Current Steel Structures Research

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This quarter, we focus on a selection of current research projects at three major Japanese universities. The descriptions do not discuss all of the current projects at the schools. Instead, selected studies give a representative picture of the research efforts and demonstrate the schools' importance to the efforts of industry and the profession worldwide.

The universities and their structural steel researchers are very well known in the world of steel construction: University of Kyoto, Tokyo Institute of Technology and Osaka University. Researchers at these institutions have been very active for many years, as evidenced by their participation and leading roles in the seismic and other standards development efforts of Japan, and indeed of the United States and many other countries. In fact, all three universities have collaborated actively with several American schools, sharing testing facilities and involving numerous faculty members and graduate students. Large numbers of outstanding technical papers, reports and conference presentations have been published, contributing to a collection of landmark studies that continue to offer practical 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.

SELECTED RESEARCH AT THE UNIVERSITY OF KYOTO

Focusing on the all-important issues of earthquake resistance and performance of materials and structures, the Disaster Prevention Research Institute (DPRI) was established in 1962 at the University of Kyoto by the late Professor Minoru Wakabayashi. Over the years, it has been a uniquely successful undertaking, not the least through a significant number of doctoral graduates who have occupied leadership roles in Japan and in the international arena.

One of the current leaders of DPRI is Professor Masayoshi Nakashima. A Lehigh University Ph.D. graduate, Professor Nakashima is also the Director of the Hyogo Earthquake Engineering Research Center, one of the central operations of the Japanese National Research Institute for Earth Science and Disaster Prevention (NIED). He has been the director or a primary leader of the four research projects that are discussed in the following sections of the paper.

Development of Distributed Hybrid Testing Techniques and Their Application to Collapse Simulation of Steel Moment Frames: The study is a major effort that has been under way in Japan since the late 1960s. Originally, structural testing around the world was based on the static response of frames and frame components. Considering the loads and deformations that are imposed on a structure under seismic conditions, the static tests could not capture the demands associated with large displacement cyclic behavior. Originally referred to as a pseudo-dynamic test, the hybrid test has been under development and continuous application for numerous experiments over the past 40 years. Its evolution and application has been a continuing joint effort between the University of Kyoto and a number of Japanese and American universities.

Essentially, the hybrid test provides a numerical solution for the dynamics of the structure, and the restoring forces are determined from physical tests that are run in parallel with the computation. When the substructure approach is used, the advantage is that the physical test does not have to be performed in the same laboratory. Instead, the substructure is disassembled and the individual parts can be tested simultaneously in different locations. Further, it is not even necessary to do physical tests of all of the parts, since some of them may be "tested" numerically by using appropriate finite element models.

The researchers at DPRI have developed an approach that makes use of the above concepts (Pan et al., 2006). It is extremely complex but has been proven very successful. Specifically, through an extensive coordination effort, the data from tests and numerical solutions of a number of substructures are exchanged with the central management. Subsequently, the data are used to provide the prediction of the complete structural response. As an example, the complete seismic response of a four-story single bay frame was determined, using two substructures that were physically tested at different locations, along with one finite element code (Wang et al., 2008). Various levels of ground motion were used, including one that led to the collapse of the structure. The failure was initiated by excessive damage in the column bases, as shown in Figure 1.

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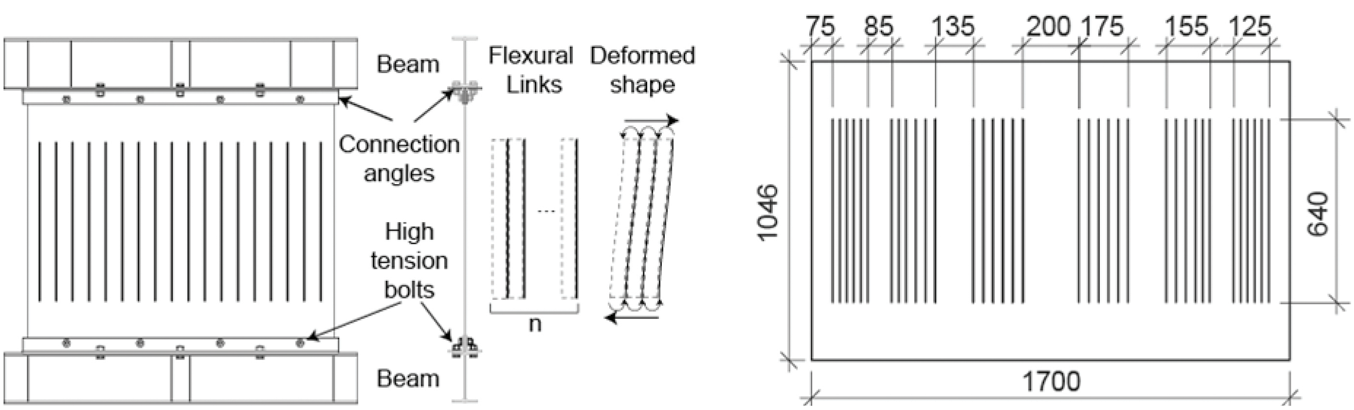
Performance and Retrofit of Steel Beam-to-Column Connections of High-Rise Buildings: High-rise buildings have been constructed in Japan for more than 40 years, and at this time there are more than 2,000 such structures in the country. Certain seismic conditions in Japan are a particular issue for such structures, because the subduction earthquakes that are generated to the south of the country have long periods and long duration. A complete four-story structure with four longitudinal bays and three transverse bays was tested with the very large shaking table of the E-Defense laboratory (Chung et al., 2010).

In addition to the shaking table test, a series of typical beam-to-column connections were also tested to determine dynamic failure characteristics and energy absorption. Retrofit methods were also examined. One of the failure modes is shown in Figure 2, where the bottom flange fractured from a crack that started at the toe of the weld access hole. This detail and its performance are, of course, very similar to what was experienced for similar connections during the 1994 Northridge earthquake. The researchers observe that it is likely that some of the older connections may suffer similar problems in future earthquakes.

Friction Resistance Developed between the Steel Base Plate and the Mortar Surface: The frictional resistance that is developed between an exposed column base plate and the underlying mortar surface is recognized in the Japanese design standards. However, the resistance is not fully utilized for seismic applications, mostly because the relationship between the friction effect and the sliding motion of the base plate is not fully understood. A series of tests was conducted, demonstrating that the surface condition of the

Fig. 1. Typical damage at column base that eventually led to frame collapse. (Photo courtesy of Professor M. Nakashima)

Fig. 2. Failure mode of older beam-to-column connection. (Photo courtesy of Professor M. Nakashima)



(a) (b)

Fig. 3. (a) Original slit-wall system and the deformed links; (b) slit-wall with unequal spacing of the slits, measurements in mm. (Drawing courtesy of Professor M. Nakashima)

base plate was critical. Thus, the friction coefficients were found to vary between 0.52 and 0.97.

Subsequent tests and analyses with rigid and flexible specimens used sinusoidal horizontal loads of various frequencies and magnitudes as well as combined horizontal and vertical loads, and nonstationary motion. These studies are continuing, seeing that sliding velocities and distances are important parameters. In particular, with increasing sliding velocities and distances, the friction coefficient decreased from the initial (static) value. This is as should be expected. The continuing study aims at providing improved practical design criteria.

Slit-Wall System Serving as a Structural Damping Mechanism and as a Condition Assessment Device for the Structure: The slit-wall system is a novel development for seismically resistant structures, with the first studies taking place at Kyoto, but there is also work going on in the United States (Purdue University). The system is particularly well suited for use in areas of cities where urban density is high and for which it is essential to have a mechanism whereby the condition of structures—their structural "health"—can be monitored effectively. Traditionally, the condition assessment is achieved through the installation of sensors, but this is neither practical nor economical for large buildings, especially when numerous structures need to be monitored.

The slit-wall system focuses on the development of a structural member that can serve both as an efficient energy dissipation element as well as a condition assessment tool or sensor. As shown schematically in Figure 3, the slit-wall consists of a steel plate shear wall with vertical slits, with the segments between the slits serving as flexural links. The flexibility of the links provides for significant ductility and energy absorption, and there is no need for out-of-plane stiffening of the links. At the same time it is also possible to utilize unequal spacing of the slits, to have links of different properties. In this fashion, the monitoring feature of the links is established, without reducing the energy absorption capacities.

Two methods may be used for the assessment of the structural condition; they have their unique advantages and disadvantages. One approach uses a brittle coating for the links; the coating cracks at a certain strain level, and the locations are recorded remotely. The links are then examined visually to determine the spread of yielding in the elements. The cracking strain level is directly related to the maximum interstory drift that has occurred during an earthquake.

The other monitoring approach focuses on the appearance of lateral-torsional buckling of the links. When different spacing is used for the slits, the individual links can be designed to develop inelastic buckling for various drift magnitudes. Together with visual inspection, this provides information on the maximum drift that has occurred in the wall. Figure 4 shows a slit-wall with buckled links; this was established in a quasi-static test accompanied by an online hybrid test. The results to date confirm that the slit-wall system will function very well for both intended functions, with a level of accuracy of 0.005 rad between different drift levels (Jacobsen et al., 2010).

SELECTED RESEARCH AT THE TOKYO INSTITUTE OF TECHNOLOGY

Tokyo Institute of Technology has two campuses, and the structural engineering faculty members at both are very prominent in Japanese research and development efforts. In fact, the school has more structural engineering faculty members than all of the other Japanese universities. The current research efforts are intense, as evidenced by the eight projects that are described in the following sections.

Response Control of Steel Structures Using Dampers: This project has been sponsored by the National Research Institute for Earth Science and Disaster Prevention (NIED) and by the Japan Society for the Promotion of Science (JSPS). A faculty member at Lehigh University before returning to Japan, Professor Kazuhiko Kasai has been the director of this project.

Passive control of building performance under seismic conditions through various forms of damping devices has increased very significantly in Japan following the 1995 Hyogo-Ken Nanbu earthquake. However, a major earthquake has not occurred in Japan since that time, and the performance of the dampers, therefore, has not been verified under such conditions. The current project aims at resolving any performance questions that may arise.

As part of the study, a full-scale five-story building with and without the damping devices was tested, using the ground motion that was recorded in the 1995 event. The E-Defense shaking table, which is the largest and most powerful in the world, was used for the test. Figure 5 shows the

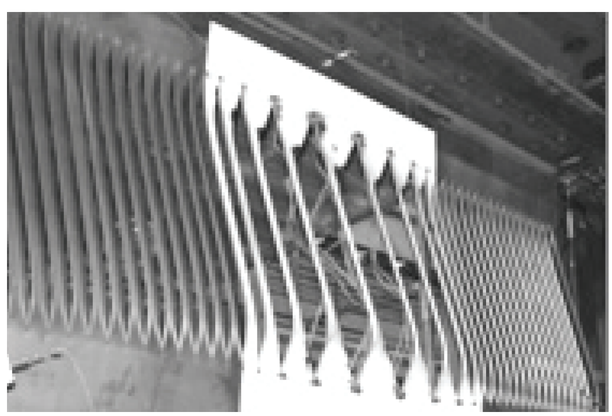


Fig. 4. Lateral-torsional buckling of links in a slit-wall with unequal spacing of slits. (Photo courtesy of Professor M. Nakashima)

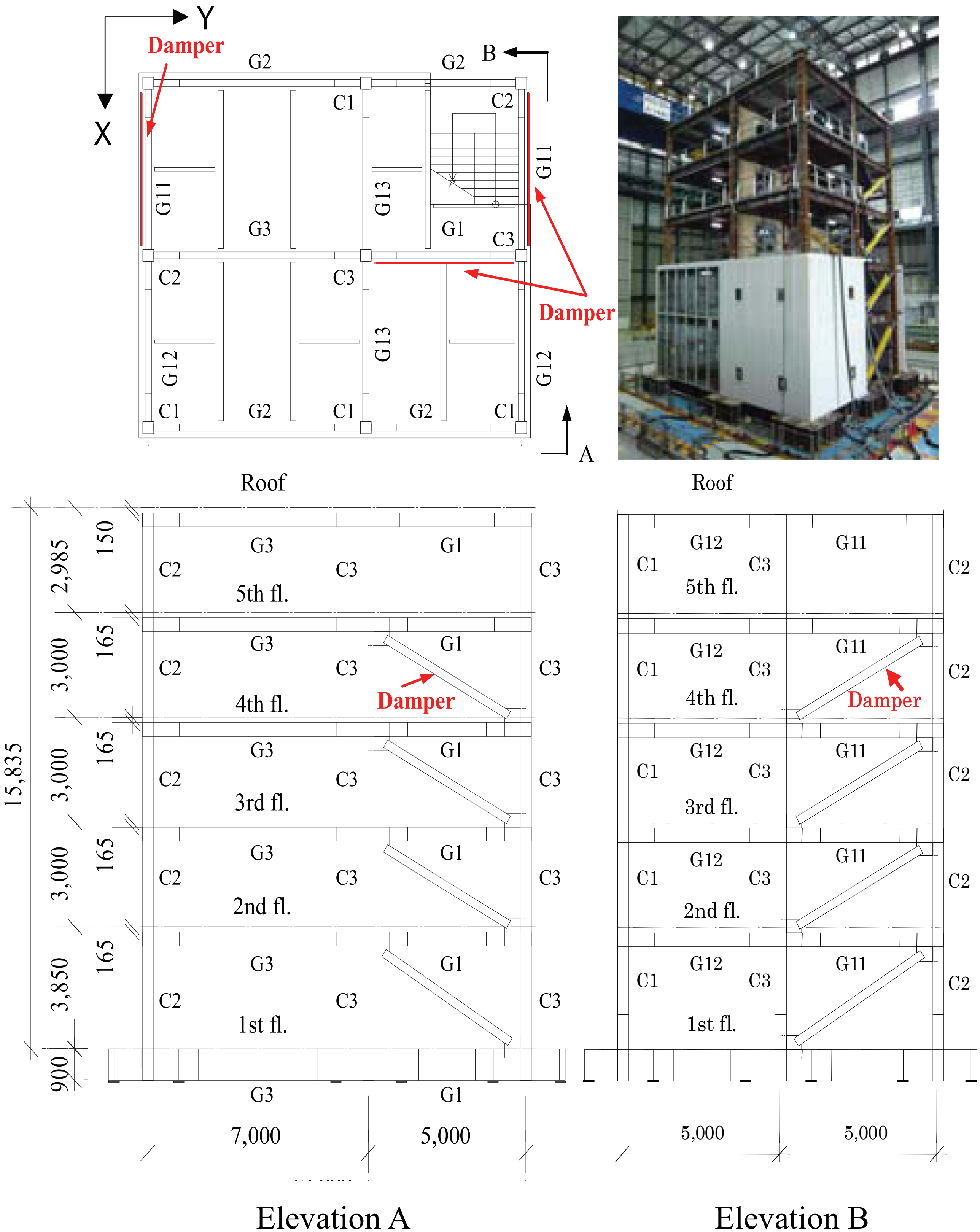


Fig. 5. Elevation and plan of building tested for damping performance. (Drawings and photo courtesy of Professor K. Kasai)

building that was used, including the placement of the 12 same-type dampers in three to four different sizes that were installed. The tests were repeated by removing the dampers and replacing them with different types. Four types of dampers were used: (1) steel, (2) viscous, (3) oil damper and (4) viscoelastic. They are illustrated in Figure 6.

The building and the dampers performed well when they were subjected to the ground motion. The analysis is continuing at this time, using the data from a total of 1,400 channels. In addition, further tests were run, with and without a concrete slab, to examine the influence of idealized boundary conditions. It is anticipated that it will be possible to validate the test method, the analysis and the design approach for passively controlled buildings. Details of the tested frame are shown in Figure 7.

Structural Behavior of Beam-Column Subassemblies with Damper Connections: This study will provide additional data for the examination of the performance of typical damping elements that are used to enhance the response of buildings during an earthquake. Professors Akira Wada and Shoichi Kishiki have been the project directors.

The study has focused on testing and analysis to establish the structural behavior of beam-columns with damper connections. The aim is to develop a design method for such

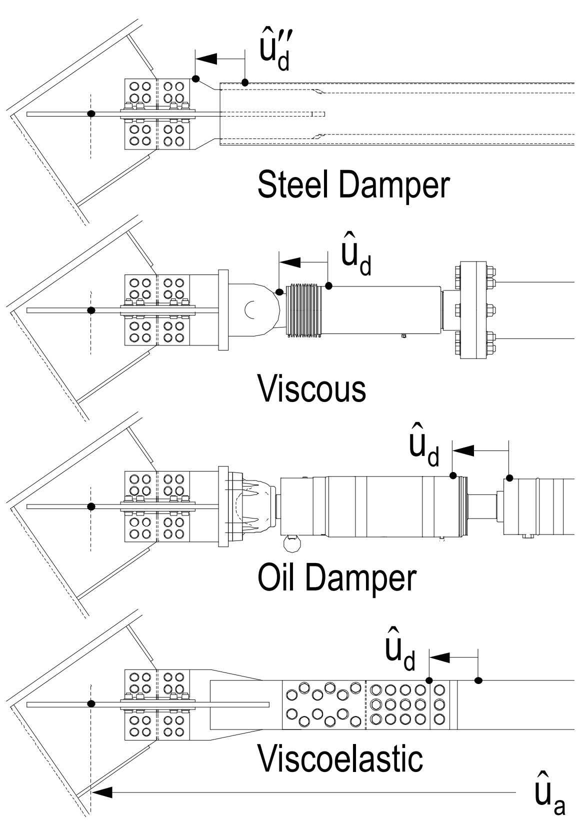


Fig. 6. Four types of dampers used in the full-scale building test. (Drawings courtesy of Professor K. Kasai)

members, including considerations for the design load level as well as loads beyond the design level. Brace-type and wall-type damping connections have been used in the tests, as illustrated in Figure 8, on page 275. Specifically, a force-controlled actuator in the test assembly functions as the reaction or as a virtual damper; a displacement-controlled actuator imposes a story drift on the test frame. Virtual dampers thus produce forces that depend on the velocity or the displacement that is developed, and this is the case even if static actuators are used in the tests.

The researchers are currently evaluating the initial findings; additional tests and analyses will be performed.

Stability Conditions of Buckling Restrained Braced (BRB) Frames: The project has been undertaken to provide improved stability design criteria for the next edition of the steel design standard of the Architectural Institute of Japan (AIJ). Professor Toru Takeuchi has been the project director.

Particular attention is being paid to the potential for out-of-plane buckling and the consequent performance demands that are imposed on the restrainer ends of the connections. Specifically, buckling must not occur before the core plates yield. Further, local buckling of the core plates is also an important limit state, although such a failure is unlikely to occur unless the BRB has only been designed for overall buckling.

Physical testing and analytical evaluations have been performed for the out-of-plane overall and local buckling limit states to ensure that the energy absorption capacity is retained. This is essential to ensure the satisfactory response of the buckling restrained braces and the structure.

Buckling and Post-Buckling Behavior of Steel Members: Professor Kikuo Ikarashi has been the director of this project. Attempting to develop a comprehensive model for the inelastic deformation capacity of wide-flange shapes, the study has examined the coupled local plate buckling effects of the shapes, taking into account the shape geometry and the stress distribution. A new plate slenderness term has been formulated, whereby the influence of the stress distribution, the yield stress level and the coupled plate instability effects are incorporated. A number of cyclic load tests have been performed, confirming the use of the new slenderness term. The correlation between test and analytical results is very good. The concepts are now being extended to the coupled instability of plate local buckling and overall buckling.

Evaluation of the Ultimate Earthquake Resistance of Moment Frames: Professor Satoshi Yamada has been the director of this study. Using random cyclic loading and focusing on the maximum strength, energy absorption capacity and hysteretic response of beams, columns and connections, and including the influence of concrete slabs in the structures, extensive analytical results have been compiled for a range of moment frames. For use with the evaluation of beam response characteristics, the properties of the steel are modeled by using the elongation response of material tests. The response of columns is based on the characteristics of stub columns, including the occurrence of local buckling. Overall member buckling is also addressed. Finally, the strength and behavior of connection panel zones as well as column bases are also incorporated, leading to a complete frame response representation.

The study is continuing, but at this stage it has been determined that the overall energy absorption of the frame can be modeled accurately by using the element characteristics. Furthermore, data are also obtained on the damage distribution in the frame, which depends on the strength and stiffness distribution of the structural components, along with the seismic load input. Using the hysteretic models of loads and the strength of the components, up to and including the deterioration behavior range, the ultimate earthquake resistance of the frame is determined by an inelastic response analysis.

Identification of Displacement-Induced Fatigue Using a Wireless Sensor Network (WSN): Professor Chitoshi Miki has been the director of this research project. The very large number of steel bridges in Japan and the large traffic volume necessitates intense attention to "traditional" fatigue cracking, as is found in various structural details due to various levels of stress range and stress concentrations. Displacement-induced fatigue cracking is much more complex in many ways, as well as difficult to observe and assess for various locations within a bridge structure (Fisher and Mertz, 1982; Fisher, 1984).

For the current research project, it was decided to instrument a bridge with wireless sensors and to assemble their responses through a network. The bridge in question is a

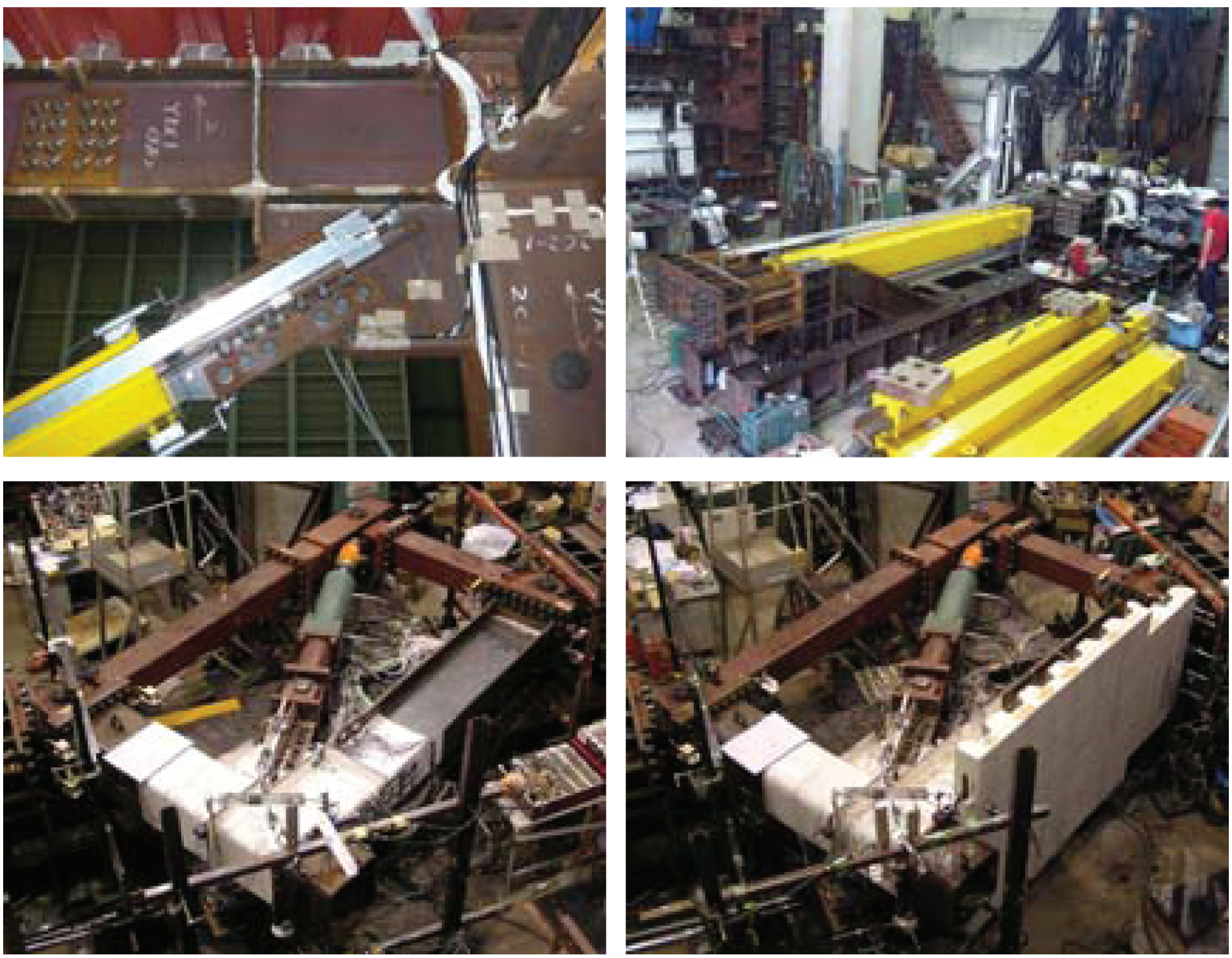


Fig. 7. Details of tested assemblies, including dampers, beam-column-gusset plate connections, with and without a concrete slab. (Photos courtesy of Professor K. Kasai)

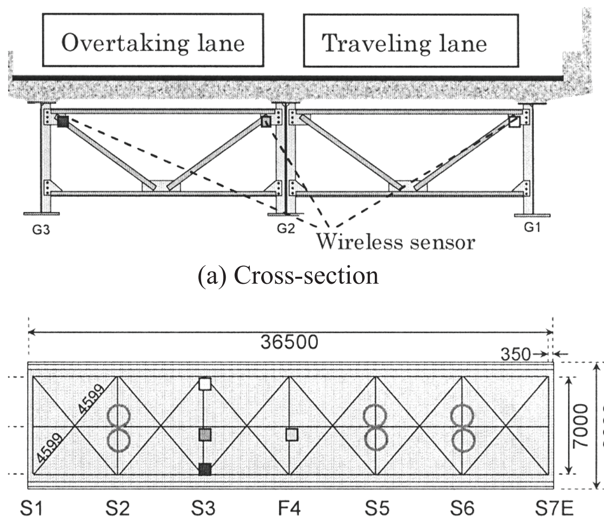
two-lane, three-girder simply supported structure, as shown in Figure 9. Figure 9a shows the cross-section along with the wireless sensor locations, and Figure 9b shows the plan view along with the sensor locations (square symbols) and the damage locations (circle symbols).

The acceleration data provided by the sensors were translated into displacement data by integration over the time domain. The sensor at the top of girder G1 indicated a displacement of 5 mm (0.2 in.). It was determined that all of the girders deflected in the same phase, but with different magnitudes for the girders. The researchers note that the fatigue damage can be attributed to the deflection differences between G1 (largest) and the other two girders.

As an extension of the project, finite element analysis is now being used to simulate the structural behavior of the bridge. In addition, an expanded WSN with 20 sensors will be installed to obtain additional details about the structural behavior.

Effect of Compressive Residual Stress to Improve the Fatigue Strength under Variable Stress Conditions: Professor Chitoshi Miki has been the director of this research project. On the premise that compressive residual stress at a weld toe will improve the fatigue strength of a detail, the effects of various types of hammer peening have been examined for high cycle fatigue tests under variable loading conditions. Three peening methods were used to introduce the compressive residual stress, as follows: (1) low-temperature transform (LTT), (2) pneumatic peening and (3) electrical peening. At this time the results are being examined, but nothing is conclusive. A girder test specimen with and without the application of peening for the weld details will be subjected to variable amplitude loading. Results for constant amplitude loading will also be incorporated into the project.

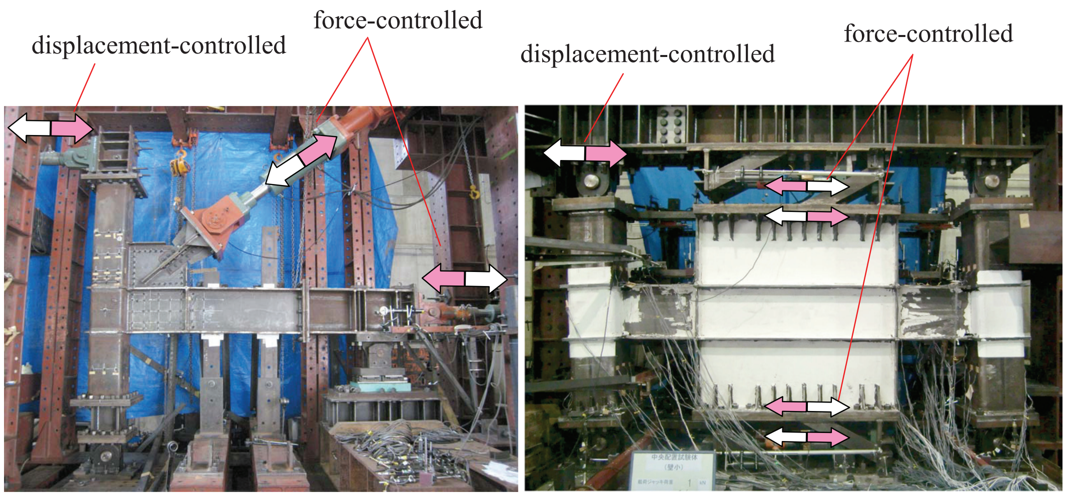
Numerical Model for the Stress-Strain Relationship of Steel, Including the Bauschinger Effect: Professor Shojiro Motoyui has been the director of this research project. The phenomenon referred to as the Bauschinger effect is neither well understood nor known to many researchers today. It was subject to much discussion during the period from 1950 to 1975, when plastic analysis and design were at the forefront of structural mechanics. Briefly, if a specimen is deformed beyond yielding in one direction (e.g., compression) and then unloaded and subjected to loading in the other direction, the yield stress in this direction will be lower than



(a) Cross-section

(b) Plan view

Fig. 9. Bridge structure schematic showing sensors (squares) and damage locations (circles). (Drawing courtesy of Professor C. Miki)



(a) brace-type damper

(b) wall-type damper

Fig. 8. Tests of beam-column assemblies with two types of damper connections. (Photos courtesy of Professors S. Kishiki and A. Wada)

the original one (Dieter, 1986; Hertzberg, 1996). Normally, the effect is ignored, but for cyclic loading such as is experienced during seismic events, it is a real question whether it might play a role, in any number of ways. The situation is further and significantly complicated when multidimensional states of stress need to be addressed.

Theoretical models have been developed, but so far these have only been applied to uniaxial problems. The intent of the researchers is to develop a numerical model that can simulate realistic multi-axial states of stress and strain. It should have real applications in many of the seismic areas of application.

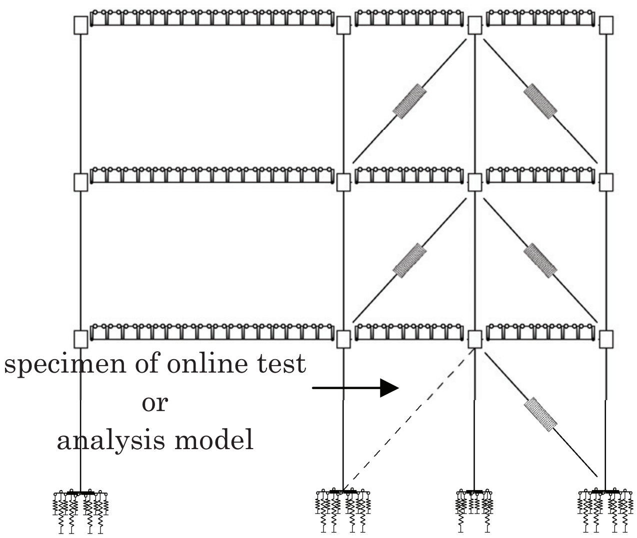


Fig. 10. Three-story frame for online test and analytical modeling. (Drawing provided by Professor Y. Kimura)

RESEARCH PROJECT AT OSAKA UNIVERSITY

Seismic Response of Steel Structures with Tubular Bracing Members: As has become a model of cooperation among Japanese researchers, tests of structures and elements may be conducted at several laboratories, with central online tie-in between the test teams and the analytical team.

In the case of the project at Osaka University, a three-story three-bay frame with tubular bracing members, as shown in Figure 10, was analyzed for various earthquake intensities (Mukaide et al., 2010).

Figure 11 shows the analytical results with and without the online test. It is noted that a brace fracture only occurred

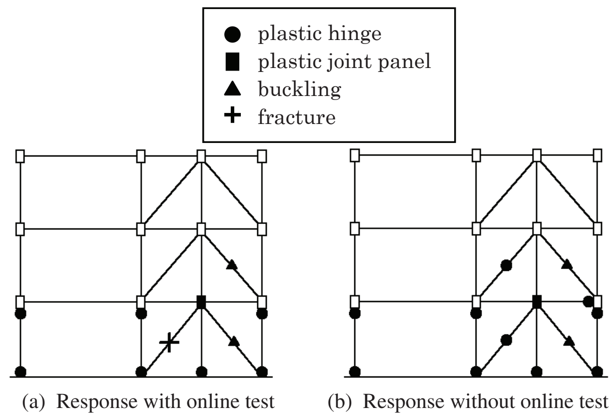


Fig. 11. Test frame results with and without the online test. (Drawing provided by Professor Y. Kimura)

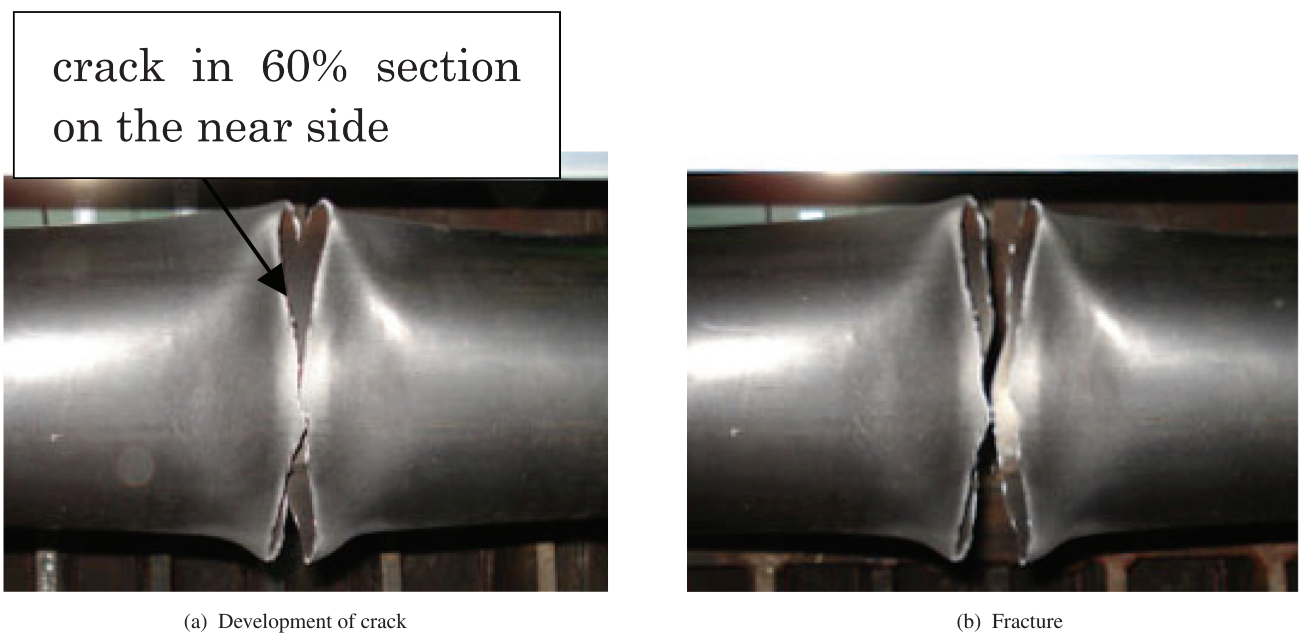


Fig. 12. Fracture of tubular bracing member for the frame. (Photo provided by Professor Y. Kimura)

for the online test. Plastic hinges developed at several locations, and the diagonal brace in one of the first-story bays buckled. Figure 12 shows the development of the crack and then the fracture that occurred in the tubular bracing member when the online test was done.

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