Current Steel Structures Research

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It is an interesting fact that extensive and very complex research on the behavior, strength, and design of steel structures for fire conditions is currently being carried out in many areas of the world. Some such work is currently underway in the United States, but the majority of investigations are taking place at several institutions in Europe, China, Singapore, and Australia. Design codes are also available, most notably the Eurocode 3 part 1-2 (CEN, 2005) that addresses structural fire design. Based on the concept of the fire limit state, this is possibly the most comprehensive code of its kind in the world today. The requirements have been based on extensive research that was carried out in several European countries over the past 25 years and more. Fire design conditions can now be found in the steel design criteria of a number of countries, and of course now also in Appendix 4 of the AISC *Specification for Structural Steel Buildings* (AISC, 2005).

Somewhat in line with fire considerations and other extreme events, numerous efforts are now also being carried out in the United States and elsewhere on the subject of robustness of structures and structural elements and connections. Some of these studies also address performance-based design (PBD), although practical and reasonably simple approaches for PBD appear to be difficult to obtain. Nevertheless, it is expected that performance-based design eventually will be applied in the analysis of many types of structures.

Very high strength steels are now being considered for applications in regular building and bridge structures. In the past such materials were primarily used in cable structures, where the full strength could be mobilized effectively. For example, at this time several European projects are examining the characteristics of welded and bolted connections in steels with yield stress levels at 100 ksi (690 MPa), 137 ksi (960 MPa), and 160 ksi (1,100 MPa). A major issue with welded joints in such steels is the concept of matching filler metal strength. Some novel solutions are being addressed, to resolve these questions. However, the S690, S960, and S1100 steel grades, as they are specified under Euronorm criteria, are not yet fully available for the construction market. The S690 grade is closely comparable to ASTM A514.

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References are provided throughout the paper, whenever they 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.

BEHAVIOR OF STEEL STRUCTURES UNDER FIRE CONDITIONS

Robustness of Common Steel Connections in Fire: This is a major project being conducted at two British universities. Under the leadership of Professors Ian Burgess and Roger Plank of the Fire Research Group at the University of Sheffield, and in collaboration with Dr. Yong Wang and Professor Colin Bailey at the University of Manchester, the study focuses on two primary areas:

1. The University of Sheffield group examines the capacity of the connections under fire conditions.

2. The University of Manchester team examines the thermal and structural response of the connections as part of the frame.

In past research work dealing with the response to fire, the connections typically did not receive a great deal of attention, since it was assumed that the structural members would be more critical to the overall frame behavior. However, the full-scale tests conducted at the Building Research Establishment facility in Cardington in England demonstrated that the connections are possibly the most sensitive elements. Tests and numerical simulations have shown that beams and slabs are capable of developing very large deflections and thus to mobilize catenary action in beams and membrane action in slabs. The catenary action in beams, for example, is resisted by the tensile capacity of the member. However, this transmits the tensile force into the beam end connections, which in most cases have not been analyzed, much less designed for combined shear and/or moment and tension. It is conceivable that some connections may fail under these conditions, leading to further spread of the fire and possibly to disproportionate collapse of the structure. On the other hand, research by Professor John Dawe at the University of New Brunswick in Canada has shown that some simple shear-type beam connections are capable of resisting significant tension, in the same mode of behavior as is found when catenary action occurs in beams (Bjorhovde, 2005).

The work at the University of Sheffield will examine the behavior of four common types of connections under the combined action of tension and shear. A total of 80 tests will be conducted, using a setup as shown in Figure 1. The test parameters are the connection temperature, the ratio of tensile to shear forces, and three connection geometries that aim at demonstrating different failure modes.

The tests are to be completed next year. The overall aim is to develop a component-based method of analysis, through which the various connection zones can be modeled as nonlinear springs. This approach has been used extensively for connections at ambient temperature, and has now been adapted to flush end-plate connections that are subjected to fire temperatures. It is expected that the 80 tests will provide an invaluable data base for further studies.

Performance-Based Fire Engineering Design of Steel and Composite Structures: This is an ongoing investigation at the National University of Singapore, under the direction of Professor Richard J.Y. Liew.

It is based on the premise that "a rational approach to fire safety assessment is to relate functional requirements, such as prevention of spreading heat and smoke, safe evacuation and rescue, etc., to fire resistance considering both local and global stability of structures" (Liew, 2006). This clearly aims toward a performance-based design approach, whereby the engineer needs to understand the level of performance that is needed and expected. The design then follows the understanding of the structural needs. The difficult aspect of the approach is to predict the performance that will be obtained with the design that has been done and to ensure that the design is reliable and sufficiently robust. As described by Professor Liew, the necessary steps of the performance-based design procedure are as follows:

1. Identify the goals and the design objectives of all members of the design and owner teams.

2. Identify all possible fire scenarios that may occur during the life of the structure.

3. Assess the likelihood and consequences of all fire scenarios.

4. Establish performance criteria that will ensure safe escape routes for all building occupants, safe fire fighting conditions, and safety for individuals in the vicinity of the building.

5. Predict the performance of the building system on the basis of available data, and compare the findings with the performance criteria that have been established.

6. Ensure that the fire protection systems that are chosen are reliable, durable, and sufficiently robust.

7. Assess, validate, review, and verify all design assumptions.

Many of these criteria are nonstructural and in fact dictated by the architect, the owner, and the building authorities. However, the structural engineer needs to provide a

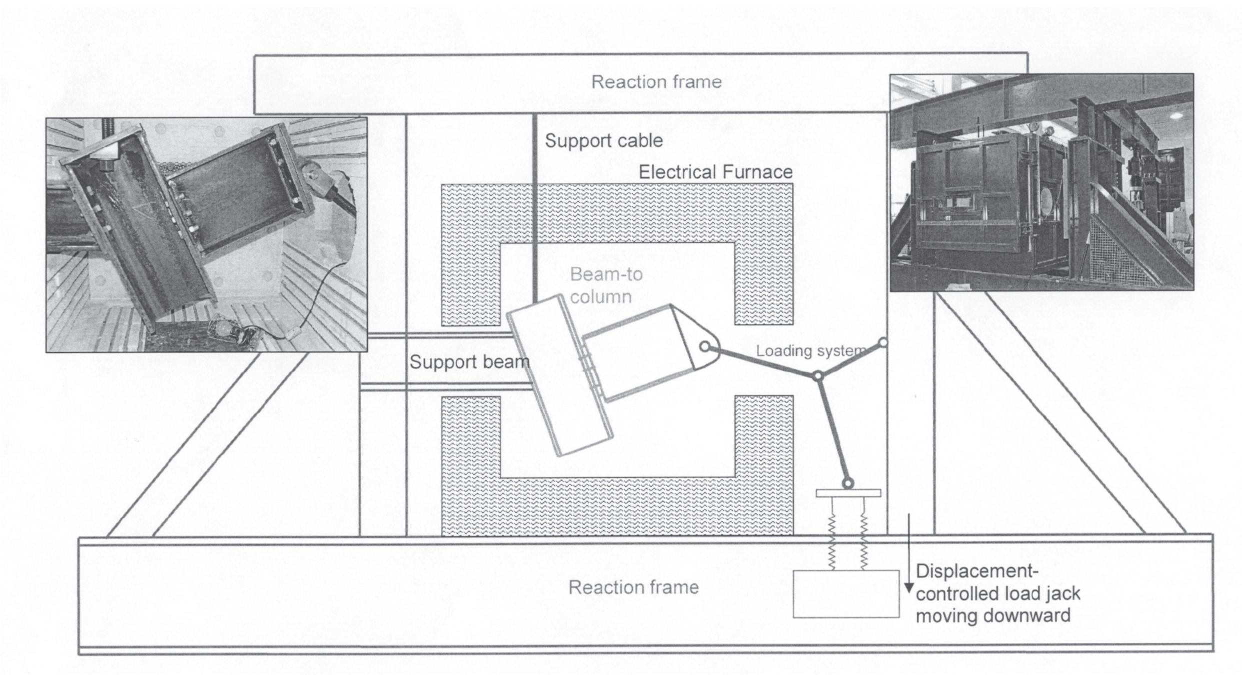


Fig. 1. University of Sheffield connection test setup.

quantitative assessment of the fire resistance of the structure. Software and other computational tools are now available to do just that (Liew, Tang, and Choo, 2002; Liew, 2006). There is no need to follow the long-used system of architect-prescribed fire resistance assemblies, but this does require that the engineer of record play an important part in the assessment and design process.

Finally, the issues associated with the use of fire tests with prescribed time-temperature relationships is a critical one. The performance-based procedures rely on so-called natural fires, which reflect much more realistic temperature levels, fire duration and fire load, etc.

Performance Based Design for the Fire Situation: Professor J.-B. Schleich, now with the University of Liège in Belgium and formerly with the research department of the steel company Arcelor, has been a long-time and consistent leader in fire engineering research and development that has been carried out in Europe for the past 25 years. His studies of performance-based design issues and criteria for fire engineering are central to the state-of-the-art. In particular, his emphasis on the use of natural fires as contrasted with the traditional fire test curve has been one of the key elements of the improved assessment of design for fire. Figure 2 contrasts the two temperature approaches, using the ISO standard fire curve and emphasizing concepts such as flash-over, temperature control by active versus passive measures, and fire duration (Schleich, 2006a, 2006b).

The principles of performance-based design as presented by Schleich are by and large in agreement with those detailed by Liew. But some of the key parameters and design considerations are very clearly tied to the limit states treatment provided through the Eurocodes. And the natural fire treatment was one of Schleich's major efforts, leading to much more realistic fire design procedures.

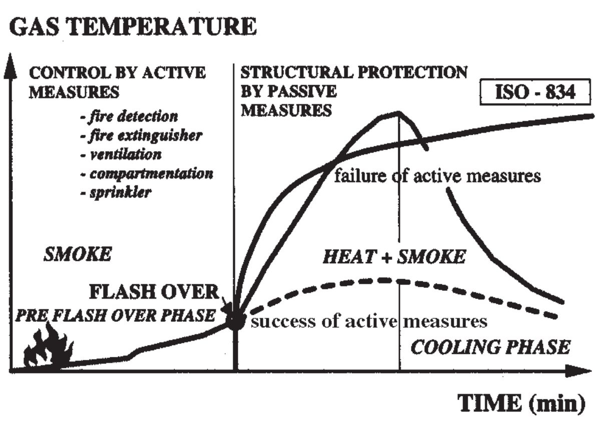


Fig. 2. Various fire temperature curves, according to Schleich (2006a).

WELDED CONNECTIONS

Testing and Numerical Modeling of Welded Joints for Very High Strength Steel: This is a major research program that aims to develop performance and design criteria for welded connections in steels with nominal yield stress levels of 100 ksi, 137 ksi, and 160 ksi. These strength levels reflect steel grades S690, S960, and S1100, all of them not yet commercially available but with apparent interest from industry as well as designers. The work is being done at the Delft University of Technology in Delft, the Netherlands, in collaboration with the Dutch applied research organization TNO. The project director is Professor Frans Bijlaard, with researchers O.D. Dijkstra and M.H. Kolstein.

The first part of this study focused on the issue of matching or overmatching filler metal for joints in such high strength steels (Dijkstra and Kolstein, 2006). Traditional design calls for matching or overmatching. This is not possible with current filler metals and the steel grades S960 and S1100. Finite element models were developed for the specimens that were to be tested, as shown in Figure 3, to establish failure modes and where the failures would take place (base metal or weld metal).

The test plate thicknesses, *T*, as shown in Figure 3, were 10, 12, and 40 mm (⅜, ½, and 1⅝ in.), with double bevel complete-joint-penetration welds. The steel grades were S690 and S1100; the welds for the S690 specimens were overmatched; they were undermatched for the S1100 tests. The two-dimensional and three-dimensional analyses predicted that three modes of failure were likely, as follows:

1. Ductile failure through necking and subsequent fracture of the base metal.
2. Failure through cracking at the weld toe.
3. Failure through fracture at the base metal-weld metal interface.

The physical tests verified the theoretical analyses. Specifically, it was found that undermatched weld metal could be used with oversized (reinforced) welds. This appears to

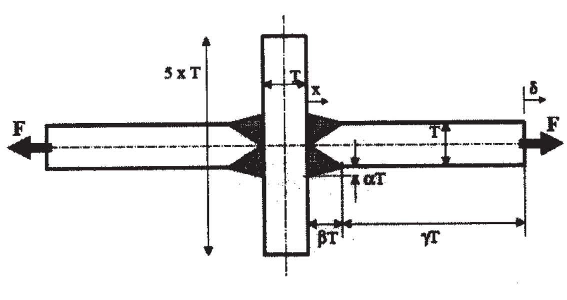


Fig. 3. Test specimen and weld configuration.

offer realistic structural uses for the very high strength steel. If the welds are not reinforced, the deformation capacity is lowered significantly.

Test specimens similar to the one described earlier were used in a large series of tests with S690 and S1100 steel (Kolstein, Bijlaard, and Dijkstra, 2006). Additional tests used cross-connected plates and fillet welds loaded in shear, and transverse groove welds with high stress concentration factors. With a total of 48 tests, overmatched weld metal was used for the 12 mm and 40 mm S690 specimens; and undermatched weld metal was used for some of the 12 mm tests. All of the S1100 tests were undermatched.

The final results offer the following observations:

1. Overmatched welds in S690 steel have very good strength and deformation capacity.

2. Undermatched weld metal can be compensated for by weld reinforcement.

3. Undermatched weld metal and incomplete penetration in welds for S1100 steel have significantly lowered deformation capacity.

The research program continues with additional analytical work, aiming to establish detailed understrength criteria. It appears that understrength by as much as 30% from the matching condition will not result in undue and premature failure.

CONNECTIONS FOR STEEL STRUCTURES

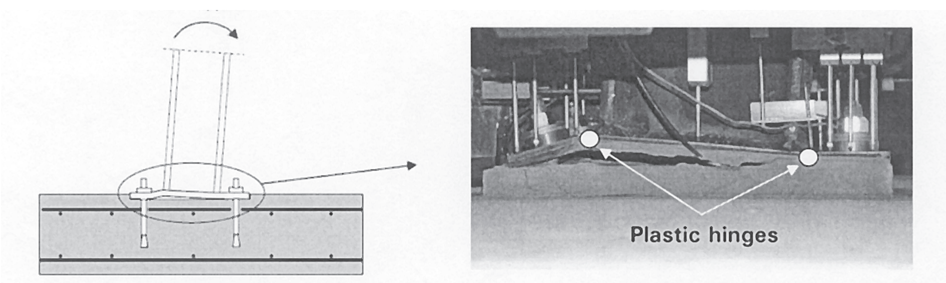
Reliability of Semi-Rigid (PR) Beam-to-Column Welded Joints: This study is being conducted at the University of Zagreb in Croatia, with Professor Darko Dujmovic as the director. Focusing on the component method of connection analysis and design, as described in Eurocode 3 (CEN, 2005) and its supporting documents, the study aims at a probabilistic evaluation of the method and the overall reliability of certain semi-rigid (partially-restrained or PR in American terminology) connections.

Physical tests have been conducted of fully welded moment connections in S235 steel (34 ksi nominal yield stress level), using IPE 240 beams and HE 200 A columns. These are relatively slender shapes, with the IPE 240 having a depth of 240 mm (9½ in.) and the HE 200 A shape having a depth of 200 mm (8 in.). Further, the shapes are supplied from six different European steel mills to allow for a limited probabilistic evaluation of material sources. It is interesting to note that the variability of material and geometric properties between the shapes supplied by the six mills is very high. But the tests are accompanied by extensive numerical analyses, considering the primary model factors as they are implied in the criteria of Eurocode 3.

The results have shown that the initial stiffness data provided by the code underestimate the actual stiffnesses significantly, although the test data variability is very high. Thus, the reliability indexes for these connections equal 5.5 to 7.9, in contrast to the value of 3.8 that is specified in the code. This would appear to indicate that some of the limit states would have a very low probability of occurrence.

The specimens were tested in traditional static fashion, using the typical one-sided, cantilevered beam arrangement. The maximum moment capacity varied by approximately 25 kN-m, or approximately 25% from the lowest test value to the highest. The specimens were prepared particularly carefully, so the variability may be attributed to the material and geometric property variations. This will have some implications for overall material and structural assessments.

Structural Behavior of Anchor Plates: This study is being carried out at the University of Stuttgart in Stuttgart, Germany, with Professors Ulrike Kuhlmann and Rolf Eligehausen as the directors. The work focuses on the response of anchor (base) plates that connect steel beams or columns to concrete elements such as slabs or foundations, using anchor rods or headed stud connectors. An illustration of the type of assembly is shown in Figure 4, including the ductile failure mode that is achieved with a semi-rigid (PR) connection. The development of the plastic hinges that is seen in Figure 4(b) is particularly advantageous.



(a) (b)

Fig. 4. Ductile anchor plates with development of plastic hinges.

A total of 20 tests were run, and a component model in line with the criteria of Eurocode 3 was developed. The connections focus their ductile response in the plates, with limited forces being developed in the fasteners and avoiding a brittle failure of the concrete. Additional work is now being done to arrive at a suitable model for anchor plates with headed studs and small edge distances. These details are practical and useful in German construction practice. As a result, the work has attracted the attention of a number of German contractors and designers.

CONNECTIONS FOR SEISMIC RESPONSE

Self-Centering Steel Moment Resistant Frames: This project is a multiyear effort that is sponsored by AISC and the National Science Foundation and is carried out at Princeton University with Professor Maria Garlock as the director. The principal aim of the work is to provide a connection system that will reduce the very large post-earthquake retrofitting costs of damaged structures.

The concept of self-centering moment-resistant frames (SC-MRF) is based on the use of high-strength steel strands that run parallel to the beams in the frame, through the column flanges, and are anchored against the back of the column flanges (Garlock, Ricles, and Sause, 2005). A schematic of the system is shown in Figure 5. Specifically, due to the very high strength of what is essentially post-tensioning elements, the strands will remain elastic through the response of the frame to the earthquake. After the earthquake, the elastic response allows the strands to restore the frame to a condition that will facilitate and minimize any repairs. Of course, as is indicated in Figure 5(b), there will always be a certain amount of structural damage, but it is anticipated that much of this can be repaired without excessive costs.

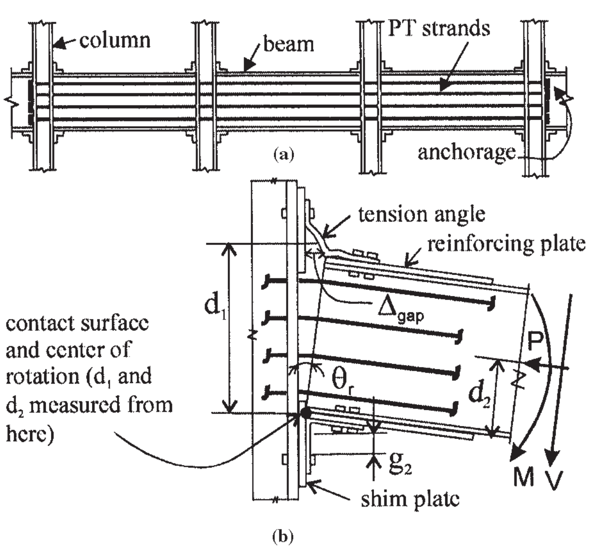


Fig. 5. Section of frame with (a) high strength strands, and (b) deformed connection.

In theory the concept of self-centering is valid, although as with any novel system, behavior, strength, and response characteristics have to be determined. The project aims at establishing the fundamental theory of SC-MRFs, and to develop performance- and reliability-based design procedures. The ultimate goal is to provide a practical design methodology with close ties to current approaches for seismic design of steel structures.

Fabrication and repair procedures also will have to be developed, and the influence of potential earthquake-related building fires and their potential effect on the connections and the strands will have to be evaluated.

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ACKNOWLEDGMENTS

Special thanks are due the following members of the International Structural Steel Research Advisors (ISSRA) who provided input to this paper:

Darko Beg, University of Ljubljana, Ljubljana, Slovenia

Frans Bijlaard, Delft University of Technology, Delft, the Netherlands

Dan Dubina, Polytechnic University of Timisoara, Timisoara, Romania

Ulrike Kuhlmann, University of Stuttgart, Stuttgart, Germany

Richard J. Y. Liew, National University of Singapore, Singapore

David B. Moore, British Constructional Steel Association, London, England

Additional assistance has been provided by Thomas Schlafly, Director of Research for AISC, and by Davor Skejic and Darko Dujmovic of the University of Zagreb in Croatia.