Closed-Form Characterization of Fundamental Section Response of Steel Columns Subjected to Realistic Fire Loading

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Abstract
Current prescriptive design approaches for structures subjected to extreme temperatures (i.e. IBC 2006 and NFPA 5000) are limited in the evaluation of the overall behavior and stability of building structures under realistic fire loading. First, the Fire Resistance Rating (FRR) values of individual structural members do not provide sufficient information to assess the fire behavior of building structures. It is more imperative to evaluate the thermal and structural interaction between individual components (members and connections) and their influence on the overall fire resistance of the building structure. Second, ASTM E119 temperature-time (T-t) curve used in these approaches does not compare favorably with the realistic T-t relationship for compartment fires. These deficiencies in the current prescriptive design method as well as the need for performance based design guidelines for fire safety have been highlighted by investigation reports on WTC towers and WTC-7 building collapses. This paper presents ongoing work towards the development of a closed-form analytical model to represent moment-curvature-temperature (M-φ-T) behavior of steel columns at elevated temperature under varying levels of axial force and temperature distributions. The model is developed from parametric studies using a fiber-based analytical approach that is calibrated to experimental and finite element results. The development of a closed-form model that considers non-uniform temperature distributions is an essential step in developing tools for practical frame analysis and design methods that do not require high degrees of discretization to capture beam-column limit states.

1. Background and Motivation

Prescriptive design approaches are used in current building codes (i.e. IBC 2006 or NFPA 5000), in which individual building components are given a fire resistance rating (FRR) based on the response when exposed to a standard fire. The FRR can be determined by testing components according to ASTM E119. Traditionally, such tests are performed by placing a member into a furnace and exposing it to a prescribed temperature-time (T-t) curve. This methodology is

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prohibitive in testing mechanically loaded members for two main reasons: (1) applying large loads in conjunction with thermal loading is very costly and (2) only a handful of testing facilities exist worldwide which are capable of performing such tests. Furthermore, standard fire T-t curves do not compare well to T-t curves for realistic compartment fires (Parkinson 2002).

The deficiencies in the current prescriptive design method as well as the need for performance based design guidelines for fire safety have been highlighted by investigative reports on WTC towers and WTC-7 building collapses. Thus, recent research has focused on the development of analytical methods to model the member response due to thermal loading. The thermal response is often modeled with traditional heat transfer analysis using either the finite difference or finite element method. These methods can be computationally inefficient for large problems such as modeling three-dimensional building fires. As a result, simplifying assumptions are often made such as neglecting longitudinal temperature variation or assuming constant or linear temperature distribution over a member's cross-section. As is the case with any assumptions, there are cases in which they are invalid. For example, longitudinal temperatures can vary during the initial stages of a fire or when fuel sources are concentrated (Franssen et al 2007); section temperatures can vary based on the continuity of the framing system (i.e. composite beams where the concrete acts as a heat sink) (Franssen et al 1995).

Thus, there still exists a need for analytical models that can simulate fire behavior of individual structural components with reasonable accuracy and computational efficiency. A closed-form section constitutive model that considers temperature gradients can be used to develop a robust section-constitutive based beam-column element to efficiently model large structures subjected to fire loading. This paper reports on the first step in developing this type of model: of the effect of constant cross-section temperature on the moment-thrust-curvature relationship of steel I-sections. A fiber model was used to perform a parametric study of the section response of beam-columns subjected to constant elevated temperatures in conjunction with applied axial and lateral loads. This model was validated with experimental results and finite element analyses.

2. Elevated Temperature Fiber Model
A fiber-based section model was used to predict the section moment-curvature response of steel beam-column specimens subjected to combined thermal, axial, and flexural loading. The model uses an iterative Newton-Raphson routine to determine the section response and was implemented using *Matlab*. Fig 1 shows a flowchart describing the program. The program uses steel material properties as described in Eurocode 3 (EC3) and assumes an elastic-perfectly plastic response. Current work at Purdue University indicates that the effects of residual stresses on section behavior are insignificant, thus they are neglected in the model. Because material plasticity is not included in the model, unloading effects are not explicitly considered. Although only steel wide flange sections have been considered in this paper, the model has been developed to work on a wide range of both steel and composite cross-sections.

As shown in Fig 1, any temperature distribution can be considered; all that is required is the fiber temperatures be known. Similarly, with the definition of fiber locations and geometry, any shape can be considered. Furthermore, composite sections are included in this shape extension, provided, temperature-dependent material properties are added to the program.
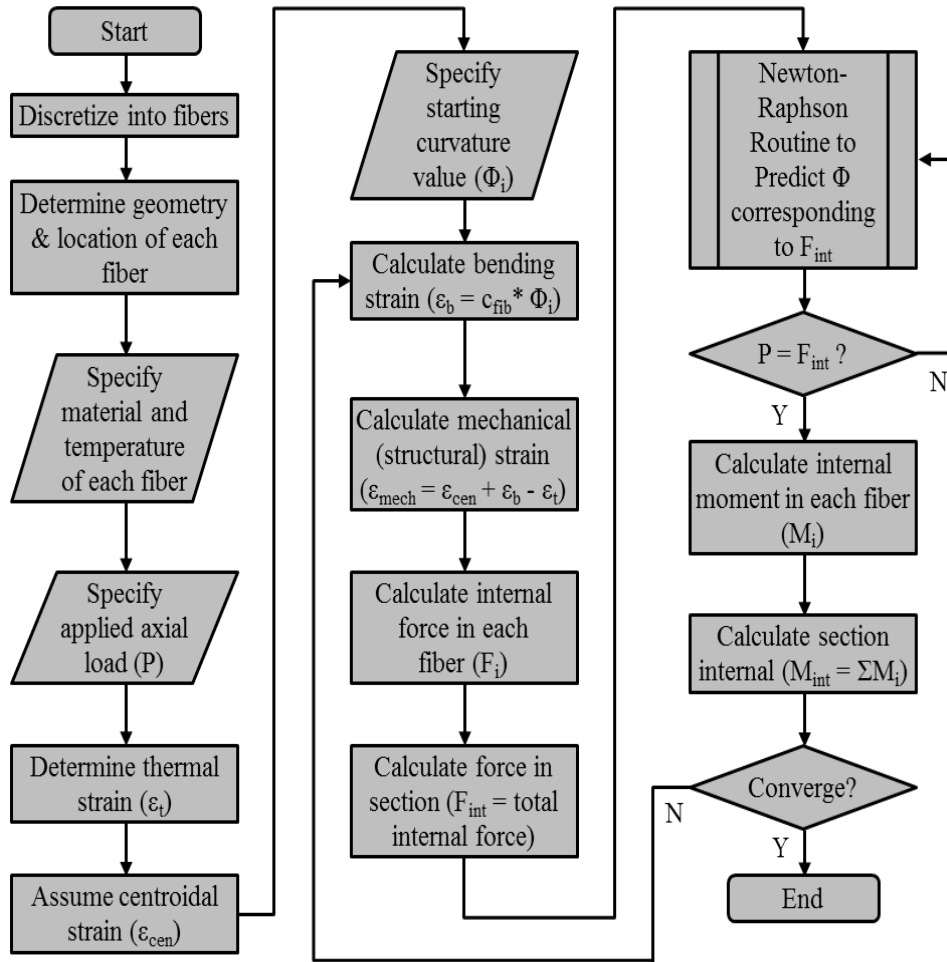
Figure 1: Flowchart for moment-curvature response.

The fiber model generates moment-curvature results for a specified cross-section, temperature distribution, and axial load level. Fig 2 shows typical results for a section with various temperatures and axial load levels.
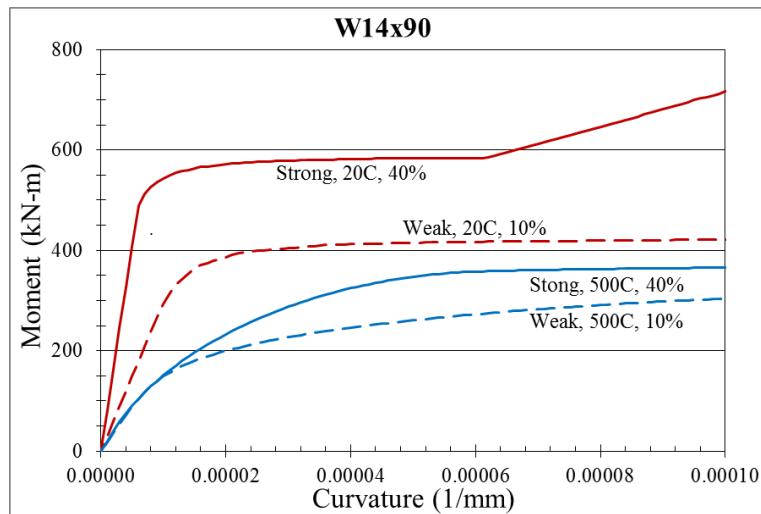

Figure 2: Fiber model results for a W14x90 with varying cross-section temperatures and axial load levels.

3. Model Validation

3.1. Experimental Program

The experimental investigation was based on the test setup and methodology originally developed by Hong (Hong & Varma 2010) to test concrete filled tube (CFT) columns. The key feature of this methodology is the utilization of radiant heaters to apply thermal loading; thus allowing the use of a digital imaging system to measure displacements of the heated region. Specimens considered were A992 W10X68 members subjected to combined thermal, axial, and lateral loading. The specimens were fixed at the base and free at the tip. The test setup is shown in Fig 3. The boundary conditions indicate that the failure section is located at the base (near the fixed end) of the beam-column, where a plastic hinge would form. Thus thermal loading was only applied to this region. Fig 4 shows the local buckling which occurred at the center of the heated region.
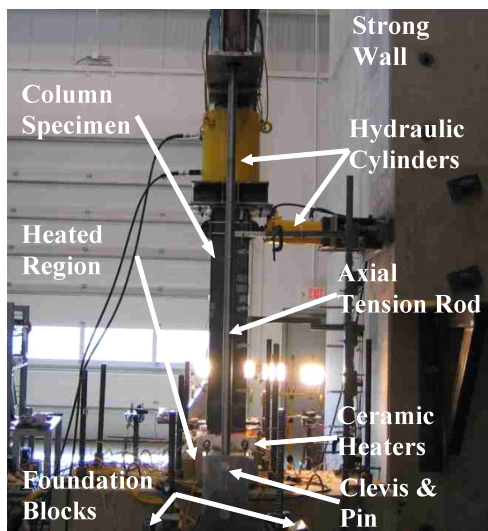

Figure 3: Test setup.

Figure 4: Local buckling at the heated region.

Two axial load levels of 15 and 30% of the column capacity and section temperatures of $20^{o}C$ (ambient), $300^{o}C$, and $500^{o}C$ were considered. The ambient temperature tests were used to verify the test setup. The loading sequence is described as follows:

1. A hydraulic cylinder applied an eccentric axial load until the desired load level was reached. This load was maintained for the remainder of the test through the use of a hydraulic controller. The axial load was free to rotate about the base of the specimen, ensuring the load continued to be centrally applied once the specimen began to bend.
2. Ceramic fiber heaters were used to apply radiant-based thermal loading. The specimen was heated until the desired section temperature was reached. Once the target temperature was reached, a steady-state heating condition was maintained by using a PID controller. This step was not performed for the ambient temperature tests.
3. A monotonically increasing lateral load was applied by a hydraulic cylinder to produce weak axis bending. The specimen was loaded until the tip deflection exceeded five inches.
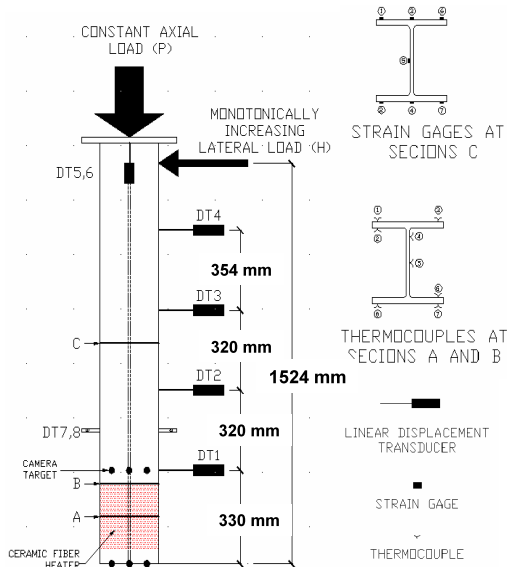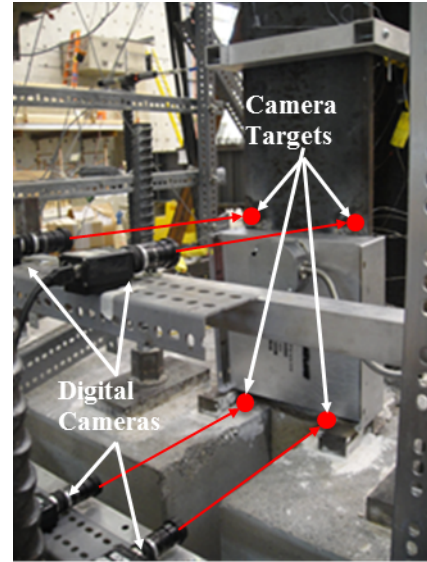
Figure 5: Instrumentation layout.

Figure 6: Digital imaging system layout.

Type K thermocouples were used to measure the surface temperature of the specimen. Strain gages were used to check the eccentricity of the loading. Potentiometers were used to measure the lateral deflection in the direction of loading. The instrumentation layout is shown in Fig 5. A two-dimensional digital imaging system (Fig 6) measured the longitudinal and transverse displacement of the heated region. This information was then post-processed to determine the lateral load-displacement (F-Δ) and axial load-moment-curvature-temperature (P-M-Φ-T) response of the specimens.

3.2. Finite Element Modeling

A three-dimensional finite element model (3D FEM) was developed using *ABAQUS* in which, four node reduced integration shell elements (S4R) were used. The 3D FEM was analyzed for the same loading conditions as the test specimens using the same three step process as the experimental studies. Geometric imperfections and residual stresses resulting from the cooling of hot-rolled sections were included in the model. The material was assumed to have a yield stress of 345 MPa and an elastic-perfectly plastic stress-strain relationship. The reduction in elastic stiffness due to thermal loading was modeled using Table 3.1 in EC3. It should be noted that using Table A-4.2.1 in the draft 2010 AISC Specification would produce similar results.

Analogous to the experiments, two axial load levels (15% & 30%) and three steel section temperatures (Ambient, 300C, & 500C) were modeled. The model was fixed at one end while free at the other again, producing a failure region near the fixed end. The thermal loading was applied at this failure region and was calibrated to match the steel surface temperature-time measurements recorded during the experiment.

3.3. Comparison of Results

The section response to thermal and mechanical loading obtained from the fiber model was compared to the 3D FEM and experimental results for various constant section temperatures and axial load levels. This comparison is shown in Figs 7 – 9. The elastic moment-curvature response specified in EC3 is also shown on these figures. The fiber model results compare favorably with

those obtained from the experiments and 3D FEM; additionally, neglecting residual stresses in the fiber model does not adversely affect the results. Furthermore, all three predict the elastic response given in EC3 reasonably well. Figures 7 through 9 show the comparison of the results for an axial load of 30% of the squash load. Variation of the axial load level does not effect the agreement between the experimental, FEM and fiber models; the 15% axial load level comparisons showed similar agreement between the methods.
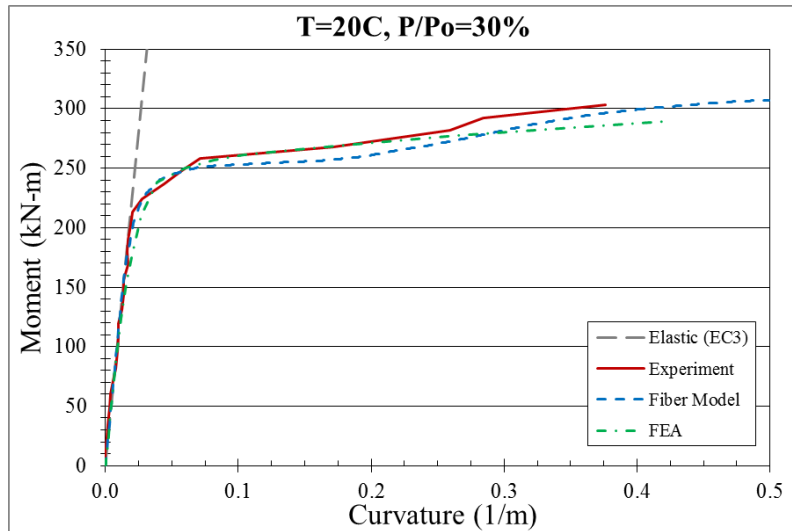
Figure 7: Section response at ambient temperature and 30% axial load level.
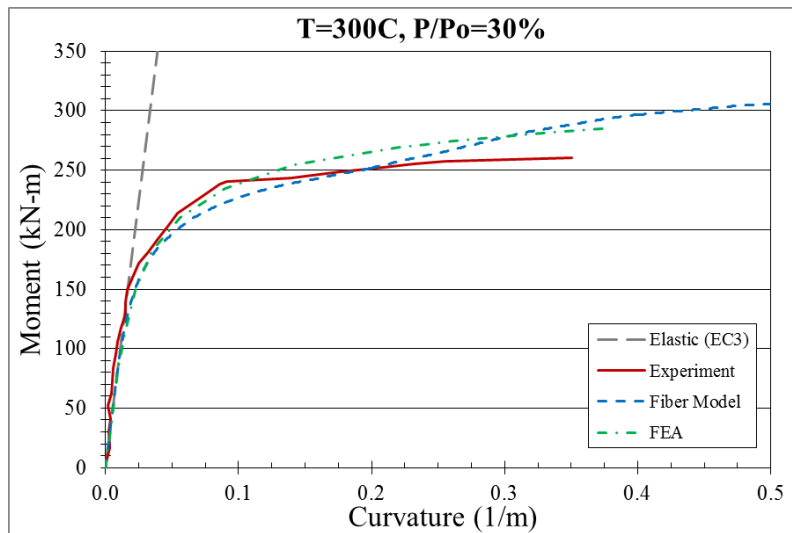
(a)   (b)
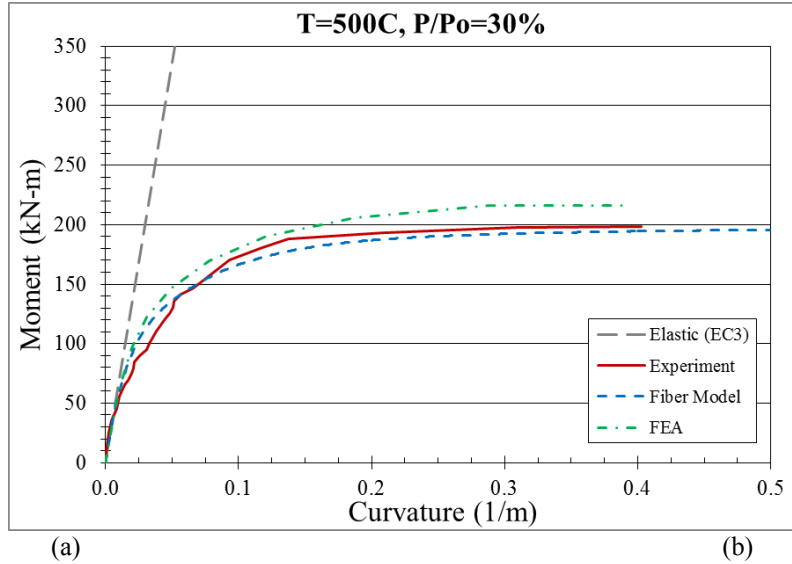
Figure 8: Section response at 300°C and 30% axial load level.

T=500C, P/Po=30%

(a) (b)

Figure 9: Section response at 500°C and 30% (b) axial load level.

4. Parametric Study

The fiber model was used to perform a parametric study in order to investigate which parameters affect the section response due to combined axial, flexural, and thermal loading. The following wide flange sections have been included in the study to represent a range of commonly used sizes: W8x35, W10x68, W12x58, W14x90, W14x159, and W14x257. Each of the sections was analyzed with three constant section temperatures (20C, 300C and 500C) and three axial load levels, measured as a percentage of the squash load (10%, 25% and 40%). Temperatures higher than 500C were not considered due to the significant loss of strength above 500C. T

The section responses are shown in Figs 10 – 16, and are normalized against the plastic bending moment and the elastic yield curvature. As evidenced by the plots, the response is independent of the designation for constant temperatures. However, the section response is inversely proportional to both the applied temperature (Figs 10-12) and the axial load level (Figs 13-15). The orientation of the section also affects the response; at elevated temperatures, the sections bent about the strong axis exhibit a higher reduction in strength – up to 25% - when compared to those bent about the weak axis (Fig 16). The fiber results were truncated in order to exclude the strength gain as discussed above; this is most apparent in Figs 10b, 11b, & 12b.
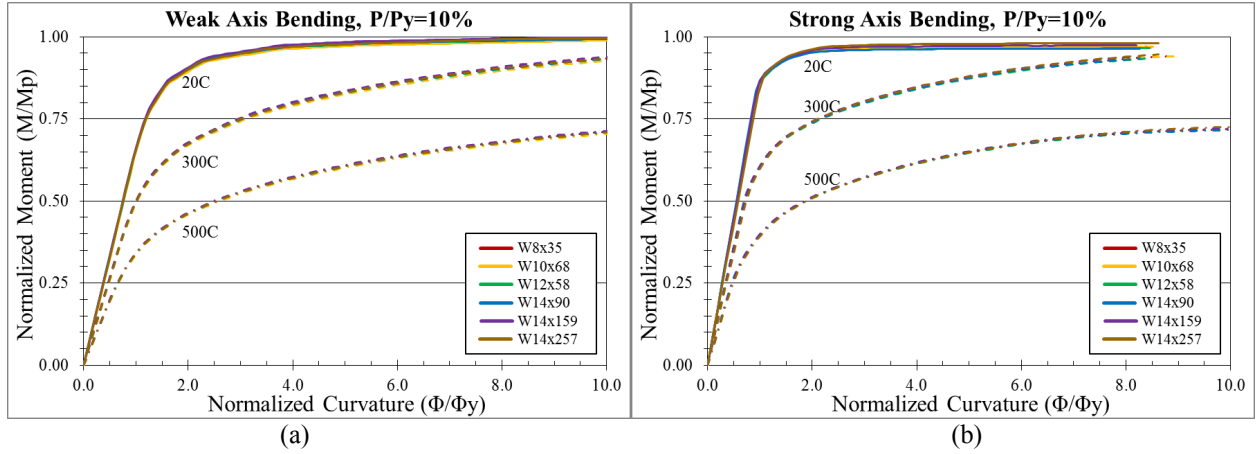
Figure 10: Section response at 10% axial load level subjected to weak (a) and strong (b) axis bending.
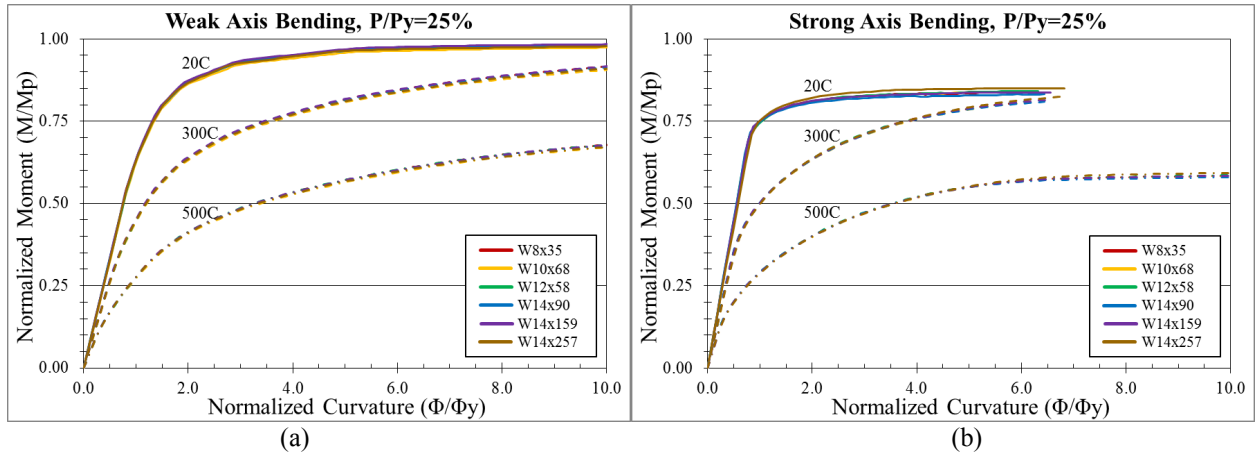

Figure 11: Section response at 25% axial load level subjected to weak (a) and strong (b) axis bending.
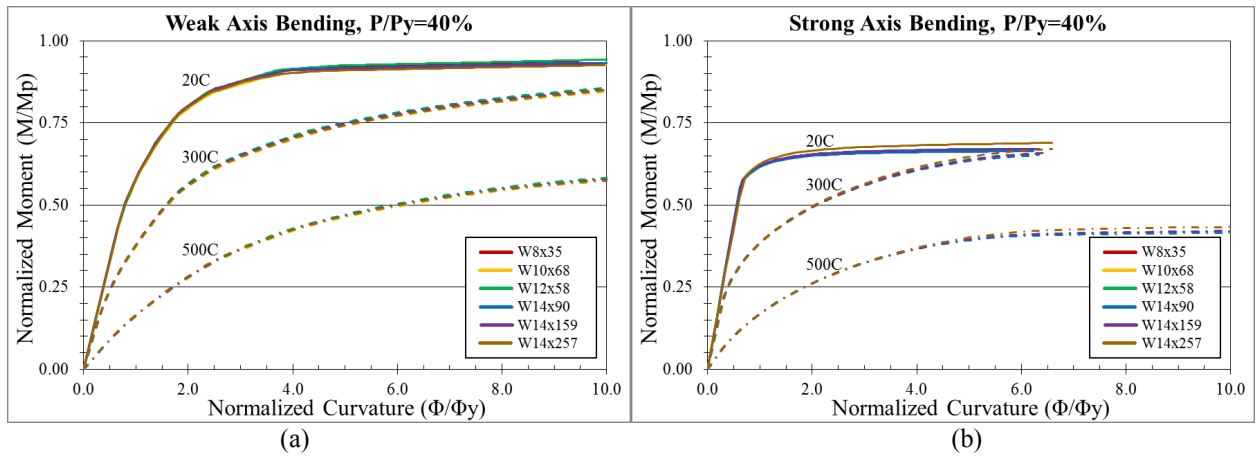

Figure 12: Section response at 40% axial load level subjected to weak (a) and strong (b) axis bending.
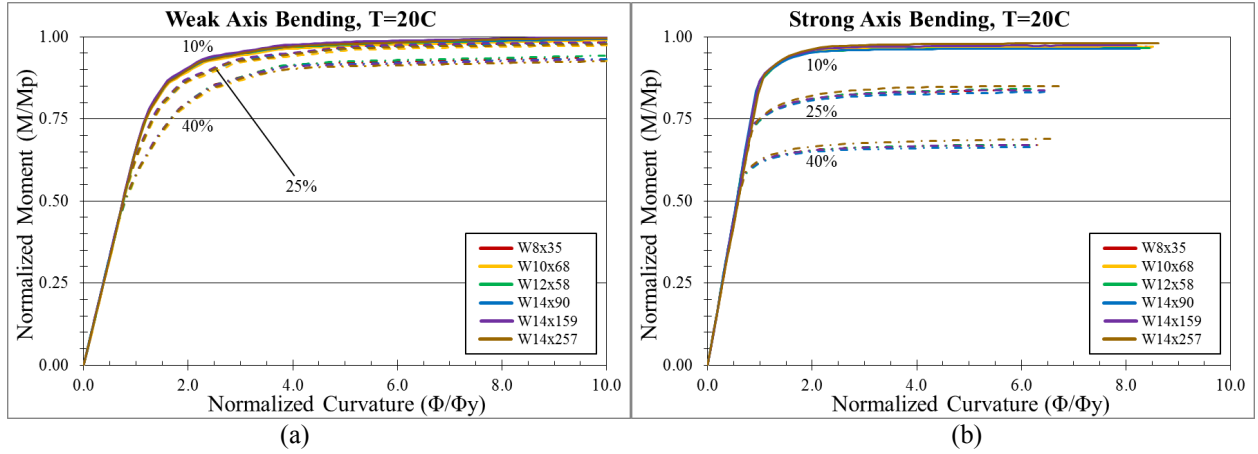
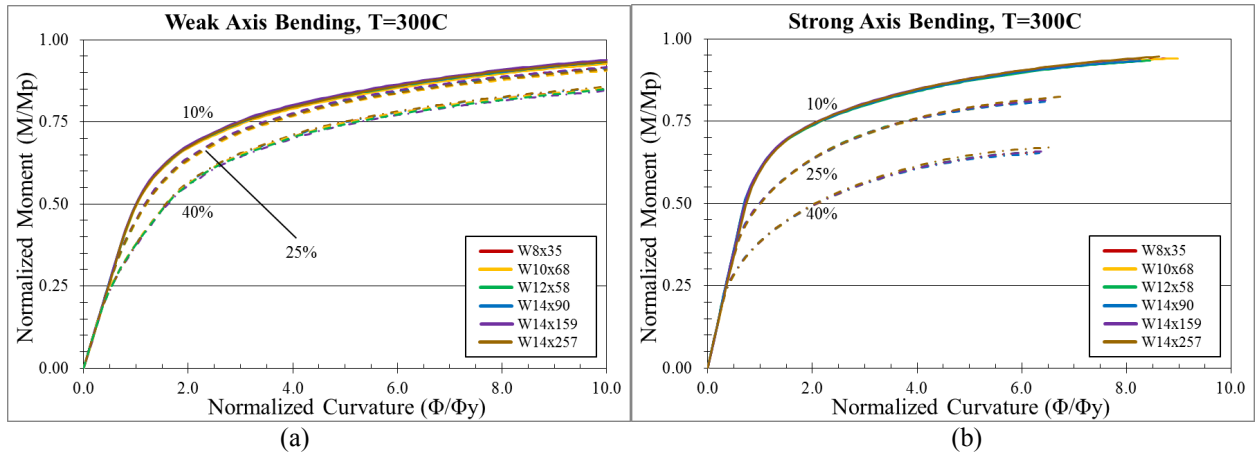Figure 13: Section response at 20C subjected to weak (a) and strong (b) axis bending.

Figure 14: Section response at 300C subjected to weak (a) and strong (b) axis bending.
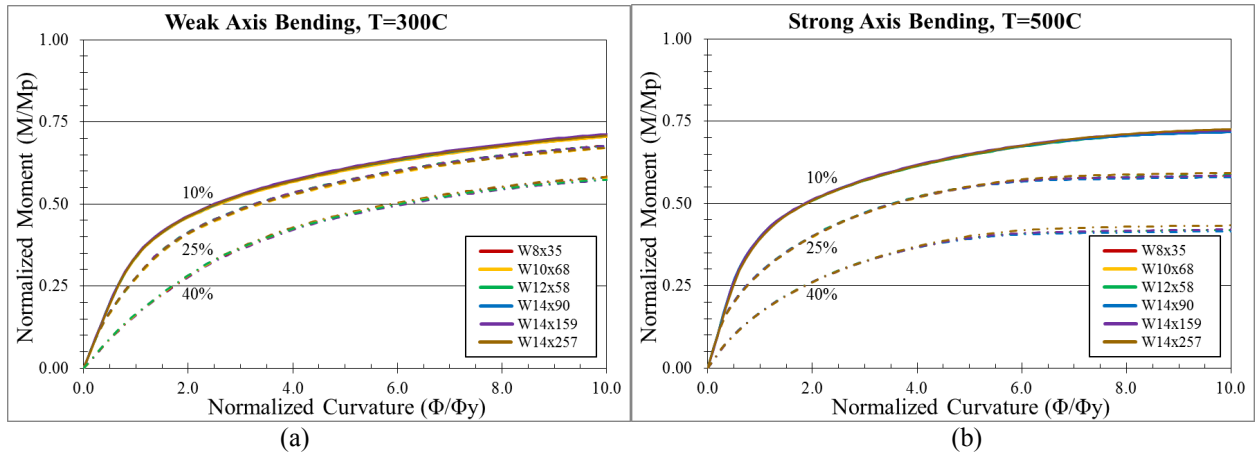

Figure 15: Section response at 500C subjected to weak (a) and strong (b) axis bending.
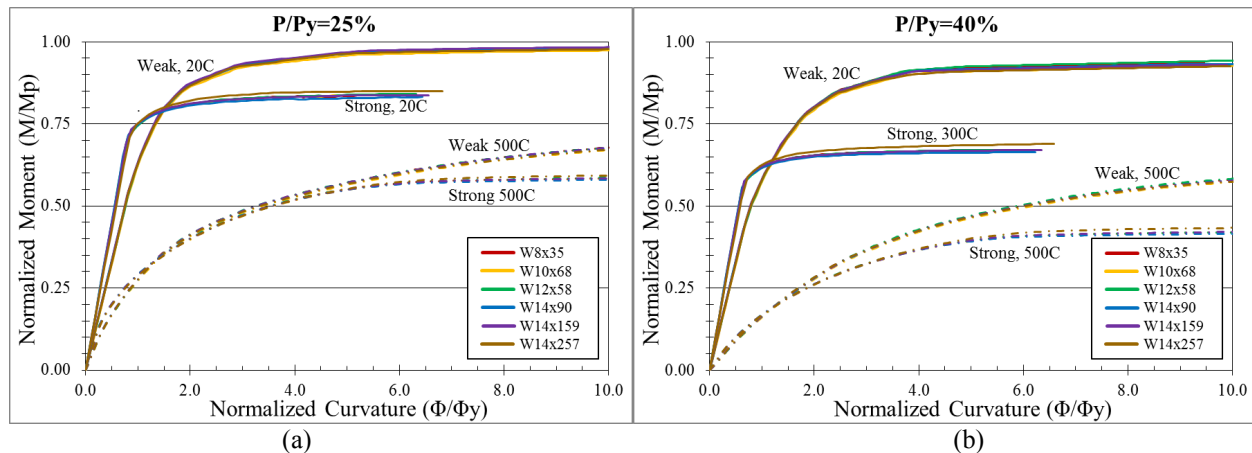
Figure 16: Section response at 20C and 500C comparing strong and weak axis bending subjected to axial load levels of 25% (a) and 40% (b).

5. Conclusions and Future Work

An experimentally and analytically verified fiber model was used to perform a parametric study of the section response due to combined thermal and mechanical loading. The study shows that for constant section temperatures, the response due to combined axial, flexural, and thermal loading is unaffected by section type. As expected, the results indicate a loss in flexural strength with increasing axial load levels and increasing section temperatures. The fiber model produces a strength gain at high curvature levels that is not

Currently, a closed form moment-curvature-temperature relationship for steel columns is being developed that accounts for variations in axial load and temperature. The next phase of parametric studies will consider temperature gradients (idealized and realistic) and their effects on section response. The closed-from section-response equation will facilitate the development of a computationally efficient, section constitutive-based beam-column model that can, with reasonable accuracy, be used to predict the general stability behavior of a complex framing system subjected to realistic temperature gradients.

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