Current Steel Structures Research

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INTRODUCTION

Among the thorniest problems for researchers in general—and maybe for American structural engineering researchers in particular—is the subject of money, that is, research funding. This is especially acute for academic researchers under the current economic conditions, what with limited governmental and private research grants funding being further reduced or in many cases entirely eliminated. What many government leaders and business executives and accountants do not appear to understand is that when markets "turn south," investment in research and marketing is more important than ever, for that is when the foundation is placed for rapid advances when business picks up again.

American university research and researchers are especially vulnerable, considering that funding must be obtained not just for graduate student support (commonly $20,000 or more per year, to cover tuition and stipend), test specimens, equipment, and other legitimate expenses, but also to cover typically three months of income for the professor(s) as well as university overhead of 40% to 60% of the contract amounts. How many Americans know that university professors (like public school teachers) are paid only for nine months of the year and that the remainder of the annual income has to come from research funds or other sources? And if the researcher wants to advance in his or her academic career, research funding *must* be obtained to ensure that results, publications and recognition will be obtained for scientific achievement. In brief, an academic career without research and attendant evidence of scholarly success equals failure in most institutions, because teaching alone is simply not sufficient. You must demonstrate scholarly success, and that comes from successful research work.

The modus operandi is different for researchers and institutions in most other parts of the world, although there are some signs that universities in the U.K., for example, are looking at the American model as a means of reducing the demands on university budgets. In most of these other locales, the research contract budgets do not need to cover the 25% of the professor's annual salary, which means that the overall cost is reduced significantly. At the same time, the sheer size of the total American academic research undertaking dwarfs that of all other countries. So the rest of the world is working hard to catch up with the American research enterprise, which is still the most effective and powerful in the world. But the efforts within the European Union, for example, are notable and very impressive, as is the support offered in countries like China, Japan, Singapore and Australia. Therefore, unless American federal and state governments and industry are prepared to address the funding issue aggressively, the leading role of U.S. universities will be eroded—significantly. That will not be helpful to anyone, anywhere.

Many of the research studies presented here have been conducted in Europe, with financial support from various instances within the European Union. Some of these are typical of many current research projects in Europe, as they reflect collaboration between universities in different countries. For example, a study of the axial and flexural capacities of welded built-up box cross sections is a joint effort between institutions in Germany and Slovenia, and an examination of the buckling capacity of slender composite tubular columns has been a joint effort between schools in the U.K. and Lithuania. Certain bridge evaluations have been conducted in Denmark and the U.K., and an interesting assessment of structural strengthening using adhesives has been done jointly by researchers in Germany and Poland. The potential performance and use of girders with corrugated webs in building structures is conducted in Germany; this is an application that until now has only been seen in bridge construction. Finally, composite construction continues to be the subject of aggressive research work in Australia, as reported here, as is a major investigation of the steel storage racks that are so important for many industrial and other manufacturing operations. By all indications, these studies are typical of research institutions that conduct high quality research on subjects that are likely to attract attention in many engineering locales.

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 many cases reports or publications have not yet been prepared for public dissemination.

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PERFORMANCE OF STRUCTURAL MEMBERS

Slender Thin-Walled Box Columns: This study has been conducted at the University of Ljubljana in Ljubljana, Slovenia, and the University of Stuttgart in Stuttgart, Germany. Professors Darko Beg (Ljubljana) and Ulrike Kuhlmann (Stuttgart) have been the directors of the project.

Focusing on the use of thin-walled box cross section columns, the members were fabricated using hot-rolled plates as well as cold-formed elements. The usual material property tests were conducted, as were complete evaluations and measurements of residual stresses, member out-of-straightnesses and out-of-plumbs. Eight full-scale column tests were conducted, using concentric and eccentric axial loads, and the correlation between the analytical and the experimental results was found to be very good (Pavlovcic et al., 2009). Figure 1 shows two of the column specimens during testing.

The residual stress magnitudes and distributions were determined using the well-known method of sectioning, as developed and used extensively at Lehigh University (Tebedge et al., 1973). There was very good agreement with the data provided by other investigations, for welded built-up as well as cold-formed members (Galambos, 1998).

The analytical computations were performed using the ABAQUS software. It predicted correct ultimate limit states and accurate failure loads for local as well as overall buckling limit states, with an accuracy of ±6 percent. This is comparable to what was found in the classical column study of Bjorhovde and others, although the earlier investigations did not have access to such advanced software as ABAQUS (Bjorhovde, 1972; Galambos, 1998).

Plate Girders with Corrugated Webs for Building Applications: This project has been conducted at the Brandenburg University of Technology in Cottbus, Germany, in partnership with the Bochum University of Applied Science in Bochum, Germany. The project director has been Professor Hartmut Pasternak.

Plate girders with corrugated webs were originally developed for use in bridge structures. The depth and spans of the typical plate girders with flat-plate webs often required extensive transverse and even longitudinal stiffeners, with attendant stability problems as well as long-term cyclic load performance and difficulties in the form of fatigue cracking. The flat-plate web thickness also could be substantial, resulting in heavy girders.

The corrugated webs of the girders that have been studied by Professor Pasternak benefit from increased web buckling strength due to the shape of the web and its innate stability. As a result, these girders are now being used in building structures, due to their reduced self weight. Plate thicknesses in these girders are typically 1.5 to 3 mm ($\frac{1}{16}$ in. to $\frac{1}{8}$ in.), and the corrugations are sinusoidally shaped (Pasternak et al., 2009a). The sinusoidal fabrication process has been automated, with the result that corrugated web thicknesses up to 12 mm ($\frac{1}{2}$ in.) can be used. The girders have seen application in storage warehouses, as shown in Figure 2, and now also in short span bridges. Design criteria for the girders are provided by Eurocode 3, Section 1-5, Annex D, although the current requirements limit the web thickness to no more than 3 mm ($\frac{1}{8}$ in.) (CEN, 2005a).

Fig. 1. Slender box column specimen during different loading stages (Photos courtesy of Professors Darko Beg and Ulrike Kuhlmann).

The researchers are now developing formulations that can be used for larger web thicknesses, taking into account nonlinear response characteristics, lateral-torsional buckling and patch loading. This effort is a joint project between the Brandenburg and Braunschweig technological universities in Germany (Pasternak et al., 2009a).

STRENGTH AND BEHAVIOR OF COMPOSITE ELEMENTS AND STRUCTURES

Behavior of Composite Beams with Deep Trapezoidal Slabs Containing Headed Stud Shear Connectors: This is a major project that has been conducted at the Centre for Infrastructure Engineering and Safety of the University of New South Wales in Sydney, Australia, with Professor Mark Bradford as the director. Funding and other support have been provided by the Australian Research Council and the Australian Steel Institute, as well as the Australian steel deck producer BlueScope Lysaght.

Composite beams using corrugated steel deck and headed stud shear connectors have been very common since an early research project was conducted at Lehigh University in the late 1960s (Fisher, 1970; Grant et al., 1977). For a number of years the types of steel deck exhibited various forms of trapezoidal and other corrugations, and the deck depths were mostly 1½ in., 2 in., and 3 in. These systems were eminently suitable for floor beams and girders in commercial and residential low- and high-rise building frames. The span of the concrete slab on top of the steel deck was commonly 8 ft to 12 ft, due to the limitations imposed by moment capacity of the slab, the shear stud length and capacity, and the deflections of the slab. Various deck types and geometric configurations have since been developed, with depths up to 6 in. to 8 in. (150 mm to 200 mm), but the shear connectors and the overall design criteria have not evolved accordingly. However, longer spans clearly would be very useful for many applications.

Fig. 2. Storage warehouse with corrugated web girders (Photo courtesy of Professor Hartmut Pasternak).

The project at the University of New South Wales developed a push-test to replace the push-out test that has been the traditional one to use to assess stud shear capacity, etc. (Ranzi et al., 2009). The push-out tests in many cases led to premature failures of a type that never occurred in full-scale beam tests, hence the need for the improved modeling and test as provided by the UNSW group. Figure 3 shows the push-test laboratory assembly, and Figure 4 shows the very favorable ductile load-slip response of the studs.

Two full-scale beam tests were run at the University of Sydney to verify and validate the results of the push-test that had been developed. With beam spans of 8 m (26 ft 8 in.), the beams performed very well, with ductile behavior as predicted by the push-test. The correlation with the analytical results was excellent. Figure 5 shows the test setup for the full-scale beams.

Additional work focuses on the development of serviceability criteria for these types of beams, including the warping effect of slab shrinkage and its interaction with the partial shear connection between the slab and the steel beam.

Fig. 3. Push-test for stud shear connector performance (Photo courtesy of Professor Mark Bradford).

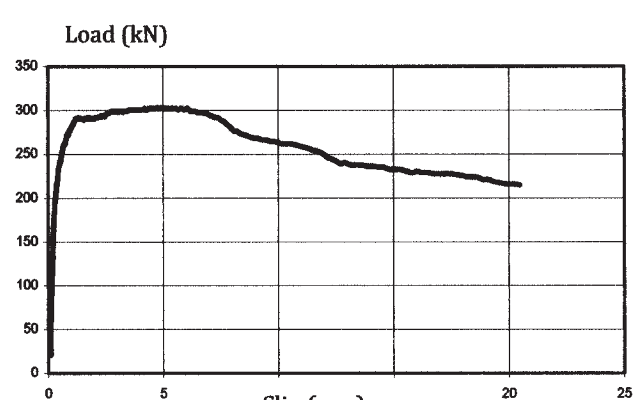

Fig. 4. Ductile load-slip performance of push-tested shear connector (Figure courtesy of Professor Mark Bradford).

Buckling of Slender Composite Concrete-Filled Steel Columns: This has been an international collaborative research project between the Vilnius Gediminas University in Vilnius, Lithuania and the University of Manchester in Manchester, England. Professors Audronis Kvedaras (Vilnius) and Cameron Goode (Manchester) have been the project directors.

The project has effected a major data collection and evaluation of test results for square and round tubular columns, to assess the design criteria that are specified in Eurocode 4 (Goode, 2008; CEN, 2005b). It has been found that Eurocode 4 tends to be conservative for circular tubular columns, and the criteria can be readily extended up to concrete cylinder strengths of 100 MPa (14 ksi), or significantly higher than the current limitation of 75 MPa (approximately 11 ksi). This does not extend to rectangular columns, for which the current limit is 50 MPa (7 ksi).

INDUSTRIAL STRUCTURES

Strength and Behavior of Steel Storage Racks: This has been a major, multi-year project at the University of Sydney in Sydney, Australia. Professor Kim Rasmussen is the project director for a study that has wide governmental and industrial support.

The study has focused on the performance of the storage racks when they are subjected to impact forces due to forklifts. This is a very common and sometimes disastrous occurrence. In addition to detailed three-dimensional strength and stability analyses of the racks, full-scale tests have also been conducted to ensure as realistic conditions as possible. Among other considerations, the tests include actual collisions of forklifts with rack columns ("uprights"), evaluating the dynamic response of the structure (Gilbert and Rasmussen, 2009). Progressive collapse scenarios are also assessed.

The pallet loading of the racks is a central issue, including what takes place when a pallet falls through several "stories" of a rack that may have experienced upright damage. The full-scale tests that have been conducted demonstrate the response of the structures under gravity and lateral loads. One such test is illustrated in Figures 6 and 7, which show the rack before the test and the condition after a typical pallet loading case, as described earlier.

Fig. 5. Full-scale composite beam test with deep trapezoidal steel deck (Photo courtesy of Professor Mark Bradford).

Fig. 6. Full-scale storage rack before testing (Photo courtesy of Professor Kim Rasmussen).

Fig. 7. Pallet-loading-induced failure of storage rack (notice the damaged upright on the right-hand side of the photograph) (Photo courtesy of Professor Kim Rasmussen).

The project work includes assessments of component tests and other aspects of various international storage rack criteria, such as the American code by RMI (Rack Manufacturers Institute) and the relevant European code. Additional component tests are being developed, including one for the stiffness of base plates subjected to uplift.

BRIDGE STRUCTURES

Stability of Girders Using U-Frames: This study was conducted at City University of London, England, while the project director, Kuldeep S. Virdi, was a faculty member at that university. He is now at Aarhus University in Aarhus, Denmark.

Lateral-torsional buckling is a major consideration for beams and girders, and maybe especially for the long-span members often used in bridge construction. While actual bracing is the most common approach to increase the stability and strength of the girders, there are a number of cases where such is not suitable, especially for through-type bridges and where overhead bracing members are not practical. The so-called U-frame provides girder stability through connections between the floor beams and the girders, as shown in Figure 8, and the floor beams also support the roadway slab.

The study examined the influence of a range of girder and floor beam spacings to determine the buckling strength of the system (Virdi and Azzi, 2009). An example of the buckled shape for one of the U-frame configurations is shown in Figure 9.

A parametric analysis of the U-frame system was performed, using a bridge span of 18 m (60 ft), a bridge deck width of 6.3 m (21 ft), 1.8-m-deep (6 ft) girders, and 0.8-m-deep (30 in.) floor beams. The bridge deck was designed as composite with the floor beams. The U-frame spacing was varied from 2 m to 3 m (6 ft 8 in. to 10 ft), giving structures with eight to five U-frames.

Figure 10 shows the variation of the effective length of the girders, as a function of the spacing of the U-frames and the buckling mode. For instance, mode 1 (top curve) is the usual single wave form, reflecting the lowest buckling load. Increasing the U-frame spacing from 2 m to 3 m increases the effective length by 20%, meaning that the buckling load is reduced by $(1.2)^2$ or 44%. This is as should be expected.

STRUCTURAL REPAIR AND RETROFIT

Use of Adhesives to Strengthen Steel Structures: This project has been a joint international effort between the Brandenburg University of Technology in Cottbus, Germany, and the Krakow University of Technology in Krakow, Poland. The project directors are Professors H. Pasternak (Brandenburg) and M. Piekarczyk (Krakow). The funding sources have not been identified, but they are likely to be major European Union programs.

Adhesives have actually been used in a number of construction projects in Germany, starting with several box girder bridges in the 1960s. These structures have continued to function properly, now after nearly 50 years of service. In the

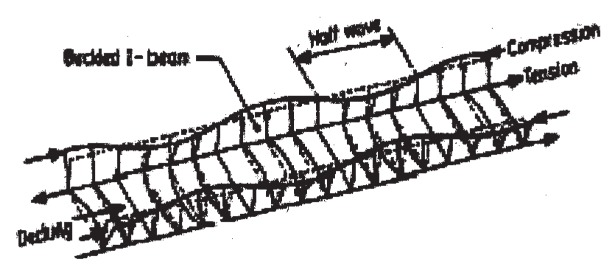

Fig. 9. One of the buckling shapes of a typical structure with U-frames (Figure courtesy of Professor Kuldeep Virdi).

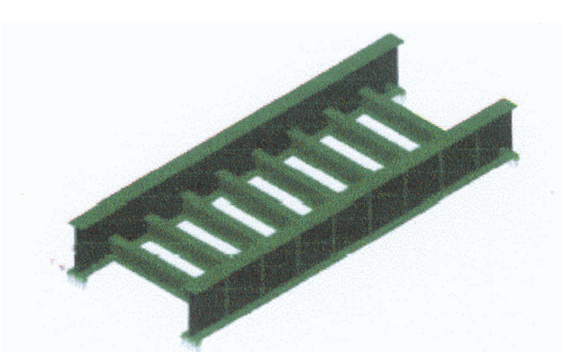

Fig. 8. Girders and floor beams constitute the U-frames of the bridge (Figure courtesy of Professor Kuldeep Virdi).

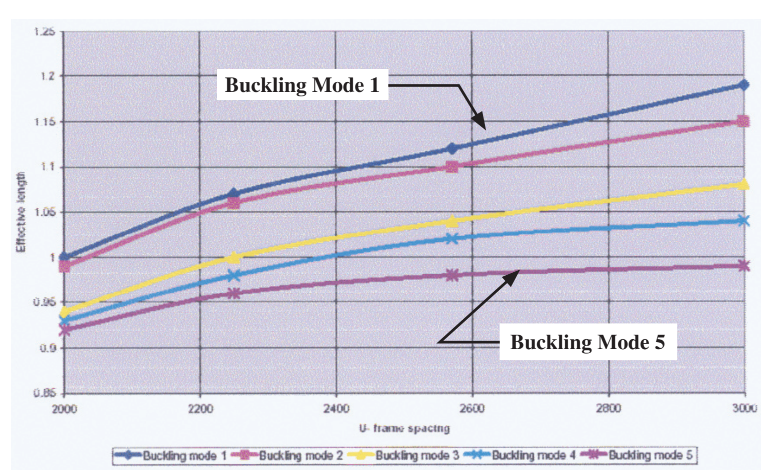

Fig. 10. Variation of girder effective length as a function of U-frame spacing (Figure courtesy of Professor Kuldeep Virdi).

current project, a box girder was tested at Krakow and knee joints were tested at Brandenburg, and ABAQUS analyses were conducted for all of the test specimens. There was good correlation between the tests and the analytical results.

For the knee joints it was found that it was better to use epoxy-glued plates on both sides of the joint; a single sided plate was sufficient when polyurethane glue was used. Similar results were found for the box girders. The increases in load-carrying capacity were substantial, including the fact that local buckling did not affect the ultimate limit states. It is clear that the use of various forms of adhesives can play an important strengthening role—it is still a question whether the organic stability of the glued joints and surfaces will suffice. However, the performance of the older German bridges speaks well for the method and the materials.

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