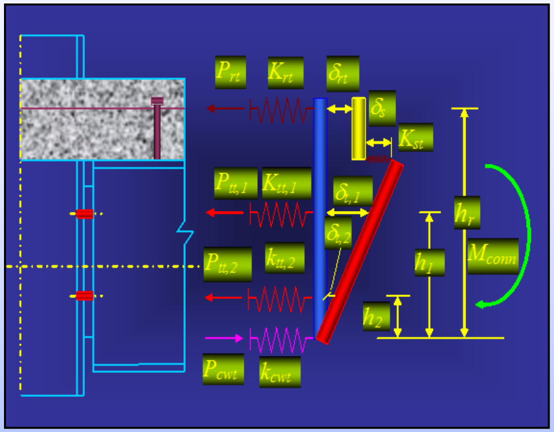
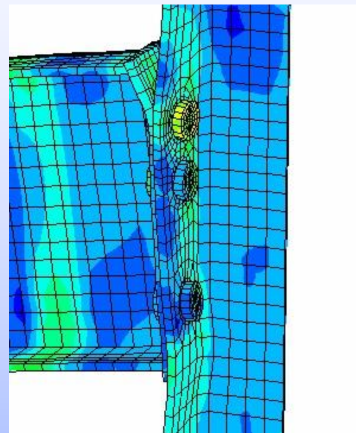
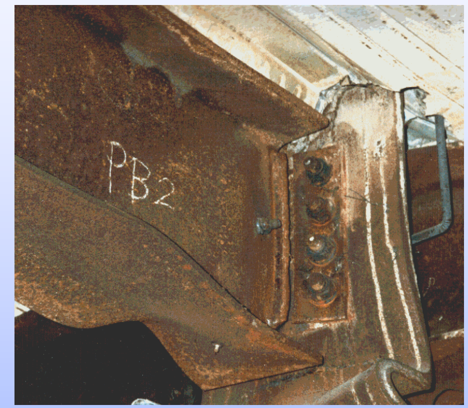
THE ROLE OF COMPOSITE JOINTS ON THE PERFORMANCE OF STEEL-FRAMED BUILDINGS IN FIRE







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Beam-to-Column Joints

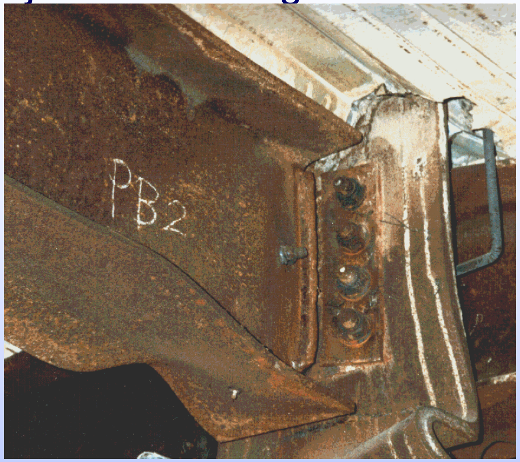
- Represent a complex structural system that connect members together

- Various types of Joint exist

- In the design process an engineer must select how to represent these connections.
- There are multiple ways to represent a connection.
- A pinned connection means that the member (column or beam) is able to rotate around one axis of that joint or connection freely while not sliding in any direction.
- A fixed connection is one that doesn’t allow the member to rotate or slide in any direction.
- Design of joints under normal condition is covered in EC3-1.8 based on the Component-based approach

Why studying the Behavior of Joints is important in the event of a fire?

- Beam-to-column joints are one of the structural elements which were found to be of great significance in enhancing structural behaviour in the event of fire.
- They have the ability to re-distribute forces to the adjacent cool regions.



- They must maintain structural integrity and the load carrying capacity during and after fire (i.e. Keep members in contact together)
- Their behaviour in fire is different from their behaviour at normal condition
- Often difficult to insulate in fire due to their location within structural frame
- Their performance in isolation is completely different from their behaviour when they form part of a structural system due to the structural continuity and restraint to axial thermal expansion provided by the adjacent connected members in fire
- They are a complex structural system

Observations from Real Accidents and from Full Scale Fire Tests

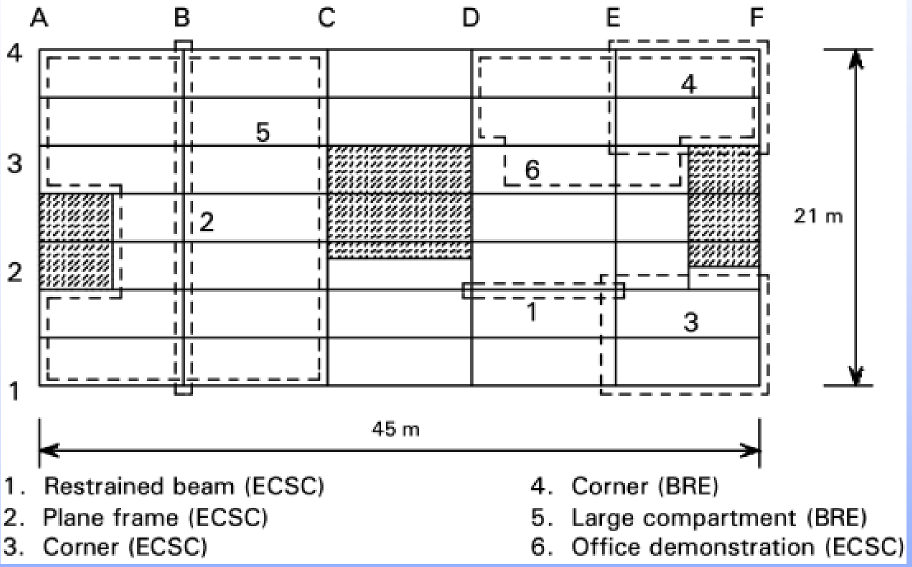
BEAHVIOUR OF FULL-SCALE STEEL-FRAMED BUILDING IN FIRE

The Cardington Full-Scale Frame

- Eight–storey steel framed building
- Constructed by the BRE in 1994-95, Cardington UK
- Designed to represent a typical medium rise commercial building
- Plan dimensions are 45x21m, with area of 945m^2

Cardington Frame Fire Tests

1. A retrained beam test
2. A plane frame test
3. The first corner test
4. The second corner test
5. The large compartment test
6. A demonstration test

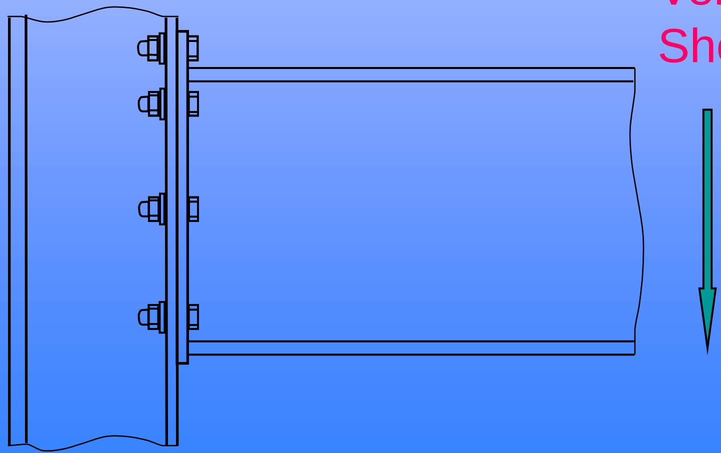


Floor plan of Cardington test frame showing locations of fire tests

Connection behaviour in real buildings in fire

Observations from Cardington and other full-scale tests, and from accidental fires show:

- Buckling of lower flange of connected beam.
- Shear buckling in web of connected beam.
- Large beam deflections (high joint rotations.
- Some bolt fracture.



<u>Ambient temperature:</u>

- Connection subjected mainly to vertical shear.

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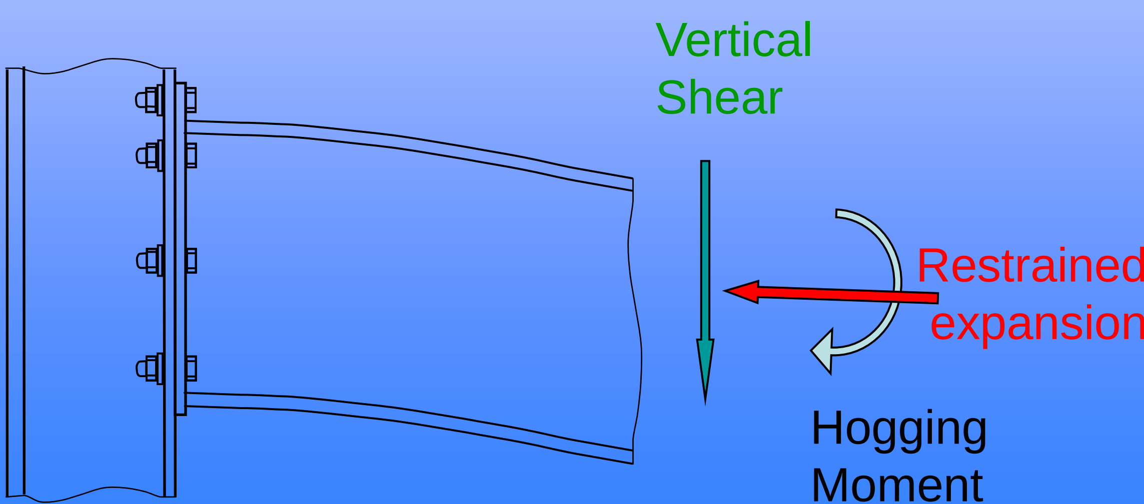

<u>Initial heating stage:</u>

- Beam attempts to expand – columns and adjacent structure resist. Net compression caused.
- Thermal curvature generates rotation and hogging moments.

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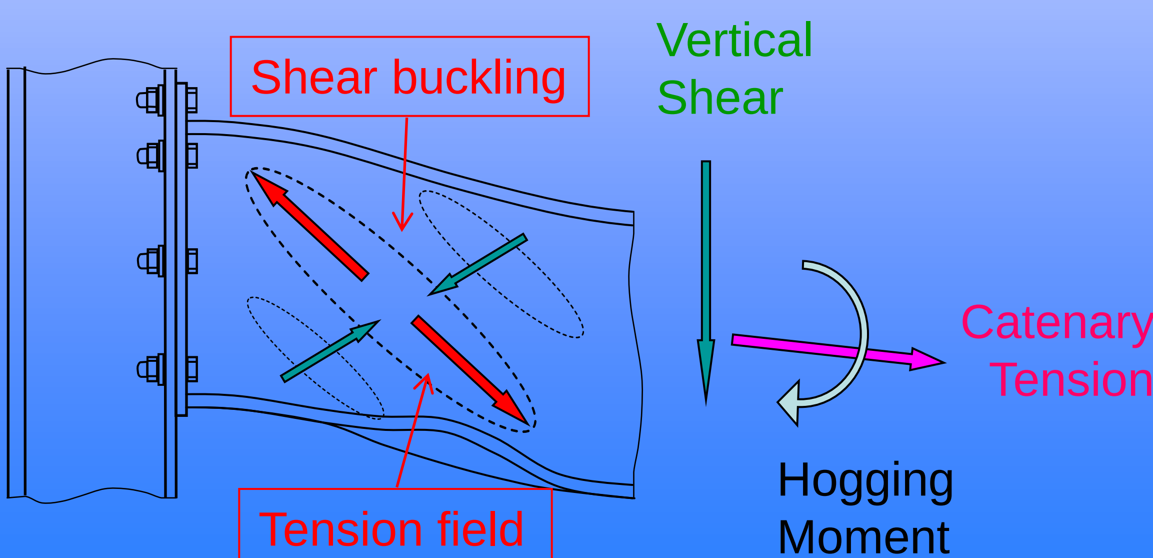
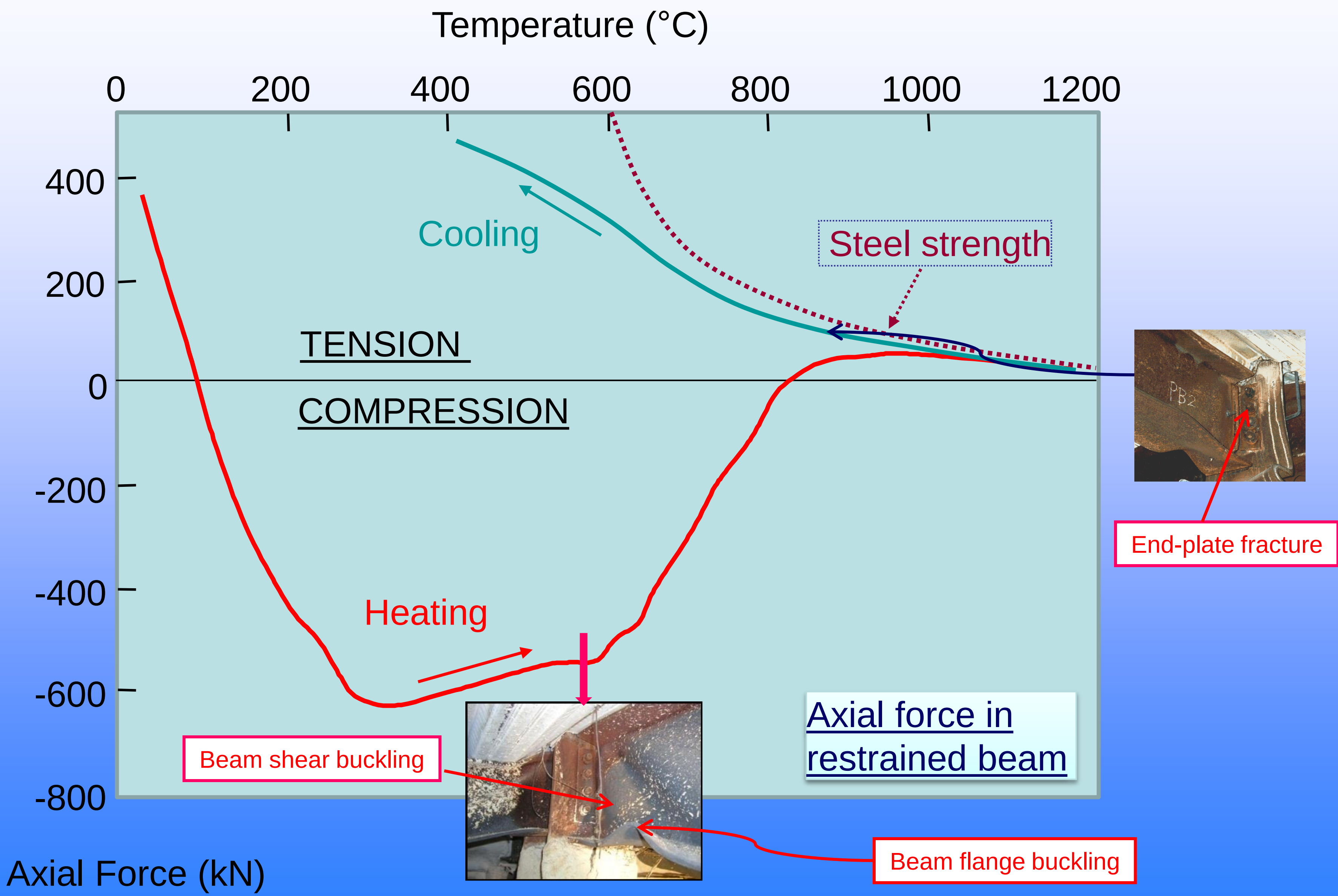


High beam temperature:

- Beam loses strength in bending – hangs in catenary. Joints have to resist catenary tension.
- Large hogging rotation caused locally by catenary action.

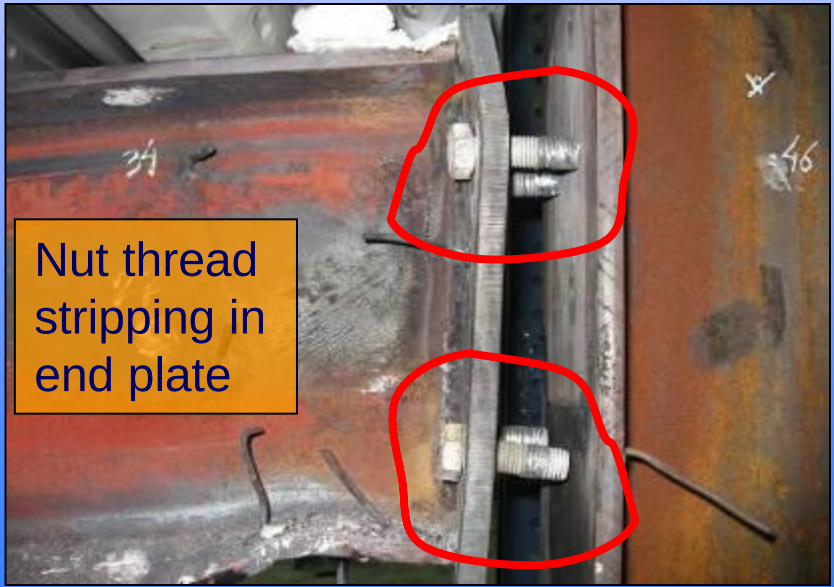
Axial force in steel downstand of composite beam



Joint failures in cooling

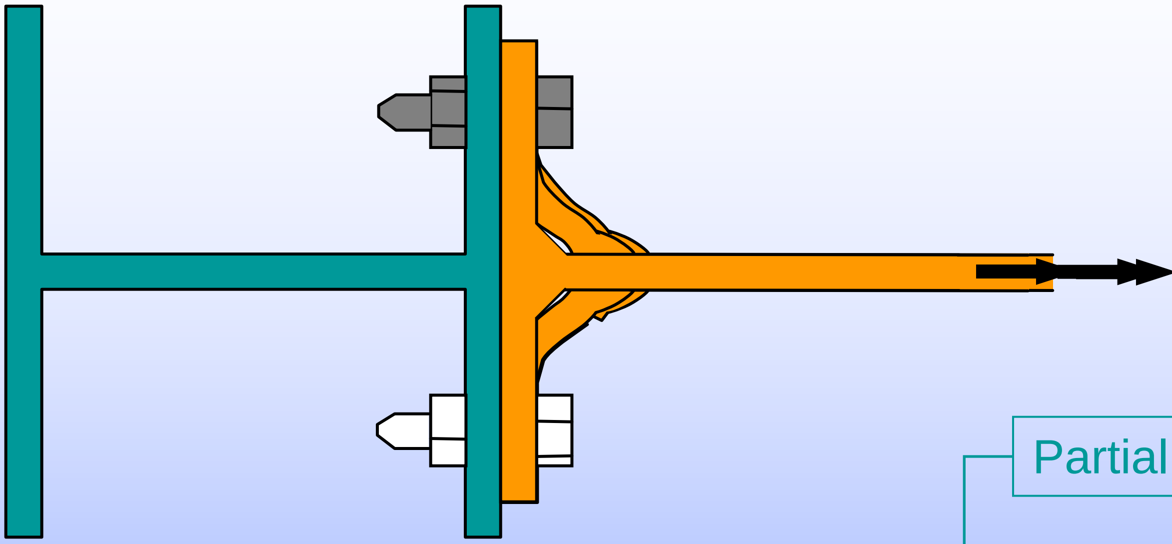
One-sided failures of partial-depth end plates

Bolt shear in fin plate

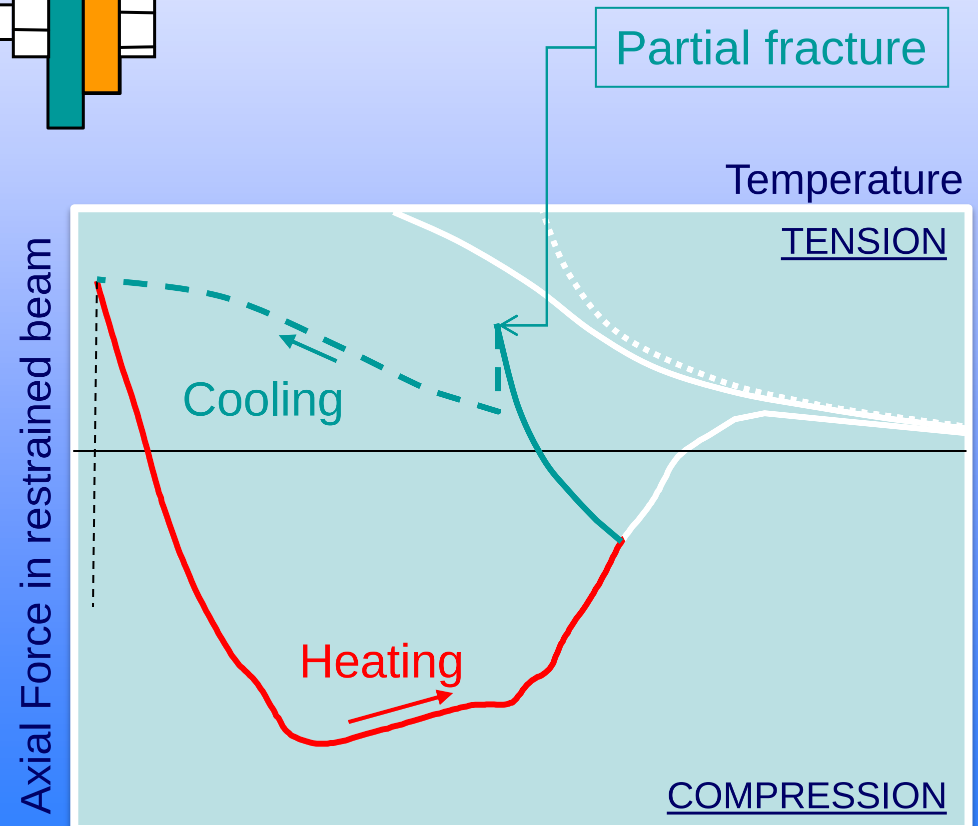


Nut thread stripping in end plate

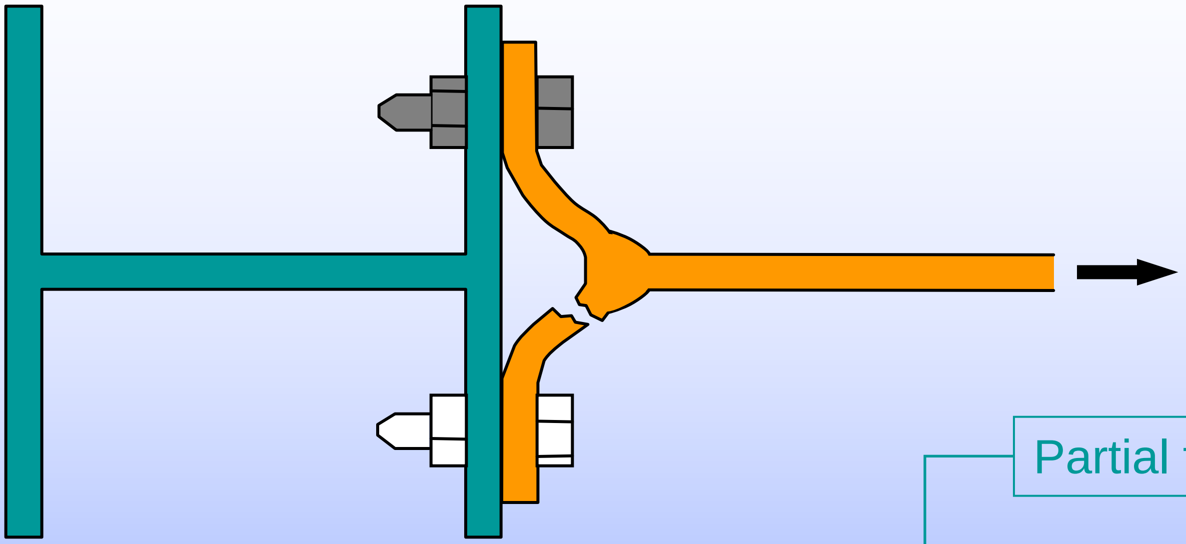
Fracture in cooling at Cardington



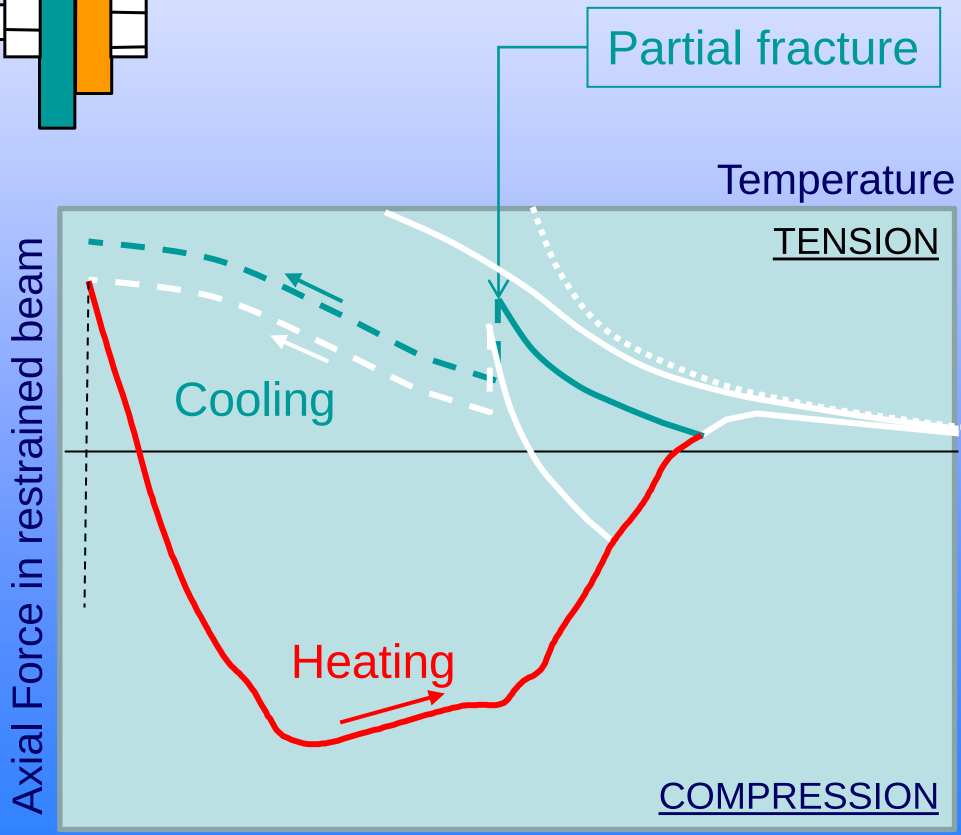
- One-sided failure of partial-depth end plates during cooling phase.
- Reduced stiffness retains joint integrity.
- Partial fracture may happen when cooling from net compression …



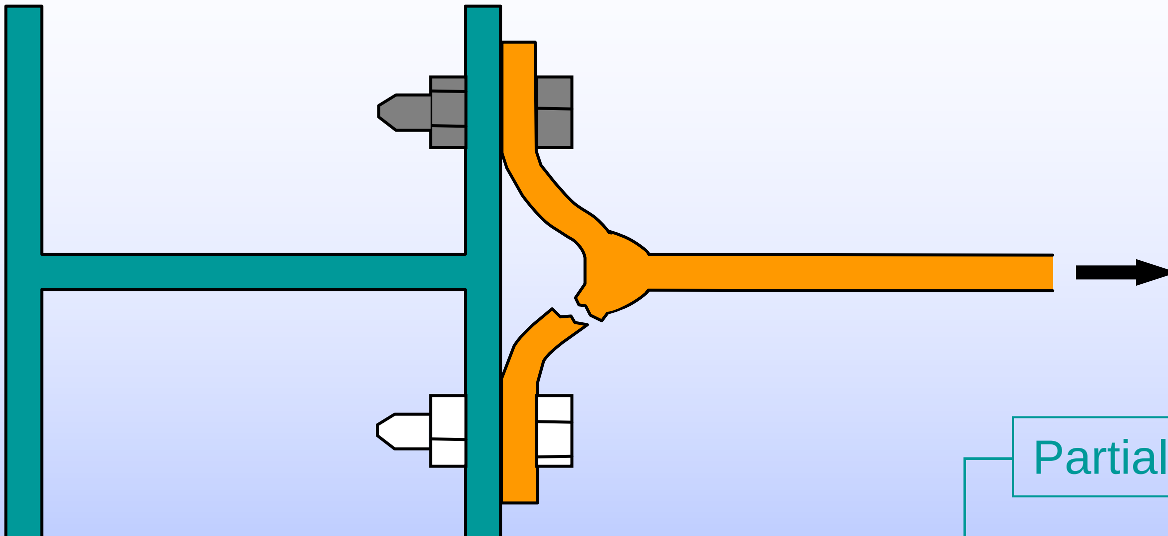
Fracture in cooling at Cardington



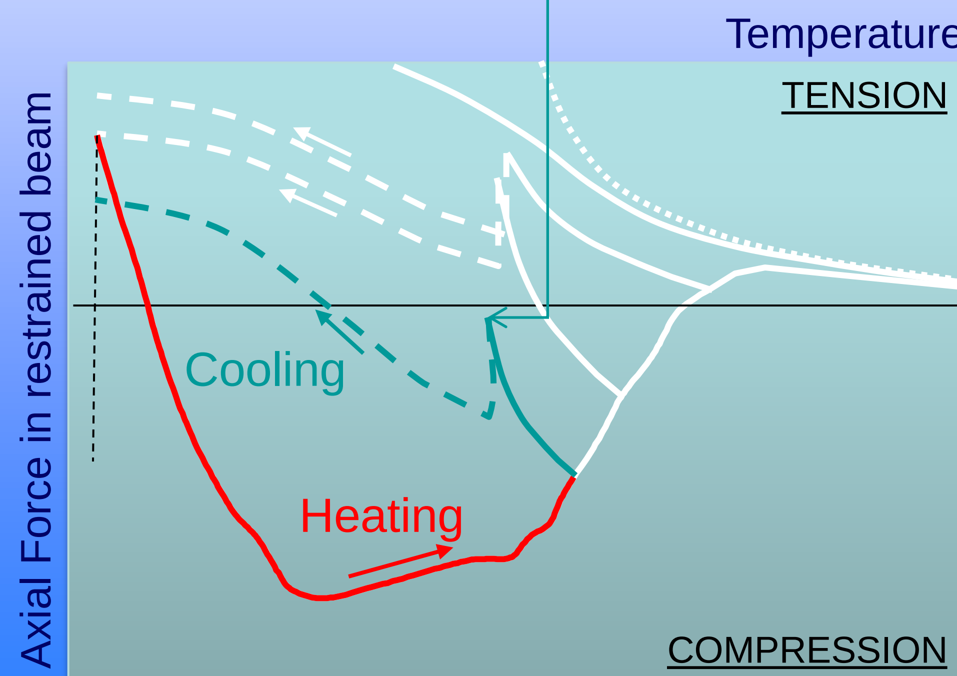
- One-sided failure of partial-depth end plates during cooling phase.
- Reduced stiffness retains joint integrity.
- Partial fracture may happen when cooling from net compression …
- … or tension



Fracture in cooling at Cardington



- One-sided failure of partial-depth end plates during cooling phase.
- Reduced stiffness retains joint integrity.
- Partial fracture may happen when cooling from net compression …
- … or tension
- … or when the net force remains compressive.
- Shear failure of bolts in fin-plates.



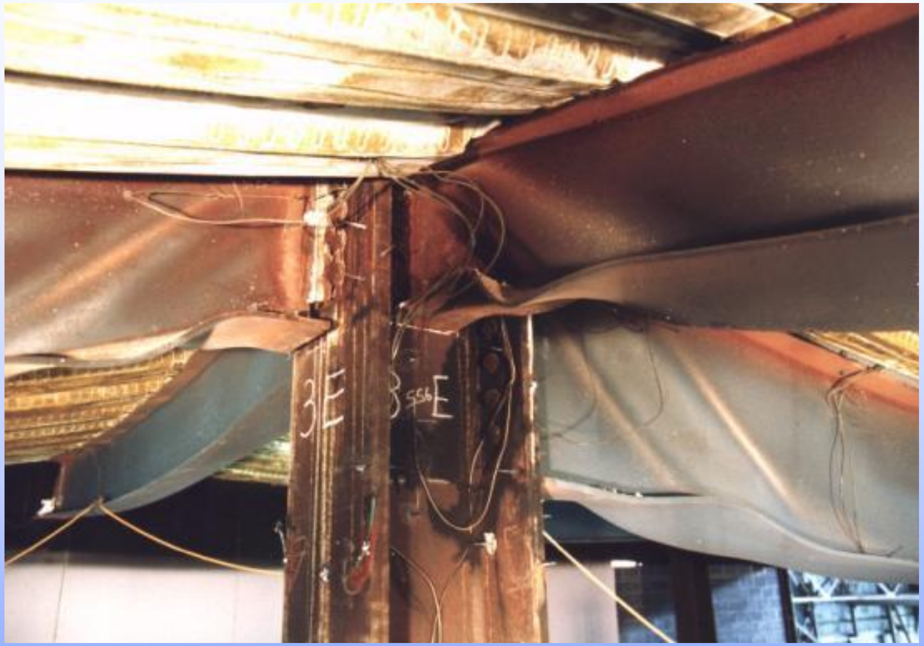
Outcomes: a few anecdotal observations

- Bolts in shear tend to fail by shearing, even at ambient temperature, although normal design attempts to avoid this.
- Bolts in tension: Thread stripping from nuts can be a problem for single nuts. Closer tolerance nuts/bolts may be needed.
- The rotation at a connection may be very significant in initiating failure at the upper connected element.
  - Shear of top bolt in fin plate or web cleat
  - Tensile failure/nut stripping of top bolts in other connections
  - Tearing of top of partial-depth endplate in shear
  - Tearing of top of web cleat in tension
  - Shear of top of flush endplate

  This may happen either in net tension or net compression.
- The ease with which the lower beam flange can contact the column face may have a considerable effect in reducing the rotation capacity of a connection and initiating above failures.
- Web cleat connections tend to have the best tying resistance, because of excellent rotational capacity and high tying ductility.
- Component-based model of connection zone seems robust enough to include in global modelling.

Local Buckling of Beams

- Occurred in most internal beams showed during the heating phase in the lower flange, and part of the web, in the vicinity of the joints.
- Caused by the restraint to thermal expansion and negative moment caused by the rotational restraint from the joint.
- The restraint to thermal expansion was provided by the surrounding cooler structure and the structural continuity of the test frame.
- This has taken place in the beam due to inability of the lower flange of the beam to transfer the high axial forces induced in the beam to the adjacent beams-columns after closure of the gap in the lower part of the joints



- Conservatively, the joints should be assumed as ‘pinned’ and the connected beams as simply supported allowing larger mid-span deflections to develop than when beams are semi-rigidly connected.

Behaviour of Columns

- The internal and external columns were subjected to high moments causing local squashing of columns.
- No collapse occurred because the structure had the ability to carry the column load using alternative load path .
- These moments are caused by expansion of the connecting beams, expansion of the heated floor relative to other floors and induced P-δ effects during a fire.

Behaviour of The Composite Slab

- The composite flooring system used in the Cardington full-scale frame comprised steel downstand beams acting compositely with a floor slab, constructed using a trapezoidal steel deck, lightweight concrete, and an anticrack A142 steel mech. The overall depth of the slab was 130mm thick, with the mesh placed 15mm above the steel deck.
- Results from isolated fire tests conducted on beam-to-column composite joints showed that the composite slab above the joints caused a 20%-30% reduction in the beam top flange temperatures in comparison with the beam bottom flange temperature .
- This is suggesting that the concrete slab is acting as insulation and as a heat sink to the top of the beam, which enhances joint performance at elevated temperature.
- Observations from the Cardington fire tests and other large building fires have shown that the behaviour of the composite floor slab plays crucial role in providing enhanced fire resistance to the structure.
- Also it has been confirmed that the performance of a steel frame, with a composite flooring system, is significantly better than that suggested by the current fire design methods due to the presence of tensile membrane action in the composite slab during the fire at large displacements.

Overall Frame Behaviour

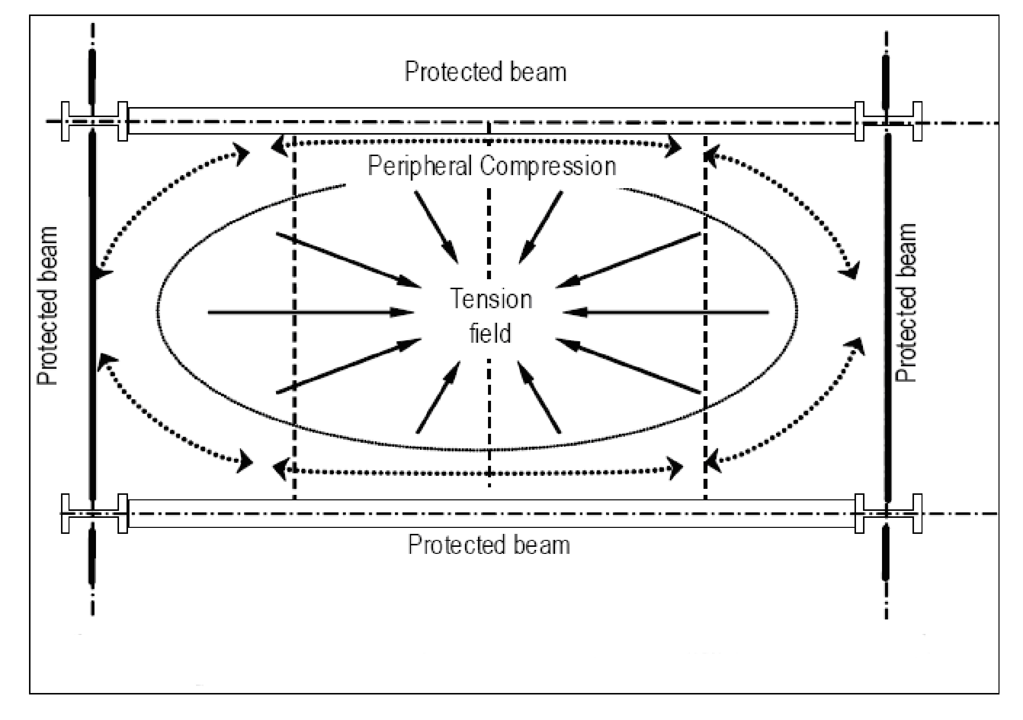
- Very large deflections was observed with no collapse
- Unprotected beams reached temperatures up to 1100° C
- Restraint to thermal expansion provided by cold structure had significant effect on the survival time of the building

Tensile Membrane Action

❖ During fire, when significant numbers of un-protected secondary steel beams damaged, the lightly reinforced composite slab acts as a membrane supported by cold perimeter beams and protected columns.

❖ Due to failure of unprotected steel beams to carry any loading, the composite slab utilises its full bending capacity in spanning between the adjacent cooler members.

❖ With increasing displacement, the composite slab acts as a tensile membrane carrying the loads in the reinforcement.



❖ In the case of simply supported edges, the supports will not anchor these tensile forces and a compressive ring will form around the edge of the slab.

❖ Failure will only occur at large displacements with fracture of the reinforcement.

New Design Method

- The beneficial effect of the tensile membrane action at large displacements that occurred in the composite slab during fire is completely ignored by the current fire engineering design methods.

- In order to take advantage of this behaviour when designing structures in fire, a new design method has been developed for calculating the performance of steel-framed buildings, with composite flooring systems, subject to fire.

- The method is valid for both square and rectangular slabs and conforms to the mode of behaviour observed in the Cardington full-scale fire tests

- This method uses a simple energy approach to calculate the load-carrying capacity of a composite flooring system and beams acting compositely.

- This method is commonly known as the BRE design method which has been developed further by Newman into a series of design tables which allow the designer to leave large numbers of secondary beams unprotected in buildings requiring 30 and 60 minutes fire resistance although some compensation features, such as increased mesh size and density may be required.

From the Cardington frame fire tests, the following observations were drawn

- The fact that the frame survived the severe fire conditions raised a number of fundamental issues whether the current design methods are reflecting the true behaviour of structures in fire or not.

- Unprotected beams in steel deck composite frames can withstand temperatures over 900ºC without any sign of collapse which indicates that the existing fire design codes are too conservative, predicting structural collapse at 680ºC.

- Columns are more critical than beams and will need protection in multi-storey buildings

- The behaviour of the structure was different and better than that shown in standard fire tests. The floor slab makes a major contribution to frame stability and was extremely beneficial to the survival of the frame in fire

- Local buckling typically occurred in the heated steel beams in the proximity of the connections. Therefore, conservatively, the connections should be assumed to be pinned.

- Behaviour of the connections during cooling needs to be addressed.

Major areas for future work

- **Vertical fire spread** makes progressive collapse very much more likely – design to prevent this makes structural fire engineering much easier.

- **Whole frame/subframe numerical modelling** gives much more complete picture of real behaviour than prescriptive or isolated member design. But needs to deal with local failures without treating them as overall failure. Use dynamic analysis.

- **Connection thermo-structural models** needed – especially for ultimate capacity and ductility. Component based models seem most promising.

Thank you …