Current Steel Structures Research

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Standardization is essential to activities in all walks of life, but probably nowhere as important as it is for all aspects of the construction industry. The approaches vary somewhat from country to country and region to region, but it is a fact that quality in all respects depends on a body of practically oriented standards. The complexity of the subject cannot be overestimated, since there are so many materials and components and methods of fabrication and erection that govern the quality of the final product. The various steel construction institutes play key roles in all of these efforts, primarily because that is where the technical expertise resides. However, the interaction between any institute and its constituency is critical as well, and the model of cooperation that is used in North American standardization work is an excellent vehicle to bring all interested parties to the table, so to speak. The AISC Committee on Specifications, for example, is made up of approximately 45 individuals, with one third from consultants, one third from academia and one third from industry. The arrangement works extremely well, producing a steel design standard that is second to none in terms of state-of-the-art approaches and practical usefulness.

On the other hand, design manuals are the final element of the research and development and standardization work. Whether the manuals appear in the form of "hard" printed copies or as electronic tools is immaterial: the point is that they are critical to the users of the standards that have been developed. The AISC *Manual of Steel Construction* is currently in its 13th edition, and is accompanied by numerous other manuals and design guides that together aim to make the work of steel construction professionals easier. This approach is pursued just about everywhere in the world, most recently in Europe, where the European Convention for Constructional Steelwork (ECCS) has embarked on an aggressive program of design manual development. The ECCS program aims at having a full complement of manuals that will ease the acceptance and adoption and use of Eurocodes 3 (steel structures) and 4 (composite construction) by professionals throughout Europe. This is a major effort, for certain, but it is critical for industry and indeed the economies of the various countries.

The projects that are presented in this paper reflect a broad range of state-of-the-art work. A recent project in Spain has provided a broad assessment of the methods that are used to determine the moment capacity of laterally unsupported beams. One German study focuses on residual stresses in high strength steel shapes, using a new measurement technique, and another German project looks at the influence of the Bauschinger Effect on the deflections of cambered beams. Projects addressing seismic effects continue to be very prominent in the US and many other locales, and a novel structural system utilizing repairable "fuses" is examined in a major, multi-university and design firm US project. Full-scale testing forms part of several investigations, including a four-story building that has been tested to collapse in Japan. Finally, numerous researchers continue to develop software that may eventually be used in practice, and one such recent product from Belgium deals with analysis and design of plated structures.

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.

EFFECTS OF MATERIAL CHARACTERISTICS ON MEMBER BEHAVIOR

Residual Stresses in Hot-Rolled Shapes of S460 Steel: This project is conducted at the Technical University of Darmstadt in Darmstadt, Germany, with Professor Jörg Lange as the director.

The S460 steel grade is a high strength low alloy material with a specified minimum yield stress of 460 MPa (65 ksi). There is significant interest in the use of this and similar high strength grades for construction, but a drawback to their application continues to be that knowledge of the residual stress magnitudes in high strength steel shapes is very limited. Although the value of the modulus of elasticity is the same for all grades of steel and the levels of residual stress therefore should not vary much between identical shapes in different grades, there are still applications where the actual stress levels are needed. This is especially the case for stability issues such as column buckling, and also for girders where fatigue and fracture may play a role.

Traditional residual stress measurements are commonly made via destructive test methods, such as sectioning and hole drilling, to mention the two most common methods (Tebedge, Alpsten and Tall, 1971; Galambos, 1998). These approaches are very accurate but extremely costly and time-

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consuming. The Darmstadt project focuses on the use of a magnetic effect ("Barkhausenrauschen") and the fact that the spatial structure of magnetic fields changes during de-magnetization. Further, stresses in the ferromagnetic material change the magnetic fields significantly, and this change can be quantified. With appropriate calibration tests, the values of the residual stresses can be determined.

This testing method offers major potential for the determination of uniaxial and biaxial residual stress distributions. The work continues to improve calibration techniques and hence the accuracy of the stress magnitudes that are determined. It is expected that the residual stress data base for such high strength steel members will be significantly enlarged. The benefits for bridge construction in particular may be very useful.

Influence of the Bauschinger Effect on Deflections of Cambered Beams: This is another study that has been conducted at the Technical University of Darmstadt, also with Professor Jörg Lange as the director.

The Bauschinger Effect is a phenomenon that affects the response characteristics of steels that undergo strain hardening. It is also referred to as the directionality of strain hardening (Dieter, 1986). For example, a specimen that has been loaded in tension past the yield level and into strain hardening will unload elastically. Upon reloading in the same direction as the original load, the material will appear to have a level of yield stress that is the same as the level of stress at which the original test was stopped. Reversing the sense of the loading to zero and then into compression, the point at which yielding commences in compression is significantly lower than the original compressive yield stress. This is the Bauschinger Effect. It is completely reversible, to the effect that if the original loading were in compression, the higher yield stress would occur under this state of stress and the lower value would be found for tension. The Bauschinger Effect is important for high-deformation operations such as plate bending or other functions where the material is alternately subjected to high strains in tension and compression.

The study at the Technical University of Darmstadt started out as an investigation of the strength and behavior of steel and composite beams under service conditions, and specifically aimed at determining the deflections of such members (Grages, 2007; Grages, Lange and Sauerborn, 2007). One of the original issues was that the calculated deflections often understated the measured values. The measurements were made at various stages of various structures, and one of the interesting findings was that cambered beams deflected more than straight members. It was initially thought that this was caused by the residual stresses in the members, although it should have been clear that such could not be the case. The magnitudes of the service loads and the accompanying deflections and rotations are very small and the response of the beams is elastic for all practical purposes. Any local yielding

due to the combination of service load stresses and residual stresses would almost certainly not take place, and the local yielding that was developed during the cambering operation would also be very limited. Of course, the latter would depend on the amount of cambering or curving, but it will be very small for the usual fraction of the dead load camber, as is common in American practice.

Short beam segments in S355 steel (50 ksi yield stress) were loaded to varying levels of strain beyond yield, and then loaded in the opposite direction. These tests imposed various degrees of prestrain, as high as 2%, and demonstrated that the Bauschinger Effect was clearly reflected in the cyclic stress-strain relationships. Using 18 m (60 feet) long beams that were curved to varying degrees, tests and additional analyses showed significant differences between the measured and computed deflections, as illustrated in Figure 1. The agreement between tests and theory is generally very good. A non-cambered beam was included for reference.

It is certainly possible to take this type of behavior into account in the analysis of a structure, but it is a question whether it is strictly necessary. The study demonstrates and explains the behavior that can be anticipated. On the other hand, the structural displacements will stabilize once the loads have been applied, and no further deflection increases should be expected. Finally, the amount of cambering that is needed can take these kinds of increases into account, if it is deemed necessary for the service performance of the members and the structure.

STRUCTURAL MEMBER RESPONSE MODELING

Equivalent Moment Distribution Factors for Lateral-Torsional Buckling: This research project has been conducted at the University of Navarra in Pamplona, Spain, with Professor Miguel Serna and Dr. Aitziber Lopez as the directors.
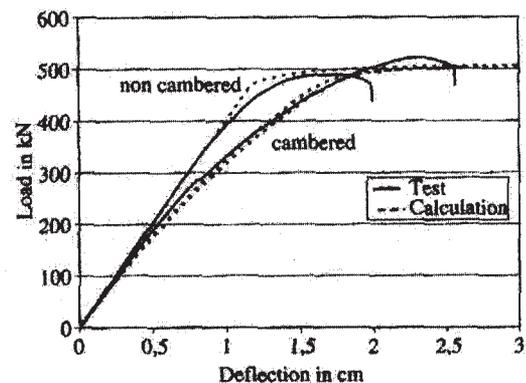

Fig. 1. Deflections of cambered and non-cambered beams (courtesy of Hauke Grages).

The equivalent moment factor, C_b, has been used for many years and by many design codes worldwide in the design of laterally unsupported beams that may fail in lateral-torsional buckling. It is a convenient conversion factor that translates the actual moment distribution into an equivalent uniform distribution, for which the theoretical elastic buckling solution is well known. Some of the early research studies on the subject were conducted in the 1960s and 70s by W.J. Austin, J.W. Clark and others (Galambos, 1998). Very significant work has been done for the past 25 years or so by Galambos, Trahair, Nethercot and other researchers. The C_b equation that has been used in the AISC *Specification* (AISC, 2005) for several editions is attributed to Kirby and Nethercot (1979), and it offers the convenience of applicability to all types of moment distributions.

The investigation by Serna and Lopez focused on the fact that the current C_b equation does not take into account any lateral bending or warping restraint at the supports or support points for the beam. Examining a wide range of beam support and moment distribution cases, using finite element as well as finite difference solutions, the study incorporated the following restraint conditions:

(i)   no restraint to lateral bending and warping

(ii) full restraint to lateral bending and warping

(iii) restraint to lateral bending only

(iv) restraint to warping only

As an example, Figure 2 shows a typical symmetric moment distribution that was used for the analysis of an 8 m (26 ft 8 in.) long IPE 500 beam. This is a 20-in.-deep hot-rolled shape with no closely comparable American counterpart; the flange width of the IPE 500 is 8 in., the flange thickness is ⅝ in. and the web thickness is ⅜ in. Figure 3 shows the resulting equivalent moment factor values, as determined by the finite difference solution, by the solution of the researchers, and by the AISC C_b expression from the 1994 *LRFD Specification for Structural Steel Buildings* (which is the same as in the 2005 *Specification for Structural Steel Buildings*).
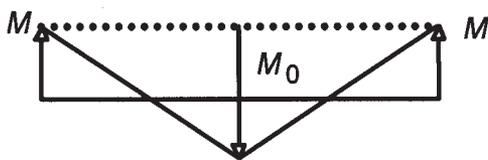
The values of the end moment ratio M/M_0 are shown in the horizontal axis; the values of the equivalent moment factor are shown on the vertical axis. Albeit much more complex than the expression used in the current codes, the researchers observe that including the warping restraint leads to significantly higher C_b-values than what is predicted by the expressions of the 1994 AISC LRFD *Specification* and the 2000 British code BS 5950; further, including the effect of the bending restraint leads to lower C_b-values. These findings are demonstrated by the data shown in Figure 3. The study included a broad range of comparisons with the two code documents, and the researchers note that the lower C_b-values for the end-restraint case indicate that the codes may be unconservative for such cases. The higher values for the warping-included cases obviously indicate conservative code criteria.

SEISMIC RESPONSE OF STEEL STRUCTURES

Controlled Rocking of Steel-Framed Buildings with Replaceable Energy Dissipating Fuses: This is a very substantial investigation of the performance of a novel type of structural system, currently underway as a joint project of the University of Illinois, Stanford University, Hokkaido University in Japan, and the California consulting firms Tipping & Mar Associates and GPLA. The directors are Professors Gregory G. Deierlein of Stanford University and Jerome F. Hajjar of the University of Illinois. It is supported by funding from the NEES program of the National Science Foundation.

The principal aim of the project is to arrive at performance and design criteria that will eliminate residual drift and also concentrate the structural damage in the replaceable fuses of the braced frame. Residual drift is the permanent sway that
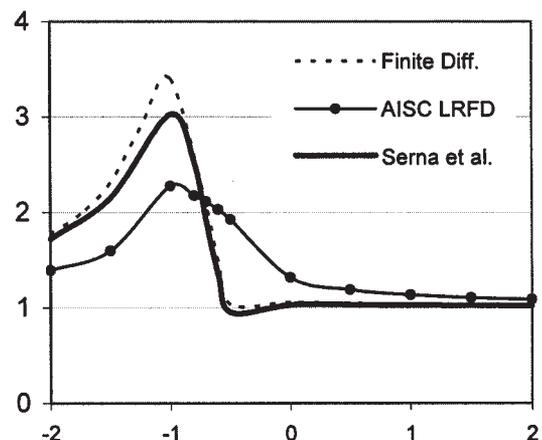
Fig. 2. Linear moment distribution used in computational example (courtesy of M. Serna).

Fig. 3. Values of C_b for the IPE 500 example beam (courtesy of M. Serna).

remains in the building following an earthquake. The revolutionary concept of this system is that the seismic damage will be focused primarily, if not entirely, in the replaceable shear fuses that are incorporated in the frame, along with the self-centering post-tension bars that form an integral part of the system. That is, rather than focusing totally on limiting or preventing the local or overall failure of the frame, the rocking concept and shear fuses aims specifically at providing for economical repair of a damaged structure. Figure 4 illustrates the basic elements and the key behavioral aspects.

The project is further enhanced by the collaboration with researchers for a project of Hokkaido University in Japan. A full-scale test of a frame with square built-up tubular columns and wide-flange beams was recently (September 27, 2007) tested at the three-dimensional E-Defense facility in Japan. Figure 5 shows this frame after the completion of the test. Evaluations of the results are forthcoming.

COMPUTER SOFTWARE DEVELOPMENT

Software for Design of Plate Structures against Plate Buckling: This is a major software development that has been undertaken by the research group at the University of Liège in Liège, Belgium. The project director has been Professor René Maquoi. Funded by the COMBRI project of the European Union, the software is intended for use in the analysis and design of steel-plated structures for bridges.

The design criteria that have been used in this software development are those of the plate buckling requirements of Eurocode 3, Section 1-5 (CEN, 2005). The focus is on the following criteria:

(i)   Accurate determination of elastic plate buckling stresses for rectangular stiffened plates, covering a much wider range of design parameters than what is currently available

(ii) Accounting for the stabilizing effects of the torsional stiffness of stiffeners and the rotational stiffness of the edges of the plates
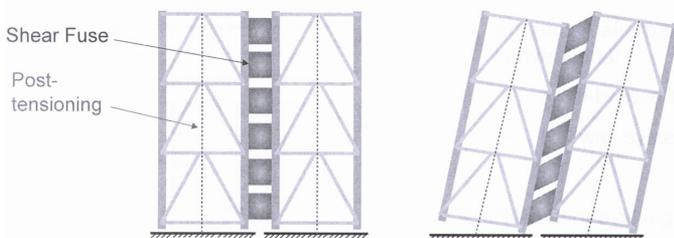
(iii) Providing an effective graphical interface to improve the interpretation of the analytical results

(iv) Offering an efficient substitute for much more complex finite element analysis

Named EBPlate, the program is available for downloading at no cost at the websites www.cticm.com and www.steelbizfrance.com . It is noted that CTICM is the French steel construction institute.

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Fig. 4. Self-centering frame with replaceable shear fuses (courtesy of J.F. Hajjar).

Fig. 5. Full-scale frame test at the E-defense facility near Kobe, Japan.

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