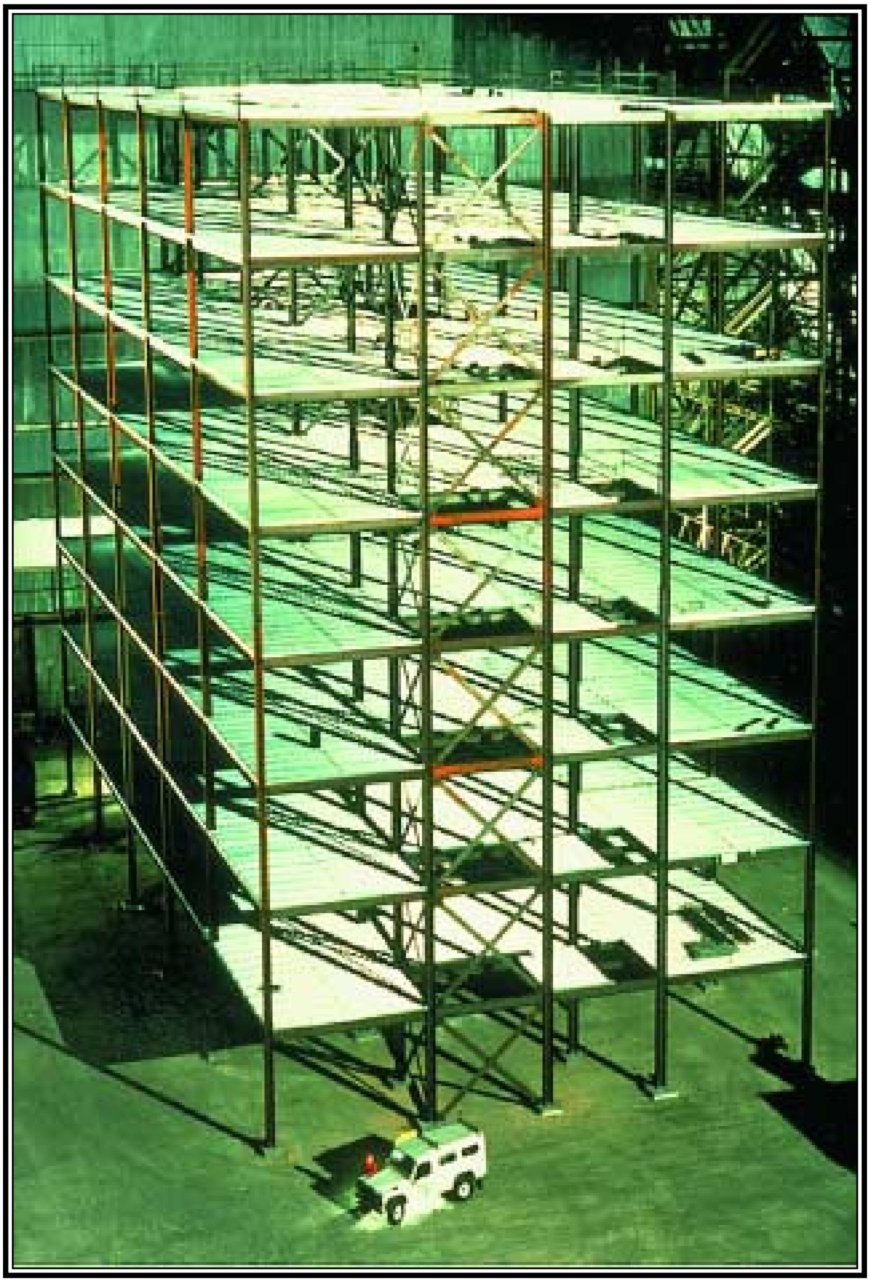
THE FUTURE OF FIRE ENGINEERING

The design community is moving from prescriptive to performance-based design



A full-scale, eight-story test facility has been built inside a hangar at Cardington in Bedforshire, UK.

THE INTERNATIONAL TREND TOWARD PERFORMANCE-BASED BUILDING REGULATIONS and away from prescriptive codes for fire engineering is creating new opportunities for steel building design, according to P.F. Johnson of Arup Fire Engineering in Melbourne Vic, Australia. Johnson was one of 15 speakers to discuss fire-related topics at the recent Second World Steel Congress in San Sebastian, Spain. "Performance-based regulations have been introduced into countries including the United Kingdom, New Zealand, Sweden and Australia, and others, such as the U.S.A. and Canada will follow shortly," Johnson stated. Other countries with evolving fire codes include Hong Kong, Singapore, Japan and Israel. "The benefits of the performance approach are believed to include greater flexibility in design, increased opportunities for innovation, equal or better levels of safety and greater cost effectiveness in construction."

Writing in the Journal of Constructional Steel Research, Johnson expounds that "there has been a great deal of research into performance of steel structures in fire. In simple terms, what has been found is that a structural steel frame of a building performs much better than the individual elements that are tested in the laboratory furnace test using standard time-temperature curve."

Added Jef Robinson, B.SC., C.Eng., of British Steel, another speaker at the conference: "For many years it has been recognized that it is necessary to build structures that will resist collapse in the event of fire because all materials weaken when they are heated. The traditional response to this phenomenon has been to consider designing a structure and ensuring its fire resistance as two separate, even to some extent conflicting, activities. Design is governed by Codes and Standards that are derived from studies and assessment of structural behavior, while fire resistance is governed by building regulations evolved largely in response to fire disasters. The normally accepted way to satisfy both design codes and building regulations is to cover steel with insulating fire protection on-site during construction.

"However, natural fire tests in simulated buildings, which have been carried out from time-to-time for many years, have consistently shown that the behavior of structural elements in whole frames differs markedly from that of single elements in standard fire tests that are used to assess regulations requirements."

A variety of tests were carefully monitored in the Cardington test facility.

Fire Tests

In Robinson's paper, he cites a number of recent fire tests:

Liverpool Hospital (UK)

One of the first indications that real structures might behave differently from single members in standard fire tests came when a test was carried out on a simulation of the Liverpool Hospital roof back in 1978. The natural fire test was done in a large rig of 300m^2 (20 × 15m) inside which was a fire compartment of 42m^2 (6 × 7m) connected by open doors to the larger volume. The roof comprised one-way spanning beams of 254 × 146 × 31kg/m with lateral purlins supporting 1.8 hectares of roof decking. The fire load was very high at 95kg/m^2 giving a heat output of 15MW and a fire temperature of 1100°C. A partial collapse of the roof occurred.

At the time, the beams were expected to fail at 550°C and it came as a surprise to find that some beams actually reached 950°C before the roof collapse occurred. The reason for this enhanced performance was given as interaction between members—which implies that beams in structures have better performance than beams in standard fire tests..

Washington

A few years later, in 1981, an interesting large-scale test was done in Washington. A two-story test structure with plan dimensions 40 × 32 ft (12 × 9 m) was built to simulate the ninth and tenth floors of a 20-story building. The beams in the fire compartment were 305 × 102 × 33 spanning 6 meters and with a floor loading of 80lbs. /sq. ft. were subject to the maximum permissible stress. A fire test carried out in one quarter of the ground floor (6 × 5 × 3m) using a wood crib fire of 50 kg/m^2 generated a fire temperature of 1070°C—equivalent to a one-hour standard rating. The beams, however, had been given only ½-hour protection by mineral fiber spray. In spite of this under-protection, stability was maintained. Even though the beam temperature reached 644°C the maximum deflection was only 168mm in the 6-meter span (span/36).

William Street - Australia

The 41-story, steel-framed building at 140 William Street was Melbourne's tallest when completed in 1971. The columns were concrete encased but the steel beams and the underside of the metal deck floors were fire protected with an asbestos containing product. The sprinkler system was of extra-light hazard category with no sprinklers in the ceiling spaces. After 20 years the building became due for its first refit and the asbestos-based protection had to be removed.

At the time of the refurbishment the Building Code of Australia required a fire resistance time of 120 minutes for the beams and slab, an ordinary hazard level sprinkler system and sprinklers in the ceiling voids. The reinforcement details in the slab were such that without protection to the soffit 120 minutes would not be achieved on the basis of standard fire test assessments. Similarly, to attain 120 minutes in the beams protection would be required. The total cost was estimated to exceed $2 million. The questions then arose - "Does the fire protection need to be replaced? Does the sprinkler system need to be upgraded?" To answer the questions a test building was constructed at the BHP Laboratories in Melbourne that simulated a section of a typical story of the 410-story structure. It consisted of an open plan office area 12m square in plan containing a partitioned small office 4m square in the middle of one of the glazed walls. Natural fire tests were carried out with real office furniture, with the most severe test having a fire load equivalent to 65kg of wood/m2. Columns were protected with fire resistant plasterboard; the beams (above a non-fire rated suspended ceiling) were unprotected.

The test program showed that the existing extra-light sprinkler level was effective in controlling both developing and well-developed fires in both the open plan and small office areas. In a test carried out when the beams and slab were unprotected and the sprinkler system switched off, the maximum temperature reached at any point on the castellated central beam above the non-fire rated suspended ceiling was 632°C at 112 minutes. It's deflection was 120mm at the mid point of it's 12 meter span. The deflection recovered almost completely when the structure cooled.

As a result of the tests and a risk assessment program, the building was approved by the authorities with unprotected beams, with unprotected floor slabs and without upgrading the extra-light hazard sprinkler system.

380 Collins Street - Australia

This test, also conducted by BHP Research, Melbourne, was carried out to collect temperature data under real fire conditions of furniture in a typical office compartment of this multi-story commercial building. The compartment, 8.4m × 3.6 m, was glazed on two sides and again had a non-fire rated suspended ceiling. The fire load comprising desks, chairs, carpet, computer terminals, paper etc. was equivalent to 44kg of wood/m2. The fire was started in a waste bin and allowed to burn out naturally, though it was found necessary to leave open the door in order to allow the fire to grow. The atmosphere reached a maximum temperature of 1163°C while unprotected beams above the suspended ceiling reached 430°C. Unprotected freestanding columns were placed both inside and outside the compartment to generate data. Maximum temperature of columns inside was 730°C and 480°C for external columns 300 mm from the windows. The results of the tests were sufficient to justify unprotected beams and external columns.

Broadgate - UK

Unlike the previous examples of experimental fire tests, at Broadgate a severe fire of over 4-1/2 hours duration occurred during construction of a real 14-story building. The opportunity was taken, with the client's support, to conduct a detailed investigation to seek to establish the structural performance during the fire in addition to the normal structural survey under such circumstances, which is aimed primarily at defining the needs for reinstatement.

Building contractors offices and storage facilities on the first floor level, which had been erected around the steel columns at that level, caught fire and were completely destroyed. The columns of the building, which passed through the heart of the fire, had not been fire protected. Atmosphere temperatures in the fire were estimated to be of the order of 1000°C and metallurgical examination of the steelwork suggested beam temperatures of around 600°C.

In the fire the heavier columns survived undamaged but the lighter columns deformed in the heat and shortened by 100 mm, an effect considered to be due to restrained thermal expansion of the columns from the surrounding moment frame. The surrounding frame however would also support the columns once they had reached their maximum capacity. As a result of load re-distribution no structural failure occurred and the integrity of the floor slab was maintained. The structure was repaired in 30 days at a cost of less than 5% of the total loss and no lives were lost.

Fire Tests: Cardington

As a natural progression from the earlier fire tests cited above, British Steel's Swinden Technology Centre has recently carried out a series of tests on a full-scale, eight-story, steel-framed composite test building located in a huge hangar at Cardington in Bedfordshire, UK.

"The test structure was designed as a normal commercial office building to national design requirements and was built using normal fabrication and construction processes, explained M.A. O'Connor and D.M. Martin, both of British Steel, in their paper presented at the Second World Steel Congress and printed in the Journal of Constructional Steel Research. The braced-frame structure incorporates three stiff cores (a central lift shaft and two stairwells at either side of the building) and a composite floor construction. The floor layout consists of five 9m (32') bays along the elevation and three bays across the structure.

Johnson described the various Cardington tests in his paper presentation.

The first test was conducted in January 1995 on steel work supporting the 7th floor. A restrained, unprotected secondary beam and associated composite slab were heated to temperatures approaching 870°C over a period of 2 hours and 45 minutes. The maximum deflection of the beam and slab at the end of the test was only 230mm (i.e. span/39). Through significant restraining action, the test indicated that single composite beams possess a significant degree of inherent structural fire resistance, which suggested that passive fire protection could be eliminated for such members in multi-story buildings.

In a second test carried out in May 1995, a 2.5m strip across the full 21m width of the structure was subjected to a gas fire furnace test. The furnace surrounded two internal columns, two peripheral columns and three primary composite beams designed to support the 4th floor steelwork. The column members were fire protected to within 200mm of the lower flanges of the beams.

In this test, exposed steelwork temperatures of 802°C were recorded over a period of approximately 2 hours. This test showed the inherent fire resistance of composite beams in the absence of passive protection with a maximum beam deflection of approximately span/34.

Severe local distortions did occur in the internal columns in the exposed connection areas. This damage was similar to that observed in the Broadgate fire in London in 1992. The external columns showed little deflection.

The next test was the BRE Corner Fire Test, which was conducted on the second. The aim was to demonstrate the ability of the structure to survive a severe fire within a compartment representative of a corner office. The fuel involved was wood cribs designed to create a fire load density of 40kg/m2. The walls of the compartment consisted of fire resistant gypsum and there were double glazed windows on one face.

After ignition and a period of time, the fire reached a temperature of 265°C and became starved of oxygen. After one pane of glazing was broken, the temperature rose to 265°C but there was still insufficient oxygen for sustained fire growth. Only after a second pane was broken was there sufficient oxygen available for flashover to occur. Some 6 minutes after flashover, the temperatures had increased rapidly to a maximum compartment temperature of 1051°C. A maximum steel temperature of 903°C was reached after a further 12 minutes.

The results of this test may be summarized as follows:

- The floor slab continued to withstand the applied load from above.
- The partitions retained their integrity throughout the test.
- The masonry wall retained its integrity despite significant thermal stress and lateral deformation.
- A maximum mid span steel displacement of 270mm occurred 128 minutes into the test; after cooling, this had recovered by 110mm.
- The fire did not develop significantly until the double-glazing was deliberately broken
- The structure remained totally intact.

A second major fire test took place on 2 April 1996. This was the largest test planned for the eight-story steel structure. The fire was situated on the second floor in a corner compartment and this affected the third floor steelwork. The total floor area under test was 342m2. Two sides of the fire compartment had fire-resisting walls, with the other two sides consisting of a dado wall with double glazed windows with an open section in each wall. All columns and connections were fire protected but the beams, including edge beams, were left unprotected.

A total of 42 large timber cribs were placed within the compartment to give a fire load of approximately 40kg/m2 or a total fuel weight of 13,680kg. Floor loads of 5.48kN/m2, representing the dead load plus one third of the imposed load, were applied throughout the building using sandbags.

As with previous tests, the ventilation governed the development and severity of the fire. Rapid ignition led to window breakage, leading to lower peak temperatures although a much longer fire duration. The maximum compartment temperature was 763°C, approximately 62 minutes from ignition. The maximum steel temperature of 691°C occurred on the bottom flange of one of the main deep beams. The maximum temperature in the secondary beams was 685°C and in the edge beams of 536°C.

The maximum-recorded value of the displacement of the floor slab was 557mm. The limiting of any damage within the particular compartment boundaries and the floor immediately above demonstrated the integrity of the overall steel structure and the benefits of continuity and member interaction.

Test results were quite interesting and confirm the results of earlier studies. "The tests indicate that the behavior of unprotected steelwork in a composite framework is substantially better than indicated in single-member fire tests," O'Connor and Martin concluded.

"The Cardington tests have shown that steel beams have remained in place, supporting their load, at temperatures as much as 330°C higher than BS5950: Part 8 would predict," Johnson states. "Any deformations were very localized, with the structure totally undamaged away from the fire compartment."

According to Johnson, "the design implications appear to be:

- unprotected beams in composite frames can withstand 1100°C without collapse
- columns are more critical and will need protection in multi-story buildings
- the floor slab gives stability in fire
- load transfer is not part of current design procedures but it obviously occurs

A sustained fire caused distortion but no collapse.

- slab membrane action also occurs
- where double glazed windows do not break, fire development is often insignificant."

Added Robinson: "Analysis of the data from the Cardington project is still in its early stages and we cannot, as yet, draw conclusions. However, there are a number of inferences that we can draw from simple observation" of both the Cardington results and of several major fires.

STRUCTURAL BEHAVIOR

1. Modern steel-framed steel deck composite structures are remarkably resilient in fires. Members have deformed [in the tests] but none have collapsed.
2. Global structural stiffness seems unaltered by six major fires so far.
3. In dead load tests after fires, severely deformed slabs withstood loads significantly higher than their design load.
4. Longitudinal expansion of unprotected beams has been minimal.
5. End plate connections can split on cooling - revised design details could overcome this.

FIRE RESISTANCE

1. Unprotected beams in steel deck composite frames can withstand 1100°C without collapse.
2. Columns are more critical than beams and will need protection in multi-story buildings.
3. The floor slab makes a major contribution to stability in fire. Further studies are needed to understand and quantify its behavior.

DESIGN

1. Bridging (load transfer) is not incorporated in design procedures and yet it obviously occurs. Can we design for it; likewise, should we design for it?
2. Slab membrane action is also not incorporated in design but is obviously happening. Should we design for it?
3. Double glazed windows did not break and lack of ventilation stifled the fire. Can fire growth be controlled by design of the glazing?

"One message that comes through clearly from the Cardington Project is that modern steel framed structures can be designed to survive fires without protection to the beams," Robinson concludes. "This should give designers and regulators alike the confidence to substitute active for passive protection and make it possible to gain the undoubted benefits of sprinklers without cost penalty, since the cost of passive protection and sprinklers is often about the same.

"In a building that remains stable the hazard to life is the same whether the beams are protected or not. It is smoke that kills people and since sprinklers cut down smoke we could expect an active/passive substitution policy to enhance life safety. In terms of financial losses a substitution policy would also pay dividends. The main cost of fire doesn't come from structural repair, it comes from damage to building contents and from loss of business—sprinklers stifle fires before they have a chance to cause such damage.

"Ultimately the ability to predict real structure behavior in real fires and to adjust the probability of unwanted events are key elements to an engineering approach to fire. The challenge is to ensure that the methodology is presented in a way that is easy to use and easy to check. We have to make certain that the new methods are as accessible to the Building Control Officer as they are to the Fire Safety Engineering experts, otherwise they will be relegated to unusual specialist applications—which would be a tragic fate for an emerging discipline that holds so much promise."

(Copies of the Proceedings of the Second World Steel Congress can be purchased from Elsevier Science for $425. For more information, consult their web site at www.elsevier.com)

Alternative Fire Protection Methods

In recent years, significant improvements in fire protection materials have taken place. Low-cost mineral fiber or vermiculite sprays are often used for beams and columns (which are then covered usually covered with suspended ceilings or wallboard to improve aesthetics). Also, thin intumescent coatings (which expand when heated to form a solid protective foam) are gaining a foothold in the marketplace.

Another approach that is gaining some popularity is the use of concrete in-filling both for wide flange members and HSS.

Concrete In-Filled Columns

The use of poured concrete, rather than blockwork, between the flanges of steel members further increases fire resistance. According to studies cited by Robinson and others at the 2nd World Steel Congress, dense poured concrete is more effective than lightweight blocks at drawing heat from the steel section. Without reinforcement, other than shear studs fixed to the web at 500mm intervals to carry nominal load to prevent bursting of the concrete, the failure temperature with poured concrete between the flanges is raised to over 800 degrees C. Further, it can give a fire rating of one hour without application of fire protection on site.

When reinforcement is included in the concrete, loads from the hot flanges can be transferred, not just to the cool web of the steel section, but also to the load bearing concrete and fire resistance up to two hours is obtainable without further protection. One additional advantage of concrete-filled columns is that they have a high resistance to impact damage from vehicles.

Concrete-Filled Hollow Sections

Some designers are utilizing concrete-filled hollow sections in which hollow structural sections (HSS) act as permanent formwork for the concrete. The load transfer mechanism is similar to that of in-filled columns and fire resistance times of up to two hours can be achieved. Concrete reinforcement may be by standard bars or through injecting steel fibers into the wet concrete mix. The HSS members can be filled off-site or erected and then filled.