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ABSTRACT

A breakthrough in moment frame and braced frame connection technology in the design and construction of ductile steel frame buildings, known as *SidePlate*™, was born in the disastrous aftermath of the January 17, 1994 Northridge earthquake. The technical reaches of this new connection technology and its associated integrated practical applications in severe design environments are keenly suited for the heightened performance expectations of global structural building systems in the new millennium. A working understanding of this fully-developed pre-qualified connection technology is essential.

SidePlate™ is a patented connection technology in the United States of America and New Zealand, developed and owned by SidePlate Systems, Inc. (a connection specialty consultant headquartered in the greater Los Angeles area of California), with patents pending in Japan, China, Europe, Latin America and other Pacific Rim Countries. The basic geometry of *SidePlate™'s* connection technology inherently provides versatility to address both moment frame and braced frame design applications. These structural systems include both moment-resisting frame structures and braced dual system frame structures that combine rigidly-connected heavy bracing and moment-connected beams within the same connection, for both uniaxial and biaxial framing applications. Such performance standards and versatility are needed to competently address severe lateral load phenomena associated with both natural disasters such as earthquakes, as well as malevolent disasters such as that caused by terrorist bomb blast.

SidePlate™'s connection geometries eliminate recognized brittle behavioral uncertainties that are intrinsic with the use of a T-joint complete-penetration groove weld to connect beam flanges directly to a column flange, or to connect brace flanges directly to either the column flange or beam flange. *SidePlate*™ eliminates through-thickness column flange divot pullout, complex high-order magnitude triaxial strains at the beam-to-column interface, and inherently weak panel zone participation of the column web. The significance of these uncertainties is notably characterized by the unprecedented reported losses that resulted from the January 17, 1994 Northridge earthquake and from the January 17, 1995 Kobe earthquake (both events magnitude 6.7). *SidePlate*™ uses all shop fillet-welded fabrication, ductile weld configurations, and the column tree/link beam erection sequence for increased quality control, cost efficiency, and speed of erection. The unique beam/column separation, simple design configuration, and proven construction methods that characterize the attributes of the *SidePlate* connection system collectively eliminate vulnerability to premature brittle fracture. Connection ductility and robustness are achieved by using redundant simplified load paths, giving due design consideration to the direction of applied load on a weld, and by eliminating reliance on recognized uncertain brittle material properties and complex triaxial strain concentrations. The result is a cost-efficient connection system that performs reliably with repeatable ductility. Linkage between the results of full-scale cyclic testing, corroborative independent non-linear analyses, and detailed finite-element parametric studies provides rigorous system qualification for any practicable combination of beam and column sizes without the need for additional testing. This conclusion has been independently reached and pre-qualified by an internationally recognized jurisdictional authority.

STEEL FRAME CONNECTION TECHNOLOGY OF THE NEW MILLENIUM: SATISFYING HEIGHTENED PERFORMANCE EXPECTATIONS WITH SIMPLICITY AND RELIABILITY AT LOW COST

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SUMMARY

A new generation connection technology, known as *SidePlate*™, uniquely provides the basis for an integrated family of proven pre-qualified solutions for ductile steel frame connection systems, including moment resisting frame systems and braced dual systems. It is a breakthrough technology that squarely addresses the challenges of the new millennium because of its proven performance and reliability, durability, versatility, and cost efficiency. It eliminates all recognized technical uncertainties that are intrinsic with the heretofore more "traditional" use of a T-joint complete-penetration groove weld to connect a beam flange directly to a column flange, or to connect a heavy diagonal brace to a column or beam flange. The unique trademark geometry, simple design configurations, increased connection stiffness, and proven construction methods that collectively characterize the attributes of the *SidePlate* connection technology are ideally suited to satisfy a wide variation and technically diverse set of design environments and construction applications.

The System Pre-Qualification of *SidePlate* connection technology provides rigorous justification for any practicable combination of rolled-shape beam and column sizes without the need for additional testing and analysis, freeing the structural engineer to accommodate myriad design challenges and imposed space limitations.

SidePlate™ is developed for both new and retrofit construction. Implemented design applications and environments include:

- Earthquakes of low, moderate and severe seismicity
- Extreme wind; including typhoon, hurricane and tornado
- Explosive threat and mitigation of progressive floor collapse, either accidental or malevolent in origin, for both conventional steel frame buildings and pre-engineered steel frame industrial structures with varying-depth column and beam sections.
- Specialty Structures, such as airport traffic control towers and off-shore drilling platforms
- Petrochemical applications, such as global piperack structures
- Power generation applications, such as turbine buildings and electrical dead end bus structures

SidePlate™*'s* rapid proprietary research and design development and unparalleled independent scrutiny provide structural engineers and owners of buildings and specialty structures with a cost-efficient, robust, and versatile moment connection system that performs with predictable and repeatable ductility, and competently addresses the heightened challenges of the new millennium.

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INTRODUCTION

Following the January 17, 1994 Northridge earthquake (magnitude 6.7), in the wake of discovering that the "traditional" prescriptive steel moment-resisting frame connection had suffered unexpected widespread premature brittle fracture of welds and base metal, structural engineers were faced with a connection crisis. Protracted pondering of or ignoring the known major contributors to premature brittle fractures in weldments and base metal, in what has become known as the Pre-Northridge moment connection, culminated in its sudden demise and an unfortunate legacy of unprecedented financial losses and technical uncertainties concerning both existing and proposed new construction. These uncertainties include:

- Through-thickness divot pull-out of the column flange due to cyclic loading of the column flange/heat affected zone, without a rigorous determination of a reliable design stress at this highly-restrained and most critical connection interface.
- Sudden weld rupture due to complex triaxial/peaked stress concentrations at the welded beam-to-column juncture, which include shear stresses due to localized lateral torsional buckling of the beam flange and unaccounted for end-of-beam shear.
- Premature brittle fracture of the column web and/or kinking of column flange due to reliance on column web weak panel zone participation to achieve rotational performance, including vulnerability to random sudden rupture initiating along the fillet transition between flange and connecting web (known as the "k-line") of rolled shapes due to a severe reduction in ductility and fracture resistance in this transition area created during the mill's rotary straightening process.
- The reality of less-than-perfect construction and ultrasonic testing inspection shortcomings.

Collectively these uncertainties are intrinsic to moment resisting connections and heavy diagonal braced connections that employ the use of a T-joint complete-penetration groove weld to connect the beam flange directly to the column flange, or to connect flanges of a heavy diagonal brace to the flange of either a beam or column [AISC Seismic Provisions for Structural Steel Buildings (1997)]. Random brittle fractures using such a connection type in a one-sided connection configuration continue to be cited in post-Northridge moment connection testing, despite intentional efforts to mitigate such fractures. Such efforts include: 1) use of high fracture-resistant (i.e., high Charpy V-notch toughness) weld metal, 2) removal of backing bar, backgouging, and providing a reinforcing fillet weld, 3) use of improved ultrasonic testing techniques, and 4) localized modifications to the geometric stiffness properties of the rolled beam which include reducing the flange cross-section by up to 50% and other surgical softening techniques. Even more alarming, however, is the disturbing recognition that, while due focus on such connection types by the post-Northridge research community has been targeted at mitigating the threat of through-thickness divot pull-out of the column flange and/or reducing the complex triaxial/peaked stress concentrations at the welded beam-to-column juncture, the problem of weak column web panel zone vulnerability to brittle fracture has been seemingly ignored altogether because of the almost exclusive testing of one-sided connections. In two-sided connections, wherein the shears of both connected beams are additive, the panel zone strains that are already at plastic levels in a one-sided connection are increased to almost a factor of two larger. The critical deficit in available test data for two-sided connection configurations precludes, by its very definition, the ability of the research community to credibly proclaim the pre-qualification of such connection types on the strength of existing tests, regardless of the number of one-sided tests performed. The imprudence and uncertainty of using a two-sided connection configuration in design for such connection types, by extrapolating from published design parameters of "successful" tests, is exacerbated in engineering practice with the common use by many engineers of deeper (i.e., more economical) column sections than those typically tested. Such column sections exhibit a significantly larger column web depth-to-thickness ratio compared to the preponderance of the columns sizes used in post-Northridge testing to date. This dilemma is compounded even more with the common use by engineers of web doubler plates which are typically welded directly to the column web panel zone with the intent of increasing the shear strength of the panel zone rather than accepting the penalty of increased column tonnage in order to increase the column web thickness. Such a practice concentrates and heightens the already highly plastic levels of strain along the weld line, precisely where the panel zone is most vulnerable to the uncertainty of reduced physical toughness properties.

Conversely, the unique geometry, design configuration, and construction methods that characterize the *SidePlate* connection technology eliminate the recognized vulnerabilities cited above by their very definition. Collectively these attributes exhibit a wide tolerance for accommodating the less-than-perfect realities of steel fabrication, erection and inspection practices, including random and inordinate variations in the material properties of rolled shapes observed in steel produced by mills throughout the world [Kuwamura, et al. (1990)].

ATTRIBUTES OF THE CONNECTION SYSTEM

Column/Beam Separation

SidePlate™'s trademark geometry provides physical separation between the face of column and end of beam by means of parallel full-depth side plates (see Figure 1). This key attribute eliminates reliance on brittle and premature behavioral uncertainties that are intrinsic to both moment connections and heavy braced connections that employ the use of a T-joint complete-penetration groove weld to connect the beam's flanges directly to the column flange, or to connect the bracing member's flanges directly to the column or beam flange, as applicable. These uncertainties, made infamous by the January 17, 1994 Northridge earthquake, include sudden through-thickness divot pull-out of base metal and/or heat affected zone, and/or brittle weld fracture due to complex triaxial/peaked stress concentrations at this highly-restrained and most critical welded juncture.

Full-Depth Side Plates

SidePlate™'s use of full-depth side plates ensures that all significant energy dissipation/connection deformation occurs ductilely outside the column, and connection welds and plates. Rotational performance completely avoids dependence on column web weak panel zone participation, thus escaping vulnerability to column kinking and to sudden pre-mature rupture along the rolled fillet between flange and web, i.e., k-line fracture syndrome [AISC Advisory (1997)], which is a critical boundary of the panel zone. *SidePlate*™'s inherent increased lateral stiffness on global frame performance, provided by the full-depth side plates, significantly reduces the number of beam-to-column steel frame connections and/or the total steel frame tonnage required to satisfy building drift requirements by replacing beam stiffness with simulated connection stiffness.

Shop Fillet-Welded Column Tree Construction

For new construction, *SidePlate*™ uses all shop fillet-welded fabrication, ductile weld configurations, and the column tree/link beam erection sequence (see Figure 2) for increased quality control and cost efficiency. Column design options include rolled or built-up 'H' wide flange sections, and tube steel or built-up box columns. The length of column trees can be fabricated, transported and erected up to a building height of three stories and are typically transported in multiples per truck bed or rail car to the job site without requiring special escort. Fillet welds are loaded longitudinally in shear which is inherently very ductile; eliminating vulnerability to brittle fracture or "unzipping". In addition, fillet welds do not require special inspection and/or ultrasonic testing.

Simplified Load Paths

Unlike more "traditional" looking welded moment connections and welded heavy brace connections that are subject to unreliable, brittle, and indeterminate behavior, *SidePlate*™ combines redundant simplified load paths with time-proven fabrication practices and tested material properties. Actual load transfer (i.e., load distribution), from beam to side plates and/or brace to side plates, and from side plates to column, is accomplished by the use of plates and fillet welds loaded in a predictable manner. The ability to identify realistic and redundant load transfer mechanisms provides a clear understanding of the function of each element of the connection, leading to a rational design procedure and reliable performance.

CYCLIC PERFORMANCE

Full-scale cyclic testing of the *SidePlate* moment connection system was conducted at the University of California, San Diego to determine the plastic rotational performance and verify the predicted strength of connection elements, including welds. Three one-sided prototype uniaxial connection test specimens, consisting of a W36x150 beam connected with full depth side plates to a W14x426 column, were successfully tested in December, 1994, and January, 1995 (Uang, Latham 1995). In May, 1996, the first-ever full scale dual strong axis connection was successfully tested (Uang et al. 1996), demonstrating that the *SidePlate* connection technology can be used for biaxial applications and that orthogonal effects of severe earthquake forces can be successfully resisted. The biaxial dual strong axis specimen was configured as a three-sided moment connection consisting of W36x170 beams and a built-up cruciform column fabricated with W36x230 sections.

All four test specimens were heavily instrumented to record actual strain histories at critical locations in order to corroborate design controls imposed on key elements. The full-depth side plates experienced limited yielding within the control limits set in *SidePlate*™'s design methodology. The connections of all tested specimens demonstrated robustness and reliability in sustaining sustain multiple inelastic cyclic rotations with no reduction in strength in any of the connection plates, weld elements, or column, while permitting the beam to develop its full strain-hardened plastic flexural strength. Figure 3 depicts the typical ductile behavior of the beam, as evidenced by significant flange and web local buckling. The average actual plastic rotation capacity achieved was 0.036 radian (measured from face of column flange) for at least one complete cycle while maintaining a minimum of 83% of the nominal strength of the beam. This performance clearly exceeds internationally recognized acceptance criteria.

CONNECTION SYSTEM QUALIFICATION

Strain readings measured at key connection locations during both the prototype uniaxial and biaxial dual strong axis moment connection tests were consistently either at elastic or controlled plastic levels. These readings are corroborated by the results of independent nonlinear analyses of the prototype test specimen, performed by the University of Utah (Trautner 1995) and by Myers, Houghton & Partners, Inc. - Structural Engineers, Lawndale, California, which utilized material strengths and nonlinear properties obtained from prototype coupon tests. Reliable nonlinear analytical verification of the prototype's beam yielding and buckling (see Figure 4), and the predictability of measured distribution of applied load through critical load transfer mechanisms and the associated behavior of connection components was clearly demonstrated. An extensive suite of linear and non-linear analyses was conducted by Myers, Houghton & Partners, Inc. - Structural Engineers to rigorously investigate the load demand and distribution through each critical load transfer mechanism of the connection, for member sizes other than those tested, to determine reasonable limits of extrapolation.

The upper and lower bound beam and column sections selected for parametric study envelope the practicable and reasonable limits of variation in the flange compactness index $b_f/2t_f$ (where b_f is the flange width and t_f is the flange thickness) for both beams and columns. For the *SidePlate* connection system, flange compactness as it affects the relative stiffness between connecting elements is a primary determinant of stress level and load distribution through each critical load transfer mechanism. Compatible linkage between 1) the measured strains and the distribution of applied load through critical transfer mechanisms obtained from the prototype cyclic testing, and 2) the same information analytically computed from the results obtained from both the prototype nonlinear and linear elastic analyses was clearly demonstrated. This fact, coupled with detailed linear and nonlinear parametric analyses addressing relative stiffness between connecting elements and pertinent relative flange compactness considerations, competently qualify the extrapolation of connection implementation to any practicable combination of beam and column sizes (rolled-shape or built-up sections) selected by the structural engineer. These conclusions were independently evaluated and accepted by the ICBO Evaluation Service, Inc., a subsidiary corporation of the International Conference of Building Officials (see ICBO Evaluation Report No. 5366 issued on January 1, 1999, accessible on the Internet, for allowable values and/or conditions of use).

SidePlate™ is the only moment connection system of its kind that has been evaluated by the ICBO Evaluation Service, Inc. and pre-qualified for both uniaxial and biaxial connection configurations without restriction on column and beam sizes.

RELIABILITY AT LOW COST

The cost effectiveness of erected steel frame buildings using the *SidePlate* connection system, as corroborated by cost records of dozens of successfully completed projects, is demonstrated by the new 5-story steel frame San Diego North County Regional Courthouse in Vista, California, U.S.A. The building is designed by Henningson, Durham & Richardson, Inc. (HDR), a nationally recognized A/E firm in the United States. Actual costs were lowered to less than $1350 per short ton for fabrication and erection of structural steel, resulting in a net cost savings to the County of San Diego, California of approximately $700,000 when compared to other alternative post-Northridge moment connections. Typical pre-Northridge moment connection costs in the U.S.A. averaged $1200-$1400 per ton. Comparable buildings using other post-Northridge connections that employ the use of a T-joint complete penetration groove weld to join beam flanges to face of column, such as reduced beam section ("dogbone") designs, have cost $1500-$1900 per ton in the U.S.A. over the past four years, clearly demonstrating *SidePlate™'*s ability to combine cost efficiency with reliability. The intangible benefits of rapid simplified erection is clearly another significant cost-saving attribute, in addition to the substantial hard cost savings already identified.

*SidePlate™'*s erected moment connection system is demonstrated in Figure 5. Moment frame curvature to accommodate architectural facade requirements, which is common in high-rise building applications, can be easily achieved by mitering the ends of the link beam between column trees, while retaining an orthogonal moment connection as tested and qualified.

OTHER APPLICATIONS

Mitigation of Blast Pressure Effects

Strategic facilities and specialty structures needed to house politically sensitive government agencies and functions, police and fire stations, hospitals, and critical petrochemical installations can be designed and constructed using the *SidePlate* moment connection system to mitigate progressive floor collapse and maximize global structural stability when subjected to blast pressure effects. Life-safety concerns associated with either an accidental or malevolent explosive threat can be minimized, while maintaining economy. As mentioned earlier herein, the unique geometry, design configuration, and construction methods that characterize *SidePlate*™ by definition eliminate vulnerability to premature brittle fracture of the connection and members framing into the connection. Collectively these attributes increase the amount of ductility available for connection deformations, therefore enhancing the performance of the connection under deformations exceeding its elastic limit.

Column axial load-carrying integrity is significantly increased by using tube steel or built-up box columns filled with high-slump lean concrete to effectively reduce the slenderness ratio Kl/r of the column and thereby preclude column buckling and instability. Because *SidePlate* connection technology inherently eliminates the need for costly traditional internal diaphragm plates in tube steel or box column at the beam flange elevations, the filling of the column with lean concrete is, by definition, unimpeded. The use of tube steel columns or built-up box columns with the *SidePlate* moment connection system is an approved option.

In a worst-case design scenario, wherein it is assumed that an interior column has been taken out of service due to proximate blast effects, mitigation of progressive floor collapse is achieved by allowing the moment frame beams on either side of the failed column to resist tributary gravity floor loads from above through catenary action (i.e., cable action). The resulting catenary can span two bay lengths between the two columns that are located on either side of the failed column (see Figure 6). *SidePlate*™'s two full-depth vertical side plates connected to the failed column act as effective continuity elements to transfer axial load in catenary action, using horizontal fillet welds loaded in shear along their length to transfer the axial load to the adjacent moment frame beams. The resulting catenary system can sustain the formation of one or more plastic hinges along its length at each column connection location, while remaining structurally stable. Like the design case for high seismicity, the weldments and plates for the *SidePlate* connection, including the link beam-to-column tree connection are designed to develop the full strain-hardened plastic flexural capacity of the connecting beam. Accordingly, the *SidePlate* moment connection technology is ideally suited for this worst case scenario.

Braced Dual System Structures

Structures that are designed with both diagonally-braced and moment-resisting lateral load systems are called *dual systems*. Braced dual systems include steel frame airport traffic control towers and off-shore drilling platforms. Drilling platforms are subjected to severe and continual ocean wave dynamic pressures and gradients that require reliability, durability and robustness. In addition, due to their strategic energy and economic importance, drilling platforms could be subject to malevolent explosive threat. Airport traffic control towers, again because of their strategic importance to both national and international security and stability, could and have been subjected to malevolent explosive threat. *SidePlate*™ is easily adaptable to a braced dual system connection geometry. To do this, its two parallel side plates are extended by sculpting the plate geometry to receive the end of a diagonal bracing member whose web has been intentionally oriented in the flat position (i.e., flanges of the bracing member are oriented in the vertical plane). The diagonal bracing member is field-bolted between the extended "ears" of the two parallel side plates, using slip-critical high-strength twist-off bolts, and oversized bolt holes, to facilitate fit-up and inspection (see Figure 7). Since most global braced dual systems require both moment-resisting frame action and diagonal bracing in each principal direction (i.e., a biaxial dual strong axis connection configuration), adapting *SidePlate*™'s successfully tested biaxial dual strong-axis moment connection is again ideally suited to competently satisfy the rigorous design requirements of this type of specialty structure.

Other more traditional building applications using *SidePlate™'s* braced dual systems include combinations of special moment resisting frame (SMRF) systems and special concentric braced frame (SCBF) systems, which collectively provide increased global frame system ductility and stiffness with a corresponding reduction in design base shear of at least 17% over a solely SCBF system, resulting in significant additional cost savings. Even greater global frame system ductility, together with inherent increased stiffness, can be achieved with the combination of a SMRF system and an eccentric braced frame (EBF) system, which collectively provide increased global frame system ductility with a corresponding reduction in design base shear of at least 20% over a solely EBF system, resulting in even greater cost savings.

Structures Subject to Extreme Wind and/or Low-to-Moderate Seismicity

The *SidePlate* moment connection system is also an ideal choice for design environments of extreme wind and low-to-moderate seismicity. These design environments include office buildings, and petrochemical and power generation applications such as piperacks, turbine buildings, and electrical dead-end bus structures. In these less severe design environments, *SidePlate* connection technology still provides its characteristic increased lateral connection stiffness which is common to all its other design applications, including explosive blast and high seismicity. This results in either a significant reduction in the number of connections and/or steel frame tonnage. In many instances, steel frame buildings that require fixed-base boundary conditions to control lateral drift using other connection systems can instead satisfy the same drift criteria with pinned boundary conditions using *SidePlate* connection technology, resulting in significant savings in foundation costs. In addition, such applications enjoy an additional benefit since connections need only be designed for the equivalent effects of a statically applied design pressure, at service load levels, which is relatively much smaller in magnitude than the severe design environments just cited. Accordingly, the connection's fillet weld sizes can be approximately cut in half. In turn, the link beam-to-column tree connection can be a fully field-bolted connection that requires no special inspection, including no ultrasonic testing. With the use of slip-critical high-strength bolts and oversize bolt holes, the final erection is rapid, predictable and greatly simplified using shop-fabricated column trees.

CONCLUSIONS

The *SidePlate* connection system is a breakthrough technology because of its proven performance and reliability, durability, versatility, and cost efficiency. It eliminates recognized technical uncertainties that are intrinsic with the heretofore more "traditional" use of a T-joint complete-penetration groove weld to connect beam flanges directly to a column flange, and/or to connect a heavy bracing member's flanges to either a column flange or beam flange. Connection ductility and robustness are achieved by using redundant clearly-defined load paths that can be determined by simple statics, giving due design consideration to the direction of applied load on each weld. The unique trademark geometry, simple design configuration, increased connection stiffness, and proven construction methods that collectively characterize the attributes of the *SidePlate* connection system are ideally suited to satisfy a wide variety and technically diverse set of design environments and construction applications for steel frame structures. The System Pre-Qualification of the *SidePlate* moment connection provides rigorous justification for any practicable combination of rolled-shape beam and column sizes without the need for additional testing.

The heightened performance standards and diversity of steel frame applications achieved by *SidePlate* connection technology are clearly equal to the challenges that the new millennium will exact from structural engineers. The result is an integrated cost-efficient set of ductile steel frame connection solutions that perform with reliable and repeatable ductility, while providing virtually unlimited design expression for both uniaxial and biaxial applications, and for both moment frame systems and braced dual systems.

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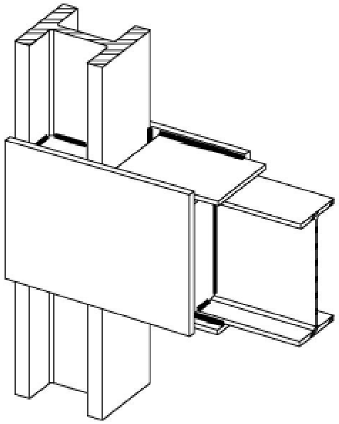


Figure 1: SidePlate™'s unique beam/column separation.

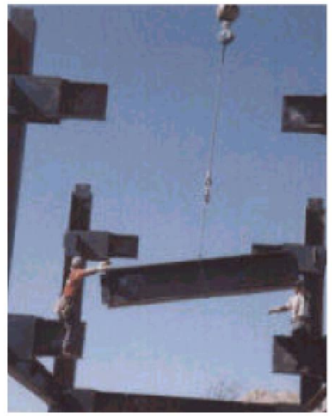


Figure 2: Column Tree/Link Beam erection.

Figure 3: Yielding and buckling pattern of prototype SidePlate™ Uniaxial Test Specimen 3.

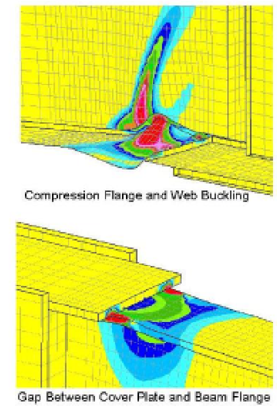


Figure 4: Corroboration of test results through nonlinear analysis.

Figure 5: Completed erection of SidePlate™ Connection System.

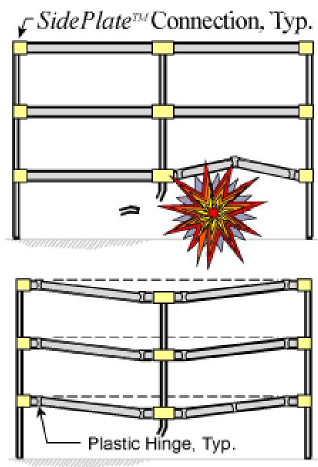
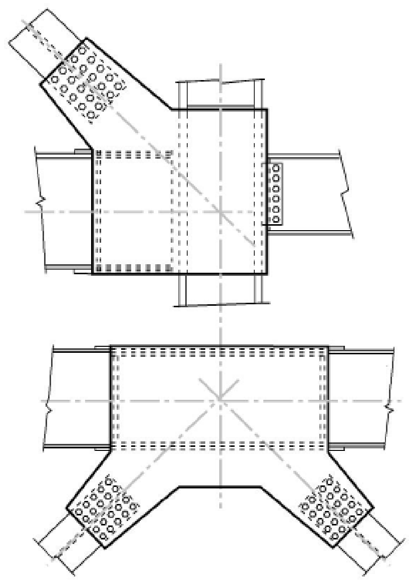


Figure 6: Mitigation of progressive floor collapse due to catenary action using SidePlate™ Connection Technology.



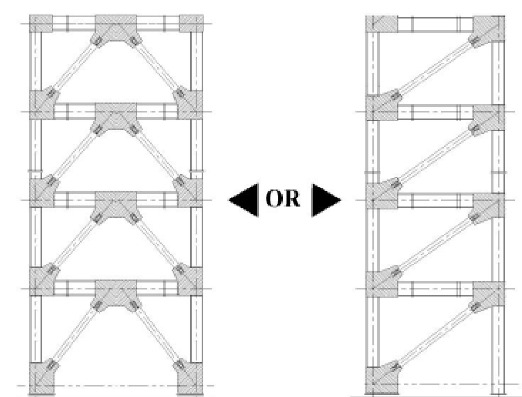


Figure 7: SidePlate™ braced dual systems.