

CIB W14 Collaborative Program to Advance Structural Fire Resistance

Background

The collapse of several buildings on September 11, 2001 have raised questions globally concerning the adequacy of understanding of the structural performance of buildings under design level and extreme fire events. A central objective of building regulations is public safety, and safety centers on structural stability under prescribed loads and load combinations, and on life safety in fires. The recognition that fires can result in collapse has led to the desire to integrate fire loading into the structural design process for design level events. Further, regulators need to understand the potential consequences of extreme events to establish as a matter of public policy, the degree to which these consequences should be mitigated.

The development of numerical capabilities to couple fire dynamics, thermal, and mechanical effects in the structural systems is critical to the implementation of science-based tools to design structures for high temperature loading. Current design methods are based on fire endurance tests of single components and do not account for the behavior of inter-component connections. Moreover, the role of structural connections to enable load transfer during a fire is completely ignored in structural design. Design professionals, code officials, and researchers agree that there are inadequate data available to develop reliable response models for connections at elevated temperatures and that substantial research is needed to fill this gap. CIB W14 is attempting to organize a global collaboration that would bring to bear the significant resources needed to develop a useful design methodology in a relatively short time.

Technical Program

Overview The technical issues surrounding structural fire resistance are many, and will require a sustained effort of research before they can be resolved. The focus of the current 24 month collaborative study is on the fire performance of steel structural frames. Currently, methods exist that can reasonably predict the loss of strength of structural steel members at elevated temperatures and the impacts on a structural frame of thermal expansion of restrained and unrestrained members. Major gaps in knowledge exist with respect to the performance of connections whose failure can lead to collapse. Some reasons for focusing on this system include:

- Steel construction is common, especially for tall buildings.
- Unprotected steel loses its strength at temperatures well below the maximum temperatures produced in a fire.
- The field performance of different approaches to fire-proofing steel (e.g., spray-on, gypsum boards, intumescent) and the positive attributes of new fire resistant steels are impossible to determine from current fire resistance test methods and ratings.
- Current test methods and facilities are insufficient to evaluate the changing load carrying capacity of full-scale structural connections and assemblies at the temperatures to which they are likely to be exposed in a large building fire.
- Compared to other common structural materials such as concrete and timber, the properties of steel are fairly well established, as are its modes of failure.
- Unlike concrete and timber, steel is relatively homogeneous.

The goal of this program is to develop a methodology to predict the response of structural steel frames in an actual fire environment up to the point of failure, including the uncertainty of the prediction. This will be accomplished through a coordinated plan of research involving bench-scale property measurements, multi-scale thermally and mechanically loaded structure experiments, coupled finite element and finite difference simulations, and a demonstration of the ability to predict the response of a full-scale column/beam assembly subjected simultaneously to large thermal and multi-axial loads.

There are a large number of independent variables that will affect the response of the full-scale test specimen in the final demonstration. Those that can be controlled and that are to be included in the research program are the following:

- initial design of assembly (size, means of connection, fire proofing)
- boundary restraint conditions (magnitude, gradients, axial, shear, and moment)
- boundary heat flux (magnitude, time and spatial gradients)

Numerical methods will be adapted and developed based upon existing simulation software, with the major challenge being the coupling of the fire models to the structural models. Material properties, to the extent that they are required for analysis but not known, will need to be measured, along with their variability.

Understanding the performance of connections in fire A key element of the proposed research will involve the comparison of the thermal/structural behavior of two typical beam-to-column connections at elevated temperatures. The connection assemblies will be composed of W-shape columns and beams in a horizontal T-formation. The size of the connections used in the full-scale demonstration should be typical of a 40-story building. The response of the assembly will be quantified in terms of the following dependent variables: deflections, forces, and moments at the three ends of the Tee. (The temperature distribution in the assembly is a convenient dependent parameter to measure, as well, although it is the structural response and not the thermal response that is the bottom line in performance.)

A shear connection and a moment-resistant connection will be tested under the same thermal and structural loading conditions. Simple shear connections are assumed to allow the ends of the members free to rotate (i.e., members are assumed to be unrestrained). On the other hand, moment resistant connections, or rigid frame connections, do not allow the ends of the members to rotate (i.e., the frame is assumed to be restrained). Comparison of the behavior of both types of connections under fire loading will provide engineering practitioners, code officials, and researchers with the largest amount of information regarding endurance and failure modes of typical connections.

The test assemblies will only differ on the connections themselves. Assembly A in the proposed plan will represent a typical simple beam-to-column shear connection. The connection will be an all-bolted double angle connection (see Fig.1). Assembly B in the proposed plan will represent a typical beam-to-column moment resistant connection. The connection will be a directly welded flange connection (see Fig.2).

Experiments will be conducted on both of these assemblies with the steel exposed directly to the heat flux. In addition, fire proofing will be applied to one of these assemblies to see how that affects the response, and our ability to predict the performance. Which fire proofing product to apply will be decided based upon documented knowledge of the thermal properties of the material over the full range of temperatures expected, and our ability to precisely control its application to the specimen and for it to maintain its integrity.

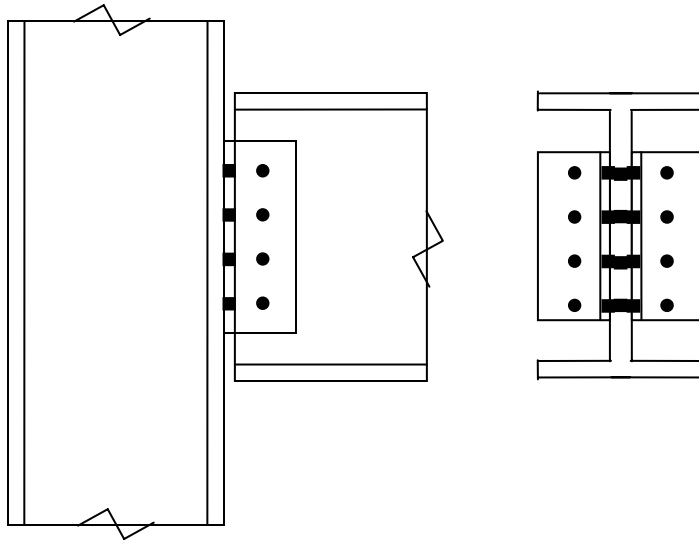


Fig. 1 All-Bolted Shear Connection

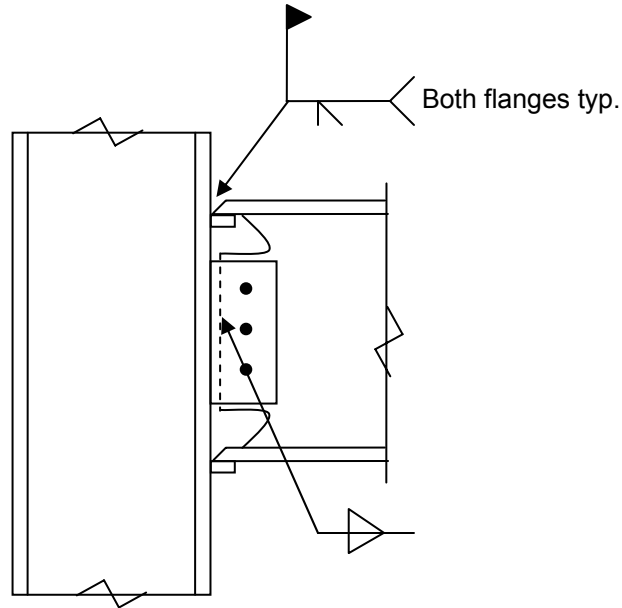


Fig. 2 Directly Welded Flange FR Moment Connection

Boundary Restraint: The choices for restraint of the ends of the Tee are limited by the facilities that are available. The Architectural and Building Research Institute (ABRI) in Chinese Taipei has a new test furnace capable of loading full-scale beam/column connections along two axes. The specifications of the ABRI facility will dictate the flexibility and range of constraint conditions in the full-scale demonstration. Full-scale testing in other furnaces with a single degree of freedom on loading may also prove useful. Reduced-scale testing with more control on the end loads and displacements will be critical to conduct as a means to develop accurate geometric scaling laws. New test fixtures and measurement devices are likely to be required.

Boundary Heat Flux: The heat flux to/from the test specimen is a result of a combination of conduction through the gas boundary layer (i.e., convection), conduction along the specimen due to thermal gradients in the steel, and radiation from the hot surroundings. The source of heat can be from a radiant panel (gas-fired or electric), an open flame (pool fire or gas jet), or from a confined flame within a fire room or furnace. The physical dimensions and materials of the ABRI furnace will dictate the heat flux magnitude and distribution (spatial and temporal) that can be obtained in the full-scale demonstration. Tests run in other full-scale furnaces need to be adequately instrumented to measure the heat flux to the specimen. Reducing the scale will greatly simplify the control of the thermal boundary conditions. Here, again, new test fixtures and measurement devices are likely to be required in order to develop meaningful scaling relationships. Temperature measurements made at strategic locations (in the regions of high thermal gradients) will be useful (if they are accurate) for comparison against numerical predictions.

Structural response at high heating rates: Testing of structural elements and connections at high heating rates is needed to determine performance under extreme events which would involve fires with faster growth and/or higher peak energy release rates than design level events. Some participating laboratories have developed furnaces that can follow higher heating rates (such as the ISO Hydrocarbon curve) and other tests might be conducted with exposure to large gas jets.

Structural response to high thermal gradients: Furnace testing typically involves uniform heating of the element(s) but real fire exposures may involve very significant thermal gradients over the length of the element. These gradients could result in torsional forces on connections or other effects that could lead to failure. Experiments designed to explore the effects of high thermal gradients on restrained and unrestrained steel frames are needed.

Structural response during cooling phase: Most structural fire response tests only examine the heating phase, but structural collapse might be initiated in the cooling phase after the fire is extinguished. This possibility needs to be examined in a set of carefully designed experiments that would not need a furnace facility.

Numerical Simulations There is a crying need for fire models, heat transfer models and structural behavior models to be integrated to go beyond the conventional question of whether or not a building will meet the minimum requirements of the building code, to the unconventional question of how will the building respond to a structural load that exceeds the design load. As part of the investigation into the collapse of the World Trade Center, a considerable effort has gone into the extension of the National Institute of Standards and Technology (NIST) Fire Dynamic Simulator (FDS) and its communication with the commercial finite element code ANSYS, which contains many details of the structural design. The results from ANSYS are then communicated to a structural frame model.

Alternative formulations for the simulation of a structure in a fire exist, and need to be explored for comparison. This activity is currently underway by the Building Research Establishment (BRE) in the UK.

Material Properties at elevated temperatures The materials used in the various experiments and testing programs can depend upon the country of origin and the commercial source. The properties of common steel, weld materials, and bolts, are likely to be well established at room temperature, but need to be assembled into a single data base for consistent use by all of the participants in this research program. Data at high temperatures (stress/strain relationships, thermal conductivity, heat capacity, coefficient of thermal expansion) may need to be collected. These data are needed for common structural steels and for newly developed fire resistant steels. There is a paucity of data on fire proofing materials. Whatever material is selected for the program, there is a need for accurate and consistent data on thermal conductivity, heat capacity, and density. New experimental fixtures and measurement methods may need to be developed for this.

Proposed Timeline and Major Milestones

- 3//04 Draft research plan completed
- 4//04 Agreement reached on final research plan and participant assignments
- 5/04 Specifications for full-scale demonstration (dimensions, heat flux and loading conditions) submitted by ABRI
- 6/04 Material database developed and significant holes in data identified
- 6/04 Agreement reached by BRE and NIST on computational domain, initial and boundary conditions, and means to compare output variables
- 7/04 Detailed half- and quarter-scale experimental plans developed
- 12/04 Progress meeting held
- 4/05 Full-scale single element testing completed of beam and column, bare and with fireproofing
- 4/05 Material database completed
- 8/05 Reduced-scale experiments completed
- 9/05 Simulation of reduced-scale experiments completed
- 10/05 Prediction of full-scale demonstration completed
- 1/06 Full-scale demonstration completed (2 connection designs, with and without fireproofing)
- 2/06 Scaling laws developed
- 3/06 Symposium held to present results

Participation and Coordination

This Program is being conducted under the auspices of CIB W14, and is being coordinated by Richard Bukowski, the W14 chair. Each participating laboratory will have a single representative on a technical advisory committee, which NIST proposes to chair. Based upon discussions to date, the following assignments are suggested:

Task	Lead Organization	Participating Laboratories
1 Overall coordination	CIB W14	
2 Technical Direction	NIST	all
3 Fire/Structure Simulation	NIST and BRE	SINTEF
4 Full-scale tests of connections	ABRI	CSIRO
5 High heating rates testing	CTICM	BRANZ
6 High temp properties of steel and fire resistant steel	BRI Japan	NRCC, SP
7 High thermal gradients	CSIRO	SINTEF
8 Cooling phase	SKLFS	BRANZ
9 Symposium and Proceedings	NIST	all

Each laboratory is requested to develop a research plan including objectives, statement of work, budget, schedule, and deliverables to be submitted to the CIB W14 for coordination and which is also suitable for submission to their funding agency as a proposal. The funding agencies will evaluate the proposals and if accepted, will fund the work directly with the organization conducting the work. Progress will be followed by email circulation of quarterly progress reports, a mid-program meeting of the technical advisory committee, and a CIB W14 sponsored workshop at the end to disseminate the results.