

Monday 11th April 2011
CIB W14 Commission Meeting - Paris, France



CIB W14 WG IV Innovation & Research Project (Phase II)
Structural Reliability & Fire-Induced Progressive Collapse

www.cjwalsh.ie/progressive-collapse-fire



Introduction

In August 2008 ... the National Institute of Standards & Technology (USA) issued **NIST NCSTAR 1A: 'Final Report on the Collapse of World Trade Center Building 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." [Page 58, NIST NCSTAR 1A]

2008 NIST NCSTAR 1A Recommendation A (re-statement and confirmation of the earlier 2005 NIST Recommendation 1):

NIST recommends that: (1) progressive collapse be prevented in buildings through the development and widespread adoption of consensus standards and code provisions, along with the decision support tools and design guidelines needed for their use in practice;

Phase II of this CIB W14 Innovation & Research Project is examining ...

- ◆ Gaps in our understanding of Structural Fire Engineering ;
- ◆ Institutional Barriers delaying our response to NIST Recommendation A above ;
- ◆ A Rational Route Forward to meet that complex Technical Challenge.





WTC Complex, New York

11 September 2001

Catastrophic Failure in All Practices & Procedures ...

- **Architectural / Structural Engineering / Fire Engineering ;**
- Building Management Systems ;
- Emergency Responders / Firefighters / Rescue Teams ;
- Control Organizations Having Authority (AHJ's) or Jurisdiction ;
- **Fire Safety Objectives in Building Legislation, Codes & Standards.**



Fire Engineering **After** 9-11 & Mumbai

◆ NIST(USA) 2005 Final Report on 9-11 WTC 1 & 2 Tower Collapses

Introduced a New Benchmark for International Fire Engineering

30 Recommendations (1-30) contained in Chapter 9 ...

- 3R's - 'Reality' - 'Reliability' - 'Redundancy'
- Design for Evacuation & Way-Finding in Fire
 - 'Intuitive & Obvious' & 'Use of Lifts/Elevators'
 - 'Firefighter Contraflow'
- Design for Structural Reliability in Fire
 - 'Fire-Induced Progressive Collapse'

◆ NIST(USA) 2008 Final Report on 9-11 WTC 7 Building Collapse

Confirmed this New Benchmark

13 Recommendations contained in Chapter 5 ... 12 Recommendations (A, C-M) re-state earlier 2005 Recommendations + **1 New Recommendation B** ...

Dramatic, Full-Scale Demonstration of Fire-Induced Progressive Collapse

A Rational Fire Engineering Design Response is Still Required !





Building Evacuees Requiring Assistance / All Building Types, excluding Health Facilities

Buildings Must Remain Serviceable =

- ◆ While People wait in '**Areas of Rescue Assistance**' [ISO FDIS 21542] ;
+
- ◆ Until all of these People can be rescued by Firefighters **and** every person can reach a '**Place of Safety**', via an accessible route [ISO FDIS 21542] ;
- ◆ With an assurance of Individual Health, Safety & Welfare for All.



European Union

Council Directive 89/106/EEC, of 21 December 1988,
on the approximation of laws, regulations and administrative provisions
of the Member States relating to Construction Products

Annex I - Essential Requirements 1 & 2 (of 6) ...

1. Mechanical Resistance & Stability

The construction works must be designed and built in such a way that the loadings that are liable to act on it during its construction and use will not lead to any of the following:

- (a) collapse of the whole or part of the works ;
- (b) major deformations to an inadmissible degree ;
- (c) damage to other parts of the works or to fittings or installed equipment as a result of major deformation of the load-bearing construction ;
- (d) damage by an event to an extent disproportionate to the original cause.

2. Safety in Case of Fire

The construction works must be designed and built in such a way that in the event of an outbreak of fire:

- the load-bearing capacity of the construction can be assumed for a specific period of time ;
- the generation and spread of fire and smoke within the works are limited ;
- the spread of the fire to neighbouring construction works is limited ;
- occupants can leave the works or be rescued by other means ;
- the safety of rescue teams is taken into consideration.



Structural Reliability

[ISO 2394:1986 + Addendum 1:1988]

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

In structural design for fire, 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'.

Limit State Design ... (Ultimate Limit State &) Fire Serviceability Limit States
with performance monitoring !

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.



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.

[NIST Priority Buildings: High-Rise + Iconic + Critical Function + Innovative Design]
CIB W14 WG IV: Both concepts are fundamental to all Structural Fire Engineering !

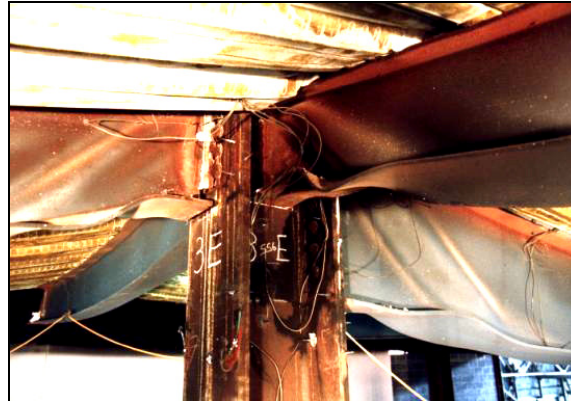
Fire-Induced Progressive Collapse

The sequential growth and intensification of distortion, displacement and 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-Induced Progressive Collapse can commence before any breach occurs even in the improved and increased fire resistance of a Fire Compartment Boundary



1995-96 Cardington Fire Tests



Large-Scale, Purposefully Designed Fire Tests



Fire Resistance (Building Fabric)

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.

Fire Compartmentation

The division of a building into fire-tight compartments, by fire resisting elements of construction, in order ...

- to contain an outbreak of fire ;
- to prevent damage, within the building, to other adjoining compartments and/or spaces ;
- to protect a compartment interior from external fire attack, e.g. fire spread across the building's facade or from an adjacent building ;
- to minimize adverse, or harmful, environmental impacts outside the building.



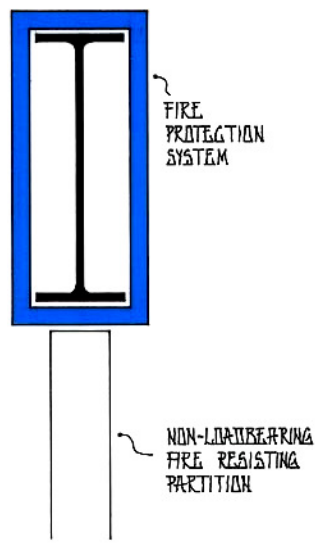
Early 1990's Dublin Hotel Project

A Typical Architectural Detail:

10m Span Steel Beam ... with non-loadbearing steel stud partitioning beneath, separating corridor from bedrooms ... each with 1hr. fire resistance (??) ...

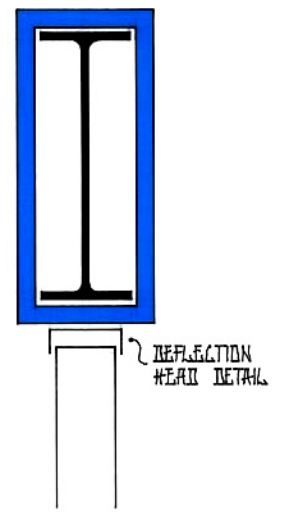


Situation A
no deflection possible



as built

Situation B
25mm deflection possible



industry option / not tested



Regulatory Approach in Britain

[Building Regulations for England & Wales]

[2004 / Part A - Structure:

Requirement A3. Disproportionate Damage ...

The building shall be constructed so that, in the event of an accident, the building will not suffer collapse to an extent disproportionate to the cause.]

◆ 2006 - amended 2007 / Approved Document B - Fire Safety:

Requirement B3.(1) Internal Fire Spread (Structure) ...

The building shall be designed and constructed so that, in the event of a fire, its stability will be maintained for a reasonable period.

British National Standard BS 9999:2008

Code of Practice for Fire Safety in the Design, Management and Use of Buildings

Takes no account of any of the NIST WTC 9-11 Recommendations, Fire-Induced Progressive Collapse, or Disproportionate Damage ... and conflicts with Building Regulations



Notional Hotel Project in Cardiff, Wales

Same Typical Architectural Detail: 10m Span Steel Beam ... with non-loadbearing steel stud partitioning beneath, separating corridor from bedrooms

[Approved Document B is 'deemed-to-satisfy' the Part B Requirements]

- ◆ Approved Document B / Appendix E - Definitions ...

Fire-Resisting (Fire Resistance):

The ability of a component or construction of a building to satisfy, for a stated period of time, some or all of the appropriate criteria specified in the relevant standard test.

The concept of 'fire resistance' is not defined.

- ◆ Approved Document B / Table D1 - Classification of Purpose Groups ...

Group 2(b)	Residential (Other)	Hotel, Boarding House, etc.
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- ◆ Approved Document B / Table A1 - Specific Provisions of Test for Fire Resistance of Elements of Structure, etc ...

Structural Frame, Beam or Column	See table A2
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Enclosure / Fire Resisting Construction	EI 30 (minutes) EI 60 ✓
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(sleeping hazard & part m)



◆ Approved Document B / Table A2 - Minimum Periods of Fire Resistance ...

Purpose Group: Residential - Other Residential

Elements of Structure at
Ground or Upper Storey

Height of top floor above ground is not
more than 18 metres [Diagram C6]

Minimum Period of Fire Resistance

60 minutes ... R 60

[1992 - amended 2000 / Regulation 7 - Materials & Workmanship:

- (1) Building work shall be carried out:
 - (a) with adequate and proper materials which:
 - (i) are appropriate for the circumstances in which they are used;
 - (ii) are adequately mixed and prepared; and
 - (iii) are applied, used or fixed so as adequately to perform the functions for which they are designed; and
 - (b) in a workmanlike manner.]

{In this Part,

Requirement D3 of Irish Building Regulations

'proper materials' means materials which are fit for the use for which they are intended and for the conditions in which they are to be used, and includes materials which:

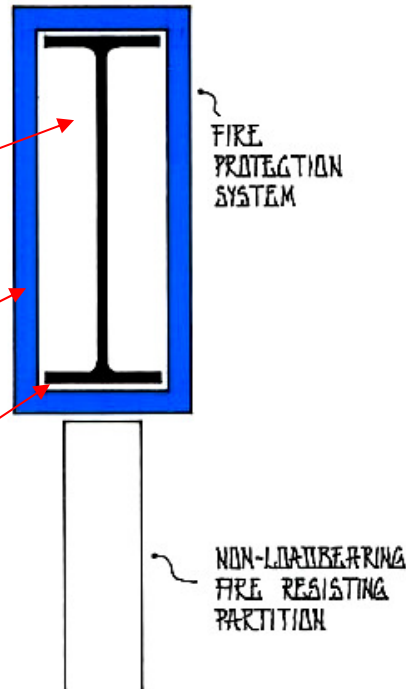
- (a) bear a CE Marking in accordance with the provisions of the Construction Products Directive; or
- (b) comply with an appropriate harmonized standard, European Technical Approval or national technical specification as defined in article 4(2) of the Construction Products Directive; or
- (c) comply with an appropriate Irish Standard or Irish Agrément Board Certificate or with an alternative national technical specification of any State which is a contracting party to the Agreement on the European Economic Area, which provides in use an equivalent level of safety and suitability.}



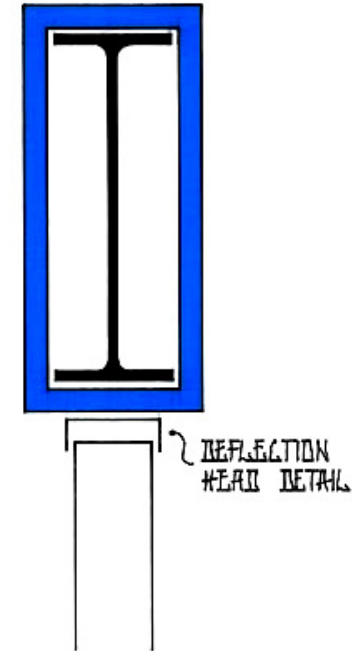
Reliability of Steel Fire Protection System ?

Site Inspection:

- continuous cavity (not fire/smoke sealed) containing services ... water pipes
- gaps in board fire protection system
- electrical services fixed directly to steel



as built



industry option / not tested
25mm deflection possible ?



... the appropriate criteria specified in the relevant standard (fire resistance) test ...

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).

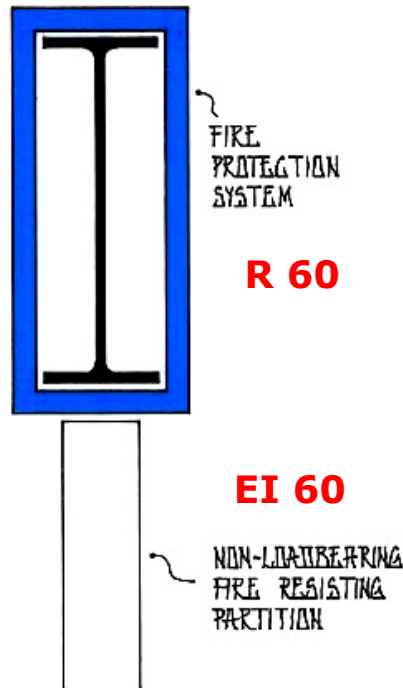
However, this rate of deflection limit shall not apply before a deflection of $L/30$ is exceeded.

Test Failure (60 mins) Deflection of Steel Beam 10m/20 > 500mm



A Fundamental Flaw in Fire Engineering

Long before 60 minutes has elapsed, the steel beam will have deflected more than sufficiently ... to seriously impair the fire resistance capability of the partition below.



This is where, and how, 'fire-induced progressive collapse' begins; and that is why, in large fire compartments, it commences before any breach occurs in a compartment boundary with improved and increased fire resistance.

" Possible options ... include:

- 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.**" [Page 59, NIST NCSTAR 1A]

Durability of Thermal Insulation ? Resistance to Mechanical Damage ?



New Recommendation B (2008 NIST NCSTAR 1A)

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.

" Possible options ... 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.** [Page 59, NIST NCSTAR 1A]



Fire Serviceability Limit States

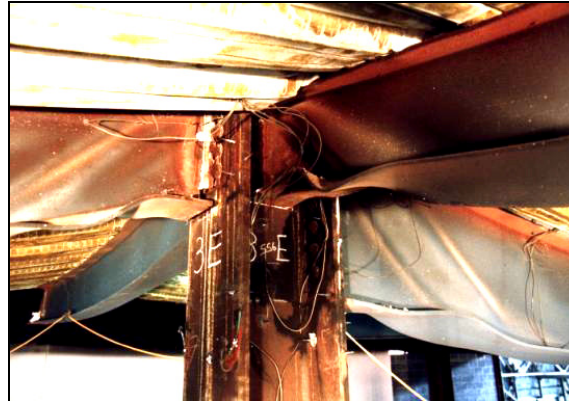
Fire Serviceability Limit States in Structural Fire Engineering, which are of more immediate and direct relevance to the protection of both human health and property, and necessary re-construction after a fire, would correspond to, for example ...

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

To control 'hot form' serviceability limit states by design, therefore, it is necessary to use one or more constraints which describe acceptable deformations (+/- deflection, expansion, distortion, etc), accelerations, crack widths, spalling, etc.



Specify Fire Serviceability Limit States



+/- Beam Deflection, Expansion, Distortion - Robust Connections ?



Specify Structural Fire Protection System

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

Material	unit mass ρ_p [kg / m ³]	moisture 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 / 2009

Draft for Comment

- Check that the Fire Protection System is 'Fit for its Intended Use'
- Check Robustness of Connections (+ Frame), i.e. what is their capacity to withstand deformation effects of connected steel members in fire ?
- Specify Thermal Insulation Thicknesses to ensure that Steel Deformations remain within Design Parameters



CIB W14 WG IV: 'Structural Reliability & Fire-Induced Progressive Collapse' - A Rational Route Forward

1. **Mainstream** the Language, Practices, Procedures and Design Methodologies of Fire Science & Engineering ... so that other design disciplines can appreciate that **Ethical Fire Science & Engineering** also has a sound, modern, rational and empirical basis. [CIB W14]
2. **Raise awareness about the primacy, and encourage the wide acceptance, of Fire Serviceability Limit States in Structural Fire Engineering ... and the universal requirement that buildings must resist Fire-Induced Progressive Collapse and, in addition, also resist Disproportionate Damage.**
3. Indicate the need for, and foster the development of, innovative **Thermal Insulation Structural Fire Protection Systems** which are durable, can resist mechanical damage in ambient **and** fire conditions, and can be properly shown to be 'fit for their intended life-cycle use'. [Industry]
4. **In steel construction ... depending on its location in a building and having designed sufficiently robust connections for fire conditions ... show why, where and how Thermal Insulation must now be used to maintain a Lower Temperature in the Steel ... in order to ensure that its deformations (+/- deflection, expansion and distortion, etc.) remain within design parameters ... both during the fire and, for a minimum period afterwards, during the 'cooling phase'.**
5. Encourage the development of **Fire Engineering Design Guidelines** for new and existing buildings, along with the **Decision Support Tools** needed for their use in practice ... to support #2 and #4 above. And propose how **Existing Code/Regulation Provisions** and **Standards** should be suitably updated and revised. [International Fire Science & Engineering Community]

