Current Steel Structures Research

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Research is not always tied to industrial or societal needs, and sometimes not even closely related to such needs. This is most unfortunate, especially for all of engineering, since it would appear that if a study does not have any practical applications and ultimately does not end up in the form of real-life projects, why should it be undertaken in the first place? Of course, it is always interesting and challenging to solve complex problems, but for engineers there is a clear missing link if the subject has not emanated from a practical need. Nevertheless, esoteric subjects form the basis of many projects, and the key to satisfactory solutions is to maintain a levelheaded view of progress and goals.

On this background, it is a fact that research around the world tends to progress in waves and cycles. The initial idea may have come from a study in the United States or any other country, but reports and publications and interpersonal relationships communicate with the research community at large. A good idea is a good idea anywhere, and elements of the broad subject matter that lend themselves to additional study get picked up by students or professors or practicing engineers and eventually to solutions that address real needs. As a "for instance," the entire subject matter dealing with robust structures, structural integrity and resistance to disproportionate (progressive) collapse is currently being addressed by researchers in a dozen or more countries. To a certain extent, these studies are tied to the seismic performance of structures and connections. Five years ago, research on robustness was essentially nonexistent. Thus, three of the studies presented in this paper deal with robust performance in one or another form, and the analyses and applications demonstrate degrees of sophistication the attest to levels of advanced knowledge that even a few years ago was limited to very few institutions.

The performance of various types of industrial structures is now being addressed by groups in the United States, Switzerland and South Africa, to mention three efforts. This includes a novel framing system that has broad applications within certain industries, not because of the complex nature of the frames themselves but because manufacturing companies need them. A new seismic standard has in fact been developed to reflect the design needs of these frames.

Work on numerous applications of hollow structural sections is actively pursued in a number of countries, for structural as well as architectural reasons. Finally, an interesting project is focusing on imperfections of various kinds, using an optimization approach to determine the most unfavorable combination of imperfections in certain types of structural elements.

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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ROBUST STRUCTURAL PERFORMANCE AND STRENGTH UNDER SEISMIC LOADS

Robustness of Seismically Resistant Multi-Story Frames with Accidental Column Loss Scenarios: This project has been conducted at the Polytechnic University of Timisoara in Timisoara, Romania, with Professor Dan Dubina as the director, in collaboration with the Timisoara Branch of the Romanian Academy of Sciences.

Several projects over the past few years have suggested that seismically resistant framing systems also will provide significant robustness against disproportionate collapse. In particular, the study of Hayes et al. (2005) showed that special moment frame detailing of structures led to improved response to blast and similar loading conditions, in comparison with the performance of ordinary moment frames under the same type of loading conditions. Further, the capacity design approach that forms the basis for the seismic criteria of Eurocode 8 (CEN, 2005b) emphasizes energy dissipation in certain members (normally beams and girders) and structural overstrength in the columns. This design philosophy achieves satisfactory ductility and prevents failure modes that involve soft story mechanisms (Dinu and Dubina, 2009).

The current project has specifically examined the progressive collapse resistance of certain types of multistory frames that have been designed for seismic performance. Various failure scenarios were investigated, specifically by looking at the structural behavior for cases of loss of interior columns and loss of corner columns, located at mid-height of the frame or at the first floor level. The building in question is shown in Figure 1— it is a 26-story structure that had been designed for seismic accelerations of 0.24-g and a multilevel performance requirement with a ground acceleration of

0.36 g. The building is located in the high seismicity region of Bucharest in Romania; it was completed in 2007.

Three performance levels were used in the evaluation of the structure: (1) serviceability limit state, (2) ultimate limit state, and (3) collapse prevention limit state. Nonlinear dynamic analyses were used for an accurate performance assessment of the structure as a whole. For the column removal evaluations, two cases were used, as follows: Case 1 involved the loss of the first floor interior columns; Case 2 examined the performance of the frame with the loss of the 14th-floor interior columns. The columns were removed one by one, and three-dimensional nonlinear static analysis was used to examine the response of the structure. The nonlinear modeling incorporated material as well as geometric effects.

The analyses of Case 1 showed that the structure was able to carry the gravity loads when as many as 15 to 20% of the 1st-floor interior columns were removed (five columns). Plastic hinges developed in the beams of the 1st through the 13th stories, with plastic rotations up to 0.015 radian. For Case 2, the structure was stable after the loss of five columns, but the rotations were no larger than 0.007 radian. The researchers note that the rotation demands associated with the loss of 15 to 20% of the columns is similar to what would be expected for a strong earthquake. They also observe that columns in high-strength steel [yield stress of 65 ksi (460 MPa)] may further improve the structural performance.

Finally, any effects of strain hardening, different strain rates and overstrength of the steel have not been examined. Similarly, the dynamic (i.e., brittle) effects of column removal have not been studied; this would be an important addition to the state of the art. It is anticipated that these topics will be addressed in further studies.

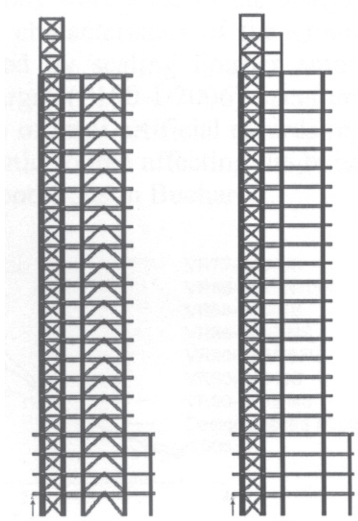

Fig. 1 (a). Elevation of frame for column removal study (courtesy of Professor Dan Dubina).

Robustness of Parking Garages against Localized Fire: This three-year project is a major collaborative study, involving universities, companies and research centers in five European countries. The lead institution is the University of Liège in Liège, Belgium; the other institutions are Imperial College in London, England; University of Coimbra in Coimbra, Portugal; the steel producer ArcelorMittal in Luxembourg; and CTICM, the French steel construction institute. Funding has been provided by the Research Fund for Coal and Steel of the European Commission. Professor Jean-Pierre Jaspart of the University of Liège is the director of the project.

The project was recently started, so any results are not yet available. However, input from the research partners and access to the European fire research database will be critical to the success of the work. The effects of nonuniform temperature distributions, connection behavior and other aspects of the response of the parking structures to localized fires will be examined, with the aim of providing practical design criteria and realistic performance descriptions.

It is interesting to observe that a parking garage fire test was conducted by the American Iron and Steel Institute (AISI) in Scranton, Pennsylvania, in 1972, using a full-size American car as the source of the fire (Gage-Babcock, 1973; Harris, 1979). The steel structure had no fire protective materials for any components. The garage and its members behaved very well, with no local or overall member or structural failure.

Robust Structures by Joint Ductility: This is a three-year collaborative research project that was completed in 2007. Involving the University of Liège in Liège, Belgium, the University of Stuttgart in Stuttgart, Germany, and the University of Trento in Trento, Italy, the industrial partner was the steel producer ARBED, Arcelor Group, from Luxembourg. Funding was provided by the Research Fund for Coal and Steel of the European Commission. Professor Ulrike Kuhlmann of the University of Stuttgart was the project director.

The project focused on how redundancy and general structural system robustness could be mobilized to prevent a local failure from progressing to overall failure of the

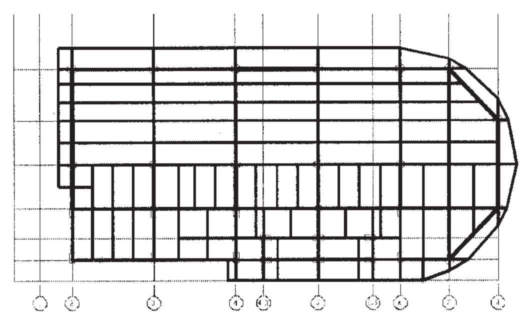

Fig. 1(b). Floor plan for building (courtesy of Professor Dan Dubina).

structure. In particular, the ductility of steel and the capacity of the connections to undergo very large deformations were examined as key elements of the stress resultant redistribution throughout the frame. The full-scale tests at the University of Liège are especially interesting, as they focused on column removal within a two-bay substructure of a composite frame, examining the robustness of the connections as well as the frame (Demonceau, 2008; Demonceau and Jaspart, 2008). Complete nonlinear finite element analyses of the structure and the substructure that was tested have been conducted, using static loads. Figure 2 shows one of the specimens after the completion of the test.

The final report of the project is not yet available. It will be published by the Science Research Development arm of the European Commission.

INDUSTRIAL STRUCTURES AND APPLICATIONS

Uplift Criteria for Unanchored Circular Tanks Subjected to Seismic Loads: This is a research project that is just getting started at the Swiss Federal Institute of Technology in Lausanne, Switzerland. The project director is Professor Alain Nussbaumer.

The European experience with circular silos and tanks has shown that there may be significant risk for uplift and failure of the welded bottom connections when these structures are subjected to seismic loads. The design criteria are provided by Eurocodes 3 and 8 (CEN, 2005a; 2005b); analyses have shown that the anchoring for many of the silos and tanks need to be strengthened to ensure satisfactory performance. Various models for uplift have been developed, but the problems are highly complex and are not completely understood. The results also vary a great deal and do not provide consistent predictions for slender and stocky tanks alike. The project aims at resolving the technical issues as far as behavior and strength are concerned, including questions related to low-cycle fatigue of the welded base plate to tank connections. It is also anticipated that improved code criteria will be developed.

Based on finite element analyses, Figure 3 gives an example of the relationship between the uplift force (*V*), the vertical displacement (*w*) and the uplift length of the base (*L*) for a tank with a height to radius aspect ratio of *H/R* = 0.5 (Scharf, 1989).

Geometric Nonlinear Analysis of Slender Structures: This is a major collaborative research and development project involving universities in Germany, Russia and South Africa, with Professor Peter Dunaiski of the University of Stellenbosch in Stellenbosch, South Africa, as the project director and lead researcher. The project has been under way for some time, and a book that will feature the nonlinear techniques and software that have been developed will be published by the University of Stellenbosch in 2009.

As an example, the approach to nonlinear analysis has been applied to a study of slender, long-span trusses that has been conducted at Stellenbosch. Coupled with full-scale tests, among other findings is the observation that the effective lengths of truss verticals and diagonals are significantly smaller than the system lengths. Figure 4 shows one of the trusses that was analyzed. Another study examined the design of slender portal frames, determining that serviceability governs these structures as opposed to strength.

Seismic Response of Cold-Formed Steel Structural Systems in Special Bolted Moment Frames: This project was conducted at the University of California at San Diego, with

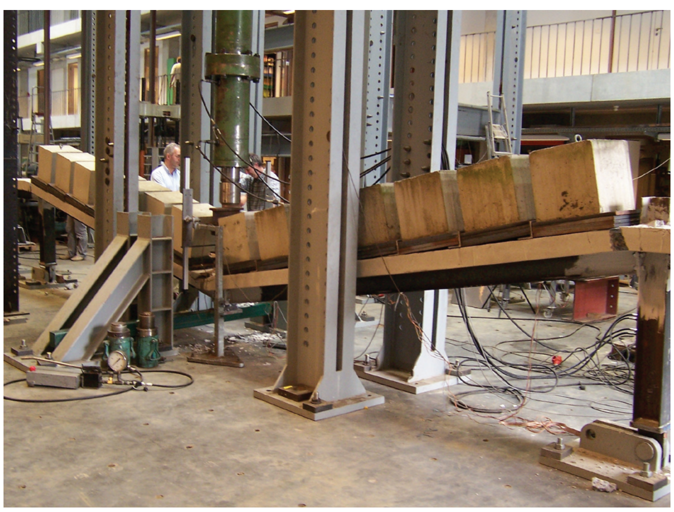

Fig. 2. Robustness test of two-span composite beam with column removed (courtesy of Jean-François Demonceau).

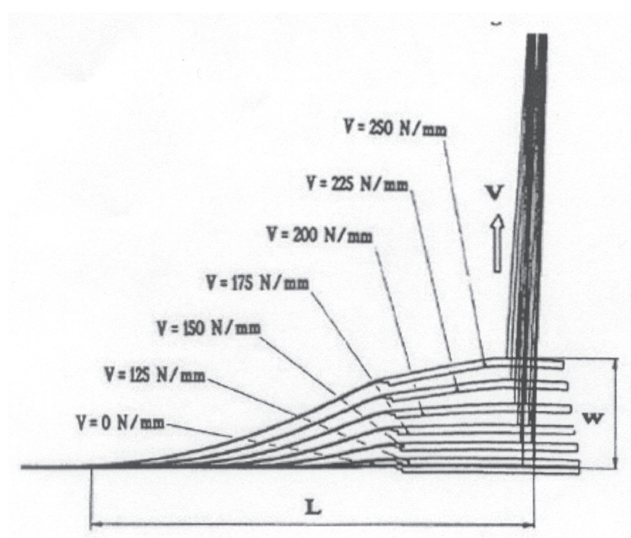

Fig. 3. Tank uplift force in relation to displacement and uplift length (Scharf, 1989) (courtesy of Professor Alain Nussbaumer).

Professor Chia-Ming Uang as the director. The study was funded by the American Iron and Steel Institute and was completed in 2007, including the development of a new AISI/ANSI design standard for these types of frames (AISI, 2007; Sato and Uang, 2008). A notable achievement, it is emphasized that this is the first time a seismic standard has been developed for use with cold-formed members.

These special bolted moment frames (SBMF) are commonly one story only and are used as mezzanine or platform structures within other structures typically industrial installations. They are very common and economical solutions for unique needs and are used a great deal in California and other seismically active areas. The SBMF uses HSS columns with cold-formed C-shape beams, as shown in Figure 5. The connections are bolted, as shown, most commonly with 1-in.-diameter HS bolts; these are installed as snug-tight bolts only.

Fig. 4. Long-span slender truss (courtesy of Professor Peter Dunaiski).

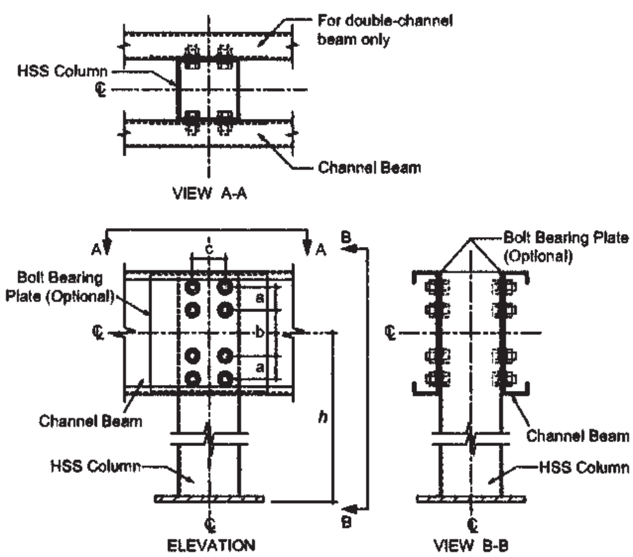

Fig. 5. Connection for special bolted moment frames with cold-formed beams (courtesy of Professor C.-M. Uang).

The project examined the response of the frames to a large number of ground motions and determined that most of the energy absorption took place in the connections. Nine full-scale tests were conducted (Sato and Uang, 2008), and no local or overall buckling occurred during the tests. Using a capacity design approach in the development of the connection model, the analyses also predicted such behavior. It is interesting to observe the hysteretic response of the connection and compare this to what is commonly seen for many hot-rolled connections. An example is shown in Figure 6, demonstrating very different behavior but excellent connection rotation and energy absorption capacity.

ANALYSIS OF STEEL STRUCTURES

Application of Optimization Techniques to Assess Effects of Imperfections: This study has been conducted at the University of Ljubljana in Ljubljana, Slovenia, with Professor Joze Korelc as the project director.

Many structures are imperfection sensitive, especially structures with very slender members such as cold-formed elements and certain plate girders with very thin webs. It is important to find the most critical types, locations and orientation of the imperfections and to determine the ultimate limit state(s) that is governed by each of these. Using optimization philosophy, an algorithm has been developed that takes into account nonlinear primal and first-order sensitivity analysis to arrive at the moist suitable objective function

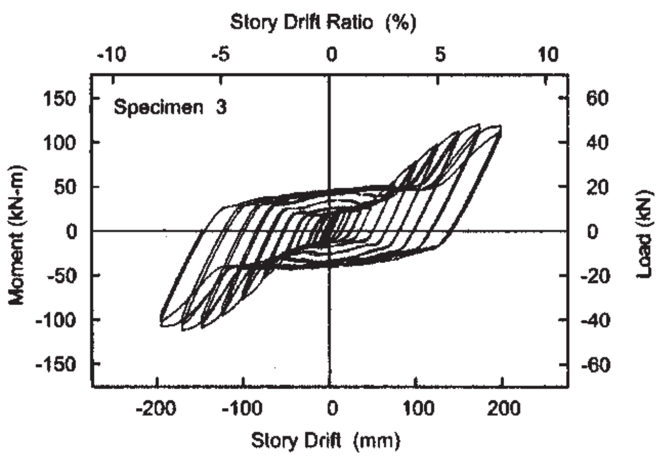

Fig. 6. Hysteresis characteristics for the connection of a special bolted moment frame (courtesy of Professor C.-M. Uang).

(Kristanic and Korelc, 2008). The method is capable of dealing with a range of imperfection magnitudes, using linear combinations of certain basic types. Constraints can be set to allow for the selection of various basic shapes, including selection of boundary conditions and characteristic shapes.

It has been found that if only the amplitude of the imperfections is constrained, the solution gives significantly lower ultimate loads than what is found in physical experiments. Part of the problem is that some of these imperfection shapes are, in fact, technically impossible. Although the method is very powerful, it is, therefore, important to ensure that the imperfection shape is realistic. The magnitude of the imperfections must also be controlled, to avoid getting unrealistic, very low ultimate loads.

Figure 7 shows a girder with exaggerated (for illustration purposes) imperfections, but the form of the deflections is realistic. The method is very efficient for computations.

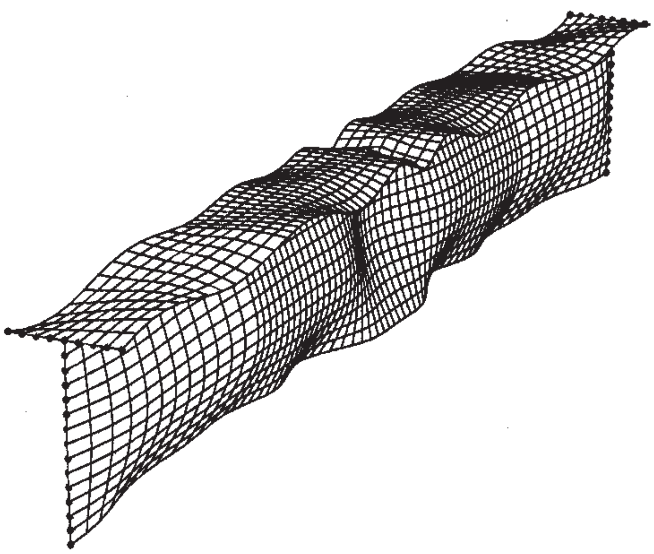

Fig. 7. Girder with the optimized governing imperfections (courtesy of Professor Joze Korelc).

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