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Effects of Mechanical Bar Splices on Seismic Performance of Reinforced Concrete Buildings

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EFFECTS OF MECHANICAL BAR SPLICES ON SEISMIC PERFORMANCE OF

REINFORCED CONCRETE BUILDINGS

BY

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EFFECTS OF MECHANICAL BAR SPLICES ON SEISMIC PERFORMANCE OF REINFORCED CONCRETE BUILDINGS

This thesis is approved as a creditable and independent investigation by the candidate for the Master of Civil Engineering degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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LIST OF ABBREVIATIONS

Abbreviation	**Definition**
ACI	American Concrete Institute
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
CA	California
CIP	Cast-in-place
FE	Finite Element
Ft	Feet
GC	Grouted coupler
HC	Headed coupler
IMRF	Intermediate moment-resisting frame
in.	Inch
Kip	1000 pounds
plf	Pound per linear foot
kN	Kilonewton
ksi	Kip per square inch
lbs	Pounds
MPa	Mega pascal
MRF	Moment-resisting frame
m	Meter
mm	Millimeter
N/m	Newton per meter
N/m^2	Newton per square meter
NY	New York
OMRF	Ordinary Moment-resisting frame
psf	Pound per square foot
RC	Reinforced Concrete
SD	South Dakota
SDC	Seismic Design Category

SDSU	South Dakota State University
SMRF	Special Moment-resisting system
TC	Threaded Coupler

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ABSTRACT

EFFECTS OF MECHANICAL BAR SPLICES ON SEISMIC PERFORMANCE OF REINFORCED CONCRETE BUILDINGS

ABDULLAH AL HASHIB

2017

Mechanical bar splices, which are commonly referred to as couplers, are currently used in reinforced concrete structures to directly connect steel bars in lieu of conventional lap splicing. With proper detailing, couplers can be utilized to connect precast beams and columns to accelerate the construction. However, the experimental and analytical studies regarding their effect on the performance of RC moment-resisting frames (MRFs) are scarce. Current ACI 318 restricts the use of couplers in plastic hinge regions of special moment-resisting frames (SMRFs). Nevertheless, they can be incorporated at any location of the intermediate and ordinary MRFs. The seismic performance of RC frames incorporating mechanical bar splices in plastic hinge regions was analytically investigated in the present study.

Ordinary, intermediate, and special moment-resisting frames (OMRF, IMRF, and SMRF) were included in the study. Three-, six-, and nine-story buildings were designed for each frame type (nine frames in total) according to current ASCE 7 and ACI 318 codes. Modeling methods were proposed for mechanically spliced RC members then the results were verified against large-scale test data from literature. Subsequently, more than 100 pushover analyses were performed on the nine frames by varying the coupler rigid length factor and the coupler length. The results showed that the coupler length, the coupler rigidity, the height and the type of frames affect the displacement capacity of mechanically RC frames. Long and rigid couplers may reduce the displacement capacity of a short SMRF up to 42%. A simple design equation was proposed to quantify the effect of mechanical bar splices on the displacement capacity of RC frames.

1. Introduction

This study presents the findings of an extensive parametric study to quantify the effect of mechanical bar splices on the seismic performance of reinforced concrete moment-resisting buildings. This chapter includes problem statement and background, objectives and scope, and the organization of the document.

1.1 Background

Reinforcing steel bars are needed to be spliced to provide continuity in reinforced concrete (RC) structures. Bars can be spliced either through overlapping two adjoining reinforcement, “lap splicing”, or using mechanical bar splices, which are commonly referred to as “couplers”. Bar couplers can also be utilized to connect prefabricated concrete members to accelerate construction. Two types of couplers are allowed in ACI 318-14 (2014). Type 1 in which couplers shall resist at least 1.25 times the yield strength of the reinforcement, and Type 2 in which couplers shall resist the ultimate tensile strength of the reinforcement. Type 1 couplers are currently not allowed in the plastic hinge region of special moment-resisting frames neither in longitudinal nor in the transverse bars. Type 2 couplers cannot be used within one-half of the beam depth in special moment-resisting frames but are allowed in any other locations and members.

The restriction of mechanical bar splices in special moment-resisting RC frames is mainly due to a lack of performance data and uncertainty regarding coupler effects on the seismic performance of frames with couplers especially the displacement capacity.

1.2 Objectives and Scope

The main objective of the present study is to analytically investigate the effect of mechanical bar splices on the seismic behavior of moment-resisting RC buildings. Ordinary, intermediate, and special moment-resisting RC buildings were designed for different seismic categories. Three-, six-, and nine-story buildings were selected for the analytical studies. The effect of bar couplers on the displacement capacity and displacement ductility capacity of the frames is investigated and quantified for practical use. The effect of coupler is quantified and new design recommendations are proposed to facilitate the design of RC buildings incorporating couplers.

A literature review is performed to compile building component test data in which couplers were used in the critical regions. Modeling methods are developed and verified using the test data. RC frames are designed according to current codes to meet the requirements of ordinary, intermediate, and special moment-resisting frames per ACI seismic specifications. A parametric study is performed to investigate the effect of bar couplers on the displacement capacity of the frames. The findings of the analytical studies are compiled and evaluated then a design guideline is proposed for RC frames incorporating mechanical bar splices.

1.3 Document Organization

This study contains analytical investigation carried out on spliced RC frames to determine the effects of couplers on the seismic behavior of the frames. Chapter 1 presents the rationale, objective and a brief overview of the work done. Chapter 2 presents a review of literature on mechanically spliced RC specimens. Chapter 3 presents the analytical studies on the RC components and modeling method for parametric study. Chapter 4 presents the design and detailing of the RC frames to be studied for parametric study. Chapter 5 presents the analytical modeling method for spliced RC frames and shows the effects of coupler on the frames. Chapter 6 presents the summary and conclusions of the study.

2. Literature Review

A literature review was conducted on the performance of mechanical bar splices, which is commonly referred to as “couplers”, and reinforced concrete (RC) members incorporating mechanical bar splices. The bulk of information provided in the literature was also evaluated for potential analytical studies. This chapter presents a summary of the findings from the literature.

2.1 Introduction to Mechanical Bar Splices

This section covers the definition, advantage, and type of mechanical bar splices available in the market.

2.1.1 What is Mechanical Bar Splices

Reinforcing steel bars are needed to be spliced to provide continuity in RC members. Bars can be spliced either through overlapping two adjoining reinforcement, “lap splicing”, or using mechanical bar splices. Mechanical bar splices are mechanical devices that connect two adjacent bars together. Figure 2.1 shows one sample of lap and mechanical splices. Couplers reduce the width and length of the lap compared to the conventional lap splicing. Therefore, couplers reduce the congestion in splicing regions especially the joints. Coupler may reduce the construction time if proper detailing is used.

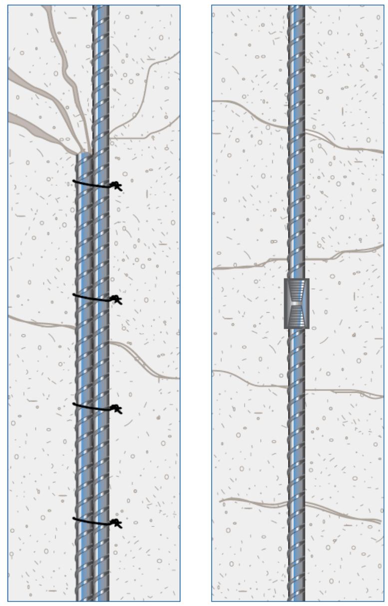


Figure 2.1- Comparison of Lap and Mechanical Splicing (Lenton, 2017)

2.1.2 Advantages of Couplers

The main advantages of using couplers over conventional bar splicing are:

- Couplers act like a continuous bar in the connecting region. Loading path and structural integrity are then improved.
- Less congestion of reinforcement in joints.
- Lower amount of reinforcement in a structure will be used when couplers are incorporated.
- Bar couplers may be used in precast member connections to accelerate construction.
- Lap splice is prohibited for No. 14 (Ø43 mm) and No. 18 (Ø57 mm) reinforcing bars. Thus, couplers should be used for these bar sizes.

2.1.3 Types of Mechanical Bar splices

Different manufacturers produce different coupler types. Tazarv and Saiidi (2015) categorized the available couplers as: shear screw, headed bar, grouted sleeve, threaded, and swaged (Fig. 2.2). Note that couplers with the same anchoring mechanism may be entitled differently by manufacturers.

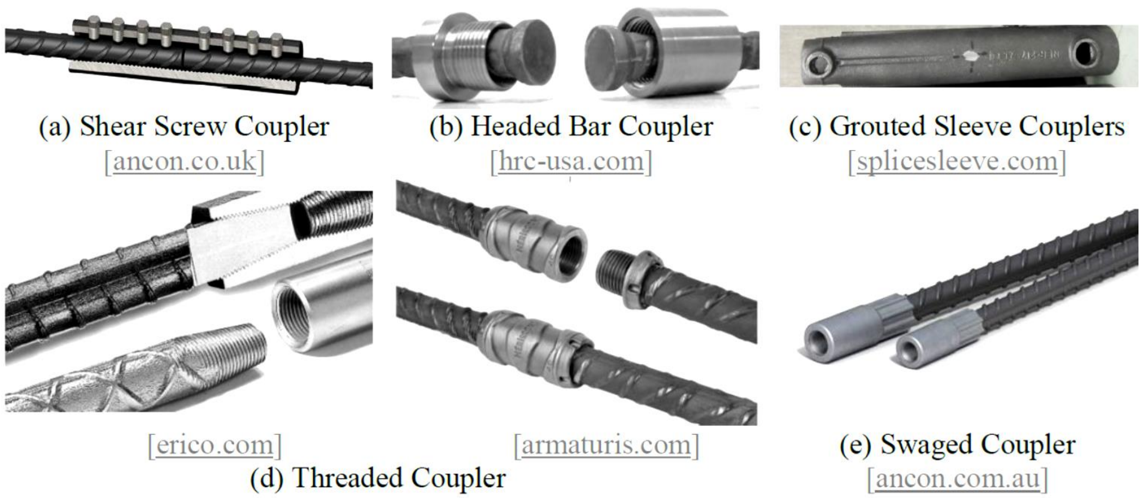


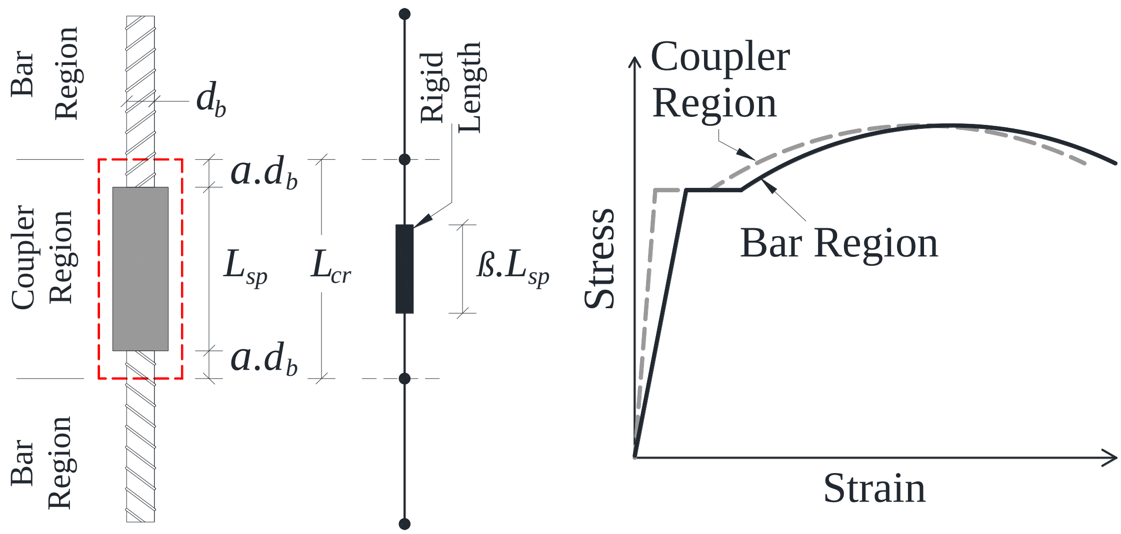
Figure 2.2- Sample of Mechanical Bar Splices (Tazarv and Saiidi, 2015)

2.2 Material Model for Couplers

Mechanical bar splices exhibit different behavior than reinforcing steel bars due to the anchoring mechanism. Stress-strain relationship for couplers proposed by Tazarv and Saiidi (2016) was adopted in the present study and is discussed in this section.

2.2.1 Stress-Strain Relationship for Couplers

Limited tensile test data on the bar couplers showed that the stress-strain behavior of couplers follows the reinforcement behavior but stiffer with lower strain capacities (Fig. 2.3). Tazarv and Saiidi (2016) found that the relatively large diameter of couplers and the anchoring mechanism contribute to this rigid behavior. They developed a procedure to determine the stress-strain relationship of coupler region based on the mechanical properties of reinforcement, the coupler length, and a new parameter named "coupler rigid length factor" (Fig. 2.3). Coupler rigid length factor is discussed in the next section (Sec. 2.2.2). The proposed material model is generic and can be used for any type of couplers.



(a) Coupler Uniaxial Model (b) Stress-Strain Relationship

Figure 2.3- Generic Stress-strain Material Model for Couplers (Tazarv and Saiidi, 2015)

2.2.2 Coupler Rigid Length Factor

Coupler rigid length factor, β, is required to determine the full stress-strain relationship of couplers, which can be calculated form a tensile test data as:

$$\frac{\varepsilon_{sp}}{\varepsilon_s} = (L_{cr} - \beta\, L_{sp})/L_{cr} \qquad 2.1$$

where,

ε_{sp} = The strain of the coupler region (Fig. 2.3),

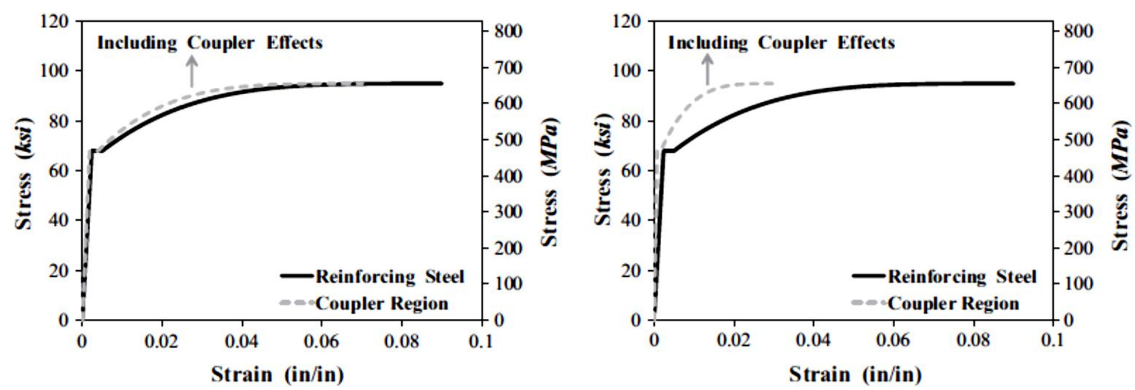
ε_s = The strain of connecting reinforcing steel bar,

L_{cr} = The coupler region length (Fig. 2.3), ($L_{cr} = L_{sp} + \alpha d_b$ from each end of the coupler, α = 1.0 to 2.0)

β = The coupler rigid length factor,

L_{sp} = The coupler length (Fig 2.3).

The main assumption is that a portion of the coupler length is rigid and does not contribute to the total elongation of the splice. Stress-strain relationship of coupler region will be the same as unspliced reinforcing bar when β = 0. When β = 1, the entire length of the coupler is rigid. Figure 2.4 shows the stress-strain relationship of couplers for two coupler rigid length factors (β = 0.25 and β = 0.75). Based on the test data in Haber et al. (2015), Tazarv and Saiidi (2016) calculated the coupler rigid length factor for grouted and headed bar couplers using Eq. 2.1, which were 0.65 and 0.75, respectively.



(a) Low Rigid Length Factor ($\beta = 0.25$) (b) High Rigid Length Factor ($\beta = 0.75$)

Figure 2.4- Effect of Coupler Rigid Length Factor on Stress-strain Relationship (Tazarv and Saiidi, 2015)

2.3 Behavior of Mechanical Bar Splices

Matsuzaki et al. (1987b) tested 26grouted sleeve couplers (Fig. 2.5) under monotonic and cyclic loading to investigate their performance. It was found that the properties of the grouted couplers depend on the pull out or slippage characteristics.

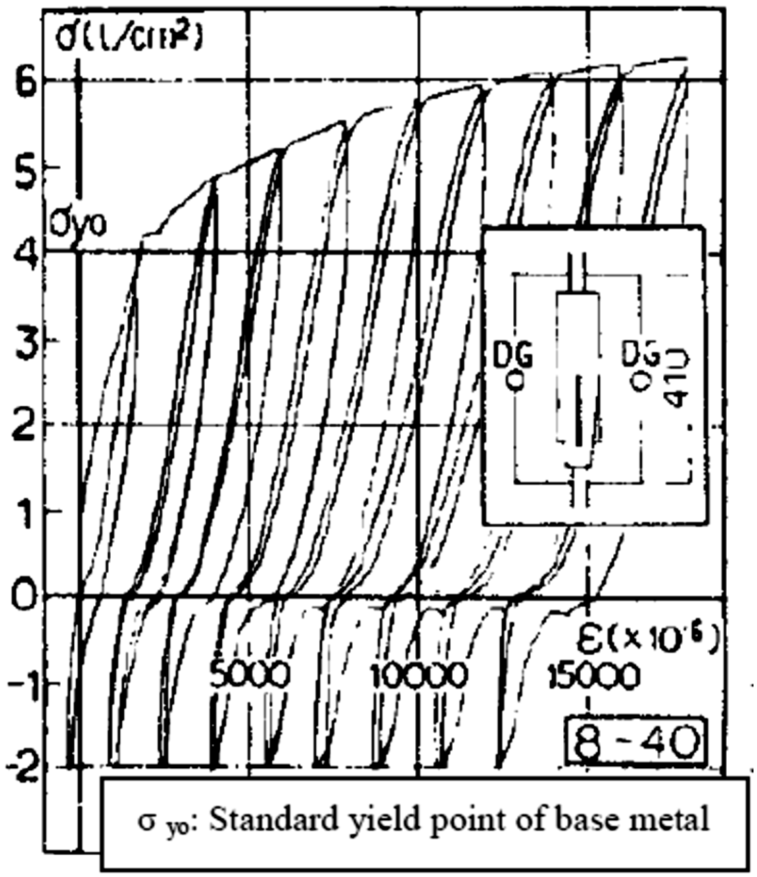


Figure 2.5- Stress-Strain Relationship of a sample Grouted Coupler Tested by Matsuzaki et al. (1987b)

Aida et al. (2005) tested two grouted splice sleeves to determine the stress-strain relationship of the coupler. Figure 2.6 shows cut-in-half of one of the specimens. They measured the properties of couplers by tensile test.

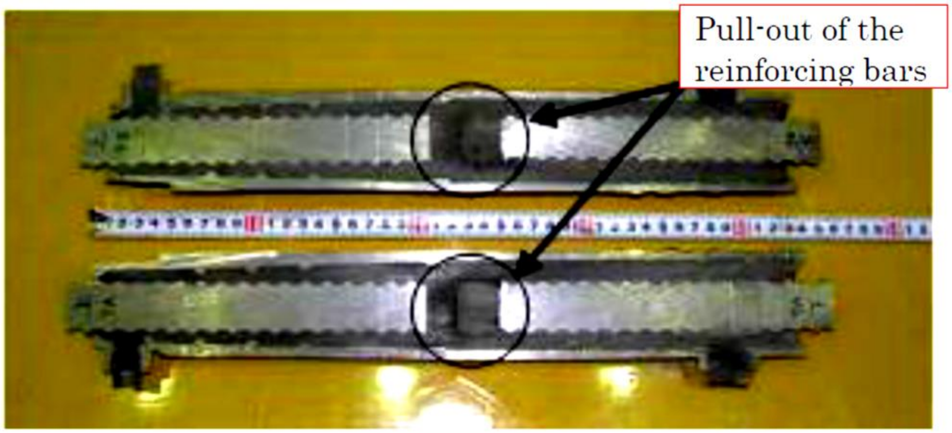


Figure 2.6- Inside view of Grouted Splice Sleeve Tested by Aida et al. (2005)

Haber et al. (2013) tested two types of mechanical bar splices under tensile loads, three per mechanical bar splices: headed coupler (HC) and grouted sleeve coupler (GC). Figure 2.7 shows a sample test result. The couplers were tested under static, dynamic, cyclic loading to failure. They found that both type of couplers exhibited consistent mode of failure of bar fracture. The ultimate strains of the spliced bars were lower than those for the unspliced bars.

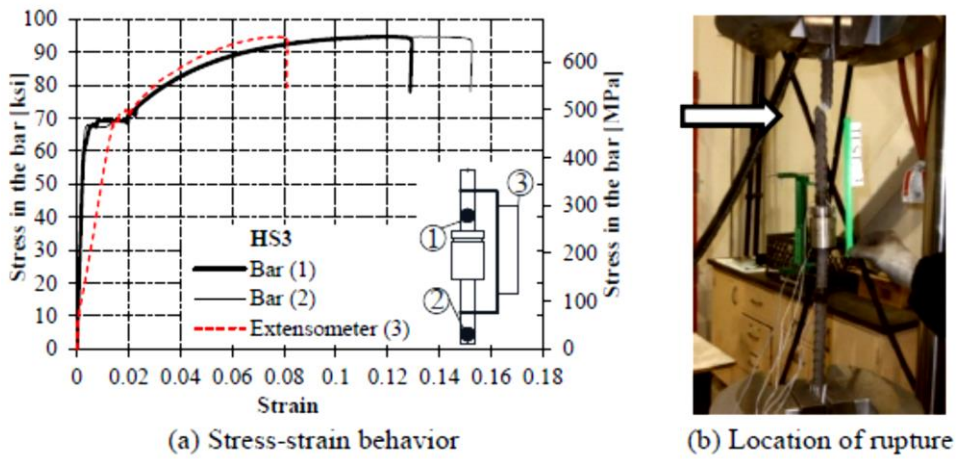


Figure 2.7- Stress-Strain Relationship of a sample Headed Bar Coupler Tested by Haber et al. (2013)

Phuong and Mutsuyoshi (2015) performed tensile tests on six threaded couplers (TC) (Fig. 2.8). Five of the splices were intentionally assembled improperly. Only one of the splices (MS-6me) was assembled as required by the manufacturer. Tensile test showed that only the correctly assembled splice exhibited almost same initial stiffness and strength as the reference unspliced reinforcing bar. Other specimens failed by bar pullout before reaching the ultimate strength.

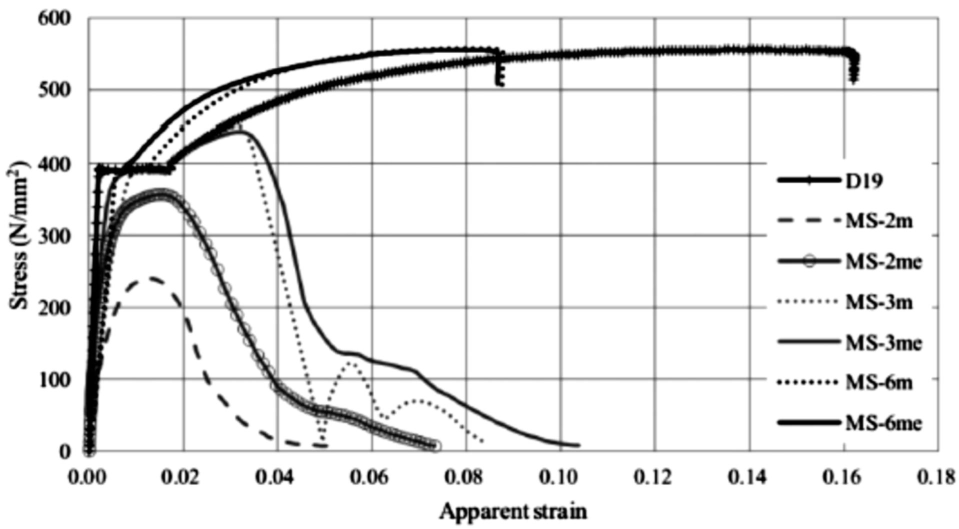


Figure 2.8- Stress-Strain Relationship of Threaded Couplers Tested by Phuong and Mutsuyoshi (2015)

2.4 RC Members Incorporating Mechanical Bar Splices

The performance of RC beams and columns incorporating mechanical bar splices was investigated in several studies. However, no data was found regarding the performance of RC frames with couplers. This section presents a summary of the finding of studies in which the bulk of the information presented was sufficient to construct an analytical model for further investigations.

2.4.1 Beams with Mechanical Bar Splices

Matsuzaki et al. (1987a) tested one RC beam without any splicing as reference model and two beams incorporating bar couplers. Grouted sleeve couplers were incorporated (Fig. 2.9). Of the two coupler incorporated members, the sleeve was incorporated only in beam in Specimen No. 2 (Fig. 2.9). The sleeve was incorporated in both beam and beam-column joint in Specimen No. 3 (Sec. 2.4.3). Figure 2.10 shows the load-deformation relationship of the three beams. They reported that the effect of grouted couplers on member performance was insignificant.

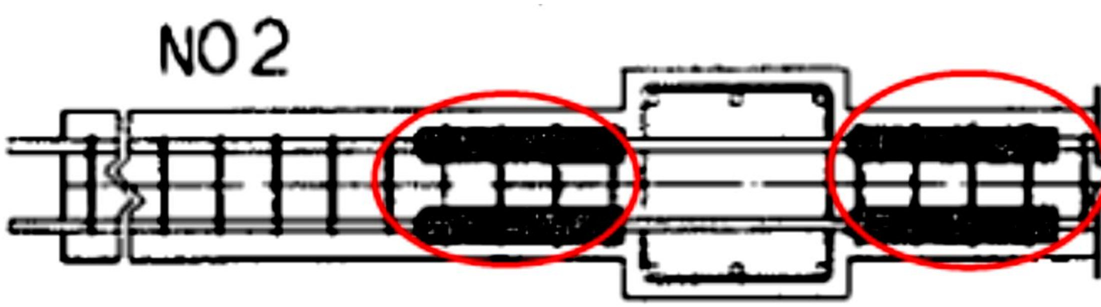


Figure 2.9- Beam with Grouted Couplers Tested by Matsuzaki et al. (1987a)

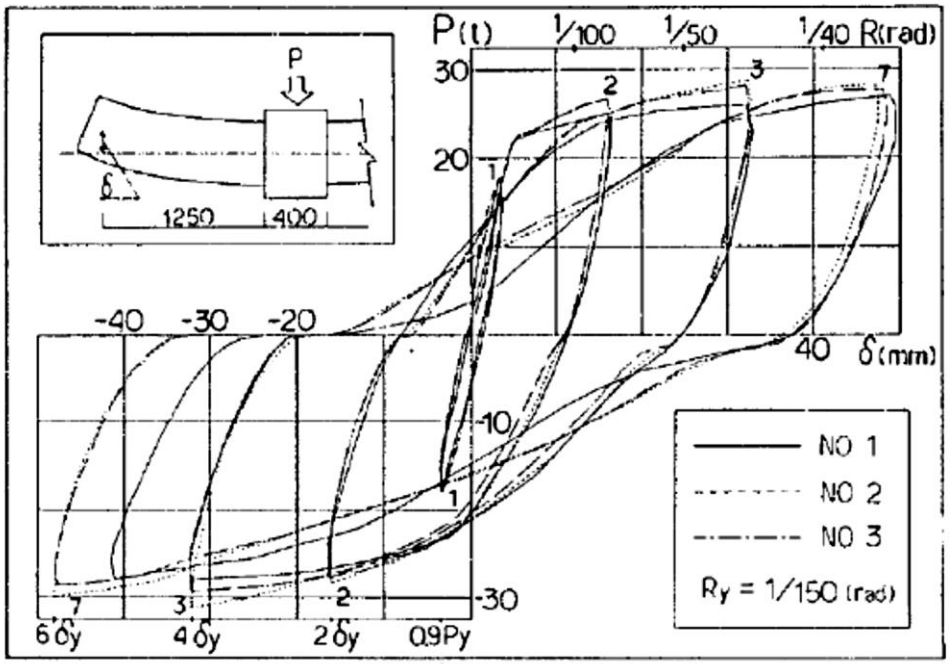


Figure 2.10- Load-Deformation Relationship for Beams and Beam-Column Joint Tested by Matsuzaki et al. (1987a)

Yoshino et al. (1996) tested 73 columns and 18 beams some incorporating grouted couplers. The purpose of their test was to determine the performance of precast concrete members using intensive shear reinforcing (ISR) and the contribution of ISR to the shear capacity of the members. Figure 2.11 shows the detailing of two specimens and Fig. 2.12 shows the force-displacement relationship. They reported that the performance of spliced specimens were comparable to that of reference specimens in terms of strength and displacement capacity.

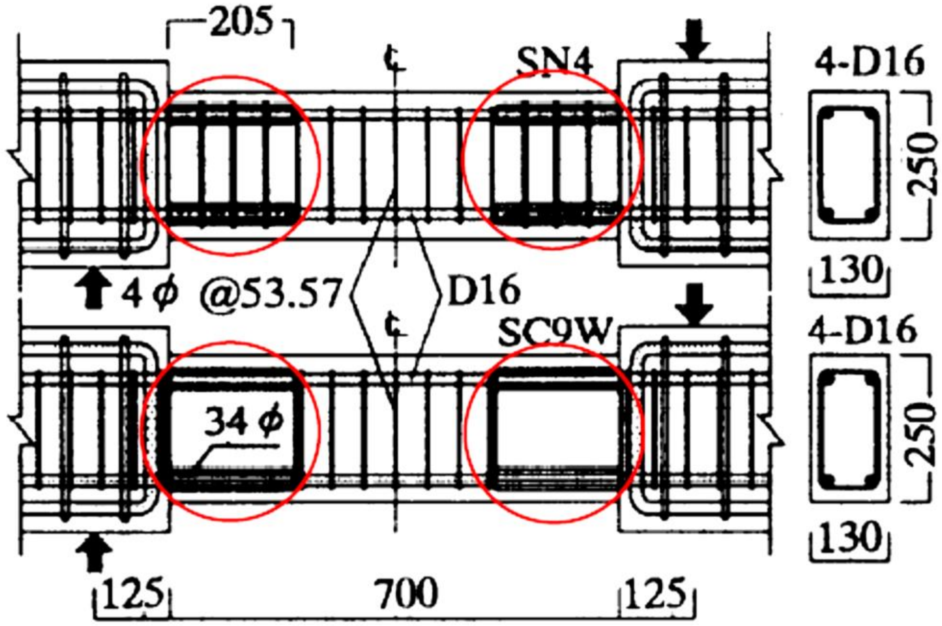


Figure 2.11- Specimen with Grouted Couplers Tested by Yoshino et al. (1996)

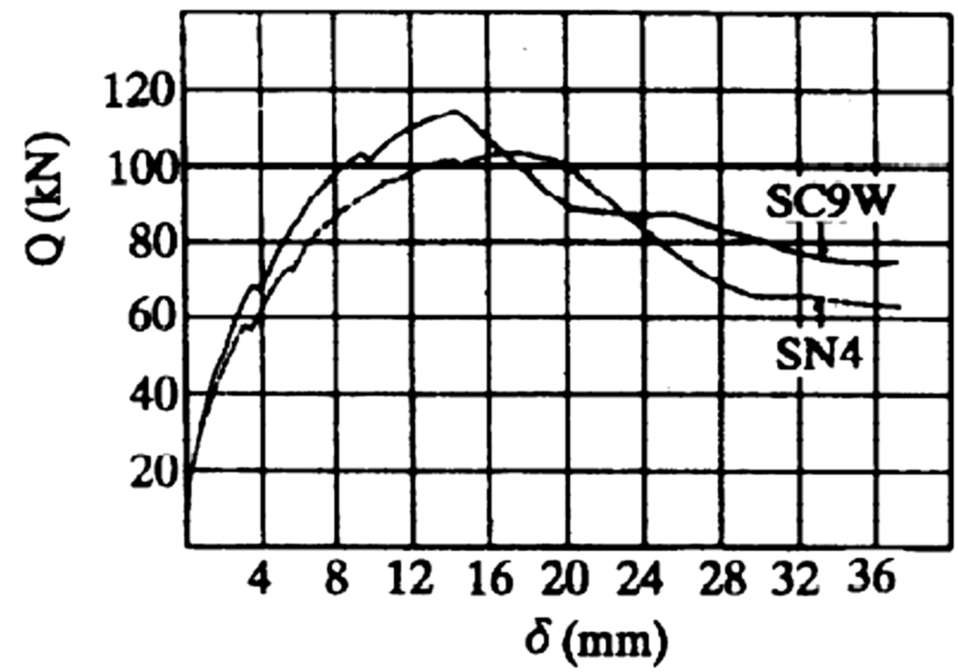


Figure 2.12- Load-Deformation Relationship for Specimen with Grouted Couplers Tested by Yoshino et al. (1996)

Phuong and Mutsuyoshi (2015) investigated the effect of improperly installed bar couplers on the behavior of RC beams. They tested ten beams including a reference beam with no splice (B1) and a beam with correctly installed threaded coupler (B10-6me-0d). Eight other beams had threaded couplers with improper detailing either by shorter length or by lack of epoxy. Figure 2.13 shows elevation and top view of a beam. Figure 2.14 shows the load-displacement relationship of three spliced beams. They have found that the beams with properly installed threaded splices performed the same as the control beam.

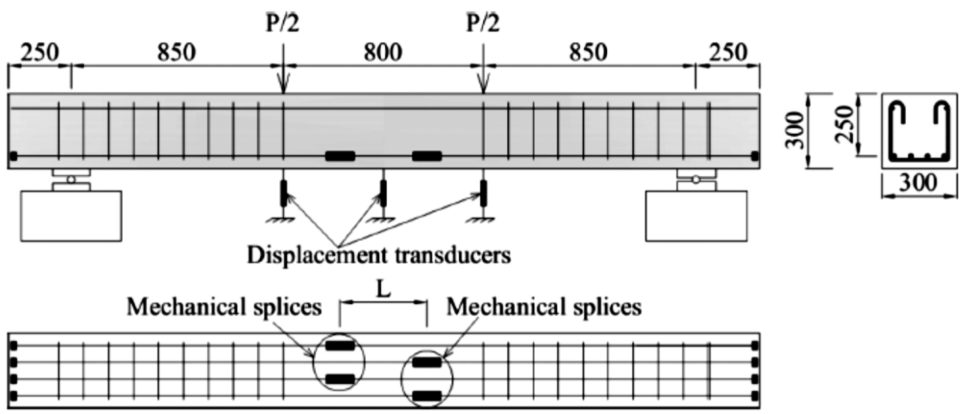


Figure 2.13- Beam Tested by Phuong and Mutsuyoshi (2015)

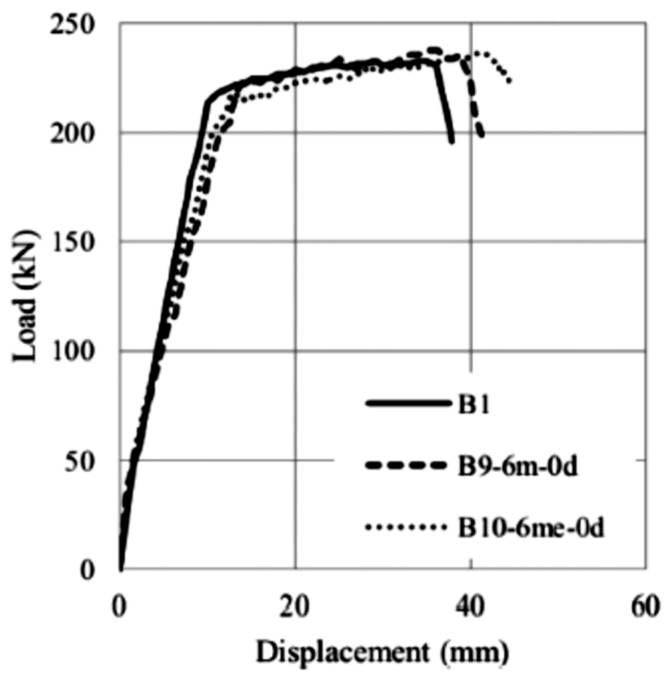


Figure 2.14- Load-Displacement Relationship for Beams Tested by Phuong and Mutsuyoshi (2015)

2.4.2 Columns with Mechanical Bar Splices

Tazarv and Saiidi (2016) preformed a state-of-the-art literature review of the performance of mechanically spliced columns. The readers are referred to this study for complete review.

2.4.3 Joints with Mechanical Bar Splices

Matsuzaki et al. (1987a) tested a specimen incorporating couplers in beams and beam-column joint (Fig. 2.15) to investigate the structural performance. Figure 2.10 shows the load-displacement relationship of the specimen (Specimen No. 3). They reported that the effect of grouted sleeve couplers on member performance was insignificant.

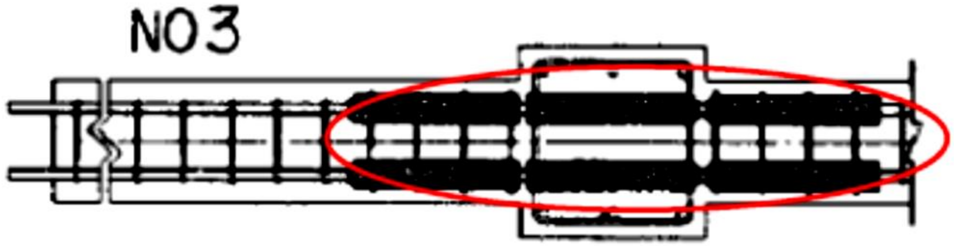


Figure 2.15- Grouted Couplers in Beams and Beam-Column Joint Tested by Matsuzaki et al. (1987b)

2.4.4 Frames with Mechanical Bar Splices

No experimental study was found on the performance of mechanically spliced RC frames.

2.4.5 Conventional Frames

Of several large-scale experiments on the performance of conventional RC frames and buildings, a few studies were selected to be used in following chapters to verify the proposed modeling methods.

Vecchio and Emara (1992) tested a one-bay two-story frame under lateral loads. Figure 2.17 shows the details of the frame and Fig. 2.18 shows the force-displacement response. The main goal of the study was to determine the effect of shear forces on the ductility of RC frames. They reported that load capacity and failure mechanism are affected by the shear deformation.

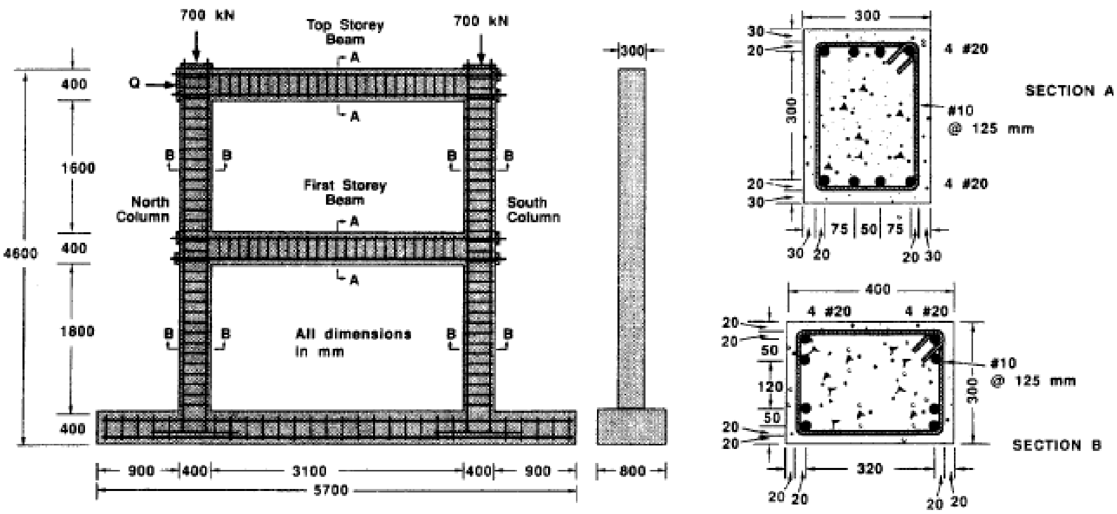


Figure 2.17- Unspliced Frame Tested by Vecchio and Emara (1992)

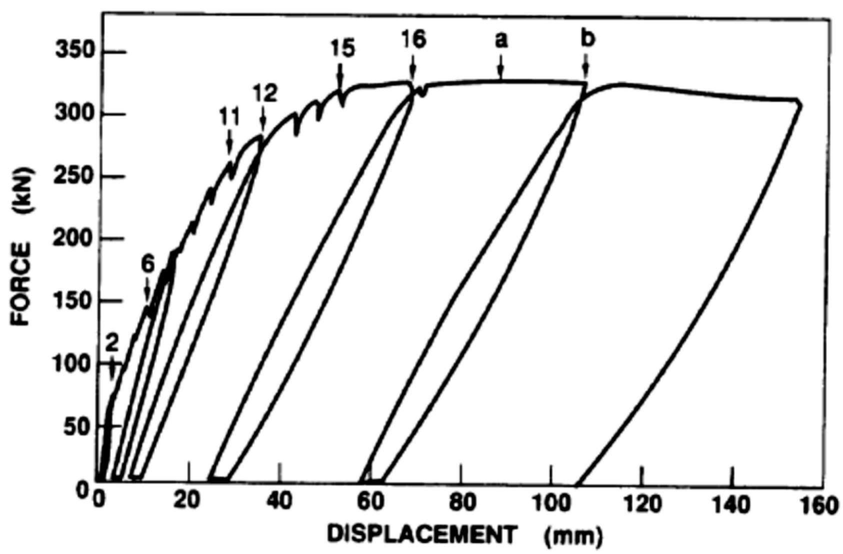


Figure 2.18- Force-Displacement Relationship of Unspliced Frame Tested by Vecchio and Emara (1992)

Calvi et al. (2001) tested a three-bay three-story RC frame designed for gravity loads (Fig 2.19) to determine the seismic behavior of this type of frame under lateral load. Figure 2.20 shows the force-displacement relationship of the frame. They have reported the local and global damage and failure of the frame.

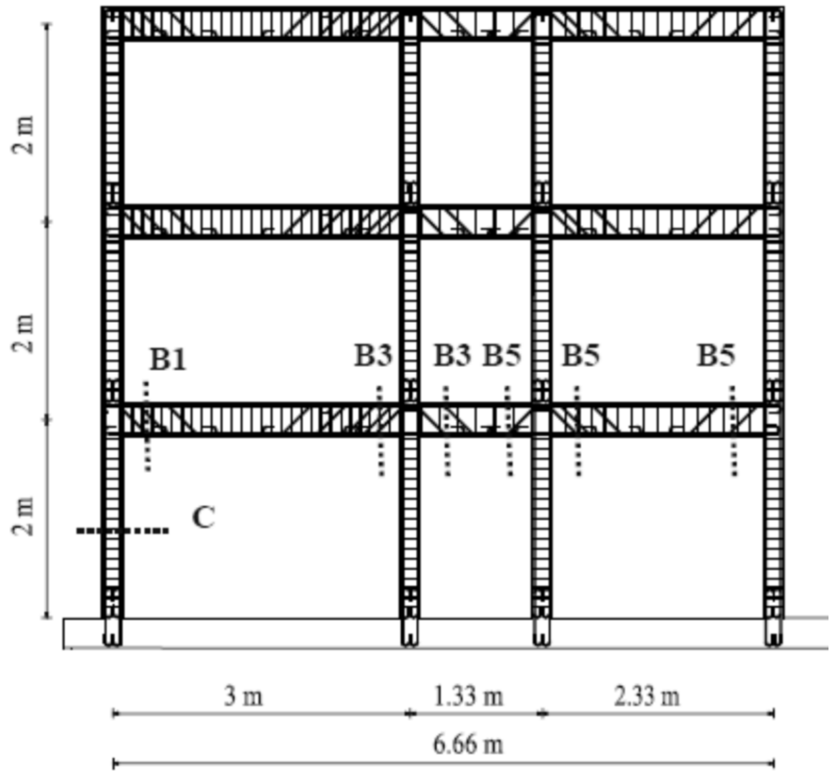


Figure 2.19- Gravity Frame Tested by Calvi et al. (2001)

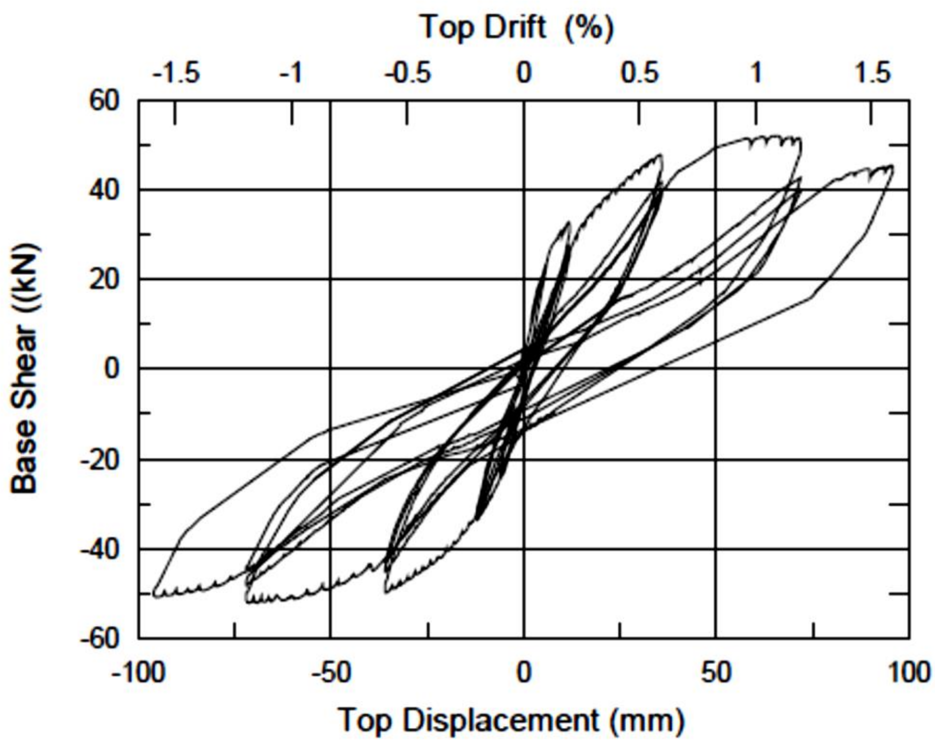


Figure 2.20- Force-Displacement of Gravity Frame Tested by Calvi et al. (2001)

Calvi et al. (2004) tested one one-bay one-story bare frame and one infilled frame (Fig. 2.21) under cyclic loading to determine the effect of reinforcement in masonry infilled RC frames. Figure 2.22 shows the force-displacement relationship. They reported that using reinforcement in the infilled frames improves the seismic performance.

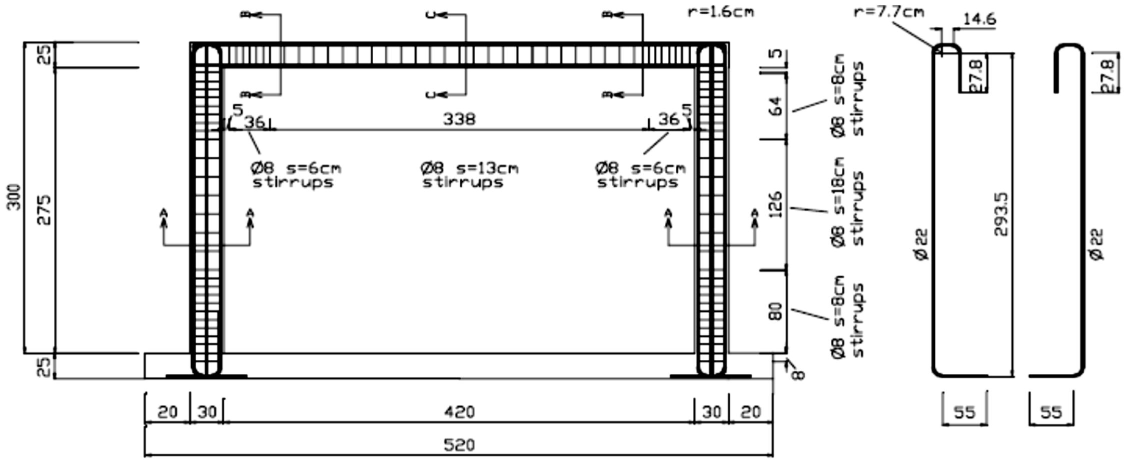


Figure 2.21- Unfilled Unspliced Frame Tested by Calvi et al. (2004)

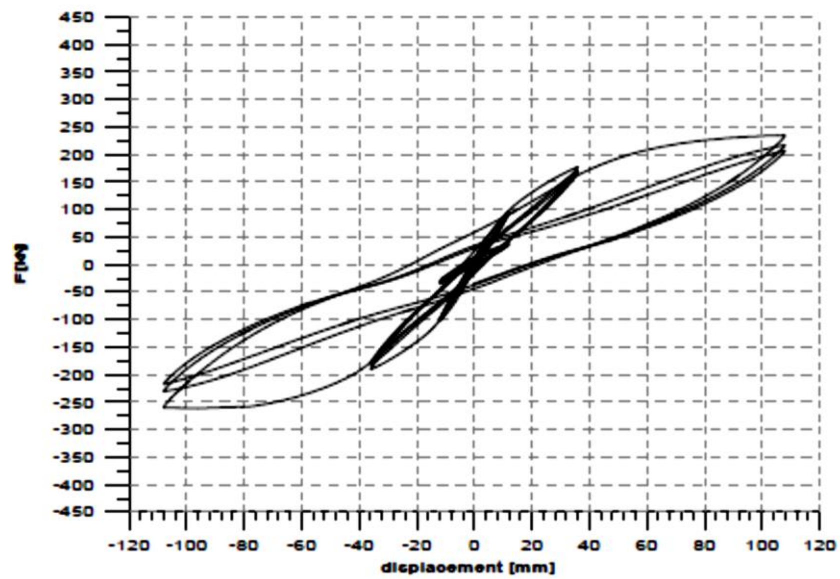


Figure 2.22- Force-Displaement Relationship of Unfilled Unspliced Frame Tested by Calvi et al. (2004)

2.5 References

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3. Analytical Modeling Methods for RC Buildings

An extensive literature review on reinforced concrete (RC) members incorporating mechanical bar splices was conducted and a summary of the findings was presented in Chapter 2. This chapter presents analytical modeling methods for mechanically spliced RC components such as beams and columns. Different models were selected from the experimental studies available in the literature, and the calculated response using the proposed modeling methods was compared to that measured in the experiments. Since there is no experimental study on the performance of RC frames with mechanical bar splices at the time of this writing, the modeling method for frames was for those without bar couplers. The verified modeling methods are utilized in the next chapter to investigate the seismic performance of RC frames with couplers.

3.1 Analysis of RC Beams Incorporating Couplers

Previous studies extensively investigated force-displacement behavior of RC beams with different geometries and reinforcement. However, test data pertaining to mechanically spliced RC beams is scarce. In this section, a simply supported mechanically spliced beam tested by Phuong and Matsuyoshi (2015) was selected for further studies.

3.1.1 Description of Mechanically Spliced Beam Test Model

Phuong and Matsuyoshi (2015) tested 10 beams under two-point load configuration. Of which, B10-6me-0d was selected for analytical studies (Fig. 3.1). The beam was 9.84-ft (3-m) long with a span length of 8.2 ft (2.5 m). Two rollers supported the beam at the ends. Two point loads were equally applied at 16 in. (400 mm) away from the mid-span. Four threaded couplers were utilized at the mid-span of the beam to connect the beam bottom reinforcement. Length of each coupler was 6 in. (152.4 mm). The couplers were located in the uniform bending moment region, and no stirrups were used in this region assuming that the shear demand is zero.

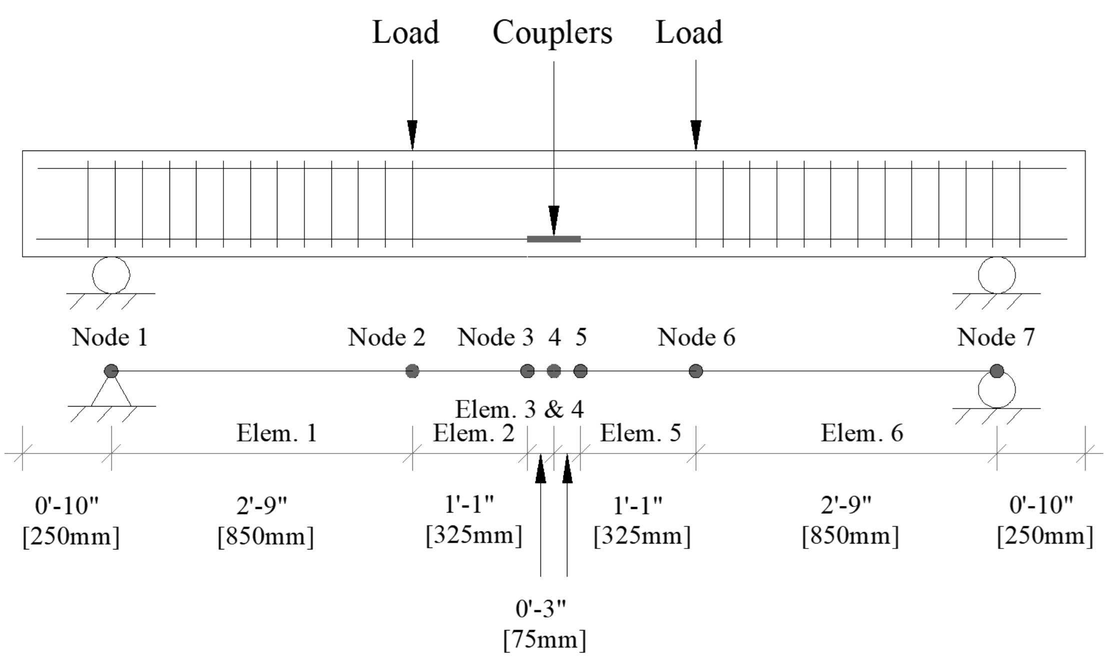

Figure 3.1- Test Setup for B10-6me-0d in Phuong and Matsuyoshi (2015)

Figure 3.2 shows the details of the beam cross-section. Four No. 6 bars (Ø19 mm) and two No. 2 bars (Ø6 mm) were used at the bottom and the top of the beam, respectively.

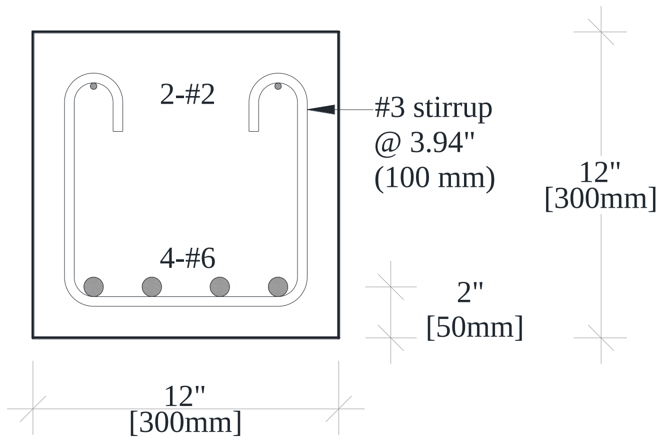

Figure 3.2- Cross-Section of B10-6me-0d Tested by Phuong and Matsuyoshi (2015)

The yield and ultimate strength of the beam longitudinal reinforcement were 56.8 ksi (391.62 MPa) and 80.3 ksi (553.65 MPa), respectively. The yield and ultimate strength of the beam transverse reinforcement were 56.8 (391.62 MPa) and 80.3 ksi (553.65 MPa), respectively. The beam concrete compressive strength was 4.57 ksi (31.51 MPa).

Phuong and Matsuyoshi (2015) also tested the beam longitudinal reinforcement with and without the coupler under tensile forces. Figure 3.3 shows the measured stress-strain relationship for the unspliced and mechanically spliced reinforcing steel bars. It can be seen that the initial stiffness of the two specimens is the same but the spliced bar exhibited significantly lower strain capacity (56%) compared to the unspliced bar.

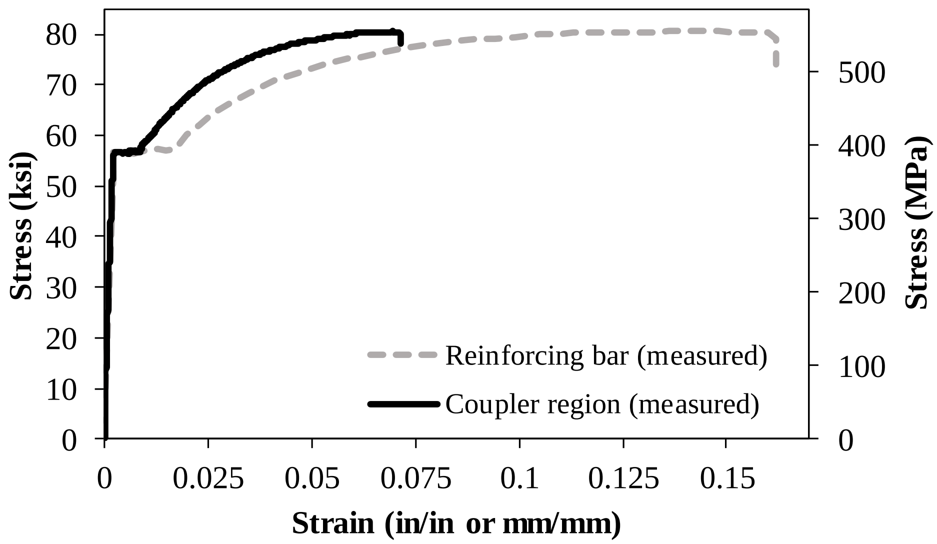

Figure 3.3- Measured Stress-Strain Relationships for Mechancially Spliced and Unspliced Reinforcing Steel Bars Tested by Phuong and Matsuyoshi (2015)

3.1.2 Modeling Methods for Beam with Couplers

OpenSees (2016) was used for modeling of RC members in the present study. Seven nodes and six elements in a two-dimensional fiber-section model were used to simulate B10-6me-0d. Figure 3.1 shows the analytical model parameters for the beam. Table 3.1 presents the detail of the parameters and how they were simulated in OpenSees.

Table 3.1: Modeling Method for B10-6me-0d Tested by Phuong and Mutsuyoshi (2015)

Remarks	
Two Dimensions with 3 Degrees of freedom per node Geometrical Properties: Number of nodes: 7 Number of Elements: 6 Element type: "forcebeamcolumn" with 5 integration points per element No bond-slip effects	Sectional Properties: Fiber Section Cover Concrete Discretization: 50 by 50 Core Concrete Discretization: 50 by 50 Confinement based on the actual transverse reinforcement.
Concrete Fibers	
Application: unconfined concrete (cover) Type: "Concrete01" f'_{cc} = -4.57 ksi (-31.51 MPa) ε_{cc} = -0.002 in./in. f'_{cu} = 0.0 ksi (0.0 MPa) ε_{cu} = -0.005 in./in.	Application: confined concrete (core) based on Mander's model Type: "Concrete01" (corner elements) f'_{cc} = -6.33 ksi (43.64 MPa) ε_{cc} = -0.006 in./in. f'_{cu} = -4.39 ksi (30.27 MPa) ε_{cu} = -0.032 in./in. Type: "Concrete01" (middle elements) f'_{cc} = -4.75 ksi (32.75 MPa) ε_{cc} = -0.002 in./in. f'_{cu} = -2.36 ksi (16.27 MPa) ε_{cu} = -0.009 in./in.
Unspliced / Spliced Reinforcing Steel Fibers	
Application: Unspliced Bars Type: "ReinforcingSteel" f_y = 56.8 ksi (391.62 MPa) f_{su} = 80.3 ksi (553.65 MPa) E_s = 29000 ksi (199947.96 MPa) E_{sh} = 984.6 ksi (6788.58 MPa) ε_{sh} = 0.017 in./in. ε_{su} = 0.162 in./in.	Application: Spliced Bars Type: "ReinforcingSteel" b= 0.7 (Coupler Rigid Length Factor) f_y = 56.8 ksi (391.62 MPa) f_{su} = 80.3 ksi (553.65 MPa) E_s = 64285.84 ksi (443235.26 MPa) E_{sh} = 2228.73 ksi (15366.55 MPa) ε_{sh} = 0.0075 in./in. ε_{su} =0.0716 in./in.

Tazarv and Saiidi (2016) developed a stress-strain material model for mechanical bar splices. The input of the model is the mechanical properties of the unspliced bar and the "coupler rigid length factor, β", which can be estimated using the measured stress-strain behavior for spliced bars. The coupler rigid length factor was 0.7 based on the measured data (Fig. 3.3). Figure 3.4 presented the measured and calculated stress-strain relationships for the spliced bar used in the beam test. It can be seen that the calculated response was in good agreement with that measured in the test especially the ultimate strain, which was essentially the same.

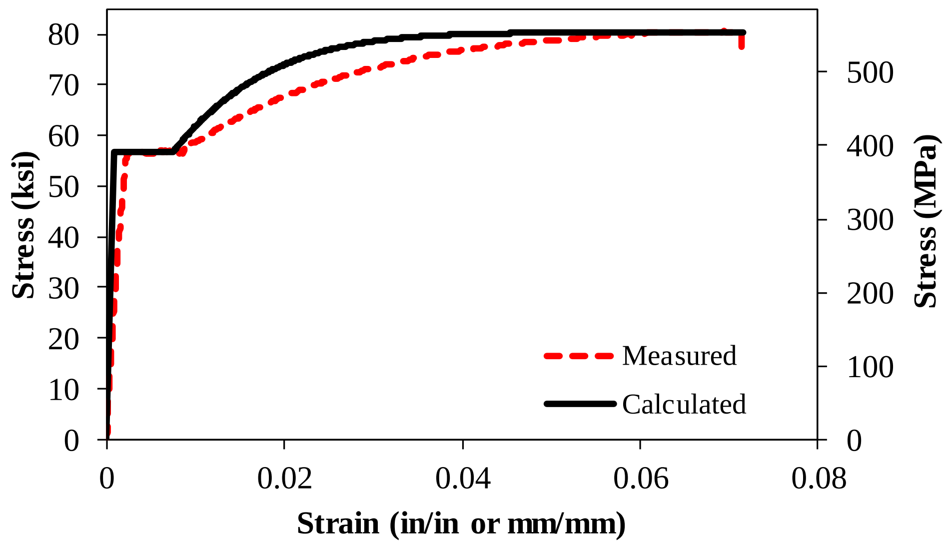

Figure 3.4- Measured and Calculated Stress-Strain Relationships for Spliced Bars Used in B10-6me-0d Tested by Phuong and Matsuyoshi (2015)

"ReinforcingSteel" material model from the OpenSees library was used to simulate the beam steel reinforcement in both the spliced and unspliced regions. For the unspliced section, the original properties of reinforcement were used. The mechanical properties of the coupler region (Fig. 3.4) were utilized in the sections with couplers. Confined concrete properties were calculated based on Mander's model (Mander et al. 1988). "Concrete01" material model was utilized for both cover and core concrete. Two displacement-based loads were applied at nodes 2 and 6 to failure.

3.1.3 Results of Analysis for Beam with Couplers

Figure 3.5 shows the calculated and the measured force-displacement relationships of the beam tested by Phuong and Mutsuyoshi (2015). The calculated ultimate displacement was defined where the core concrete failed, the reinforcement fractured, or the drop in the load carrying capacity was more than 15% with respect to the peak load. It can be seen that the calculated displacement capacity was 1.95 in. (49.53 mm) whereas the measured displacement capacity was 1.8 in. (45.72 mm), a 7.7% difference. The model successfully reproduced the initial stiffness but the overall strength was overestimated by an average of 5.5%.

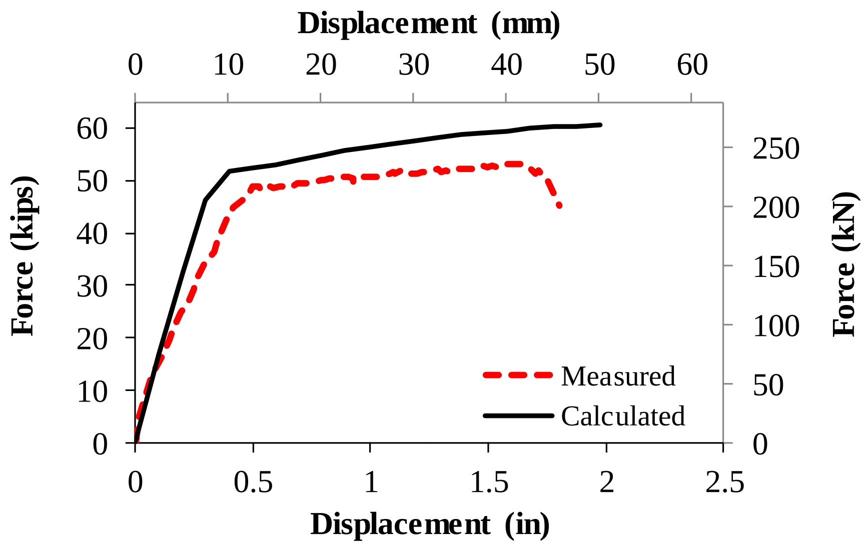

Figure 3.5- Measured and Calculated Force-Displacement Relationships for B10-6me-0d Tested by Phuong and Mutsuyoshi (2015)

3.2 Analysis of RC Columns Incorporating Couplers

A few studies have experimentally investigated the seismic performance of columns incorporating mechanical bar splices. A handful of those presented systematic modeling methods for this type of columns. Of which, modeling methods developed by Tazarv and Saiidi (2015) were adopted in the present study.

3.2.1 Test Model for Column with Couplers

Haber et al. (2013) tested a precast column with partial pedestal and grouted couplers above the pedestal, GCPP, to failure. Figure 3.6 shows the details of GCPP.

The circular column had a length of 108 in. (2743.2 mm) and a diameter of 24 in. (609.6 mm). The column was longitudinally reinforced with 11 No. 8 (Ø25 mm) bars and transversely with No. 3 (Ø10 mm) spirals at 2 in. (50.8 mm) pitch. The yield and the ultimate strength of the longitudinal reinforcement were 66.8 ksi (460 MPa) and 111.3 ksi (767 MPa), respectively. The yield and ultimate strength of the transverse reinforcement were 81.8 (564 MPa) and 112 ksi (768 MPa), respectively. The column concrete compressive strength was 3.83 ksi (26.4 MPa).

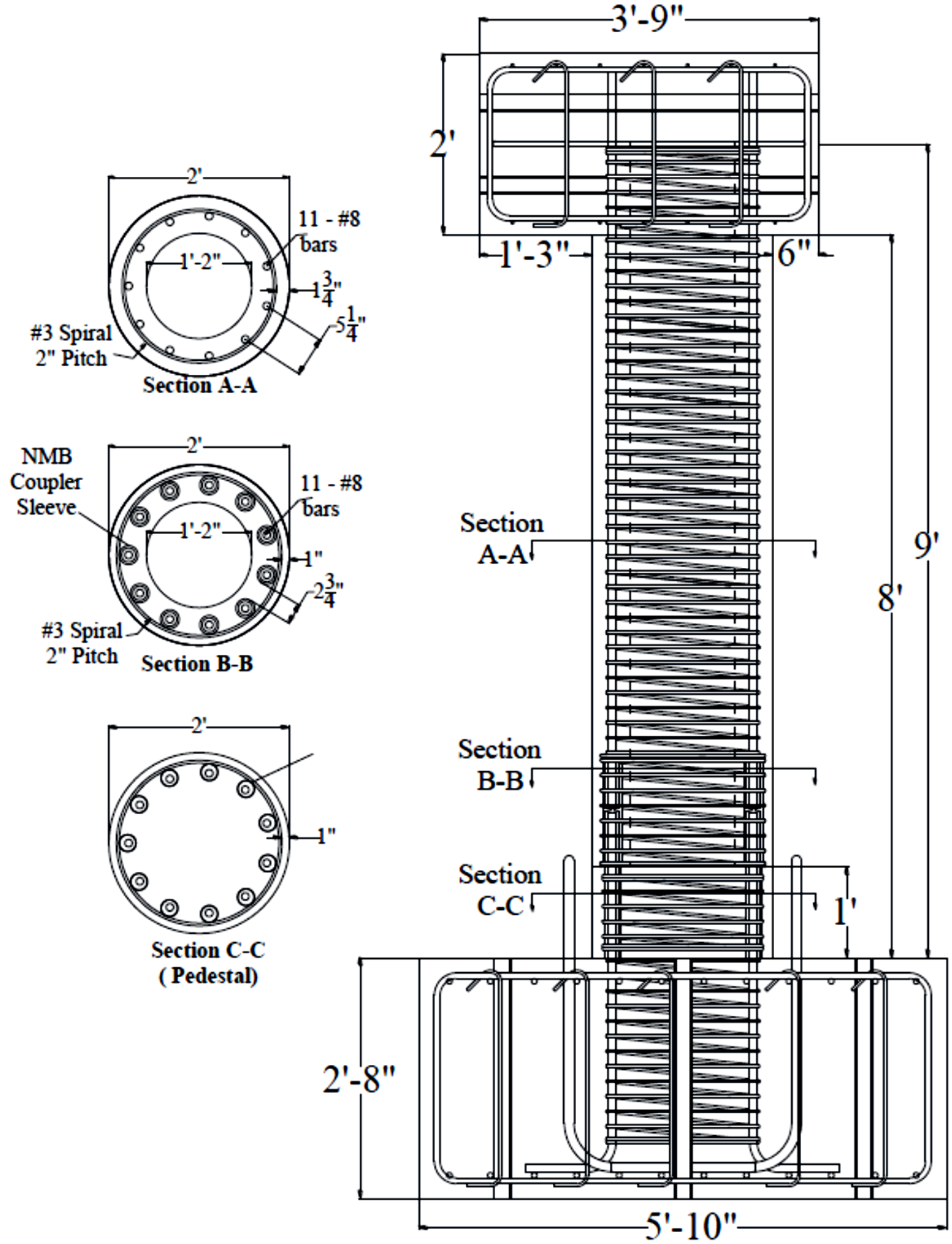

Figure 3.6- GCPP Column Incorporating Grouted Couplers Tested by Haber et al. (2013)

3.2.2 Modeling Methods for Column with Couplers

Tazarv and Saiidi (2015) developed an analytical modeling methods for columns in which the stress-strain relationship of the column sections with couplers is modified to account for the coupler effect (similar to what was done in section 3.1 for mechanically spliced beam). Details of the modeling methods can be found in that study.

3.2.3 Results of Analysis for Column with Couplers

Figure 3.7 shows the measured and calculated force-displacement relationships for GCPP. It can be seen that the analytical model was able to reproduce the test data with a reasonable accuracy.

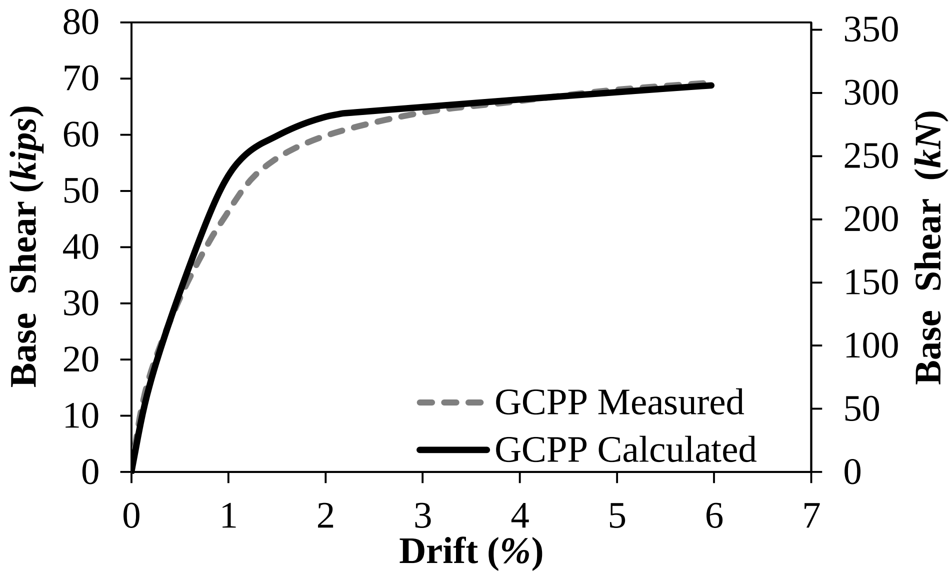

Figure 3.7- Measured and Calculated Force-Displacement Relationships for GCPP Tested by Haber et al. (2013)

3.3 Analysis of Frames without Couplers

It was mentioned that there is no experiment on the performance of RC frames incorporating mechanical bar splices. However, the seismic performance of RC frames without bar couplers has been experimentally investigated in a few studies (Calvi et al., 2001; Calvi et al., 2004; Vecchio and Emara, 1992). Of which, the study by Vecchio and Emara (1992) was selected for further investigation.

3.3.1 Test Model for Frame without Coupler

The test specimen was a one-bay two-story frame (Fig. 3.8) tested laterally to failure. The span length was 137.8 in. (3500 mm). The height of each story was 78.74 in. (2000 mm). The base columns were fixed to a strip footing, which was tied down to the floor.

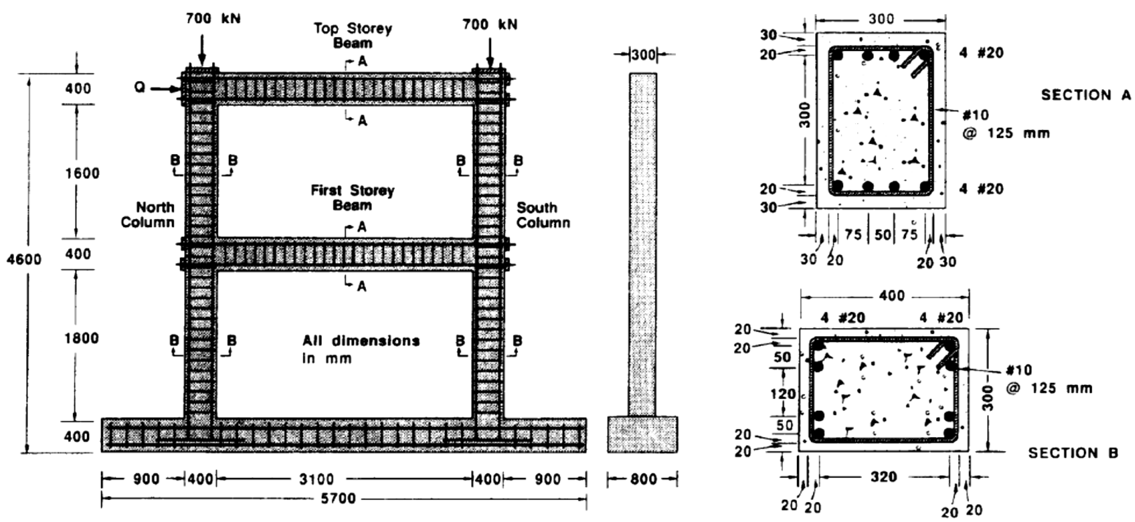

Figure 3.8- Elevation View and Section Properties of Frame Tested by Vecchio and Emara (1992)

Both beams and columns were rectangular with side dimensions of 12 in. (300 mm) by 16 in. (400 mm). No. 20 (mm) bars (according to the Canadian codes) were used as longitudinal reinforcement for both beams and columns. No. 10 (mm) bars (were utilized as transverse reinforcement. Stirrups were spaced at 5 in. (125 mm) in both beams and columns. Clear cover for the beams and columns was 1.2 in. (30 mm) and 0.8 in. (20 mm), respectively.

The yield stress and ultimate tensile strength of the longitudinal reinforcement were 60 ksi (418 MPa) and 86 ksi (596 MPa), respectively. The yield stress and ultimate tensile strength of the transverse reinforcement were 66 ksi (454 MPa) and 93 ksi (640 MPa), respectively. The frame concrete compressive strength was 4.35 ksi (30 MPa). An axial load of 157 kips (700 kN) was applied to each column. Lateral loads were applied to the top left beam-column joint.

3.3.2 Modeling Method for Frame without Coupler

A three-dimensional fiber-section model with six nodes and six elements was developed to simulate the frame behavior. Figure 3.9 shows the frame main model parameters.

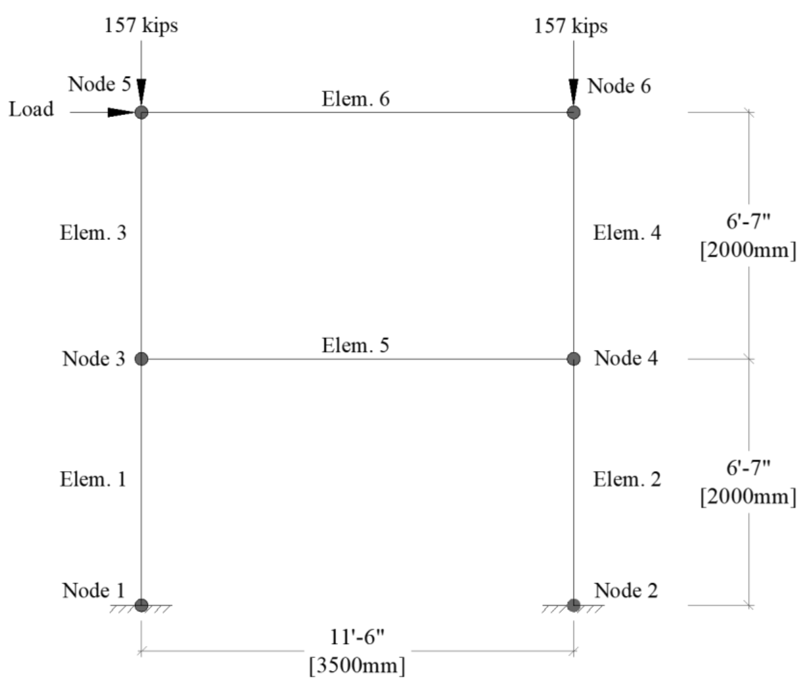

Figure 3.9- Modeling Method for Frame Tested by Vecchio and Emara (1992)

Table 3.2 presents a summary of modeling methods for the frame. For each beam and column, nonlinear "forcebeamcolumn" element with five integration points was utilized. Material properties were based on the measured data. P-Δ effect was included in the analysis for column elements only. No torsional or bond slip effect was included in the analysis.

"Concrete04" was used for both unconfined and confined concrete (Fig. 3.10). Confinement properties were found from Mander's model (Mander et al. 1988) based on the information from the cross-section of the beams and columns.

Two types of reinforcing material models were used in the analyses as shown in Fig. 3.11: (1) "ReinforcingSteel" material model, and (2) "Pinching4" material model. "ReinforcingSteel" material model can simulate the backbone and hysteresis behavior of reinforcing steel bars. However, the model does not exhibit a sudden drop at the failure point. "Pinching4" model requires 17 parameters to simulate the backbone of a stress-strain relationship of a material and needs 41 parameters to simulate the hysteretic behavior of a material. "Pinching4" was included in the analysis since it can simulate the failure point of a steel bar with a sudden drop in the strength as shown in Fig. 3.11. Note that the measured data was available up to 2.2% strain.

Table 3.2: Modeling Method for Frame Tested by Vecchio and Emara (1992)

General Remarks	
3 Dimensions with 6 Degree of freedoms Geometrical Properties: Number of nodes: 6 Number of Elements: 6 Element type: *forcebeamcolumn* with 5 integration points for both beams and columns P-Δ effects in columns No torsional or bond-slip effects	Sectional Properties: Fiber Section Cover Concrete Discretization: 50 by 30 Core Concrete Discretization: 50 by 30 Same section in all beams Same section in all columns
Concrete Fibers	
Application: unconfined concrete (cover) Type: Concrete04 for both beam and column f'_{cc} = -4.35 ksi (30 MPa) ε_{cc} = -0.002 in./in. f'_{cu} = 0.0 ksi (0.0 MPa) ε_{cu} = -0.005 in./in.	Application: confined concrete (core) based on Mander's model Type: Concrete04 for beam f'_{cc} = -6.177 ksi (42.59 MPa) ε_{cc} = -0.0062 in./in. f'_{cu} = -4.7351 ksi (32.65 MPa) ε_{cu} = -0.0266 in./in. Type: Concrete04 for column f'_{cc} = -6.0683 ksi (41.84 MPa) ε_{cc} = -0.006 in./in. f'_{cu} = -4.6247 ksi (31.89 MPa) ε_{cu} = -0.0253 in./in.
Steel Fibers	
Application: Longitudinal reinforcement Type: ReinforcingSteel F_y = 60 ksi (413.69 MPa) F_{su} = 86 ksi (592.95 MPa) E_s = 27900 ksi (192363.73 MPa) E_{sh} = 0.043* E_s ε_{sh} = 0.0095 in./in. ε_{su} = 0.12 in./in.	Application: Longitudinal reinforcement Type: Pinching4 F_1 = 60 ksi (413.69 MPa) F_2 = 82 ksi (565.37 MPa) F_3 = 86 ksi (592.95 MPa) F_4 = 0.5 ksi (3.45 MPa) ε_{s1} = 0.0023 in./in. ε_{s2} = 0.0365 in./in. ε_{s3} = 0.11 in./in. ε_{s4} = 0.12 in./in.

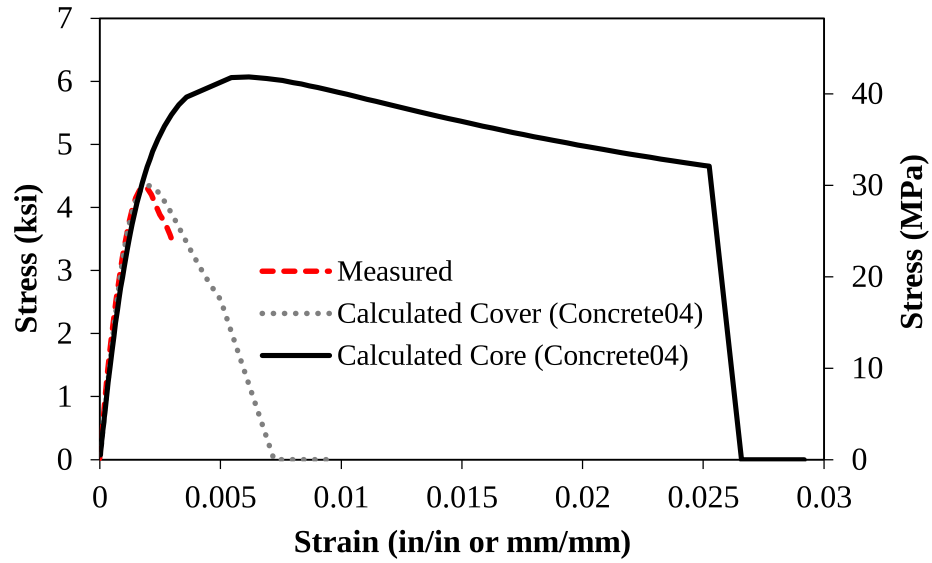

Figure 3.10- Measured and Calculated Stress-Strain Relationship for Concrete in Frame Tested by Vecchio and Emara (1992)

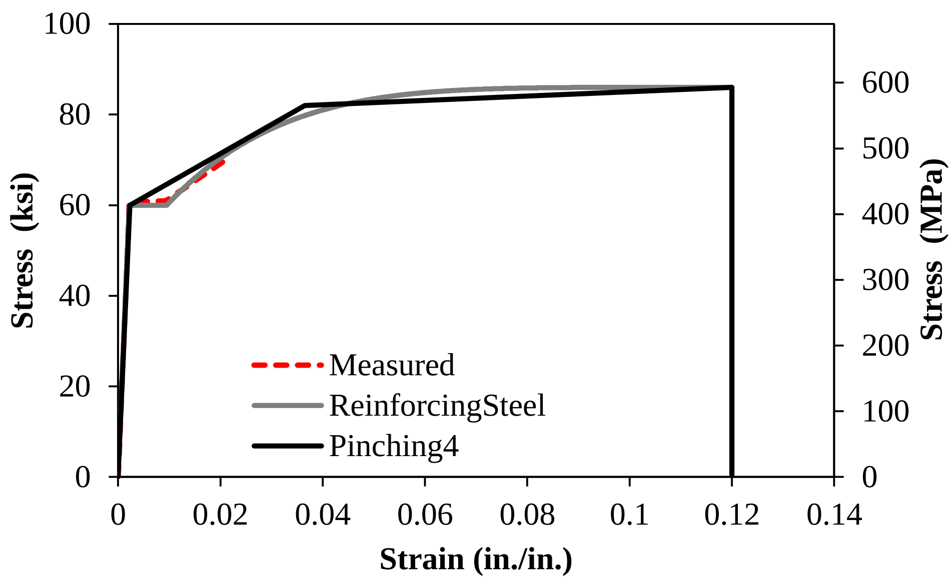

Figure 3.11- Measured and Calculated Stress-Strain Relationships for Reinforcement in Frame Tested by Vecchio and Emara (1992)

3.3.3 Results of Analysis for Frame without Coupler

Figure 3.12 shows the measured and calculated force-displacement relationships for the frame without couplers. Results from two analytical models are included in the figure: “ReinforcingSteel” material model was used for the longitudinal reinforcement in one model and “Pinching4” was utilized in the other one. It can be seen that both models reproduced the test data with reasonable accuracy. In the model with “ReinforcingSteel” material model, the stress-strain relationships of all reinforcement in all fiber sections were monitored to identify the ultimate displacement. However, the identification of the failure point in the model utilizing “Piching4” material model was relatively easy and simple since the reinforcement failure resulted in sudden drop in the lateral force carrying resistance of the frame. The calculated displacement capacity of the frame using “Pinching4” and “ReinforcingSteel” material models was 4.85 in. (123.2 mm) and 6.82 in. (173.2 mm), respectively. Note that the test frame did not fail but the test was stopped at 6-in. (150-mm) displacement due to stroke limitations of the actuator. Because of the use of “Concrete04” material model for concrete, a gradual strength degradation can be seen in both models due to failure of the core concrete in different sections.

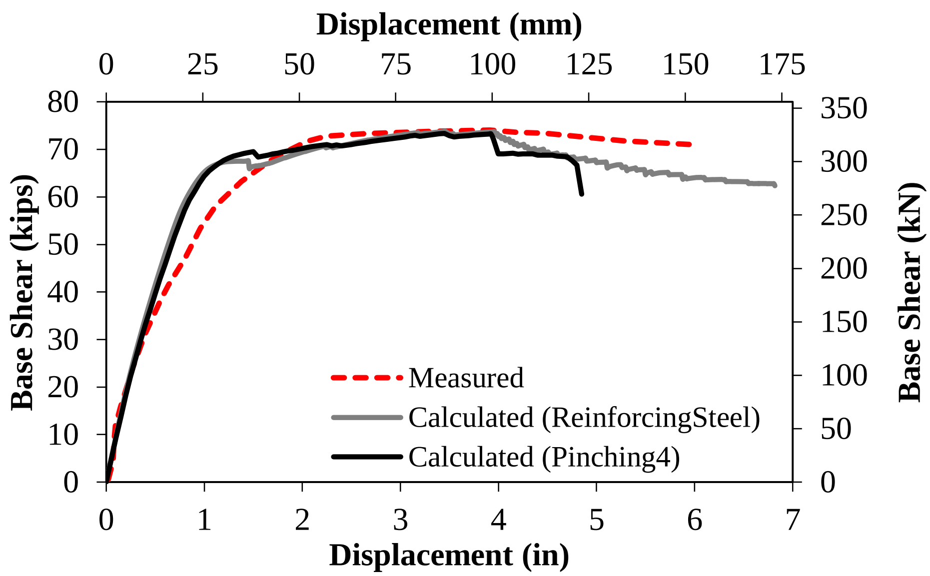

Figure 3.12- Measured and Calculated Pushover Response for Frame Tested by Vecchio and Emara (1992)

3.4 Summary and Conclusions

This chapter discussed the analytical modeling methods for different reinforced concrete components spliced with bar couplers. A mechanically spliced beam, a mechanically spliced column, and a conventional unspliced (without couplers) frame were selected for analytical studies. Based on the analytical studies, the following conclusions can be drawn:

- The measured and calculated initial stiffness as well as the ultimate displacement of the beam model were approximately the same using the proposed modeling method. The base shear was overestimated.
- The proposed modeling method for columns successfully reproduced the measured force-displacement relationship.

- The proposed modeling method for the unspliced frame was successful in reproducing the test force-displacement behavior. The "Pinching4" material model was found to be a simpler model for reinforcing steel bars in frames since the ultimate displacement of the frame can be easily identified using a sudden drop in the lateral strength.

Overall, the proposed modeling methods for mechanically spliced RC components were simple and sufficiently accurate to be used in further analysis.

3.5 References

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4. Design of Moment Resisting RC Frames

Design of moment resisting reinforced concrete (RC) frames to be used in analytical studies is presented in this chapter. Three-, six- and nine-story office buildings were designed according to the Ordinary, Intermediate and Special moment-resisting requirements per current design codes. Three site with different Seismic Design Categories (SDCs) were selected as the construction site. Design specifications, loading, and the results of the design are presented herein.

4.1 Design Specifications and Methods

ASCE 7-10 (2010) was used to determine the design loads and combinations. ACI 318-14 (2014) was used for the design of the moment-resisting RC frames and members. The buildings were to be used as office. Risk category of all buildings were II. Seismic importance factor, I_e, which depends on the risk category of the building, was 1. Site class or soil condition was considered as type D (stiff soil) for the design of all buildings.

4.1.1 Building Geometry and Sites

Each building was assumed to have four spans in each direction. However, only an interior frame of the buildings was selected for further investigation as shown in Fig. 4.1. The height and the span length of each frame were 12 ft. (3.66 m) and 20 ft. (6.1 m), respectively. Each frame was designed for three site locations (different SDC): Sioux Falls (SD) for SDC A, New York city (NY) for SDC B and Los Angeles (CA) for SDC E. Therefore, the total number of the frames was nine.

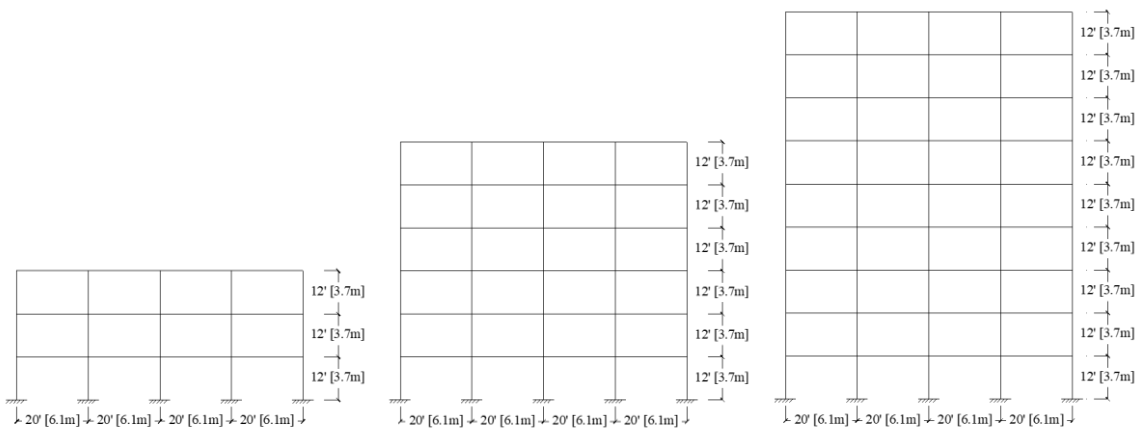


Figure 4.1- RC Frames for Analytical Studies

4.1.2 Material Properties

The compressive strength of normal-weight concrete and the yield strength of reinforcing steel bars were considered as 5 ksi (34.47 MPa) and 60 ksi (413.69 MPa), respectively. Reinforcing steel bars were ASTM A706 Grade 60.

4.1.3 Element Geometry

The size of beams and columns were kept the same for every three story of each frame for the ease of analysis. Section sizes were modified using a 6-in. (152 mm) increment. Only two sizes of longitudinal reinforcement were used: No. 7 (Ø22 mm) and

No. 9 (Ø29 mm). No. 3 (Ø10 mm) stirrups were used as transverse reinforcement in beams and columns. The clear concrete cover was 1.5 in. (38.1 mm) and 2 in. (50.8 mm) for the beam and column sections, respectively.

4.1.4 Load Combinations

The design load combinations were according to ASCE 7-10 (2010) as:

1. 1.4D
2. 1.2D + 1.6L + 0.5L_r
3. 1.2D + L + 1.6L_r
4. 1.2D + L $\pm$ E
5. 0.9D $\pm$ E
6. 1.2D + 1.6L_r + 0.5W
7. 1.2D + L + 0.5L_r + 1.0W
8. 0.9D + 1.0W

where D is the dead load, L is the live load, L_r is the roof live load, E is the earthquake load and W is the wind load. Wind and seismic loads should be applied in both directions of a frame.

4.2 Gravity Loads

Since only two-directional frames were considered, tributary gravity loads were applied directly on the beams of the floors. Tributary area for each beam was 400 ft^2 (37.16 m^2). Dead loads consisted of slab self-weight, floor finish, and wall loads. Roof dead load consisted of slab self-weight, plaster (ceilings), and coverings.

The floor slab thickness was assumed to be 6 in. (150 mm). Thus, the slab dead load that transfers to the beams was 1500 plf (2034 N/m). The floor finish and wall loads were estimated to be 660 plf (895 N/m) and 63 plf (85 N/m), respectively. The total superimposed dead load for each beam was 2223 plf (3014 N/m).

For the roofs, the slab load was the same as that for the floors. The roof ceilings and coverings loads were 300 plf (407 N/m) and 400 plf (542 N/m), respectively. Therefore, the roof total deal load was 2200 plf (2983 N/m).

For office type building, 50 psf (2394 N/m^2) live load is required by the code. The live load was not reduced per the code requirement. Partition load was considered to be 15 psf (718 N/m^2). Therefore, the total live load per floor beam was 1300 plf (1763 N/m).

Ordinary flat roof live load is 20 psf (958 N/m^2), which was reduced to 19 psf (910 N/m^2) per live load code requirements. Therefore, the total live load for each roof beam was 384 plf (521 N/m).

4.3 Lateral Loads

Lateral wind and seismic loads were also applied to the frames. Only the greater of which was selected for the design per the code requirements.

4.3.1 Seismic Loads

Seismic loads vary in different parts of the country due to the seismic activity of regions. Three cities in the USA were selected to include the effect of the seismic loads in the design. Table 4.1 presents seismic ground motion properties of the three site locations. Figure 4.2 shows the design response spectrum for the selected regions.

Table 4.1: Seismic Ground Motion Values for Three Selected Regions

City	S_s	S_1	S_{MS}	S_{M1}	S_{DS}	S_{D1}	Seismic Design Category
New York city, NY	0.089	0.035	0.142	0.084	0.094	0.056	SDC A
Sioux Falls, SD	0.278	0.072	0.439	0.172	0.293	0.114	SDC B
Los Angeles, CA	0.252	0.793	0.252	0.189	0.501	0.793	SDC E

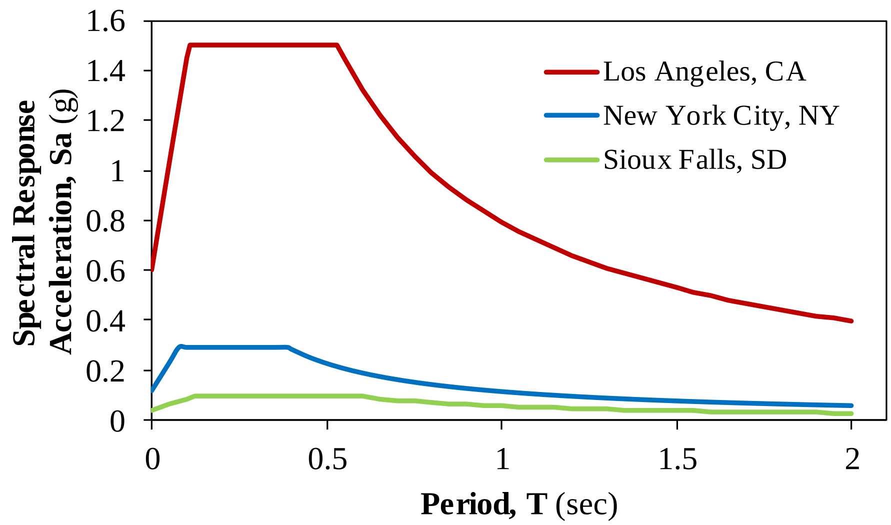


Figure 4.2- Design Response Spectrum for Three Selected Regions

To meet the seismic requirements, there types of moment-resisting frames (MRF) should be utilized: ordinary (or OMRF), intermediate (or IMRF), and special (or SMRF). Table 4.2 presents the design coefficients and factors for three MRFs per ASCE 7-10 (2010).

Table 4.2: Design Coefficients and Factors for Different Moment-Resisting Frames

Seismic Force-Resisting System	Response Modification Coefficient, R	Overstrength Factor, Ω	Deflection Amplification Factor, C_d
OMRF	3	3	2.5
IMRF	5	3	4.5
SMRF	8	3	5.5

4.3.2 Wind Loads

Wind loads were also included in the design based on ASCE 7-10 (2010). Directional procedure was used to determine the wind load. According to the code, a structure is rigid if the fundamental frequency is greater than or equal to 1 *Hz*, is flexible when the fundamental frequency is less than 1 *Hz*.

Based on the calculated period, it was concluded that the three-story buildings were rigid structures and the six- and nine-story buildings are flexible. Basic wind speed for SD, NY and CA were 115 mph (185 kph), 121 mph (195 kph), and 130 mph (209 kph). Directionality factor, K_d, was 0.85. Surface roughness was considered as type B assuming that all buildings are in urban and suburban areas. Exposure category was D. Topographic factor, K_{zt}, was 1. The building was classified as enclosed building. Velocity pressure exposure coefficient, K_z, varies with height of the building. K_z was equal to 1.196, 1.316, and 1.45 for three-, six-, and nine-story buildings, respectively. Wall pressure coefficients, C_p, was 0.8 and 0.5 for windward wall and leeward wall, respectively.

4.3.3 Base Shear Comparison

According to the code, only the greater of the lateral seismic and wind loads should be used for the design. Base shear demands were calculated by hand and using a commercial software (SAP2000, 2015) for all frames under the seismic and wind loads, and a summary is presented in Table 4.3. Highlighted cells are the larger of the two. It can be seen that the seismic loads are higher than the wind loads only in SMRFs, which were located in SDC E (Table 4.1).

Table 4.3: Comparison of Base Shear

Type of frame	Seismic load		Wind load	
	SAP2000, kips (kN)	Hand Calculation, kips (kN)	SAP2000, kips (kN)	Hand Calculation, kips (kN)
Three story Ordinary	18.11 (80.56)	18.37 (81.71)	37.36 (166.19)	37.36 166.19)
Three story Intermediate	24.92 (110.85)	23.82 (105.96)	41.36 (183.98)	41.36 (183.98)
Three story Special	126.17 (561.23)	127.97 (569.24)	47.74 (212.36)	47.74 (212.36)
Six story ordinary	21.6 (96.08)	21.33 (94.88)	82.2 (365.64)	82.11 (365.24)
Six story Intermediate	29.34 (130.51)	27.05 (120.32)	91.01 (404.83)	91.01 (404.83)
Six story Special	155.6 (692.14)	154.91 (689.07)	105.07 (467.37)	105.07 (467.37)
Nine story ordinary	24.3 (108.09)	23.34 (103.82)	135.69 (603.58)	135.69 (603.58)
Nine story Intermediate	30.98 (137.81)	29.53 (131.36)	150.25 (668.35)	150.25 (668.35)
Nine story Special	194.83 (866.65)	194.82 (866.6)	173.49 (771.72)	173.49 (771.72)

4.4 Summary of Design and Detailing

All nine RC frames were analyzed and designed satisfying the code requirements. The lateral displacement is usually the controlling parameter in the design of a building. Interstory drift is usually used in the design instead of the displacement, which is defined as the ratio of the relative displacements of the two adjacent stories to the story height. The allowable interstory drift is 0.025 for four-story buildings or shorter, and is 0.02 for five-story buildings and taller. The amplified interstory drifts (Table 4.2) were smaller than the allowable drifts.

Special moment-resisting frames were designed in a way that the columns were at least 1.25 stronger than the beams (strong column, weak beam design philosophy). ACI seismic detailing was utilized in all frames. A summary of the final design for each frame is presented herein.

4.4.1 Three-Story Ordinary Moment Resisting RC Frame

The detailing for the three-story ordinary moment-resisting frame is shown in Fig. 4.3 and 4.4. Table 4.4 presents the general design output.

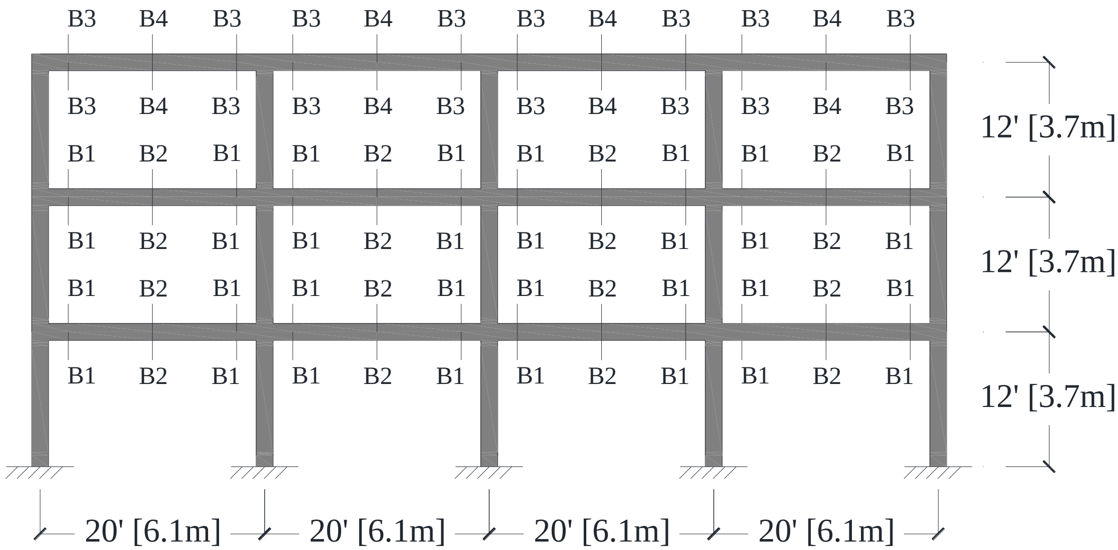


Figure 4.3- Three-Story Ordinary Moment-Resisting Frame

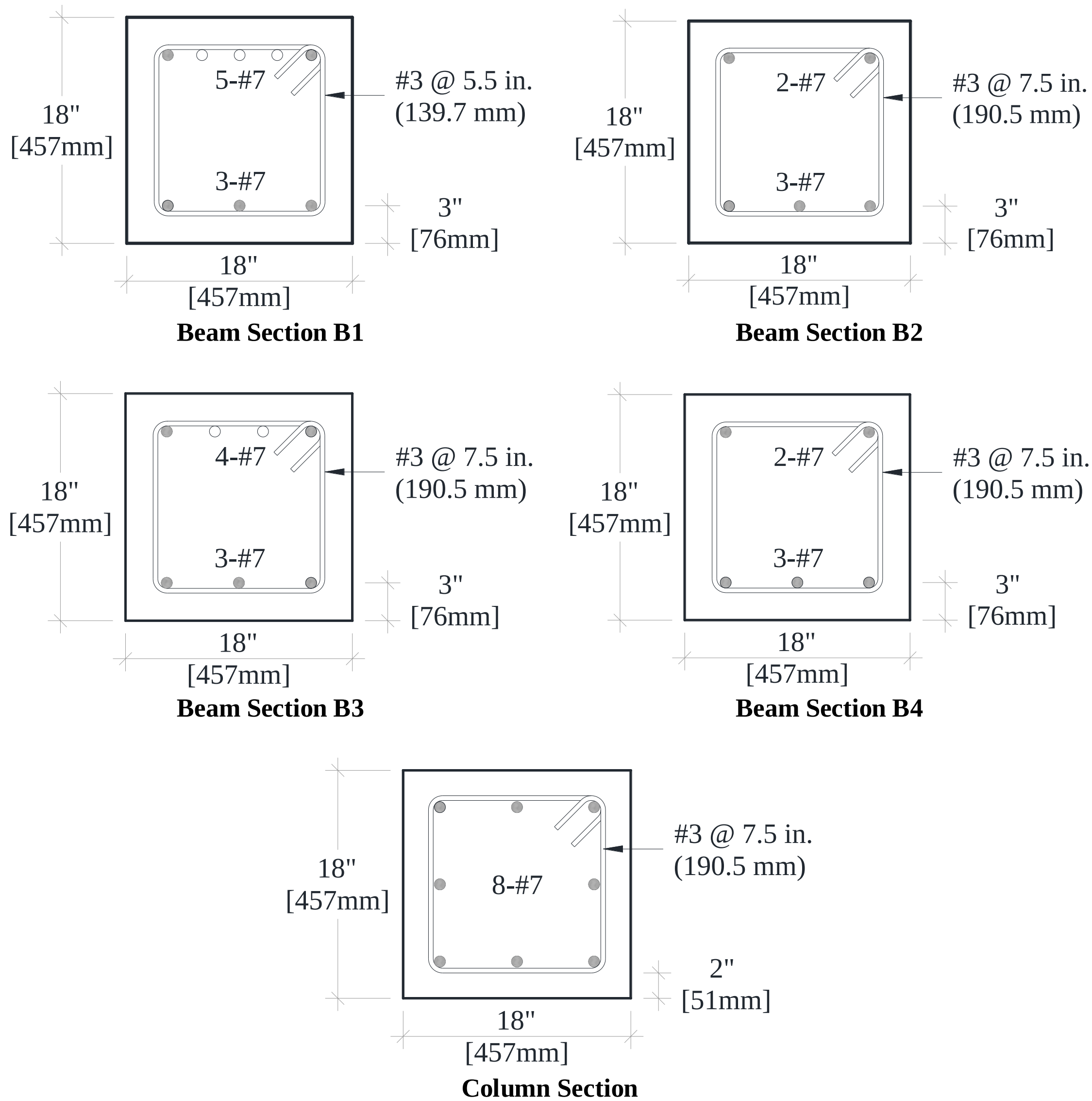


Figure 4.4- Section Details for Three-Story Ordinary Moment-Resisting Frame

Table 4.4: Summary of Design for Three-Story Ordinary Moment-Resisting Frame

Member	Story	Section	Size (in.)	Longitudinal Reinf.	Transverse Reinf.
Beam	Story 1 to 2	B1 (end)	18 by 18	Top 5 No. 7 Bottom 3 No. 7	No. 3 @ 5.5 in.
	Story 1 to 2	B2 (middle)	18 by 18	Top 2 No. 7 Bottom 3 No. 7	No. 3 @ 7.5 in.
	Story 3	B3 (end)	18 by 18	Top 4 No. 7 Bottom 3 No. 7	No. 3 @ 7.5 in.
	Story 3	B4 (middle)	18 by 18	Top 2 No. 7 Bottom 3 No. 7	No. 3 @ 7.5 in.
Column	Story 1 to 3	C	18 by 18	8 No. 7	No. 3 @ 7.5 in.

Note: 1 in. = 25.4 mm, Bar No. 3 = No. 10 mm, Bar No. 7 = No. 22 mm

4.4.2 Three-Story Intermediate Moment Resisting RC Frame

The detailing for the three-story intermediate moment-resisting frame is shown in Fig. 4.5 and 4.6. Table 4.5 presents the general design output.

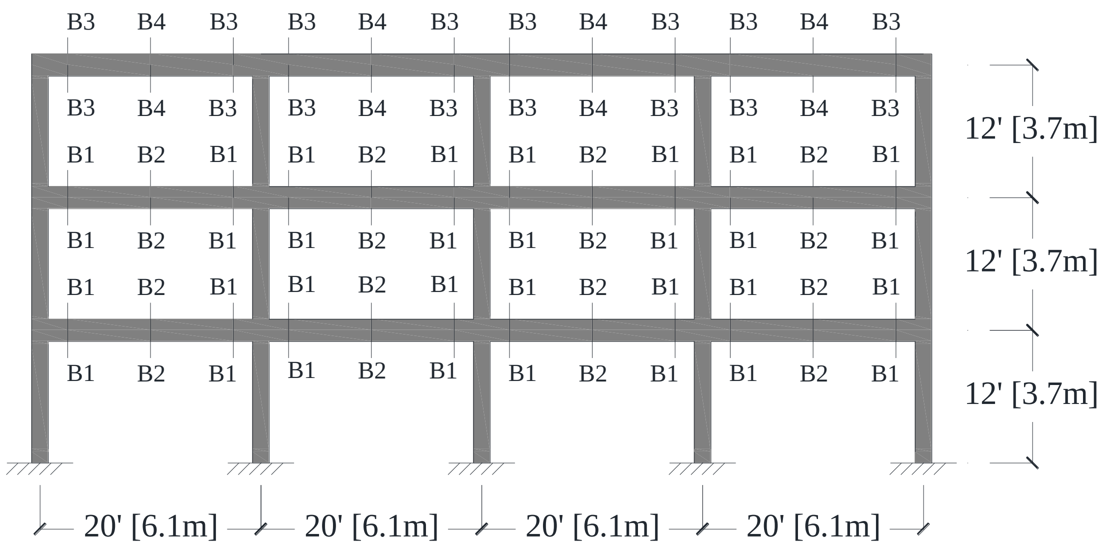


Figure 4.5- Three-Story Intermediate Moment-Resisting Frame

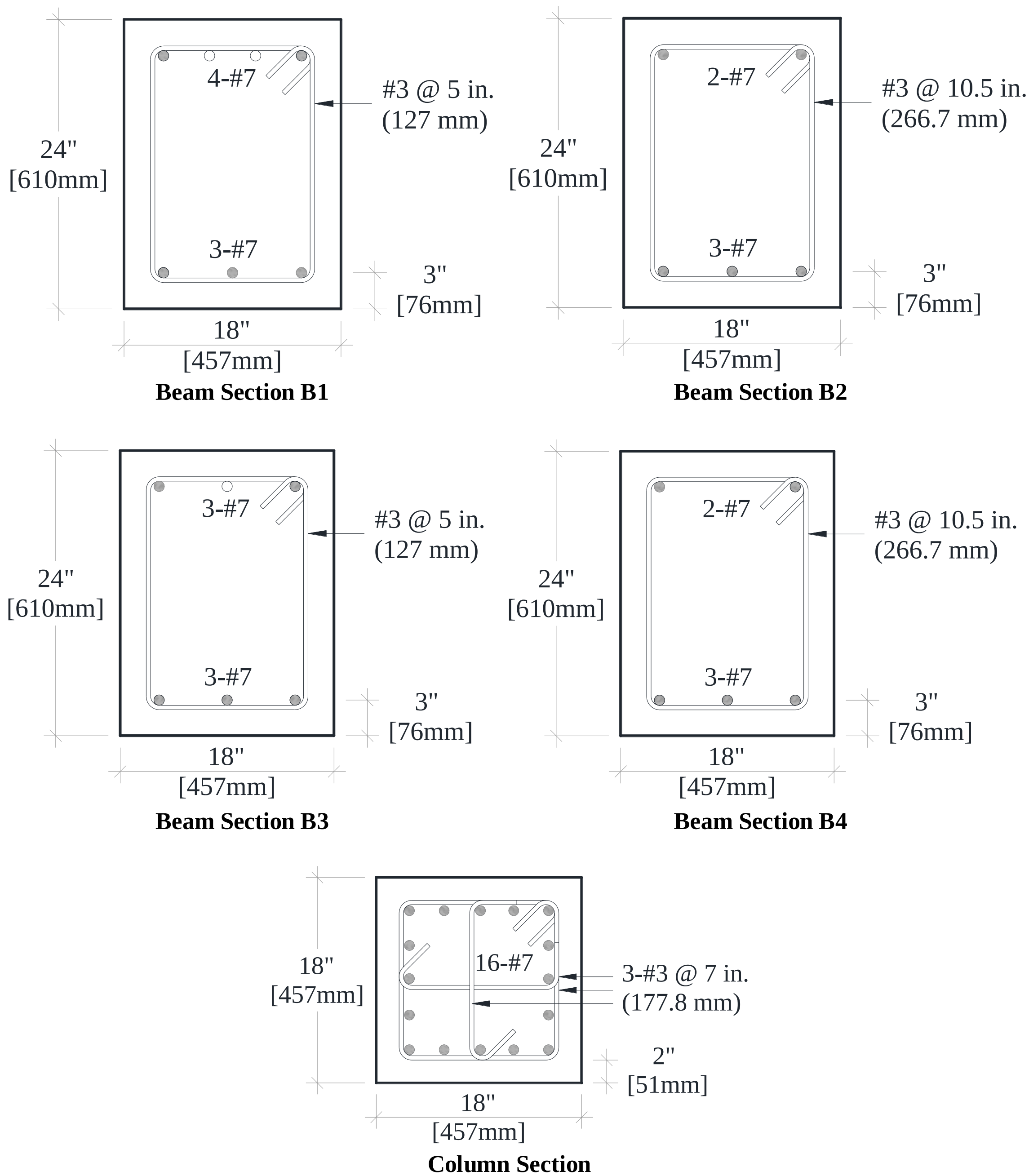


Figure 4.6- Section Details for Three-Story Intermediate Moment-Resisting Frame

Table 4.5: Summary of Design for Three-Story Intermediate Moment-Resisting Frame

Member	Story	Section	Size (in.)	Longitudinal Reinf.	Transverse Reinf.
Beam	Story 1 to 2	B1 (end)	18 by 24	Top 4 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 1 to 2	B2 (middle)	18 by 24	Top 2 No. 7 Bottom 3 No. 7	No. 3 @ 10.5 in.
	Story 3	B3 (end)	18 by 24	Top 3 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 3	B4 (middle)	18 by 24	Top 2 No. 7 Bottom 3 No. 7	No. 3 @ 10.5 in.
Column	Story 1 to 3	C	18 by 18	16 No. 7	3 No. 3 @ 7 in.

Note: 1 in. = 25.4 mm, Bar No. 3 = No. 10 mm, Bar No. 7 = No. 22 mm

4.4.3 Three-Story Special Moment Resisting RC Frame

The detailing for the three-story special moment-resisting frame is shown in Fig. 4.7 and 4.8. Table 4.6 presents the general design output. Two columns sections were included with the same longitudinal reinforcement but different transverse reinforcement satisfying the code seismic requirements. Section C1 was used at the ends of the columns and Section C2 was utilized at the middle portion of the column.

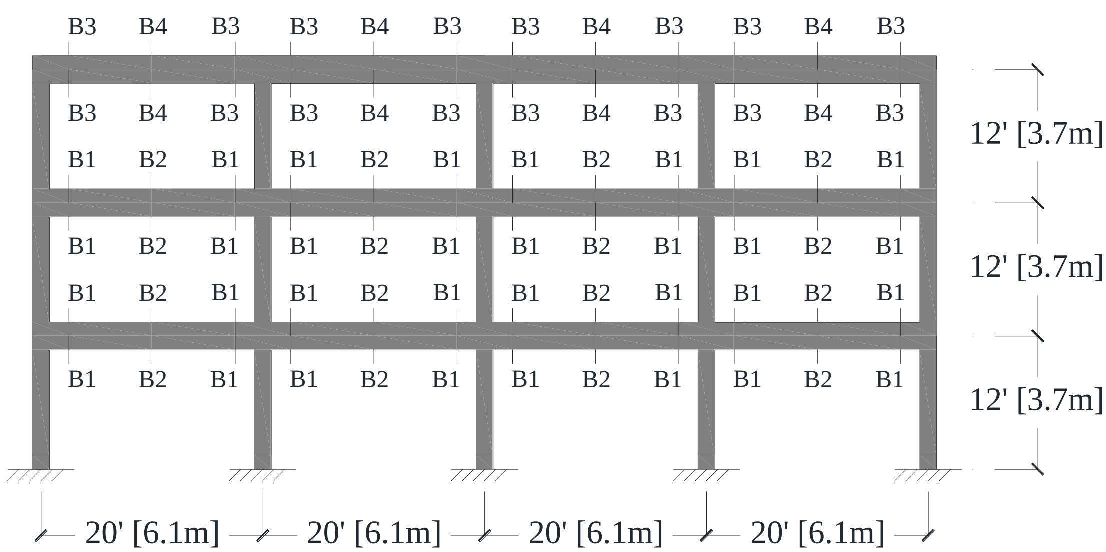


Figure 4.7- Three-Story Special Moment-Resisting Frame

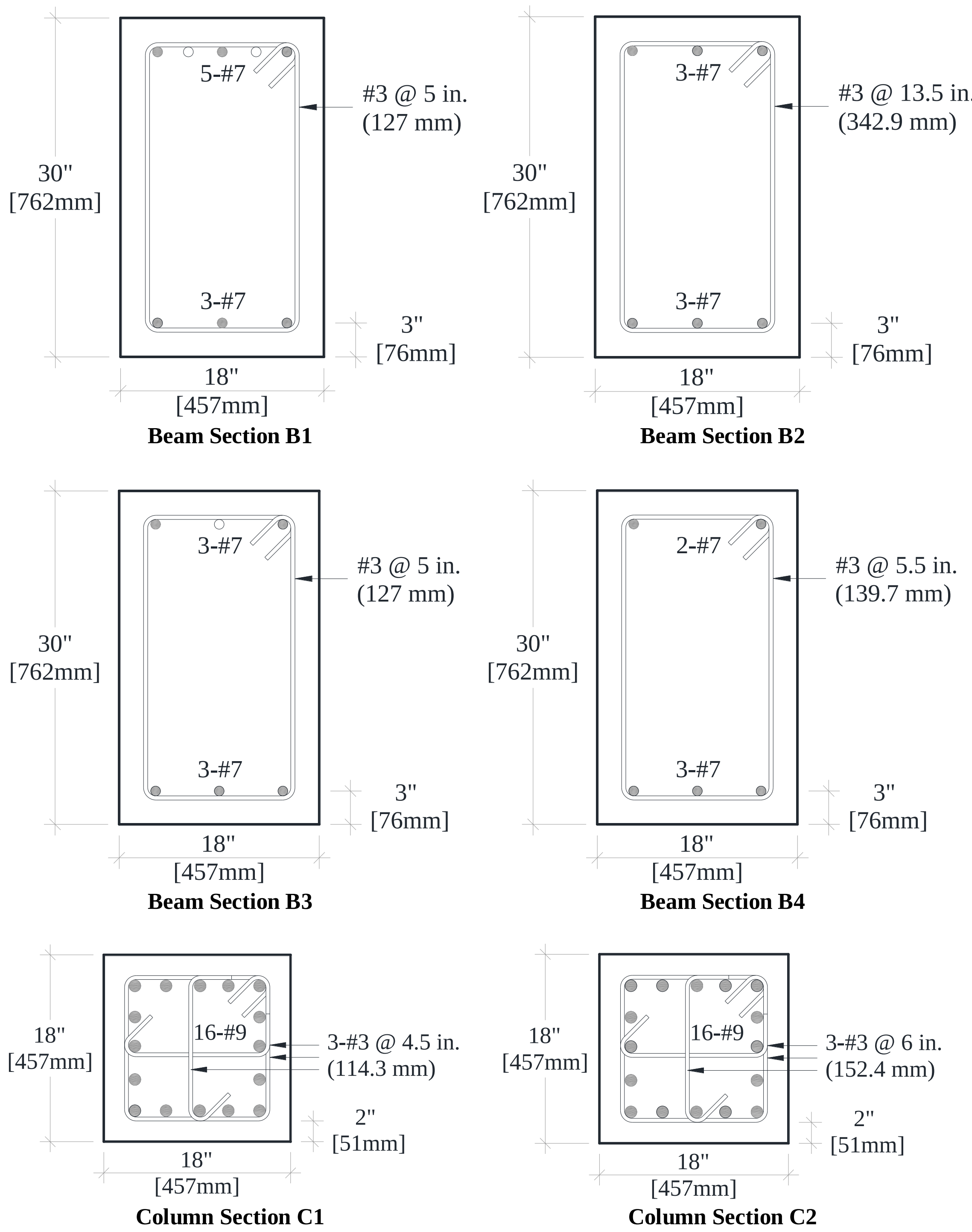


Figure 4.8- Section Details for Three-Story Special Moment-Resisting Frame

Table 4.6: Summary of Design for Three-Story Special Moment-Resisting Frame

Member	Story	Section	Size (in.)	Longitudinal Reinf.	Transverse Reinf.
Beam	Story 1 to 2	B1 (end)	18 by 30	Top 5 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 1 to 2	B2 (middle)	18 by 30	Top 3 No. 7 Bottom 3 No. 7	No. 3 @ 13.5 in.
	Story 3	B3 (end)	18 by 30	Top 3 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 3	B4 (middle)	18 by 30	Top 2 No. 7 Bottom 3 No. 7	No. 3 @ 13.5 in.
Column	Story 1 to 3	C1 (end)	18 by 18	16 No. 9	3 No. 3 @ 4.5 in.
		C2 (middle)	18 by 18	16 No. 9	3 No. 3 @ 6 in.

Note: 1 in. = 25.4 mm, Bar No. 3 = No. 10 mm, Bar No. 7 = No. 22 mm, Bar No. 9 = No. 29 mm

4.4.4 Six-Story Ordinary Moment Resisting RC Frame

The detailing for the three-story special moment-resisting frame is shown in Fig. 4.9 and 4.10. Table 4.7 presents the general design output.

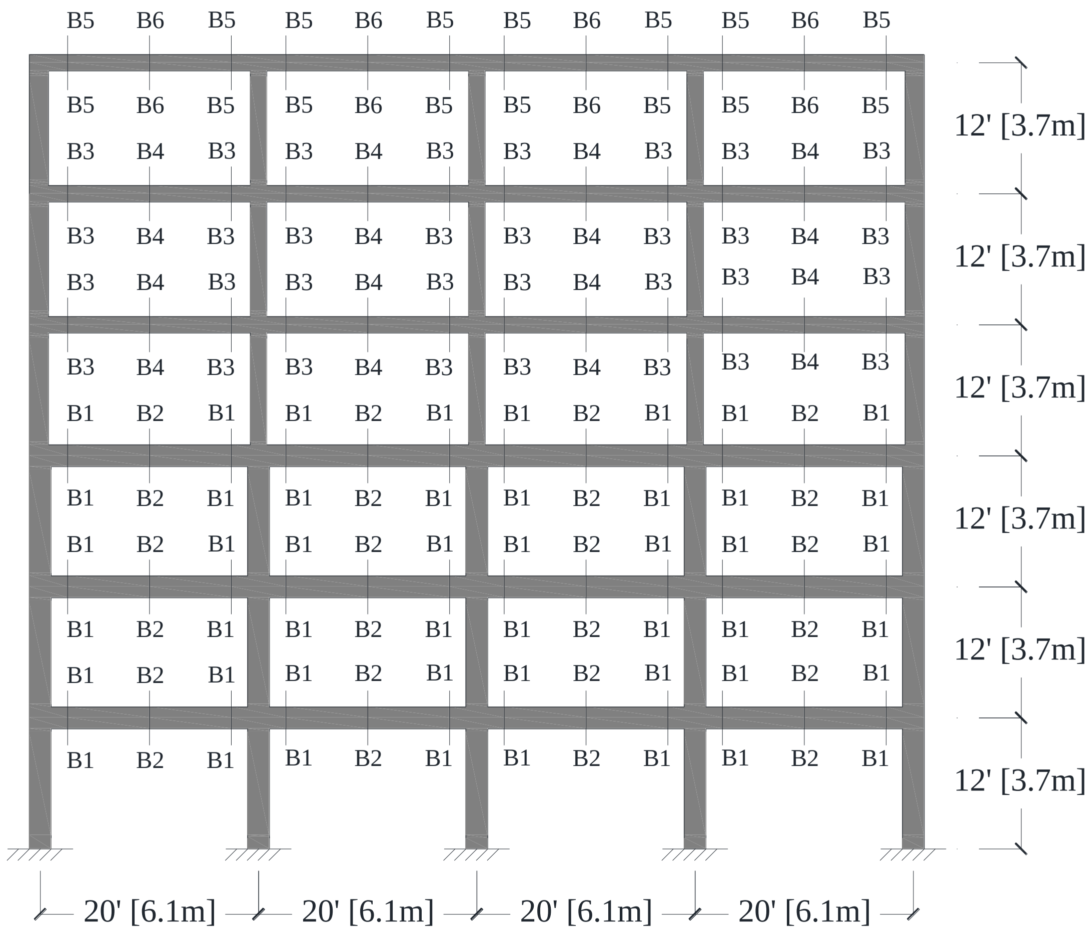


Figure 4.9- Six-Story Ordinary Moment-Resisting Frame

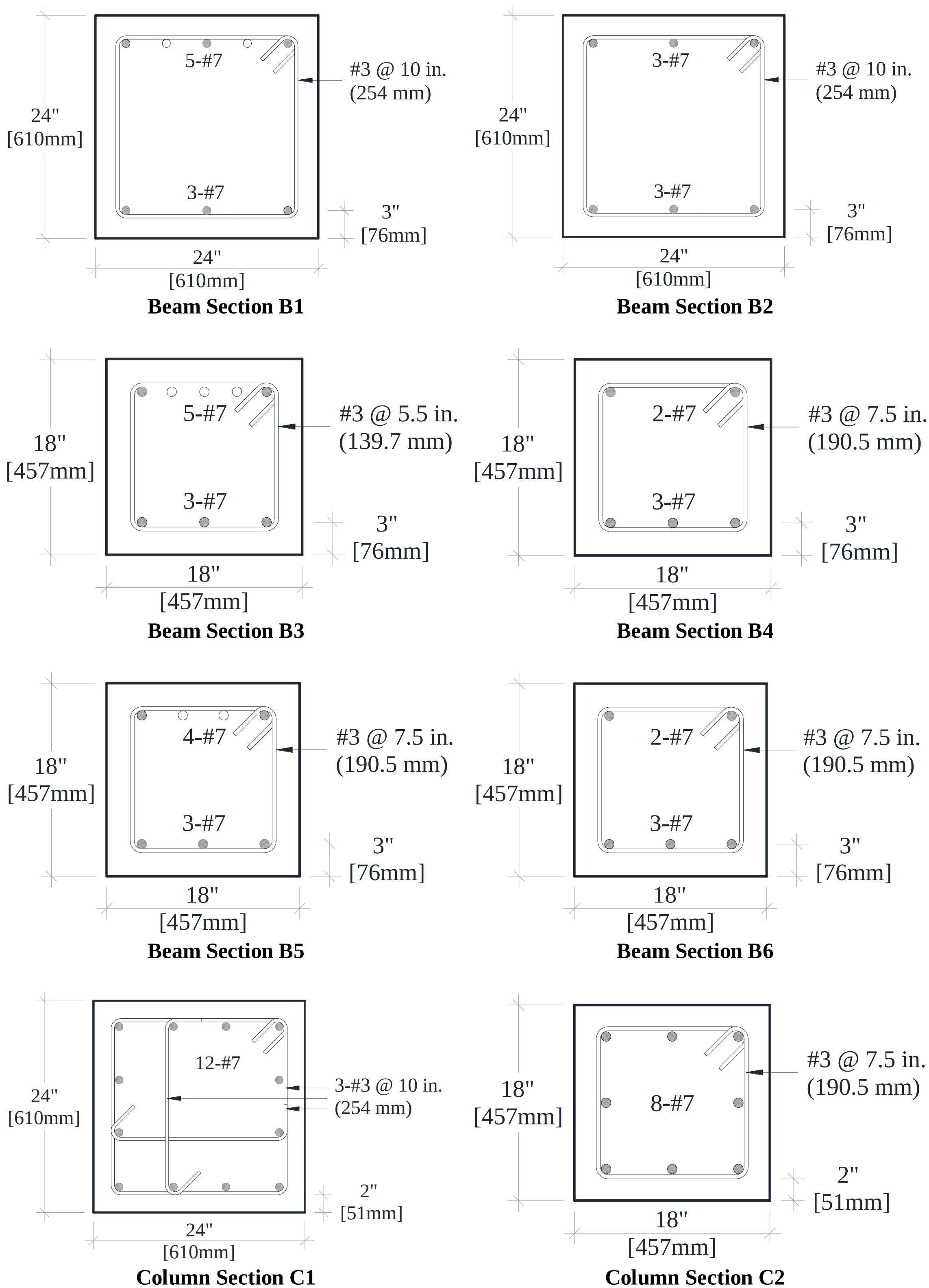


Figure 4.10- Section Details for Six-Story Ordinary Moment-Resisting Frame

Table 4.7: Summary of Design for Six-Story Ordinary Moment-Resisting Frame

Member	Story	Section	Size (in.)	Longitudinal Reinf.	Transverse Reinf.
Beam	Story 1 to 3	B1 (end)	24 by 24	Top 5 No. 7 Bottom 3 No. 7	No. 3 @ 10 in.
	Story 1 to 3	B2 (middle)	24 by 24	Top 3 No. 7 Bottom 3 No 7	No. 3 @ 10 in.
	Story 4 to 5	B3 (end)	18 by 18	Top 5 No. 7 Bottom 3 No. 7	No. 3 @ 5.5 in.
	Story 4 to 5	B4 (middle)	18 by 18	Top 2 No. 7 Bottom 3 No. 7	No. 3 @ 7.5 in.
	Story 6	B5 (end)	18 by 18	Top 4 No. 7 Bottom 3 No. 7	No. 3 @ 7.5 in.
	Story 6	B6 (middle)	18 by 18	Top 2 No. 7 Bottom 3 No. 7	No. 3 @ 7.5 in.
Column	Story 1 to 3	C1	24 by 24	12 No. 7	3 No. 3 @ 10 in.
	Story 4 to 6	C2	18 by 18	8 No. 7	No. 3 @ 7.5 in.

Note: 1 in. = 25.4 mm, Bar No. 3 = No. 10 mm, Bar No. 7 = No. 22 mm

4.4.5 Six-Story Intermediate Moment Resisting RC Frame

The detailing for the three-story special moment-resisting frame is shown in Fig. 4.11 and 4.12. Table 4.8 presents the general design output. Two columns sections were included for the bottom 3 stories with the same longitudinal reinforcement but different transverse reinforcement satisfying the code seismic requirements. Section C1 was used at the ends of the columns and Section C2 was utilized at the middle portion of the column.

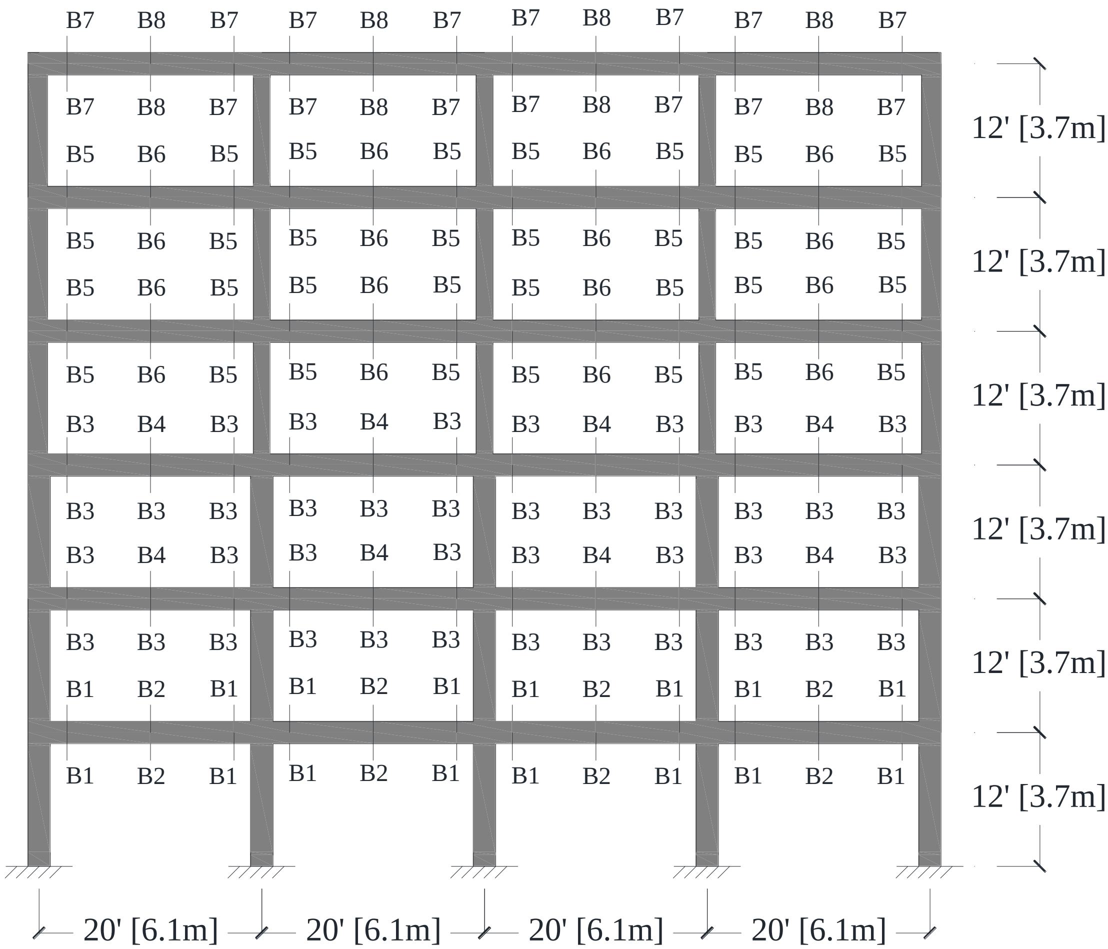


Figure 4.11- Six-Story Intermediate Moment-Resisting Frame

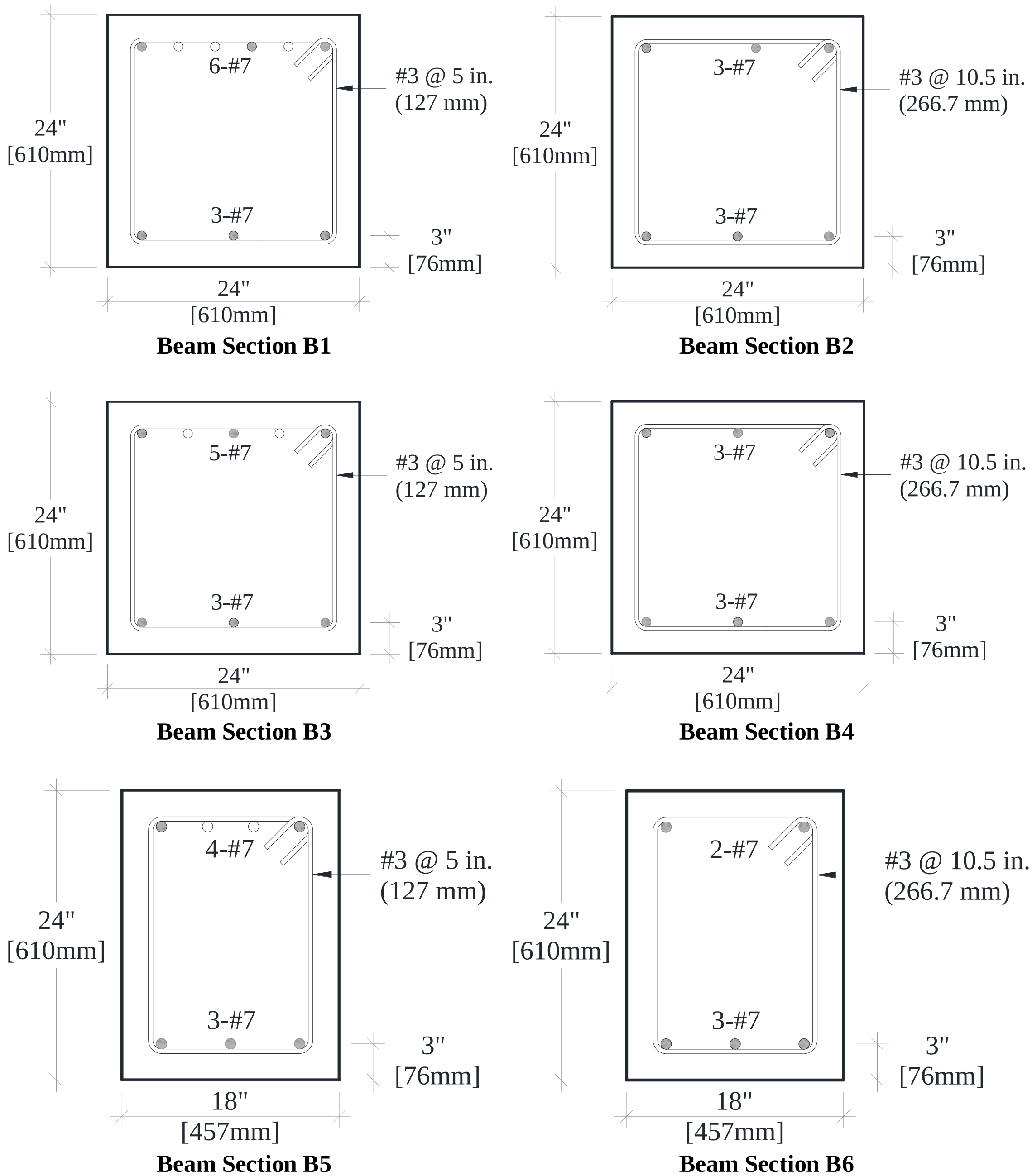
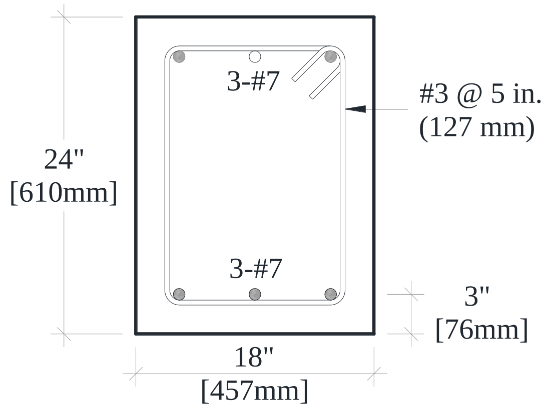
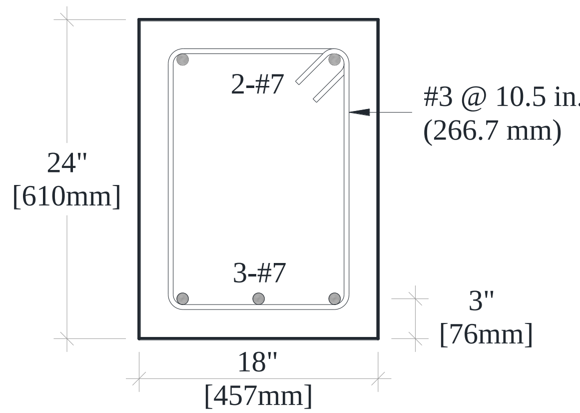


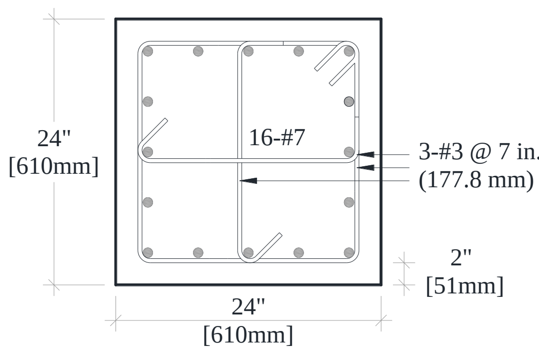
Figure 4.12- Section Details for Six-Story Intermediate Moment-Resisting Frame



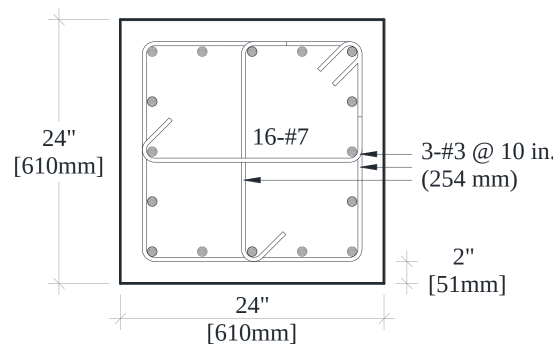
Beam Section B7



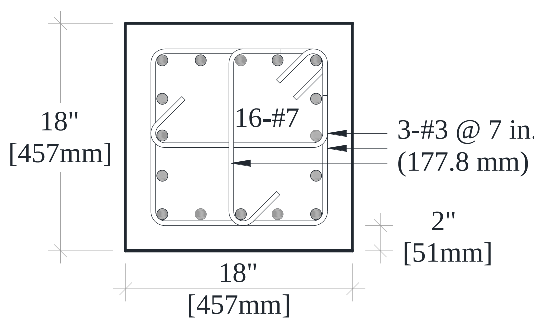
Beam Section B8



Column Section C1



Column Section C2



Column Section C3

Figure 4.12- Continued

Table 4.8: Summary of Design for Six-Story Intermediate Moment-Resisting Frame

Member	Story	Section	Size (in.)	Longitudinal Reinf.	Transverse Reinf.
Beam	Story 1	B1 (end)	24 by 24	Top 6 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 1	B2 (middle)	24 by 24	Top 3 No. 7 Bottom 3 No. 7	No. 3 @ 10.5 in.
	Story 2 to 3	B3 (end)	24 by 24	Top 5 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 2 to 3	B4 (middle)	24 by 24	Top 3 No. 7 Bottom 3 No. 7	No. 3 @ 10.5 in.
	Story 4 to 5	B5 (end)	18 by 24	Top 4 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 4 to 5	B6 (middle)	18 by 24	Top 2 No. 7 Bottom 3 No. 7	No. 3 @ 10.5 in.
	Story 6	B7 (end)	18 by 24	Top 3 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 6	B8 (middle)	18 by 24	Top 2 No. 7 Bottom 3 No. 7	No. 3 @ 10.5 in.
Column	Story 1 to 3	C1 (end)	24 by 24	16 No. 7	3 No. 3 @ 7 in.
		C2 (middle)	24 by 24	16 No. 7	3 No. 3 @ 10 in.
	Story 4 to 6	C3	18 by 18	16 No. 7	3 No. 3 @ 7 in.

Note: 1 in. = 25.4 mm, Bar No. 3 = No. 10 mm, Bar No. 7 = No. 22 mm

4.4.6 Six-Story Special Moment Resisting RC Frame

The detailing for the three-story special moment-resisting frame is shown in Fig. 4.13 and 4.14. Table 4.9 presents the general design output. Two columns sections were included for top 3 stories with the same longitudinal reinforcement but different transverse reinforcement satisfying the code seismic requirements. Section C2 was used at the ends of the columns and Section C3 was utilized at the middle portion of the column.

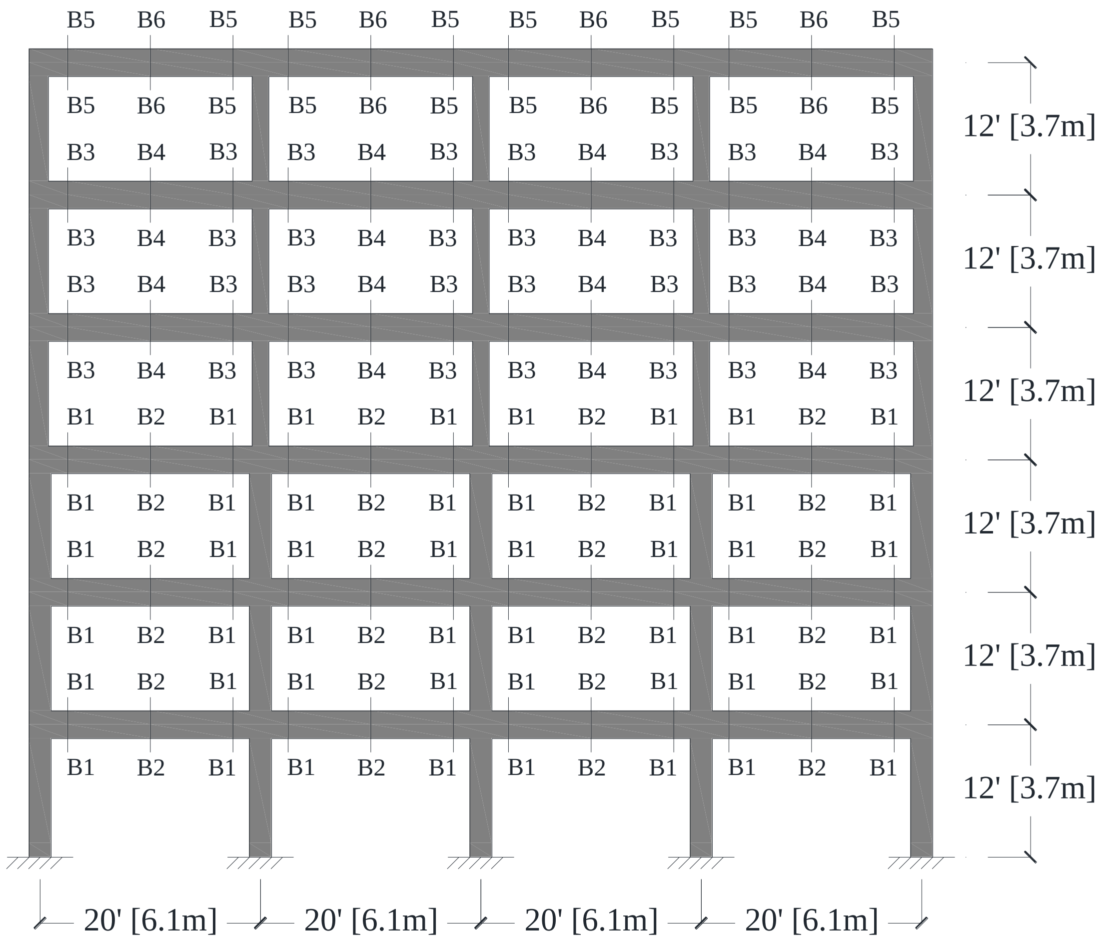


Figure 4.13- Six-Story Special Moment-Resisting Frame

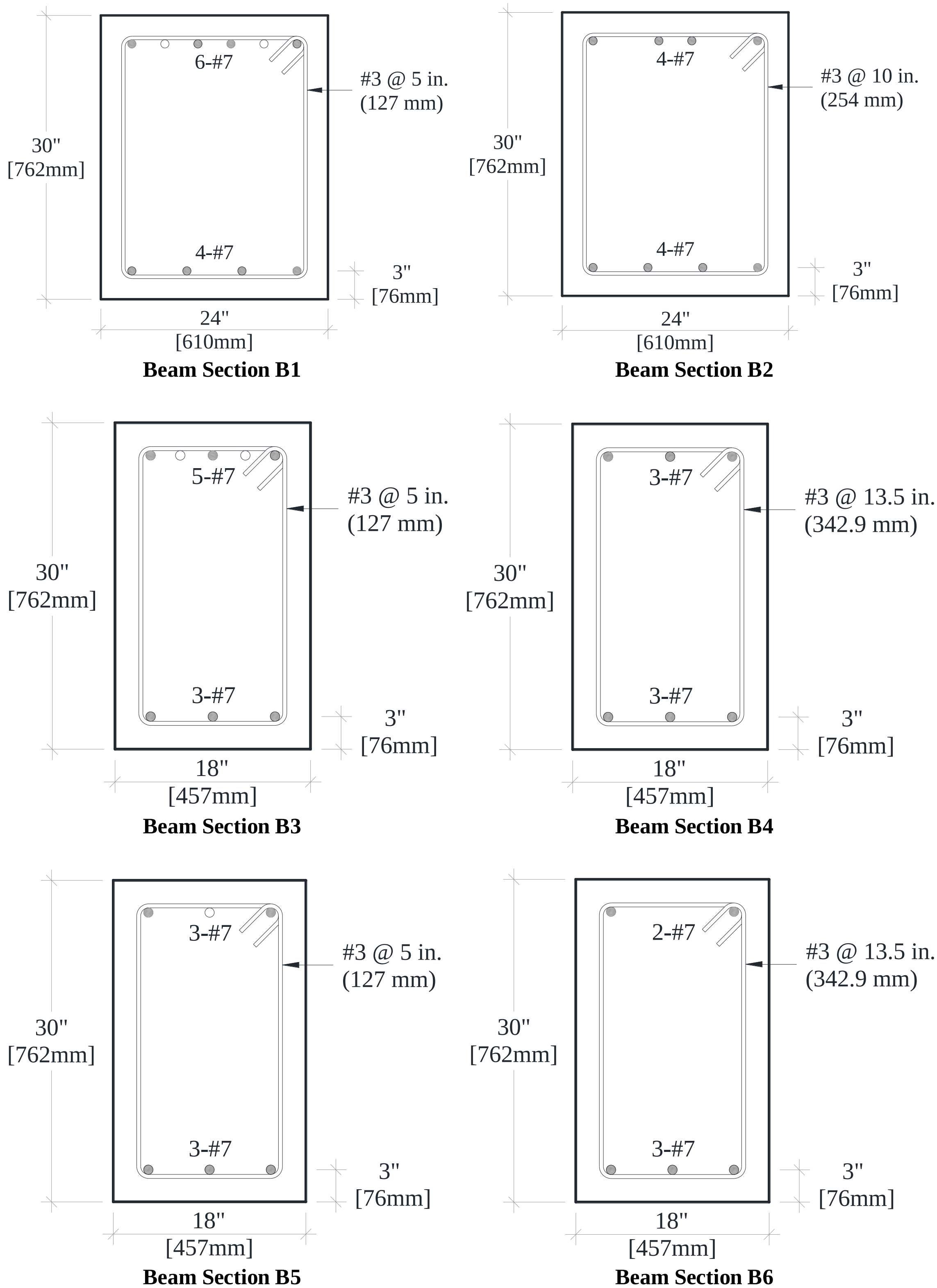


Figure 4.14- Section Details for Six-Story Special Moment-Resisting Frame

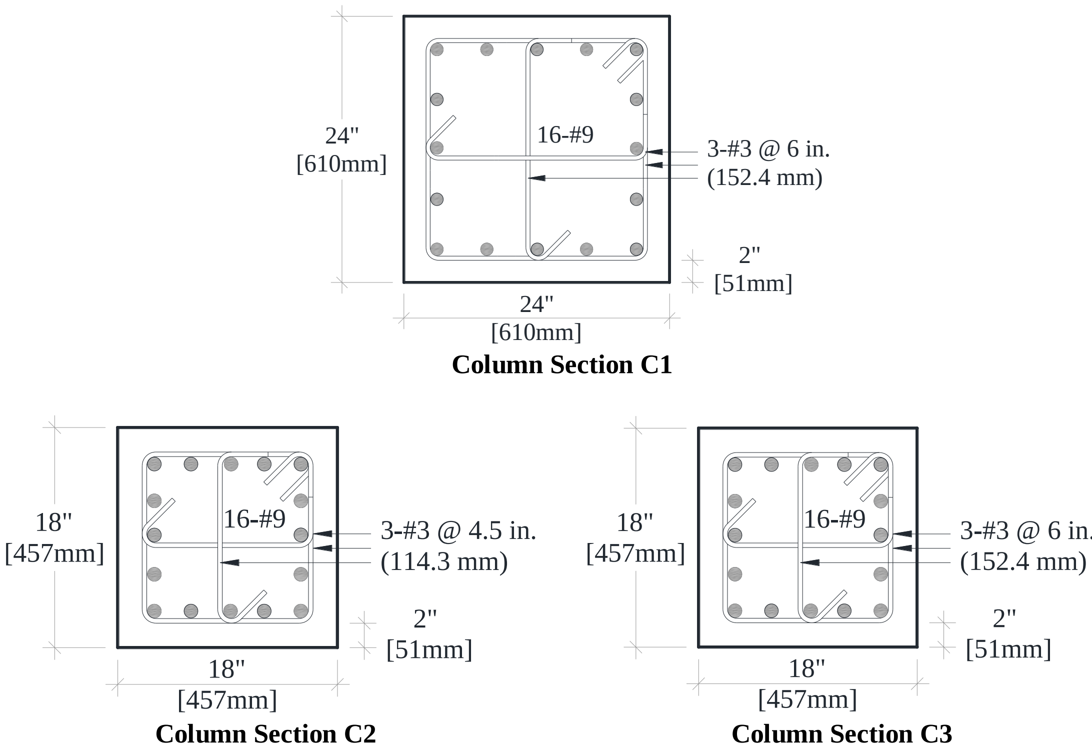


Figure 4.14- Continued

Table 4.9: Summary of Design for Six-Story Special Moment-Resisting Frame

Member	**Story**	**Section**	**Size (in.)**	**Longitudinal Reinf.**	**Transverse Reinf.**
Beam	Story 1 to 3	B1 (end)	24 by 30	Top 6 No. 7 Bottom 4 No. 7	No. 3 @ 5 in.
	Story 1 to 3	B2 (middle)	24 by 30	Top 4 No. 7 Bottom 4 No. 7	No. 3 @ 10 in.
	Story 4 to 5	B3 (end)	18 by 30	Top 5 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 4 to 5	B4 (middle)	18 by 30	Top 3 No. 7 Bottom 3 No. 7	No. 3 @ 13.5 in.
	Story 6	B5 (end)	18 by 30	Top 3 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 6	B6 (middle)	18 by 30	Top 2 No. 7 Bottom 3 No. 7	No. 3 @ 13.5 in.
Column	Story 1 to 3	C1	24 by 24	16 No. 9	3 No. 3 @ 6 in.
	Story 4 to 6	C2 (end)	18 by 18	16 No. 9	3 No. 3 @ 4.5 in.
		C3 (middle)	18 by 18	16 No. 9	3 No. 3 @ 6 in.

Note: 1 in. = 25.4 mm, Bar No. 3 = No. 10 mm, Bar No. 7 = No. 22 mm, Bar No. 9 = No. 29 mm

4.4.7 Nine-Story Ordinary Moment Resisting RC Frame

The detailing for the three-story special moment-resisting frame is shown in Fig. 4.15 and 4.16. Table 4.10 presents the general design output.

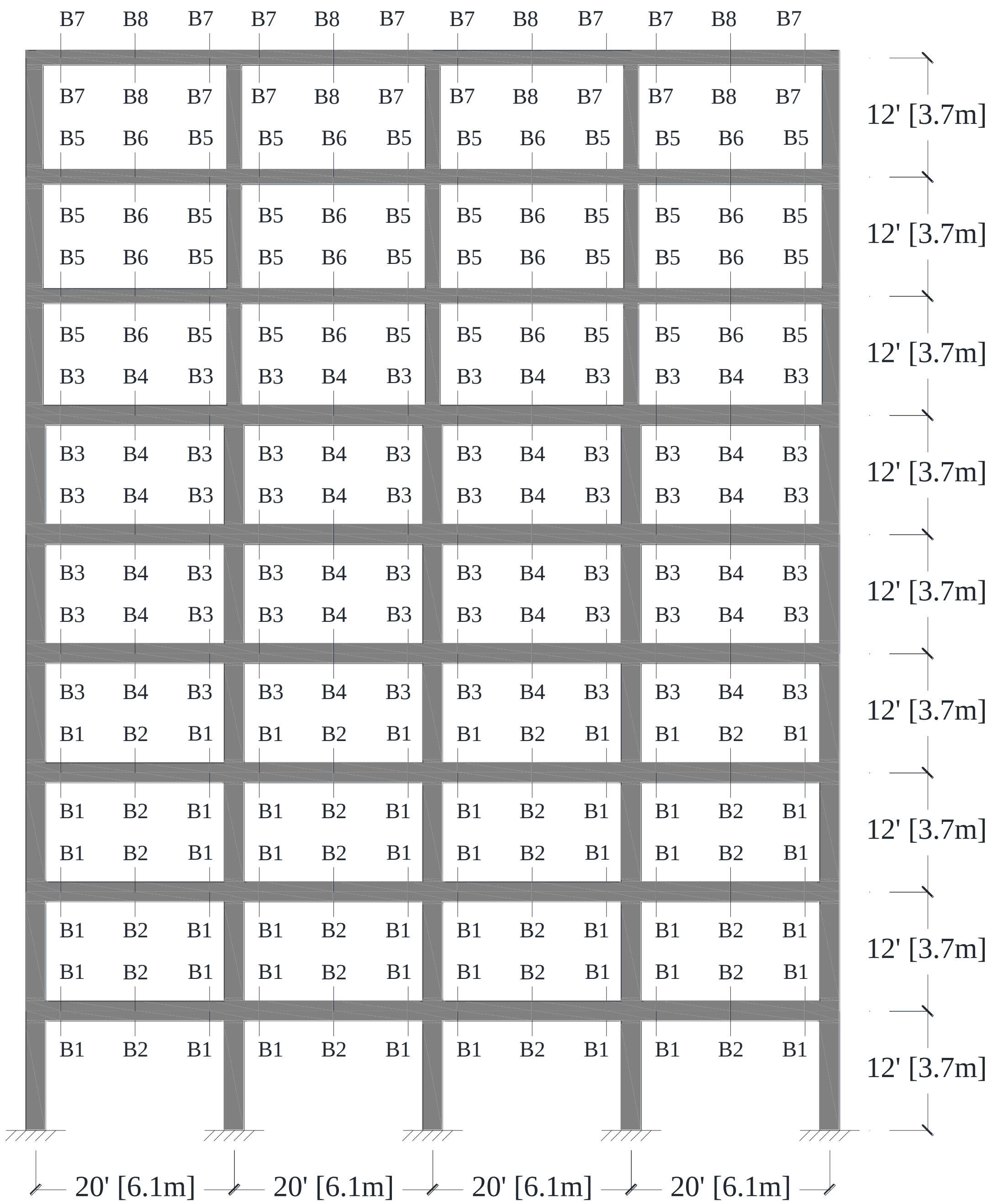
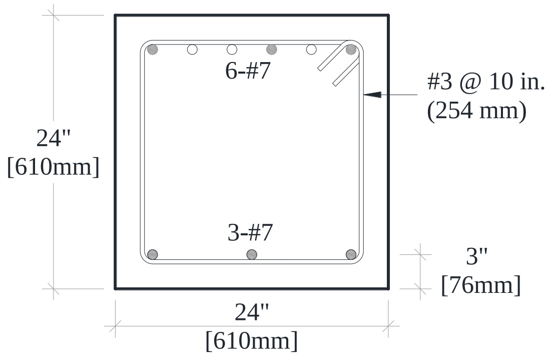
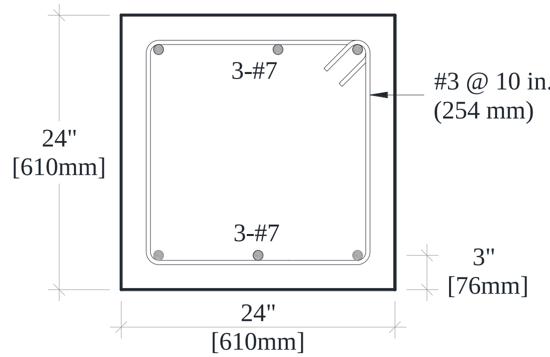


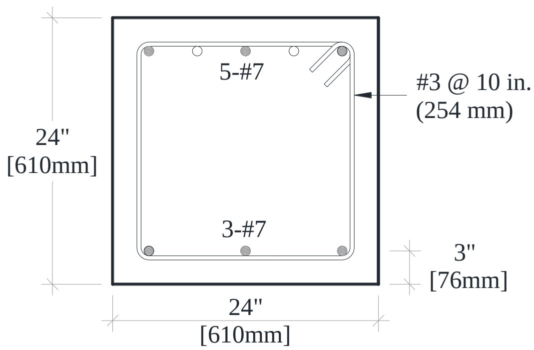
Figure 4.15- Nine-Story Ordinary Moment-Resisting Frame



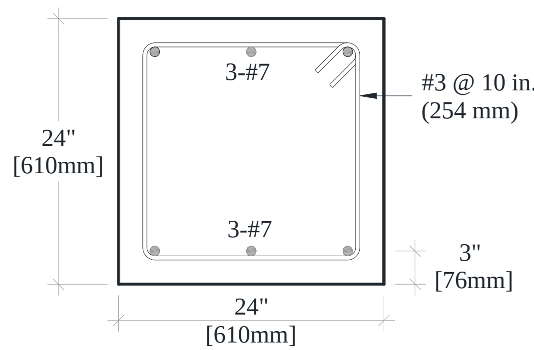
Beam Section B1



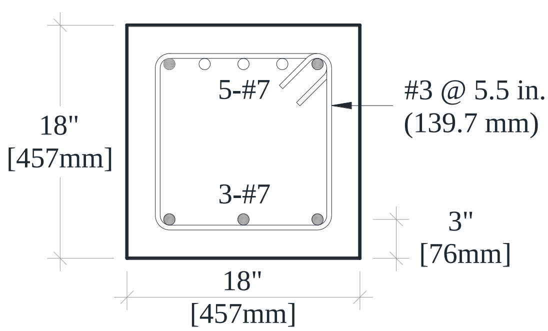
Beam Section B2



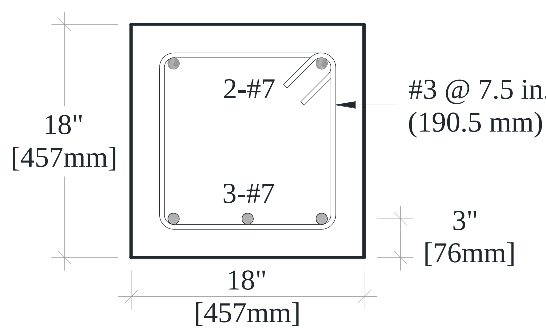
Beam Section B3



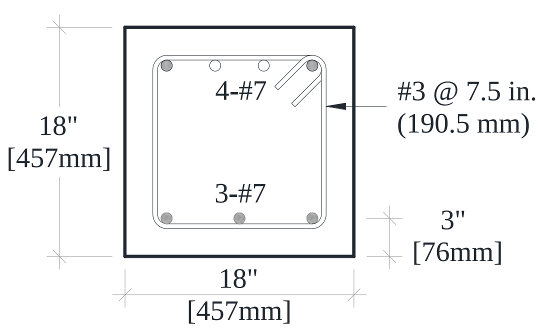
Beam Section B4



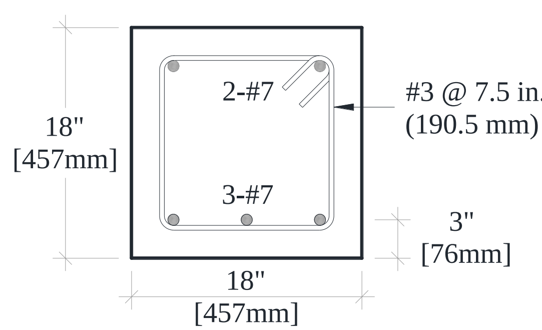
Beam Section B5



Beam Section B6

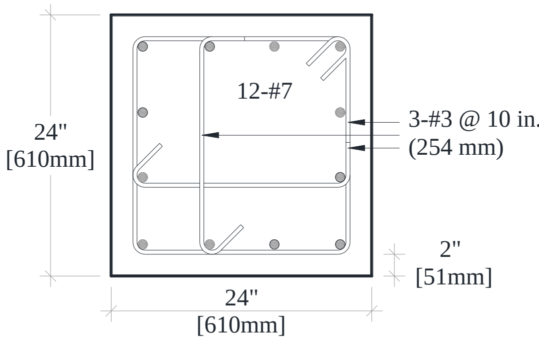


Beam Section B7

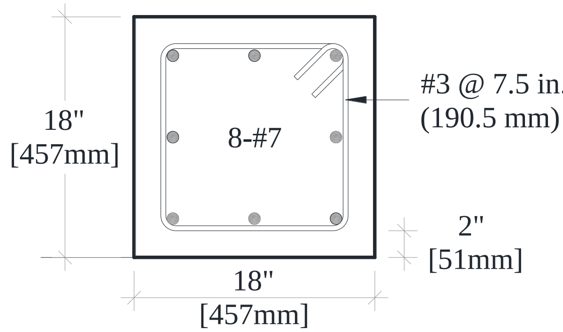


Beam Section B8

Figure 4.16- Section Details for Nine-Story Ordinary Moment-Resisting Frame



Column Section C1



Column Section C2

Figure 4.16- Continued

Table 4.10: Summary of Design for Nine-Story Ordinary Moment-Resisting Frame

Member	Story	Section	Size (in.)	Longitudinal Reinf.	Transverse Reinf.
Beam	Story 1 to 3	B1 (end)	24 by 24	Top 6 No. 7 Bottom 3 No. 7	No. 3 @ 10 in.
	Story 1 to 3	B2 (middle)	24 by 24	Top 3 No. 7 Bottom 3 No. 7	No. 3 @ 10 in.
	Story 4 to 6	B3 (end)	24 by 24	Top 5 No. 7 Bottom 3 No. 7	No. 3 @ 10 in.
	Story 4 to 6	B4 (middle)	24 by 24	Top 3 No. 7 Bottom 3 No. 7	No. 3 @ 10 in.
	Story 7 to 8	B5 (end)	18 by 18	Top 5 No. 7 Bottom 3 No. 7	No. 3 @ 5.5 in.
	Story 7 to 8	B6 (middle)	18 by 18	Top 2 No. 7 Bottom 3 No. 7	No. 3 @ 7.5 in.
	Story 9	B7 (end)	18 by 18	Top 4 No. 7 Bottom 3 No. 7	No. 3 @ 7.5 in.
	Story 9	B8 (middle)	18 by 18	Top 2 No. 7 Bottom 3 No. 7	No. 3 @ 7.5 in.
Column	Story 1 to 6	C1	24 by 24	12 No. 7	3 No. 3 @ 10 in.
	Story 7 to 9	C2	18 by 18	8 No. 7	No. 3 @ 7.5 in.

Note: 1 in. = 25.4 mm, Bar No. 3 = No. 10 mm, Bar No. 7 = No. 22 mm

4.4.8 Nine-Story Intermediate Moment Resisting RC Frame

The detailing for the three-story special moment-resisting frame is shown in Fig. 4.17 and 4.18. Table 4.11 presents the general design output. Two column sections were included for bottom 6 stories with the same longitudinal reinforcement but different transverse reinforcement satisfying the code seismic requirements. Section C1 was used at the ends of the columns and Section C2 was utilized at the middle portion of the column.

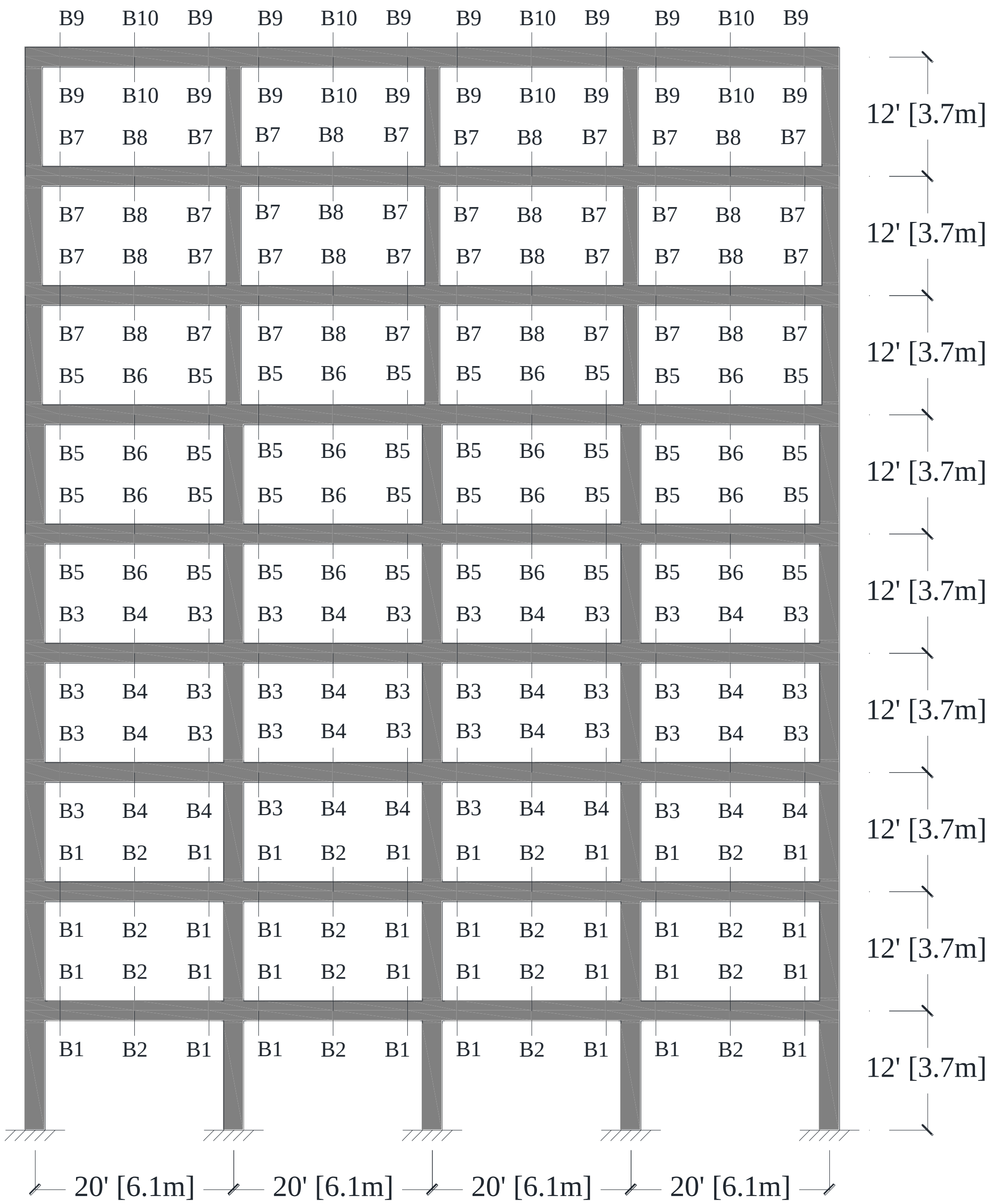


Figure 4.17- Nine-Story Intermediate Moment-Resisting Frame

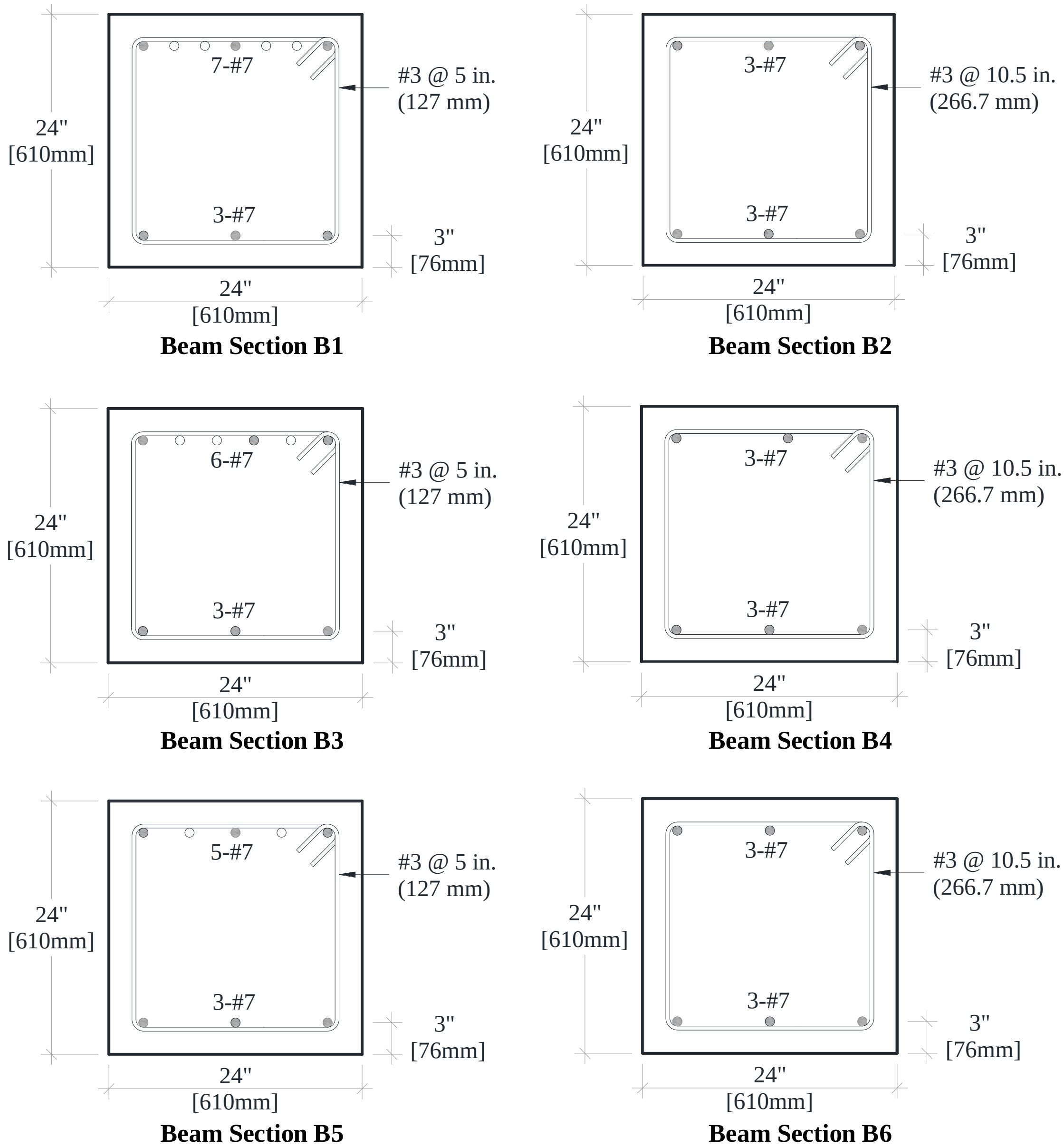
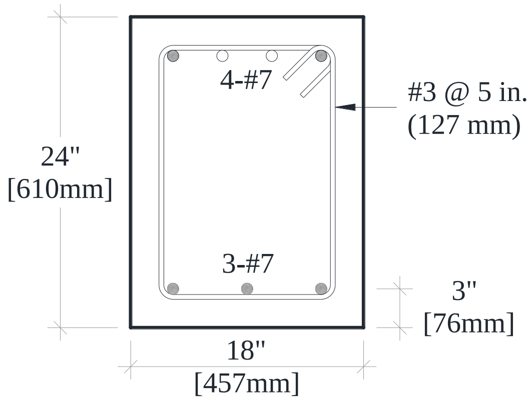
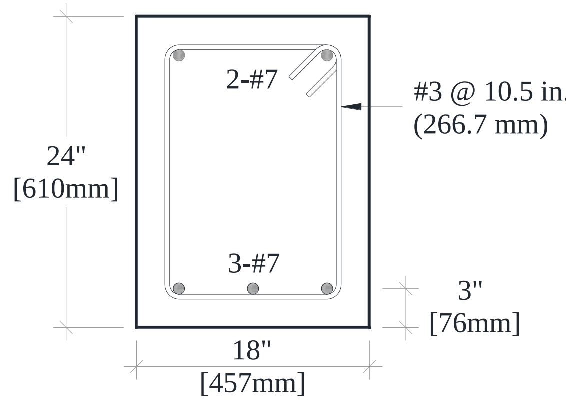


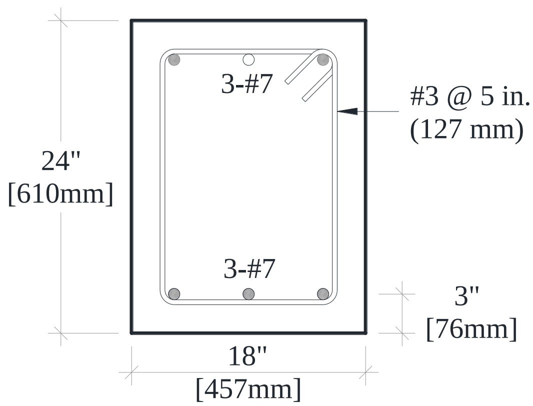
Figure 4.18- Section Details for Nine-Story Intermediate Moment-Resisting Frame



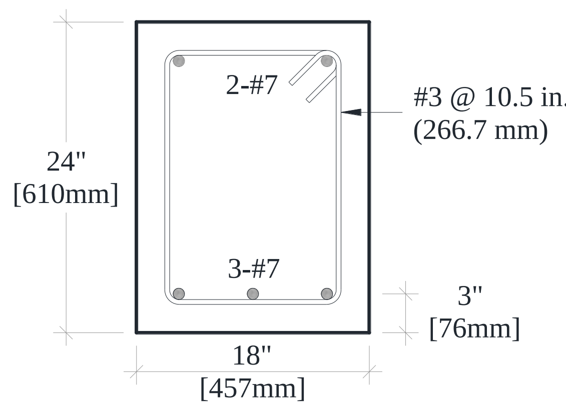
Beam Section B7



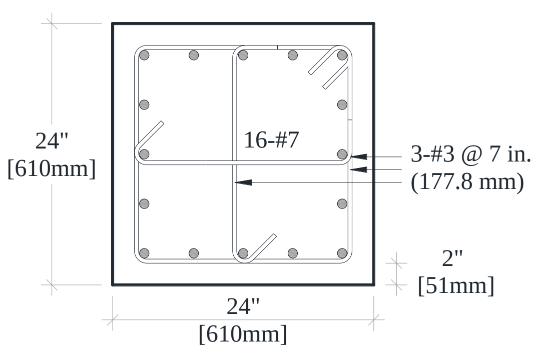
Beam Section B8



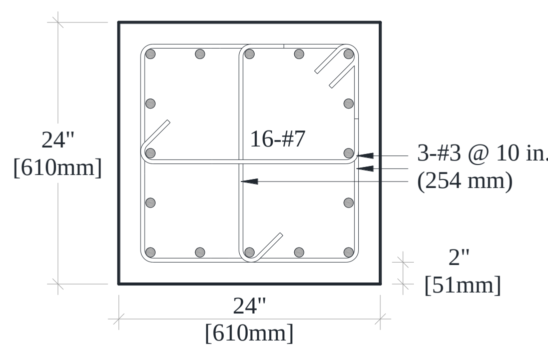
Beam Section B9



Beam Section B10

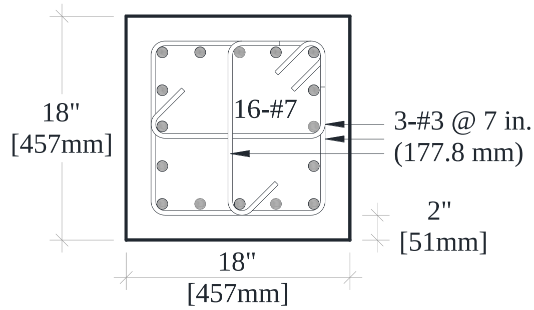


Column Section C1



Column Section C2

Figure 4.18- Continued



Column Section C3

Figure 4.18- Continued

Table 4.11: Summary of Design for Nine-Story Intermediate Moment-Resisting Frame

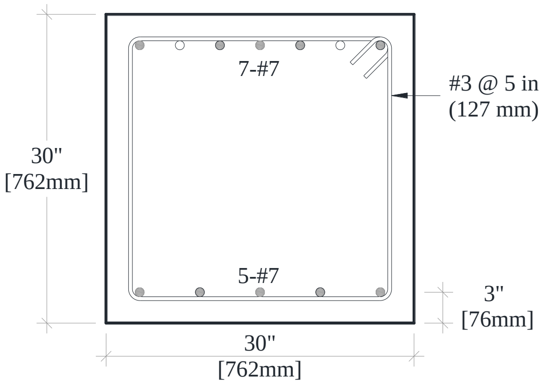
Member	Story	Section	Size (in.)	Longitudinal Reinf.	Transverse Reinf.
Beam	Story 1 to 2	B1 (end)	24 by 24	Top 7 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 1 to 2	B2 (middle)	24 by 24	Top 3 No. 7 Bottom 3 No. 7	No. 3 @ 10.5 in.
	Story 3 to 4	B3 (end)	24 by 24	Top 6 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 3 to 4	B4 (middle)	24 by 24	Top 3 No. 7 Bottom 3 No. 7	No. 3 @ 10.5 in.
	Story 5 to 6	B5 (end)	24 by 24	Top 5 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 5 to 6	B6 (middle)	24 by 24	Top 5 No. 7 Bottom 3 No. 7	No. 3 @ 10.5 in.
	Story 7 to 8	B7 (end)	18 by 24	Top 4 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 7 to 8	B8 (middle)	18 by 24	Top 2 No. 7 Bottom 3 No. 7	No. 3 @ 10.5 in.
	Story 9	B9 (end)	18 by 24	Top 3 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 9	B10 (middle)	18 by 24	Top 2 No. 7 Bottom 3 No. 7	No. 3 @ 10.5 in.
Column	Story 1 to 6	C1 (end)	24 by 24	16 No. 7	3 No. 3 @ 7 in.
		C2 (middle)	24 by 24	16 No. 7	3 No. 3 @ 10 in.
	Story 7 to 9	C3	18 by 18	16 No. 7	3 No. 3 @ 7 in.

Note: 1 in. = 25.4 mm, Bar No. 3 = No. 10 mm, Bar No. 7 = No. 22 mm

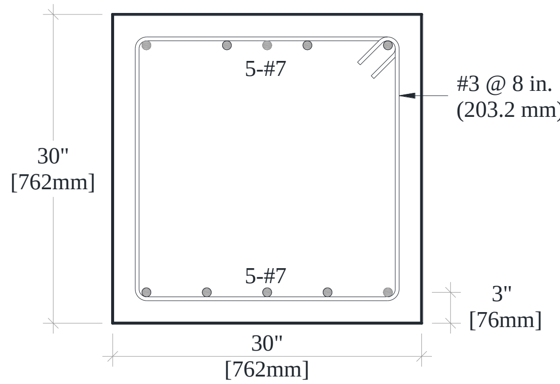
4.4.9 Nine-Story Special Moment Resisting RC Frame

The detailing for the nine-story special moment-resisting frame is shown in Fig. 4.19 and 4.20. Table 4.12 presents the general design output. Two columns sections were included for top 3 stories with the same longitudinal reinforcement but different transverse reinforcement satisfying the code seismic requirements. Section C3 was used at the ends of the columns and Section C4 was utilized at the middle portion of the column.

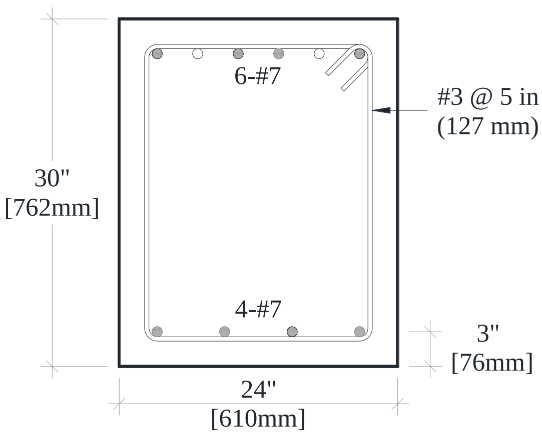
Figure 4.19- Nine-Story Special Moment-Resisting Frame



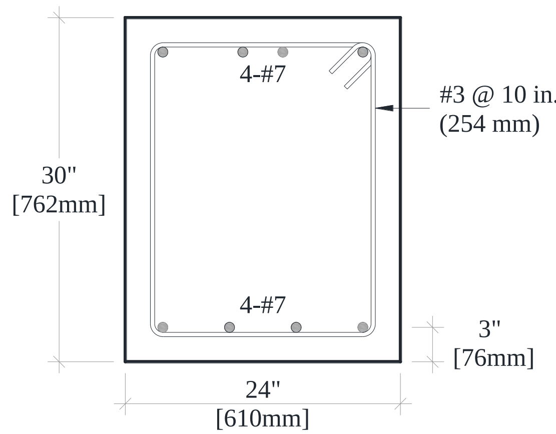
Beam Section B1



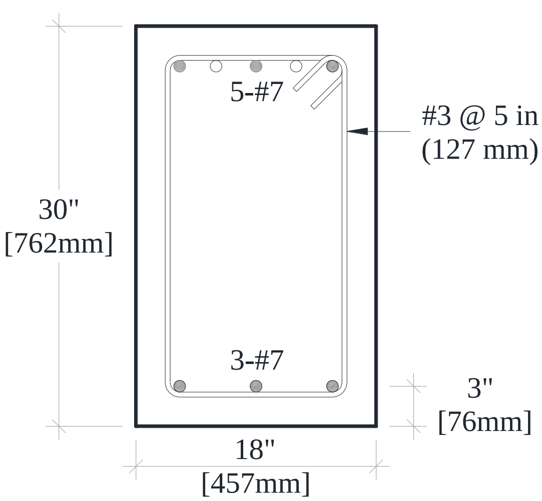
Beam Section B2



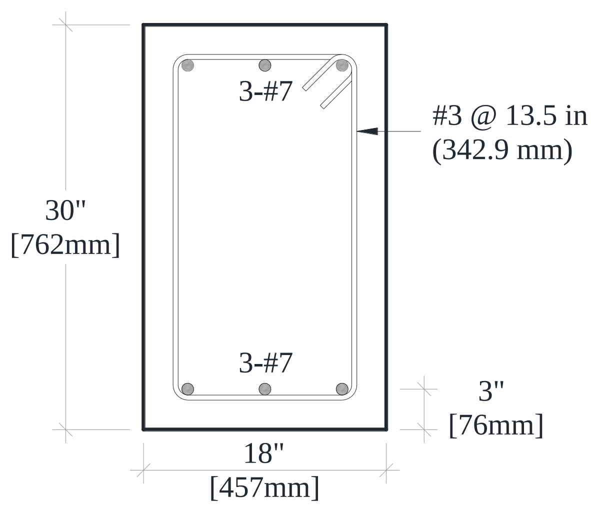
Beam Section B3



Beam Section B4



Beam Section B5



Beam Section B6

Figure 4.20 Section Details for Nine-Story Special Moment-Resisting Frame

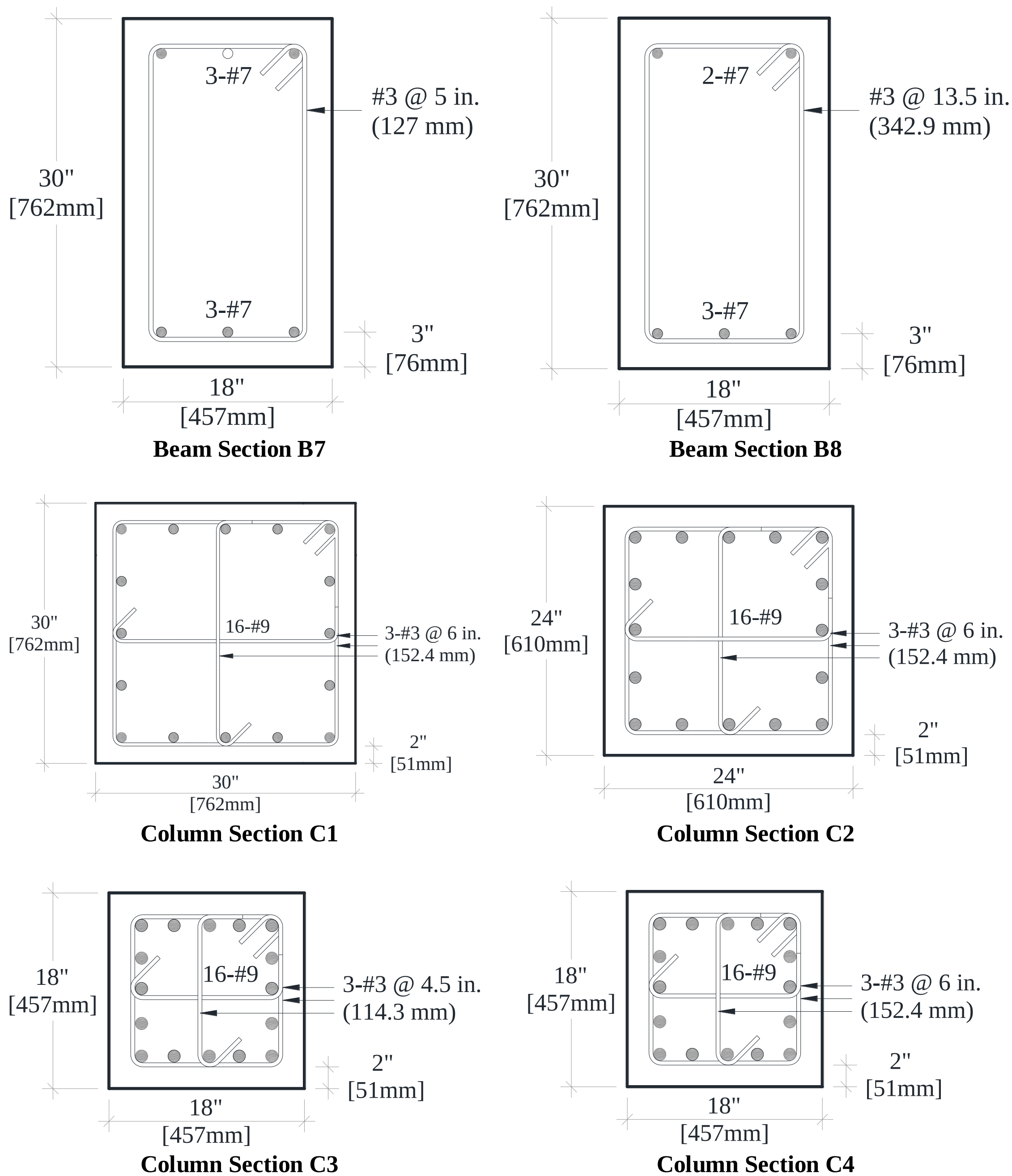


Figure 4.20- Continued

Table 4.12: Summary of Design for Nine-Story Special Moment-Resisting Frame

Member	Story	Section	Size (in.)	Longitudinal Reinf.	Transverse Reinf.
Beam	Story 1 to 3	B1 (end)	30 by 30	Top 7 No. 7 Bottom 5 No. 7	No. 3 @ 5 in.
	Story 1 to 3	B2 (middle)	30 by 30	Top 5 No. 7 Bottom 5 No. 7	No. 3 @ 8 in.
	Story 4 to 6	B3 (end)	24 by 30	Top 6 No. 7 Bottom 4 No. 7	No. 3 @ 5 in.
	Story 4 to 6	B4 (middle)	24 by 30	Top 4 No. 7 Bottom 4 No. 7	No. 3 @ 10 in.
	Story 7 to 8	B5 (end)	18 by 30	Top 5 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 7 to 8	B6 (middle)	18 by 30	Top 3 No. 7 Bottom 3 No. 7	No. 3 @ 13.5 in.
	Story 9	B7 (end)	18 by 30	Top 3 No. 7 Bottom 3 No. 7	No. 3 @ 5 in.
	Story 9	B8 (middle)	18 by 30	Top 2 No. 7 Bottom 3 No. 7	No. 3 @ 13.5 in.
Column	Story 1 to 3	C1	30 by 30	16 No. 9	3 No. 3 @ 6 in.
	Story 4 to 6	C2	24 by 24	16 No. 9	3 No. 3 @ 6 in.
	Story 7 to 9	C3 (end)	18 by 18	16 No. 9	3 No. 3 @ 4.5 in.
		C4 (middle)	18 by 18	16 No. 9	3 No. 3 @ 6 in.

Note: 1 in. = 25.4 mm, Bar No. 3 = No. 10 mm, Bar No. 7 = No. 22 mm, Bar No. 9 = No. 29 mm

4.5 References

ACI 318-14 (2014). “Building Code Requirements for Structural Concrete”. American Concrete Institute.

ASCE 7-10 (2010). “Minimum Design Loads for Buildings and Other Structures”. American Society of Civil Engineers.

SAP2000. Version 18.1.1. Computers and Structures, Inc. Berkeley, CA (2015).

5. Analytical Study on Mechanically Spliced Moment-Resisting RC Frames

The effect of mechanical bar splices on the seismic performance of moment-resisting RC frames, which were designed and presented in the previous chapter, is investigated in this chapter through analytical studies. First, modeling method for spliced frames is discussed. Then parameters of the analytical study are presented. Finally, the results of the analytical study are discussed, and ACI 318 requirements for mechanically spliced frames are evaluated. Furthermore, an equation was developed based on the results of the analytical study to quantify the effect of couplers on the displacement capacity of RC frames.

5.1 Modeling Methods

It was discussed in the previous chapter that there is no test data regarding the performance of mechanically spliced RC frames. Modeling methods for spliced RC members and unspliced RC frames were proposed and verified in the previous chapter. Based on the findings, modeling methods for mechanically spliced RC frames are summarized herein. OpenSees (2016) was used for the analytical studies.

Mechanical bar splices, or couplers, were assumed to be utilized at the end of each beam and column representing a connection for precast members. A typical corner beam-column joint for such a scenario is shown in Fig. 5.1. Note L_{sp} is the length of the splice, which might be different for beams and columns. The construction sequence will be (1) erect the precast columns of the first story, (2) form the beam-column joints, place the connecting reinforcement, and pour the joints (3) installed the precast beams, and (4) erect the precast columns of the second floor. Continue for all stories.

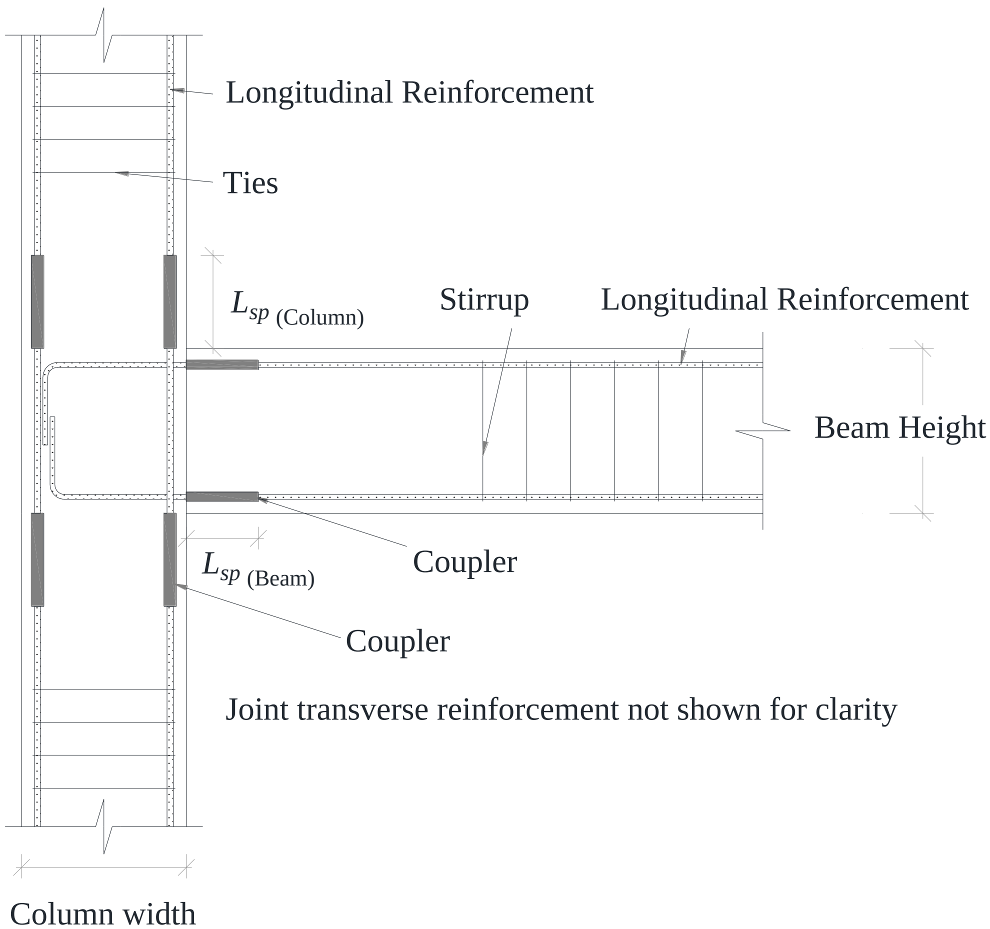


Figure 5.1- Elevation View for a Mechanically Spliced Beam-Column Joint

Three-, six-, and none-story moment-resisting frames were designed according to the current codes and detailed in the previous chapter. Finite element models for these frames but incorporating mechanical bar splices are shown in Fig. 5.2 to 5.4. Each column and beam was modeled with seven sub-elements. Nodes were shown with circles. The location of the applied load for pushover analysis is also shown. Figure 5.5 shows a close-up of the finite element model for a typical beam-column joint. Nodes were used at the centerline of the joint, the face of the beams and columns, and at the ends of the couplers. H_{sp} is the distance between the face of either the beam or column and the coupler end face. H_{sp} was assumed to be zero in the present study, which is for the cases where the couplers are exactly at the ends of the beams and columns. Table 5.1 presents a summary of the modeling methods for mechanically spliced RC frames.

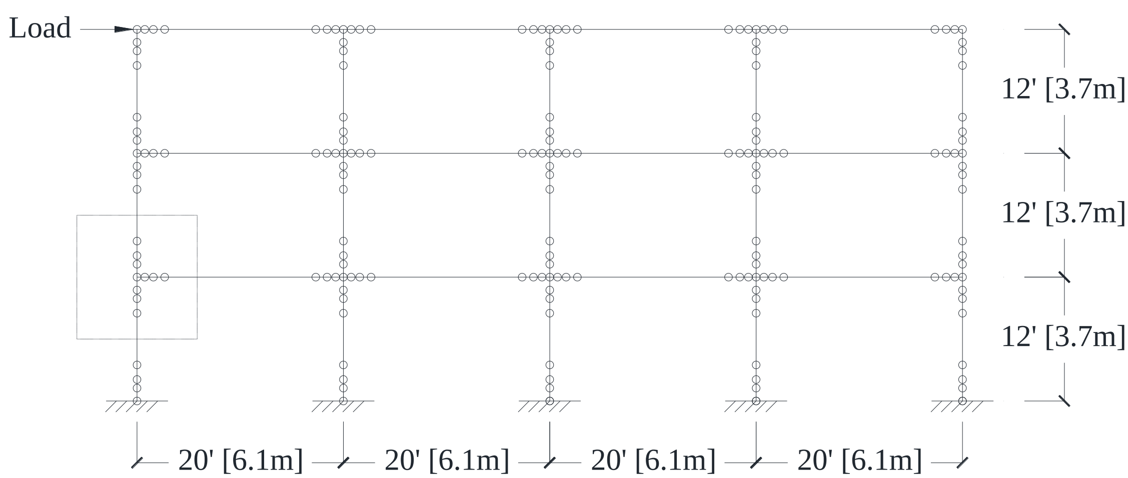


Figure 5.2- Finite Element Model for Three Story Moment-Resisting Frames

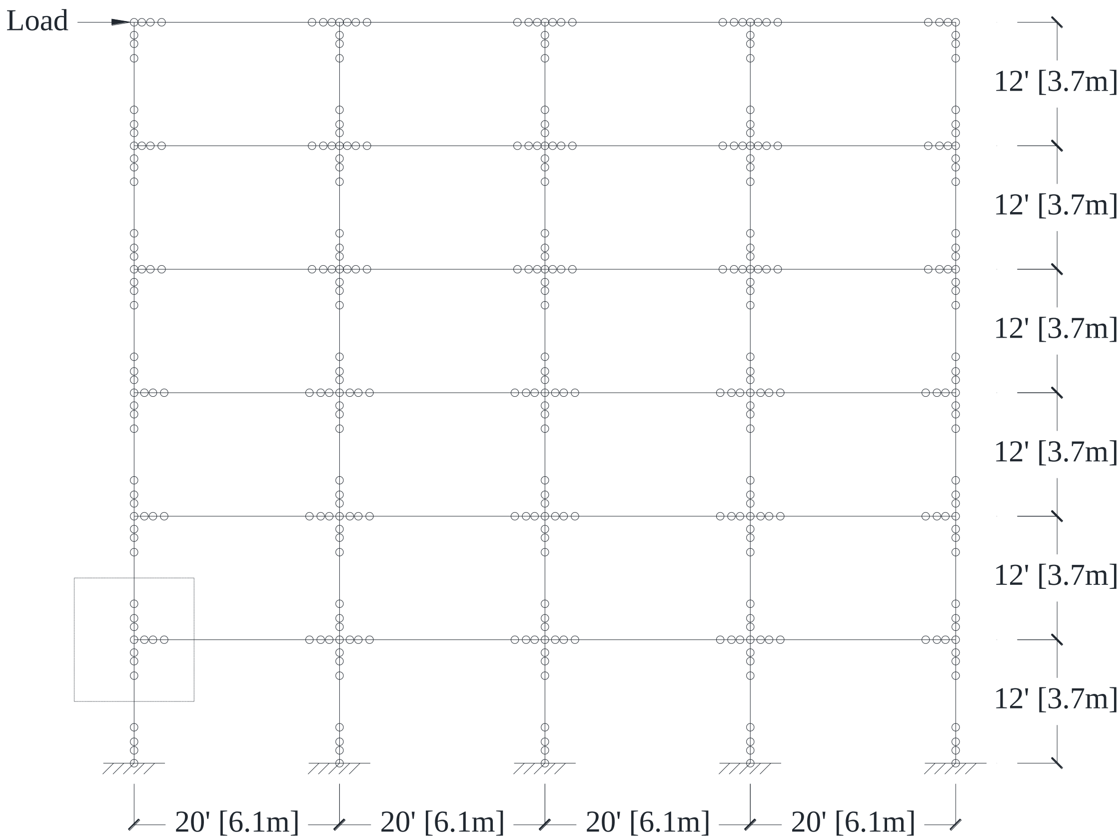


Figure 5.3- Finite Element Model for Six Story Moment-Resisting Frames

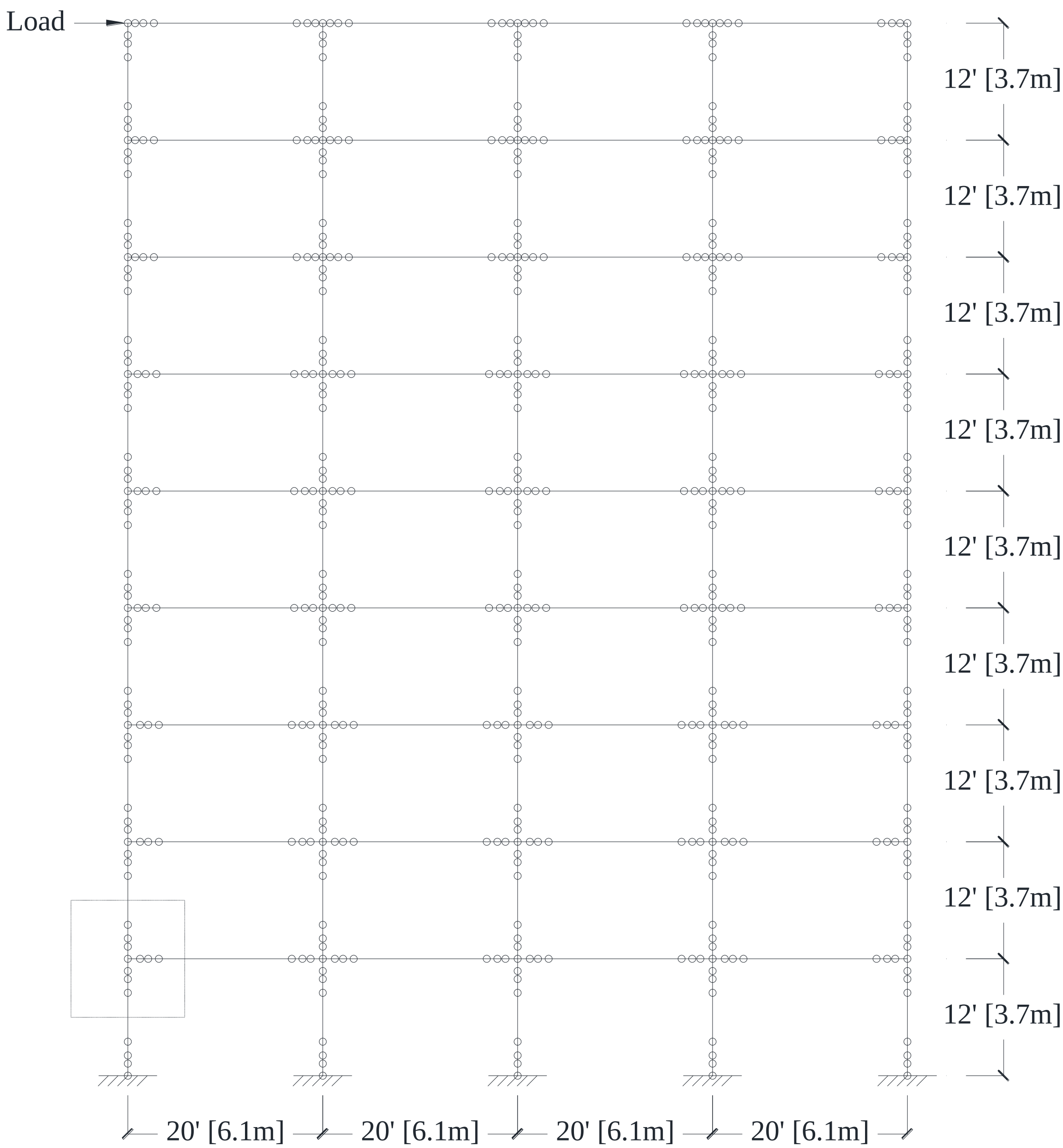


Figure 5.4- Finite Element Model for Nine Story Moment-Resisting Frames

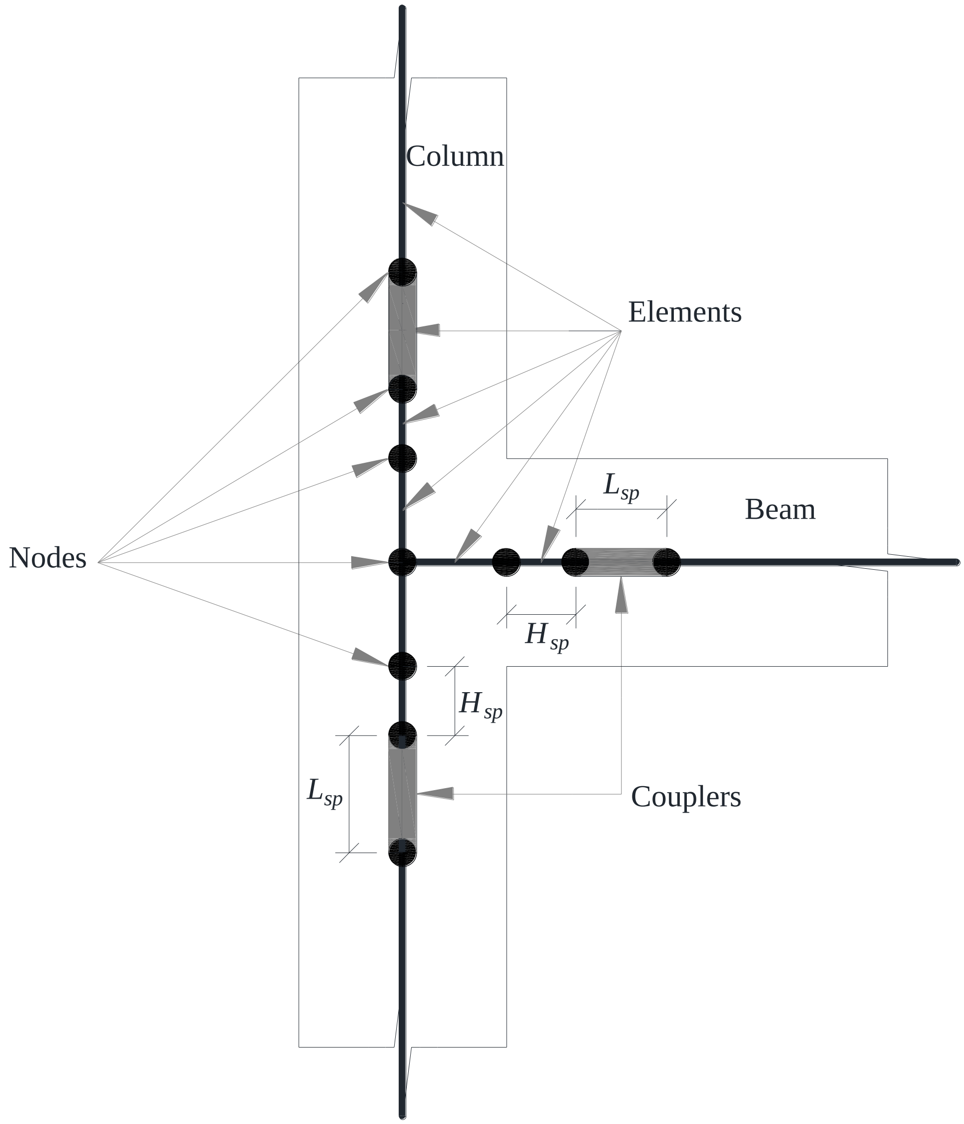


Figure 5.5- Finite Element Model for a Typical Beam-Column Joint

Table 5.1: Modeling Methods for Mechanically Spliced RC Frames

General Remarks	
Two Dimensions with 3 Degrees of freedom per node. Supports are fixed. Geometrical Properties: Number of nodes in beam: 8, Number of nodes in column: 8, Number of Elements in beam: 7, Number of Elements in column: 7. Element type: *forcebeamcolumn* with 5 integration points except for the smallest element, H_{sp} which is close to 0. H_{sp} is the distance from the face of beam or column to the end face of coupler. Two integration points were used along this very short element. Gravity load and P-Δ effects were considered, No torsional or bond-slip effects	Sectional Properties: Fiber Section, Core Concrete Discretization: 30 by 30, Cover Concrete Discretization: 10 by 10. Element in the middle of the beam or column has less transverse reinforcement. The Beam-Column joint region is rigid. "elasticBeamColumn" elements with large moment of inertia were used in joint region.
Concrete Fibers	
Application: unconfined concrete (cover) Type: Concrete04 f'_{cc} = - 5 ksi (34.47 MPa) $\mathcal{E}_{cc}$ = -0.002 in./in. f'_{cu} = 0.0 ksi (0.0 MPa) $\mathcal{E}_{cu}$ = -0.005 in./in. E_c = [57000 x √(5000)] / 1000 = 4030.51 ksi (27789.39 MPa)	Application: confined concrete (core) based on Mander's model. Type: Concrete04 (for all sections i.e. for both beam and column) f'_{cc}, $\mathcal{E}_{cc}$, f'_{cu} and $\mathcal{E}_{cu}$ depends on cross-section, transverse bar size, type, and spacing, and clear cover according to Mander's model.
Steel Fibers	
Application: Longitudinal bar Type: ReinforcingSteel f_y = 68 ksi (468.84 MPa) f_{su} = 95 ksi (655 MPa) E_s = 29000 ksi (199947.96 MPa) E_{sh} = 1247 ksi (8597.76 MPa) $\mathcal{E}_{sh}$ = 0.015 in./in. $\mathcal{E}_{su}$ = 0.12 in./in.	Application: Longitudinal bar Type: Pinching4 f_1 = 68 ksi (468.84 MPa) f_2 = 91.22 ksi (628.94 MPa) f_3 = 95 ksi (655 MPa) f_4 = 0.5 ksi (3.45 MPa) $\mathcal{E}_1$ = 0.0023 in./in. $\mathcal{E}_2$ = 0.05 in./in. $\mathcal{E}_3$ = 0.11 in./in. $\mathcal{E}_4$ =0.12 in./in.

As discussed before, "ReinforcingSteel" material model does not show any sudden drop in strength at the ultimate strain. Therefore, an alternative material model, "Pinching4" was used. Figure 5.6 shows the stress-strain relationships for both types of the material models for an ASTM A706 Grade 60 steel bar. The use of "Pinching4" and

“Concrete04” material model allows to identify the ultimate displacement of a frame without monitoring the stress-strain of the steel and core concrete fibers.

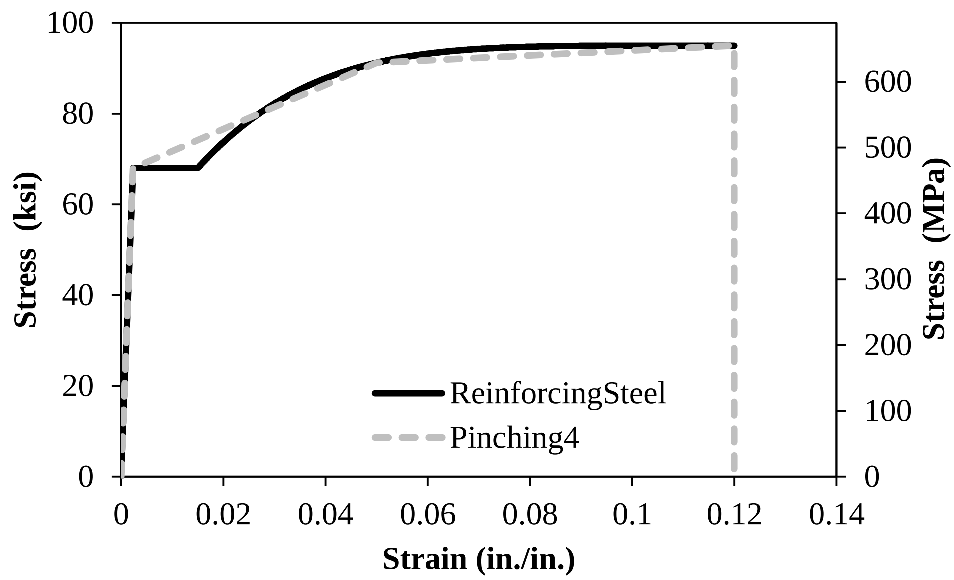


Figure 5.6- Stress-Strain Relationship for “ReinforcingSteel” and “Pinching4” Material Models

Coupler properties were determined according to the coupler material model developed by Tazarv and Saiidi (2016) and are summarized in Table 5.2 for different coupler rigid length factor, β, and different coupler length, L_{sp}. Only No. 7 bars (Ø22 mm) and No. 9 bars (Ø29 mm) were utilized in the frames.

Table 5.2: Coupler Properties for Parametric Study

Coupler Length of L_{sp} = 5d_b			
Original Steel Bar	β = 0.25	β = 0.5	β = 0.75
Type: ReinforcingSteel, f_y = 68 ksi (468.84 MPa), f_{su} = 95 ksi (655 MPa), E_s = 29000 ksi (199947.96 MPa), E_{sh} = 1247 ksi (8597.76 MPa), ε_{sh} = 0.015 in./in., ε_{su} =0.12 in./in.	Type: ReinforcingSteel, f_y = 68 ksi (468.84 MPa), f_{su} = 95 ksi (655 MPa), E_s = 35304.35 ksi (243414.92 MPa), E_{sh} = 1518.09 ksi (10466.86 MPa), ε_{sh} = 0.0123 in./in., ε_{su} =0.099 in./in.	Type: ReinforcingSteel, f_y = 68 ksi (468.84 MPa), f_{su} = 95 ksi (655 MPa), E_s = 45111.11 ksi (311030.15 MPa), E_{sh} = 1939.78 ksi (13374.31 MPa), ε_{sh} = 0.0096 in./in., ε_{su} =0.077 in./in.	Type: ReinforcingSteel, f_y = 68 ksi (468.84 MPa), f_{su} = 95 ksi (655 MPa), E_s = 62461.54 ksi (430657.16 MPa), E_{sh} = 2685.85 ksi (18518.28 MPa), ε_{sh} = 0.0069 in./in., ε_{su} =0.056 in./in.
Coupler Length of L_{sp} = 10d_b			
Original Steel Bar	β = 0.25	β = 0.5	β = 0.75
Type: ReinforcingSteel, f_y = 68 ksi (468.84 MPa), f_{su} = 95 ksi (655 MPa), E_s = 29000 ksi (199947.96 MPa), E_{sh} = 1247 ksi (8597.76 MPa), ε_{sh} = 0.015 in./in., ε_{su} =0.12 in./in.	Type: ReinforcingSteel, f_y = 68 ksi (468.84 MPa), f_{su} = 95 ksi (655 MPa), E_s = 36631.58 ksi (252565.85 MPa), E_{sh} = 1575.16 ksi (10860.35 MPa), ε_{sh} = 0.0119 in./in., ε_{su} =0.095 in./in.	Type: ReinforcingSteel, f_y = 68 ksi (468.84 MPa), f_{su} = 95 ksi (655 MPa), E_s = 49714.29 ksi (342767.96 MPa), E_{sh} = 2137.71 ksi (14738.99 MPa), ε_{sh} = 0.0088 in./in., ε_{su} =0.07 in./in.	Type: ReinforcingSteel, f_y = 68 ksi (468.84 MPa), f_{su} = 95 ksi (655 MPa), E_s = 77333.33 ksi (533194.54 MPa), E_{sh} = 3325.33 ksi (22927.34 MPa), ε_{sh} = 0.0056 in./in., ε_{su} =0.045 in./in.
Coupler Length of L_{sp} = 15d_b			
Original Steel Bar	β = 0.25	β = 0.5	β = 0.75
Type: ReinforcingSteel, f_y = 68 ksi (468.84 MPa), f_{su} = 95 ksi (655 MPa), E_s = 29000 ksi (199947.96 MPa), E_{sh} = 1247 ksi (8597.76 MPa), ε_{sh} = 0.015 in./in., ε_{su} =0.12 in./in.	Type: ReinforcingSteel, f_y = 68 ksi (468.84 MPa), f_{su} = 95 ksi (655 MPa), E_s = 37207.54 ksi (256536.96 MPa), E_{sh} = 1599.92 ksi (11031.06 MPa), ε_{sh} = 0.0117 in./in., ε_{su} =0.094 in./in.	Type: ReinforcingSteel, f_y = 68 ksi (468.84 MPa), f_{su} = 95 ksi (655 MPa), E_s = 51894.74 ksi (357801.64 MPa), E_{sh} = 2231.47 ksi (15385.44 MPa), ε_{sh} = 0.0084 in./in., ε_{su} =0.067 in./in.	Type: ReinforcingSteel, f_y = 68 ksi (468.84 MPa), f_{su} = 95 ksi (655 MPa), E_s = 85739.13 ksi (591150.49 MPa), E_{sh} = 3686.78 ksi (25419.45 MPa), ε_{sh} = 0.005 in./in., ε_{su} =0.041 in./in.

The stress-Strain relationship for an original steel bar and 15d_b-long couplers with three rigid length factors of 0.25, 0.5, and 0.75 are shown in Fig. 5.7. It can be seen that stiffener couplers significantly reduces the ultimate strain capacity of the reinforcement in the spliced region.

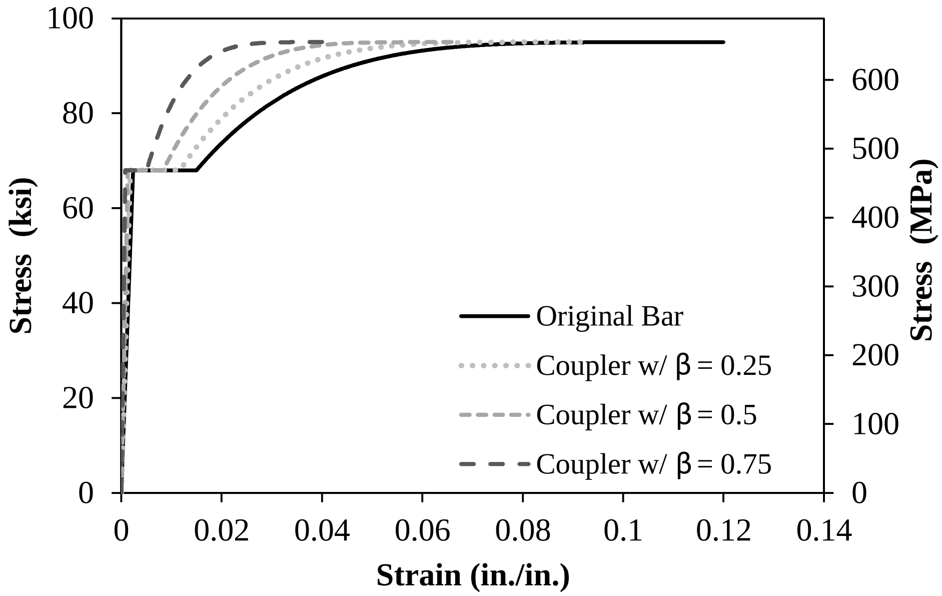


Figure 5.7- Stress-Strain Relationships for Original Steel Bar and Couplers Used in Parametric Study

Concrete confinement varies throughout the length of the beams and columns depending on the sectional properties, the size and properties of the longitudinal bars, and the spacing and detailing of the transverse reinforcement (different frame types). Mander's model (Mander et al., 1988) was used to calculate the properties of the confined concrete. Tables 5.3 to 5.11 present a summary of the confined concrete properties for different frame types. "Concrete04" was used in all beam and column sections to model the core concrete fibers since it shows a sudden drop in the strength when the ultimate strain is reached.

Table 5.3: Properties of Core Concrete Fibers in Three-story Ordinary MRF

Beam B1	Beam B2, B3 and B4	Column C
f'_{cc} = -5.95 ksi (41.03 MPa) $\mathcal{E}_{cc}$ = -0.0039 in./in. f'_{cu} = -3.763 ksi (25.94 MPa) $\mathcal{E}_{cu}$ = -0.0164 in./in.	f'_{cc} = -5.75 ksi (39.64 MPa) $\mathcal{E}_{cc}$ = -0.0035 in./in. f'_{cu} = -3.6375 ksi (25.08 MPa) $\mathcal{E}_{cu}$ = -0.0131 in./in.	f'_{cc} = -5.75 ksi (39.64 MPa) $\mathcal{E}_{cc}$ = -0.0035 in./in. f'_{cu} = -3.5942 ksi (24.78 MPa) $\mathcal{E}_{cu}$ = -0.0134 in./in.

Table 5.4: Properties of Core Concrete Fibers in Three-story Intermediate MRF

Beam B1 and B3	Beam B2	Column C
f'_{cc} = -5.95 ksi (41.03 MPa) $\mathcal{E}_{cc}$ = -0.0039 in./in. f'_{cu} = -3.885 ksi (26.79 MPa) $\mathcal{E}_{cu}$ = -0.0154 in./in.	f'_{cc} = -5.45 ksi (37.58 MPa) $\mathcal{E}_{cc}$ = -0.0029 in./in. f'_{cu} = -3.2029 ksi (22.08 MPa) $\mathcal{E}_{cu}$ = -0.0099 in./in.	f'_{cc} = -6.25 ksi (43.09 MPa) $\mathcal{E}_{cc}$ = -0.0045 in./in. f'_{cu} = -4.3776 ksi (30.18 MPa) $\mathcal{E}_{cu}$ = -0.0175 in./in.

Table 5.5: Properties of Core Concrete Fibers in Three-story Special MRF

Beam B1 and B3	Beam B2 and B4	Column C1
f'_{cc} = -5.95 ksi (41.02 MPa) $\mathcal{E}_{cc}$ = -0.0039 in./in. f'_{cu} = -4.0365 ksi (27.83 MPa) $\mathcal{E}_{cu}$ = -0.0143 in./in.	f'_{cc} = -5.25 ksi (36.2 MPa) $\mathcal{E}_{cc}$ = -0.0025 in./in. f'_{cu} = -2.7229 ksi (18.77 MPa) $\mathcal{E}_{cu}$ = -0.0083 in./in.	f'_{cc} = -6.925 ksi (47.75 MPa) $\mathcal{E}_{cc}$ = -0.0059 in./in. f'_{cu} = -5.208 ksi (35.91 MPa) $\mathcal{E}_{cu}$ = -0.0234 in./in.
Column C2		
f'_{cc} = -6.325 ksi (43.61 MPa) $\mathcal{E}_{cc}$ = -0.0047 in./in. f'_{cu} = -4.308 ksi (29.7 MPa) $\mathcal{E}_{cu}$ = -0.0199 in./in.		

Table 5.6: Properties of Core Concrete Fibers in Six-story Ordinary MRF

Beam B1 and B2	Beam B3	Beam B4, B5 and B6
f'_{cc} = -5.25 ksi (36.2 MPa) $\mathcal{E}_{cc}$ = -0.0025 in./in. f'_{cu} = -2.4763 ksi (17.07 MPa) $\mathcal{E}_{cu}$ = -0.0092 in./in.	f'_{cc} = -5.95 ksi (41.02 MPa) $\mathcal{E}_{cc}$ = -0.0039 in./in. f'_{cu} = -3.763 ksi (25.94 MPa) $\mathcal{E}_{cu}$ = -0.0164 in./in.	f'_{cc} = -5.75 ksi (39.64 MPa) $\mathcal{E}_{cc}$ = -0.0035 in./in. f'_{cu} = -3.5942 ksi (24.78 MPa) $\mathcal{E}_{cu}$ = -0.0134 in./in.
Column C1	Column C2	
f'_{cc} = -5.6 ksi (38.61 MPa) $\mathcal{E}_{cc}$ = -0.0032 in./in. f'_{cu} = -3.4956 ksi (24.1 MPa) $\mathcal{E}_{cu}$ = -0.0112 in./in.	f'_{cc} = -5.75 ksi (39.64 MPa) $\mathcal{E}_{cc}$ = -0.0035 in./in. f'_{cu} = -3.6375 ksi (25.08 MPa) $\mathcal{E}_{cu}$ = -0.0131 in./in.	

Table 5.7: Properties of Core Concrete Fibers in Six-story Intermediate MRF

Beam B1, B3 and B5	Beam B2, B4 and B6	Beam B7 and B9
f'_{cc} = -5.8 ksi (39.99 MPa) ε_{cc} = -0.0036 in./in. f'_{cu} = -3.7425 ksi (25.8 MPa) ε_{cu} = -0.0134 in./in.	f'_{cc} = -5.25 ksi (36.2 MPa) ε_{cc} = -0.0025 in./in. f'_{cu} = -2.541 ksi (11.52 MPa) ε_{cu} = -0.009 in./in.	f'_{cc} = -5.95 ksi (41.02 MPa) ε_{cc} = -0.0039 in./in. f'_{cu} = -3.8848 ksi (26.78 MPa) ε_{cu} = -0.0154 in./in.
Beam B8 and B10	Column C1	Column C2
f'_{cc} = -5.45 ksi (37.58 MPa) ε_{cc} = -0.0029 in./in. f'_{cu} = -3.2029 ksi (22.08 MPa) ε_{cu} = -0.0099 in./in.	f'_{cc} = -5.85 ksi (40.33 MPa) ε_{cc} = -0.0037 in./in. f'_{cu} = -3.8292 ksi (26.4 MPa) ε_{cu} = -0.0138 in./in.	f'_{cc} = -5.6 ksi (38.61 MPa) ε_{cc} = -0.0032 in./in. f'_{cu} = -3.4956 ksi (24.1 MPa) ε_{cu} = -0.0112 in./in.
Column C3		
f'_{cc} = -6.25 ksi (43.09 MPa) ε_{cc} = -0.0045 in./in. f'_{cu} = -4.3776 ksi (30.18 MPa) ε_{cu} = -0.0175 in./in.		

Table 5.8: Properties of Core Concrete Fibers in Six-story Special MRF

Beam B1	Beam B2	Beam B3 and B5
f'_{cc} = -5.7 ksi (39.3 MPa) ε_{cc} = -0.0034 in./in. f'_{cu} = -3.6006 ksi (24.83 MPa) ε_{cu} = -0.0124 in./in.	f'_{cc} = -5.25 ksi (36.2 MPa) ε_{cc} = -0.0025 in./in. f'_{cu} = -2.6498 ksi (18.27 MPa) ε_{cu} = -0.0086 in./in.	f'_{cc} = -5.7 ksi (39.3 MPa) ε_{cc} = -0.0034 in./in. f'_{cu} = -3.2455 ksi (22.38 MPa) ε_{cu} = -0.0147 in./in.
Beam B4 and B6	Column C1	Column C2
f'_{cc} = -5.25 ksi (36.2 MPa) ε_{cc} = -0.0025 in./in. f'_{cu} = -2.7229 ksi (18.77 MPa) ε_{cu} = -0.0083 in./in.	f'_{cc} = -5.95 ksi (41.02 MPa) ε_{cc} = -0.0039 in./in. f'_{cu} = -3.8856 ksi (26.79 MPa) ε_{cu} = -0.0154 in./in.	f'_{cc} = -6.925 ksi (47.75 MPa) ε_{cc} = -0.0059 in./in. f'_{cu} = -5.208 ksi (35.91 MPa) ε_{cu} = -0.0234 in./in.
Column C3		
f'_{cc} = -6.325 ksi (43.61 MPa) ε_{cc} = -0.0047 in./in. f'_{cu} = -4.308 ksi (29.7 MPa) ε_{cu} = -0.0199 in./in.		

Table 5.9: Properties of Core Concrete Fibers in Nine-story Ordinary MRF

Beam B1, B2, B3 and B4	Beam B5	Beam B6, B7 and B8
f'_{cc} = -5.25 ksi (36.2 MPa) ε_{cc} = -0.0025 in./in. f'_{cu} = -2.4763 ksi (17.07 MPa) ε_{cu} = -0.0092 in./in.	f'_{cc} = -5.95 ksi (41.02 MPa) ε_{cc} = -0.0039 in./in. f'_{cu} = -3.763 ksi (25.94 MPa) ε_{cu} = -0.0164 in./in.	f'_{cc} = -5.75 ksi (39.64 MPa) ε_{cc} = -0.0035 in./in. f'_{cu} = -3.5942 ksi (24.78 MPa) ε_{cu} = -0.0134 in./in.
Column C1	Column C2	
f'_{cc} = -5.6 ksi (38.61 MPa) ε_{cc} = -0.0032 in./in. f'_{cu} = -3.4956 ksi (24.1 MPa) ε_{cu} = -0.0112 in./in.	f'_{cc} = -5.75 ksi (39.64 MPa) ε_{cc} = -0.0035 in./in. f'_{cu} = -3.6375 ksi (25.08 MPa) ε_{cu} = -0.0131 in./in.	

Table 5.10: Properties of Core Concrete Fibers in Nine-story Intermediate MRF

Beam B1, B3 and B5	Beam B2, B4 and B6	Beam B7 and B9
f'_{cc} = -5.8 ksi (39.99 MPa) ε_{cc} = -0.0036 in./in. f'_{cu} = -3.7425 ksi (25.8 MPa) ε_{cu} = -0.0134 in./in.	f'_{cc} = -5.25 ksi (36.2 MPa) ε_{cc} = -0.0025 in./in. f'_{cu} = -2.541 ksi (11.52 MPa) ε_{cu} = -0.009 in./in.	f'_{cc} = -5.95 ksi (41.02 MPa) ε_{cc} = -0.0039 in./in. f'_{cu} = -3.8848 ksi (26.78 MPa) ε_{cu} = -0.0154 in./in.
Beam B8 and B10	Column C1	Column C2
f'_{cc} = -5.45 ksi (37.58 MPa) ε_{cc} = -0.0029 in./in. f'_{cu} = -3.2029 ksi (22.08 MPa) ε_{cu} = -0.0099 in./in.	f'_{cc} = -5.85 ksi (40.33 MPa) ε_{cc} = -0.0037 in./in. f'_{cu} = -3.8292 ksi (26.4 MPa) ε_{cu} = -0.0138 in./in.	f'_{cc} = -5.6 ksi (38.61 MPa) ε_{cc} = -0.0032 in./in. f'_{cu} = -3.4956 ksi (24.1 MPa) ε_{cu} = -0.0112 in./in.
Column C3		
f'_{cc} = -6.25 ksi (43.09 MPa) ε_{cc} = -0.0045 in./in. f'_{cu} = -4.3776 ksi (30.18 MPa) ε_{cu} = -0.0175 in./in.		

Table 5.11: Properties of Core Concrete Fibers in Nine-story Special MRF

Beam B1	Beam B2	Beam B3
f'_{cc} = -5.625 ksi (38.78 MPa) ε_{cc} = -0.0033 in./in. f'_{cu} = -3.5516 ksi (24.49 MPa) ε_{cu} = -0.0113 in./in.	f'_{cc} = -5.4 ksi (23.44 MPa) ε_{cc} = -0.0028 in./in. f'_{cu} = -3.2929 ksi (22.71 MPa) ε_{cu} = -0.0088 in./in.	f'_{cc} = -5.7 ksi (39.3 MPa) ε_{cc} = -0.0034 in./in. f'_{cu} = -3.6006 ksi (24.83 MPa) ε_{cu} = -0.0124 in./in.
Beam	Beam B5 and B7	Beam B6 and B8
f'_{cc} = -5.25 ksi (36.2 MPa) ε_{cc} = -0.0025 in./in. f'_{cu} = -2.6498 ksi (18.27 MPa) ε_{cu} = -0.0086 in./in.	f'_{cc} = -5.7 ksi (39.3 MPa) ε_{cc} = -0.0034 in./in. f'_{cu} = -3.2455 ksi (22.38 MPa) ε_{cu} = -0.0147 in./in.	f'_{cc} = -5.25 ksi (36.2 MPa) ε_{cc} = -0.0025 in./in. f'_{cu} = -2.7229 ksi (18.77 MPa) ε_{cu} = -0.0083 in./in.
Column C1	Column C2	Column C3
f'_{cc} = -5.75 ksi (39.64 MPa) ε_{cc} = -0.0035 in./in. f'_{cu} = -3.6728 ksi (25.32 MPa) ε_{cu} = -0.0129 in./in.	f'_{cc} = -5.95 ksi (41.02 MPa) ε_{cc} = -0.0039 in./in. f'_{cu} = -3.8856 ksi (26.79 MPa) ε_{cu} = -0.0154 in./in.	f'_{cc} = -6.925 ksi (47.75 MPa) ε_{cc} = -0.0059 in./in. f'_{cu} = -5.208 ksi (35.91 MPa) ε_{cu} = -0.0234 in./in.
Column C4		
f'_{cc} = -6.325 ksi (43.61 MPa) ε_{cc} = -0.0047 in./in. f'_{cu} = -4.308 ksi (29.7 MPa) ε_{cu} = -0.0199 in./in.		

The stress-strain relationship for the unconfined and a sample confined concrete (section C3 for nine-story SMRF) is shown in Fig. 5.8.

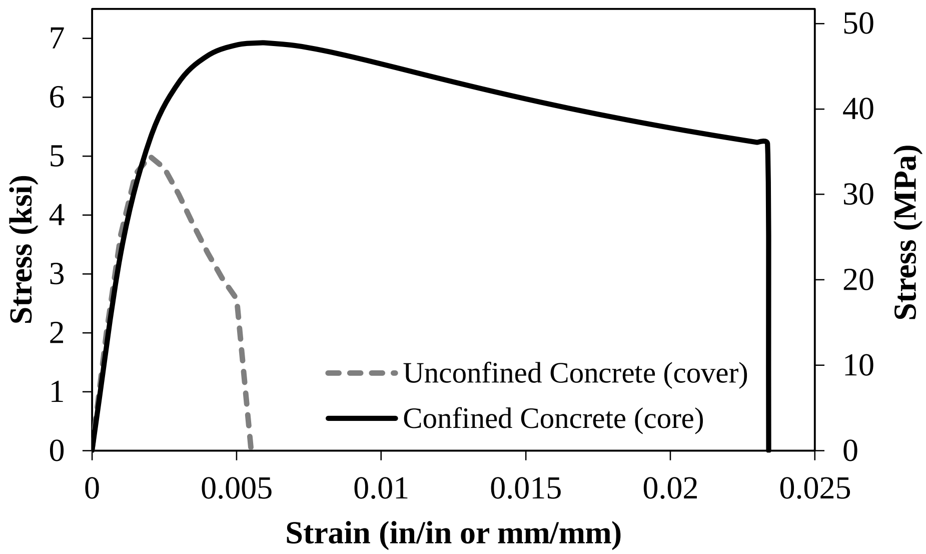


Figure 5.8- Stress-Strain Relationship for Unconfined and Confined Concrete Used in Parametric Study

The displacement capacity of frames is the interest of the analytical studies. Since both steel and core concrete fibers show sudden drop in the strength at the ultimate strains, the ultimate displacement of a frame in a pushover analysis can be defined as the point where the lateral load carrying capacity of the frame drops by 15% with respect to the peak base shear. Therefore, the effect of bar fracture and core concrete failure are included in the system performance. The geometric nonlinearity was included in all analyses. Both displacement capacity and displacement ductility capacity were calculated from each analysis. The displacement ductility capacity is the ratio of the displacement capacity and the effective yield displacement. Effective yield displacement was calculated per ASCE 41-13 (2014). Since the displacement ductility capacity was not consistent, it was excluded from further data processing.

OpenSees modeling for the nine-story IMRF is presented in Appendix A.

5.2 Analytical Study

In total, 108 pushover analyses were performed. Of which, nine analysis were performed on reference unspliced frames and 99 analyses were carried out on the spliced frames to determine the effect of couplers on their seismic performance.

5.2.1 Parameters

Previous study by Tazarv and Saiidi (2016) showed that the coupler rigid length factor, the coupler length, and the coupler location affect the displacement capacity of mechanically spliced bridge columns. For RC frames, four parameters were included in the analyses: (1) the coupler rigid length factor, (2) the coupler length, (3) the number of stories or the building height, and (4) the moment-resisting frame system.

There are many coupler types available in the market. Due to lack of test data, a range of β from 0.25 to 0.75 was included in the present study to cover all practical cases. Tazarv and Saiidi (2016) recommended to only use couplers with a length less than $15d_b$ (d_b is the diameter of the reinforcing bar) for seismic applications. Therefore, three L_{sp} of $5d_b$, $10d_b$, and $15d_b$ were selected for the parametric study. Height of three-, six-, and nine-story buildings provides another parameter to the analysis. The fourth parameter was the frame type: ordinary moment-resisting force (OMRF), intermediate moment-resisting force (IMRF), and special moment-resisting force (SMRF).

5.2.2 Results of Parametric Study

Effect of the individual parameter on the seismic performance of mechanically spliced RC frames is evaluated herein.

5.2.2.1 Coupler Rigid Length Factor, β

Figure 5.9 shows the effect of the coupler rigid length factor on the pushover curve of nine-story SMRF. It can be seen that couplers with higher rigid length factors increase the initial stiffness of RC frames but significantly reduce the frame displacement capacity. For example, the initial stiffness for the nine-story SMRF spliced with $15d_b$–long couplers was increased by 22%, and the displacement capacity was reduced by 21% when the coupler rigid length factor increased from 0.25 to 0.75. Similar trend was observed in other frames with different number of stories.

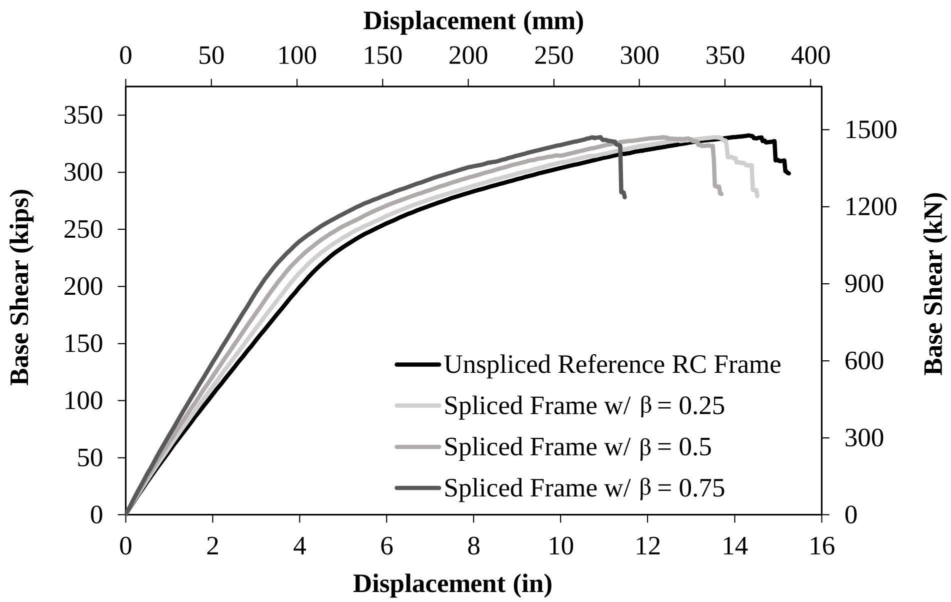


Figure 5.9- Pushover Response of Nine-Story SMRF with L_{sp} = $15d_b$ and Different Coupler Rigid Length Factors

5.2.2.2 Coupler Length, L_{sp}

Figure 5.10 shows the effect of the coupler length on the force-displacement relationship of nine-story SMRFs. It is obvious that the coupler length has a significant effect on the initial stiffness and the displacement capacity of the frames. Longer couplers reduce the displacement capacities of RC frames more than the shorter couplers.

For example, the displacement capacity of the mechanically spliced nine-story SMRF with β = 0.5 was reduced by 14% when the coupler length increased from 5d_b to 15d_b. The same trend was observed in other frames.

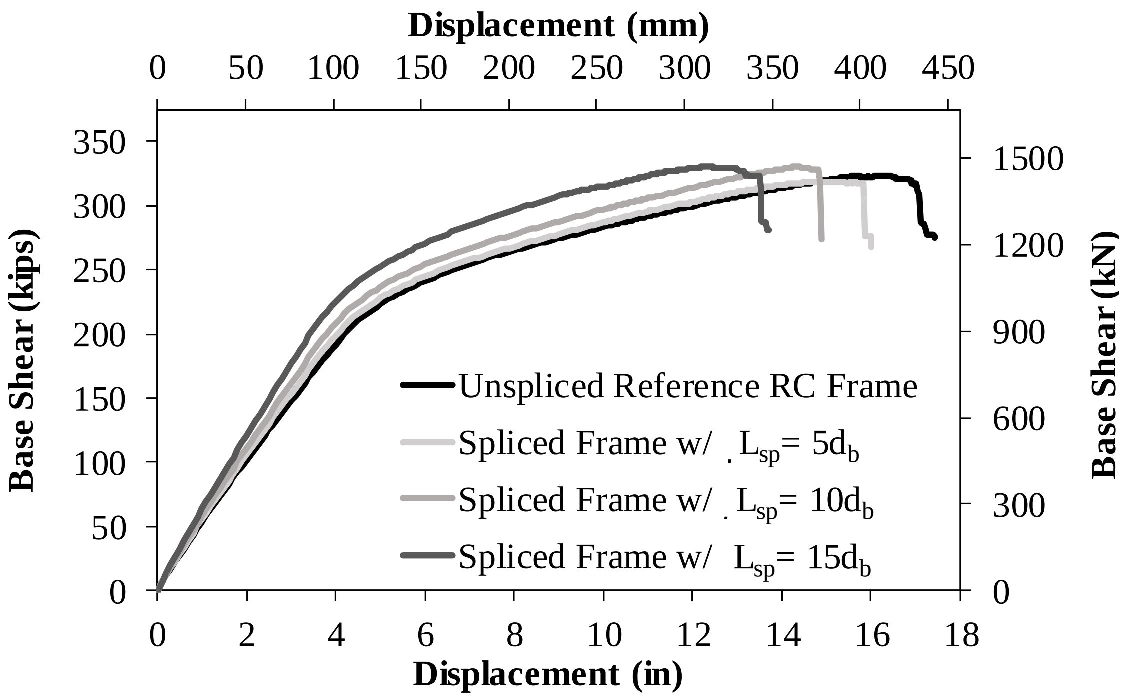


Figure 5.10- Pushover Response of Nine-Story SMRF with β=0.5 and Different Coupler Lengths

5.2.2.3 Height of Building

Figure 5.11 shows the effect of the building height on the pushover response of SMRFs with L_{sp} = 15d_b and β = 0.75. It can be seen that the height of the RC frames affects the overall pushover response thus they have to be included in the evaluation of coupler effects on the seismic performance of RC frames. Similar trend was observed in other frames.

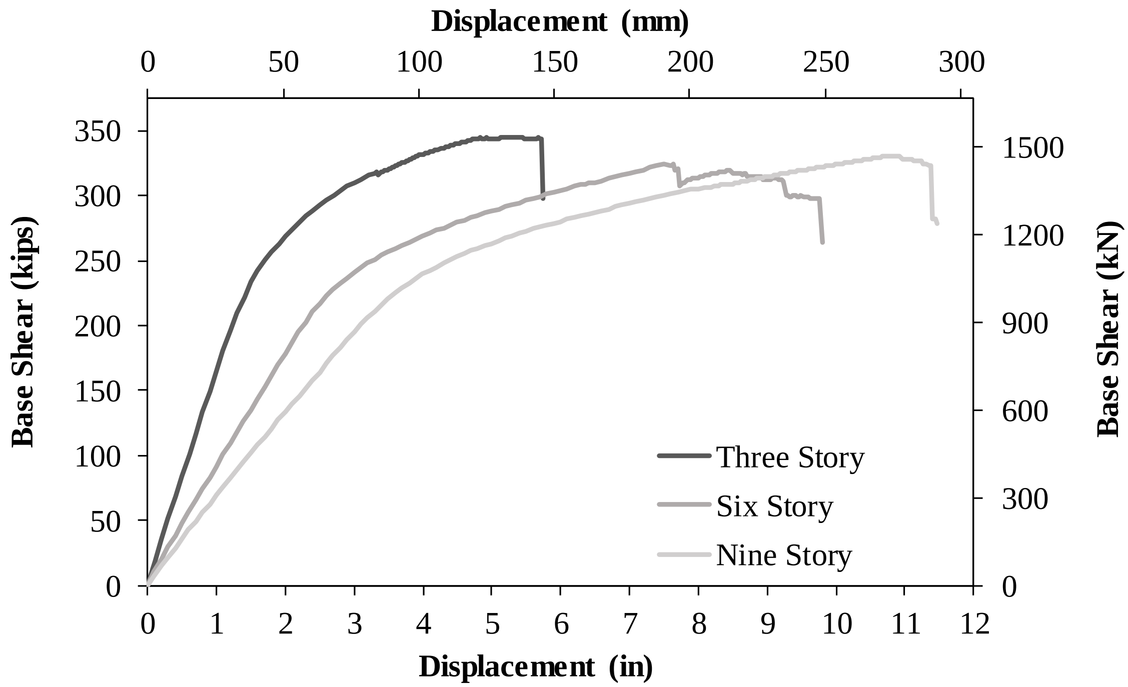


Figure 5.11- Pushover Response of SMRFs with L_{sp} = 15d_b, β = 0.75, and Different Buidling Hights

5.2.2.4 Moment-Resisting Frame System

Figure 5.12 shows the effect of moment-resisting frame systems on the pushover response. It can be seen that the frame seismic detailing is another critical parameter to evaluate the coupler effect. The general trend is that RC frames with better seismic detailing are more ductile than others.

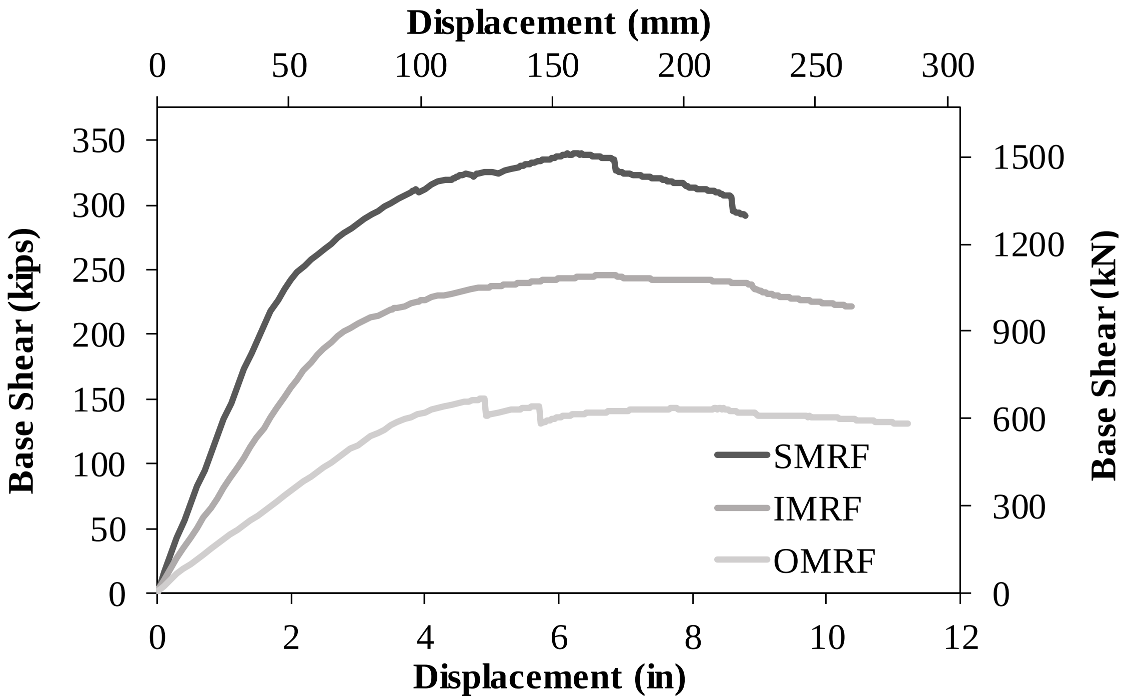


Figure 5.12- Pushover Response of Three-Story MRFs with L_{sp} = 10d_b, β = 0.25, and Different Seismic Detailing

5.2.3 Summary of Results

More than 100 pushover analyses were performed to investigate the effect of mechanical bar splices on the seismic performance of RC frames. The analytical study showed how much displacement capacity will reduce due to the use of different types of couplers in plastic hinge regions region in various types of buildings.

The data was clustered per frame type then the reduction in the displacement capacity (the ratio of the spliced frame displacement capacity, δ_{sp}, to the unspliced reference frame displacement capacity, δ_{RC}) was plotted against the ratio of the coupler length to the building height. Figure 5.13 shows such a graph for SMRFs. Outlier data was removed from the graph. Linear, logarithmic, polynomial, and exponential curves were fitted to the data to find the best match. It was found that a logarithmic equation represents the behavior. Based on the observed behavior, an equation was developed for SMRFs then it was expanded for other types of moment-resisting RC frames (Fig. 5.14 and 5.15). It can be seen that the effect of mechanical bar splices on the displacement capacity of RC frames is more significant for SMRFs. For example, at 100Lsp/Height=2 and Beta=0.75, the displacement capacity reduction was 35% in SMRF due to the use of the couplers while the displacement capacity reduction for IMRF and OMRF was 32% and 29%, respectively.

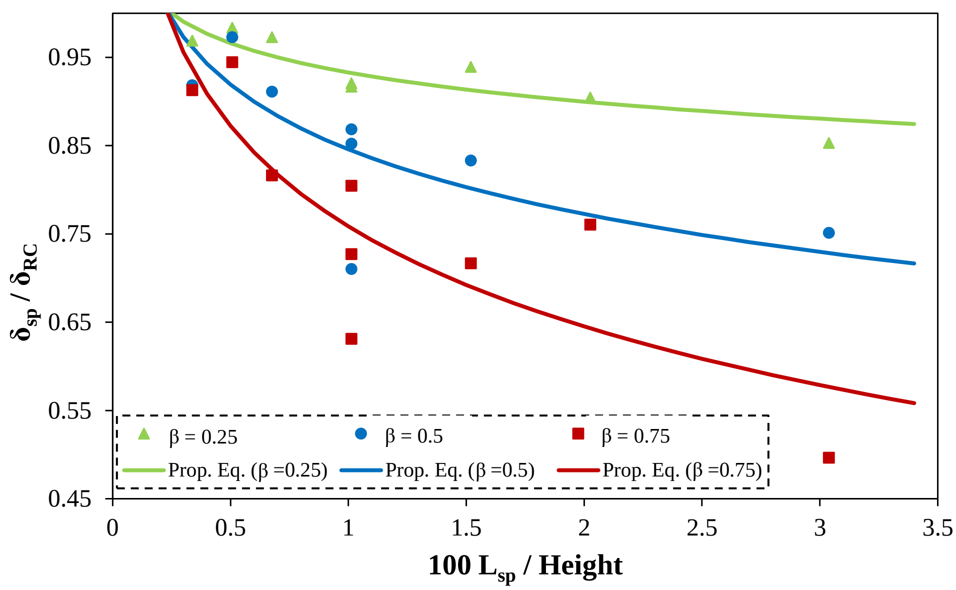


Figure 5.13- Summary of Results for SMRFs

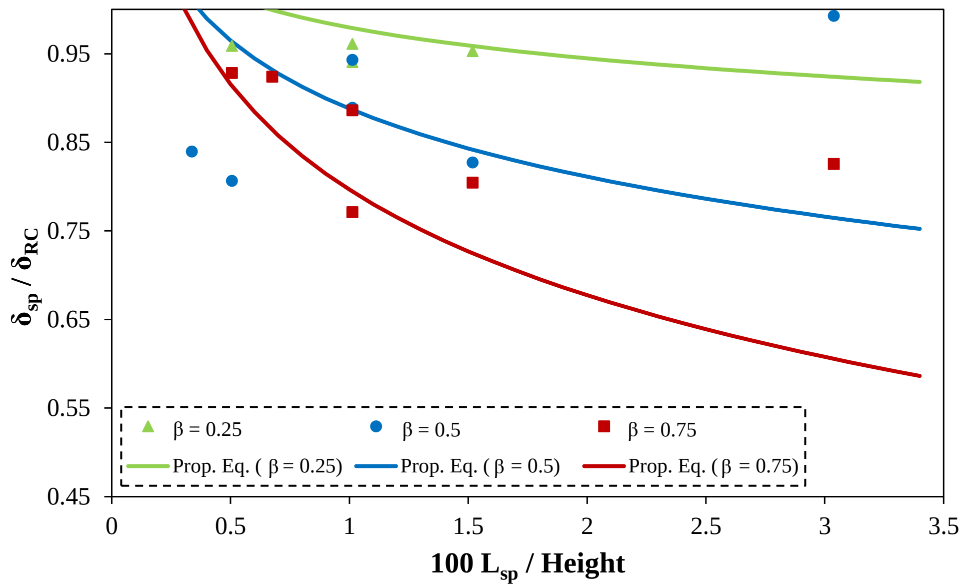


Figure 5.14- Summary of Results for IMRFs

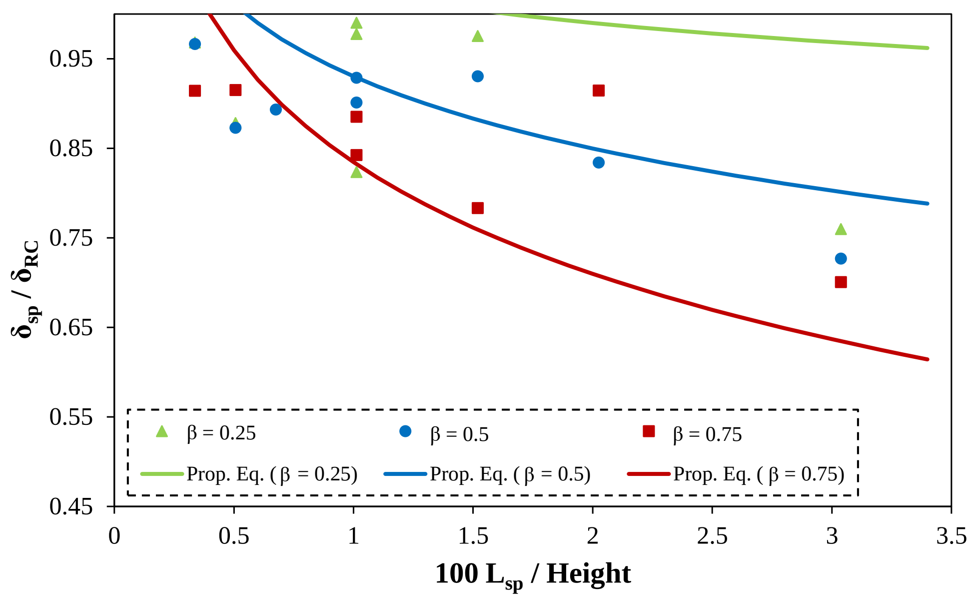


Figure 5.15- Summary of Results for OMRFs

5.3 Proposed Design Equation

It was shown that four parameters affect the displacement capacity of mechanically spliced moment-resisting RC frames: the coupler rigid length factor (β), the coupler length (L_{sp}), the height of the building, and the moment-resisting frame system (ordinary, intermediate, and special). Based on the statistical analysis, a simple design equation was proposed accounting for the four aforementioned parameters:

$$\frac{\delta_{sp}}{\delta_{RC}} = \Omega\,[1 - 0.35\,\beta + (0.01 - 0.2\,\beta)\,\ln\frac{100L_{sp}}{H}] \leq 1 \qquad (5.1)$$

where,

Ω = The type of MRF system (1 for SMRF, 1.05 for IMRF, and 1.1 for OMRF)

L_{sp} = The coupler length (in. or m)

β = The coupler rigid length factor

H = The height of the building (in. or m)

The proposed equation was shown in Fig. 5.13 to 5.15 with solid lines for three different coupler rigid length factors. It can be seen that the proposed equation estimates the reduction in the displacement capacity of moment-resisting RC frames due to the use of mechanical bar splices in the plastic hinge regions with reasonable accuracy.

5.4 Discussion

The analytical studies presented above showed that couplers reduce the displacement capacity of RC frames. ACI 318-14 (2014) allows two types of bar couplers: Type 1 and Type 2. Type 2 couplers, which are stronger than the ultimate strength of bars, were utilized and modeled in the present study. The code restricts the use of these couplers in certain locations. Table 5.12 presents the summary of the ACI 318-14 (2014) requirements and the findings of the present study.

Table 5.12: Summary of Results and ACI 318-14 (2014) Requirement

<table>
<tr><th rowspan="3">Frame Type</th><th rowspan="3">Code Requirements</th><th colspan="4">Present Study</th></tr>
<tr><th colspan="4">Reduction in Displacement Capacity (β=0.75, L_{sp}=15d_b)</th></tr>
<tr><th>Three-Story</th><th>Six-Story</th><th>Nine-Story</th><th>Remarks</th></tr>
<tr><td>OMRF</td><td>No restriction</td><td>36%</td><td>25%</td><td>19%</td><td>Type 2 couplers may be incorporated in plastic hinge regions but the reduced displacement capacity (Eq. 5.1) shall be higher than the displacement demand.</td></tr>
<tr><td>IMRF</td><td>No restriction</td><td>39%</td><td>29%</td><td>23%</td><td>Type 2 couplers may be incorporated in plastic hinge regions but the reduced displacement capacity (Eq. 5.1) shall be higher than the displacement demand.</td></tr>
<tr><td>SMRF</td><td>Type 1 coupler:
• Shall not be located within twice the member depth from the beam or column face or from critical sections where yielding of reinforcement may occur due to lateral displacement.
• Restricted in all reinforcement resisting earthquake effects.

Type 2 coupler:
• Shall not be located in beam closer than half the height of the beam from the joint face in ductile connections constructed using precast concrete.
• Can be used with documentation in regions of potential yielding of members resisting earthquake effects</td><td>42%</td><td>32%</td><td>26%</td><td>Type 2 couplers may be incorporated in plastic hinge regions but the reduced displacement capacity (Eq. 5.1) shall be higher than the displacement demand.</td></tr>
</table>

Note: Story height was assumed 12 ft (3.66 m)

The findings of the present study show the use of mechanical bar splices can be allowed for all three types of RC MRFs mainly to accelerate the construction. However, the coupler shall be Type 2 (bar fracture shall be ensured outside the coupler region), the coupler length shall not exceed 15 times the anchoring bar diameter, and the displacement capacity shall be modified according to the proposed equation (Eq. 5.1) to be checked against the displacement demand. Type 1 shall not be used in the plastic hinge region of ductile member of any frame type since large inelastic deformations of spliced bars cannot be guaranteed.

In summary, the ACI restrictions for SMRFs can be relaxed. However, new restrictions are needed for OMRFs and IMRFs if the seismic demands are significant.

5.5 References

ACI 318-14 (2014). "Building Code Requirements for Structural Concrete". American Concrete Institute.

ASCE 41-13 (2014). "Seismic Evaluation and Retrofit of Existing Buildings". American Society of Civil Engineers.

Mander J. B., Priestly M. J. N. and Park R. (1988a). "Theoretical stress-strain model for confined concrete," Journal of Structural Engineering, ASCE Vol 114, No. 8, pp. 1804 – 1826.

OpenSees. Open System for Earthquake Engineering Simulation. Version 2.5, Berkeley, CA available online:Available from: http://opensees.berkeley.edu.2016

SAP2000. Version 15. Computers and Structures, Inc. Berkeley, CA. 2015.

Tazarv, M. and Saiidi, M.S. (2016). "Seismic design of bridge columns incorporating mechanical bar splices in plastic hinge regions," Engineering Structures, DOI: 10.1016/j.engstruct.2016.06.041, Vol 124, pp. 507-520.

6. Summary and Conclusions

6.1 Summary

Effects of mechanical bar splices on the seismic behavior of RC frames were analytically investigated in the present study. Three-, six-, and nine-story ordinary moment-resisting frames (OMRFs), intermediate MRFs (IMRFs), and special MRFs (SMRFs) were designed and detailed according to ASCE 7-10 and ACI 318-14. Previous experimental data was selected from literature to verify the modeling methods presented for mechanically spliced RC members. More than 100 pushover analyses were performed. Four variables were included in the analytical studies of the nine frames: the coupler rigid length factor (β = 0.25, 0.50, and 0.75), the coupler length, ($L_{sp} = 5d_b$, $10d_b$, and $15d_b$), the height of building (with an interval of 12 ft per story), and the type of moment-resisting frame system (ordinary, intermediate, and special). A simple design equation was proposed to quantify the effect of coupler on the displacement capacity of spliced frames.

6.2 Conclusions

Based on the analytical studies, following conclusions can be drawn:

- The proposed modeling methods for mechanically spliced RC members was simple and reasonably accurate.
- Mechanical splices significantly affect the force-displacement relationship of all three types RC frames.
- Couplers with higher rigid length factors and longer couplers increase the stiffness of RC frames and reduce their displacement capacities.
- Taller RC frames are less affected by mechanical bar splices.
- The adverse effect of couplers on the displacement capacity is more profound for SMRFs compared to other frame types. Very rigid and long couplers can reduce the displacement capacity of a short SMRF up to 42% while this reduction in the displacement capacity can be up to 39% and 36% for IMRF and OMRF, respectively.

Overall, the effect of coupler on all RC frame types is significant and must be included in the design.

APPENDIX A: SAMPLE OPENSEES CODE

OpenSees was used for the parametric study. A sample of the code for nine-story intermediate moment-resisting frame is presented to further help the researchers.

```
# 3D modeling of 2D RC frame w/ Nonlinear Beam and Column and Inelastic Fiber Section for
non-linear static procedure (NSP)
# Abdullah Al Hashib, 2016
# Advisor: Dr. Mostafa Tazarv

#              ^Y
#              |
#   (100110)|________(100120)_____(100130)_____(100140)_____(100150)   _,_
#              |       |       |       |           |          |
#              |       |       |       |              |          LCol
#    (90110)|____(90120)|____(90130)|____(90140)|___________|(90150)   _|_
#              |       |       |       |              |          |
#              |              |              |              |              |
LCol
#    (80110)|____(80120)|____(80130)|____(80140)|___________|(80150)   _|_
#              |       |       |       |       |              |
#              |       |              |       |              |          LCol
#    (70110)|________(70120)_____(70130)_____(70140)______(70150)       _|_
#              |       |       |       |           |          |
#              |       |       |       |              |          LCol
#    (60110)|____(60120)|____(60130)|____(60140)|___________|(60150)   _|_
#              |       |       |       |              |          |
#              |              |              |              |              |
LCol
#    (50110)|____(50120)|____(50130)|____(50140)|___________|(50150)   _|_
#              |       |       |       |       |              |
#              |       |              |       |              |          LCol
#    (40110)|________(40120)_____(40130)_____(40140)______(40150)       _|_
#              |       |       |       |           |          |
#              |       |       |       |              |          LCol
#    (30110)|____(30120)|____(30130)|____(30140)|___________|(30150)   _|_
#              |       |       |       |              |          |
#              |              |              |              |              |
LCol
#    (20110)|____(20120)|____(20130)|____(20140)|___________|(20150)   _|_
#              |       |       |       |       |              |
#              |       |              |       |              |          LCol
#   (10110)_|_  (10120)_|_  (10130)_|_  (10140)_|_  (10150)_|_  ___X   _|_
#          ```          ```          ```          ```          ```
       `
#              |<--LBeam-->|<--LBeam-->|<--LBeam-->|<--LBeam-->|


# SET UP ----------------------------------------------------------------------------
wipe;                                                    # clear memory of all past model
definitions
model BasicBuilder -ndm 3 -ndf 6;            # Define the model builder, ndm=#dimension,
ndf=#dofs
set dataDir Data;                                       # set up name of data directory
file mkdir $dataDir;                             # create data directory
source LibUnits.tcl;                             # define units
source DisplayPlane.tcl;                         # procedure for displaying a plane in model
source DisplayModel3D.tcl;                       # procedure for displaying 3D perspectives
of model
source BuildRCrectSection.tcl;                   # procedure for definining RC fiber section

# ------ frame configuration
set NStory 9;                     # number of stories above ground level
set NBay 4;                                # number of bays in X direction
set NBayZ 0;                      # number of bays in Z direction
puts "Number of Stories in Y: $NStory Number of bays in X: $NBay Number of bays in Z:
$NBayZ";
```

```
set NFrame [expr $NBayZ + 1]; # actually deal with frames in Z direction, as this is an
easy extension of the 2d model

# define structure-geometry paramters
set LCol [expr 12.*$ft];            # column height (parallel to Y axis)
set LBeam [expr 20.*$ft];           # beam length (parallel to X axis)
set LGird [expr 0.*$ft];            # girder length (parallel to Z axis)

# Section Properties:
set HCol1 [expr 24.*$in];           # square-Column
set BCol1 $HCol1;
set HCol2 [expr 24.*$in];           # square-Column
set BCol2 $HCol2;
set HCol3 [expr 18.*$in];           # square-Column
set BCol3 $HCol3;

set HBeam [expr 24.*$in];           # Beam depth -- perpendicular to bending axis
set BBeam1 [expr 24.*$in];          # Beam width -- parallel to bending axis
set BBeam2 [expr 24.*$in];          # Beam width -- parallel to bending axis
set BBeam3 [expr 18.*$in];          # Beam width -- parallel to bending axis

# Reinforcing Bar Property----------------------------------------------------------
-------------
set BarAreaBeam 0.6*$in*$in;       # Area of longitudinal-reinforcement bars.
set BarAreaCol 0.6*$in*$in;        # Area of longitudinal-reinforcement bars.

set BeamBarDia 0.875*$in;          # Area of longitudinal-reinforcement bars.
set ColBarDia 0.875*$in;           # Area of longitudinal-reinforcement bars.

# Define Coupler Geometry-----------------------------------------------------------
-----
set betaspBeam 0.75;                # Coupler rigid length factor (can be 0 to 1)
set betaspColumn 0.75;              # Coupler rigid length factor (can be 0 to 1)

set LspBeam  [expr 15.*$BeamBarDia];        # Coupler Length, [e.g. 5db, 10db, 15db]
set LspCol  [expr 15.*$ColBarDia];  # Coupler Length, [e.g. 5db, 10db, 15db]

set HspBeam [expr 0.01*$HBeam];             # Distance from face of beam to start or end
of coupler

set HspCol1 [expr 0.01*$HCol1];             # Distance from face of column to start or
end of coupler
set HspCol2 [expr 0.01*$HCol2];             # Distance from face of column to start or
end of coupler
set HspCol3 [expr 0.01*$HCol3];             # Distance from face of column to start or
end of coupler

puts "-------------------------------------------------------------------";
puts " Coupler Regid Length Factor (beta) in beam = [expr $betaspBeam]";
puts " Coupler Regid Length Factor (beta)in column = [expr $betaspColumn]";
puts " Coupler Length in Beam (in.)= [expr $LspBeam]";
puts " Coupler Length in Column (in.)= [expr $LspCol]";
puts " Distance of Coupler from Beam-Column Interface in BEAM (in.)= [expr $HspBeam]";
puts " Distance of Coupler from Beam-Column Interface in Bottom COULMNs (in.)= [expr
$HspCol1]";
puts " Distance of Coupler from Beam-Column Interface in Middle COULMNs (in.)= [expr
$HspCol2]";
puts " Distance of Coupler from Beam-Column Interface in Top COULMNs (in.)= [expr
$HspCol3]";
puts "-------------------------------------------------------------------";

# define NODAL COORDINATES

# Story 1 to 3
set Dlevel 10000;       # numbering increment for new-level nodes (y axis)
set Dframe 100;         # numbering increment for new-frame nodes (z axis)
set Dpier 10;   # numbering increment for new-pier nodes (x axis)
for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
        set Z [expr ($frame-1)*$LGird];
        for {set level 1} {$level <=[expr 3+1]} {incr level 1} {
                set Y [expr ($level-1)*$LCol];
```

```
                for {set pier 1} {$pier <= [expr $NBay+1]} {incr pier 1} {
                        set X [expr ($pier-1)*$LBeam];
                        set nodeID [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier];
                        node $nodeID $X $Y $Z;                  # actually define node
#puts "Nodes at Beam-Column Joints = $nodeID";
set A [expr $X + $HCol1/2];                                     # For Beams
set B [expr $A + $HspBeam];                                     # For Beams
set C [expr $B + $LspBeam];                                     # For Beams
set F [expr $X + $LBeam - $HCol1/2];                    # For Beams
set E [expr $F - $HspBeam];                                     # For Beams
set D [expr $E - $LspBeam];                                     # For Beams

set nodeID1 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+1];
                        node $nodeID1 $A $Y $Z;                 # actually define node
        #puts " Node 1 (beam) = $nodeID1";
set nodeID2 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+2];
                        node $nodeID2 $B $Y $Z;                 # actually define node
        #puts " Node 2 (beam) = $nodeID2";
set nodeID3 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+3];
                        node $nodeID3 $C $Y $Z;                 # actually define node
        #puts " Node 3 (beam) = $nodeID3";
set nodeID4 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+4];
                        node $nodeID4 $D $Y $Z;                 # actually define node
        #puts " Node 4 (beam) = $nodeID4";
set nodeID5 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+5];
                        node $nodeID5 $E $Y $Z;                 # actually define node
        #puts " Node 5 (beam) = $nodeID5";
set nodeID6 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+6];
                        node $nodeID6 $F $Y $Z;                 # actually define node
        #puts " Node 6 (beam) = $nodeID6";

set A [expr $Y+ $HBeam/2];                                      # For Columns
set B [expr $A + $HspCol1];                                     # For Columns
set C [expr $B + $LspCol];                                      # For Columns
set F [expr $Y + $LCol - $HBeam/2];                             # For Columns
set E [expr $F - $HspCol1];                                     # For Columns
set D [expr $E - $LspCol];                                      # For Columns

set nodeID1 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+1000];
                        node $nodeID1 $X $A $Z;                 # actually define node
        #puts " Node 1 (column) = $nodeID1";
set nodeID2 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+2000];
                        node $nodeID2 $X $B $Z;                 # actually define node
        #puts " Node 2 (column) = $nodeID2";
set nodeID3 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+3000];
                        node $nodeID3 $X $C $Z;                 # actually define node
        #puts " Node 3 (column) = $nodeID3";
set nodeID4 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+4000];
                        node $nodeID4 $X $D $Z;                 # actually define node
        #puts " Node 4 (column) = $nodeID4";
set nodeID5 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+5000];
                        node $nodeID5 $X $E $Z;                 # actually define node
        #puts " Node 5 (column) = $nodeID5";
set nodeID6 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+6000];
                        node $nodeID6 $X $F $Z;                 # actually define node
        #puts " Node 6 (column) = $nodeID6";
                }
        }
}

# Removing unnecesary nodes created at the bottom most layers
for {set pier 1} {$pier <=[expr $NBay+1]} {incr pier 1} {
set level 1;
        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+1];
        remove node $nodeID;                    #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+2];
        remove node $nodeID;                    #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+3];
        remove node $nodeID;                    #puts "$nodeID";
```

```
        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+4];
        remove node $nodeID;                  #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+5];
        remove node $nodeID;                  #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+6];
        remove node $nodeID;                  #puts "$nodeID";
}

# Removing unnecesary nodes created at the right most side
for {set level 2} {$level <=[expr 3+1]} {incr level 1} {
        set pier [expr $NBay+1];

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+1];
        remove node $nodeID;          #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+2];
        remove node $nodeID;          #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+3];
        remove node $nodeID;          #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+4];
        remove node $nodeID;          #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+5];
        remove node $nodeID;          #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+6];
        remove node $nodeID;          #puts "$nodeID";
}

# Story 4 to 6
set Dlevel 10000;      # numbering increment for new-level nodes
set Dframe 100;        # numbering increment for new-frame nodes
set Dpier 10;   # numbering increment for new-pier nodes
for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
        set Z [expr ($frame-1)*$LGird];
        for {set level 5} {$level <=[expr 6+1]} {incr level 1} {
                set Y [expr ($level-1)*$LCol];
                for {set pier 1} {$pier <= [expr $NBay+1]} {incr pier 1} {
                        set X [expr ($pier-1)*$LBeam];
                        set nodeID [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier];
                        node $nodeID $X $Y $Z;                # actually define node
#puts "Nodes at Beam-Column Joints = $nodeID";
set A [expr $X + $HCol2/2];                                   # For Beams
set B [expr $A + $HspBeam];                                   # For Beams
set C [expr $B + $LspBeam];                                   # For Beams
set F [expr $X + $LBeam - $HCol2/2];                  # For Beams
set E [expr $F - $HspBeam];                                   # For Beams
set D [expr $E - $LspBeam];                                   # For Beams

set nodeID1 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+1];
                        node $nodeID1 $A $Y $Z;               # actually define node
        #puts " Node 1 (beam) = $nodeID1";
set nodeID2 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+2];
                        node $nodeID2 $B $Y $Z;               # actually define node
        #puts " Node 2 (beam) = $nodeID2";
set nodeID3 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+3];
                        node $nodeID3 $C $Y $Z;               # actually define node
        #puts " Node 3 (beam) = $nodeID3";
set nodeID4 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+4];
                        node $nodeID4 $D $Y $Z;               # actually define node
        #puts " Node 4 (beam) = $nodeID4";
set nodeID5 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+5];
                        node $nodeID5 $E $Y $Z;               # actually define node
        #puts " Node 5 (beam) = $nodeID5";
set nodeID6 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+6];
```

```
                        node $nodeID6 $F $Y $Z;                 # actually define node
                #puts " Node 6 (beam) = $nodeID6";

set A [expr $Y+ $HBeam/2];                                      # For Columns
set B [expr $A + $HspCol2];                                     # For Columns
set C [expr $B + $LspCol];                                      # For Columns
set F [expr $Y + $LCol - $HBeam/2];                             # For Columns
set E [expr $F - $HspCol2];                                     # For Columns
set D [expr $E - $LspCol];                                      # For Columns

set nodeID1 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+1000];
                        node $nodeID1 $X $A $Z;                 # actually define node
                #puts " Node 1 (column) = $nodeID1";
set nodeID2 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+2000];
                        node $nodeID2 $X $B $Z;                 # actually define node
                #puts " Node 2 (column) = $nodeID2";
set nodeID3 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+3000];
                        node $nodeID3 $X $C $Z;                 # actually define node
                #puts " Node 3 (column) = $nodeID3";
set nodeID4 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+4000];
                        node $nodeID4 $X $D $Z;                 # actually define node
                #puts " Node 4 (column) = $nodeID4";
set nodeID5 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+5000];
                        node $nodeID5 $X $E $Z;                 # actually define node
                #puts " Node 5 (column) = $nodeID5";
set nodeID6 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+6000];
                        node $nodeID6 $X $F $Z;                 # actually define node
                #puts " Node 6 (column) = $nodeID6";
                        }
                }
}

# Removing unnecesary nodes created at the right most side
for {set level 5} {$level <=[expr 6+1]} {incr level 1} {
        set pier [expr $NBay+1];

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+1];
        remove node $nodeID;            #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+2];
        remove node $nodeID;            #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+3];
        remove node $nodeID;            #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+4];
        remove node $nodeID;            #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+5];
        remove node $nodeID;            #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+6];
        remove node $nodeID;            #puts "$nodeID";
}

# Story 7 to 9
set Dlevel 10000;       # numbering increment for new-level nodes
set Dframe 100;         # numbering increment for new-frame nodes
set Dpier 10;   # numbering increment for new-pier nodes
for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
        set Z [expr ($frame-1)*$LGird];
        for {set level 8} {$level <=[expr $NStory+1]} {incr level 1} {
                set Y [expr ($level-1)*$LCol];
                for {set pier 1} {$pier <= [expr $NBay+1]} {incr pier 1} {
                        set X [expr ($pier-1)*$LBeam];
                        set nodeID [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier];
                        node $nodeID $X $Y $Z;                  # actually define node
#puts "Nodes at Beam-Column Joints = $nodeID";
set A [expr $X + $HCol3/2];                                     # For Beams
set B [expr $A + $HspBeam];                                     # For Beams
set C [expr $B + $LspBeam];                                     # For Beams
```

```
set F [expr $X + $LBeam - $HCol3/2];                # For Beams
set E [expr $F - $HspBeam];                                 # For Beams
set D [expr $E - $LspBeam];                                 # For Beams

set nodeID1 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+1];
                      node $nodeID1 $A $Y $Z;               # actually define node
       #puts " Node 1 (beam) = $nodeID1";
set nodeID2 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+2];
                      node $nodeID2 $B $Y $Z;               # actually define node
       #puts " Node 2 (beam) = $nodeID2";
set nodeID3 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+3];
                      node $nodeID3 $C $Y $Z;               # actually define node
       #puts " Node 3 (beam) = $nodeID3";
set nodeID4 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+4];
                      node $nodeID4 $D $Y $Z;               # actually define node
       #puts " Node 4 (beam) = $nodeID4";
set nodeID5 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+5];
                      node $nodeID5 $E $Y $Z;               # actually define node
       #puts " Node 5 (beam) = $nodeID5";
set nodeID6 [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier+6];
                      node $nodeID6 $F $Y $Z;               # actually define node
       #puts " Node 6 (beam) = $nodeID6";

set A [expr $Y+ $HBeam/2];                                  # For Columns
set B [expr $A + $HspCol3];                                 # For Columns
set C [expr $B + $LspCol];                                  # For Columns
set F [expr $Y + $LCol - $HBeam/2];                         # For Columns
set E [expr $F - $HspCol3];                                 # For Columns
set D [expr $E - $LspCol];                                  # For Columns

set nodeID1 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+1000];
                      node $nodeID1 $X $A $Z;               # actually define node
       #puts " Node 1 (column) = $nodeID1";
set nodeID2 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+2000];
                      node $nodeID2 $X $B $Z;               # actually define node
       #puts " Node 2 (column) = $nodeID2";
set nodeID3 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+3000];
                      node $nodeID3 $X $C $Z;               # actually define node
       #puts " Node 3 (column) = $nodeID3";
set nodeID4 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+4000];
                      node $nodeID4 $X $D $Z;               # actually define node
       #puts " Node 4 (column) = $nodeID4";
set nodeID5 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+5000];
                      node $nodeID5 $X $E $Z;               # actually define node
       #puts " Node 5 (column) = $nodeID5";
set nodeID6 [expr $level*$Dlevel+$Dframe+$pier*$Dpier+6000];
                      node $nodeID6 $X $F $Z;               # actually define node
       #puts " Node 6 (column) = $nodeID6";
               }
       }
}

# Removing unnecesary nodes created at the right most side
for {set level 8} {$level <=[expr $NStory+1]} {incr level 1} {
       set pier [expr $NBay+1];

       set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+1];
       remove node $nodeID;          #puts "$nodeID";

       set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+2];
       remove node $nodeID;          #puts "$nodeID";

       set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+3];
       remove node $nodeID;          #puts "$nodeID";

       set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+4];
       remove node $nodeID;          #puts "$nodeID";

       set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+5];
       remove node $nodeID;          #puts "$nodeID";
```

```
        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+6];
        remove node $nodeID;          #puts "$nodeID";
}


# Removing unnecesary nodes created at the top most layers
for {set pier 1} {$pier <=[expr $NBay+1]} {incr pier 1} {
set level [expr $NStory+1];

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+1000];
        remove node $nodeID;          #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+2000];
        remove node $nodeID;          #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+3000];
        remove node $nodeID;          #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+4000];
        remove node $nodeID;          #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+5000];
        remove node $nodeID;          #puts "$nodeID";

        set nodeID [expr $level*$Dlevel+$Dframe+$pier*$Dpier+6000];
        remove node $nodeID;          #puts "$nodeID";
}

# Print out the state of nodes
#print -node;

# determine support nodes
set iSupportNode "";
for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
        set level 1;
        for {set pier 1} {$pier <= [expr $NBay+1]} {incr pier 1} {
                set nodeID [expr $level*$Dlevel+$frame*$Dframe+$pier*$Dpier];
                lappend iSupportNode $nodeID;
        }
}
puts "support nodes are = $iSupportNode";

# BOUNDARY CONDITIONS
#fixY 0.0  1 1 1 1 1 1;              # pin all Y=0.0 nodes
fix 10110 1 1 1 1 1 1;
fix 10120 1 1 1 1 1 1;
fix 10130 1 1 1 1 1 1;
fix 10140 1 1 1 1 1 1;
fix 10150 1 1 1 1 1 1;

# Define SECTIONS -------------------------------------------------------------

# define section tags:
set ColSecTag 1;
set BeamSecTag 2;
set ColSecTagAgg 3;
set BeamSecTagAgg 4;
set BeamSecTagAggStory1 5;
set BeamSecTagAggStory2 6;
set BeamSecTagAggStory3 7;

set ColSecTagFiber 100;

set ColSecTagFiberCorner1 111;
set ColSecTagFiberCoupler1 112;
set ColSecTagFiberMiddle1  113;

set ColSecTagFiberCorner2 121;
set ColSecTagFiberCoupler2 122;
set ColSecTagFiberMiddle2  123;
```

```
set ColSecTagFiberCorner3 131;
set ColSecTagFiberCoupler3 132;
set ColSecTagFiberMiddle3  133;

set BeamSecTagFiber 10;

set BeamSecTagFiberStory1Corner 11;
set BeamSecTagFiberStory1Coupler 12;
set BeamSecTagFiberStory1Middle 13;

set BeamSecTagFiberStory2Corner 21;
set BeamSecTagFiberStory2Coupler 22;
set BeamSecTagFiberStory2Middle 23;

set BeamSecTagFiberStory3Corner 31;
set BeamSecTagFiberStory3Coupler 32;
set BeamSecTagFiberStory3Middle 33;

set BeamSecTagFiberStory4Corner 41;
set BeamSecTagFiberStory4Coupler 42;
set BeamSecTagFiberStory4Middle 43;

set BeamSecTagFiberStory5Corner 51;
set BeamSecTagFiberStory5Coupler 52;
set BeamSecTagFiberStory5Middle 53;

set BeamSecTagFiberStory6Corner 61;
set BeamSecTagFiberStory6Coupler 62;
set BeamSecTagFiberStory6Middle 63;

set BeamSecTagFiberStory7Corner 71;
set BeamSecTagFiberStory7Coupler 72;
set BeamSecTagFiberStory7Middle 73;

set BeamSecTagFiberStory8Corner 81;
set BeamSecTagFiberStory8Coupler 82;
set BeamSecTagFiberStory8Middle 83;

set BeamSecTagFiberStory9Corner 91;
set BeamSecTagFiberStory9Coupler 92;
set BeamSecTagFiberStory9Middle 93;

        source LibMaterialsRC.tcl;                      # define library of
Reinforced-concrete Materials
# column section properties:
        set ACol1 [expr $HCol1*$BCol1];
        set ACol2 [expr $HCol2*$BCol2];
        set ACol3 [expr $HCol3*$BCol3];

#       set IzCol [expr 1./12*$BCol*pow($HCol,3)];   # about-local-z Rect-Column gross
moment of inertia
        set IzCol $Ubig;                                              # about-local-z Rect-
Column gross moment of inertia
#       set IyCol [expr 1./12*$HCol*pow($BCol,3)];   # about-local-z Rect-Column gross
moment of inertia
        set IyCol $Ubig;                                              # about-local-z Rect-
Column gross moment of inertia
#       set JCol [expr $IzCol+$IyCol];
        set JCol $Ubig;

# beam sections:
        set ABeam1 [expr $HBeam*$BBeam1];
        set ABeam2 [expr $HBeam*$BBeam2];
        set ABeam3 [expr $HBeam*$BBeam3];

#       set IzBeam [expr 1./12*$BBeam*pow($HBeam,3)];       # about-local-z Rect-Beam
cracked moment of inertia
        set IzBeam $Ubig;                                             # about-local-z Rect-
Beam cracked moment of inertia
#       set IyBeam [expr 1./12*$HBeam*pow($BBeam,3)];       # about-local-y Rect-Beam
cracked moment of inertia
```

```
        set IyBeam $Ubig;                                          # about-local-y Rect-
Beam cracked moment of inertia
#       set JBeam [expr $IzBeam+$IyBeam];
        set JBeam $Ubig;

#       section Elastic $ColSecTag $Ec $ACol $IzCol $IyCol $G $JCol;
#       section Elastic $BeamSecTag $Ec $ABeam $IzBeam $IyBeam $G $JBeam;

# FIBER SECTION properties
        # Column section geometry:
        set coverBeam [expr 3.*$in];                # rectangular-RC-Beam cover
        set coverCol [expr 2.8125*$in];             # rectangular-RC-Column cover
        set numBarsTopCol 5;                        # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotCol 5;                        # number of longitudinal-
reinforcement bars on bottom layer
        set numBarsIntCol 6;                        # TOTAL number of reinforcing bars on
the intermediate layers
        set barAreaTopCol [expr 0.6*$in*$in]; # longitudinal-reinforcement bar area
        set barAreaBotCol [expr 0.6*$in*$in]; # longitudinal-reinforcement bar area
        set barAreaIntCol [expr 0.6*$in*$in]; # longitudinal-reinforcement bar area

        set numBarsIntBeam 0;                       # TOTAL number of reinforcing bars on
the intermediate layers
        set barAreaTopBeam [expr 0.6*$in*$in];      # longitudinal-reinforcement bar area
        set barAreaBotBeam [expr 0.6*$in*$in];      # longitudinal-reinforcement bar area
        set barAreaIntBeam [expr 0.6*$in*$in];      # longitudinal-reinforcement bar area

        set numBarsTopBeamStory1Corner 7;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory1Corner 3;           # number of longitudinal-
reinforcement bars on bottom layer
        set numBarsTopBeamStory1Middle 3;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory1Middle 3;           # number of longitudinal-
reinforcement bars on bottom layer

        set numBarsTopBeamStory2Corner 7;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory2Corner 3;           # number of longitudinal-
reinforcement bars on bottom layer
        set numBarsTopBeamStory2Middle 3;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory2Middle 3;           # number of longitudinal-
reinforcement bars on bottom layer

        set numBarsTopBeamStory3Corner 6;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory3Corner 3;           # number of longitudinal-
reinforcement bars on bottom layer
        set numBarsTopBeamStory3Middle 3;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory3Middle 3;           # number of longitudinal-
reinforcement bars on bottom layer

        set numBarsTopBeamStory4Corner 6;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory4Corner 3;           # number of longitudinal-
reinforcement bars on bottom layer
        set numBarsTopBeamStory4Middle 3;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory4Middle 3;           # number of longitudinal-
reinforcement bars on bottom layer

        set numBarsTopBeamStory5Corner 5;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory5Corner 3;           # number of longitudinal-
reinforcement bars on bottom layer
        set numBarsTopBeamStory5Middle 3;           # number of longitudinal-
reinforcement bars on top layer
```

```
        set numBarsBotBeamStory5Middle 3;           # number of longitudinal-
reinforcement bars on bottom layer

        set numBarsTopBeamStory6Corner 5;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory6Corner 3;           # number of longitudinal-
reinforcement bars on bottom layer
        set numBarsTopBeamStory6Middle 3;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory6Middle 3;           # number of longitudinal-
reinforcement bars on bottom layer

        set numBarsTopBeamStory7Corner 4;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory7Corner 3;           # number of longitudinal-
reinforcement bars on bottom layer
        set numBarsTopBeamStory7Middle 2;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory7Middle 3;           # number of longitudinal-
reinforcement bars on bottom layer

        set numBarsTopBeamStory8Corner 4;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory8Corner 3;           # number of longitudinal-
reinforcement bars on bottom layer
        set numBarsTopBeamStory8Middle 2;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory8Middle 3;           # number of longitudinal-
reinforcement bars on bottom layer

        set numBarsTopBeamStory9Corner 3;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory9Corner 3;           # number of longitudinal-
reinforcement bars on bottom layer
        set numBarsTopBeamStory9Middle 2;           # number of longitudinal-
reinforcement bars on top layer
        set numBarsBotBeamStory9Middle 3;           # number of longitudinal-
reinforcement bars on bottom layer

        set nfCoreY 30;             # number of fibers in the core patch in the y
direction
        set nfCoreZ 30;             # number of fibers in the core patch in the z
direction
        set nfCoverY 10;            # number of fibers in the cover patches with long
sides in the y direction
        set nfCoverZ 10;            # number of fibers in the cover patches with long
sides in the z direction

        BuildRCrectSection $ColSecTagFiberCorner1 $HCol1 $BCol1 $coverCol $coverCol
$IDconcCoreColumnCorner1 $IDconcCover $IDPinching $numBarsTopCol $barAreaTopCol
$numBarsBotCol $barAreaBotCol $numBarsIntCol $barAreaIntCol  $nfCoreY $nfCoreZ $nfCoverY
$nfCoverZ;
        BuildRCrectSection $ColSecTagFiberCoupler1 $HCol1 $BCol1 $coverCol $coverCol
$IDconcCoreColumnCorner1 $IDconcCover $IDcouplerCol $numBarsTopCol $barAreaTopCol
$numBarsBotCol $barAreaBotCol $numBarsIntCol $barAreaIntCol  $nfCoreY $nfCoreZ $nfCoverY
$nfCoverZ;
        BuildRCrectSection $ColSecTagFiberMiddle1 $HCol1 $BCol1 $coverCol $coverCol
$IDconcCoreColumnMiddle1 $IDconcCover $IDPinching $numBarsTopCol $barAreaTopCol
$numBarsBotCol $barAreaBotCol $numBarsIntCol $barAreaIntCol  $nfCoreY $nfCoreZ $nfCoverY
$nfCoverZ;

        BuildRCrectSection $ColSecTagFiberCorner2 $HCol2 $BCol2 $coverCol $coverCol
$IDconcCoreColumnCorner1 $IDconcCover $IDPinching $numBarsTopCol $barAreaTopCol
$numBarsBotCol $barAreaBotCol $numBarsIntCol $barAreaIntCol  $nfCoreY $nfCoreZ $nfCoverY
$nfCoverZ;
        BuildRCrectSection $ColSecTagFiberCoupler2 $HCol2 $BCol2 $coverCol $coverCol
$IDconcCoreColumnCorner1 $IDconcCover $IDcouplerCol $numBarsTopCol $barAreaTopCol
$numBarsBotCol $barAreaBotCol $numBarsIntCol $barAreaIntCol  $nfCoreY $nfCoreZ $nfCoverY
$nfCoverZ;
        BuildRCrectSection $ColSecTagFiberMiddle2 $HCol2 $BCol2 $coverCol $coverCol
$IDconcCoreColumnMiddle1 $IDconcCover $IDPinching $numBarsTopCol $barAreaTopCol
```

```
$numBarsBotCol $barAreaBotCol $numBarsIntCol $barAreaIntCol  $nfCoreY $nfCoreZ $nfCoverY
$nfCoverZ;

       BuildRCrectSection $ColSecTagFiberCorner3 $HCol3 $BCol3 $coverCol $coverCol
$IDconcCoreColumnCorner2 $IDconcCover $IDPinching $numBarsTopCol $barAreaTopCol
$numBarsBotCol $barAreaBotCol $numBarsIntCol $barAreaIntCol  $nfCoreY $nfCoreZ $nfCoverY
$nfCoverZ;
       BuildRCrectSection $ColSecTagFiberCoupler3 $HCol3 $BCol3 $coverCol $coverCol
$IDconcCoreColumnCorner2 $IDconcCover $IDcouplerCol $numBarsTopCol $barAreaTopCol
$numBarsBotCol $barAreaBotCol $numBarsIntCol $barAreaIntCol  $nfCoreY $nfCoreZ $nfCoverY
$nfCoverZ;
       BuildRCrectSection $ColSecTagFiberMiddle3 $HCol3 $BCol3 $coverCol $coverCol
$IDconcCoreColumnCorner2 $IDconcCover $IDPinching $numBarsTopCol $barAreaTopCol
$numBarsBotCol $barAreaBotCol $numBarsIntCol $barAreaIntCol  $nfCoreY $nfCoreZ $nfCoverY
$nfCoverZ;


       BuildRCrectSection $BeamSecTagFiberStory1Corner $HBeam $BBeam1 $coverBeam
$coverBeam $IDconcCoreBeamCorner1 $IDconcCover $IDPinching $numBarsTopBeamStory1Corner
$barAreaTopBeam $numBarsBotBeamStory1Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
       BuildRCrectSection $BeamSecTagFiberStory1Coupler $HBeam $BBeam1 $coverBeam
$coverBeam $IDconcCoreBeamCorner1 $IDconcCover $IDcouplerBeam $numBarsTopBeamStory1Corner
$barAreaTopBeam $numBarsBotBeamStory1Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
       BuildRCrectSection $BeamSecTagFiberStory1Middle $HBeam $BBeam1 $coverBeam
$coverBeam $IDconcCoreBeamMiddle1 $IDconcCover $IDPinching $numBarsTopBeamStory1Middle
$barAreaTopBeam $numBarsBotBeamStory1Middle $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;

       BuildRCrectSection $BeamSecTagFiberStory2Corner $HBeam $BBeam1 $coverBeam
$coverBeam $IDconcCoreBeamCorner1 $IDconcCover $IDPinching $numBarsTopBeamStory2Corner
$barAreaTopBeam $numBarsBotBeamStory2Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
       BuildRCrectSection $BeamSecTagFiberStory2Coupler $HBeam $BBeam1 $coverBeam
$coverBeam $IDconcCoreBeamCorner1 $IDconcCover $IDcouplerBeam $numBarsTopBeamStory2Corner
$barAreaTopBeam $numBarsBotBeamStory2Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
       BuildRCrectSection $BeamSecTagFiberStory2Middle $HBeam $BBeam1 $coverBeam
$coverBeam $IDconcCoreBeamMiddle1 $IDconcCover $IDPinching $numBarsTopBeamStory2Middle
$barAreaTopBeam $numBarsBotBeamStory2Middle $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;

       BuildRCrectSection $BeamSecTagFiberStory3Corner $HBeam $BBeam1 $coverBeam
$coverBeam $IDconcCoreBeamCorner1 $IDconcCover $IDPinching $numBarsTopBeamStory3Corner
$barAreaTopBeam $numBarsBotBeamStory3Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
       BuildRCrectSection $BeamSecTagFiberStory3Coupler $HBeam $BBeam1 $coverBeam
$coverBeam $IDconcCoreBeamCorner1 $IDconcCover $IDcouplerBeam $numBarsTopBeamStory3Corner
$barAreaTopBeam $numBarsBotBeamStory3Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
       BuildRCrectSection $BeamSecTagFiberStory3Middle $HBeam $BBeam1 $coverBeam
$coverBeam $IDconcCoreBeamMiddle1 $IDconcCover $IDPinching $numBarsTopBeamStory3Middle
$barAreaTopBeam $numBarsBotBeamStory3Middle $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;

       BuildRCrectSection $BeamSecTagFiberStory4Corner $HBeam $BBeam2 $coverBeam
$coverBeam $IDconcCoreBeamCorner1 $IDconcCover $IDPinching $numBarsTopBeamStory4Corner
$barAreaTopBeam $numBarsBotBeamStory4Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
       BuildRCrectSection $BeamSecTagFiberStory4Coupler $HBeam $BBeam2 $coverBeam
$coverBeam $IDconcCoreBeamCorner1 $IDconcCover $IDcouplerBeam $numBarsTopBeamStory4Corner
$barAreaTopBeam $numBarsBotBeamStory4Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
       BuildRCrectSection $BeamSecTagFiberStory4Middle $HBeam $BBeam2 $coverBeam
$coverBeam $IDconcCoreBeamMiddle1 $IDconcCover $IDPinching $numBarsTopBeamStory4Middle
$barAreaTopBeam $numBarsBotBeamStory4Middle $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;

       BuildRCrectSection $BeamSecTagFiberStory5Corner $HBeam $BBeam2 $coverBeam
$coverBeam $IDconcCoreBeamCorner1 $IDconcCover $IDPinching $numBarsTopBeamStory5Corner
```

```
$barAreaTopBeam $numBarsBotBeamStory5Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
	BuildRCrectSection $BeamSecTagFiberStory5Coupler $HBeam $BBeam2 $coverBeam
$coverBeam $IDconcCoreBeamCorner1 $IDconcCover $IDcouplerBeam $numBarsTopBeamStory5Corner
$barAreaTopBeam $numBarsBotBeamStory5Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
	BuildRCrectSection $BeamSecTagFiberStory5Middle $HBeam $BBeam2 $coverBeam
$coverBeam $IDconcCoreBeamMiddle1 $IDconcCover $IDPinching $numBarsTopBeamStory5Middle
$barAreaTopBeam $numBarsBotBeamStory5Middle $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;

	BuildRCrectSection $BeamSecTagFiberStory6Corner $HBeam $BBeam2 $coverBeam
$coverBeam $IDconcCoreBeamCorner1 $IDconcCover $IDPinching $numBarsTopBeamStory6Corner
$barAreaTopBeam $numBarsBotBeamStory6Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
	BuildRCrectSection $BeamSecTagFiberStory6Coupler $HBeam $BBeam2 $coverBeam
$coverBeam $IDconcCoreBeamCorner1 $IDconcCover $IDcouplerBeam $numBarsTopBeamStory6Corner
$barAreaTopBeam $numBarsBotBeamStory6Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
	BuildRCrectSection $BeamSecTagFiberStory6Middle $HBeam $BBeam2 $coverBeam
$coverBeam $IDconcCoreBeamMiddle1 $IDconcCover $IDPinching $numBarsTopBeamStory6Middle
$barAreaTopBeam $numBarsBotBeamStory6Middle $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;

	BuildRCrectSection $BeamSecTagFiberStory7Corner $HBeam $BBeam3 $coverBeam
$coverBeam $IDconcCoreBeamCorner2 $IDconcCover $IDPinching $numBarsTopBeamStory7Corner
$barAreaTopBeam $numBarsBotBeamStory7Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
	BuildRCrectSection $BeamSecTagFiberStory7Coupler $HBeam $BBeam3 $coverBeam
$coverBeam $IDconcCoreBeamCorner2 $IDconcCover $IDcouplerBeam $numBarsTopBeamStory7Corner
$barAreaTopBeam $numBarsBotBeamStory7Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
	BuildRCrectSection $BeamSecTagFiberStory7Middle $HBeam $BBeam3 $coverBeam
$coverBeam $IDconcCoreBeamMiddle2 $IDconcCover $IDPinching $numBarsTopBeamStory7Middle
$barAreaTopBeam $numBarsBotBeamStory7Middle $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;

	BuildRCrectSection $BeamSecTagFiberStory8Corner $HBeam $BBeam3 $coverBeam
$coverBeam $IDconcCoreBeamCorner2 $IDconcCover $IDPinching $numBarsTopBeamStory8Corner
$barAreaTopBeam $numBarsBotBeamStory8Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
	BuildRCrectSection $BeamSecTagFiberStory8Coupler $HBeam $BBeam3 $coverBeam
$coverBeam $IDconcCoreBeamCorner2 $IDconcCover $IDcouplerBeam $numBarsTopBeamStory8Corner
$barAreaTopBeam $numBarsBotBeamStory8Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
	BuildRCrectSection $BeamSecTagFiberStory8Middle $HBeam $BBeam3 $coverBeam
$coverBeam $IDconcCoreBeamMiddle2 $IDconcCover $IDPinching $numBarsTopBeamStory8Middle
$barAreaTopBeam $numBarsBotBeamStory8Middle $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;

	BuildRCrectSection $BeamSecTagFiberStory9Corner $HBeam $BBeam3 $coverBeam
$coverBeam $IDconcCoreBeamCorner2 $IDconcCover $IDPinching $numBarsTopBeamStory9Corner
$barAreaTopBeam $numBarsBotBeamStory9Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
	BuildRCrectSection $BeamSecTagFiberStory9Coupler $HBeam $BBeam3 $coverBeam
$coverBeam $IDconcCoreBeamCorner2 $IDconcCover $IDcouplerBeam $numBarsTopBeamStory9Corner
$barAreaTopBeam $numBarsBotBeamStory9Corner $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;
	BuildRCrectSection $BeamSecTagFiberStory9Middle $HBeam $BBeam3 $coverBeam
$coverBeam $IDconcCoreBeamMiddle2 $IDconcCover $IDPinching $numBarsTopBeamStory9Middle
$barAreaTopBeam $numBarsBotBeamStory9Middle $barAreaBotBeam $numBarsIntBeam
$barAreaIntBeam  $nfCoreY $nfCoreZ $nfCoverY $nfCoverZ;

# ------------------------------------------------------------------------------------------
-----------------------------------------
# set up geometric transformations of element
# separate columns and beams, in case of P-Delta analysis for columns
set IDColTransf 1;                                     # all columns
set IDBeamTransf 2;                                    # all beams
set ColTransfType PDelta  ;                            # options for columns: Linear PDelta
Corotational
```

```
geomTransf $ColTransfType  $IDColTransf  0 0 1;      # orientation of column stiffness
affects bidirectional response.
geomTransf Linear $IDBeamTransf 0 0 1;

# Define Beam-Column Elements
set numIntgrPts 5;     # number of Gauss integration points for nonlinear curvature
distribution
set numIntgrPtsHsp 2;  # number of Gauss integration points for nonlinear curvature
distribution
set numIntgrPtsLsp 5;  # number of Gauss integration points for nonlinear curvature
distribution

set i 1;
set j 1;

# COLUMNS

# Story 1 to 6 [Columns]

set Locations "0.0 0.25 0.5 0.75 1.0";
set SectagCol "$ColSecTagFiberCorner1 $ColSecTagFiberCorner1 $ColSecTagFiberMiddle1
$ColSecTagFiberCorner1 $ColSecTagFiberCorner1";

set level 0;
for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
        for {set level 1} {$level <=6} {incr level 1} {
                for {set pier 1} {$pier <= [expr $NBay+1]} {incr pier 1} {

                        set elemID [expr $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+1000];
                        set nodeI [expr  $level*$Dlevel + $frame*$Dframe+$pier*$Dpier];
                        set nodeJ  [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+1000];
                        element elasticBeamColumn $elemID $nodeI $nodeJ $ACol1 $Ecc $G
$JCol $IyCol $IzCol $IDColTransf;                    # columns

                        set elemID [expr $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+2000];
                        set nodeI [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+1000];
                        set nodeJ  [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+2000];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsHsp
$ColSecTagFiberCorner1 $IDColTransf;                # columns

                        set elemID [expr $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+3000];
                        set nodeI [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+2000];
                        set nodeJ  [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+3000];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsLsp
$ColSecTagFiberCoupler1 $IDColTransf;               # columns

                        set elemID [expr $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+4000];
                        set nodeI [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+3000];
                        set nodeJ  [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+4000];
                        element forceBeamColumn $elemID $nodeI $nodeJ $IDColTransf
FixedLocation $numIntgrPts $SectagCol $Locations;    # columns

                        set elemID [expr $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+5000];
                        set nodeI [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+4000];
                        set nodeJ  [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+5000];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsLsp
$ColSecTagFiberCoupler1 $IDColTransf;               # columns
```

```
                        set elemID [expr $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+6000];
                        set nodeI [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+5000];
                        set nodeJ  [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+6000];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsHsp
$ColSecTagFiberCorner1 $IDColTransf;                # columns

                        set elemID [expr $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+7000];
                        set nodeI [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+6000];
                        set nodeJ  [expr  ($level+1)*$Dlevel +
$frame*$Dframe+$pier*$Dpier];
                        element elasticBeamColumn $elemID $nodeI $nodeJ $ACol1 $Ecc $G
$JCol $IyCol $IzCol $IDColTransf;                   # columns
                }
        }
}

# Story 7 to 9 [Columns]

for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
        for {set level 7} {$level <=$NStory} {incr level 1} {
                for {set pier 1} {$pier <= [expr $NBay+1]} {incr pier 1} {

                        set elemID [expr $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+1000];
                        set nodeI [expr  $level*$Dlevel + $frame*$Dframe+$pier*$Dpier];
                        set nodeJ  [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+1000];
                        element elasticBeamColumn $elemID $nodeI $nodeJ $ACol3 $Ecc $G
$JCol $IyCol $IzCol $IDColTransf;                   # columns

                        set elemID [expr $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+2000];
                        set nodeI [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+1000];
                        set nodeJ  [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+2000];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsHsp
$ColSecTagFiberCorner3 $IDColTransf;                # columns

                        set elemID [expr $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+3000];
                        set nodeI [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+2000];
                        set nodeJ  [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+3000];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsLsp
$ColSecTagFiberCoupler3 $IDColTransf;               # columns

                        set elemID [expr $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+4000];
                        set nodeI [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+3000];
                        set nodeJ  [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+4000];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPts
$ColSecTagFiberMiddle3 $IDColTransf;                        # columns

                        set elemID [expr $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+5000];
                        set nodeI [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+4000];
                        set nodeJ  [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+5000];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsLsp
$ColSecTagFiberCoupler3 $IDColTransf;               # columns
```

```
                        set elemID [expr $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+6000];
                        set nodeI [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+5000];
                        set nodeJ  [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+6000];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsHsp
$ColSecTagFiberCorner3 $IDColTransf;              # columns

                        set elemID [expr $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+7000];
                        set nodeI [expr  $level*$Dlevel +
$frame*$Dframe+$pier*$Dpier+6000];
                        set nodeJ  [expr  ($level+1)*$Dlevel +
$frame*$Dframe+$pier*$Dpier];
                        element elasticBeamColumn $elemID $nodeI $nodeJ $ACol3 $Ecc $G
$JCol $IyCol $IzCol $IDColTransf;                 # columns
                }
        }
}

# beams -- parallel to X-axis
# Story 1 to 2 (Beam)
set SectagBeam12 "$BeamSecTagFiberStory1Corner $BeamSecTagFiberStory1Corner
$BeamSecTagFiberStory1Middle $BeamSecTagFiberStory1Corner $BeamSecTagFiberStory1Corner ";

for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
        for {set level 2} {$level <=[expr 2 + 1]} {incr level 1} {
                for {set pier 1} {$pier <= [expr $NBay]} {incr pier 1} {

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+1];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+1];
                        element elasticBeamColumn $elemID $nodeI $nodeJ $ABeam1 $Ecc $G
$JBeam $IyBeam $IzBeam $IDBeamTransf;             # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+2];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+1];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+2];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsHsp
$BeamSecTagFiberStory1Corner $IDBeamTransf;       # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+3];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+2];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+3];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsLsp
$BeamSecTagFiberStory1Coupler $IDBeamTransf;      # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+4];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+3];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+4];
                        element forceBeamColumn $elemID $nodeI $nodeJ $IDBeamTransf
FixedLocation $numIntgrPts $SectagBeam12 $Locations; # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+5];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+4];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+5];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsLsp
$BeamSecTagFiberStory1Coupler $IDBeamTransf;      # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+6];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+5];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+6];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsHsp
$BeamSecTagFiberStory1Corner $IDBeamTransf;       # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+7];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+6];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+
($pier+1)*$Dpier];
```

```
                      element elasticBeamColumn $elemID $nodeI $nodeJ $ABeam1 $Ecc $G
$JBeam $IyBeam $IzBeam $IDBeamTransf;                # beams
               }
        }
}

# Story 3 to 4 (Beam)
set SectagBeam34 "$BeamSecTagFiberStory3Corner $BeamSecTagFiberStory3Corner
$BeamSecTagFiberStory3Middle $BeamSecTagFiberStory3Corner $BeamSecTagFiberStory3Corner ";

for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
        for {set level 4} {$level <=[expr 4 + 1]} {incr level 1} {
               for {set pier 1} {$pier <= [expr $NBay]} {incr pier 1} {

                      set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+1];
                      set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier];
                      set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+1];
                      element elasticBeamColumn $elemID $nodeI $nodeJ $ABeam1 $Ecc $G
$JBeam $IyBeam $IzBeam $IDBeamTransf;                # beams

                      set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+2];
                      set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+1];
                      set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+2];
                      element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsHsp
$BeamSecTagFiberStory3Corner $IDBeamTransf;          # beams

                      set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+3];
                      set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+2];
                      set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+3];
                      element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsLsp
$BeamSecTagFiberStory3Coupler $IDBeamTransf;         # beams

                      set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+4];
                      set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+3];
                      set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+4];
                      element forceBeamColumn $elemID $nodeI $nodeJ $IDBeamTransf
FixedLocation $numIntgrPts $SectagBeam34 $Locations; # beams

                      set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+5];
                      set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+4];
                      set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+5];
                      element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsLsp
$BeamSecTagFiberStory3Coupler $IDBeamTransf;         # beams

                      set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+6];
                      set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+5];
                      set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+6];
                      element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsHsp
$BeamSecTagFiberStory3Corner $IDBeamTransf;          # beams

                      set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+7];
                      set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+6];
                      set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+
($pier+1)*$Dpier];
                      element elasticBeamColumn $elemID $nodeI $nodeJ $ABeam1 $Ecc $G
$JBeam $IyBeam $IzBeam $IDBeamTransf;                # beams
               }
        }
}

# Story 5 to 6 (Beam)
set SectagBeam56 "$BeamSecTagFiberStory5Corner $BeamSecTagFiberStory5Corner
$BeamSecTagFiberStory5Middle $BeamSecTagFiberStory5Corner $BeamSecTagFiberStory5Corner ";

for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
        for {set level [expr 5+1]} {$level <=[expr 6+1]} {incr level 1} {
               for {set pier 1} {$pier <= [expr $NBay]} {incr pier 1} {

                      set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+1];
                      set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier];
                      set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+1];
```

```
                        element elasticBeamColumn $elemID $nodeI $nodeJ $ABeam2 $Ecc $G
$JBeam $IyBeam $IzBeam $IDBeamTransf;                # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+2];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+1];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+2];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsHsp
$BeamSecTagFiberStory5Corner $IDBeamTransf;          # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+3];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+2];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+3];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsLsp
$BeamSecTagFiberStory5Coupler $IDBeamTransf;         # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+4];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+3];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+4];
                        element forceBeamColumn $elemID $nodeI $nodeJ $IDBeamTransf
FixedLocation $numIntgrPts $SectagBeam56 $Locations; # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+5];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+4];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+5];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsLsp
$BeamSecTagFiberStory5Coupler $IDBeamTransf;         # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+6];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+5];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+6];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsHsp
$BeamSecTagFiberStory5Corner $IDBeamTransf;          # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+7];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+6];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+
($pier+1)*$Dpier];
                        element elasticBeamColumn $elemID $nodeI $nodeJ $ABeam2 $Ecc $G
$JBeam $IyBeam $IzBeam $IDBeamTransf;                # beams
                }
        }
}

# Story 7 to 8 (Beam)
set SectagBeam78 "$BeamSecTagFiberStory7Corner $BeamSecTagFiberStory7Corner
$BeamSecTagFiberStory7Middle $BeamSecTagFiberStory7Corner $BeamSecTagFiberStory7Corner";

for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
        for {set level [expr 7+1]} {$level <=[expr 8+1]} {incr level 1} {
                for {set pier 1} {$pier <= [expr $NBay]} {incr pier 1} {

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+1];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+1];
                        element elasticBeamColumn $elemID $nodeI $nodeJ $ABeam3 $Ecc $G
$JBeam $IyBeam $IzBeam $IDBeamTransf;                # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+2];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+1];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+2];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsHsp
$BeamSecTagFiberStory7Corner $IDBeamTransf;          # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+3];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+2];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+3];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsLsp
$BeamSecTagFiberStory7Coupler $IDBeamTransf;         # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+4];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+3];
```

```
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+4];
                        element forceBeamColumn $elemID $nodeI $nodeJ $IDBeamTransf
FixedLocation $numIntgrPts $SectagBeam78 $Locations; # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+5];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+4];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+5];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsLsp
$BeamSecTagFiberStory7Coupler $IDBeamTransf;         # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+6];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+5];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+6];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsHsp
$BeamSecTagFiberStory7Corner $IDBeamTransf;          # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+7];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+6];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+
($pier+1)*$Dpier];
                        element elasticBeamColumn $elemID $nodeI $nodeJ $ABeam3 $Ecc $G
$JBeam $IyBeam $IzBeam $IDBeamTransf;                # beams
                }
        }
}

# Story 9 (Beam)
set SectagBeam90 "$BeamSecTagFiberStory9Corner $BeamSecTagFiberStory9Corner
$BeamSecTagFiberStory9Middle $BeamSecTagFiberStory9Corner $BeamSecTagFiberStory9Corner ";

for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
        for {set level [expr $NStory+1]} {$level <=[expr $NStory+1]} {incr level 1} {
                for {set pier 1} {$pier <= [expr $NBay]} {incr pier 1} {

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+1];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+1];
                        element elasticBeamColumn $elemID $nodeI $nodeJ $ABeam3 $Ecc $G
$JBeam $IyBeam $IzBeam $IDBeamTransf;                # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+2];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+1];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+2];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsHsp
$BeamSecTagFiberStory9Corner $IDBeamTransf;          # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+3];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+2];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+3];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsLsp
$BeamSecTagFiberStory9Coupler $IDBeamTransf;         # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+4];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+3];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+4];
                        element forceBeamColumn $elemID $nodeI $nodeJ $IDBeamTransf
FixedLocation $numIntgrPts $SectagBeam90 $Locations; # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+5];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+4];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+5];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsLsp
$BeamSecTagFiberStory9Coupler $IDBeamTransf;         # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+6];
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+5];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+6];
                        element forceBeamColumn $elemID $nodeI $nodeJ $numIntgrPtsHsp
$BeamSecTagFiberStory9Corner $IDBeamTransf;          # beams

                        set elemID [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+7];
```

```
                        set nodeI [expr $level*$Dlevel + $frame*$Dframe+ $pier*$Dpier+6];
                        set nodeJ  [expr $level*$Dlevel + $frame*$Dframe+
($pier+1)*$Dpier];
                        element elasticBeamColumn $elemID $nodeI $nodeJ $ABeam3 $Ecc $G
$JBeam $IyBeam $IzBeam $IDBeamTransf;                # beams
                }
        }
}

#print -ele;

# ------------------------------------------------------------------------------------------
-----------------------------------------
# Define GRAVITY LOADS, weight and masses
# calculate dead load of frame, assume this to be an internal frame
# calculate distributed weight along the beam length
set GammaConcrete [expr 150.*$pcf];
set QdlCol1 [expr $GammaConcrete*$HCol1*$BCol1];     # self weight of Column, weight per
length
set QdlCol2 [expr $GammaConcrete*$HCol2*$BCol2];     # self weight of Column, weight per
length
set QdlCol3 [expr $GammaConcrete*$HCol3*$BCol3];     # self weight of Column, weight per
length
set QdlBeam1 [expr $GammaConcrete*$HBeam*$BBeam1];  # self weight of Beam, weight per
length
set QdlBeam2 [expr $GammaConcrete*$HBeam*$BBeam2];  # self weight of Beam, weight per
length
set QdlBeam3 [expr $GammaConcrete*$HBeam*$BBeam3];  # self weight of Beam, weight per
length

# ------------------------------------------------------------------------------------------
-----------------------------------------

# Set up MODEL PARAMETERS, for displacement control
#set IDctrlNode [expr int(($NStory+1)*$Dlevel+(1*$Dframe)+10)];     # node where
displacement is read for displacement control
set IDctrlNode 100110;                                                      # node where
displacement is read for displacement control
puts "_______________________________________
Node where displacement is read for displacement control = $IDctrlNode";

# LATERAL-LOAD distribution for static pushover analysis
# distribution of lateral load based on mass/weight distributions along building height
set IDctrlDOF 1;                                                                    #
degree of freedom of displacement read for displacement control
set iNodePush "$IDctrlNode";
puts "Nodes to be pushed = $iNodePush";

set iFPush 50.;                                                                     #
lateral load for pushover, vectorized
puts "iFPush = $iFPush";

# Define RECORDERS -------------------------------------------------------------
set FreeNodeID $IDctrlNode;
puts "Node to be recorded for displacement = $FreeNodeID";
recorder Node -file $dataDir/DFree.out -node $FreeNodeID  -dof 1 disp;     #
displacements of free node

recorder Node -file $dataDir/RBase1.out -node 10110 -dof 1 reaction;       # support
reaction
recorder Node -file $dataDir/RBase2.out -node 10120 -dof 1 reaction;       # support
reaction
recorder Node -file $dataDir/RBase3.out -node 10130 -dof 1 reaction;       # support
reaction
recorder Node -file $dataDir/RBase4.out -node 10140 -dof 1 reaction;       # support
reaction
recorder Node -file $dataDir/RBase5.out -node 10150 -dof 1 reaction;       # support
reaction

# Define DISPLAY -------------------------------------------------------------
```

```
DisplayModel3D DeformedShape;                                                  # options:
DeformedShape NodeNumbers ModeShape

# GRAVITY -------------------------------------------------------------
# define GRAVITY load applied to beams and columns -- eleLoad applies loads in local
coordinate axis
pattern Plain 101 Linear {
        for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
                for {set level 1} {$level <=3} {incr level 1} {
                        for {set pier 1} {$pier <= [expr $NBay+1]} {incr pier 1} {

                                set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+1000];
                                        eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol1;       # COLUMNS (Story 1 to 3)

                                set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+2000];
                                        eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol1;       # COLUMNS (Story 1 to 3)

                                set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+3000];
                                        eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol1;       # COLUMNS (Story 1 to 3)

                                set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+4000];
                                        eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol1;       # COLUMNS (Story 1 to 3)

                                set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+5000];
                                        eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol1;       # COLUMNS (Story 1 to 3)

                                set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+6000];
                                        eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol1;       # COLUMNS (Story 1 to 3)

                                set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+7000];
                                        eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol1;       # COLUMNS (Story 1 to 3)
                        }
                }
        }

for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
                for {set level 4} {$level <=6} {incr level 1} {
                        for {set pier 1} {$pier <= [expr $NBay+1]} {incr pier 1} {

                                set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+1000];
                                        eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol2;       # COLUMNS (Story 4 to 6)

                                set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+2000];
                                        eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol2;       # COLUMNS (Story 4 to 6)

                                set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+3000];
                                        eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol2;       # COLUMNS (Story 4 to 6)

                                set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+4000];
```

```
                              eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol2;      # COLUMNS (Story 4 to 6)

                          set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+5000];
                              eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol2;      # COLUMNS (Story 4 to 6)

                          set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+6000];
                              eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol2;      # COLUMNS (Story 4 to 6)

                          set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+7000];
                              eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol2;      # COLUMNS (Story 4 to 6)
                      }
                  }
          }

for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
                  for {set level 7} {$level <=$NStory} {incr level 1} {
                      for {set pier 1} {$pier <= [expr $NBay+1]} {incr pier 1} {

                          set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+1000];
                              eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol3;      # COLUMNS (Story 7 to 9)

                          set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+2000];
                              eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol3;      # COLUMNS (Story 7 to 9)

                          set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+3000];
                              eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol3;      # COLUMNS (Story 7 to 9)

                          set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+4000];
                              eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol3;      # COLUMNS (Story 7 to 9)

                          set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+5000];
                              eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol3;      # COLUMNS (Story 7 to 9)

                          set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+6000];
                              eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol3;      # COLUMNS (Story 7 to 9)

                          set elemID [expr $level*$Dlevel
+$frame*$Dframe+$pier*$Dpier+7000];
                              eleLoad -ele $elemID -type -beamUniform 0. 0. -
$QdlCol3;      # COLUMNS (Story 7 to 9)
                      }
                  }
          }

          for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
                  for {set level 2} {$level <=[expr 3+1]} {incr level 1} {
                      for {set pier 1} {$pier <= $NBay} {incr pier 1} {

                          set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+1];
                              eleLoad -ele $elemID  -type -beamUniform -$QdlBeam1
0.;     # BEAMS (Story 1 to 3)
```

```
                              set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+2];
                                      eleLoad -ele $elemID  -type -beamUniform -$QdlBeam1
0.;     # BEAMS (Story 1 to 3)

                              set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+3];
                                      eleLoad -ele $elemID  -type -beamUniform -$QdlBeam1
0.;     # BEAMS (Story 1 to 3)

                              set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+4];
                                      eleLoad -ele $elemID  -type -beamUniform -$QdlBeam1
0.;     # BEAMS (Story 1 to 3)

                              set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+5];
                                      eleLoad -ele $elemID  -type -beamUniform -$QdlBeam1
0.;     # BEAMS (Story 1 to 3)

                              set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+6];
                                      eleLoad -ele $elemID  -type -beamUniform -$QdlBeam1
0.;     # BEAMS (Story 1 to 3)

                              set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+7];
                                      eleLoad -ele $elemID  -type -beamUniform -$QdlBeam1
0.;     # BEAMS (Story 1 to 3)
                        }
                }
        }

        for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
                for {set level 5} {$level <=[expr 6+1]} {incr level 1} {
                        for {set pier 1} {$pier <= $NBay} {incr pier 1} {

                              set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+1];
                                      eleLoad -ele $elemID  -type -beamUniform -$QdlBeam2
0.;     # BEAMS (Story 4 to 6)

                              set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+2];
                                      eleLoad -ele $elemID  -type -beamUniform -$QdlBeam2
0.;     # BEAMS (Story 4 to 6)

                              set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+3];
                                      eleLoad -ele $elemID  -type -beamUniform -$QdlBeam2
0.;     # BEAMS (Story 4 to 6)

                              set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+4];
                                      eleLoad -ele $elemID  -type -beamUniform -$QdlBeam2
0.;     # BEAMS (Story 4 to 6)

                              set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+5];
                                      eleLoad -ele $elemID  -type -beamUniform -$QdlBeam2
0.;     # BEAMS (Story 4 to 6)

                              set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+6];
                                      eleLoad -ele $elemID  -type -beamUniform -$QdlBeam2
0.;     # BEAMS (Story 4 to 6)

                              set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+7];
```

```
                                    eleLoad -ele $elemID  -type -beamUniform -$QdlBeam2
0.;     # BEAMS (Story 4 to 6)
                        }
                }
        }

        for {set frame 1} {$frame <=[expr $NFrame]} {incr frame 1} {
                for {set level 8} {$level <=[expr $NStory+1]} {incr level 1} {
                        for {set pier 1} {$pier <= $NBay} {incr pier 1} {

                                set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+1];
                                    eleLoad -ele $elemID  -type -beamUniform -$QdlBeam3
0.;     # BEAMS (Story 7 to 9)

                                set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+2];
                                    eleLoad -ele $elemID  -type -beamUniform -$QdlBeam3
0.;     # BEAMS (Story 7 to 9)

                                set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+3];
                                    eleLoad -ele $elemID  -type -beamUniform -$QdlBeam3
0.;     # BEAMS (Story 7 to 9)

                                set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+4];
                                    eleLoad -ele $elemID  -type -beamUniform -$QdlBeam3
0.;     # BEAMS (Story 7 to 9)

                                set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+5];
                                    eleLoad -ele $elemID  -type -beamUniform -$QdlBeam3
0.;     # BEAMS (Story 7 to 9)

                                set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+6];
                                    eleLoad -ele $elemID  -type -beamUniform -$QdlBeam3
0.;     # BEAMS (Story 7 to 9)

                                set elemID [expr $level*$Dlevel +$frame*$Dframe+
$pier*$Dpier+7];
                                    eleLoad -ele $elemID  -type -beamUniform -$QdlBeam3
0.;     # BEAMS (Story 7 to 9)
                        }
                }
        }


}

puts goGravity;
# Gravity-analysis parameters -- load-controlled static analysis
set Tol 1.0e-2;                                    # convergence tolerance for test

variable constraintsTypeGravity Plain;      # default;
#variable constraintsTypeGravity Lagrange;# default;

constraints $constraintsTypeGravity ;      # how it handles boundary conditions
numberer RCM;                               # renumber dof's to minimize band-width
(optimization), if you want to
system BandGeneral ;                        # how to store and solve the system of
equations in the analysis (large model: try UmfPack)
test EnergyIncr $Tol 6 ;                    # determine if convergence has been achieved
at the end of an iteration step
algorithm Newton;                                  # use Newton's solution algorithm:
updates tangent stiffness at every iteration
set NstepGravity 10;                        # apply gravity in 10 steps
set DGravity [expr 1./$NstepGravity];       # first load increment;
integrator LoadControl $DGravity;           # determine the next time step for an
analysis
```

```
analysis Static;                                    # define type of analysis static or
transient
analyze $NstepGravity;                       # apply gravity

# ------------------------------------------------ maintain constant gravity loads and
reset time to zero
loadConst -time 0.0;

# ------------------------------------------------------------
puts "Model Built";
```