Current Steel Structures Research

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The terms *robustness* and *robust structures* have been the key features of a number of research projects that have been conducted over the past few years. Briefly, a robust structure is one that exhibits the characteristics of resistance to disproportionate (progressive) collapse. Following upon catastrophes such as the Oklahoma City Murrah Building and the World Trade Center in New York, numerous investigations focused on the features of these and other building collapses. The studies aimed at determining the nature of the failures, assessing common characteristics of the events and attempting to devise structural systems that would be capable of resisting the kind of overall collapses that had been initiated by localized failures.

The famous Ronan Point disaster in England was caused by a gas explosion in one of the apartments of a multi-story precast concrete building; it resulted in the collapse of a large portion of the structure. For a long time this was commonly referred to as a progressive collapse. However, Nair (2005) has identified this type of failure more correctly as *disproportionate collapse*, seeing that a small, localized event has an effect that goes very much beyond the initial breakage. A robust structure therefore is capable of arresting the progression of a small failure into a larger one. The focal point is structural integrity, and several governmental, professional and industry groups are now aiming at developing reasonable and realistic code requirements for such characteristics.

It is fortunate that many studies that address seismic strength and behavior also lend themselves to assessment of robustness. The connections are key elements of the structures in this respect, but member and frame redundancy and deformation capacity are critical as well. Several of the projects described in this paper address a number of these issues, and it is anticipated that they will have significant input to the current discussions on structural integrity.

References are provided throughout the paper, whenever such are available in the public domain. However, much of the work is still in progress, and reports or publications have not yet been prepared for public dissemination.

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BEHAVIOR OF STEEL STRUCTURES UNDER SEISMIC CONDITIONS

Cyclic Testing and Analysis of Steel Columns Subjected to High Axial Loads and Rotation Demand: This project is being carried out at the University of California in San Diego, with Professor Chia-Ming Uang as the director.

Focusing on the performance of buckling-restrained braced frames (BRBFs), the study was undertaken in response to the increased use of the system in the United States. The characteristics of buckling-restrained braces are now well known, and their stable hysteretic behavior has been demonstrated through physical tests as well as numerous analyses. However, nonlinear static and dynamic (time history) evaluations have shown that the columns in BRBFs are subjected to high axial loads as well as high inelastic rotation demand. Analytical studies have demonstrated that maximum story drift ratios up to 2% are common. Because the columns in these structures are typically modeled with fixed bases and rigid beam-to-column connections, along with BRBs that connect to the columns with gusset plates, the large drift level produces very high inelastic rotation demand in addition to the large axial forces. These axial load levels are particularly prevalent at the column bases, but are also found for other stories of the structure.

These performance characteristics of the columns are found in concentrically and eccentrically braced frames. The problem is that the reliability of the columns under these conditions has not been confirmed, hence the need for the study. The project therefore aims at developing a rational loading protocol for the tests, and to perform full scale tests with nine W14 columns. The members will be subjected to reversed and increasing amplitude loads and rotations. As a part of the study, three-story and seven-story buckling-restrained braced frame models have been designed and subjected to nonlinear time-history analyses for 20 ground motion records. The loading is controlled by the magnitude of the story drift ratio, and the axial loads are based on the BRB demand on the columns.

The results for W14×132 and W14×176 columns demonstrate acceptable behavior when tested at the target axial load of 35% of the yield load. Some localized yielding was found in the column flanges near the fixed base; this occurred at a drift of 1.5%. Flange local buckling took place at 5% drift for the W14×132 column and at 6% drift for the W14×176 column. Because the expected drift in a structure is about 1.5%, the performance of these members is good. Additional results may demonstrate equally acceptable behavior for other column sizes, but this is not known at this time.

Evaluation of Cumulative Plastic Deformation Capacity for Buckling-Restrained Braces in Frames: This study has been conducted at the Tokyo Institute of Technology in Japan, with Professor Toru Takeuchi as the director.

Japanese researchers for several years have used the cumulative plastic deformation capacity as a more representative and realistic measure of the performance of members and connections (Nakashima, Suita, Morisako, and Maruoka, 1998). This contrasts with what was the tradition in the United States for a number of years, of using the maximum plastic rotation capacity (now the interstory drift is the measure) and the associated number of cycles. The premise of the cumulative rotation capacity is that it reflects the actual energy absorption ability of the element or the connection. An American study indicated that the application of the cumulative capacity would be feasible and practical, especially for connections in steel structures (Bjorhovde, Goland, and Benac, 2000).

The cumulative deformation capacity is also important for the vibration-control dampers that are sometimes used to control building response. However, for such applications the loading history plays a major role. Nevertheless, buckling-restrained braces are one form of elasto-plastic damping units, and their cumulative deformations and loading histories as demonstrated through various physical tests can be used to develop simple behavior prediction models for which time-history analyses will not be required. This is the essence of the study conducted by Professor Takeuchi and his team.

As part of the project, 180 cases of time-history analyses were performed for buckling-restrained structures with 7, 15, and 21 stories and different levels of stiffness for the BRBs. Figure 1 illustrates the relationship between the cumulative plastic strain, χ_w and the plastic strain, ε_{pm}, and gives the equation for the relationship between these variables and the relationship to time-history analyses. It appears that the predictions provided by the proposed method are quite accurate. For these kinds of structures it may therefore be possible to provide cumulative strain predictions without having to use time-history evaluations.

Seismic Behavior and Response Modification Factors of Structural Steel Systems: This study is the continuation of a large investigation into the seismic response characteristics of various steel framing systems. It is being carried out at the Technical University Federico Santa Maria in Valparaiso, Chile, with Professor Carlos Aguirre as the director.

The current project focuses on buckling-restrained braced frames (BRBFs) and special truss moment frames (STMFs). The same series of buildings as were used for the previous projects are included in the study, using the same floor plans and numbers of stories. The structures were designed in accordance with the requirements of the Chilean Building Seismic Code. Nonlinear analyses are currently being done, to arrive at the appropriate capacity and demand diagrams. The tentative findings indicate that BRBFs and STMFs exhibit desirable characteristics for use in the Chilean construction industry. It is anticipated that suitable, updated values of R and C_d for use in the seismic code will be developed.

Seismic Design of Buckling-Restrained Braced Frames (BRBFs): The project is conducted at the University of Chile in Santiago, Chile, with Professor Ricardo Herrera as the director. The primary aim is to develop a methodology for design of BRBFs that can be adapted to Chilean practice.

Specifically, it is expected that the project will provide:

1. Definition of a response modification factor R that is consistent with the current seismic design criteria
2. Development of a constitutive law for buckling-restrained braces
3. Detailed data on the nonlinear behavior of BRBs
4. Analysis and design of BRBFs with a simplified analytical model that only accounts for the nonlinearity of the BRBs
5. Comparison of the seismic performance responses of BRBFs and concentrically braced frames (CBFs)
6. Evaluation of the potential advantages of BRBFs versus CBFs

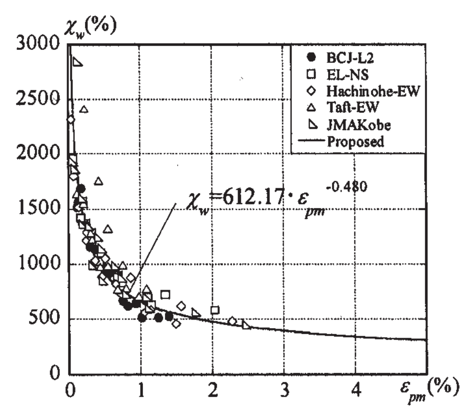

Fig. 1. Relationship between cumulative plastic deformation and plastic strain.

The frames that are included in the study were designed on the basis of the AISC Seismic criteria (AISC, 2005), but using the loads and analysis techniques that are required by the Chilean codes. Due to the lower stiffness of the BRBFs as compared to CBFs, it was found that the design of the former was controlled by drift rather than strength. Because the Chilean seismic code has a restriction on the minimum base shear that must be resisted by the frame, regardless of the criterion that governs the design (in other words, drift or strength), the results indicate that it may be necessary to limit the value of the response modification factor that can be used with BRBFs.

Experimental data and average overstrength values for tension and compression of the buckling-restrained braces have been used to develop a simplified analytical model for BRBFs that only takes into account the nonlinearity of the braces. Inelastic pushover and time-history analyses have shown that the BRBs did not exhibit any strength degradation, "soft stories" did not develop in the BRBFs, and the performance demand imposed on other structural elements was reduced. The results therefore show that BRBFs are a suitable alternative to CBFs. Additional analyses will be conducted to examine the performance characteristics further, before an improved value of the response modification factor can be proposed.

WELDED CONNECTIONS

Strength and Ductility of Welded High Strength Steel Connections: This study is a major collaborative research project involving four German institutions, with Professor Ulrike Kuhlmann of the University of Stuttgart as the director. The other researchers are located at the Bauhaus-University in Weimar, the Technical University of Darmstadt, and the Günter-Köhler Institute of Joining Technology in Jena. This form of cooperation has become very common in Germany and other European countries over the past few years. It is particularly advantageous when broad analytical and experimental investigations are contemplated, since it is uncommon to have a single university or research laboratory that offers significant research capacity in all areas of the investigations. This is of course the case for most institutions in the world today, but collaboration is still uncommon. In the United States the Network for Earthquake Engineering Simulation (NEES) program of the National Science Foundation (NSF) is a major undertaking of this kind, and it is expected to be highly successful.

The investigation aims at determining the ductility and strength of welded joints with single and combined grades of steel (in other words, with different grades welded to each other). Specimens of 50, 65, and 100 ksi yield stress steel are as shown in Figure 2 and are used in physical tests and analytical evaluations to determine the strength and behavior of under-, over-, and matched-base metal-weld metal configurations. The lap and cruciform joints use fillet welds; the butt joint is a partial-joint-penetration groove weld. The data for undermatched joints are felt to be particularly important, because current codes require matched or overmatched joints. Similar work for different types of connections and grades of steel is underway at Delft University of Technology in the Netherlands (Bjorhovde, 2007).

The experimental program consists of approximately 200 specimens, and most of them have been tested at room temperature—35 of the specimens were tested at −40 °C (= −40 °F). The analytical evaluations incorporate the temperature field and residual stresses of the welding process, as well as a strength simulation and a fracture mechanics assessment. It is anticipated that the project will provide an update and

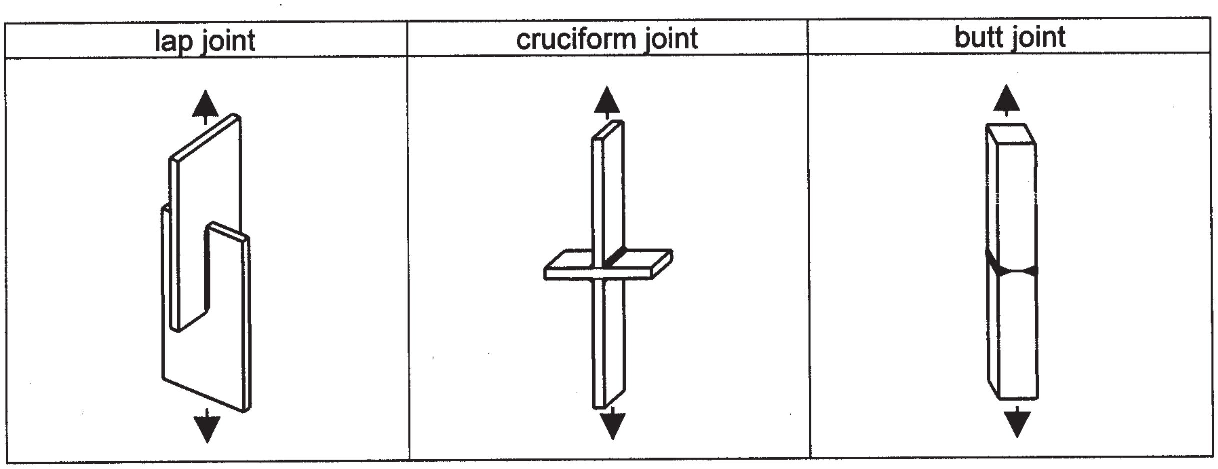

Fig. 2. High-strength welded joints for study of ductility and strength.

improvement of the current Eurocode 3 criteria. The new provisions will take into account the actual strength of the filler metal. They will also allow the designer and the fabricator to choose an optimal combination of base and filler metals as well as welding parameters.

ROBUSTNESS OF STRUCTURES

Robustness in Structural Steel Framing Systems: This is a major project that has been conducted at Marquette University in Milwaukee, Wisconsin, with Professor Christopher Foley as the director. The work was initiated by AISC, in response to discussions in the profession of broad issues such as performance-based design, design for seismic effect, design for blast and fire, and progressive or disproportionate collapse. The study was to assess structural ductility and deformation demands, and to establish criteria for such for connections and structural members. Rational requirements are clearly needed for structural integrity under the action of normal and abnormal loads and other events that might compromise the overall building and its occupants. It was also anticipated that the results of the investigation might be useful in the current efforts of building officials to develop general code requirements for structural integrity and hence public safety.

As an important part of the project, the researchers examined past and current studies that have examined progressive collapse characteristics and remediation protocols, in the United States and elsewhere. This provided direction to the work, to the effect that essential gaps in current knowledge were identified.

As part of the study, three moment-resisting steel frames were evaluated to determine the robustness of the structure following the elimination of the exterior columns ["the columns had been rendered ineffective" as expressed by Foley, Martin, and Schneemann (2006)]. The frames were pre-Northridge buildings located in Boston, Massachusetts, with 3, 10, and 20 stories; they had been examined in the SAC project. In addition to developing complete assessments of the demands of the member and connection stress resultants, it is anticipated that the demands can be used to formulate advanced models for physical testing as well as additional analyses. The researchers observe that minimum connection forces are determined, in addition to the Vierendeel-like response of the structures.

The Vierendeel action plays a major role for certain types of frames. For structures where such action is not feasible because of member or frame subassemblage failure, two-way membrane and catenary action of the floor system can be critical. However, the inherent deformations associated with catenary action, for example, can be substantial. Damage levels and the retention of integrity may be important financial considerations.

The results demonstrate how these mechanisms can be established in different systems, and thus lend essential structural integrity to the frames. Most importantly, the investigation has shown that steel-framed structures offer very significant robustness in connections as well as elements, to the effect that it is an unusual steel building that will not provide numerous areas of deformation capacity and the ability to arrest the propagation of local failures. Any further research efforts are likely to confirm these results.

Robustness Test for a Steel-Concrete Composite Floor: This study is currently under way at the University of Liege in Liege, Belgium. Professor Jean-Pierre Jaspart is the project director. The study is part of a large-scale, three-year collaborative research effort on "Robust Structures by Joint Ductility" that is funded by the European Union. The overall project was initiated in 2004; design and construction guidelines will be forthcoming over the next year or so.

Figure 3 shows a substructure that was recently tested at the University of Liege. The test aimed at simulating the loss of a column in a composite frame. The elements and dimensions that were used to design the specimen were based on a structure that had been designed for "normal" loading conditions, in accordance with Eurocode 1 (the load code). The columns are all steel; the floor is a composite slab and steel beam. The specimen was designed to simulate the response of an actual structure, including lateral restraints, horizontal tying forces in the beams, large connection rotations, and large beam deflections.

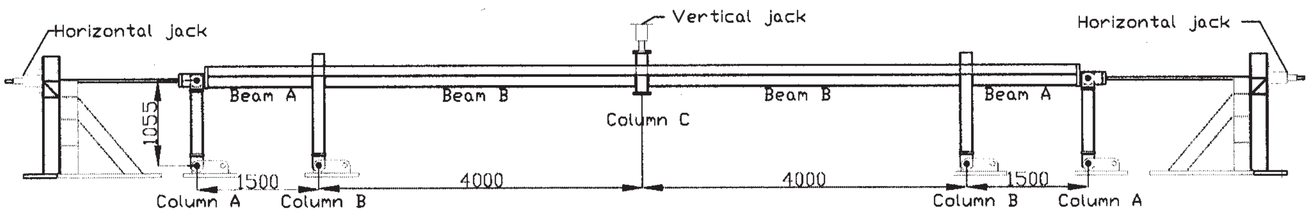

Fig. 3. Composite substructure for robustness test.

At the start of the test, Column C is supported in the same way as the other columns in the structure. The floor is uniformly loaded over the two 4000 mm (13 ft-4 in.) spans. Column C is then slowly removed until the "new" structure stabilizes in the deflected configuration. A load is then applied at the top of the Column C location, to simulate the influence of higher stories as Column C has been removed. A schematic of the loading sequence is shown in Figure 4.

The primary results of the test are illustrated in Figure 5 by the load-displacement curve for the location of Column C. Briefly, the connections and the beams are initially subjected to bending moments and shear forces. As Column C is removed (in other words, it loses its load-carrying capacity), catenary action develops in the beams until a plastic hinge is developed in the beam or in the connection. By the end of the test, the deflection at Column C has reached 800 mm (32 in.) and the end-plate connection rotation is 170 mrad before any weld or other local failure occurs. However, the structure has maintained its integrity, even at this very large level of deformation, so the systems and its members and the connections are clearly very robust.

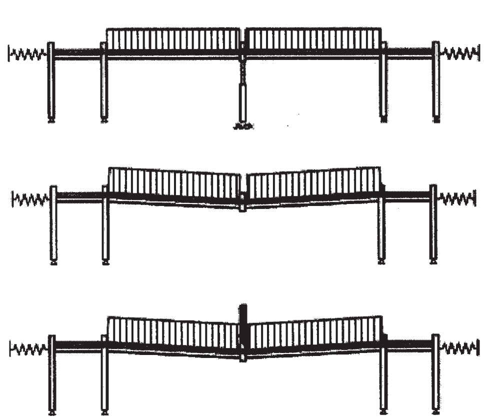

Fig. 4. Loading sequence to simulate removal of central Column C.

PERFORMANCE OF BRIDGE STRUCTURES

Renovation Techniques for Fatigue Cracked Orthotropic Steel Bridge Decks: This project has been a major research investigation by Ph.D. student Peter de Jong at Delft University of Technology in Delft, the Netherlands, with Professor Frans Bijlaard as the director (de Jong, 2006).

Orthotropic steel bridge decks have been used extensively all over the world, but probably the most in the Netherlands and Germany and other European countries, and especially over the period 1960 to 1980. They were also used in the U.S. for several years, but problems like fatigue cracking of welds and plate material prompted a retreat from significant applications in this country. There is now a resurgence of such deck applications all over the world, which is why the study of Dr. de Jong is so important.

As described by Dr. de Jong, the most frequently observed crack is also the most severe. Specifically, the crack is found in the deck plate at the intersection of a transverse floor beam and the trough girder, as shown in Figure 6. The trough girder is also referred to as a closed deck stiffener or a trapezoidal stiffener. In the Netherlands the crack was observed for the first time in 1997; that structure was a seven-year-old bridge. At this time, a total of 10 bridges have been

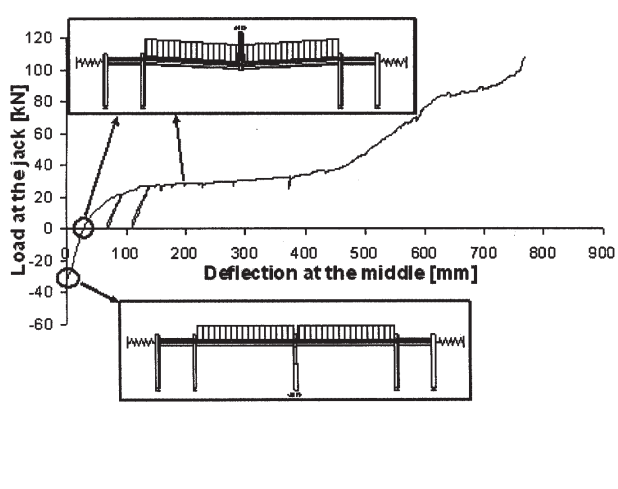

Fig. 5. Load-deflection curve for substructure test.

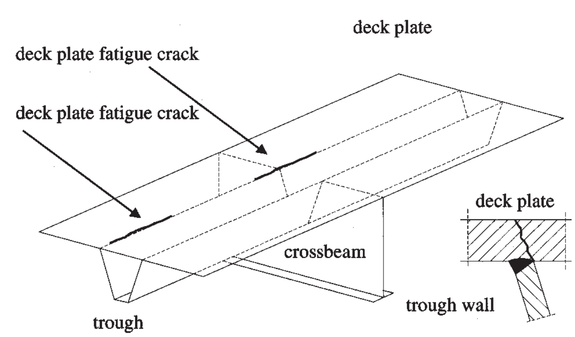

Fig. 6. Orthotropic deck detail and fatigue crack location (used by permission of P. de Jong).

found with this type of crack, with movable structures as well as fixed bridges, with thin epoxy plate surfacing as well as thick asphalt surfacing.

The research project aimed at resolving the following major issues:

1. When can these fatigue cracks be expected to occur?
2. How can these fatigue cracks be discovered most efficiently and economically?
3. At what point will the bridge have to be renovated?
4. What is the expected service life of the bridge following the renovation?
5. Can a suitable, practical, and economical maintenance protocol be devised?

The investigation evaluated bridge traffic loads, stress ranges for truck axle and vehicle loads and tire foot prints. The latter proved to be very important. The deck surfacing materials were critical to the fatigue performance, and their influence was in fact the main purpose of the testing program. Extensive testing was done for various deck panels, and a fatigue detail classification was developed.

As part of the general conclusions, it was determined that replacing the asphalt surfacing of fixed bridge decks with approximately 50 mm (2 in.) of reinforced high performance concrete is an effective renovation method. Such was not the case for movable bridge decks, for which no significant lifetime extension was achieved. Although the current methods of using bonded steel plates or reinforced high performance concrete require additional study, it appears that the best alternative for movable bridges is simply to replace the deck entirely, or even to build a new bridge. The financial implications are obvious.

The maintenance philosophy that has been developed has a reliability index of 1.8. This is considered acceptable, in view of the computation model that has been devised for accumulated fatigue damage. The model is suitable for use with existing bridge decks with fatigue damage as well as for the design of new bridge decks.

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