

Current Steel Structures Research

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INTRODUCTION

This issue of “Current Steel Structures Research” for the *Engineering Journal* focuses on a selection of research projects of one major American university. The descriptions will not discuss all of the current projects at the school—there are simply too many. But selected studies provide a representative picture of the research work, and demonstrate the importance of the school to the United States and indeed to the efforts of industry and the profession worldwide.

The university and its many researchers and graduate students are very well known in the world of steel construction: Virginia Polytechnic Institute and State University. Commonly known today as Virginia Tech, over the years the school has significantly expanded its graduate program offerings. The size of the civil engineering faculty in general—and especially the structural engineering group—has become a critical part of one of the leading institutions in the United States. The studies that are presented here reflect elements of the projects as well as other long-time efforts of a primary U.S. advanced academic institution. As has been typical of American, European and worldwide engineering research projects for years, many of the projects are multi-year, and a number are also multipartner efforts. This calls for very careful planning, cooperation and implementation of needs and applications, including the education of graduate students and advanced researchers. The outcomes of the projects focus on industry needs and implementation in design standards.

The Virginia Tech researchers have been active for many years, as evidenced by their leading roles in research and development in the United States, but they have also been frequent participants in the work of other countries and regions. Large numbers of high-quality technical papers and conference presentations have been published, contributing to a collection of studies that continues to offer solutions to complex problems for designers as well as fabricators and erectors.

References are provided throughout the paper, whenever such are available in the public domain. However, much

of the work is still in progress, and in some cases reports or publications have not yet been prepared for public dissemination.

SOME CURRENT RESEARCH WORK AT VIRGINIA TECH

Virginia Tech has been active in steel structures research for a number of years, and research as well as education and professional service thrive at the university. With the growth of the number of faculty members and students focused on structural steel, the Via Department of Civil and Environmental Engineering is recognized as one of the leading programs in the field. There are currently six faculty members and one emeritus faculty member who are actively involved in steel research, education, specification development and outreach. Three of these are past recipients of the T.R. Higgins Award, five serve on AISC task committees, and three serve on the AISC Committee on Specifications.

Steel-related research and education were not always part of the focus of the civil engineering program at Virginia Tech. Prior to 1987, one faculty member in the department was responsible for all structural steel instruction, and there was no structural engineering laboratory. In 1987, Professors Thomas M. Murray and W. Samuel Easterling were hired and charged with developing an experimental structural engineering program. This started with the design and construction of a structural engineering laboratory. The initial 12,000-ft² laboratory opened in 1990. Since that time, expansion of the facility has increased the size to more than 25,000 ft². In 2009, the laboratory was named the Thomas M. Murray Structural Engineering Laboratory, in recognition of Professor Murray's signal efforts to establish the facility and the overall program.

The Structural Engineering and Materials group has grown to a total of 11 faculty members, with seven professors focusing on steel research: Finley Charney, W. Samuel Easterling, Matthew Eatherton, Roberto Leon, Cris Moen and William Wright. Thomas Murray (emeritus) continues to be active in several areas. Some of the ongoing research is described in the following sections, in alphabetical order of the faculty. The primary interest areas of the individual professors are:

- Charney: Earthquake engineering; steel frame analysis and behavior.
- Easterling: Steel-concrete composite floor systems.

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- Eatherton: Steel frame structures; earthquake engineering.
- Leon: Steel and composite structures; earthquake engineering.
- Moen: Cold-formed steel structures; structural stability.
- Murray: Vibrations of steel-framed floors; steel connections.
- Wright: Fatigue and fracture of steel bridges.

Research support is provided by a number of organizations, both private and governmental, including the American Steel Construction Institute (AISC), the American Iron and Steel Institute (AISI), the Federal Highway Administration (FHWA), the National Cooperative Highway Research Program (NCHRP), the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), Nucor Corporation, the Metal Building Manufacturers Association (MBMA), the Steel Deck Institute (SDI), the Steel Structures Technology Center (SSTC) and Virginia Tech.

Professor W. Samuel Easterling is the Department Head of Civil Engineering at Virginia Tech. Over the years, he has conducted a great many significant research projects in composite construction, cold-formed structures and metal building systems. As the chief of a large academic department, his time available for teaching and research has become restricted over the past several years, but he continues to be very active in various projects and is a prominent participant in the research and development activities of AISC, AISI, ASCE, MBMA and SDI.

Selected Projects of Professor Finley Charney

Improved Structural Systems for Performance Based Earthquake Engineering: Funded by NIST, this project aims to develop new or improved existing systems that inherently satisfy seismic performance requirements at multiple limit states. Further, the computed performance of the new systems must be based on realistic models, including gravity framing. To improve the reliability of the predicted behavior, a variety of uncertainties in modeling and computational procedures are included in the analysis. A preliminary study that evaluated the performance of a hybrid energy-dissipating device that performs like a viscoelastic damper at low levels of deformation and transforms into a metallic yielding device (a buckling restrained brace) at higher levels of deformation provided the basis for the project (Marshall and Charney, 2011).

Assessment of Gravity Framing Contributions to System Behavior: During the Northridge earthquake in 1994, many steel structures exhibited failure of primary moment-resisting connections, but the structures did not collapse

because the gravity system framing acted as a backup partially restrained frame system. Thus, to provide an accurate assessment of the collapse performance of new systems developed under the NIST project, it is essential that the gravity system be included in the analysis. The first phase of the study is complete, using special steel moment frame archetypes that were analyzed as part of the ATC 76 project. The gravity system was not included in the ATC 76 analysis.

In the current study, the original ATC 76 archetypes of two-, four- and eight-story frames without consideration of the gravity system have been reanalyzed. Additional analysis was performed using a variety of assumptions related to the flexural capacity of the gravity connections, the location of gravity column splices and methodologies for including yielding in the gravity columns. The beam-to-column connections in the gravity system were modeled using the recommendations of ASCE 41-06 (ASCE, 2007). The main lateral load-resisting system was modeled as was done in ATC 76.

A series of pushover curves for the four-story system with elastic gravity columns and nonstaggered splices is shown in Figure 1. The GS suffix in the legend (e.g., 35GS) indicates the percent of the flexural capacity of the gravity beam that was assumed to be developed at the connection. It is noted that the gravity columns, acting alone (0GS), have a minor influence on the frame response, as seen when compared to the line curve below the 0GS curve. The latter applies to the structure modeled without the gravity system. It is expected that the 35GS system is realistic in terms of the types of practical gravity systems, and for this system, the pushover behavior is considerably improved. The project has also provided analyses of probabilities of collapse for various ground motions, taking into account connection strengths, column modeling and column splice modeling.

Development of Collapse-Prevention Systems: In the central and eastern United States, the level of ground shaking for serviceability events (50% probability of being exceeded in 50 years) is very low compared with the expected shaking for the more rare maximum considered event (2% in 50 years). In contrast, ground shaking for serviceability on the West Coast is very significant. In Charleston, South Carolina, for example, the serviceability shaking is negligible and damage is highly unlikely. This is compared with some locations in California, where the serviceability event can produce ground motions as high as 30% of the design level event, resulting in significant damage to nonstructural components and to inelastic deformation in the main lateral load-resisting system.

The preceding observation has led to the concept of developing “collapse prevention” systems in the central and eastern United States, for which the *only* design limit state to be considered is collapse. The design of the main structure is for gravity plus wind only, and seismic collapse safety is

provided by auxiliary systems that are benign under low-level shaking but engage and prevent collapse under the extremely rare design events.

Several schemes for collapse prevention in steel structures are being examined, including slack cables and slack linkages. These systems would engage only after a set interstory drift is attained. The cable or linkage becoming taught, plus the residual strength of the main lateral load resisting system, provide ultimate resistance of the system. Preliminary results from this research are shown in Figure 2, where response history traces are shown of the roof drift of a four-story steel moment frame with and without a slack linkage collapse prevention system. The linkage is designed to engage at 2% interstory drift. The result is a stable response, although there is significant residual deformation after the event, but this is more desirable than the collapse that occurs without the linkage. Traditional design of the structure would require significant increases in strength and stiffness, which leads to larger seismic forces and larger structural components—hence, additional cost.

Hybrid Frame Systems: Funded by AISC, this project expands on previous efforts to develop a new, hybrid moment-resisting steel frame (Charney and Atlayan, 2011). The goal of the study is to develop an improved type of seismic lateral force-resisting system that will perform better than traditional systems under various ground motion intensities. The key concept is to provide early yielding in some elements of the structure and to delay it in the other elements, as illustrated in Figure 3. The energy dissipation due to early yielding provides vibration control and reduces

the likelihood of resonant buildup. The delayed yielding increases post-yield stiffness, which reduces the residual deformations and reduces the likelihood of dynamic instability under high ground motion intensities.

Hybrid behavior can be achieved using various strategies, including mixed materials and mixed systems. In a hybrid material strategy, the hybrid behavior shown in Figure 3 can be achieved through the combination of a low yield point (LYP) steel, which may have a yield strength of 14.5 ksi, and high performance steel (HPS), which has a yield strength of 70 to 100 ksi. The hybrid multicore buckling restrained brace (BRB) shown in Figure 4 is an example of the mixed material strategy. Similarly, LYP steel can be used in moment frame connections where early yielding is desired, and high-strength reinforcement can be added to other connections in the moment frame to delay yielding (Atlayan and Charney, 2012a, 2012b). An example of the mixed-system strategy is the hybrid moment frame where three different types of connections (e.g. special moment frame, intermediate moment frame and ordinary moment frame) can be combined in a single hybrid moment frame (Charney and Atlayan, 2011). In this system, the special connections are designed to yield first, followed by the intermediate connections and then the ordinary connections.

The hybrid BRB part of the research work has been completed. The performance generally improves with the level of hybridity. It has also been found that the improvement in response at lower-level ground motions is somewhat higher than for higher-level motions, which enhances the serviceability behavior of the system. This is the main benefit of allowing minor yielding at lower-level ground motions.

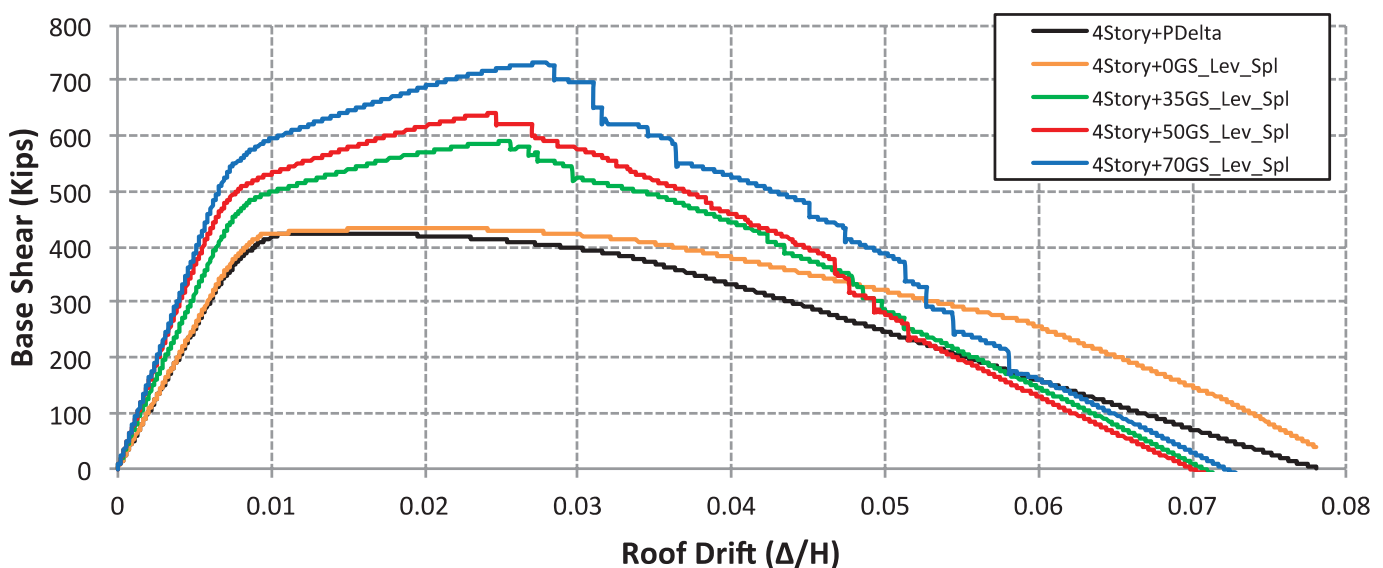


Fig. 1. Pushover curves for four-story frame with various gravity connection capacities (figure courtesy of Professor Finley Charney).

Selected Projects of Professor Matthew Eatherton

Effect of Defects on the Seismic Behavior of Steel Moment Connections: Steel moment frames in seismic regions depend on large inelastic strains in the beam-to-column connections to dissipate seismic energy. For that reason, the ends of the beams in a moment frame are defined as protected zones, and many types of attachments are prohibited. Examples of unauthorized attachments in the protected zone are commonplace. However, there are almost no data available on how moment frames that have fasteners, defects or repaired defects in the connection region will behave during an earthquake. Physical testing is critical to determine whether connections with these types of conditions will provide adequate seismic performance.

Such a testing program is currently under way at Virginia Tech. Twelve full-scale connection tests are being performed on W24×62 and W36×150 beams with and without reduced beam sections (RBS). Figure 5 shows a specimen with a powder-actuated fastener that has sustained significant inelastic deformations without fracture. To further evaluate the low cycle fatigue fracture potential of these types of connections, a large coupon test program will be conducted

in coming year. The testing will include control specimens with no defects, powder-actuated fasteners, self-drilling screws, tack welds and specimens repaired using welding or grinding.

Super-High-Tension Bolts: Super-high-tension bolts were developed in Japan and are currently being used in construction in that country. The specified minimum tensile strength is 200 ksi, as compared to 150 ksi for ASTM A490 bolts (and the European grade 10.9). There is a desire to make super-high-tension bolts available for use in the United States to facilitate more compact connections using fewer bolts. However, to use super-high-tension bolts in the United States, it is necessary to develop installation procedures that are similar to current U.S. practice, as described in the Research Council on Structural Connections (RCSC) specifications. Japanese bolt installation procedures are generally more restrictive than U.S. procedures in that the torque at the snug-tight condition and the subsequent angle of nut turn are controlled even for twist-off type bolts.

The current project aims to develop suitable installation procedures for twist-off super-high-tension bolts. More than 300 pretension tests are being conducted, using various bolt

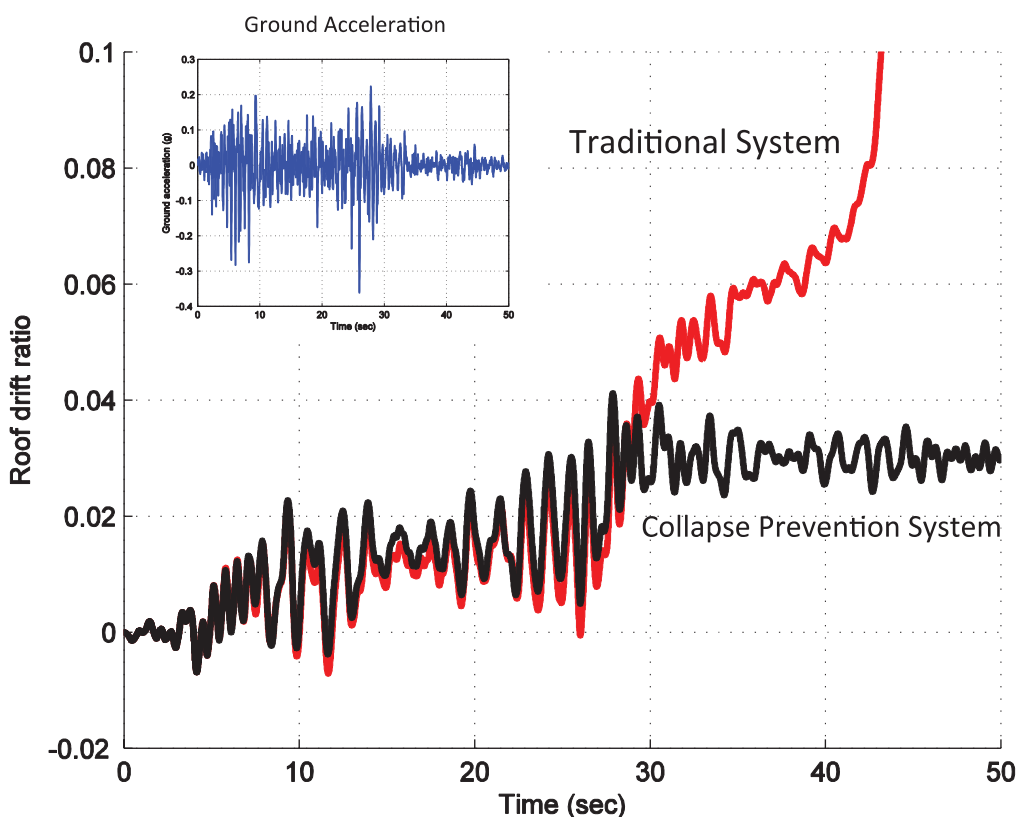


Fig. 2. Computed responses of traditional and collapse-prevention system (figure courtesy of Professor Finley Charney).

diameters, bolt lengths, temperature, number of threads in the grip, variations in lubrication from as-received to rusted or relubricated, and bolt hole geometry. The pretension tests use an instrumented Skidmore-Wilhelm machine to record bolt tension during the installation, including for the snug-tight condition, twist-off of the spline and, in some cases, tightening past yield with a hydraulic wrench. The nut angle of turn is also recorded at key times during each test. It is anticipated that recommendations will be made for appropriate installation procedures.

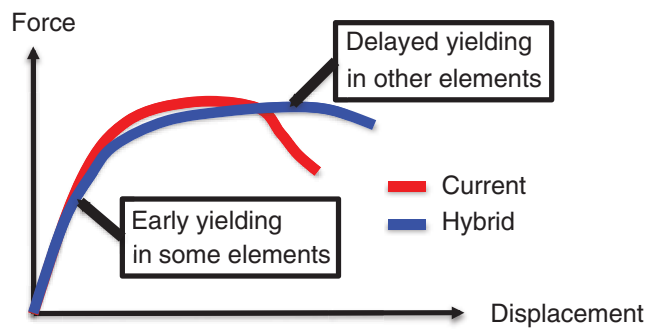


Fig. 3. Effect of hybrid detailing on pushover response (figure courtesy of Professor Finley Charney).

Ring-Shaped Steel Plate Shear Walls: The ring-shaped steel plate shear wall (RS-SPSW) builds on the advantages of conventional, solid steel plate shear walls but improves seismic performance, reduces demands on boundary elements and allows simple shear beam-to-column connections. The wall consists of an SPSW in which the web plate is cut with a pattern of holes, leaving ring-shaped portions of steel connected by diagonal links. The ring shape resists out-of-plane buckling through the mechanics of how a circular ring deforms into an ellipse. Tests and finite element analyses

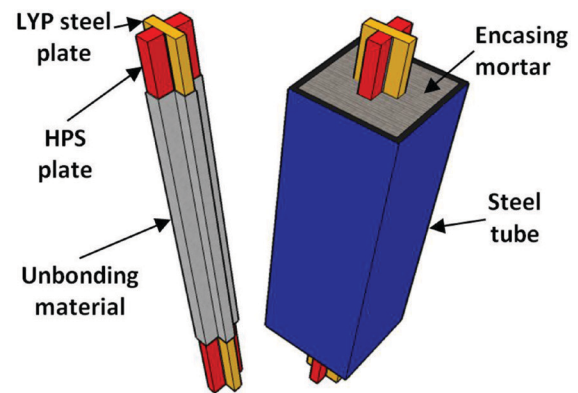


Fig. 4. Hybrid buckling restrained brace (figure courtesy of Professor Finley Charney).



Fig. 5. Deformed protected zone with intermittent powder-actuated fasteners in the flange (photograph courtesy of Professor Matthew Eatherton).

have shown that the compression diagonal of the ring will shorten a similar amount as the tension diagonal elongates. Essentially, the slack is removed in the direction perpendicular to the tension field, thus resisting the tendency for the plate to buckle. Because of the unique features of the ring's mode of distortion, the load-deformation response of the resulting RS-SPSW system can exhibit full hysteretic behavior. Improved energy dissipation and stiffness make the moment connections that are required for conventional steel plate shear walls unnecessary. Furthermore, through the introduction of more design variables associated with the geometry of the rings, it is possible to tune the strength, stiffness and ductility of the RS-SPSW system.

Parametric finite element modeling has been performed to identify key variables and quantify their effect on system behavioral characteristics (Maurya, 2012). Tests on panels that are approximately 40 in. by 40 in. (see Figure 6) have validated the RS-SPSW concept, and full-scale panel tests are planned for next year. Further computational studies will be conducted to examine the behavior of the RS-SPSW buildings and determine appropriate design procedures.

Self-Centering Beams for Resilient Earthquake Resistance: A self-contained self-centering beam (SC-beam) has been

developed that provides self-centering seismic behavior with enhanced constructability (Darling, 2012). The SC-beam consists of either a beam or a truss with concentric tubes for the bottom chord. The tubes of the bottom chord are precompressed with post-tensioning strands and connected to the top chord and columns to produce restoring forces regardless of whether the SC-beam is racked to the right or left.

Preliminary analyses show that the system offers several advantages as compared with other self-centering systems. Thus, the SC-beam can be shop fabricated and erected with conventional field techniques. Post-tensioning in the field and fit-up of bearing surfaces is not needed. Preliminary designs required approximately the same amount of steel as the comparison special moment-resisting frame. There will likely be a cost premium because of fabrication needs (Darling and Eatherton, 2012). Finally, the strength, stiffness and ductility can be independently tuned. Frame layout in a floor plan is not constrained by special detailing, as is currently required for SC moment frames that experience floor expansion.

Seismic Moment Connections for Deep Beams with Slender Webs: Typical built-up sections for pre-engineered metal

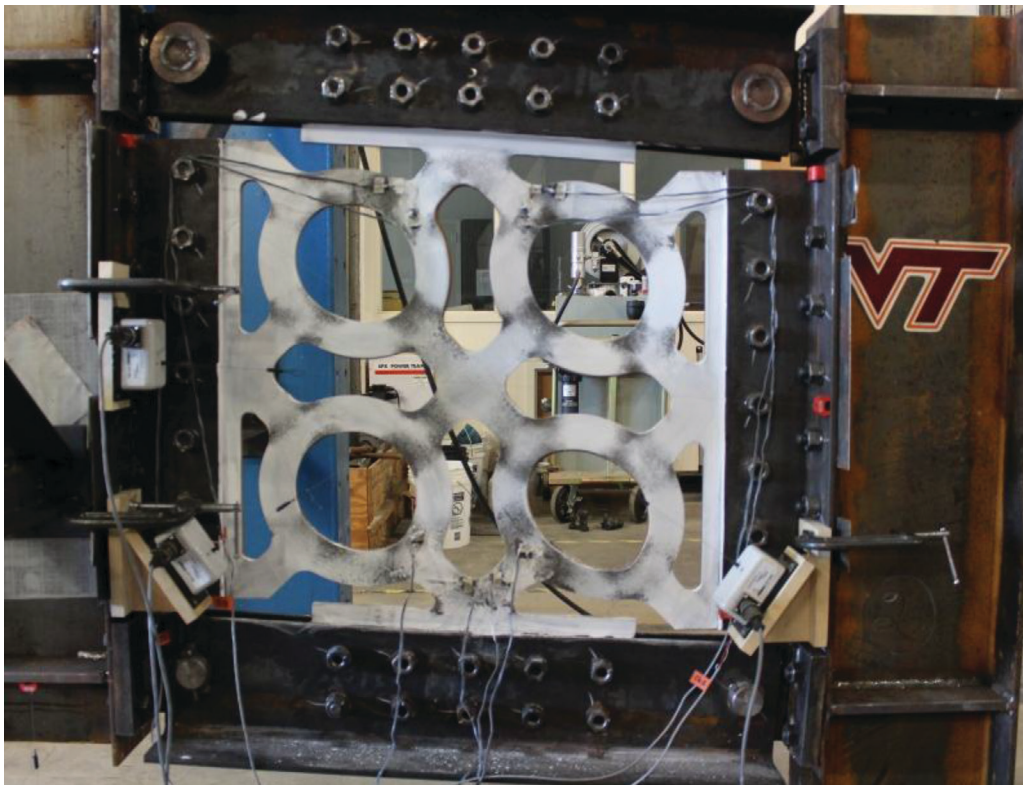


Fig. 6. RS-SPSW test specimen subjected to large drift angle with negligible buckling (photo courtesy of Professor Matthew Eatherton).

buildings have thinner webs than what is used for wide-flange shapes. The web slenderness for deep built-up members can be considerably larger than the limits for highly ductile members or moderately ductile members, as specified in the AISC *Seismic Provisions* (AISC, 2010). However, previous tests suggest that with proper detailing, these members may be able to develop adequate cyclic performance (Ryan, 1999).

Research is now being conducted on connections for deep built-up members with slender webs to improve their seismic performance. Several configurations have been evaluated, using finite element analysis and full-scale tests of 48-in. built-up sections. Figure 7 illustrates the behavior of an unstiffened slender-web beam, undergoing buckling of web and flanges. The web provides little rotational restraint to the flanges, which therefore buckle when subjected to relatively small story drift. Possible schemes for stiffening the web have been identified; these will be further studied for practical implementation.

Selected Projects of Professor Roberto Leon

For many years a professor at Georgia Tech in Atlanta, Georgia, Dr. Leon recently joined the faculty at Virginia Tech, where he is continuing his research in the areas of steel and composite structures with emphasis on seismic design. He recently completed a large experimental program on the behavior of concrete-filled tube (CFT) composite columns. The project included testing the longest and most slender specimens ever tested under different combinations of axial and biaxial flexural loads, and included the use of high-strength concrete ($f'_c > 12$ ksi). Columns with equivalent length to diameter (kL/d) ratios of > 100 were tested. The results are being used to validate and improve current AISC composite column design provisions. The experiments also shed light on the influence of wet concrete forces on the tubes, local buckling and plastic hinge length.

Dr. Leon is continuing work on composite systems in the area of seismic performance system factors and through studies on connections to composite columns. The connections study emphasizes the development of innovative through-bolted connections to rectangular columns that utilize combinations of shape memory alloy (SMA) rods for recentering and conventional steel rods for energy dissipation. Further, detailed analytical models, physical tests and design provisions for connections to composite columns utilizing through, internal or external diaphragms are examined. This second type of connection is very common in Asia but not in the United States due to the perceived complexity of fabrication. This project aims at developing economic connections to CFT columns for use in low-rise construction (fewer than 10 stories) in North America.

Additional work focuses on the development of a robust brace in which (1) the need for energy dissipation does

not lead to residual deformations and (2) the reuse of the recentering components and easy replacement of the energy dissipating components damaged in an event are easily achievable. This device uses conventional buckling-restrained struts to dissipate energy and superelastic shape memory alloy (SMA) wires to recenter the structure (see Figure 8). These hybrid braces could reduce permanent drift considerably. They are assembled from easily replaceable damageable elements.

Dr. Leon continues to examine the validity of the equations that are used to predict the deflection of composite beams, the influence of long-term effects (creep and shrinkage) on composite columns performance, the applicability for design of plastic section analysis to unsymmetrical composite sections and the effects of composite diaphragm action on 3D building analysis. The study on floor diaphragms includes determination of appropriate values of stiffness and strength to be used in analysis, the effects of openings in the floor slab and any preexisting slab cracking, as well as the modeling of connections to chord and collectors and interactions between in-plane and out-of-plane forces at the local level.

Selected Projects of Professor Cristopher Moen

Steel Beam Deflections and Stresses during Lifting: The behavior of steel beams during lifting is often challenging for engineers and contractors, and a new analysis approach is now available (Plaut, Moen and Cojocar, 2012). The equation-based approach assumes that the beams are horizontally curved, doubly symmetric, prismatic and linearly elastic and are suspended at two symmetric locations. The two cables lifting the beams may be vertical or inclined symmetrically. Weak-axis and strong-axis deflections, roll angle and cross-sectional twist, internal forces, bending and twisting moments, and longitudinal stresses can be calculated using the newly derived analytical solutions (Plaut and Moen, 2012) implemented as a freely available spreadsheet at www.moen.cee.vt.edu/. Lifting locations along a steel beam that minimize displacements and stresses can also be identified.

Capacity Prediction of Open-Web Steel Joists Partially Braced by a Standing Seam Roof: A new strength prediction approach has been developed for open web steel joists partially braced by a standing seam roof (Moen, Cronin and Fehr, 2012). The approach uses the AISC column curve to calculate the top chord flexural buckling capacity and to determine the elastic buckling load, including standing seam roof bracing stiffness. Recently derived buckling load equations are presented that account for the lateral stiffness provided by the roof and the parabolically varying axial load from a uniform vertical pressure along the span. A new hybrid experimental-computational protocol is introduced

for approximating standing seam roof lateral stiffness for systems without and with intermediate bridging. Figure 9 illustrates the roof system with trusses and the standing seam roof.

Limit State Design of Metal Building Wall and Roof Systems: A multiyear project aims at developing and validating an equation-based strength prediction framework for simple- and continuous-span metal building wall and roof systems subjected to gravity loads or wind uplift. The intent is to provide a procedure that can be used in lieu of the current empirical test-based approaches. The limit state checks include girt or purlin flexural capacity, panel capacity and panel connection strength. The connection strength is an addition to the current method. The connection limit state

was incorporated on the basis of suction load tests with wall girt rotation and fastener failures (Fisher, 1996; Gao and Moen, 2012, 2013).

The limit state design procedure is based on the AISI direct strength method (AIS, 2012). In the past, the restraints of the system could only be determined by tests, but now hand solutions are available for through-fastened metal panels (Gao and Moen, 2012). Significant advances have been made in this very complex area, and work is continuing to extend the procedures to continuous girt and purlin spans, subjected to uplift and suction, and to derive screw demand equations for the connection strength check.

Strength Prediction of Steel Columns and Beams with Holes: The extension of the direct strength method to columns and



Fig. 7. Full-scale test of 48-in. slender web beam with end-plate moment connection (photograph courtesy of Professor Matthew Eatherton).

beams with holes was recently approved for inclusion in the Specification for Cold-Formed Steel Structural Members (AISI, 2012). The method is based on simplified elastic buckling solutions—including local, distortional and global buckling—and takes into account discrete holes of any size, shape and spacing (Moen and Schafer, 2009, 2010). The simplified elastic buckling prediction methods were derived for cold-formed steel members, but they are also applicable to hot-rolled steel members. Finally, the method has been modified to address the strength and behavior of columns with periodic perforations, of the type found in the columns of rack structures (Smith and Moen, 2013).

Selected Projects of Professor William Wright

Highway Bridge Fire Hazard Assessment: Fires involving highway bridge structures are relatively rare, but the consequences can be significant when they occur. In extreme cases, the fire can result in a bridge collapse, but the typical case involves some degree of serviceability impairment. When fires do occur, there is an immediate need to assess the safety of the structure and its potential re-opening. Longer-term decisions also have to be made concerning subtle damage that can reduce the service life of the structure. The goal of the project is to develop a guide for fire damage evaluation specific to bridge structures. As a starting point, the research team developed a database that details bridge fires that were found through a thorough literature search and through communications with state departments of transportation (DOTs).

A survey of the available fire data in the United States shows that most fires involving bridges do not cause damage. For typical steel and concrete bridges, the bridge itself is not a combustible fuel source. The predominant cause of fire exposure is burning vehicles on or underneath the structure. Wildfires, stored combustible materials, utility pipelines and construction operations have also been documented. Focusing on vehicle fires, the data show that most are minor events that do not cause significant damage to bridges. There have been three reported cases of complete bridge collapse due to fire, all involving ignition of fuel-carrying vehicles at a critical location underneath the bridge. Approximately 25 cases have been found where the bridges were either totally or partially incapacitated for carrying traffic. That compares to approximately 500 events per year involving collisions on bridges involving fire.

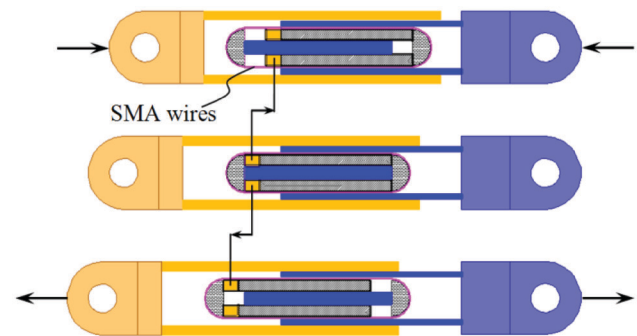


Fig. 8. Behavior and schematic view of a robust brace (figure courtesy of Professor Roberto Leon).

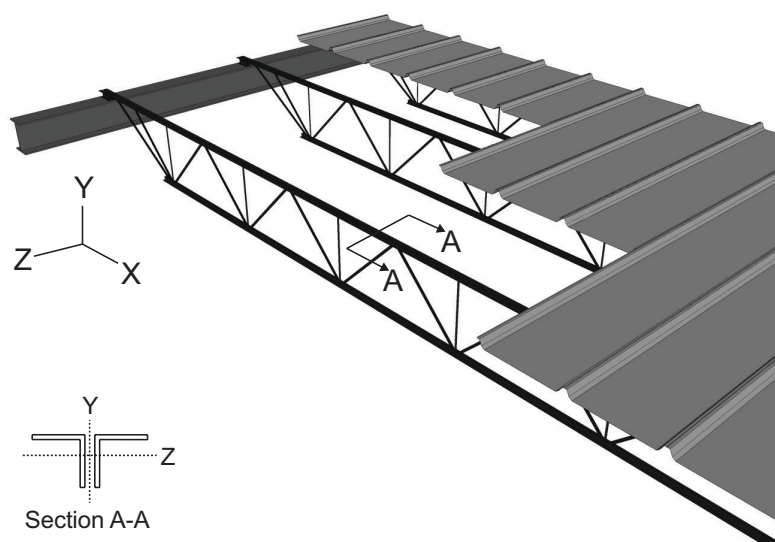


Fig. 9. Structural system with trusses and standing seam roof (figure courtesy of Professor Cristopher Moen).

One goal of this study is to understand the specific situations that cause damage. This is being accomplished by performing a series of finite element fire simulations involving a typical grade separation structure. The variables being investigated include vehicle fire intensity, fire position and vertical clearance over the fire source. A fire case study involving a grade separation structure on I-65 in Birmingham, Alabama, was selected as the basis for developing the simulation methodology. A collision involving a fuel truck caused a severe fire close to one of the bridge piers. Figure 10 shows the charred pavement and indicates the fire location and the resulting deflection of the superstructure.

A methodology for simulating fire events on bridge structures has been developed. The fire dynamics simulation (FDS) software developed by NIST was utilized to generate the heat flux applied to the bridge. Fires can be generated with different footprints and fuel content to simulate the range of vehicles that may be involved in fires. The bridge geometry with cavities between the girders underneath the bridge creates a boundary condition that greatly affects the longitudinal and transverse flame spread under the structure. The heat fluxes generated in FDS are then applied to a finite element thermal analysis model developed in ABAQUS. The model generates a temperature–time history for all elements in the bridge. The final step applies these temperatures to a structural analysis model to determine the time-dependent structural response of the bridge. Because

steel properties change at increasing temperatures, the non-linear material model accounts for the changes in the stress-strain curve at elevated temperatures. Steel creep also has a significant effect on the response, depending on temperature and fire event duration.

The modeling methodology has been calibrated against several significant structural system tests that have been performed on building floor structures. The next step was to model the fire event shown in Figure 10, and it was possible to predict the actual deflections. A parametric study was then conducted to understand the effect of fire size (vehicle and contents type), fire location and clearance under the bridge.

Fracture Critical System Analysis: Current design and inspection practices for highway bridges require nonredundant tension members to be classified as *fracture critical* (FC). Fracture critical members are defined as those whose failure may reasonably be expected to cause collapse. Once designated, FC members must be fabricated from materials with a higher Charpy V-Notch (CVN), including higher standards for welding and weld inspection. FC members must also be subjected to higher levels of in-service inspection as mandated by the National Bridge Inspection Standards. This requires a bi-annual, hands-on inspection of every fracture critical member that is more rigorous than the general inspection protocol for all bridges. The intent of the



Fig. 10. Fuel tanker fire below an overpass on I-65 in Birmingham, Alabama (photograph courtesy of Professor William Wright).

FC designation is to reduce the probability of defects that can lead to fatigue cracks and to provide a higher probability of detecting fatigue cracks before they grow to critical size for fracture.

History has shown that fabrication quality is beneficial to reduce fatigue vulnerability of structures. However, much of the effort expended to perform fracture critical in-service inspections has had questionable success in preventing fracture. The cost of hands-on FC inspection is significant and should only be utilized when there is a clear benefit to bridge safety. Therefore, this project is developing guidelines for using refined analysis to take advantage of 3D system capacity in determining which members may cause collapse.

The inspection adds significant maintenance costs to structures with FC members. The current approach of classifying bridge members as fracture critical is largely based on simple analysis assumptions such as girder-line analysis and 2D pin-connected truss models. These methods are very conservative because they ignore the 3D system performance of the structure.

Research is under way to understand the system strength of damaged structures. Fracture events create a sharp discontinuity in members that significantly alters the load path assumed by the bridge designers. However, observation of girder-type bridges that experience fracture of one girder indicates that significant alternate load paths exist. There has never been a system collapse of a girder-type bridge due to fracture, even when one girder in a two-girder system is completely fractured. The structures typically do not experience large deflections in the damaged condition, demonstrating that alternate load paths exist.

The study is developing highly detailed finite element simulations of several bridges that have experienced brittle fracture of a main load-carrying member. As a prime example, the Hoan Bridge on I-794 in Milwaukee, Wisconsin, shown in Figure 11, experienced brittle fracture in two of the three girders that support the end span of a continuous plate girder structure. The bridge did not collapse, despite the approximate 4-ft vertical deflection above the fracture location. This is a very severe test of system capacity because the fractures occurred in an end span and the girders were noncomposite with the concrete deck. Simplified analysis approaches indicate that collapse would have been expected with this level of damage, yet the system strength was sufficient to prevent collapse. Using the documented condition of the Hoan Bridge as a verification benchmark, this study has developed a highly detailed, nonlinear model of the damaged structure, as shown in Figure 12.

As a first step, the model is being used to understand the load paths that prevented collapse of the bridge. Loss of two main load-carrying members caused shedding of loads to the concrete deck, floor beams and other secondary members that were never considered to be part of the load path of

the structure. The capacity of the secondary members and their connections must be determined to validate the system capacity. A major goal of the project is to establish procedures to validate system-modeling results to ensure that any members carrying load in the model have the integrity to actually carry loads in the structure.

Design and Fabrication Standards to Eliminate Fracture Critical Concerns for Steel Members Traditionally Classified as Fracture Critical: This project is a research collaboration between Purdue University (Professor Robert Connor) and Virginia Tech (Professor Wright). The aim is to develop improved requirements for steel toughness that provide a quantifiable measure of fracture resistance. Brittle fracture became a major concern following the collapse of the Silver Bridge in Point Pleasant, West Virginia. There have been dozens of cases where structures are seriously damaged following brittle fracture of a main load-carrying member. A review of these cases reveals that there are three general causes of brittle fracture:

- Fatigue cracks grow to a critical size that allows brittle fracture to initiate under live load.
- High constraint details or local brittle zones allow brittle fracture to initiate under live load without any preexisting fatigue.
- Vehicle impact events cause a dynamic shock load to steel members.

Of the three, only the fatigue cracks are addressed by the American Association of State Highway and Transportation Officials (AASHTO) Fracture Control Plan (FCP) that was developed in 1978. The FCP places a strong emphasis on preventing fatigue cracks through fabrication quality control and in-service inspection. CVN toughness requirements are established for bridge steels that help prevent brittle fracture initiation from small fatigue cracks. The intent of the FCP is to either prevent fatigue cracks or to detect them through inspection before they reach critical size. Large fatigue cracks, constraint conditions and impact events can still cause brittle fracture initiation for structures meeting the requirements of the FCP. In addition, the toughness requirements in the FCP do not provide any appreciable crack arrest capability once fracture initiates. Therefore, when brittle fracture is initiated, it typically does not arrest in members or portions of members under tension.

The use of high-performance steel (HPS) grades in the ASTM A709 Specification for Bridge Steels is a major advance for fracture control. These grades can be produced with CVN values that far exceed those provided by conventional structural steels. The property enhancement leads to a much higher level of fracture initiation resistance from fatigue cracks and constraint details under live loads. More importantly, it also offers a significant capacity for crack

arrest that can limit the propagation of damage if fracture does initiate. Given the volume and scale of steel bridge fabrication, it is unlikely that 100% quality control and 100% inspection reliability can be achieved. Crack arrest resistance provides a significant approach to limit damage in the rare cases where a critical defect is not found. Once the

fracture propagates from the local defect initiation site, it runs into tougher material and arrests. This prevents sudden total member loss that has been the main concern from the fracture limit state.

The work at Virginia Tech focuses on a series of small specimen fracture tests to establish the fracture initiation



Fig. 11. Two of three girders with full-depth fractures in the Hoan Bridge in Milwaukee, Wisconsin (photograph courtesy of Professor William Wright).

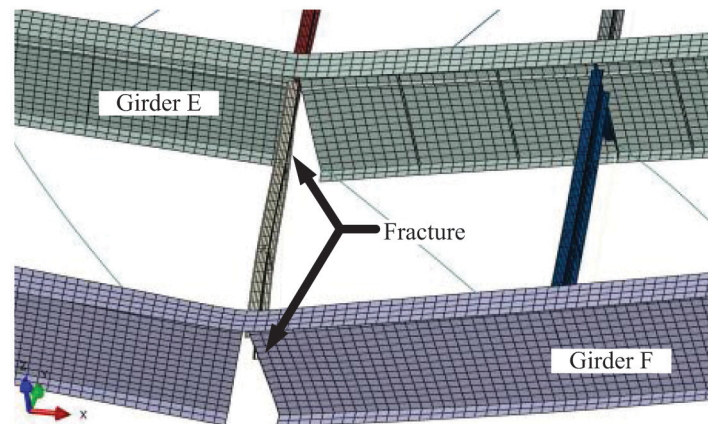


Fig. 12. Nonlinear finite element model to study the system capacity of the Hoan Bridge (figure courtesy of Professor William Wright).

resistance and crack arrest resistance of HPS and conventional bridge steels. While the CVN test is used for quality control in steel production, the test results cannot be directly used to predict fracture resistance. A more elaborate version of this test using precracked CVN specimens is being used to better quantify fracture resistance. This allows the establishment of a master curve for fracture resistance as a function of material temperature. Once the performance is established, correlations are developed to set material testing requirements based on the conventional CVN testing procedures.

In coordination with the work at Virginia Tech, the researchers at Purdue University will perform a series of full-scale fracture tests of bridge members. This will ensure that the small specimen test results translate into realistic performance criteria of actual bridge members. The final product will be a new supplemental material toughness specification (FC-Plus) that provides enhanced fracture initiation resistance and crack arrest resistance. The intent is that these criteria can be specified by designers for certain low-redundancy members in order to improve system reliability. This may eliminate the need for special FC inspection for bridge types such as two-girder systems.

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