SEISMIC DESIGN

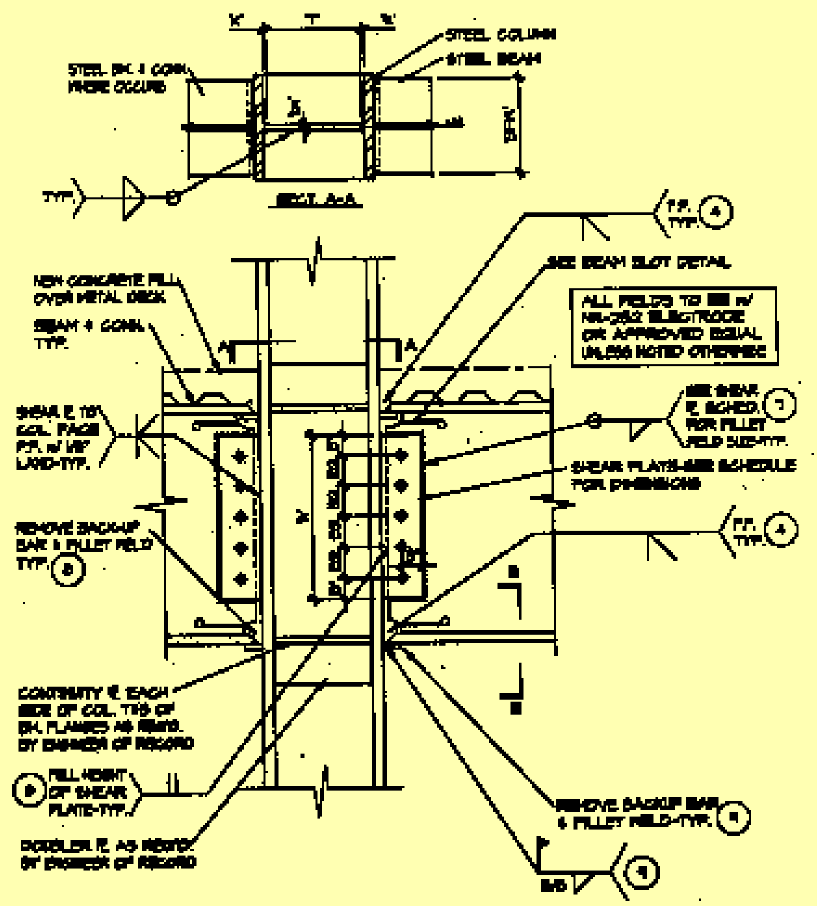

Figure 1: Slotted beam connection detail

PROPRIETARY SLOTTED BEAM CONNECTION DESIGNS

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AFTER THE NORTHRIDGE EARTHQUAKE, EXTENSIVE DAMAGE WAS WAS REPORTED IN MOMENT RESISTING FRAMES (MRF) that used beam-to-column connections in which beam flanges were attached to the column flanges with full penetration welds and the beam webs were bolted to single plate shear tabs. Consequently, it has been concluded that this prescribed connection, shown in UBC 2211.7.1.2, is flawed.

This conclusion, stated in the 1996 SEAOC *Blue Book* (C706 Commentary), was determined through: surveys of connection damage and modes of fracture; a review of literature on historic tests; recently performed ATC-24 tests (e.g., see *MSC*, May 1995); and finite element analyses (e.g., see *MSC*, October 1995) that showed high stress and strain concentrations and gradients in the beam flange/welds.

After comprehensive elastic, plastic, and buckling analyses using finite element models coupled with ATC protocol testing of modified designs, Seismic Structural Design Associates, Inc. (SSDA), developed proprietary slotted beam connection designs that essentially salvage the "pre-Northridge" connection designs and may be used for both new construction and retrofitting existing buildings. This connection, shown in Figure 1, uses horizontal beam web slots, a fully welded and bolted single plate shear tab, and a beam web to column flange weldment. Additionally, a ductile weld material is specified, and in composite construction only the lower beam flange backing bar needs to be removed.

The SSDA Slotted Beam web connection designs reduce the Stress Concentration Factor (SCF) at the beam-to-column flange interface at the column web from typical values ranging from 4.5 to 5.5 in non-slotted beams down to a typical value of about 1.4 by providing a nearly uniform beam flange/weld stress and strain distribution. The large SCFs, computed by finite element analyses and measured experimentally (*MSC* October 1995), exist in the pre-Northridge, reduced beam section (dogbone), and cover plate connection designs. These SCFs result from large stress and strain gradients that occur horizontally across and vertically through the beam flanges/welds at the face of the column in these connections. The vertical stress and strain gradients through the beam flange welds are most severe at the center of the beam flange and result in a beam flange prying action on the face of the column. This can lead to a typical connection mode of failure by rupture of a divot from the center of the column flange and has been observed both in the field and laboratory tests (*MSC* April 1996).

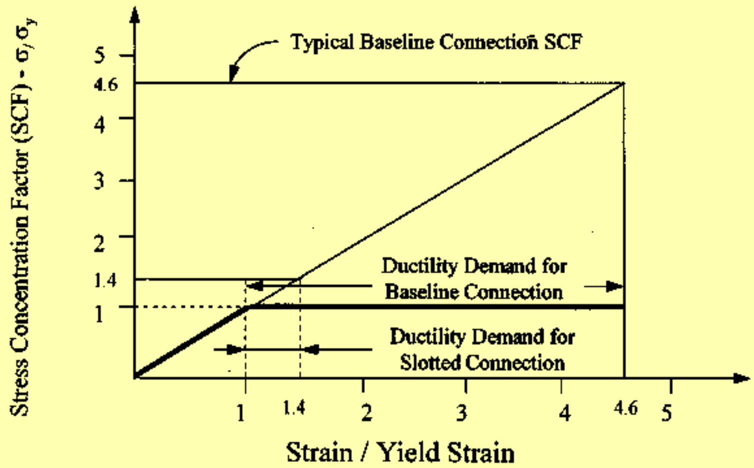


Figure 2: Stress concentration factor and ductility demand relationship

In order to quantify the demand for local ductility in the column flange/beam flange/weld that is based upon the elastic SCF, the concept of a Ductility Demand Factor (DDF), which is equal to SCF-1 as shown in Figure 2, was developed. As illustrated in Figure 2, if a connection is modified so that the elastic SCF is reduced from 4.6 to 1.4, then the local ductility demand for elastic-plastic materials is reduced from 3.6 to 0.4 or by a factor of nine (9).

Equally important, the SSDA slotted beam design allows the beam flanges and beam web to buckle independently as shown by the elastic buckling modes in Figures 3 and 4. This circumvents the beam lateral-torsional buckling mode shown in Figure 5 that occurs in non-slotted beams, and thereby eliminates the torsional moment and torsional stresses in the beam flanges and welds at the column flange that result from this buckling mode. Tests of non-slotted beams (see *MSC* May 1995, January 1996, April 1996, and August 1996) showed that non-slotted test specimens typically exhibited considerable twist that accompanied local flange and web buckling as shown in Figure 5. Testing was often stopped when this twisting occurred to avoid test fixture and equipment damage. One mode of connection failure reported in these tests was the fracture of the beam flange/weld at one tip and progressing to the other tip which indicates the role of the torsional moment and stresses in this mode of buckling.

Additionally, the beam web slot provides flexibility between the beam web and beam flange weldments to the column flange that reduces the residual welding stresses and thereby enhances the connection ductility.

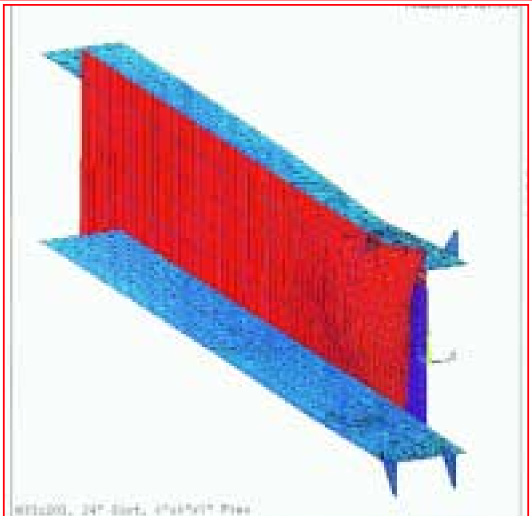


Figure 3: Slotted beam elastic buckling Mode 1

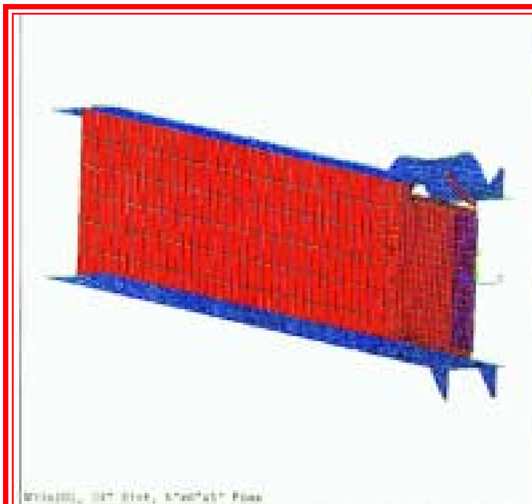


Figure 4: Slotted beam elastic buckling Mode 2

Analytical Studies

Shown in Figure 6 are the results of an elastic and plastic

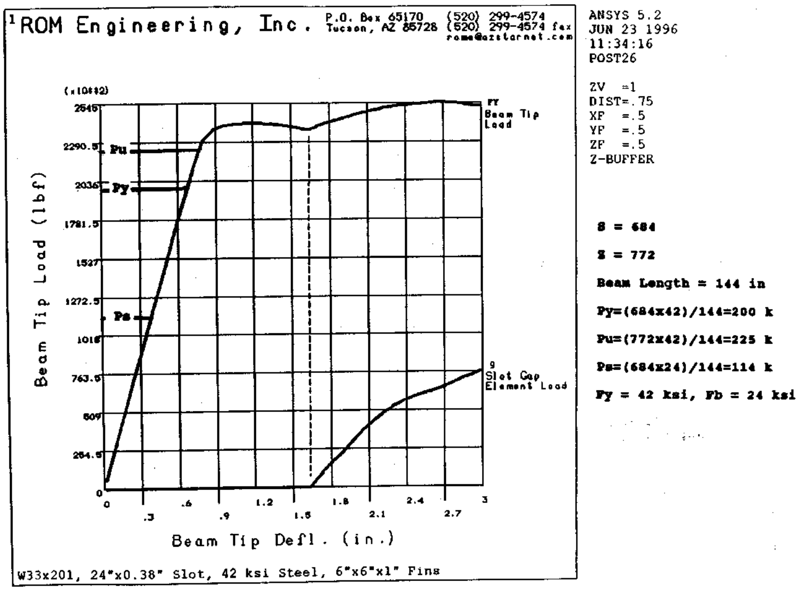


Figure 6: Load vs. displacement relationship for a W33x201 slotted beam

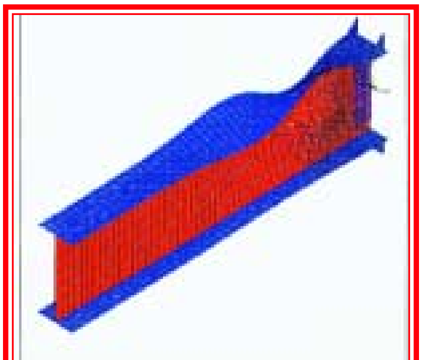


Figure 5: Non-slotted beam elastic buckling Mode 1

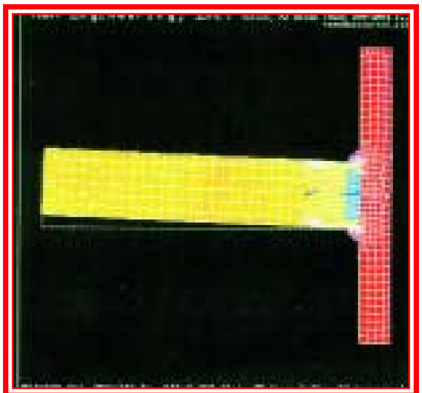


Figure 7: Deflected shape for a W14x500 column and a W36x280 beam ATC-24 test assembly

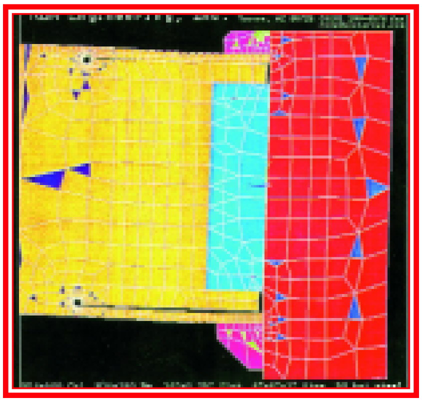


Figure 8: Effect of slots on beam flange curvatures

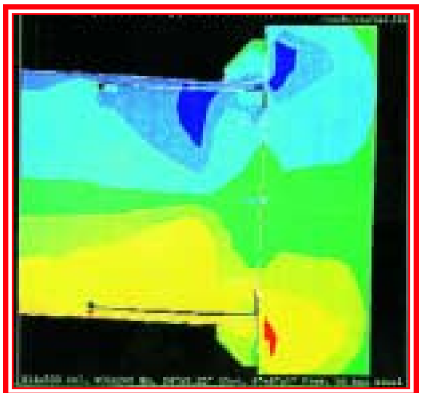


Figure 9: Flexural stress distribution in the W36x280 beam

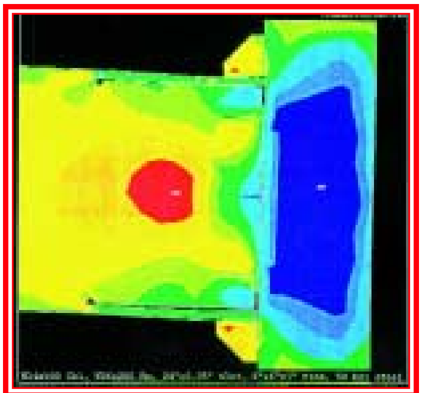


Figure 10: Shear stress distribution in te W36x280 beam

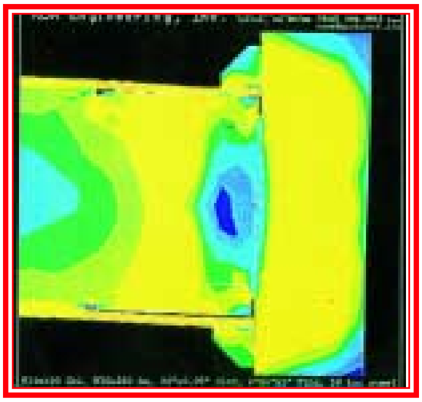


Figure 11: von Mises stress distribution in the W36x280 beam

buckling analysis of a 12' W33X201 slotted beam. The plastic buckling load on this cantilever beam with a yield stress of 42 ksi is approximately 250 kips whereas its first mode linear elastic buckling load, shown in Figure 3, is 1240 kips. Typical analyses such as this and ATC-24 test results demonstrate that the SSDA beam web slots do not reduce the strength of the beam. Moreover, these finite element analyses have shown that these slots did not reduce the elastic stiffness of the ATC-24 assemblies. The beam web slot lengths are the smaller of either 1.5 times the beam flange width measured from the column face or the length of the beam web plastic hinge length measured from the end of the shear plate. The latter length criterion usually governs in short beam spans.

Shown in Figure 7 is the deflected shape (and the finite element mesh used for the analysis) for a 14' W14X500 column and a 14' W36X280 beam ATC-24 test assembly with a 380 kip tip load which results in a 7" tip deflection. Figure 8 shows how the slots, which close on the compression side and open on the tension side, very effectively reduce the beam flange curvatures, and therefore the flange stresses and strains, at the column face. The 6"x6"x1" vertical fins shown in this figure are added to the SSDA connection detail if the yield stress of the jumbo column is less than or equal to that of the beam to avoid through thickness column flange fracture modes. Figures 9, 10, and 11 give the distributions of the beam and column flexural stresses, shear stresses, and von Mises stresses, respectively, for the 380 kip load.

ATC-24 Test Results

A plot of the cyclic hysterisis curve for the W14X500 column and W36X280 ATC-24 assembly is shown in Figure 12. Shown in Figures 13 and 14 are the yielded and hinged specimens at -7 and +7 times delta yield, respectively. These two figures show the buckled 1.57" lower beam flange for the downward loading followed by the straightening of this flange during the upward loading. SSDA has successfully completed a total of seven ATC-24 protocol tests using columns ranging from W14X176 to W14X550 with beams ranging from W27X94 to W36X280. None of these assemblies experienced the lateral-torsional buckling modes that are typical of non-slotted beam and column assemblies.

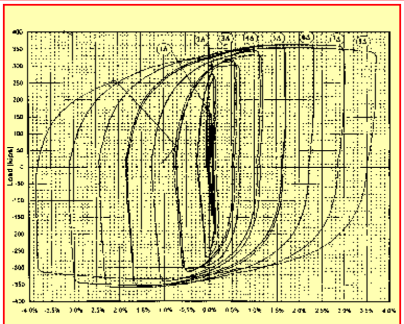


Figure 12: Moment vs. plastic rotation for the W36x280 beam

Projects

SSDA has completed or is currently completing connection designs for seven new steel moment frame buildings. These include the eight story St. Francis Medical Center (OSHPD Approved) in Los Angeles, CA, and the Gateway West twenty story office building in Salt Lake City, UT. Thompson and La Brie Structural Consulting Engineers, Pasadena, CA, is the engineer of record for the former, and Reaveley Engineers and Associates, Inc., Salt Lake City, for the latter. Additional new projects under contract or pending with Culp & Tanner, Inc., Lake Forest, CA, are a nine-story office tower in Las Vegas, NV and a two story addition to the John Ascuaga's Nugget Hotel & Casino in Reno, NV. New projects pending include a six-story office tower in Long Beach, CA and a five story office tower in Los Angeles, CA. The slotted connection cost is between $400 and $900 per connection, depending upon beam and column sizes, above the "pre-Northridge" connection.

Four buildings in the Los Angeles area have been or are being retrofitted using the SSDA Slotted Beam connection. Included is a 10-story office building in Burbank, CA, where 194 "pre-Northridge" connections were repaired as required and retrofitted at an average cost of $2700 each, and a three-story medical office building in Woodland Hills, CA, where 97 "pre-Northridge" connections were repaired and/or retrofitted at a cost of $3000 per connection. The latter project costs includes the repair of 22 connections and the retrofitting of 97 connections. Web access holes were made in 32 of these connections to make the beam web to column flange weldment without removing the building skin. The above costs include removal and replacement of fireproof materials and cleanup and all design and contractor costs. Additionally, a three-story medical office building in Granada Hills, CA and a 3 story office building in Thousand Oaks, CA are under contract.

Summary

The SSDA Slotted Beam design develops the full plastic moment capacity of the beam, moves the plastic hinge region in the beam away from the face of the column, and results in nearly uniform tension and compression stresses, strains across and through the beam flanges from the face of the column to the end of the slot, eliminates the lateral-torsional buckling mode that occurs in non-slotted beams, and enhances ductility by reducing the residual weld stresses.

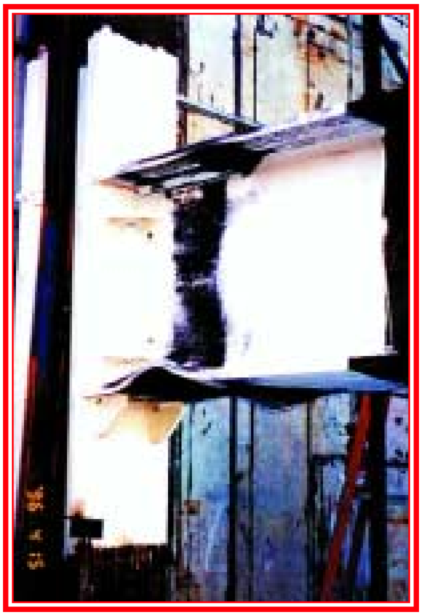
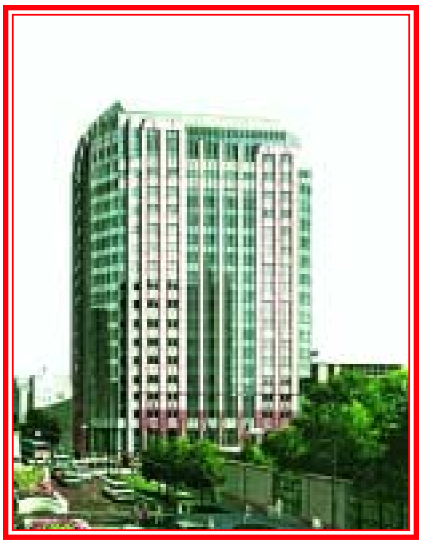


Figure 13: Hinging and buckling at -7 Delta yield for the W36x280 beam

Figure 14: Hinging and buckling at +7 Delta yield for the W36x280 beam



Gateway West: This 20-story building in Salt Lake City is under construction and will utilize the SSDA connection. The design calls for 1,053 welded steel moment connections. Typical floor-to-floor height is 15' and total building height is 318'-8".

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