TORSIONAL CONTROL OF TWO ADJACENT OFFICE BUILDINGS USING VISCOUS DAMPERS

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Abstract

Two adjacent wings of a three-story office building in Southern California were found by analysis to be excessively responsive in torsion under an earthquake on the near-by Newport-Inglewood fault, some five miles from the site. The generous 4½" seismic separation between the two office building segments was found to be inadequate to prevent heavy pounding even in a moderate event, having a high probability of occurrence at this location.

A variety of structural retrofit schemes were evaluated to mitigate the excessive torsional responses of the two building segments. These included converting the perimeter gravity frames to moment resisting frames, adding diagonal bracing to the perimeter frames, tying the two structures together at each floor level, and using viscous dampers as attachments between the buildings. The best solution from a cost, schedule, construction disruption, and earthquake performance standpoint, turned out to be joining the two building segments with horizontally oriented viscous dampers at a single floor level.
This paper describes the analysis and retrofit solution that was used, and discusses the advantages and disadvantages of the retrofit options studied.

Introduction

Background. The seismic retrofit project presented in this paper was initiated as the result of the sale of the building. During the due diligence study for property transfer, seismic weaknesses were identified and the need for retrofit modification of the structure was quantified.

Building Description. The three story steel frame office building was configured as two rectangles to produce an 'L' shaped building plan as shown in Figure 1. The overall plan dimensions were 306' x 214' with a total enclosed floor area of 105,000 square feet.

The two rectangular wings were separated with a 4½ inch seismic separation joint. Lateral loads were resisted by the eccentric braced frame central cores. Vertical loads were carried by the typical steel gravity frames composed of simply supported beams and columns. The gravity frames were supported on reinforced concrete spread footings and the central core braced frames were supported on a massive four foot thick reinforced concrete mat foundation designed to resist seismic overturning and sliding.

The building was designed under the 1988 Uniform Building Code for seismic Zone 4 requirements and constructed in 1991 in Southern California. It is located near the seismically active Newport Inglewood fault. The seismic design included consideration of plan irregularity by separating the building into two regular rectangles. However, it failed to recognize the torsional irregularity introduced in each wing by the single central core composed of eccentric braced frames.

Structural Weakness. When torsional irregularity was reviewed under the 1988 UBC seismic design provisions, the lateral load resisting bracing system was found to be overstressed. Worse yet, lack of adequate torsional stiffness resulted in horizontal floor and roof deflections at the 4 ½ inch seismic separation joint (See Figure 1) under code design loads that exceeded the separation space by a factor of 4. This meant

that the seismic separation was seriously inadequate based on seismic design requirements. This condition was further confirmed through a dynamic three-dimensional analysis of the structure using estimated site specific seismic ground motions. Pounding of the two wings across the seismic separation could be anticipated at low levels of earthquake motion, about one-third to one-quarter the building code design basis event (e.g. 475 year return period event or 10% probability of being exceeded in 50 years).

The purpose of the seismic separation joint is to prevent pounding impact between buildings. Pounding has been shown in past earthquakes to be a major contributor to heavy nonstructural damage such as falling ceilings as well as collapsed partitions and exterior façades. It has also led to local building collapse and in some instances to total building collapse.

Retrofit options. To mitigate torsional weakness in the two wings, four retrofit schemes were investigated:

1. Perimeter moment resisting frames

2. Perimeter braced frames

3. Rigid structural linkage of wings to form one structure

4. Viscous damper linkage of wings.

All four retrofits options achieve compliance with the intent of the 1988 UBC and all provide for life safety. However, each had special considerations that led to the selection of the final option. These conditions included:

5. Improved seismic performance above minimum building code standards with reduced risk of damage.

6. Reduced risk of operational disruption following earthquake.

7. Minimizing construction costs.

8. Minimizing construction schedule.

9. Minimizing disruption to business operations during construction.

10. Aesthetic impact of retrofit scheme.

1. **Perimeter Moment Resisting Frames.** In this scheme the perimeter gravity frames were conceptually connected to moment resisting frames by modifying the beam-column connections. This scheme did not provide adequate torsional stiffness to the wings without costly modification of the columns and beams as well as to their connections. Construction of the retrofit was also very disruptive to business operations.

2. **Perimeter Braced Frames.** This scheme added diagonal bracing to the perimeter gravity frames. The concept was feasible and satisfied the strength and stiffness upgrade needed to meet building code requirements. If energy dissipating friction connections were added to the braces, such as a slotted - bolted - connection, this scheme would even reduce seismic motions in the structure in the upper floors. This would reduce potential nonstructural damage and operational disruption to critical business and computer functions on the upper floors. However, the aesthetic impact on the appearance of the building with exposed braces visible in the perimeter glass window walls was not considered acceptable and construction disruption as well as costs were excessive.

3. **Rigid Structural Linkage.** The objective of this concept was to rigidly tie the two wings together as one structure. Torsional irregularity would be eliminated with the floor diaphragms coupling the two central cores. However, plan irregularity added a design constraint. Both floor framing and bracing members had to be strengthened as well as connections in the central cores. Cost was excessive due to the extensive disruption during construction at all floor levels and the long construction schedule with 27 sequential mobilization and demobilization cycles.

4. **Viscous Damper Linkage.** Instead of rigidly linking the two wings, this option connected the two wings together with hydraulic dampers that provided a highly damped coupling between the two independent wings. The dampers were found to be most efficient and cost effective if located only at the underside of

the third floor level of each wing. This scheme minimized construction impact on the most business disruption sensitive third floor, minimized the number of dampers used to 7 as compared with 21 if all three levels were coupled, and located the coupling forces of the dampers at the optimum level in the building to prevent pounding by any uncoupled floor or roof diaphragm.

The added damping improved the performance over normal building code design, reduced floor motion that could cause functional disruption such as ceiling collapse in an earthquake, and eliminated the need to strengthen the braced frames in the central cores. This scheme was the least costly, required the shortest construction time, and was the least disruptive to business functions of the four options considered. This was the retrofit option selected.

Estimated Cost The introduction of dampers in buildings has been studied by others and shown to provide a very positive cost benefit when the potential future earthquake damage is rationally included in a life cycle cost analysis of the building. Unfortunately, many evaluations incorrectly neglect this benefit and only evaluate the damper option on the basis of initial construction cost. It is clear in this study that one option to control building torsional drift would have been the inclusion of new braced steel frames on the building perimeter. This would stiffen the building and minimize deflections at the seismic separation. If this braced frame option were selected, then the damping in the building would have changed very little from the existing (approximately three percent) but the stiffness would increase significantly, the accelerations of the floors would increase in an earthquake, and the nonstructural damage to the building contents and occupants would increase. Dampers increase the gross building damping to about eight percent, reduce response and actually reduce accelerations and floor motion in future earthquakes.

Structural Analysis

Existing Structure Review. To assess the design performance of the existing building, a three-dimensional ETABS computer model was prepared with both building wings in the same computer run. The model included all of the gravity frame beam and column elements as well as the beams, columns and braces of the central core eccentric braced frame. Diaphragm action of the floor slabs, floor and roof framing were treated as rigid in the model.

The design of the existing building was reviewed under the 1988 UBC seismic force criteria with torsional mass eccentricity amplified due to torsional irregularity. The lack of torsional stiffness was evident in the dynamic mode shapes and associated periods, as well as in the static code evaluation process. The 1988 UBC methodology for amplified mass eccentricity would have resulted in an accidental mass eccentricity of e = 15 % as opposed to e = 5 % for a torsionally regular building. Computed deflection across the 4 ½ inch seismic separation was four times the space provided. The eccentric braced frame elements in the central cores were stressed beyond allowable by more than 10%.

The same model was used to assess the dynamic response of the existing structure to earthquake. A site specific seismic response spectrum for the 475 year return (equivalent to the 1988 UBC seismic code design event) was developed and run against the model. Results from the analysis confirmed the seismic weaknesses in the design.

Damper Retrofit Analysis. A more sophisticated model was required to evaluate the damper retrofit solution, one that captured the nonlinear behavior of the damper as well as any effects of flexibility in the roof diaphragm (assumed rigid in the first model). A three-dimensional SAP 2000 computer model was developed of the two damper-connected structures that formed the wings of the building. The flexibility of the roof was modeled with a mesh of shell elements with in-plane stiffness. Floor masses were offset with an accidental eccentricity of five percent of the combined long building dimension. The critical direction of mass offset was determined using a separate sensitivity analysis.

Nonlinear viscous damper elements were explicitly incorporated into the model with properties optimized using various trial force-velocity relationships, resulting in the final relationship of $F=CV^\alpha$ where C=50 and

α=0.3, see Figure 2. Global viscous damping was modeled as seven percent. This value was reasonable because at the Maximum Capable Earthquake (MCE), a 950-year return period event, elements of the lateral force resisting system are at or near yield and significant soil passive deformation at the mat footings is expected.

A suite of site-specific time history ground motions was developed for the MCE event. Three simulated earthquake motions were applied to the model. Each event consists of a pair of earthquake time history components acting simultaneously in orthogonal directions. Events were run in both orthogonal directions, making for a total of six MCE time history load cases.

Earthquake forces and displacements in the damper retrofit analysis proved very favorable. Pounding between the 2 building segments was eliminated (4.3" relative roof displacement vs. 4.5" gap). Also acceptable under the retrofit were interstory drifts and force levels in braced frames and the connections of the two central cores.

Design Methodology. The seismic retrofit of the structure was on a voluntary basis. It incorporated passive energy dissipation systems (the dampers) and was peer reviewed as recommended for special building designs under the 1988 UBC as well as the draft copy of Appendix H of the Structural Engineers Association of California (SEAOC) Blue Book in preparation at the time.

The retrofit performance criteria met or exceeded the intent of the building code under which the structures were originally designed. The Uniform Building Code implies a Life Safety performance level for the Design Basis Earthquake (DBE), a 475-year return period event. The viscous damper retrofit was designed to achieve Life Safety Performance for MCE, a 950-year return period event as defined in the SEAOC Blue Book – Appendix H.

The retrofit design with the nonlinear viscous dampers addressed the following issues:

1. Torsional irregularity

2. Cantilevered floor and roof diaphragms

3. Flexible roof diaphragm

4. Seismic separation with associated pounding – drift control

5. Existing lateral force resisting system strengthening under new force patterns resulting from coupling the two building wings at the third floor level with damper devices

The damper devices, yokes and collectors used to carry the tension and compression forces from the dampers and distribute them to the floor framing on either side of the seismic joint were designed to remain elastic under the MCE earthquake, in accordance with the SEAOC Blue Book criteria. The existing central core braced frames and drags satisfy FEMA-273 acceptability criteria for Life Safety performance under the MCE event.

The buildings were evaluated using unreduced elastic forces (as opposed to base shear divided by R in accordance with conventional code practices for new design). Reduction factors in FEMA-273 were used to evaluate the retrofit structure for Life Safety performance. The SEAOC Blue Book Appendix H was used to define site-specific ground motions and for design of the damper devices.

Peer Review

The structural engineering analysis of all buildings for earthquake loading could benefit from peer review. This review is now required for buildings with nonlinear dampers. The peer review for this project was done under the direction of Dr. Gary Hart of the Hart-Weidlinger Division of Weidlinger Associates. The review started at the conceptual stage of the retrofit design and continued to the end, including plan check and

construction observation. Throughout the project, the interaction between Dr. Hart and the structural engineer of record, Mr. Gates, was vital to the success of the peer review process.

It should be noted that this project was completed prior to the final version of the Structural Engineers Association of California Blue Book approved position on the design criteria for buildings with dampers. The peer review helped the structural design to capture the intent of the SEAOC document and also most of the details of the final document. The peer review was also valuable in gaining acceptance of the design from the Building and Safety Department of the City of Santa Ana. Several meetings were held with the City prior to completion of the structural engineering work, both Mr. Gates and Dr. Hart described the earthquake retrofit concepts that were envisioned for the building as it went through two cycles of conceptual change. In these meetings, the City of Santa Ana provided suggestions that facilitated their rapid review of the structural submittal. Dr. Hart was asked by the city to write them a letter with his stamp describing his company's role and the scope of work performed as peer reviewer.

Damper System

What Is Fluid Viscous Damping. Fluid viscous damping is a way to add energy dissipation to the lateral system of a building structure. A fluid viscous damper dissipates energy by pushing fluid through an orifice, producing a damping pressure which creates a force. These damping forces are 90° out of phase with the displacement driven forces in the structure. This means that the damping force does not significantly increase the seismic loads for a comparable degree of structural deformation.

The addition of fluid viscous dampers to a structure can provide damping as high as 30% of critical, and sometimes even more. This provides a significant decrease in earthquake response of the structure. The addition of fluid dampers can reduce horizontal floor accelerations and lateral deformations by 50% and sometimes more.

Fluid Viscous Damper Description. The fluid viscous damper used in the structure retrofit is similar in action to the shock absorber on an automobile, but operates at a much higher force level. The damper used in structures is significantly larger than an automotive damper (see Figure 3). It is constructed of stainless steel and other extremely durable materials as required to furnish a life expectancy of at least 35 years. The damping fluid is silicone oil, which is inert, non-flammable, non-toxic, and stable for extremely long periods of time. The seals in the fluid viscous damper provide leak free service. This design has been proven through rigorous testing and has been in use for over 45 years.

The damping action is provided by the flow of fluid across the piston head. The piston head is made with a deliberate clearance between the inside of the cylinder and the outside of the piston head, which forms an annular orifice. The fluid flows through this orifice at high speed as the damper strokes. The shape of the piston head determines the damping characteristics. The force vs. velocity relationship for this kind of damper can be characterized as $F=CV^\alpha$, where F is the output force in pounds, V is the relative velocity across the damper in inches per second, C is a constant determined mainly by the damper diameter and the orifice area, and exponent α is a constant which can be any value from 0.30 to 1.95. The exact value for α depends upon the shape of the piston head. Values for α ranging from 0.3 to 1.0 seem to work best for structural applications.

As the damping orifice is provided by the annular clearance between the piston head and the cylinder body, it is possible to provide inherent thermal compensation by making these two parts from different materials. By choosing materials with the correct thermal coefficients of expansion, it is possible to make the variation in the gap compensate for the variation in fluid properties as temperatures change. Through proper design techniques, variation in damping as small as +/-15% over a temperature range of +20°F to +120°F can be obtained.

Spherical bearings at each end of the fluid viscous damper permit the damper to angulate relative to the structure without binding. Figure 3 shows a detail of these spherical end bearings. These bearings permit rotation in every direction, which prevents binding in the fluid viscous damper.

Retrofit Construction with Dampers

Structural Modifications. Seven viscous dampers were installed at the third floor seismic separation joint between Column lines 5 and 5.1 which served to tie the North and South Wings together as one building. These provided an axial force in tension and/or compression that acted perpendicular to the seismic joint. The shear forces developed between the two building wings at the third floor seismic separation joint were resisted by steel tube shear keys.

Figures 4 and 5 illustrate the typical damper and shear key installations along the seismic separation joint at lines 5 and 5. 1. Two dampers were installed, one on either side of the main interior columns at the seismic joint as shown in the top of Figure 4. A single damper was installed at the exterior column at the re-entrant corner. The dampers were installed in a specially fabricated yoke of added tube steel, used to transfer the high concentrated axial forces in the dampers around the columns at the seismic joint and back into the structural framing system of the floor.

The axial loads from the yokes were transferred back into the floor framing through added tube steel welded to the bottom flange on the floor framing. These drag members were laterally braced to the underside of the floor to add stability. The tube steel yoke was shop fabricated and field welded into place.
The shear keys were shop fabricated tube steel with end plates and sliders. The low coefficient slider as shown in Figure 5 was bonded to the bearing surfaces of the two abutting shear keys. The shear keys were field installed to a continuous tube steel drag element welded to the bottom flange of the beams on either side of the seismic joint on gridlines 5 and 5.1, as shown. in Figure 5.

Damper Installation. Prior to installation of the damper support yoke, the damper manufacturer supplied a template with the same eye-to-eye distance as a regular damper at mid-point, and the same diameter mounting holes. The steel fabricator used this template to make sure that the yokes (or mounting brackets) had the correct eye-to-eye distance.

Every damper was dynamically tested before being shipped. Testing consisted of one full cycle at full velocity which produced a force of 115 kips. In addition each damper was tested under internal pressure to 2.0 times maximum operating pressure for leakage and structural integrity.

Installation of the dampers was relatively easy, requiring two men and a portable hoist, and taking less than one hour per damper. The dampers have a ball type fitting at each end as shown in Figure 3, which provides angular freedom about the three axes, keeping the damper from experiencing moment loading when the two buildings twist relative to each other. These fittings made it easy to slip the damper into the supporting yoke and insert the large mounting pins through the holes in the yoke and ball fitting. The mounting pins were secured from falling out of the clevis connection with washers and cotter pins.

Cost and Schedule. The seismic retrofit was completed in early 1999 for a construction cost of approximately $500,000. This was less than $5 per square foot of floor area. The four month construction phase took place under fully occupied and functioning office conditions with construction in critical areas performed at night.

Summary

Four seismic retrofit schemes were evaluated to mitigate torsional irregularity in the two adjacent structures that formed a three story office building. The use of viscous dampers to couple the two structures at the seismic separation joint proved to be the best solution. The retrofit design met and exceeded the minimum Life Safety requirements of the building code. Not only did the dampers prevent pounding and minimize torsion to enhance the structural safety, but they reduced the damage potential to the structures and nonstructural elements, as well as the contents, thus providing greater assurance of business continuity following earthquakes.

As far as the authors know, this is the first use of energy dissipating viscous dampers to mitigate torsional irregularity by coupling two similar multi-story structures together.
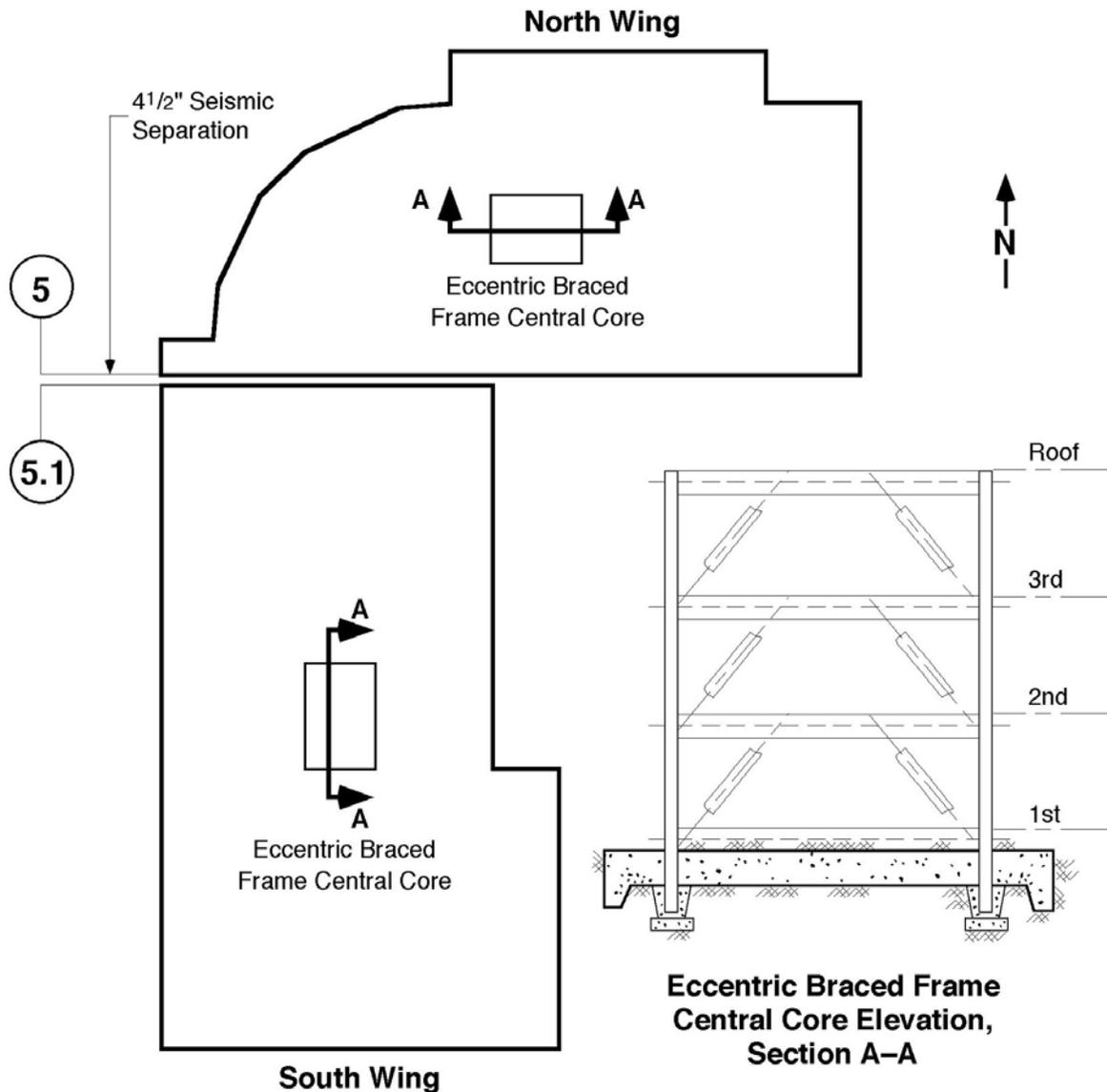
Acknowledgements

Figure 1. Typical Floor Plan
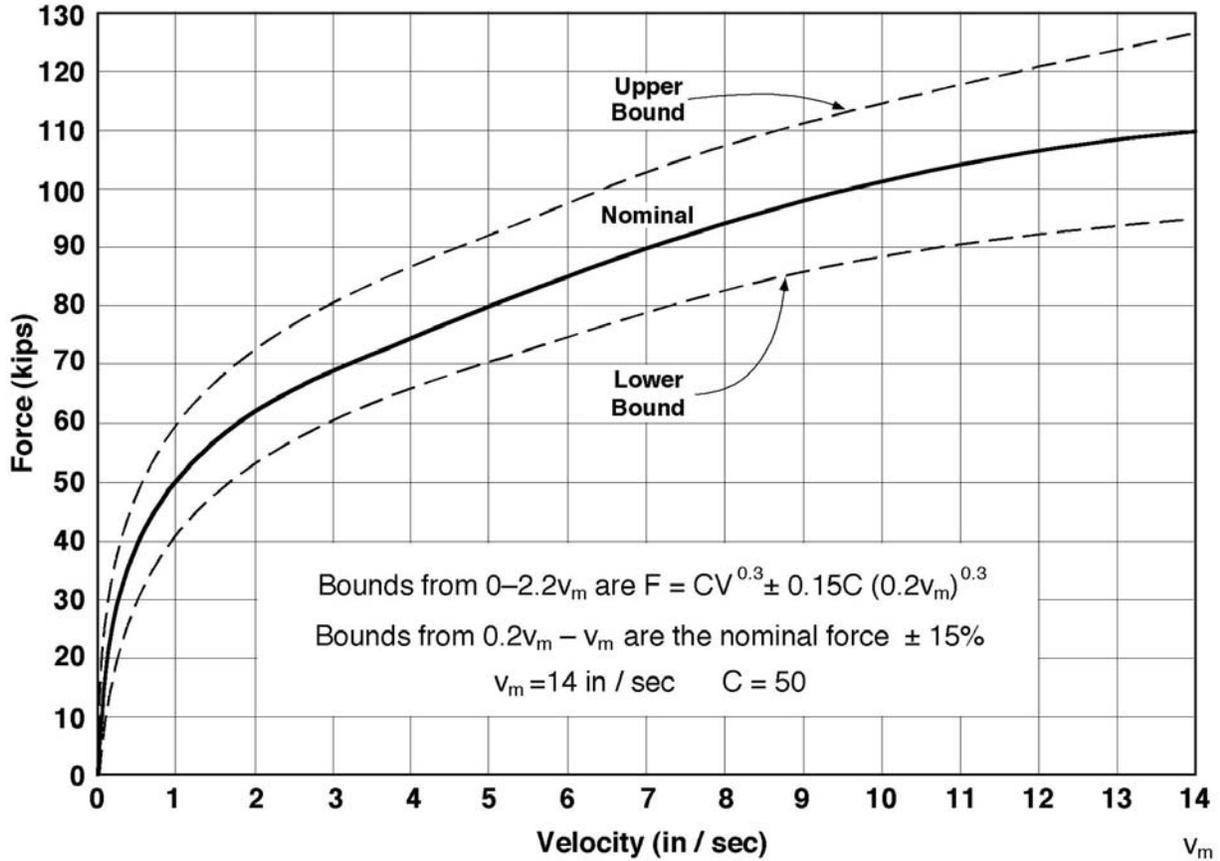
Figure 2. *Force - Velocity Envelope For Damper Design*

The figure contains the following annotations:

Upper Bound

Nominal

Lower Bound

Bounds from $0-2.2v_m$ are $F = CV^{0.3} \pm 0.15C \, (0.2v_m)^{0.3}$

Bounds from $0.2v_m - v_m$ are the nominal force $\pm 15\%$

$v_m = 14$ in / sec $C = 50$

Axis labels: Force (kips); Velocity (in / sec); v_m
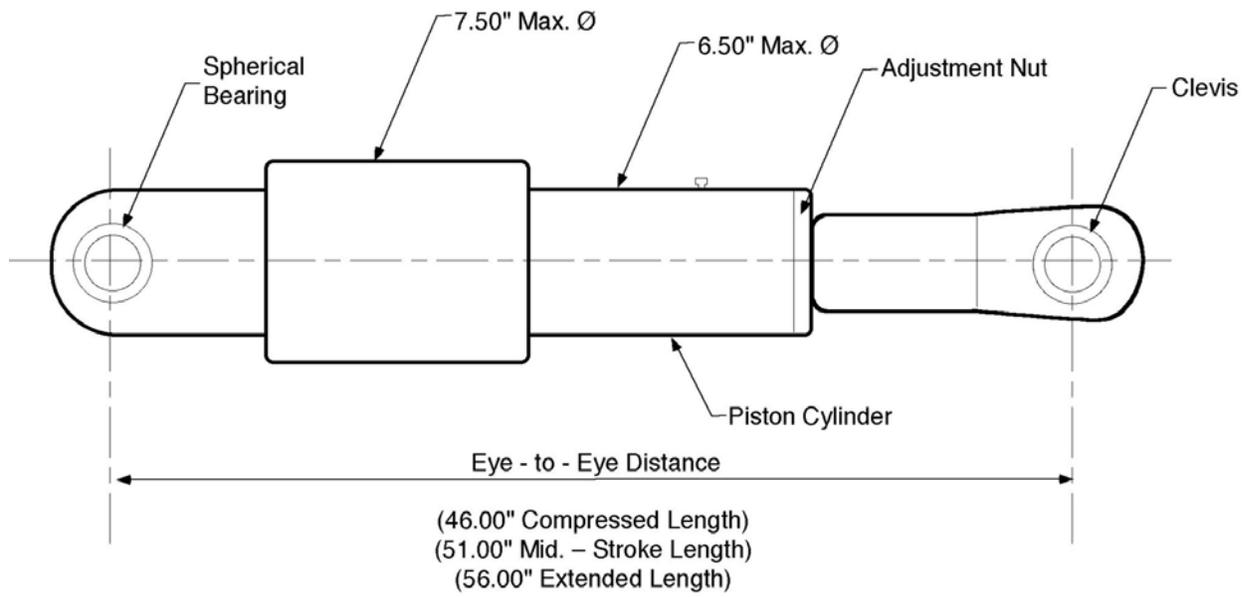
Geometry Of Viscous Fluid Damper
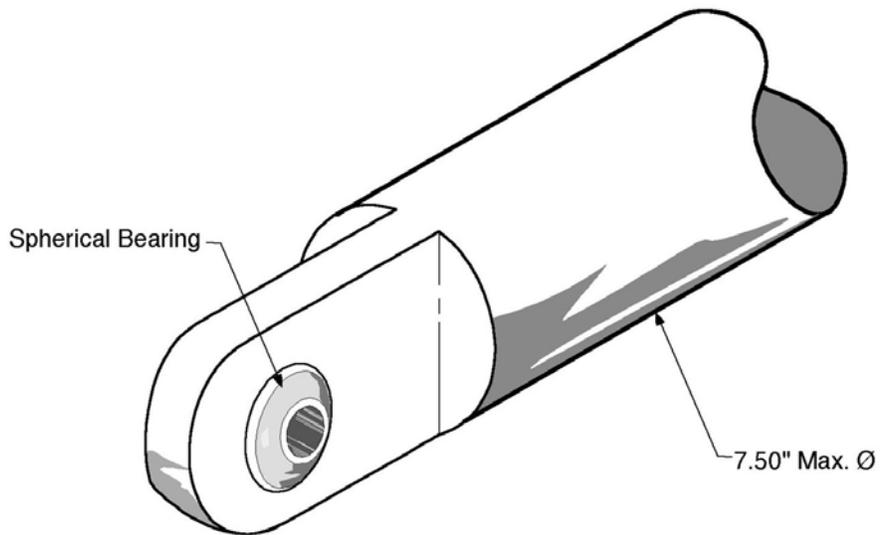
Spherical Bearing

Figure 3. Viscous Fluid Damper

Plan Section

Elevation Section
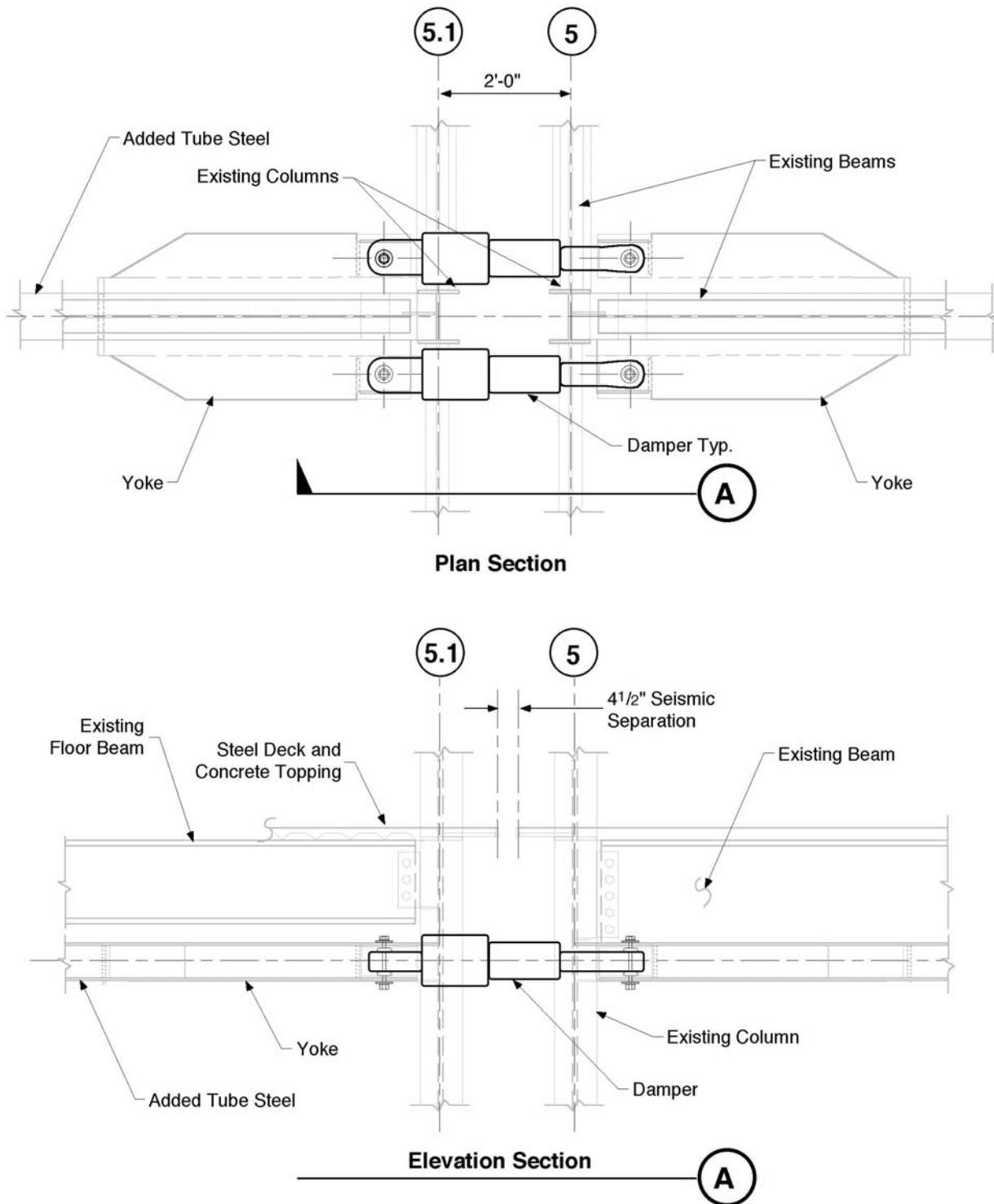
Figure 4. Typical Damper Installation

Existing Beam

Added Tube Steel

Welded Tube Steel
Connection

10 Ga. Mirror
Finish ASTM 240
Type 304, Stainless
Steel Plate Welded
to Shear Key

Shear Key

1/8" Thick Virgin
PTFE Bounded to Plate.

2 Layer of 1/2" Elastomer
With One 11 Ga. Shim
Elastomer Bonded to Steel
Plate and Shear Key

Shear Key

1/2"x8"x5" A36 Steel Plate
Bonded to PTFE and
1/2" Elastomer

Welded Tube Steel
Connection

Added Tube Steel

Sliding Surface

Existing Beam

Slider Bearing Detail

Added Tube
Steel Shear Key

Added Bottom
Tube Steel

Existing Beam

Shear Key

Shear Key
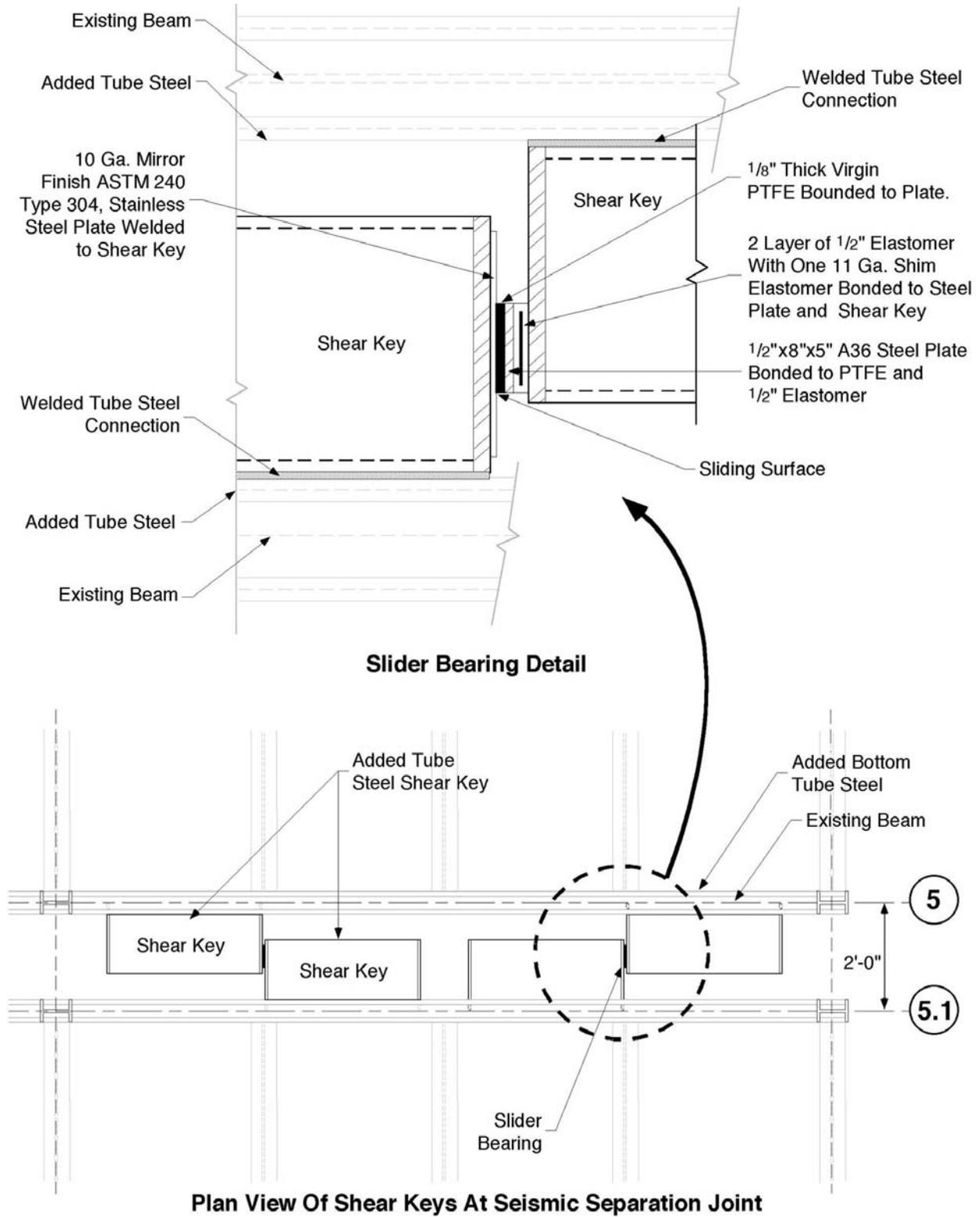
5

2'-0"

5.1

Slider
Bearing

Plan View Of Shear Keys At Seismic Separation Joint

Figure 5. Typical Shear Key Installation