.64 |
| 9   | 1.41            | 1.62                          | −8.95 | −7.89 | −6.51 | 2.44 | −2.90 | −0.04 | 1.59  | 4.49 |
| 16  | 1.69            | 1.79                          | −12.08 | −11.25 | −7.43 | 4.65 | −13.96 | −7.13 | −0.02 | 13.95 |
| 3   | 3.40            | 3.58                          | −39.78 | −39.72 | −39.60 | 0.18 | −38.59 | −38.57 | −38.56 | 0.03 |
| 10  | 4.36            | 4.27                          | −54.04 | −50.50 | −47.33 | 6.71 | −51.24 | −0.19 | 27.02 | 78.26 |
| 4   | 6.05            | 6.22                          | −59.73 | −59.55 | −59.37 | 0.36 | −46.48 | −6.25 | −3.29 | 43.19 |

Fig. 3. Plot of the maximum ratio of second- to first-order lateral displacements at any joint in each benchmark frame, shown together with function representing Merchant’s amplification factor [14].
Table 2
Details of finite element modeling of benchmark frames.

| Geometry                          |  |
|----------------------------------|---|
| Members                          | Modeled as 4 planar line (6 dof) elements |
| Multiple lean-on columns        | Modeled as single column on each side of frame |
| Imperfections                    | Global sway; Magnitude: H/500; Direction: same as lateral load (or natural lean, for gravity-only frames). Imperfections were modeled by horizontally translating all nodes by an amount equal to their vertical coordinate divided by 500. |

| Material                          |  |
|----------------------------------|---|
| Steel                            | E = 200 GPa (29,000 ksi); $F_y = 345$ MPa (50 ksi) or 250 MPa (36 ksi); Stiffness reduced to $0.8E$, per AISC's direct analysis method (DAM) \[16\], for all elastic analyses; Stiffness reduced to $0.9E$ for geometric and material nonlinear analyses with imperfections (GMNIA); |
| Elastic modulus used             | $F_y$ (for DAM), $0.9F_y$ (for GMNIA); |
| Yield strength used              |  |

| Loading                           |  |
|----------------------------------|---|
| Gravity load                     | Distributed loads modeled by equivalent concentrated loads applied at the beam quarter points. Gravity loading includes self-weight of components. |
| Lateral load                     | Applied as concentrated loads in direction as shown (Fig. 1) |
| Live/Dead load ratios            | Equal to L/D of original frame in literature (where applicable) |
| LRFD load combinations \[15\]    | Multi-story frames without wind: $1.2D + 1.6L + 0.5L_e$ |
|                                  | Single-story frames with and without wind: $1.2D + 1.6L_e + (L or 0.5W)$ |
| Load application                 | Single- and multi-story frames with wind: $1.2D + 1.6L_e + 0.5L_e + 1.0W$ |
| Load magnitudes                  | In all analyses, gravity and lateral loads are applied proportionally (simultaneously) |

2. Experimental Design, Materials and Methods

The finite element models of the benchmark frames were created in MASTAN2 as described in Table 2 below.

Several different analyses were performed on each frame model in order to validate the proposed SIPC method and examine its accuracy and precision as a function of the frame's sensitivity to second order effects. The parameter settings used for each analysis type are described in Table 3. Fig. 4 also provides an illustration of how the analysis options are selected within MASTAN2.

The described error analysis is based on comparisons of the lateral displacement of each joint and the design moment in each member in the frame, as simulated by SIPC and WC analyses. As described in \[1\], the WC data was first filtered in order to avoid error calculations on extremely small and insignificant joint displacements and/or member design moments. Specifically, a joint displacement that was less than 1/1000 of the minimum member length in the frame was removed from consideration. Similarly, each member moment was first divided by the product of the member's plastic section modulus and material yield strength, resulting in the associated proportion of the member's plastic moment capacity. These normalized moments from the WC data were then filtered, for the same reasons described above. Specifically, a normalized member moment that was less than 0.10, or 10% of the amount of moment required to form a flexural plastic hinge in the member, was removed from consideration.
Table 3
Details of the computational analyses performed in MASTAN2 on each frame.

| Frame analyses                |                                                                 |
|------------------------------|------------------------------------------------------------------|
| Elastic, first-order         | Used to compute critical buckling load ratio, $\alpha_{cr}$, corresponding to lowest sway buckling mode. Performed on perfect geometry, using stiffness 0.8E. |
| Linear (eigenvalue) buckling analysis (LBA) |                                                                 |
| Linear analysis (LA)         | Results used for computations of second-to-first-order ratios and/or amplification factors. Performed on imperfect geometry, using stiffness 0.8E. |
| Elastic, second-order        |                                                                 |
| Geometric nonlinear analysis with imperfections (GNIA) | Single increment predictor-corrector (SIPC) analysis, a proposed approximate GNIA method; Increment size = 1; Performed on imperfect geometry, using stiffness 0.8E. |
| GNIA                          | Work-control (WC) analysis with step-size = 0.001. Used as the ‘expected’ or ‘exact’ elastic solution for comparisons when assessing the accuracy of the SIPC method; Performed on imperfect geometry, using stiffness 0.8E. |
| Inelastic, second-order      | Results used only to determine magnitude of loading placed on the frames; Performed using modified tangent stiffness method [1] with imperfect geometry, stiffness 0.9E, and yield stress 0.9Fy; Objective is to have structure fail at 1.0*load factor. |
| Geometric and material nonlinear analysis with imperfections (GMNIA) |                                                                 |

Fig. 4. Illustration of MASTAN2 menu selections for SIPC analysis.
All error analyses were based on percent error calculations. For example, the comparison of the lateral displacements of joint $j$ was made by computing the percent error as,

$$\epsilon_j = 100 \times \frac{(\delta_{j}^{SPC} - \delta_{j}^{WC})}{\delta_{j}^{WC}} \tag{2}$$

**Ethics Statement**

The authors did not use any animal or human subjects, and did not use data from social media platforms. This article conforms to Elsevier’s standards of ethical publishing.

**CRediT Author Statement**

**Constance W. Ziemian** Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization; **Ronald D. Ziemian** Conceptualization, Methodology, Software, Validation, Investigation, Writing – review & editing.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that have or could be perceived to have influenced the work reported in this article.

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