A Method for Performing Automated Plastic Mechanism Analyses of Steel Special Concentrically Braced Frames

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ABSTRACT

Special concentrically braced frames (SCBFs) rely on yielding and buckling of the braces to achieve ductility of the system. AISC 341, *Seismic Provisions for Structural Steel Buildings*, requires designers to evaluate the columns, collectors, and connections in SCBFs for the capacity-limited seismic load effect associated with the expected strengths of the braces. In practice, especially for simple or regularly-shaped buildings, designers often compute these force demands by hand and manually combine them with the demands from other loads. However, for irregularly-shaped or atypical buildings, such as large industrial buildings without diaphragms or structures with unevenly distributed mass or stiffness, this can become an arduous task, especially during an iterative design process. The method described in this paper allows designers to automate a plastic mechanism analysis of an SCBF in an analysis model by imposing artificial self-straining (thermal) loads to emulate the capacity-limited seismic load effect.

INTRODUCTION

The Steel Special Concentrically Braced Frame (SCBF) is a seismic force-resisting system utilized in buildings located in regions with high seismicity. SCBFs are designed to achieve larger inelastic deformations than other concentrically braced frames through yielding and buckling of the diagonal braces. Consequently, the American Institute of Steel Construction (AISC) *Seismic Provisions for Structural Steel Buildings* (AISC, 2010a) requires SCBFs to satisfy specific design, proportioning, and detailing requirements to improve the ductility of the system. With regard to proportioning SCBFs, Section F2.3 directs designers to evaluate and design the columns, collectors, and connections in SCBFs to resist the expected strengths of the braces. Specifically, the Seismic Provisions require that designers evaluate two scenarios[1]:

- "An analysis in which all the braces are assumed to resist forces corresponding to their expected strength in compression or in tension."
- "An analysis in which all braces in tension are assumed to resist forces corresponding to their expected strength and all braces in compression are assumed to resist their expected post-buckling strength."

The above *plastic mechanism* scenarios are intended to emulate the capacity-limited seismic load effect that occurs when the braces within the SCBF yield in tension or buckle in

[1]In the most recently published edition of the Seismic Provisions for Structural Steel Buildings, AISC 341-16, Section F2.3 includes a third analysis requirement specific to multi-tiered braced frames. Although beyond the scope of this paper, the principles of the method described herein can be similarly applied to the new scenario.

compression. This seismic load effect imparts forces corresponding to the expected strengths of the braces into the other members and components of the seismic force-resisting system. When designers account for the forces produced by performing the analyses required by Section F2.3, other elements, including the columns, collectors, and connections, will remain elastic and retain sufficient gravity-load carrying capacity as the SCBF undergoes inelastic deformations during a large seismic event.

The expected strengths of the braces used in Section F2.3 are computed using R_y — the ratio of the expected yield stress to the specified minimum yield stress — listed in Chapter A of the Seismic Provisions. Equations 1, 2, and 3 below define the expected tensile, compressive, and post-buckling strengths, respectively.

$$\text{Expected tensile strength} = R_y F_y A_g \quad (1)$$

$$\text{Expected compressive strength} = 1.14 F_{cre} A_g \leq R_y F_y A_g \quad (2)$$

where F_{cre} is the critical stress computed in accordance with Chapter E of the AISC *Specification for Structural Steel Buildings* (AISC, 2010b) using R_yF_y in place of F_y.

$$\text{Expected post-buckling strength} = 30\% \text{ of the expected compressive strength} \quad (3)$$

Photo 1. Large industrial building containing SCBFs
Photo by Simpson Gumpertz & Heger Inc.

For simple or regularly-shaped buildings, designers often utilize hand calculations to evaluate the columns and collectors for the brace forces associated with the plastic mechanism scenarios. Each SCBF bent typically requires analysis of four cases to consider each analysis scenario for both lateral directions. Designers must then compare the resulting demands to those from the standard seismic analysis procedures (e.g. Equivalent Lateral Force Procedure) and combine the governing seismic demands with all other applicable loads.

Some buildings, such as multi-story industrial structures without intermediate diaphragms (Photo 1), contain features that can complicate the plastic mechanism analysis such as overhead bridge cranes and plan bracing. In addition, the design process is often iterative and it is beneficial to develop procedures to automate the plastic mechanism analysis to avoid repetitive hand calculations.

The National Earthquake Hazards Reduction Program (NEHRP) Technical Brief for SCBFs (Sabelli, 2013) addresses the need to perform a plastic mechanism analysis in SCBF design and briefly describes alternative approaches that practitioners may employ to avoid rigorous hand calculations. The approaches include spreadsheet calculations, non-linear analysis software, or performing an elastic analysis with a computer model in which the braces are removed and the forces corresponding to the expected strengths of the braces are applied to the remaining members of the bent. The NEHRP Technical Brief also identifies a variant to the latter method: using self-straining (thermal) loads and modifications to the brace element stiffness in a computer model to simulate the capacity-limited seismic load effect. The thermal loading method forms the basis for the automated plastic mechanism analysis procedure described in this paper. With proper set-up, this procedure can reduce the time required to perform plastic mechanism analyses for complex or iterative design projects.

METHODOLOGY

The automated plastic mechanism analysis method may be conducted using most structural analysis software packages. The procedure consists of the following general steps:

1. Reduce the axial stiffness of the brace elements so that they do not contribute to the lateral force-resistance of the SCBF. Reduce the flexural stiffness of the column elements so that the elements are only able to resist axial tension or compression.
2. Apply artificial lateral spring supports at each level of each SCBF bent, proportioned to match the distribution of the seismic load.
3. Increase the coefficient of thermal expansion of the brace elements and compute the applied thermal loads that produce axial forces in the braces equal to the expected tensile, compressive, and post-buckling strengths.
4. Perform elastic analyses of the structure for the various sets of artificial thermal loads to simulate the capacity-limited seismic load effect scenarios.
5. Perform a gravity load analysis of the structure with the reduced brace stiffness and artificial lateral supports to compute gravity demands without vertical load carried by the braces. Combine the results of the simulated plastic mechanism analyses with the gravity load analysis and incorporate into the complete set of member demands from all other analyses.

The following subsections expand on the general steps for conducting the automated plastic mechanism analysis listed above, including illustrative figures from a recent project for which the authors utilized this method. The example project is a rectangular, 60-ft-tall high-bay industrial structure with overall plan dimensions of approximately 90 feet by 130 feet. The lateral system consists of SCBFs in each direction with three levels of bracing. The bents are not supported out-of-plane by diaphragms or plan bracing at the intermediate levels because the structure houses an overhead bridge crane that operates over the entire length of the building. In addition, this project was subject to frequent changes in structure geometry and was therefore well suited for the automated plastic mechanism analysis method. Figure 1 depicts the east elevation bent in the example structure.

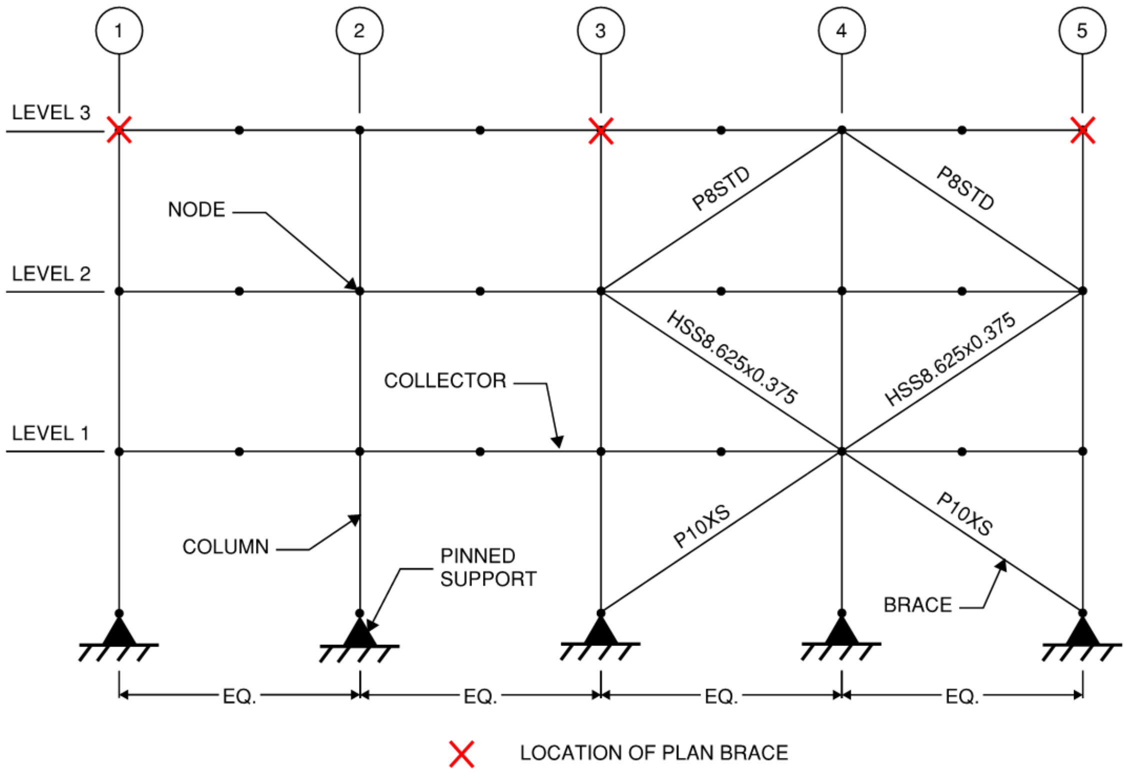

Figure 1. Example SCBF within a bent. Figure by Simpson Gumpertz & Heger Inc.

Step 1: Reduce Member Stiffness

Reduce the axial stiffness of the brace elements by several orders of magnitude so that only the columns and collectors, not the other bracing members, resist the applied brace capacity forces. The softened brace elements should effectively not act as structural members, but merely serve as a means to deliver the expected brace strengths, simulated as thermal loads (described in Step 3 below), to the other members in the SCBF. The brace stiffness may be reduced by either reducing the elastic modulus, E, of the brace element material or by applying an axial stiffness reduction factor with the analysis software. For the example project, the authors reduced the elastic modulus of steel brace elements by a factor of 2×10^6 — from 29,000 ksi to 14.5 psi.

The column elements are temporarily modified to not resist the applied brace forces through column flexure because the purpose of the plastic mechanism analysis is to evaluate the maximum vertical forces in the columns and the maximum horizontal forces in the collectors that result as the braces reach their capacity. The authors found that if column flexural stiffness is not reduced, the columns would resist some of the applied brace forces in flexure. The flexural stiffness of the column elements is reduced by decreasing the strong axis, weak axis, and polar moments of inertia by several orders of magnitude.

The authors also found that other structural members in the model, such as plan bracing, purlins, trusses, girders, and roof diaphragms, often must be softened as well so that these members do not contribute to the lateral stability of the SCBF and inadvertently resist loads from the applied brace forces. In the example project, the overhead bridge crane was explicitly modeled and the double-girder bridge behaved as a diaphragm transferring loads from one SCBF bent to another. Therefore, the stiffnesses of the crane bridge, crane runway, and connecting elements were also reduced. The process of locating and eliminating all lateral resistance pathways outside of the main bent is often iterative and can be a time-consuming task for complex structures.

Step 2: Apply Artificial Lateral Supports

Following the softening of the braces, columns, and other elements, artificial lateral supports must be added to the model at each collector level to resist the story shears induced by the brace capacity forces. The artificial lateral supports take the form of horizontal spring restraints placed at various locations along the length of the collectors. Designers must exercise care to locate and proportion the springs so that the axial force distribution along the length of the collectors closely reflects the distribution of the seismic load along the collector. Due to the softening of the braces and columns in Step 1, the lateral springs provide the only load path to resist the horizontal components of the applied brace forces. Therefore, the total stiffness of the lateral springs at each story does not need to correspond directly to the actual stiffness of the diaphragm or plan bracing. However, the total stiffness of the lateral springs should be significantly smaller than the axial stiffness of the collectors so that the resulting distribution of the horizontal forces accounts for the collector stiffness. For the example SCBF, the total story spring stiffness at each level is 100 kip/in.

At collector levels without diaphragms or plan bracing, such as levels 1 and 2 in the example SCBF, the seismic mass primarily consists of the self-weight of the structure and the mass of the perpendicular end walls. Therefore, designers can place lateral springs at the ends of the bent with a spring stiffness proportional to the distance from centerline of the SCBF. At levels 1 and 2 in the example SCBF, 25% of the total story spring stiffness is apportioned to the right end of the bent and 75% to the left end because braces are located at the quarter-point of the bent. Figure 2 shows the placement of these springs at levels 1 and 2 on the example SCBF.

At collector levels with diaphragms and uniform mass, the magnitude of the collector force varies linearly along the entire length of the bent. To generate analysis results with the correct maximum collector forces in each bay, designers can apply lateral springs at the center of the collector segment in each bay. Each spring stiffness should be proportional to the tributary seismic mass at the respective collector segment; often the tributary seismic mass is proportional to the length of the bay.

At collector levels with plan bracing, the tributary seismic mass is transferred to the collector where plan braces connect to the bent. Designers can apply lateral springs at each plan brace connection point with a stiffness proportional to the seismic mass tributary to each plan brace.

Where seismic load is transferred to a bent by two or more mechanisms (e.g. diaphragms and plan braces), designers can combine the methods described above by first distributing the total story stiffness based on the relative magnitude of seismic load transferred through each mechanism. In the example SCBF, level 3 contains both plan bracing and a flexible roof diaphragm. The seismic load transferred to the collector line from the plan bracing and from the diaphragm are approximately equal; therefore, the total story spring stiffness is divided equally between the plan brace springs and diaphragm springs. 25% of total plan brace spring stiffness (12.5% of the total story stiffness) is apportioned to each of the plan brace points at grids 1 and 5 and the remaining plan brace spring stiffness (25% of the total story stiffness) is apportioned to the plan brace point at grid 3. Meanwhile, 50% of the diaphragm spring stiffness (12.5% of the total story stiffness) is apportioned to the midpoint each of the collector segments. Figure 2 shows the placement of these springs on the example SCBF.

Where necessary, out-of-plane springs or supports must also be applied to provide stability to the structure. The need for out-of-plane support often arises at elements that are softened to prevent unwanted resistance to the brace capacity forces. Therefore, designers may find that locating artificial lateral springs is also an iterative process and contributes to a substantial portion of the effort required to implement the plastic mechanism analysis in a computer model.

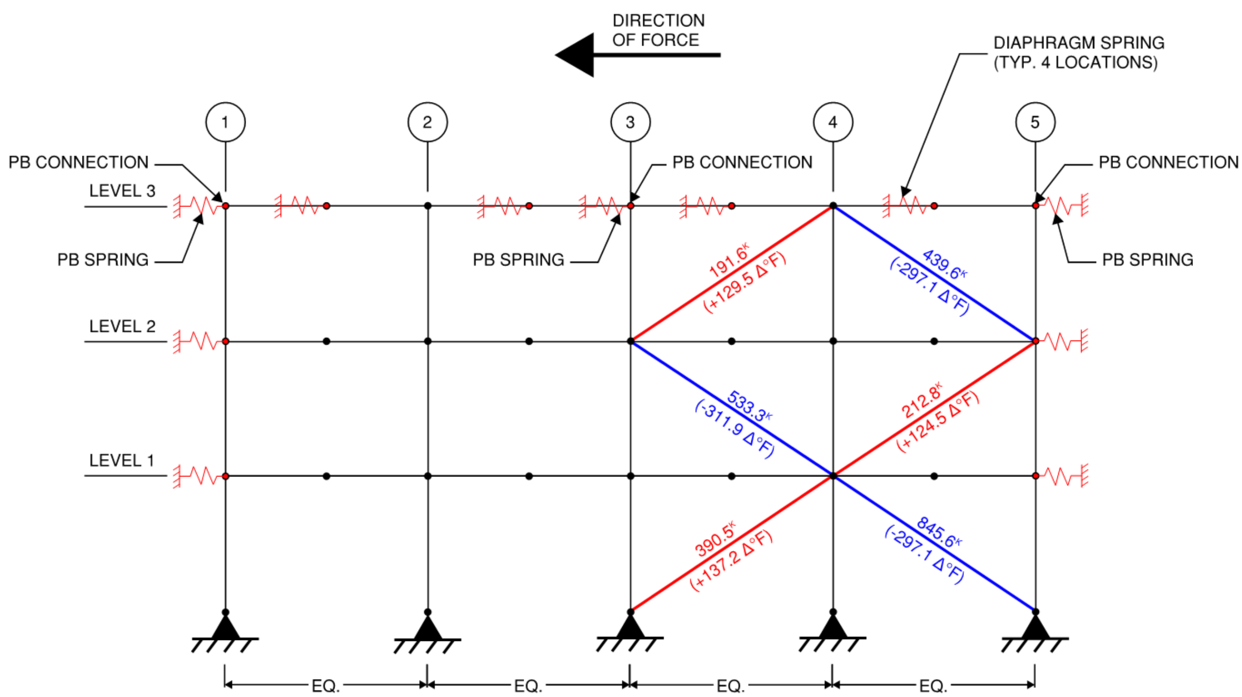

Figure 2. Artificial spring supports, expected strength forces, and associated temperate changes for an example plastic mechanism scenario (PB = plan brace). Figure by Simpson Gumpertz & Heger Inc.

Step 3: Compute Thermal Loads

For each brace within the SCBF, the expected tensile, compressive, and post-buckling strengths must be computed in accordance with Equations 1 – 3. The NEHRP Technical Brief (Sabelli, 2013) and AISC Design Guide 29 (AISC, 2014) state that it is important that the calculations for the expected critical stress (F_{cre}) consider the actual end-to-end length of the brace member. Overestimation of the brace length will cause the calculated expected compressive strength values to be too low, potentially leading to underestimated net column forces in the first plastic mechanism scenario (yielding and buckling). Conversely, underestimation of the brace length causes the calculated expected post-buckling strength value to be too high, resulting in underestimated net column and collector forces in the second plastic mechanism scenario.

The coefficient of thermal expansion, α, of the brace elements should be artificially amplified. For the example project, the authors used a modified coefficient of thermal expansion of 13 °F^{-1}, 2×10^{6} times larger than standard value for structural steel (AISC, 2011). This amplification factor was inversely proportional to the stiffness reduction factor for the braces. Compute the temperature change, ΔT, required to induce the axial force corresponding the expected strength of the brace considering the modified coefficient of thermal expansion as well as the modified elastic modulus of the brace, if applicable.

The computed temperature changes corresponding to the expected tension, compression, and post-buckling strengths are assigned to each brace for both of the plastic mechanism analysis conditions required by Section F2.3, considering both loading directions along the SCBF. Figure 2 shows the brace capacity forces and associated temperature changes applied to the brace elements to generate the capacity-limited seismic load effect in the example SCBF for the first plastic mechanism scenario described in Section F2.3 (seismic motion to the left).

Step 4: Perform Elastic Analyses with Brace Capacity Forces

Following completion of the prior steps, an elastic analysis of the structure subjected to the thermal loads will quickly generate the column and collector demands for the capacity-limited seismic load. Figure 3 shows the results of such an analysis for the example SCBF.

Designers must perform an analysis for each of the plastic mechanism analysis scenarios in each load-resisting direction of the SCBF. Additionally, buildings that contain SCBFs in both orthogonal directions must be designed for all possible combinations of loading scenarios and directionality. Where braces frame into columns in two orthogonal directions, the columns must be designed to resist the total combined vertical load from braces in both directions simultaneously reaching their expected strength.

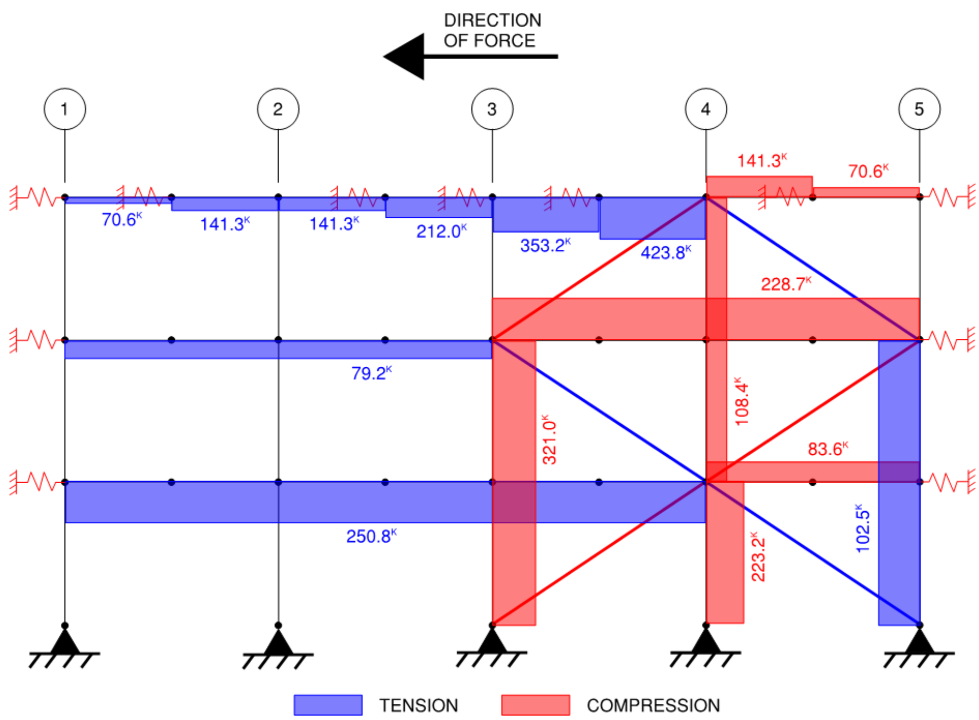

Figure 3. Axial force distribution resulting from thermal loads imposed on braces. Figure by Simpson Gumpertz & Heger Inc.

Step 5: Gravity Analysis

A gravity analysis of the modified structure provides the member demands for gravity load cases ensuring the braces do not resist gravity loads. For this analysis, the stiffnesses of all members except the braces must be restored to the unmodified values. The results of the gravity analysis should only be combined with the results from the plastic mechanism analysis and should not be used for evaluating strength and serviceability for other load combinations. To implement this in structural analysis software, two gravity load cases need to be defined with the same loads: one case to be combined with plastic mechanism analysis results and one case to be combined with other loads.

IMPLEMENTATION OF PROCEDURE IN STRUCTURAL ANALYSIS SOFTWARE

Implementation of the model modifications described above requires a specific analysis sequence to avoid a condition in which the modifications affect the results of the other loading conditions. Therefore, it is advantageous to automate the process by using structural analysis software package packages capable of running a scripted or staged analysis. Finite-element analysis programs like GT STRUDL or ANSYS have built-in programming languages that read pseudocode text files to perform actions within the program such as modifying member stiffnesses, modifying thermal coefficients, and adding lateral springs. This type of software provides an avenue for the user to write a script that completes the plastic mechanism analysis and stores the member force results separately from those of all other load cases.

NEXT STEPS AND APPLICATIONS

The automated plastic mechanism analysis method could be improved or advanced in the following ways:

- Expand the method to consider the third scenario introduced in the most recent edition of the Seismic Provisions for Structural Steel Buildings Section F2.3 (AISC, 2016). This new scenario is only required in multi-tiered braced frames and involves performing multiple analyses to account for progressive yielding and buckling of the braces from the weakest tier to the strongest tier.
- Develop a program or script to automate the computation and application of the thermal loads for each of the plastic mechanism scenarios based on the brace section properties and geometry. Automation of the other actions described above, such as member stiffness reductions and application of artificial lateral supports, may also be possible; however, designers would need to exercise caution so that the model modifications do not cause model instabilities or other erroneous results.
- Developers of structural analysis software could advance the automation of the plastic mechanism analysis process by incorporating the principles of this method into a new analysis feature that performs the following actions:
  - Assigns lateral spring supports based on the distribution of seismic load to the collectors.
  - Softens applicable columns, braces, diaphragms, and other elements.
  - Computes forces corresponding to the expected strengths of the braces.
  - Performs elastic analyses for all applicable scenarios and directions and properly incorporates the member forces into the overall analysis model results.

CONCLUSION

The automated plastic mechanism analysis method described in this paper employs relatively simple calculations, modeling techniques, and analysis procedures to integrate the capacity-limited seismic load effect into a structural analysis model and combine it with other load effects.

With proper set-up, the method can save analysis time on complex or iterative design projects.

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