CIB W14 WG IV: 'Structural Reliability & Fire-Induced Progressive Damage'

CIB
International Council for Research and Innovation in
Building and Construction

CIB W14: 'Fire Safety'
Working Commission 14 is an international, multi-stakeholder, trans-disciplinary, pre-normalization forum for discussion and action, on research and innovation in Fire Science and Engineering for the design, construction and operation of a Safe and Sustainable Built Environment.

WTC No.7  9-11 (2001)

0. CIB W14 WG IV Reflection Document

Fire-Induced Progressive Damage in Buildings is distinguished from **Disproportionate Damage** - a related but different structural concept - by the mode of ***damage initiation***, not the final condition of building failure. Until this phenomenon is properly understood, and unless it is impeded, or resisted, by building design ... Fire-Induced Progressive Damage ***will*** result in Disproportionate Damage ... and ***may*** lead to a **Collapse Level Event (CLE)**, which is entirely unacceptable to the general population of any community or society.

This is a Reflection Document issued by CIB W14 Research Working Group IV: 'Structural Reliability & Fire-Induced Progressive Damage'; its purpose is to examine the 'hot form' structural concept of **Fire-Induced Progressive Damage**, and to propose a critical update to fire engineering design practice. It is also intended to encourage a wider discussion about some of fire engineering's fundamental tenets, and the future direction of our profession in a rapidly evolving trans-disciplinary approach to the design, construction and operation of a **Safe and Sustainable Built Environment**.

1. Introduction

The long delay in incorporating the Recommendations of the following 2 Reports ...

- NIST (National Institute of Standards and Technology). September 2005. **Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Final Report on the Collapse of the World Trade Center Towers.** NIST NCSTAR 1. Gaithersburg, MD, USA.

  and

- NIST (National Institute of Standards and Technology). August 2008. **Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Final Report on the Collapse of World Trade Center Building 7.** NIST NCSTAR 1A. Gaithersburg, MD, USA.

... into building and fire codes/regulations, standards and administrative provisions at international, regional and national levels ... can partly be explained by institutional inertia and the stubborn resistance of vested interests in the construction sector. To be fair, however, although both NIST Reports made extensive reference to the term 'Fire-Induced Progressive Collapse' ... the structural concept was not defined, or elaborated, in either. This was not really a task for NIST. It is, however, ideally suited to CIB W14.

2.1 Since the publication of the 2005 NIST Report, there has been much confusion about the term 'Fire-Induced Progressive Collapse'. Refer, for example, to the Introduction - Paragraph 1.1 on Page 1 - from **NIST Document: 'Best Practices for Reducing the Potential for Progressive Collapse in Buildings' (NISTIR 7396, February 2007)** ... where a lot of people got it so wrong ...

> " The term 'progressive collapse' has been used to describe the spread of an initial local failure in a manner analogous to a chain reaction that leads to partial or total collapse of a building. The underlying characteristic of progressive collapse is that the final state of failure is disproportionately greater than the failure that initiated the collapse. ***ASCE Standard 7-05*** defines progressive collapse as 'the spread of an initial local failure from element to element resulting, eventually, in the collapse of an entire structure or a disproportionately large part of it' (ASCE 2005). The disproportionality refers to the situation in which failure of one member causes a major collapse, with a magnitude disproportionate to the initial event. Thus, 'progressive collapse' is an incremental type of failure wherein the total damage is out of proportion to the initial cause. In some countries, the term 'disproportionate collapse' is used to describe this type of failure.
>
> Based on the above description, it is proposed that the professional community adopt the following definition, which is based largely on ASCE 7-05:
>
>> ***progressive collapse*** - the spread of local damage, from an initiating event, from element to element resulting, eventually, in the collapse of an entire structure or a disproportionately large part of it; also known as ***disproportionate collapse***."

Therefore, in order to avoid the wide confusion which the term 'Fire-Induced Progressive Collapse' is continuing to cause at international level ... the preferred term should now be **Fire-Induced Progressive Damage**.

2.2 As a starting point, it is an essential exercise to return to the original NIST Reports. Below are the Group 1 & 2 Recommendations contained in NCSTAR 1A. It should be noted that, in 2008, only Recommendation B was new. This, and other new texts, are highlighted here in blue …

GROUP 1. Increased Structural Integrity

The standards for estimating the load effects of potential hazards (e.g. progressive collapse, wind) and the design of structural systems to mitigate the effects of those hazards should be improved to enhance structural integrity.

NCSTAR 1A Recommendation A (NCSTAR 1 Recommendation 1)

NIST recommends that: (1) progressive collapse be prevented in buildings through the development and nationwide adoption of consensus standards and code provisions, along with the tools and guidelines needed for their use in practice; and (2) a standard methodology be developed - supported by analytical design tools and practical design guidance - to reliably predict the potential for complex failures in structural systems subjected to multiple hazards.

Relevance to WTC 7: Had WTC 7 been expressly designed for prevention of fire-induced progressive collapse, it would have been sufficiently robust to withstand local failure due to the fires without suffering total collapse.

GROUP 2. Enhanced Fire Endurance of Structures

The procedures and practices used to ensure the fire endurance of structures should be enhanced by improving the technical basis for construction classifications and fire resistance ratings, improving the technical basis for standard fire resistance testing methods, use of the 'structural frame' approach to fire resistance ratings, and developing in-service performance requirements and conformance criteria for sprayed fire resisting materials.

NCSTAR 1A Recommendation B (New)

NIST recommends that buildings be explicitly evaluated to ensure the adequate performance of the structural system under worst-case design fires with any active fire protection system rendered ineffective. Of particular concern are the effects of thermal expansion in buildings with one or more of the following features: (1) long-span floor systems* which experience significant thermal expansion and sagging effects; (2) connection designs (especially shear connections) that cannot accommodate thermal effects; (3) floor framing that induces asymmetric thermally-induced (i.e. net lateral) forces on girders; (4) shear studs that could fail due to differential thermal expansion in composite floor systems; and (5) lack of shear studs on girders. Careful consideration should also be given to the possibility of other design features that may adversely affect the performance of the structural system under fire conditions.

[* F-6 Typical floor span lengths in tall office buildings are in the range of 12-15 metres; this range is considered to represent long-span systems. Thermal effects (e.g. thermal expansion) that may be significant in long-span buildings may also be present in buildings with shorter span lengths, depending on the design of the structural system.]

Building owners, operators, and designers are strongly urged to act upon this Recommendation. Engineers should be able to design cost-effective fixes to address any areas of concern that are identified by these evaluations. Several existing, emerging, or even anticipated capabilities could have helped prevent the collapse of WTC 7. The degree to which these capabilities improve performance remains to be evaluated. Possible options for developing cost-effective fixes include:

- More robust connections and framing systems to better resist the effects of thermal expansion on the structural system ;
- Structural systems expressly designed to prevent progressive collapse. The current model building codes do not require that buildings be designed to resist progressive collapse ;
- Better thermal insulation (i.e. reduced conductivity and/or increased thickness) to limit heating of structural steel and to minimize both thermal expansion and weakening effects. Currently, insulation is used to protect steel strength, but it could also be used to maintain a lower temperature in the steel framing to limit thermal expansion ;
- Improved compartmentation in tenant areas to limit spread of fires ;
- Thermally resisting window assemblies which limit breakage, reduce air supply, and retard fire growth.

Industry should partner with the research community to fill critical gaps in knowledge about how structures perform in real fires, particularly considering: the effects of fire on the entire structural system; the interactions between sub-systems, elements, and connections; and scaling of fire test results to full-scale structures, especially for structures with long-span floor systems.

Affected Standards: ASCE 7, ASCE/SFPE 29, AISC Specifications, and ACI 318. Development of performance objectives, design criteria, evaluation methods, design guidance, and computational tools should begin promptly, leading to new standards.

Model Building Codes: The new standard should be adopted in model building codes (IBC, NFPA 5000) by mandatory reference to, or incorporation of, the latest edition of the standard.

Relevance to WTC 7: The effects of restraint of free thermal expansion on the steel framing systems, especially for the long spans on the east side of WTC 7, were not considered in the structural design and led to the initiation of the building collapse.

NCSTAR 1A Recommendation C (NCSTAR 1 Recommendation 4)

NIST recommends evaluating, and where needed improving, the technical basis for determining appropriate construction classifications and fire rating requirements (especially for tall buildings) - and making related code changes now, as much as possible - by explicitly considering factors including*:

[* F-7 The construction classification and fire rating requirements should be ***risk-consistent*** with respect to the ***design-basis hazards*** and the ***consequences*** of those hazards. The fire rating requirements, which were originally developed based on experience with buildings less than 20 storeys in height, have generally decreased over the past 80 years since historical fire data for buildings suggest considerable conservatism in those requirements. For tall buildings, the likely consequences of a given threat to an occupant on the upper floors are more severe than the consequences to an occupant on the first floor or the lower floors. For example, with non-functioning elevators, both of the time requirements are much greater for full building evacuation from upper floors and emergency responder access to those floors. The current height and areas tables in building codes do not provide the technical basis for the progressively increasing risk to an occupant on the upper floors of tall buildings that are much greater than 20 storeys in height.]

- **timely access by emergency responders and full evacuation of occupants, or the time required for burnout without partial collapse ;**
- **the extent to which redundancy in active fire protection systems (sprinklers and standpipe, fire alarm, and smoke management) should be credited for occupant life safety*;**

  [* F-8 Occupant life safety, prevention of fire spread, and structural integrity are considered separate safety objectives.]

- **the need for redundancy in fire protection systems that are critical to structural integrity*;**

  [* F-9 The passive fire protection system (including the application of fire protection insulation, compartmentation, and fire stopping) and the active sprinkler system each provide redundancy for maintaining structural integrity in a building fire, should one of the systems fail to perform its intended function.]

- **the ability of the structure and local floor systems to withstand a maximum credible fire scenario* without collapse, recognizing that sprinklers could be compromised, not operational, or non-existent ;**

  [* F-10 A ***maximum credible fire scenario*** includes conditions that are severe, but reasonable to anticipate, conditions related to building construction, occupancy, fire loads, ignition sources, compartment geometry, fire control methods, etc., as well as adverse, but reasonable to anticipate operating conditions.]

- **compartmentation requirements (e.g. 1,200 sq.m*) to protect the structure, including fire rated doorsets and automatic enclosures, and limiting air supply (e.g. thermally resisting window assemblies) to retard fire spread in buildings with large, open floor plans ;**

  [* F-11 Or a more appropriate limit, which represents a reasonable area for active fire fighting operations.]

- **the effect of spaces containing unusually large fuel concentrations for the expected occupancy of the building ; and**

- **the extent to which fire control systems, including suppression by automatic or manual means, should be credited as part of the prevention of fire spread.**

Relevance to WTC 7: The floor systems in WTC 7 failed at lower temperatures because thermal effects within the structural system, especially thermal expansion, were not considered in setting the fire rating requirements in the construction classification, which are determined using the ASTM E 119 or equivalent testing standard.

NCSTAR 1A Recommendation D (NCSTAR 1 Recommendation 5)

NIST recommends that the technical basis for the century-old standard for fire resistance testing of components, assemblies and systems be improved through a national effort. Necessary guidance also should be developed for extrapolating the results of tested assemblies to prototypical building systems. A key step in fulfilling this Recommendation is to establish a capability for studying and testing components, assemblies, and systems under realistic fire and load conditions.

Of particular concern is that the Standard Fire Resistance Test does not adequately capture important thermally-induced interactions between structural sub-systems, elements, and connections that are critical to structural integrity. System-level interactions, especially due to thermal expansion, are not considered in the standard test method since columns, girders, and floor sub-assemblies are tested separately. Also, the performance of connections under both gravity and thermal effects is not considered. The United States currently does not have the capability for studying and testing these important fire-induced phenomena critical to structural safety.

Relevance to WTC 7: The floor systems failed in WTC 7 at shorter fire exposure times than the specified fire rating (two hours) and at lower temperatures because thermal effects within the structural system, especially thermal expansion, were not considered in setting the endpoint criteria when using the ASTM E 110 or equivalent testing standard. The structural breakdowns that led to the initiating event, and the eventual collapse of WTC 7, occurred at temperatures that were hundreds of degrees below the criteria that determine structural fire resistance ratings.

NCSTAR 1A Recommendation E (NCSTAR 1 Recommendation 7)

NIST recommends the adoption and use of the 'structural frame' approach to fire resistance ratings. This approach requires all members that comprise the primary structural frame (such as columns, girders, beams, trusses, and spandrels) be fire protected to the higher fire resistance rating required for the columns. The definition of the primary structural frame should be expanded to include bracing members that are essential to the vertical stability of the primary structural frame under gravity loading (e.g. girders, diagonal bracing, composite floor systems that provide lateral bracing to the girders) whether or not the bracing members carry gravity loads. Some of these bracing members may not have direct connections to the columns, but provide stability to those members directly connected to the columns. This Recommendation modifies the definition of the primary structural frame adopted in the 2007 supplement to the International Building Code (IBC). The IBC considers members of floor or roof construction that are not connected to the columns not to be part of the primary structural frame. This Recommendation ensures consistency in the fire protection provided to all of the structural elements that contribute to overall structural stability. State and local jurisdictions should adopt and enforce this requirement.

Relevance to WTC 7: Thermally-induced breakdown of the floor system in WTC 7 was a determining step in causing failure initiation and progressive collapse. Therefore, the floor system should be considered as an integral part of the primary structural frame.

2.3 It should be emphasized that **Fire-Induced Progressive Damage** did not manifest itself in pure virginal form, for the first time, when WTC Building 7 failed completely at approximately 17.21 hrs (local time) on the afternoon of 11 September 2001, in New York City ... having endured 'real' fires, rather than 'standard test' fires, on many floors for nearly 7 hours ! Furthermore ... it has been generally assumed that **Fire-Induced Progressive Damage** is a large-scale, macro-phenomenon only. But, this phenomenon has been observed at micro-level in small building types also.

'Progressive Collapse', as it was then known, was receiving sporadic attention as far back as the 1980's ...

- As organizer of the 1987 Dublin International Fire Conference: 'Fire, Access & Safety in Residential Buildings', I requested that the following Paper be developed for presentation ... **'Design against Progressive Collapse in Fire'** ... by Dr. Willie Crowe, who was Head of Construction Technology, in the Institute for Industrial Research & Standards (IIRS), Ireland. He later became Manager of the Irish Agrément Board (IAB). This Paper focussed on progressive collapse in small buildings.

  Now is a good time to credit Mr. Noel C. Manning, of FireBar (www.firebar.ie), for his innovative approach to Structural Fire Engineering ... and for his major contribution to the development of Dr. Crowe's Paper.

  Link to the Dublin International Fire Conferences, and a copy of this Paper ...
  www.fireox-international.eu/fire/dublinfire.htm

- At a macro-level ... the following Paper was very influential in the later development of an Irish national standard (see below): **'The Conflagration of Two Large Department Stores in the Centre of Athens'**, by Kyriakos Papaioannou, of the Department of Civil Engineering, Aristotle University, Thessaloniki, Greece ... published in Fire & Materials, Volume 10, Pages 171-177 (1986). This Paper examined the Fire-Induced Progressive Damage and Disproportionate Damage of two large multi-storey buildings with reinforced concrete structures. See Appendix I.

- For approximately 12 years from the mid-1980's, I was a Member of the National Masonry Panel - the National Standards Authority of Ireland (NSAI) Masonry Standards Advisory Committee. A significant text on Fire-Induced Progressive Damage in buildings was included, by me, in the following standard ... **Irish Standard 325: Code of Practice for Use in Masonry - Part 2: Masonry Construction (1995). Appendix A - Determination of Movement in Masonry. A.3 - Thermal Movement**.

3. Some Concepts Relevant to Modern Fire Engineering

In relation to fire engineering concepts … it is not clear when the practice began, or how long ago it started, but defining a concept simply in terms of performance in a 'standard test' fire is entirely inadequate, and fails to explain the actual meaning of the concept …

Building Adaptability: The extent to which a building is designed when new, or is capable of being easily modified at any later stage, to meet the changing life and living needs of the broad range of potential users, who may or may not have activity limitations or develop a health condition during the life cycle of that building or component.

Building Flexibility: The extent to which a building interior is designed, when new, to be capable of being easily modified at any later stage during the life cycle of that building - with minimal cost and user inconvenience - because of a person's changing living or working needs.

Built Environment: Anywhere there is, or has been, a man-made or wrought (worked) intervention in the natural environment, e.g. cities, towns, villages, rural settlements, service utilities, transport systems, roads, bridges, tunnels, and cultivated lands, lakes, rivers, coasts, and seas, etc … including the virtual environment.

Design Fire: A fire with specified exposure data intended for use in connection with structural fire engineering calculations.

[Commentary: A design fire may either be representative of the thermal exposure described by the standard time-temperature-pressure relationship in an International/European/National Standard, or some non-standard exposure intended to simulate particular fire exposure conditions.]

Disproportionate Damage: The failure of a building's structural system: (i) remote from the scene of an isolated overloading action; and (ii) to an extent which is not in reasonable proportion to that action.

Experimental Test Fire: A full or reduced scale fire in a test laboratory, with specified and controlled characteristics.

Fire Defence Plan: A pre-determined and co-ordinated use of available human and material means in order to maintain an adequate level of fire safety and protection within a building and, in the event of an outbreak of fire, to ensure that it is brought speedily under control and extinguished - with the aim of minimizing any adverse or harmful environmental impacts caused by the fire.

Fire-Induced Progressive Damage: The sequential growth and intensification of structural deformation and displacement, beyond fire engineering design parameters, and the eventual failure of elements of construction in a building – during a fire and the 'cooling phase' afterwards – which, if unchecked, will result in disproportionate damage, and may lead to total building collapse.

Fire Resistance: The inherent capability of a building assembly, or an element of construction, to resist the passage of heat, smoke and flame for a specified time during a fire.

[Commentary: This term should no longer be used in connection with any aspect of structural performance in fire.]

Life Cycle Cost: The social, environmental, economic and institutional costs, both qualitative/quantitative and direct/indirect, of the inputs, outputs and usefulness of a product (and/or service) system throughout its life cycle.

Maximum Credible Fire Scenario: A representation, and/or depiction, of fire and operating conditions in a building which are severe, but reasonable to anticipate ... including those conditions related to building construction, occupancy, ventilation, fire loads, ignition sources, building space geometry, and fire control measures.

Maximum Credible User Scenario: A representation, and/or depiction, of building user conditions which are severe, but reasonable to anticipate, i.e. ...

- 10% of people using a building (including visitors) have an impairment which may be visual or hearing, mental, cognitive or psychological, or may be related to physical function, with some impairments not being identifiable ;

  [The above performance indicator now appears in ISO 21542: 'Building Construction - Accessibility & Usability of the Built Environment' (2011).]

- The number of people using a building increases, on occasions which cannot be specified, to 120% of designed maximum building capacity.

Real Fire: A fire which develops in a real building, and is influenced by such factors as the type of building and its occupancy; the combustible content (fire load); the ventilation, geometry and thermal properties of the fire compartment, or building space (should no fire compartmentation exist); the fire control measures in the building, and the actions of the emergency fire services.

[Commentary: A real fire is a complex phenomenon. Consequently, in structural fire engineering, an idealized version of a real fire - a design fire - is used as the basis for design calculations.]

Realistic End Condition: A real fire in a real building, which is used by real people with varying abilities in relation to self-protection, independent evacuation to a place of safety remote from the building, and participation in the fire defence plan for the building.

[Commentary 1: The realistic end condition is NOT ... a standard test fire or an experimental fire in a laboratory ... or a design fire in a computer model, even if it is properly validated.]

[Commentary 2: A standard test fire in a laboratory, involving exposure of a test specimen or prototype to standard test fire conditions, gives only a limited indication of: (a) the likely performance of a particular product, material or component when exposed to 'real fire' conditions; and (b) the suitability of a product, material or component for a particular end use.]

Structural Fire Engineering: Those aspects of fire engineering concerned with structural design for fire, and the complex architectural interaction between a building's structure and fabric, i.e. non-structure, under conditions of fire and its immediate aftermath, including but not confined to the 'cooling phase'.

Structural Reliability The ability of a structural system to fulfil its design purpose, for a specified time, under the actual environmental conditions encountered in a building.

[Commentary: In structural fire engineering, the concern must be that the structure will fulfil its purpose, both during the fire - and for a minimum period afterwards, during the 'cooling phase'.]

Sustainable Design: The ethical design response, in built or wrought form, to the concept of sustainable human and social development.

Sustainable Human & Social Development: Development which meets the responsible needs of this generation, i.e. the human and social rights specified in the 1948 Universal Declaration of Human Rights - without stealing the life and living resources from future generations, especially our children … their children … and the next five generations of children.

[Commentary: There are many aspects to Sustainable Human & Social Development … social, environmental, economic, institutional, political, legal, and judicial … all within a context of effective international law and lasting peace.]

Virtual Environment: A designed environment, electronically generated from within the built environment, which may have the appearance, form, functionality and impact - to the person perceiving and actually experiencing it - of a real, imagined and/or utopian world.

[Commentary: The virtual and built environments continue to merge into a new augmented reality.]

4. Recent Architectural Development

4.1 Historical Buildings

Exemplars are characterized by ornate exterior and interior finishes … design for the privileged in society … constructed of heavy masonry, with no distinction between structure and fabric (the fabric is the structure) … highly compartmented for functional reasons … use of isolated structural elements (beams spanning over door and window openings, or used to create large rooms), with primary concern being prevention of excessive deflection and failure of the element (i.e. material strength) …

Palais de Versailles - Near Paris, France

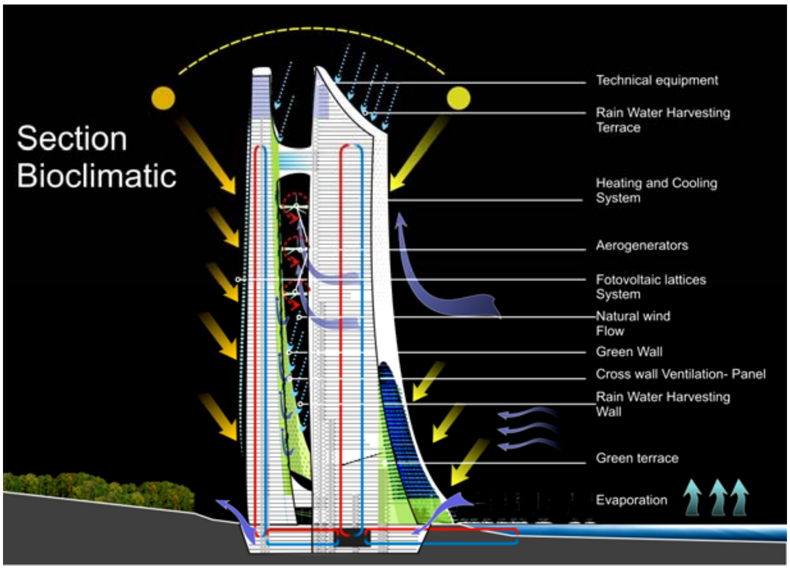
4.2 Early 20th Century Modern Buildings

Exemplars are characterized by simple, but beautiful, exterior and interior finishes … user-unfriendly design … an artistic celebration of light and space … innovative construction materials … open planning, with one functional 'space' moving, in a manner controlled by design, into the next … development of structural systems, with a clear and separate articulation of structure and fabric …

Barcelona Pavilion (1929), by Architect Mies van der Rohe

4.3 Sustainable Buildings in the 21st Century

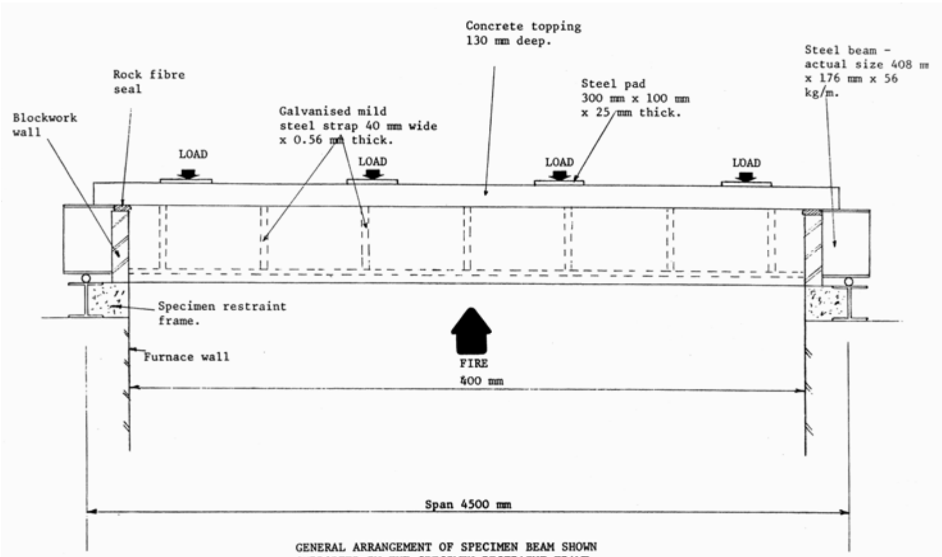
No exemplars yet … sustainable design solutions are 'person-centred', and appropriate to local geography, climate and climate change, social need, culture and economy … complex new trans-disciplinary design approaches required to respond appropriately to local conditions … development of construction systems … no compartmentation in order to use natural patterns of air movement in buildings for heating and/or cooling … 'positive energy buildings' producing far more energy than they and associated private modes of transport need, with excess returned to regional/local intelligent grid …



Project by Orlando De Urrutia, Spanish Architect

5. Current 'Standard Test' Fire - Loaded Steel Beam

Does this standard test configuration, in an English Laboratory, look familiar ?



GENERAL ARRANGEMENT OF SPECIMEN BEAM SHOWN SUPPORTED IN THE SPECIMEN RESTRAINT FRAME

And what about this criterion for 'loadbearing horizontal elements', from a British Standard ??

10.2.3 *Loadbearing horizontal elements.* The test specimen shall be deemed to have failed if it is no longer able to support the test load. For the purposes of this standard, this shall be taken as either of the following, whichever is exceeded first:

(a) a deflection of $L/20$; or

(b) where the rate of deflection (in mm/min), calculated over 1 min intervals, starting at 1 min from the commencement of the heating period, exceeds the limit set by the following equation:

$$\text{rate of deflection} = \frac{L^2}{9000d}$$

where

L is the clear span of specimen (in mm);

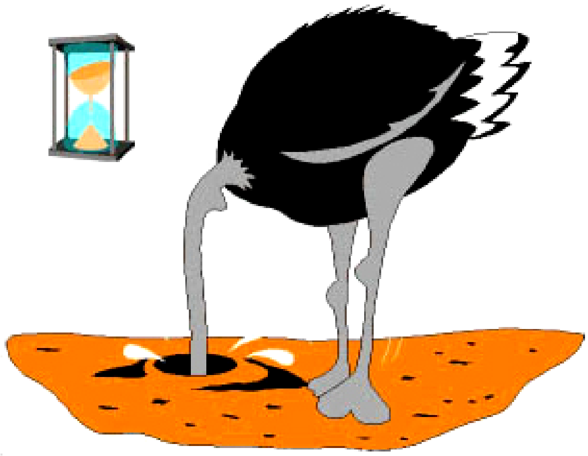
d is the distance from the top of the structural section to the bottom of the design tension zone (in mm).

However, this rate of deflection limit shall not apply before a deflection of $L/30$ is exceeded.

A single isolated loaded steel beam, simply supported, is being tested. As **deflection** is the only type of deformation being observed and measured … the **critical temperature of the steel**, i.e. the point when material strength begins to fail rapidly and the rate of beam deflection increases dramatically … is the sole focus for all stakeholders.

Coming from this background and 'heritage' … it is very difficult to communicate with mainstream, ambient structural engineers who are speaking the language of **structural reliability**, **limit state design** and **serviceability limit states**.

However … in terms of 'real' building design and construction in the 20th and 21st Centuries, this standard test fire is urgently in need of a radical overhaul !



6. Fire Engineering at a Modern Crossroads

In spite of relentless current social, environmental and economic drivers, e.g. energy security, energy conservation, much greater energy efficiency in buildings, atmospheric ozone depletion, and climate change ... conventional fire engineering still exists in an idealized bubble (the test laboratory and the computer ?), divorced from reality: (i) it is rooted in the notion that architectural expression should be 'historical' ... with an unquestioning belief in, and insistence on, 'compartmentation' (it took 10-15 years to become relatively comfortable with the atrium in buildings !); (ii) concerning structural performance in fire, its focus remains firmly on the material strength of isolated structural elements; (iii) it has reacted, ostrich-like, to the traumatizing extreme 'fire' event of 9-11, in New York City ... equivalent, in psychosocial terms, to the sinking of the Titanic Ocean Liner one hundred years ago, in April 1912; and finally, (iv) conceptual thought is unclear, illogical and irrational ... ensuring that practitioners suffer from a distinct inability to communicate meaningfully with other design disciplines.

However, time is running out ... and to discuss these challenges in detail ... 2 Series of Posts were published on FireOx International's Technical Blog (www.cjwalsh.ie), beginning on the dates indicated ...

- **2011-10-25: NIST's (2005) Recommendations on the 9-11 WTC Building Collapses** ... GROUP 1. Increased Structural Integrity – Recommendations 1, 2 & 3 (out of 30) ;

  and

  2012-01-18: Progressive Collapse of WTC 7 – 2008 NIST Recommendations - Part 1 of 2 ... GROUP 1. Increased Structural Integrity – Recommendation A ... and GROUP 2. Enhanced Fire Endurance of Structures – Recommendations B, C, D & E (out of 13).

Conventional Fire Engineering must break irrevocably with the past ... re-tune its language, and re-engineer its fundamental tenets, to emerge as **Modern Fire Engineering** ... before moving forward, with confidence, to grapple with the quantum leap in the evolution of design philosophy which will be demanded by **Sustainable Fire Engineering.**

7. Design to Resist Fire-Induced Progressive Damage

Structural Reliability

The ability of a structural system to fulfil its design purpose, for a specified time, under the actual environmental conditions encountered in a building.

Structural Fire Engineering

Those aspects of fire engineering concerned with structural design for fire, and the complex architectural interaction between a building's structure and fabric, i.e. non-structure, under conditions of fire and its immediate aftermath, including but not confined to the 'cooling phase'.

Fire-Induced Progressive Damage

The sequential growth and intensification of structural deformation and displacement, beyond fire engineering design parameters, and the eventual failure of elements of construction in a building – during a fire and the 'cooling phase' afterwards – which, if unchecked, will result in disproportionate damage, and may lead to total building collapse.

Disproportionate Damage

The failure of a building's structural system:
(i) remote from the scene of an isolated overloading action ;
and (ii) to an extent which is not in reasonable proportion to that action.

7.1 2005 NIST Report - 3 R's: 'Reality' - 'Reliability' - 'Redundancy'

This is not a 'real' building, comprising structure and fabric, i.e. non-structure ... it is an **Experimental Test Fire** ... one of a series which was carried out in the British Building Research Establishment's Cardington Large Scale Laboratory during 1995-1996.

In the early 1990's, I had a meeting with a group of the test sponsors in Dublin.

The characteristics of this test fire were pre-specified, carefully controlled and engineered ... and were certainly not as severe as those of a **maximum credible design fire**. CIB W14 has another Research Working Group looking at this concept.

Reality ... and this **is** a 'real' building in Dublin ...

During the early 1990's, while working as the Research & Technical Officer in Dublin City's Building Control Section (local authority having jurisdiction) ... I was requested by the front line building surveyor responsible for this building to accompany him on a control inspection.

The building in question (shown above in the photograph) ... is a multi-storey, structural steel framed rear extension to a Dublin Hotel, and has a dark brown brick façade.

A typical interior architectural detail (shown above in the diagram on the right) ... comprises a 10 metre span steel beam, with a board fire protection system. Underneath, and separating the bedrooms from the corridor, is a non-loadbearing steel stud partition.

The steel beam, and the partition underneath, both have a fire rating of 1 Hour Fire Resistance. No allowance, in design or construction, had been made for any deformation of the beam during a fire.

The beam's fire protection system had been badly installed ... which raises the issue of **Reliability**. Just like the Fire Resisting Doorset shown above ... will the steel beam's fire protection system perform adequately, or at all ... in a 'real' fire situation ??

On 28 July 1945, at 09.40 hrs on a foggy Saturday morning, a B-25 Bomber slammed directly into the 79th Floor of the Empire State Building, in New York City. Enormous damage was caused … but, the building remained structurally stable and erect.

Anyone passing this building today would never know what had happened back in 1945.

Bearing in mind that the minimum life cycle of a **Sustainable Building** is 100 years … **Redundancy** is required not only for **Structural Reliability**, but also for **Building Adaptability**.

The **Fundamental Flaw** in the Dublin Hotel Extension Detail is that long before the 60 minutes (1 Hour Fire Resistance for both beam and partition) has elapsed … the steel beam will have deflected more than sufficiently to seriously impair the fire resistance capability of the non-loadbearing partition underneath.

This is how **Fire-Induced Progressive Damage** begins … and why it can commence before any breach occurs in a fire compartment boundary having a very high level of fire and smoke resistance. These two concepts are only indirectly related, at best.

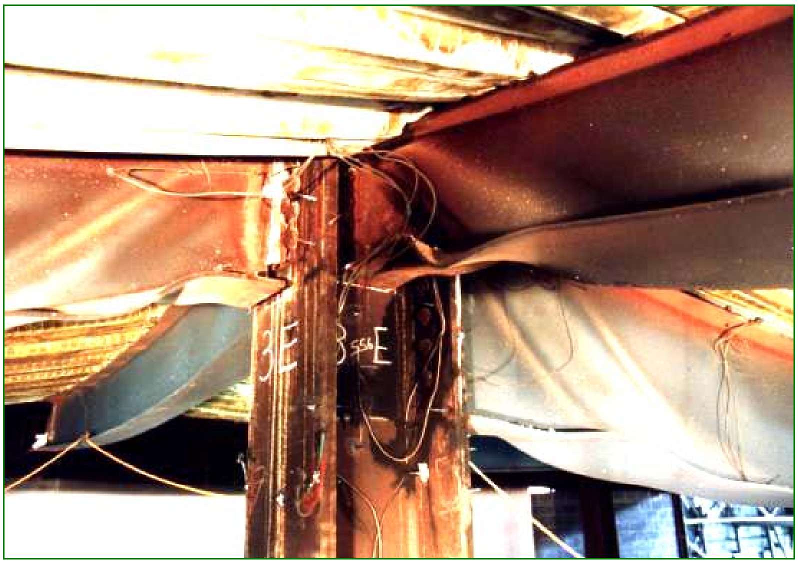
7.2 Steel Frame Connections

Looking back at some of the BRE Cardington Experimental Test Fire photographs … with fresh, innocent eyes … the connections in a 'real' steel framed building should be sufficiently robust, during a fire and the 'cooling phase' afterwards, to withstand the different types of deformation in adjoining structural elements.

Having observed the Japanese Steel Industry 20 years ago … researchers found that a standard, but oversized, approach to connection design was most economical. Is this still the case ?

Because of the deformation of surrounding structural elements … will the method of fire protecting connections stay in position, intact and undisturbed … and perform reliably in a fire situation, as intended ? Recent research suggests not.

If bolted connections are used throughout … should a certain number of these be welded … perhaps, at critical points ? How many … and at which points ??



CIB W14 has another Research Working Group looking at **Steel Connections**.

7.3 Acceptable Deformation & Whole Frame Structural Reliability

Of course, in a 'real' fire … deformation is transferred through a connection (provided it does not fail, and is sufficiently robust), and beyond, to other parts of the steel frame. At what point will this transferred deformation bring into doubt the structural reliability of the whole frame, or a disproportionately large part of it ?

In complete contrast to the photographs above … in a 'real' building (below) … there is also fabric, i.e. non-structure … for example, walls and ceilings, etc. At what point will the deformation of a beam seriously impair the fire resistance capability of, for example, an adjoining non-loadbearing partition … as already discussed in the example of the Dublin Hotel ??

And … bearing in mind the long life cycle of a **Sustainable Building** … and the necessity of facilitating **Building Adaptability** and **Building Flexibility** … it is not possible to design for a large allowable deformation in any specific location. The internal arrangement of a building might be re-designed after 20 or 30 years in use.

7.4 Fire Serviceability Limit States

Fire Serviceability Limit States in structural fire engineering, which are of more immediate and direct relevance to the protection of human health and property, a proper consideration of firefighter safety, and necessary re-construction after a fire ... would correspond to, for example ...

- deformations which affect the efficient use, i.e. the fire performance, or appearance of structural elements or fabric, i.e. non-structure ;
- local damage (including concrete spalling and cracking) which reduces the durability of a structure or affects the efficiency or appearance of structural elements or fabric, i.e. non-structure.

To design for not exceeding fire ('hot form') serviceability limit states ... it is necessary to use one or more constraints, i.e. to establish fire engineering design parameters ... which specify acceptable deformations (+/- deflection, expansion, distortion, etc), accelerations, crack widths, spalling, etc., in all structural elements ... primary and secondary.

7.5 A Critical Update to Structural Fire Engineering in 5 Easy Stages

TABLE 5.4. Thermal Properties of Common Fire Protection Material (ECCS 1995)

Material	unit mass ρ_p [kg / m^3]	mosture content p [%]	thermal conductivity λ_p [W / (m·k)]	specific heat c_p [J/(kg·K)]
Sprays				
- mineral fibre	300	1	0.12	1200
- vermiculite cement	350	15	0.12	1200
- perlite	350	15	0.12	1200
High-density sprays				
- vermiculite (or perlite) and cement	550	15	0.12	1100
- vermiculite (or perlite) and gypsum	650	15	0.12	1100
Boards				
- vermiculite (or perlite) and cement	800	15	0.20	1200
- fibre-silicate or fibre-calcium-silicate	600	3	0.15	1200
- fibre-cement	800	5	0.15	1200
- gypsum board	800	20	0.20	1700
Compressed fibre boards				
- fibre silicate, mineral-wool, stone-wool	150	2	0.20	1200
Concrete	2300	4	1.60	1000
Light weight concrete	1600	5	0.80	840
Concrete bricks	2200	8	1.00	1200
Bricks with holes	1000	-	0.40	1200
Solid bricks	2000	-	1.20	1200

NISTIR 7563 (February 2009): 'Best Practice Guidelines for Structural Fire Resistance Design of Concrete and Steel Buildings'

(i) Check that the **Fire Protection System** is properly shown to be **'Fit for its Intended Use'** - durability, and resistance to mechanical damage during initial construction **and** a fire incident, must also be considered ;

(ii) Check **Robustness of Connections**, i.e. can they withstand the deformation effects of adjoining steel structural elements in fire ?

(iii) Check **Whole Frame Reliability in Fire** - Develop a **Whole Frame Structural Reliability Matrix** for both ambient **and** fire conditions ;

(iv) Check **Fire Resisting Fabric** ... adjoining and/or adjacent to, steel structural elements ... what deformation can be accommodated, or is designed for ?

(v) Specify **Fire Protection Insulation Thicknesses** to ensure steel beam and column deformations remain within **Fire Engineering Design Parameters / Fire Serviceability Limit States**.

This updated design approach is fully consistent with NIST's Recommendations.

8. Sustainable Fire Engineering

Every year, in every country ... **Fire** is the cause of enormous direct and indirect losses ... some have not yet been fully identified, e.g. in the case of environmental damage ... and some are not yet capable of being fully quantified, e.g. business interruption and brand damage. Current Fire Statistics and Databases are unreliable. In all situations, however, the waste of valuable human and natural resources caused by **Fire** is unsustainable.

Sustainable Fire Engineering - a quantum leap in the evolution of design philosophy - is ...

- **Reliability-Based** - has an empirical, rational and scientifically sound basis ; and
- **Person-Centred** - 'real' people are placed at the centre of creative endeavours and due consideration is given to their responsible needs ... and their health, safety, welfare and security ... in the Human Environment.

Sustainable Fire Engineering Design Solutions are appropriate to **Local** geography, climate and climate change, social need, culture, economy, and language/dialect, etc.

The **Sustainable Fire Engineer**, working in an ethical, professional and trans-disciplinary manner ... elaborates project specific **Fire Engineering Design Objectives** which properly protect the interests of society, and his/her clients or client organizations (correct order of priority) ... in order to realize a Safe and Sustainable Built Environment.

In essence ... **Sustainable Fire Engineering** heavily front-loads **Fire Prevention** and **Fire Protection** ... to dramatically reduce direct and indirect fire losses in the Built Environment ... and to protect the Natural Environment.

9. This Reflection Document & Your Comments

This Reflection Document was written in a simple, generic language which is accessible to design disciplines outside the International Fire Science and Engineering Community. The next phase of this research will certainly require the use of a more technical language, complex calculations, computer modelling, etc ... and much closer liaison with CIB W14's other Research Working Groups on Connections, Design Fires & Design Fire Scenarios, and Performance Criteria.

I wish to sincerely thank those individuals and organizations who have contributed to the work of this Research Group.

Finally, the myth surrounding NIST's 9-11 WTC Recommendations, i.e. that they are only applicable in the case of Very Tall Buildings during rarely occurring extreme events ... must be completely demolished, and obliterated from the face of the earth ! Fire-Induced Progressive Damage and Disproportionate Damage, in particular, are fundamental concepts to be applied in the design of all building types. Climate Change Adaptation is already requiring a much higher level of building resilience.

Your Comments should be e-mailed to: fireox@sustainable-design.ie

C.J. Walsh, FireOx International - Ireland, Italy & Turkey.
Chair, CIB W14 Research WG IV

APPENDIX I

[see separate PDF File]

'The Conflagration of Two Large Department Stores in the Centre of Athens'

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Abstract: A conflagration of two large department stores which occurred simultaneously one night in the centre of Athens is described and the construction of buildings involved in the fire, the fire scenario and the fire damage assessment are given. The behaviour of structural elements during and after the fire has been studied and the causes and the mechanism of collapse of a large part of a multi-storey concrete building analyzed.

Published in FIRE AND MATERIALS
Volume 10, Pages 171-177 (1986)

Fire-Induced Progressive Damage is also an issue in Buildings with a Reinforced Concrete Structure

APPENDIX II

[see separate PDF File]

European Union

Regulation (EU) No.305/2011 of the European Parliament and of the Council, of 9 March 2011, laying down Harmonized Conditions for the Marketing of Construction Products and Repealing Council Directive 89/106/EEC

ANNEX I - Basic Requirements for Construction Works

1. Mechanical Resistance and Stability
2. Safety in Case of Fire
3. Hygiene, Health and the Environment
4. Safety and Accessibility in Use
5. Protection against Noise
6. Energy Economy and Heat Retention
7. Sustainable Use of Natural Resources

The Updated Approach to Fire Engineering Design discussed here … is fully consistent, not only with NIST's 2005 & 2008 9-11 WTC Recommendations, but also with Annex I of EU Regulation 305/2011