Structural Fire Safety Engineering:

Philosophy, Strategy & Means

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The Ove Arup Foundation

The Royal Academy of Engineering

Fire Safety Engineering

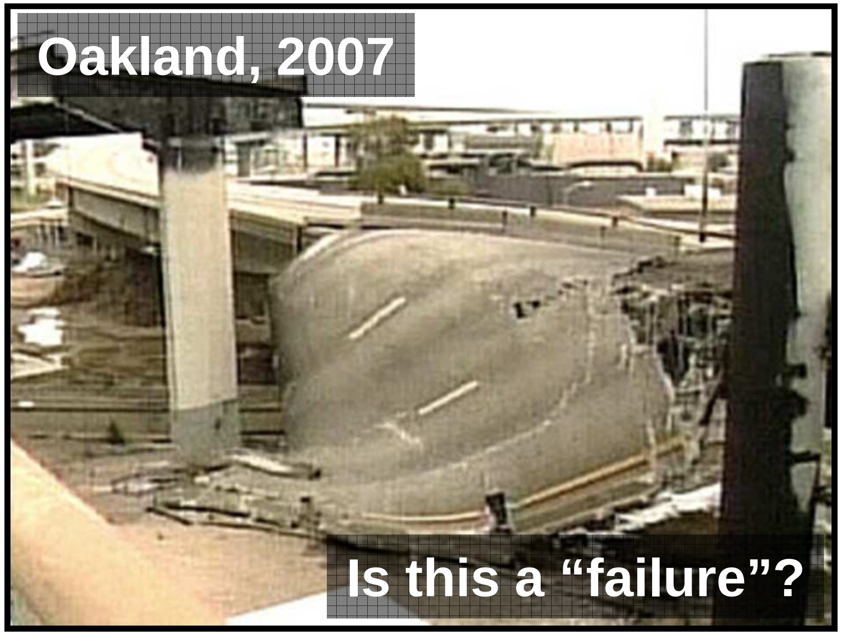
"To limit the probability of (1) death, (2) injury, and (3) property loss in an unwanted fire"

Note: All modern codes emphasize 'life safety'.
Was this always the case, and was it always the intent?

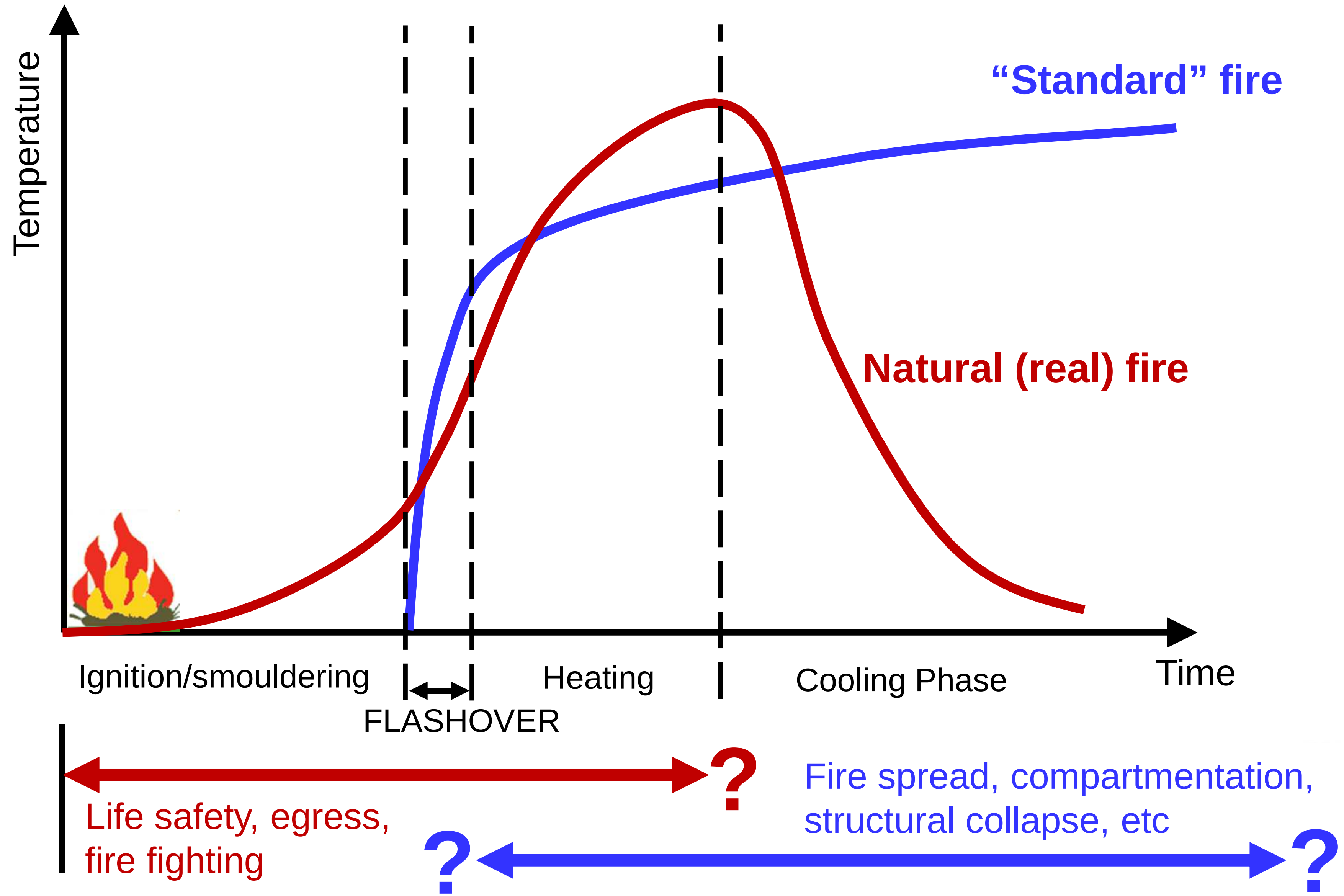
Structural Fire Engineering

"Any building shall be designed and constructed so that, in the event of fire, its <u>stability</u> will be maintained for a <u>reasonable period</u>"

Questions: What do we mean by 'stability'?
What is a 'reasonable period'?
Are we Engineers, or just playing games?



Fire Development: Considerations



Origins of Structural Fire Testing

- Initial purpose:
  - a **comparison of different building materials and systems** to assess claims of ‘fireproof’ construction in late 1800s
- Was **not intended to be a ‘solution’** for structural fire testing or regulation
  - Was a practice correction in the wake of various conflagrations (e.g. Baltimore, San Francisco)
  - Construction industry was being flooded by ‘fireproof’ building system patents which had either
    - Never been proven, or
    - Shown to fail to provide appropriate protection in real fires
- The standard fire test emerged as a test for **comparative performance** in the **most severe possible fire**

Birth of Structural Fire Testing

- Thermal scenario ***intended*** to be ***more severe than a real fire*** (based on ***qualitative*** experience)
  - "*no ordinary room would have enough inflammable material in it to maintain a **1700ºF fire for more than 30 minutes***".
  - "*When fearful consequences may result from a failure of a structure due to fire, **no test is too severe** which **reasonable care and expense in construction** can resist*"

Ira Woolson's early 'furnace'

(Stewart and Woolson, 1902)

Fire Resistance Ratings

- Over time, the temperature-time curves were formalized and became ASTM E119, ISO 834, etc.
- Assumed:
  - **No real fire could heat faster**
  - **No real fire could reach the temperatures obtained in the furnace**
  - **No real fire could last longer (thus, burnout)**
  - **Structural restraint and continuity are always helpful**

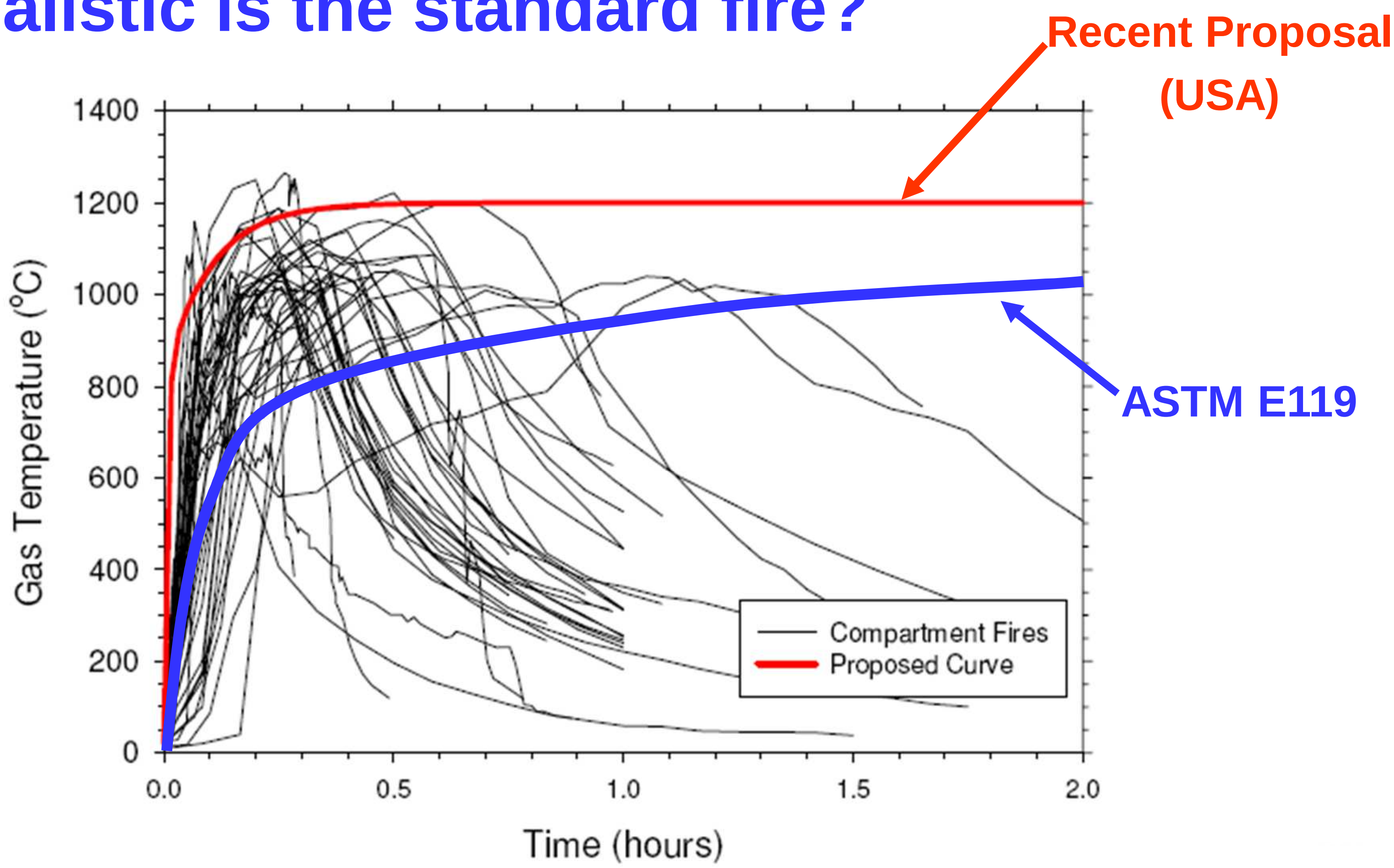
But what is the relationship to *reality??*

AND

On what basis do we say *'REI 120 minutes'??*

"Standard" versus "Real" Fire?

How realistic is the standard fire?

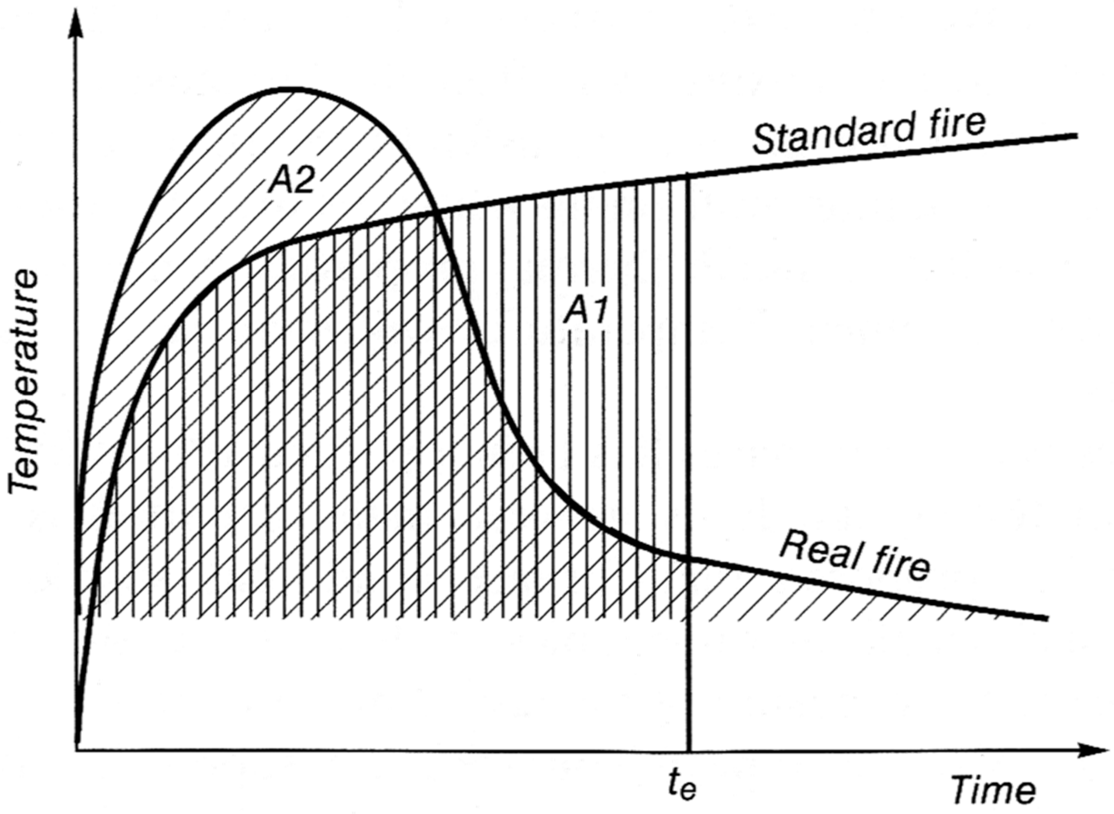


Average gas temperature in compartment fires as function of time, compared with a proposed 1200℃ 'maximum' time-temp erature curve

Iwankiw et al., SiF'08, Singapore, 2008

Ingberg & Quantification of REI Times

Around **1928**, Ingberg introduced the concept of ***'fire severity'***



(Buchanan, 2002)

Note: The intent was therefore ***'design for burnout'***

Note: 120 minutes and then collapse was ***NOT*** the intent

Ingberg's Fuel Load vs. Fire Resistance

Fire Load Of Occupancy[1]		Fuel Load[2]		Fire Resistance[3]
kg/m^2	lb/ft^2	MJ/m^2	BTU/ft^2	minutes
24.4	5	456	40,000	30
48.8	10	912	80,000	60
73.2	15	1,368	120,000	90
97.6	20	1,824	160,000	120
146.5	30	2,736	240,000	180
195	40	3,590	320,000	270

Note: (1) ratio of combustible fuel load per unit floor area.
(2) ratio of energy content of combustibles per unit area.
(3) FRR required for structures exposed to fire in room with fire load shown.

(Ingberg, 1928)

Where are we now?

The current state of practice

Fundamental Concepts:
"Performance" vs. "Prescriptive" Building Codes

- **Until recently only prescriptive SFE codes existed:**
  - A set of ***rules***
  - Describe **how a building must be constructed**
  - Little opportunity for designers to take a rational approach
- **Many countries have also adopted performance-based SFE approaches (e.g., Eurocodes):**
  - A set of ***goals***
  - State **how a building is to perform under a wide range of conditions**
  - Allows designers to use any fire safety strategy they wish, provided that **adequate safety can be demonstrated**
  - Demands a **detailed understanding**

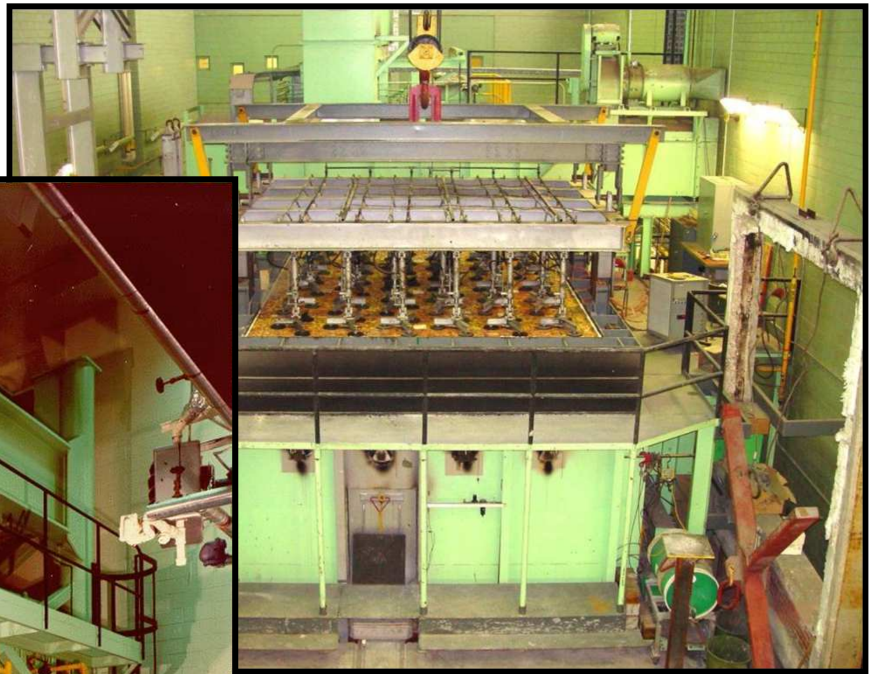
<u>*There is no such thing as prescriptive design*</u>

Structural Model / Fire Model		Materials & Partial Elements	Single Elements	Sub-Frame Assemblies	Transiently Simulated Restrained Assemblies	Full-Scale Structures
Elevated Temperature Exposures (transient or steady-state)	T, Steady-state, Transient-state, t	Generate design/model input data	O/R [T]	M/C	M/C	M/C [E.1-2]
Standard Fires	T, ISO 834, t	Generate design input data	**Obtain fire resistance ratings (STANDARD)** **[T]**	O/R [O]	M/C [W]	M/C [A]
Equivalent Fire Severity to a Standard Fire	T, ISO 834, t	Validation of fire severity concept	Obtain fire resistance ratings (using alternative metric for fire severety) [Q]	O/R	O/R	M/C [B];[G];[N]
Parametrically Defined Model Fires	T, Fire = f ( ), t	Generate design input data (highly dependant time-temperature phemnomenon)	O/R	O/R [K];[M];[R];[S]	O/R	O/R [E.3-5]; [H];[J];[L];[U];[V]
Localised Model Fires		Generate design input data (highly dependant time-temperature phemnomenon)	O/R	O/R	O/R	O/R
Zone Model Fires		Research (highly dependant time-temperature phemnomenon)	M/C	O/R	O/R	O/R [I]
Field Model Fires		Research (highly dependant time-temperature phemnomenon)	M/C	M/C	O/R	O/R
Real Fires	T, Real fire, t	Research (highly dependant time-temperature phemnomenon) [P]	M/C	M/C [C];[D];[F]	O/R	**Research REAL behaviour in a REAL fire** **[E.6]**

Standard Fire Testing

Wall Furnace

Column Furnace



Floor Furnace

‘Standard’ Testing Procedure

1. Construct test specimen to accurately represent **“as-built”** construction
2. Place specimen in **“rigid”** loading frame
3. Position **inside, next to, or over** a standard testing furnace (depending on member type)
4. Apply **“likely service load”** to the specimen
5. Maintain constant load and apply the **“standard”** time-temperature curve
6. Continue test until a ***failure criterion*** is reached
7. Test is normally **stopped once rating is obtained**

Issues for consideration…

- **Standard of Construction:**
  - Typically much **better for the test** than in reality
  - Only the **successful tests are reported**
- **Applied Loads:**
  - Choose loads which produce stresses in the tested element **“similar” to those expected in the actual building** at the time of the fire
- **Restraint & Continuity:**
  - Both have significant effects on fire resistance
  - Should use support conditions **“similar” to those expected in the actual building**
- **Size effects:**
  - Furnaces are severely **limited in size**
- **Connections & Critical Failure Modes:**
  - **Connection details are completely overlooked but often govern** in reality
  - When structures **fail in fires** it is rarely for the reasons we would expect
- **Size effects:**
  - Furnaces are severely **limited in size**

Element vs. Structure Response






4 11:06

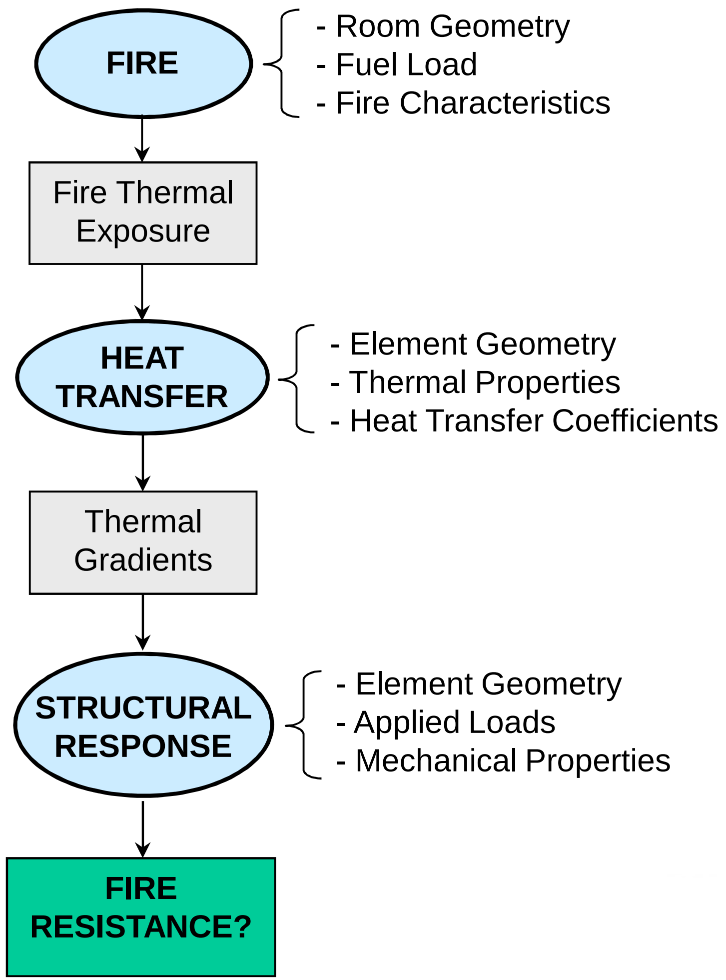

4 11:01

The Future:

Where are we going?

Performance-Based Design for Fire

- **i.e. “*Use your brain*”…**
- Modern fire safety codes allow determination of fire resistance by **‘suitable’ calculations**
- Three essential components:
  1. **Fire Model**
     (e.g. Eurocodes, CFD, etc)
  2. **Heat Transfer Model**
     (discretion??)
  3. **Structural Model**
     (rational understanding of material and ***full*** structural response)



after Buchanan[2]

Critical Concepts in PB-SFE

1. There is tremendous **complexity and uncertainty** at all levels

2. Try to achieve **“consistent crudeness”**

3. Historical **evidence may not be applicable** to modern structures/materials

Discussion?

For additional discussion/information please feel free to contact me:

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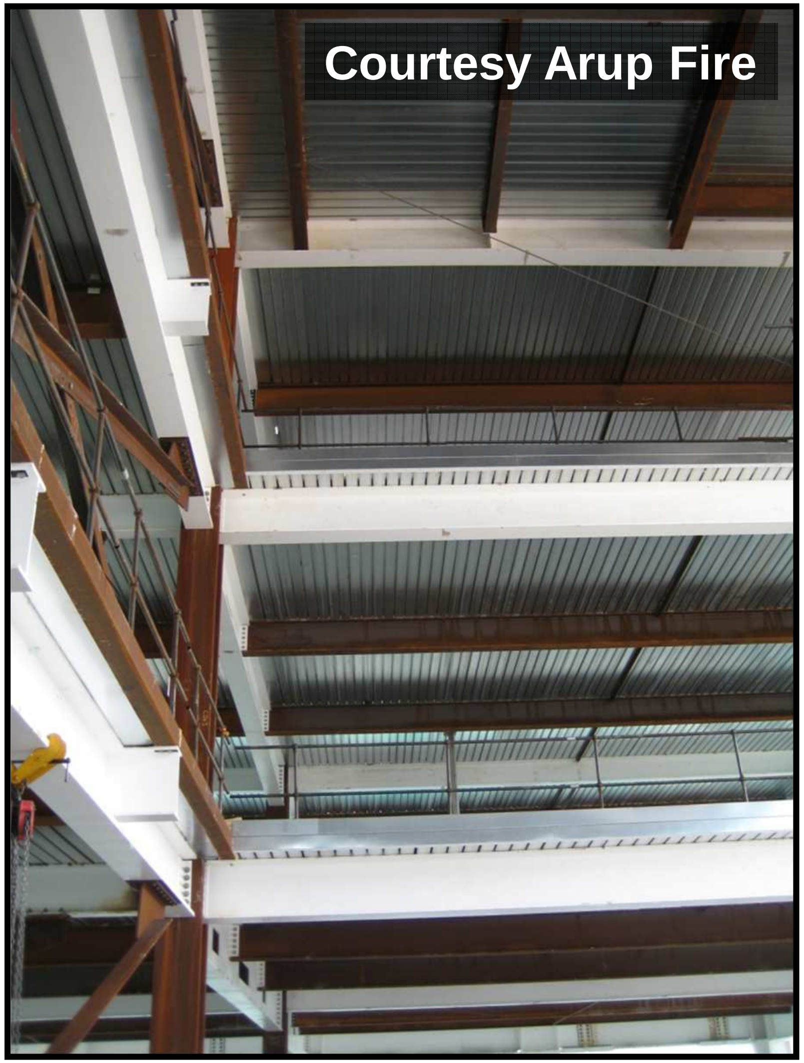
Web: www.eng.ed.ac.uk/fire

Drivers for Structural Fire Engineering?

1. **Economic**
   – Client saves money (e.g. reduced applied fire protection)
2. **Architecture**
   – Enable interesting and unusual buildings
3. **Innovation**
   – Ensure/demonstrate that new methods, materials, or innovative designs are safe
4. **Sustainability**
   – Structural optimization removes inherent redundancies
5. **Safety?**
   – Ensure methods provide “equivalent” safety



Heron Tower, London, 2010

Heron Tower (London)

ARUP

- **46 Storey** Office Building in City of London
- **3-storey atriums** forming 'villages'
- **First ever project to consider the robustness of a structure in a multi-storey fire**

Heron Tower

ARUP

Compartment floor

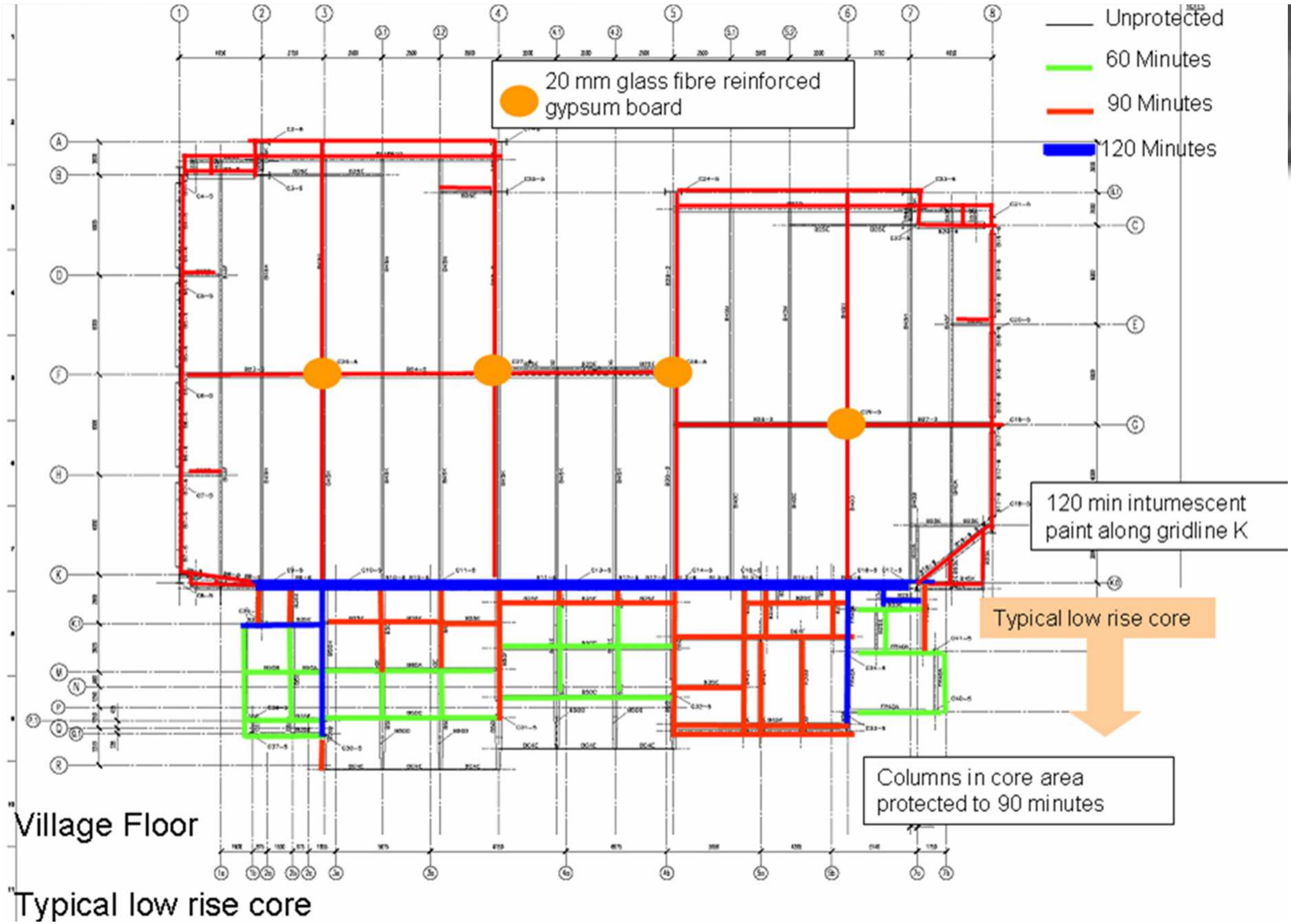
Atrium floors

Typical Village

Key Issues

- Optimisation of structural fire protection scheme
- Potential for fire occurring over three floors due to open atrium
- Structural fire analysis undertaken for 3 full floors heated simultaneously

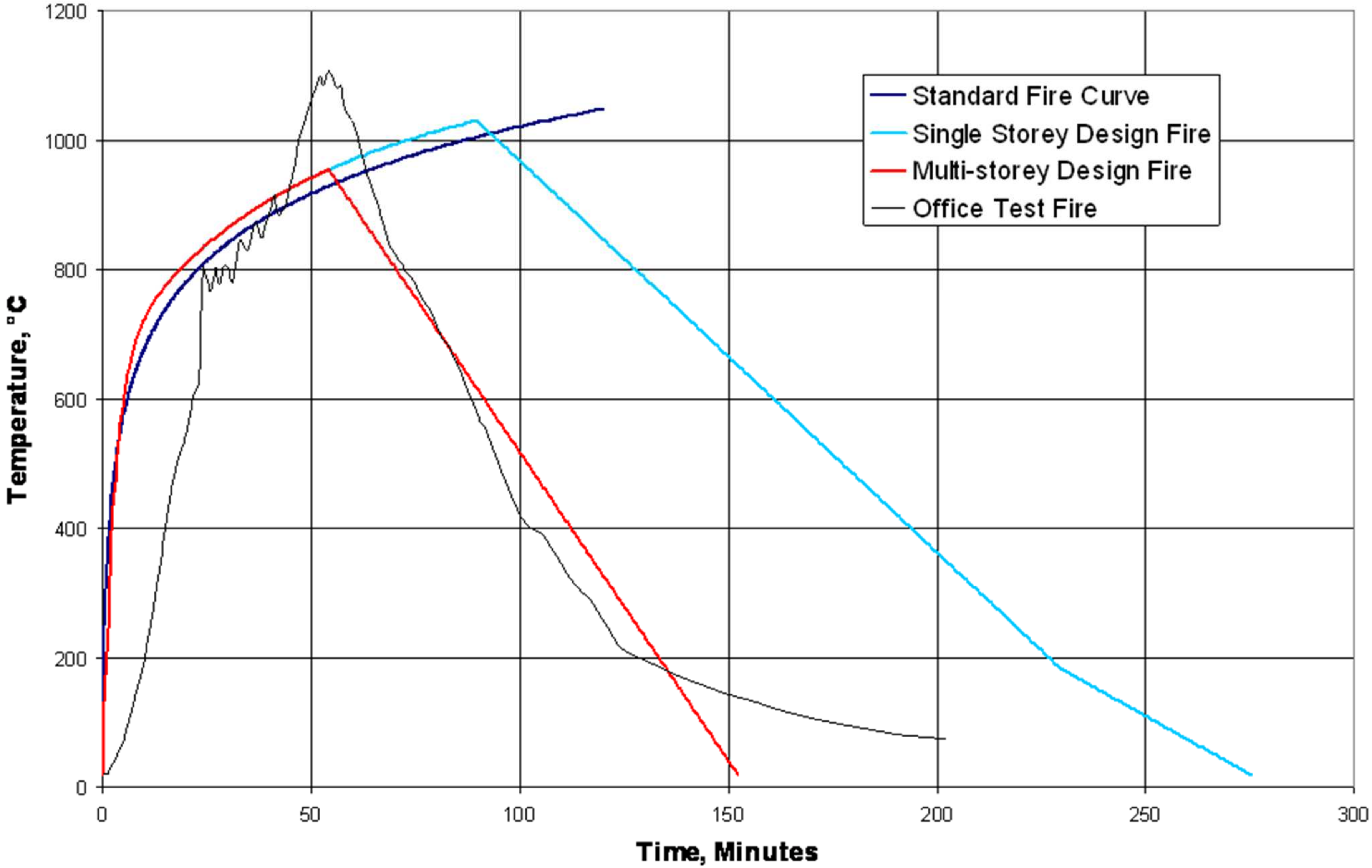
1. Specific changes and detailing to enhance structural fire response
2. Enhanced structural response to fire relative to a code compliant building



Cost savings to project

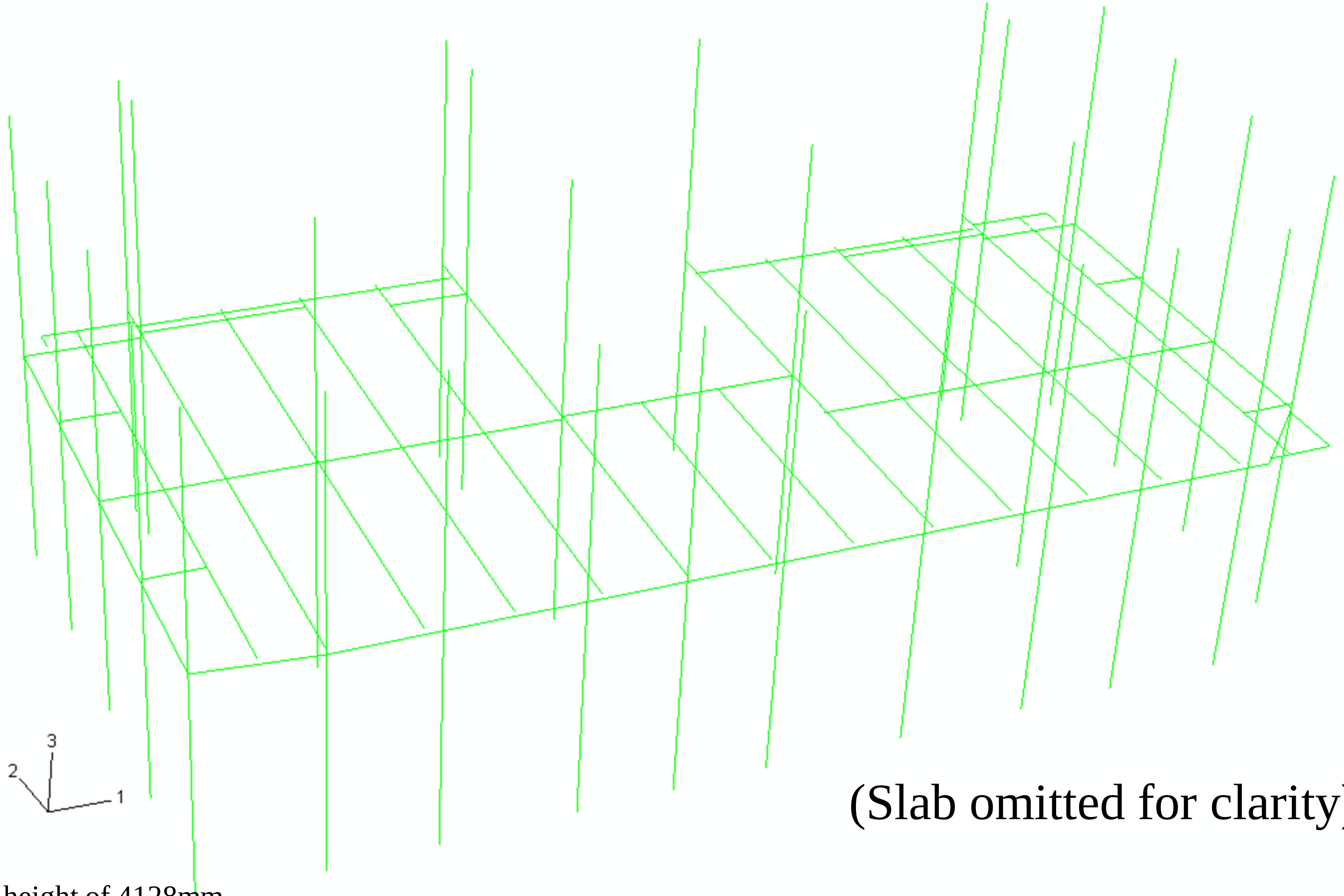
- Reduction in the overall building fire resistance rating
- Removal of passive fire protection material from infill secondary beams

Heron Tower: Design Fires



Model Extent: Single Floor Model

ARUP

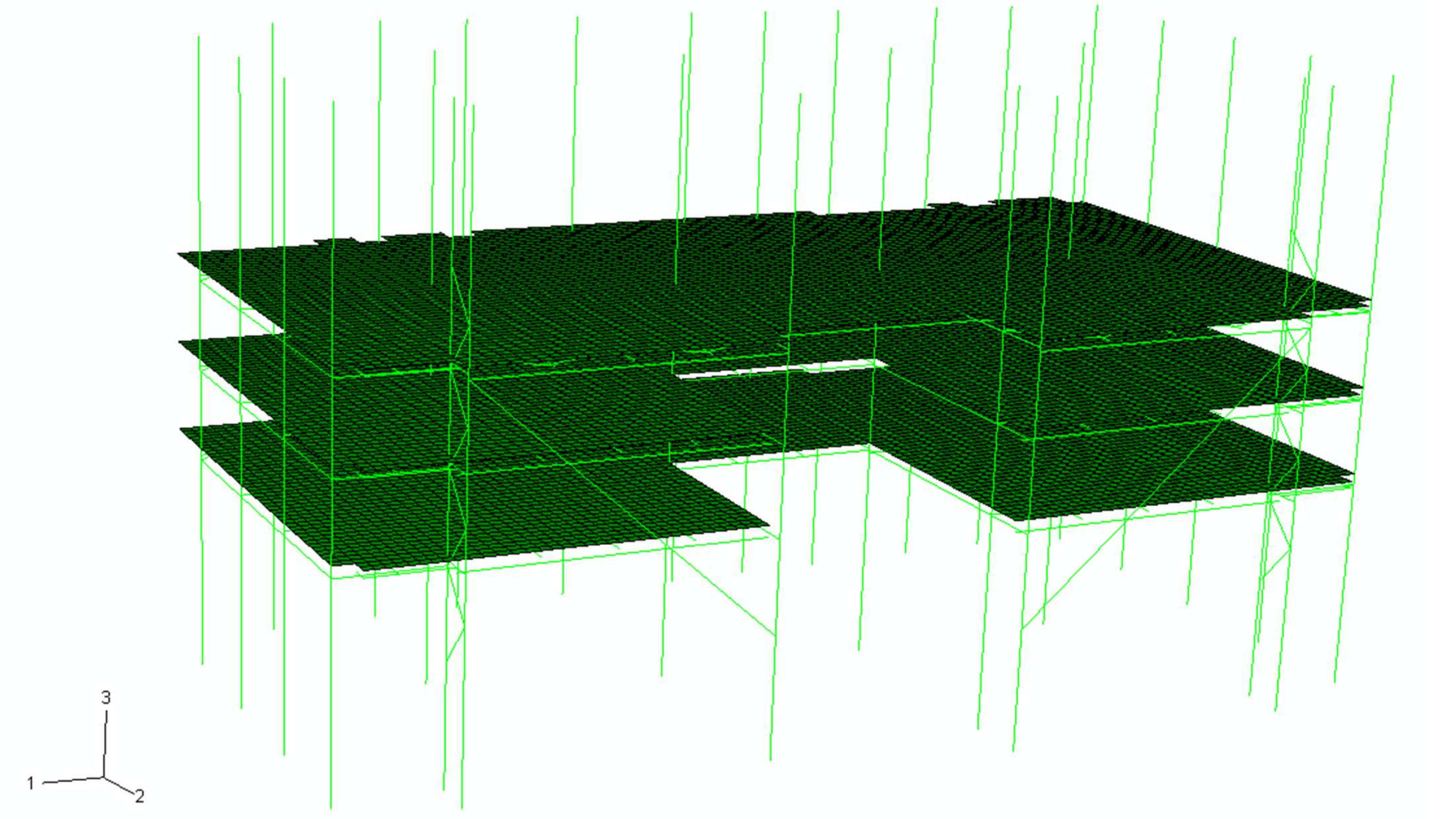


(Slab omitted for clarity)

Storey height of 4128mm

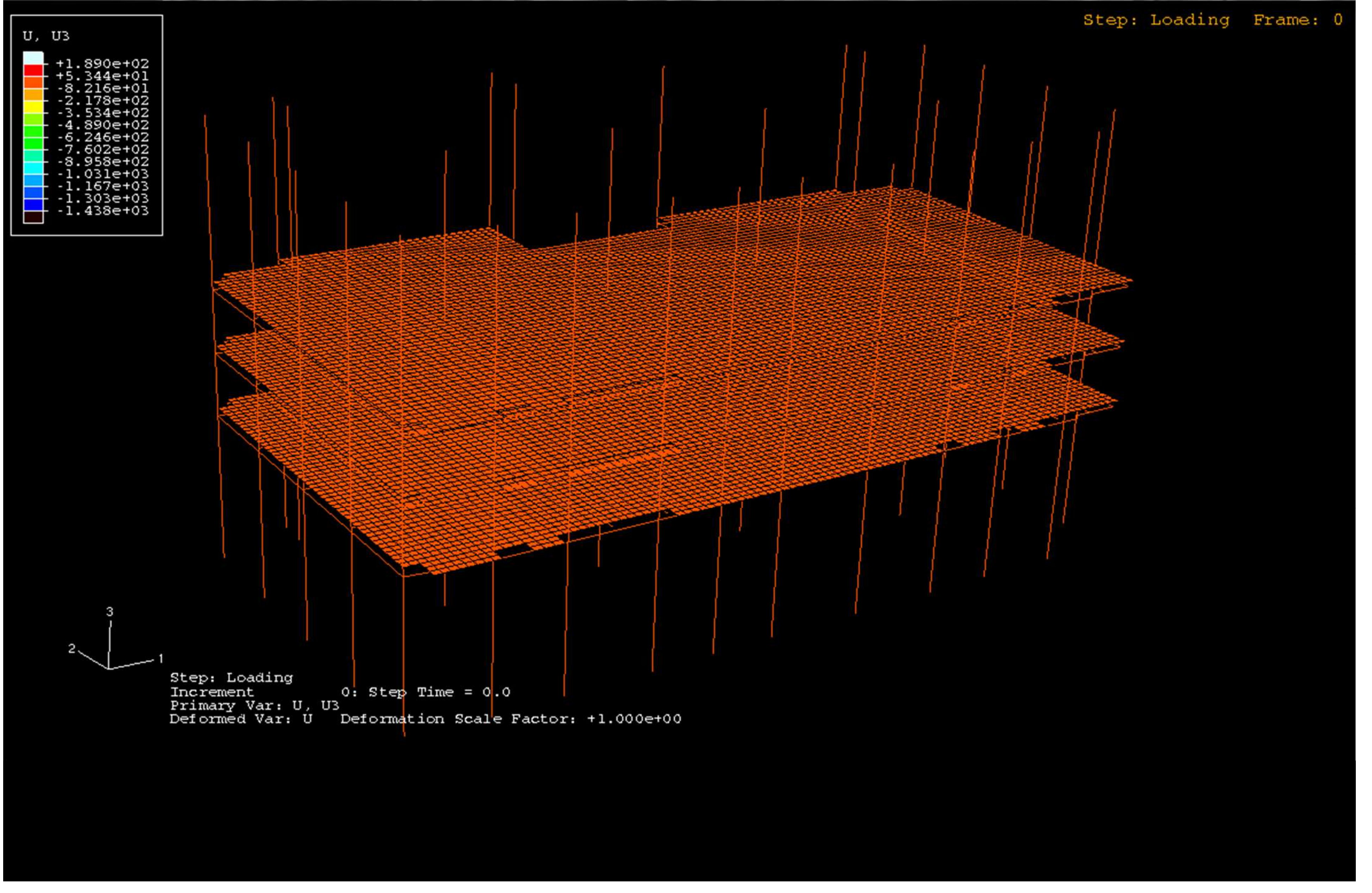
Model Extent: Village Model

ARUP



Storey height of 4128mm

Heron Tower: Multi-Storey Fire



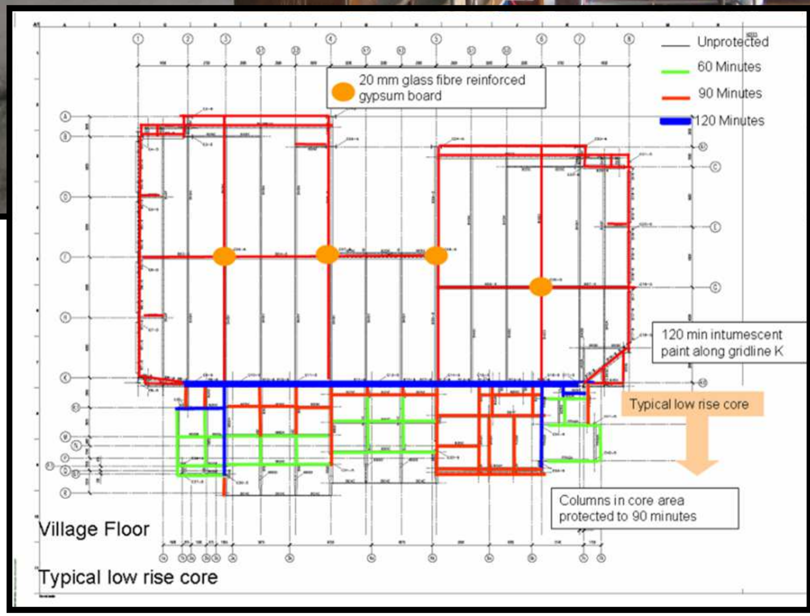
Heron Tower: Findings of Analyses

ARUP

- **Stability and compartmentation** maintained
- **Robust** response
  - Use of solid section members
  - Increased protection to internal columns
  - Additional reinforcement in key areas of the floor slab and enhanced ductility for the beam to column connections
- Similar level of response between Engineered and Code Compliant protection layouts
- Level of **safety demonstrated, *not* assumed**
- Approach was approved by the City of London DS
  - ***First building approved in UK using multi-storey fire***

Heron Tower: Site visit

ARUP



Conclusions: Structural Fire Engineering

– Significant research in this field over the last 10-15 years

– Many **simple methods available** that can be applied to many projects

– **Advanced methods:**
  - **Test the structure**
  - **Allow unprotected secondary steel**
  - **Prescriptive fire resistance ratings are not always conservative**

– Understanding of structural fire response informs **robust design**
  - In innovative design is it reasonable to ignore fire induced forces?

References

1. Buchanan, A. 2001. *Structural Design for Fire Safety*. John Wiley & Sons, 444pp.

2. CEN 2002. BS EN 1991-1-2:2002, *Eurocode 1: Actions on structures — Part 1-2: General actions — Actions on structures exposed to fire*. European Committee for Standardization, 62pp.