STEEL News & Notes
INGAPORE STRUCTURAL STEEL SOCIETY

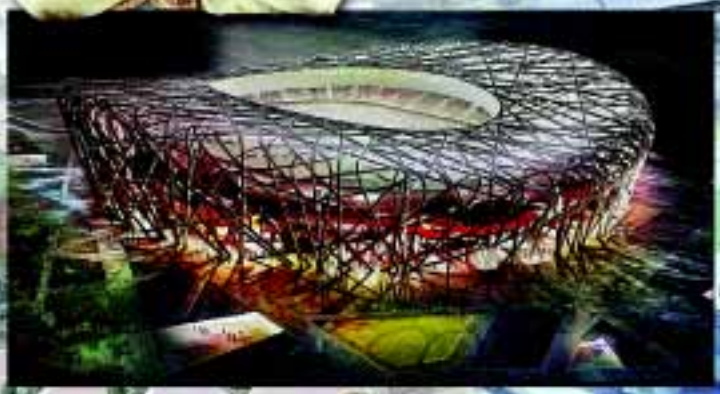
SINGAPORE STRUCTURAL STEEL SOCIETY

Commemorative Issue

21st Annual Lecture

The Structure of stadia - from exoskeletons to haute couture

by
Mr Tristram Carfrae
Arup, Sydney Australia



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The President's Corner

Dear fellow members,

The last few years have been difficult for the construction industry. Over-capacity arising from the shrinking construction pie led to hyper-competition and unsustainable low tender prices. Many companies had to close down and in some projects, safety was compromised.

The responses, by and large, were to place the blame on the current systems and processes. So, the time-tested approach of awarding to the lowest priced tender that meets specified requirements, has been questioned. A Security Of Payment Act was legislated to better ensure that subcontractors and suppliers are paid duly. Acts relating to Building Control and Workplace Health and Safety are being overhauled to tighten regulations on safety. Main contractors and specialist contractors involved in building and excavation work that impact on safety will soon be licensed. But we shall not debate the merits of these responses. Instead, I would like to share with you how the SSSS has reacted to these unhappy trends in the industry. Without pointing fingers at any party or the "system", the society has focused unwaveringly on upgrading the steel sector's professionalism.

Firstly, the SSSS has been upgrading our firms through the Accreditation Scheme for Steel Fabricators. Our Accreditation Scheme now has 34 accredited companies who meet specified criteria relating to financial standing, relevant track records and technical personnel. They are now the choice firms for projects that require steel fabricating and erection services. Steel fabricators who are not yet accredited should seriously consider participating in the scheme.

Secondly, we have been improving the technical competence of practitioners through technical publications, regular talks, seminars and training courses. This year alone, our society has already organised 3 educational site visits and 6 technical/ business-related talks since January 2005. The SSSS has also just launched the Structural Steel Inspectors' Training programme - a 30-hour course that trains and tests steel inspectors to ensure they are competent. The response to the first run in August 2005 was overwhelming. The second run is scheduled for February 2006 - already, there is a waiting list.

The focus on people, in my view, is the best way of lifting the professionalism and image of the construction industry. Bring in more talented people. Train and bring out the best in people who are in the sector. This is the most practical step to increase the SSSS and the steel sector's value to the construction industry.

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OM 698	Ho Ann Ching	Surbana Consultants Pte Ltd	9 June 2005
OM 699	Leow Yung Guan	Surbana Consultants Pte Ltd	9 June 2005
OM 700	Teh Peng Hooi	Jurong Consultants	9 June 2005
OM 701	Chan Geok Leng	GL Engineering Pte Ltd	9 June 2005
OM 702	Saravanakannan Ganapathi	Parsons Brinckerhoff Pte Ltd	14 July 2005
OM 703	Ng Wei Meng, Melvin	ST Architects & Engineers Pte Ltd	11 August 2005
OM 704	Sebastian Lee	Parsons Brinckerhoff Pte Ltd	11 August 2005
OM 705	Kwek Yong Teck	SBT Consultants	8 September 2005
OM 706	Teh Teck Lai	Maunsell	13 October 2005
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CM 63		Hup Lian Engineering Pte Ltd	11 August 2005
CM 64		Hong Giap Engineering Pte Ltd	13 October 2005
CM 65		G-Tech Metal Pte Ltd	13 October 2005
CM 66		Kian Long Engineering	13 October 2005

The Structure of stadia - from exoskeletons to haute couture

T. Carfrae
MA MIStructE MIEAust FTSE
Arup Fellow

1. Introduction

This paper traces the development of Stadia structures, particularly roof structures, from independent truss cantilevers through mast and cable solutions to three dimensional cable nets and finally the completely wrapped stadium. I will illustrate this progression with Stadia that I have helped design:

- Sydney Football Stadium – mid eighties
- San Nicola Stadium, Bari – late eighties
- Asian Games Stadium, Bangkok – early nineties
- Lang Park – late nineties
- City of Manchester Stadium – millennium
- Melbourne Cricket Ground – early noughties
- Khalifa Olympic Stadium – early noughties
- Beijing Olympic Stadium – mid noughties
- Beijing National Swimming Centre – mid noughties

This sequence of stadia not only illustrates the progression of architectural approach and resulting (or generating) structural systems but also the way that design ideas migrate from project to project.

2. Sydney Football Stadium, Sydney – aka Aussie Stadium

Cox Richardson – architects

My first foray into Stadium design in the mid eighties was with this beautifully sculptured bowl at Moore Park in Sydney. As a 40,000 seat, rectangular pitch stadium, SFS is about as intimate as you can get. It has no walls to speak of and allows the upper concourses to exist in the open air.

The roof is a completely separate element supported by a tubular space truss arrangement that integrates back into the bowl structure for elegance and economy. The original design used a three dimensional mast and cable structure, but upon award, the D&C contractor (Civil and Civic) preferred the idea of a structure where each bay was independent, which allowed more flexibility in construction programming. In fact for a thirty metre roof, this is a more economical structure.

Although the roof support structure appears to be continuous around the stadium it is in fact little more than a hit and miss affair with every other bay being a simple trussed cantilever and the remaining bays filling in between.

Significant effort was put into devising a structural topology that allowed the structure to be competent under wind uplift, whilst also permitting the use of slender tubes that look comfortable as tension elements holding the roof up – which is of course their “day job”. This approach is in theory more efficient than adding weight to the roof to ensure that the roof loads never reverse.

3. San Nicola Stadium, Bari, Italy

Renzo Piano Building Workshop – architects

In Sydney, much thought had been given to spectator amenity. Although there were no corporate boxes in the original design (they are a later addition), all patrons had easy access to food and beverage outlets and public conveniences.

In Italy it was quite a different story. All utilitarian concerns could take a back seat in favour of the overall beauty of the building. Nothing counted except the sculptural quality. The SFS roof has been criticized for being too short and being inclined upwards; both characteristics reduce its ability to keep spectators dry when it rains. The Bari roof is both shorter and higher – I have always presumed that it doesn't actually rain in this part of Italy!

Bari is a 55,000 seat bowl distributed around an athletics track. This configuration tends to be less intimate due to extended sightline distances so the overall form is working hard to try and recapture the sense of a single volume, albeit with some articulation. All public amenities are in the basement, some distance from the majority of the seats, but this does not seem to overly concern the Italian fans.

The roof structure comprises simple steel box girder cantilevers, beautifully integrated into the form of the pre-cast (on site) concrete bowl structure. These heavy beams contrast with the very delicate fabric and stainless steel (for ease of maintenance) canopy that spans between. The finished stadium appears completely alien to its surroundings – much as though it is a visiting spaceship from another planet.

4. Asian Games Stadium, Bangkok, Thailand

Cox Richardson – architects

Having learned from Sydney that it is quite difficult to make a compression capable structure look light and elegant, we took the opposite approach in Bangkok. The leading edge gutter is made from pre-cast concrete and acts as a counterweight to hold the roof down in the relatively benign wind regime in Bangkok. This decision allows the masts to rake backwards without significant structural penalty as the tension cables are relatively cheap. Whilst not the most efficient structural solution, backwards leaning masts look infinitely more pleasing than the hunched over impression given by forward leaning masts.

The bowl in Bangkok seats only 25,000 people but is made to look elegant and feel good by containing all the spectators in a single tier that is sculpted in a similar way to the SFS but without the gaping holes at each end of the upper tier.

The roof canopy itself is made very efficient by using an arched beam whose angle of thrust precisely lines up with the supporting cable. By minor geometric adjustment of this surprisingly efficient mechanism you can induce zero tip deflection (under either uniform or any other defined load) thereby compensating for the increased stretch, or reduced stiffness, of the cable stays that can therefore be simply designed for strength. This arch also creates a beautiful and airy space at the top of the stand whilst keeping the tip of the roof low to provide maximum shade – a desirable commodity in Thailand.

In a small capacity stadium that is quite spread out to accommodate an athletics track, it is not possible to provide the desired angles for the sports lighting from the leading edge of the roof alone. So Bangkok also sees the introduction of four lighting masts, propped off the bowl and inclined forwards to achieve the desired angle at minimum cost.

5. Lang Park Stadium, Brisbane – aka Suncorp Stadium

HOK Sport – architects

The roof design at Lang Park arose from its situation in a valley within a dense residential area in an inner suburb of Brisbane. It was highly desirable to keep the overall height of the stadium as low as possible whilst providing perfect sightlines for 50,000 spectators around a rectangular pitch. The seats are arranged evenly around the pitch to minimise the stand height and the roof is pushed down as hard as possible onto the stand. The roof is basically flat, only inclined by the smallest amount possible consistent with positive drainage. So where can we fit the structure? The only rational answer is to span along the grandstands near the leading edge of the roof (to avoid blocking sightlines) to supports located in the four corners.

A cunning arrangement of the four corner supports provides lateral stability for the roof whilst simultaneously allowing complete freedom for thermal expansion without any movement joints. This also permits the roof to be connected very delicately to the rear of the stands with simple props.

You will also note at Lang Park the introduction of wall cladding – albeit entirely separate from the roof.

6. The City of Manchester Stadium, Manchester, England – aka 2002 Commonwealth Games Stadium

Arup Associates – architects (and engineers)

Having failed to secure the engineering of the Sydney Olympic Stadium, I retreated to my homeland of England to design instead the 2002 Commonwealth Games, which has subsequently been converted into a soccer stadium for Manchester City Football Club.

In fact this requirement for two purposes dominated the design approach. Not only did we have to convert from the 38,000 seat stadium arranged around an athletics track to 50,000 seats around a rectangular pitch, but we only had a six month window in which to actually do this. The result was to initially build only the upper part of the stadium above ground and then to dig down and extend the bowl downwards and inwards to align with the subsequent rectangular pitch. This neatly dealt with the issues for the main stands on both sides of the pitch, preserving perfect sightlines, intimacy and proximity (the holy grail of bowl design) for both athletics and football. But it would still have left the end stands too far away from the action as a soccer stadium.

The original solution was to simply not build the end stands initially but use temporary stands at both ends for the Commonwealth Games. Whilst this was a good solution, a better one emerged from a value management workshop (one of the few times when I have witnessed a formal value management process yield a significant benefit). By shifting the whole athletics arena to the North, we could build the upper part of the Southern stand and roof before the games. This saved the cost of half the temporary stands and eased the post games construction programme, which was extremely tight.

The ideal aesthetic form for the roof was determined to be a perfect cylinder with much less swoop than the SFS. The roof suspension system was to use outwards leaning masts integrated with the ramp towers that also contained the major plant rooms (the sort of rational decision that commonly arose from an integrated design practice). The backwards leaning masts not only look good (even natural) as in Bangkok but they also increase the drama and involvement that is felt when circulating the stadium via the external concourse, which is (unusually) outside the security perimeter and available to the public at all times.

But how should we hold the roof down? We could have followed the Bangkok precedent and used mass but the curve of the roof looked too tempting – could this be used to hold the roof down against wind uplift? Unfortunately, the elegant cylindrical form did not have sufficient curvature to work efficiently against uplift. Instead we realised that form and structure do not actually have to be the same thing. That is, structure does not have to follow form despite our traditional concepts of roof and walls. We devised a hold down system of cables that effectively pre-stressed (or more properly post tensioned) the cable stay system such that it became competent to take effective compression, which is in fact a reduction of the pre-stress.

The City of Manchester Stadium is also fully clothed in that the bowl is enclosed within a conventional curtain wall. But the roof floats above the wall and is intended to appear disconnected from it. A look that is enhanced by the raking strut that both supports the rear end of the roof beams (the front end being supported by the cable system) and delivers the axial force generated by the cable system to the seating bowl below. This raking strut allows a very delicate connection indeed at the very rear of the roof as its only real job in life is to stabilise what would otherwise be a mechanism.

We carried out exhaustive wind tunnel testing of Manchester because the contributory areas and the correlation between areas was very different for the various structural effects under consideration: the cantilever zone for the roof beam – both force and deflection; the central span of the roof beam; the differential deflection between adjacent roof beams; the maximum load in any single roof stay; the maximum aggregate load on a single mast; and the overall roof load that impacts on the hold down cable system. To ensure that we properly examined all these different effects, we used a real time database of all the pressures in all the pressure tappings for a significant period of time. This sort of data can subsequently be interrogated to derive all the required correlation coefficients and can also be used as input to time history analysis such as commonly used for sophisticated seismic design.

7. Melbourne Cricket Ground North Stand, Melbourne – aka 2006 Commonwealth Games Stadium

MCG5 – architects comprising Cox, Hassell, HOK, Daryl Jackson and Brian Smith

The MCG North Stand is in essence a development of the Bangkok scheme but with additional components derived from what we learned at Manchester.

The potential problem with counterweighted cable stays is that in a fairly aggressive wind climate such as Melbourne, the counterweights become quite significant. And these additional loads need to be supported with our usual load factors applied to the weight and material factors applied to the supporting structure. This can become expensive; particularly so as each stay and weight combination have to deal with the momentary peak wind load as experienced by that particular structural bay.

But as can be seen from the Manchester wind tunnel results, when one bay is experiencing maximum wind uplift, the adjacent bays are not. So the "netting" or webbing cables you can see in the Melbourne scheme ensure that each bay can also mobilise the counterweights in the adjacent bays. And under downwards loads, the peak wind load is distributed laterally so that it is shared by several masts and back stays. This simple modification overcomes one of the great disadvantages of a bay by bay structural system whilst still allowing bay by bay construction that is so vital at the MCG to allow staged construction with continuous handover of the completed stages.

8. Khalifa Olympic Stadium, Doha, Qatar – aka 2008 Asian Games Stadium

Cox/PTW – architects, GHD – lead engineers

Cox/PTW and GHD won a design competition for the major redevelopment of this existing stadium to hold the 2008 Asian Games. The chosen scheme was an adaptation of the Sydney Olympic Stadium scheme that Cox/PTW and Arup had developed for the Lend Lease/Transfield consortium that was never built. The existing stadium would have a new upper tier, covered by a parasol roof, built on one side only. In recognition of our previous input into this scheme, GHD very kindly invited Arup to develop the roof design (and the new upper stand) as their subconsultants for the purposes of a design and construct tender. We were subsequently engaged directly by the roof subcontractor to complete the design and document it for construction.

This single sided roof is a development of Manchester (though in some respects it pre-dates Manchester having been conceived in the late nineties) and also many other complete cable nets that originated with Schlaich's design at Stuttgart. The structural system in section is essentially a cable cantilever using a curved bottom chord supported by stays in place of an upper chord. The leading edge catenary cable is pre-stressed to keep the whole system in tension and the reactions at the rear are taken by two arches, one around the back of the seating bowl and one strutted some distance above. The arches and the catenary cable all come together at the abutments where most of the forces simply cancel out to significantly reduce the foundation loads. This arrangement also permits the large prestress in the catenary cable to be installed at ground level. This is the only prestressing operation, which in turn stresses the entire cable and arch network.

Under applied load, the catenary cable stress does not change significantly, but the forces transfer from the bottom arch to the upper one and vice versa. The geometry is selected so that under self weigh, the two arches share the load. Under maximum downwards load, the force transfers to the upper arch, and under upwards load it descends to the lower arch.

The challenging part of this structure is controlling the in-plane buckling of the upper arch. The out-of-plane buckling is simply resisted by the struts supporting the arch, but the in-plane system is more complex having three separate resisting mechanisms:

1 The tension stiffening effect of the catenary cable – as the arch tries to displace, it must also displace the catenary cable as they are connected directly by the first fore-stay. This is the primary purpose of this stay which is strictly necessary for carrying gravity or wind loads. However the resistance mobilized in the catenary cable is not as great as the arch's propensity to buckle so only provides partial restraint

2 The bracing between the struts that support the arch – for the arch to buckle in its first mode (a sway mode), the centre point of the arch has to displace laterally. This is resisted by the bracing below. We know from experience that this sort of resisting mechanism has a degree of flexibility and can (on its own) only effectively brace the first four or so buckling modes which would still leave an effective length of around 60m

3 The arch is made of two tubes battened together with cross members to form an in-plane vierendeel

These three mechanisms combine to reduce the in-plane effective length to around one and a quarter bays, which is similar to the out-of-plane length of a single bay.

The fabric covering also departs from precedent as we have removed all secondary steelwork and simply support the fabric between alternating ridge and valley cables. The valley cables are bifurcated at each end (a device first used on Bari) in order to deliver their reactions to the strong points at the front and back.

To complete the somewhat one-sided architectural composition and support the sports lighting on the other side of the stadium, we designed a free spanning arch inclined against a single arcing cable. The structural action of this piece of the project is too complicated to describe in this paper but will be covered during my presentation.

The resulting stadium is a very delicate and elegant composition that suits its arid surroundings and has been likened to a "jewel in the desert"

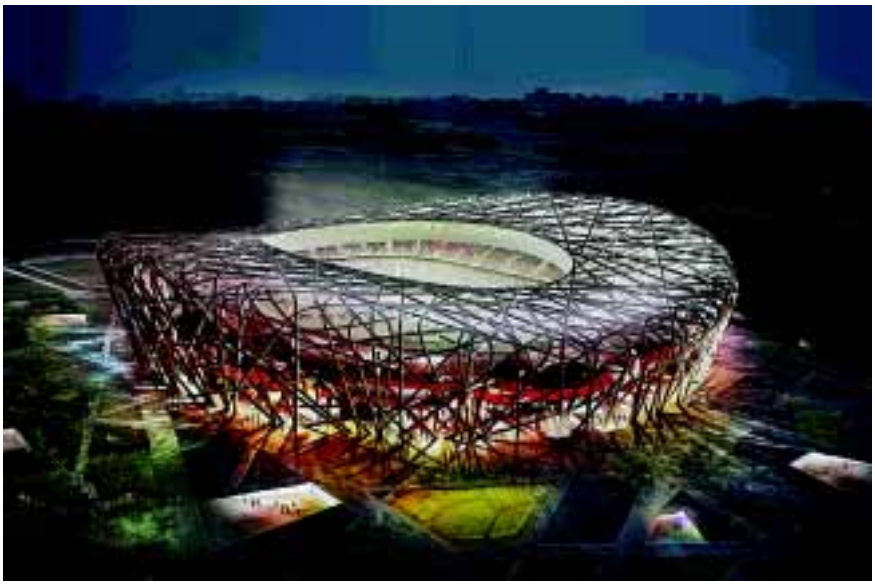
9. Beijing Olympic Stadium, Beijing, China – aka the Bird's Nest

Herzog and De Meuron – architects

This stadium illustrates the move from "roof" to "walls and roof" to "complete wrap". There is little distinction between the walls and the roof and the structural solution deals with both simultaneously.

Whilst the structure is hard to fathom at first glance, the primary structural solution is relatively simple; a series of truss portal frames spanning nearly 300m across the building at an angle, just touching the central opening. The design idea is to add secondary and tertiary elements, of the same size, to effectively camouflage the simple primary structure and produce an amazing, random sculpture.

However the presence of the large section secondary and tertiary members makes it difficult to design the roof efficiently in accordance with Chinese codes. Beijing is a highly seismic area and the codes require all structural elements to be relatively thick-walled to ensure ductility under compression. And the architectural concept demands that these lowly stressed members have the same dimension as the primary truss chords, so we get a catch-22 where we add thickness (and weight) to the secondary and tertiary members to get compliance and then have to increase the primaries to support the additional weight.



We developed methods to demonstrate that appropriately stiffened thin-walled sections would be equally ductile but our Chinese partners decided that getting Authority approval for this approach would be too difficult.

In order to achieve the "Bird's Nest" effect, the outer surface of all the structural members must conform to the overall curved form of the stadium. We have developed all the required surfaces using Catia, CAD/CAM software developed for the aviation and automotive industries. The contractor is intending to use ship building techniques to achieve these shapes in reality and several prototypes have been successfully constructed.

10. Beijing National Swimming Centre, Beijing, China – aka Watercube or Beijing Olympic Aquatic Centre

PTW/CCDI – architects, Arup/CCDI – engineers

This building is not strictly a stadium but it is major sporting venue (with 17,000 seats) and demonstrates not only the "complete wrap" but also a fully integrated system comprising structure, cladding, thermal performance, lighting performance and architecture; all generated by the same construction.

Our consortium comprising CSCEC, PTW, CCDI and Arup was short-listed as one of ten international teams competing to design the swimming centre for the 2008 Beijing Olympics. We started the competition process by setting out what we wanted to achieve technically (based on our previous experience with aquatic centres) in terms of all the different engineering disciplines. The solution that seemed to deliver most of what we desired was an insulated green house, with diffuse natural light and the main structure in a cavity isolated from both the corrosive pool hall atmosphere and the outside.

Meanwhile, the architectural planning team calculated that we needed to occupy the entire square site in order to fit in all the desired facilities and so the "cube" was born. The outstanding issue was what form the cladding/structure/cladding sandwich should take. We started discussing circles and cylinders, but it was clear that such shapes would not easily move from roof to wall without a clumsy intersection. This discussion led to the question: "what structural topology fills three dimensional space uniformly" other than the somewhat prosaic triangulated space frame.

It occurred to me that there should be many examples of this throughout nature from living cells to mineral crystals. After a few days research on the internet, I discovered that this seemingly innocuous question does not have a straight forward answer despite the number of natural examples that exist. In the late nineteenth

century, Lord Kelvin (an Irishman) asked “what is the most efficient way to subdivide space into equal volumes?” The solution is the same as the shape of an infinite array of equal volume soap bubbles, as the surface tension of the soap film will tend to minimise the surface area of the partitions.

Kelvin himself proposed a highly regular solution to his own challenge but this did not inspire me. A century later, Professor Weaire and his research assistant Phelan generated a more complex solution that was 2% more efficient and is now thought to be “the solution” to this classical problem. And it is this “Weaire Phelan foam” that we have used for the Beijing Swimming Centre.

To construct the structure of our building, we start with an infinite array of foam oriented in a particular way and then carve out a block of building size. The three major internal volumes are subtracted from this cuboid and the structure results. The structure is clad with ETFE pillows inside and out to achieve the desired insulated greenhouse with diffuse natural light.

This foam structure is a true space frame in that all the members are framed into the nodes. This might seem inefficient in a country that does not experience major earthquakes but it is a perfect energy absorbing structure for seismically active Beijing. It is equally competent in all three Cartesian axes and in torsion. For more detail of the structure itself, please refer to a separate paper being presented to this conference.

The Swimming Centre is a pure delight, not only because it solves all the technical issues in one fell swoop, but also because of the wonderful, and somewhat coincidental, fact that a building full of water should be made from a box of bubbles.

Society Events

15/7/05	9.00am	Site Visit: Republic Polytechnic Sports Complex
26/7/05	6.30pm	Talk: The Benefits of Optimised Cellular Beam Design (PEB 2 PDUs)
1/8 - 26/9/05	12 Evenings	SSSS Certification Course for Structural Steel Supervisors (Inaugural Intake) (PEB 30 PDUs)
2/8/05		SSSS Corporate Members’ Meeting
3/8/05		TASS Golf Tournament 2005
3-4/10/05	9.00am	Conference: CityParking 2005
13/10/05	6.00pm	TUCSS Lecture 2005 – Earthquake and Underground Structures (PUB Building Auditorium)
17/10/05	6.30pm	Talk: New High Corrosion Resistant Steel Coating and its Benefits (PEB 2 PDUs)
27/10/05	6.30pm	SSSS Annual Lecture and Dinner 2005 (Furama RiverFront Hotel)
13-20/11/05		SSSS Study Trip to the United Kingdom
15/11/05		BCSA Conference: Steel Construction - The Way Ahead (London)
25/11/05	12.45pm	SSSS Fund-raising Golf Tournament 2005 (Warren Golf & Country Club)
November 2005		Site Visit: Novena Medical Centre
20/2 - 17/4/06	12 Evenings	SSSS Certification Course for Structural Steel Supervisors (2nd Intake) (PEB 30 PDUs)
11-13/12/07		International Conference: Advances in Steel Structures 2007

Structural Fire Engineering Research at NTU

Author: Associate Professor Tan Kang Hai

The Fire Engineering Research Group at Nanyang Technological University (FERGAN in short), has recently been awarded a research grant from the Ministry of Education (MOE) on a research titled *"Mitigation of Progressive Collapse of Tall Buildings"*. This research project is an extension of a completed funded project from Building and Construction Authority (BCA), on *"Performance-based Design Guide for Fire Resistance of Bare Steel Structures"*, the scope of the latter was to recommend the analysis and design of steel structures under fire conditions. As the MOE research grant basically covered the manpower aspect, the contributions from Corus International Asia, TTJ Design & Engineering Pte Ltd and Richard Lees Steel Decking Ltd are gratefully acknowledged.

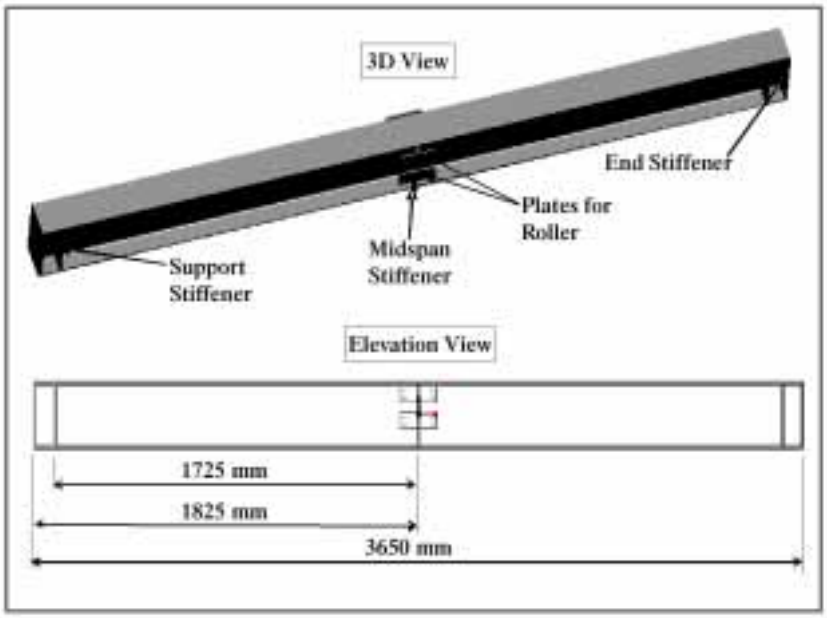


Figure 1 - Series 1 Specimens

The first series comprising 10 steel beams (Figure 1) focuses on the ductility of steel members under fire conditions. Despite extensive research on local buckling at ambient temperature and its effects on ductility has been performed since 1950's, this aspect is not at all researched under fire conditions. Local buckling of beams near the support has been observed in a number of reported Cardington tests in the United Kingdom. Thus, there is an urgent need to study the behaviour of local buckling of steel beams as it seriously limits the member ductility. The testing of I-beams is conducted in an electrical heating furnace (Figure 2) to simulate fire conditions. Most tests are conducted at isothermal condition while one or two tests on transient state heating. Another 5 steel beams will be cast together with profile decking to simulate steel beams with composite slab. They will also be tested under elevated temperatures. A section classification of I-beams with and without composite slabs at elevated temperature is proposed since current design codes have not addressed this issue. The understanding gleaned from this experimental work will help to improve member ductility under fire conditions so that premature failure will not take place and load redistribution is possible.

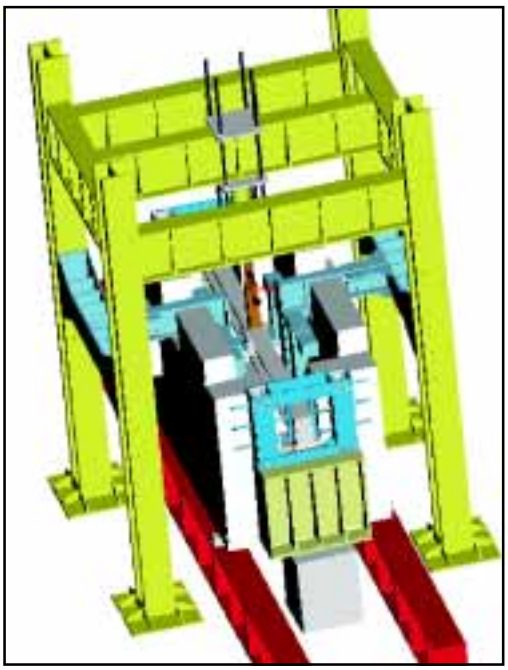


Figure 2 - Series 1 Test Set-up

The second series is on the residual strength of damaged steel columns at elevated temperature. This is to simulate the residual capacity of columns after it has been damaged, say at a close distance by a blast. This is then followed by a fire event. The damaged column will be axially restrained and tested under eccentric loading. The purpose is to model the damaged column with a single degree of freedom system such as its axial stiffness. In reality, the axial restraint comes from adjacent structure which is not damaged by blast and/or fire. Thermal expansion during the heating phase of steel members in any framed structure is likely to be restrained by adjacent unheated structure. A series of tests was carried out on steel columns to determine the fire resistance of damaged steel columns subjected to different restraint ratios and residual

deformations. Transient-state tests will be carried out in a column test rig (Figure 3). Effects of different residual deformations and axial restraint ratios are included in the column tests. Experimental tests will then be compared with Finite Element Analysis.

The third series is to investigate the behaviour of typical top-and-seat angle with web cleat connections in bare steel and composite configurations under fire conditions (Figure 4). Experimental results have shown the significance of connections in enhancing the performance of structures under fire conditions. However, there are very few experimental tests (if at all) on the behaviour of such kind of connections under elevated temperatures. The present work will study the influence of parameters such as member size, axial restraint factor, temperature and investigate different failure mechanisms. Fifteen tests in three different configurations are conducted at isothermal conditions. The objective is to utilise the experimental results from such connection tests to develop a component-based mechanical model for this type of connections.

The web site address for FERGAN can be found at:
www.ntu.edu.sg/cee/research/Research_groups/Fireresearch/research.htm

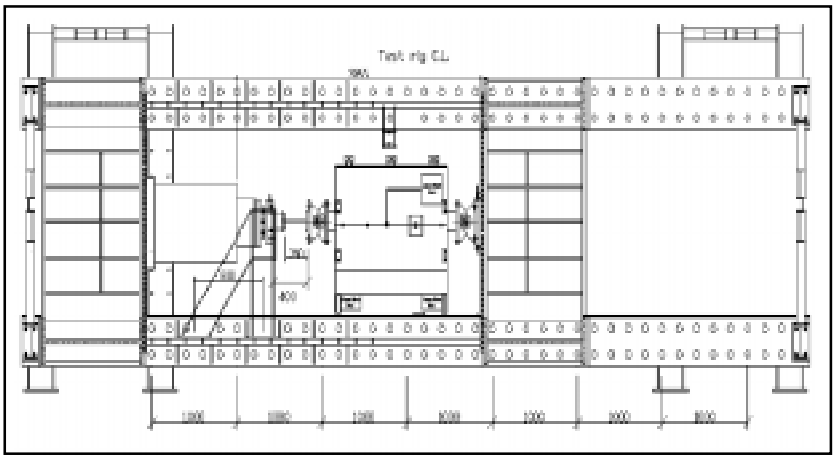


Figure 3 - Series 2 Set-up

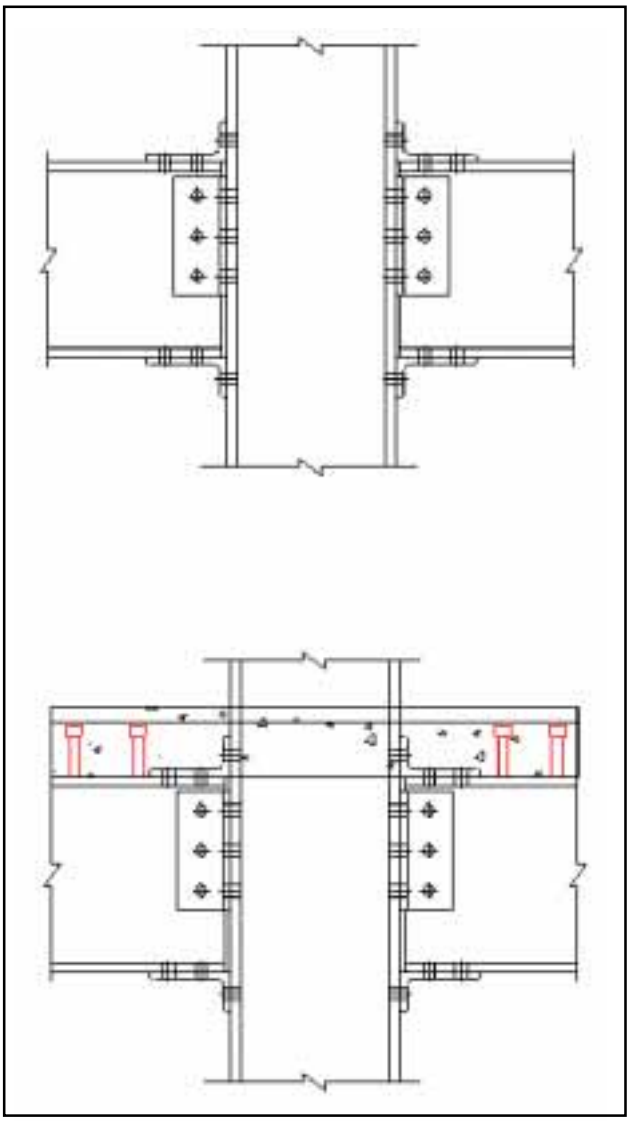


Figure 4 - Series 3 Test Specimens

Figure 5 - General Fire Test Setup

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