Seismic Behavior of Steel Reinforced Concrete Beam-Columns and Frames

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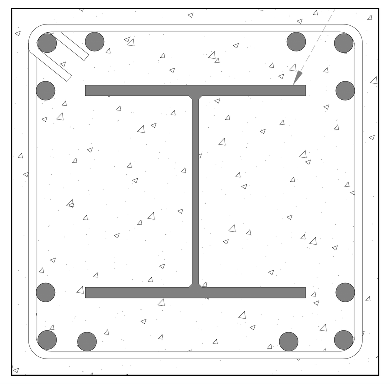
Introduction

The ability to perform accurate nonlinear simulations is a key component in the assessment of the behavior of seismic force resisting systems. A three-dimensional distributed plasticity formulation for composite beam-columns suitable for nonlinear static and dynamic analyses of composite seismic force resisting systems has been developed. New uniaxial constitutive relations are developed for the concrete and steel elements to simulate the cyclic response of steel reinforced concrete (SRC) members. The relations account for the salient features of each material, as well as the interaction between the two, including for concrete: varying levels of confinement within a section, cracking, crushing, and spalling, and for steel: cyclic plasticity and residual stresses. The accuracy of the formulation is validated against a comprehensive set of results from monotonically and cyclically loaded beam-column specimens.

This research builds off prior work by Tort and Hajjar (2010) on rectangular concrete filled steel tubes (CFT) and and Denavit and Hajjar (2010) on circular CFTs.

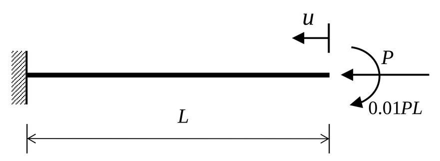


Mixed Beam Element

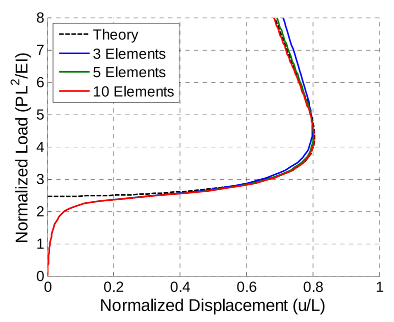
Frame analyses using distributed-plasticity beam-column elements strike a favorable balance between computational efficiency and accuracy. Additionally, mixed formulations (defined here as treating both element displacements and stress resultants as primary state variables) provide more accurate results with fewer elements as compared to either displacement- or force-based formulations.

The element stiffness and internal force are derived in the corotational frame using small strain assumptions. When accompanied with an exact transformation between the corotational and global frame the element is capable of capturing moderate deformation and rotation behavior.

Implemented within the OpenSees framework, the element can be used with the wide variety of other elements and solution algorithms available in the framework.

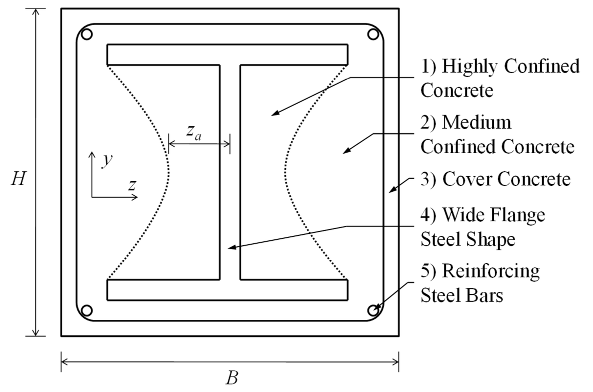


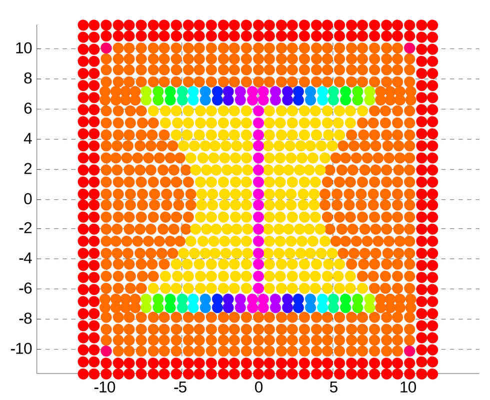
Example nonlinear elastic validation problem



Fiber Section

The formulation relies on accurate constitutive relations to achieve accurate results. The constitutive relations are defined for the finite element at the section level using a fiber model. A fiber model allows the wide variety of behavior exhibited by SRC sections to be described by the integration of uniaxial constitutive relations located throughout the section. Five distinct regions are identified within the section and separate constitutive relations are defined for each of these regions.



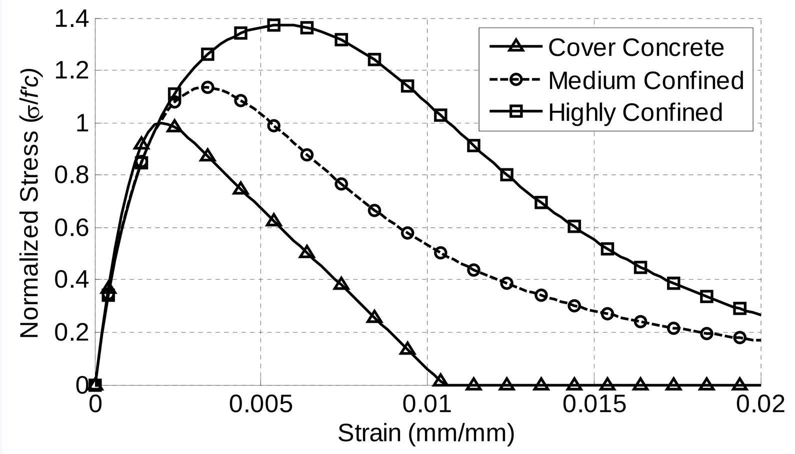


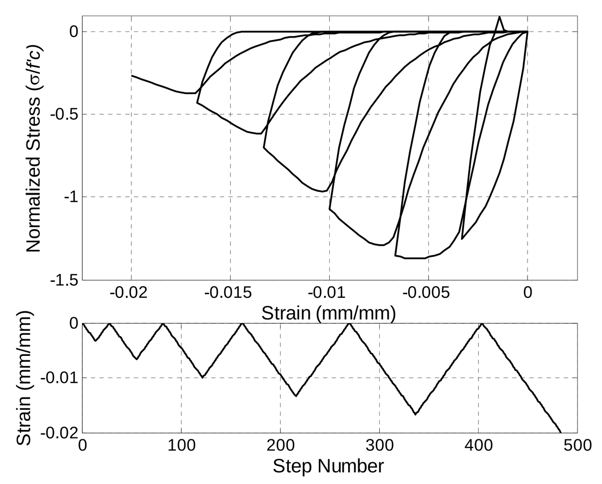
Concrete Model

The constitutive relation for the concrete is based on the rule-based model of Chang and Mander (1994). The backbone stress-strain curve for the concrete is based on the model by Tsai, which is defined by the initial stiffness E_c, peak coordinate (ε'_{cc}, f'_{cc}), and r which acts as a shape factor. The confinement model developed by Mander et al. (1988) for a triaxial state of stress is utilized to determine the peak compressive strength from the confining pressure in two orthogonal directions.

Three levels of confinement are considered:

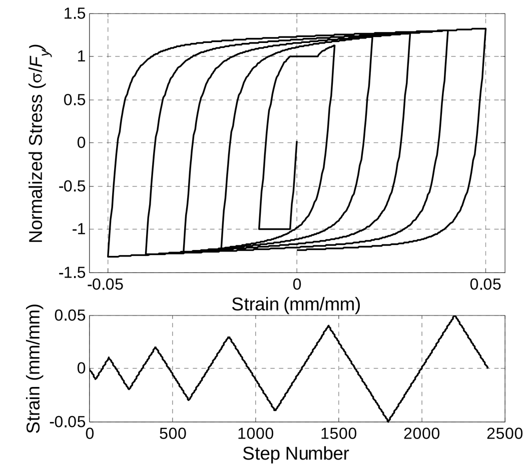
- **Cover Concrete** - The outermost concrete region of concrete is assumed to have zero confining pressure in either direction. Furthermore, it is allowed to spall.
- **Medium Confined Concrete** - The concrete inside the lateral reinforcing bars. In this region, confining pressure is provided by the lateral reinforcing bars. The magnitude of the confining pressure is computed in two orthogonal directions.
- **Highly Confined Concrete** - The concrete between the flanges of the steel shape. In this region, confining pressure is provided by the lateral reinforcing bars and the steel shape. The confining pressure provided by the steel shape acts only in the *y* direction and is computed considering the plastic moment capacity of the flange. The parabolic boundary is modeled explicitly with different constitutive relations on either side.

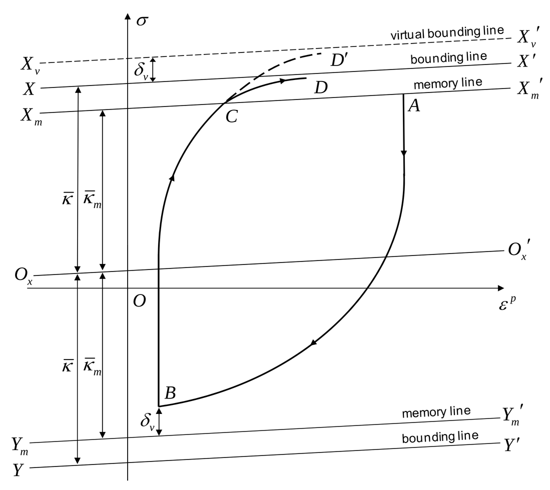




Steel Model

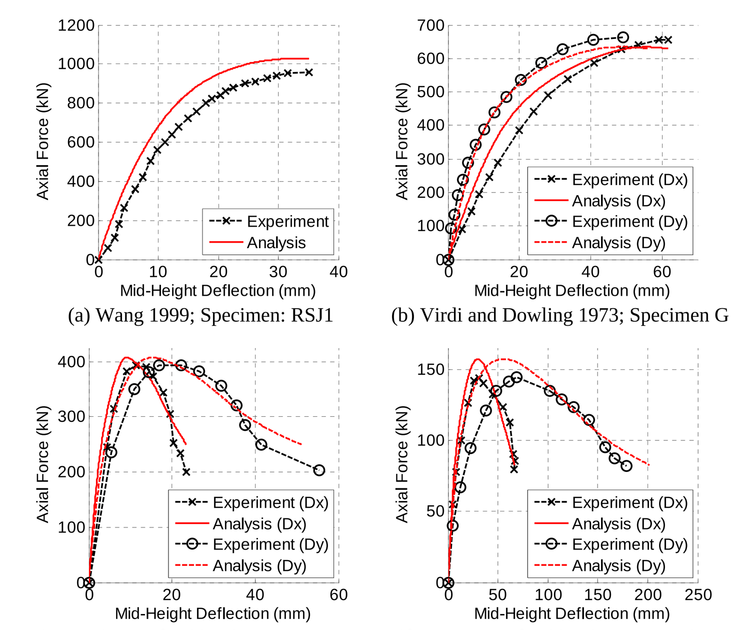
The constitutive relation used for the wide flange steel shape and the reinforcing steel bars is based on the bounding-surface plasticity model of Shen et al. (1995). Modifications were made to model the effects of residual stress within the steel section. The residual stress at a fiber is modeled explicitly as an initial elastic stress in the uniaxial constitutive relation. The Lehigh residual stress pattern is used to define the value of residual stress in the steel section with a maximum compressive residual stress of 30% of the yield strength occurring at the flange tips. The confined concrete is assumed to prevent flange and web local buckling and thus, these effects have not been included.



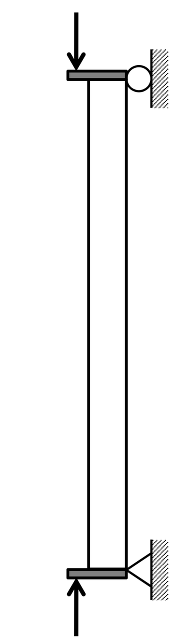


Proportionally Loaded Beam-Columns

The most common experimental configuration for testing SRC beam-columns is monotonic proportional loading. Details of four specimens from various experimental studies are presented. The results of these experiments are compared to results from analyses conducted using the model presented in this work. The results show a good correlation between experimental and computational results. This is seen in the initial stiffness, peak load, deflection at peak load, post-peak degradation, and ratio of strong and weak axis deflections. The two specimens by Morino et al. have a similar cross section and loading angle, but specimen D8-45 has approximately twice the length and eccentricity of B4-45. The higher first- and second-order moments resulted in a significantly lower peak axial load for D8-45. The model predicted the peak axial load accurately for both specimens indicating that model captures well both material and geometric nonlinearity.



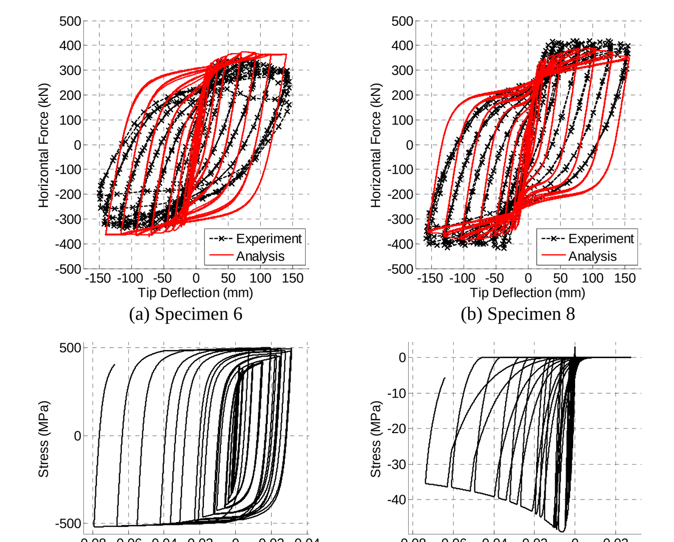
(a) Wang 1999; Specimen: RSJ1 (b) Virdi and Dowling 1973; Specimen G (c) Morino et al. 1984; Specimen B4-45 (d) Morino et al. 1984; Specimen D8-45



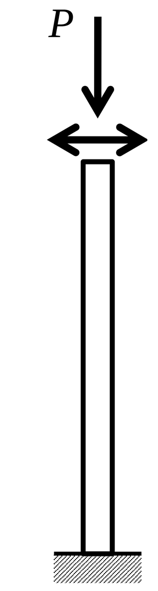
Author	Year	Spec-imen	H (mm)	B (mm)	f'_c (MPa)	Steel Section	F_y (MPa)	d_b (mm)	F_{yr} (MPa)	L (mm)	Axis	e (mm)
Wang	1999	RSJ1	200	200	55.0	RSJ 102x102	310.0	n/a	n/a	4,000	Strong	55.0
Virdi and Dowling	1973	G	254	254	44.8	UC 6x6@15.7	314.7	12.7	309	7,315	Biaxial	73.4
Morino et al.	1984	B4-45	160	160	23.4	H-100x100x6x8	287.0	4.0	387	2,309	Biaxial	40.0
Morino et al.	1984	D8-45	160	160	22.9	H-100x100x6x8	302.0	4.0	387	4,619	Biaxial	75.0

Cyclically Loaded Beam-Columns

A set of carefully controlled and well documented non-proportionally loaded cyclic SRC beam-columns tests was performed by Ricles and Paboojian (1993, 1994). The specimens were subjected to a constant axial load and cyclically increasing horizontal displacements which induced strong axis bending in the column. Details of two of specimens from this experimental study are presented. The load-deformation results of these experiments are compared to those from analyses conducted using the model presented in this work. Additionally, the stress-strain response from the extreme fiber of the steel section and the extreme fiber of the highly confined concrete as predicted from the analysis are shown. The results show a good correlation between experimental and computational results. The initial stiffness and peak strength are predicted well by the model. The unloading stiffness and yield upon unloading are less accurate, leading to the model predicting fuller hysteresis loops than observed in the experiments.



(a) Specimen 6 (b) Specimen 8 (c) Specimen 6, Steel Section Fiber Stress-Strain Relationship (d) Specimen 6, Highly Confined Concrete Fiber Stress-Strain Relationship



Spec-imen	H (mm)	B (mm)	f'_c (MPa)	Steel Section	F_y (MPa)	d_b (mm)	F_{yr} (MPa)	L (mm)	P (kN)
6	406	406	35.8	W8x40	372	28.6	448	1,930	1,490
8	406	406	62.9	W8x40	372	22.2	434	1,930	1,490

Future Directions

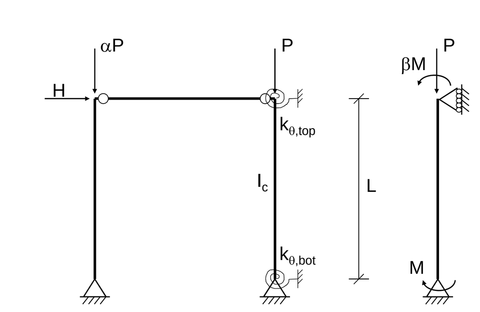
This formulation was developed and is suitable for use in large scale parametric studies to develop design recommendations for SRC members and frames. Three specific studies are planned and will be carried out using this formulation.

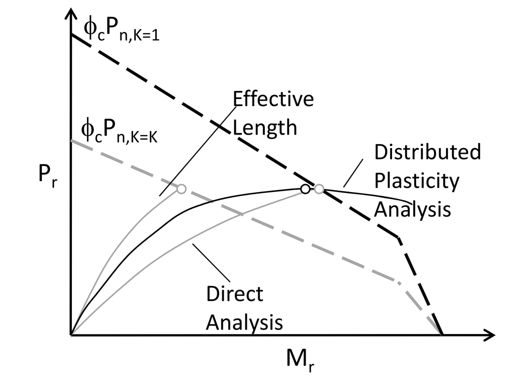
Effective Flexural Rigidity

Equivalent stiffness values for composite columns are used in elastic analyses to determine the fundamental frequencies of vibration of a structure, as well as seismic force and deformation demands. Such recommendations should account for the effect of material nonlinearity, most notable concrete cracking, on the average frame behavior. Recommendations will be developed through comparisons between computational results from static and dynamic analyses of composite frames and elastic analyses utilizing equivalent stiffness values.

Stability Design by Direct Analysis

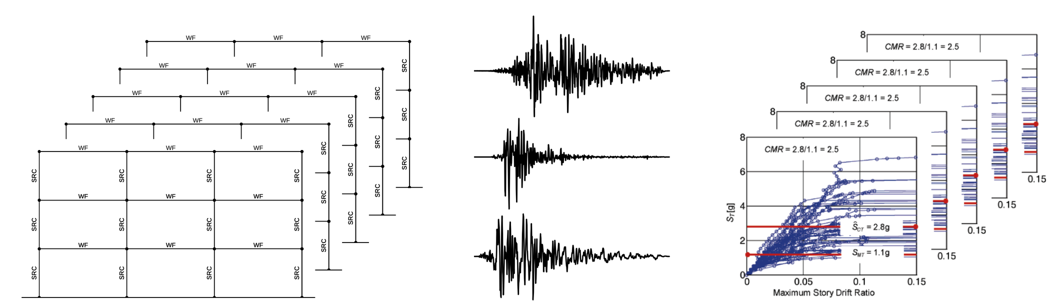
The direct analysis method provides a more straightforward and accurate way of addressing frame in-plane stability considerations than traditional effective length factor methods. In this method, required strengths are determined with a second-order elastic analysis where members are modeled with a nominal reduced elastic stiffness and a nominal initial out-of-plumbness (the initial out-of-plumbness is often modeled using notional lateral loads). However, to date, no procedure has been established to determine appropriate reduced elastic stiffness values for composite beam-columns. Design recommendations of this type will be developed and validated against computational results from the static analyses of small sensitive benchmark frames.





Seismic Performance Factors

Seismic performance factors are used to account for inelastic dynamic behavior in a design method which predominantly employs static elastic analysis techniques. However, the response modification factor for composite systems has been somewhat arbitrarily assigned. Using the methodology that was recently developed by the ATC-63 project (FEMA 2009), seismic performance factors will be determined for composite lateral force resisting systems. The specific structural systems of interest are composite special moment resisting frame and composite special concentrically braced frame systems.



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