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PROGRESSIVE COLLAPSE ANALYSIS OF COMPOSITE STEEL FRAMES SUBJECT TO FIRE FOLLOWING EARTHQUAKE

STRUCTURES IN
FIRE FORUM

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Content

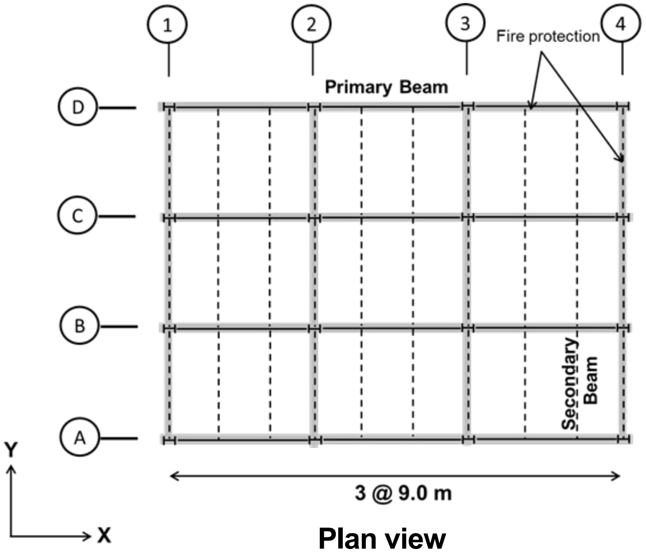
1. Introduction

- Post-earthquake fire is a major threat for buildings in seismic prone areas, e.g. 7000 buildings were destroyed by fire following the 1995 Kobe earthquake.
- Most design approaches do not consider fire following earthquake as a specific loading case.
- Seismic design philosophy allows a degree of damage to structural elements which increases vulnerability in post-earthquake fire.
- It is essential to study the behaviour of buildings under multi-hazard events such as fire following earthquake.

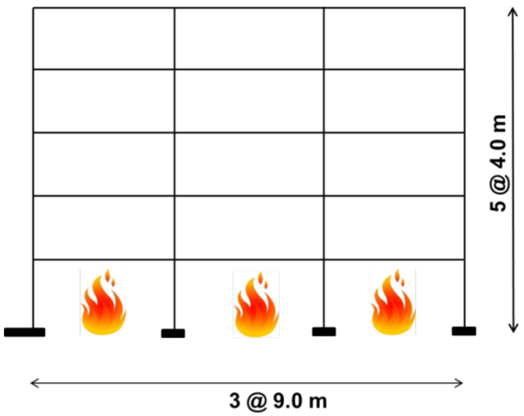
2. Progressive collapse

- In conventional fire safety design, fire resistance of buildings estimated by standard fire tests on isolated individual elements.
- In reality, the building will not perform as isolated small-scale individual elements (e.g. The UK Cardington fire test)
- This shows the importance of studying the complete structure to understand and quantify the actual behaviour of structures in fire.
- This study presents progressive collapse analyses of a 3D composite building subjected to local fire following earthquake.
- The objective of the study is to identify global behaviour of building subject to local fire after earthquake damage.

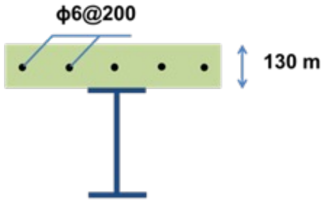
3. Generic bulding



Plan view

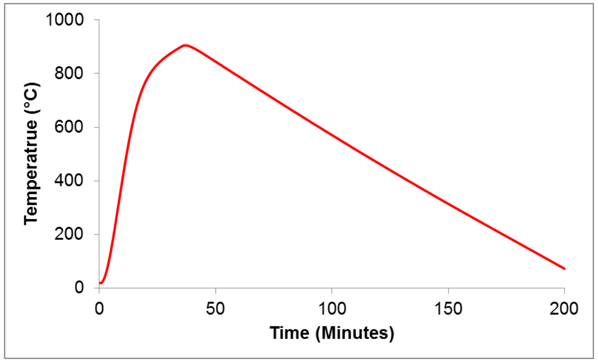


Elevation view



Composite floor slabs

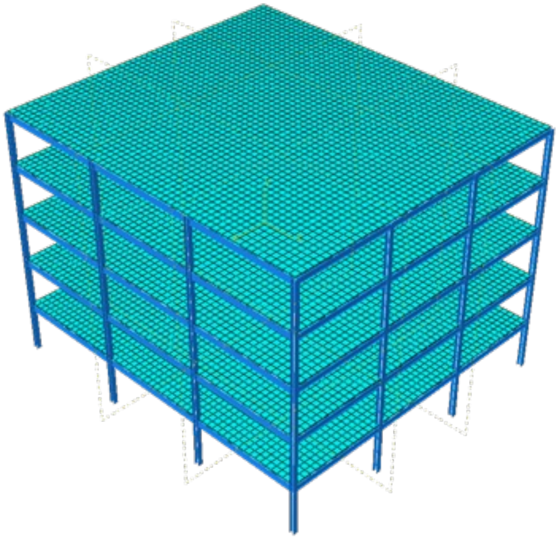
Column
UKC356x368x153
Primary Beam
UKB457x191x74
Secondary Beam
UKB356x127x39



Parametric fire

4. Numerical model

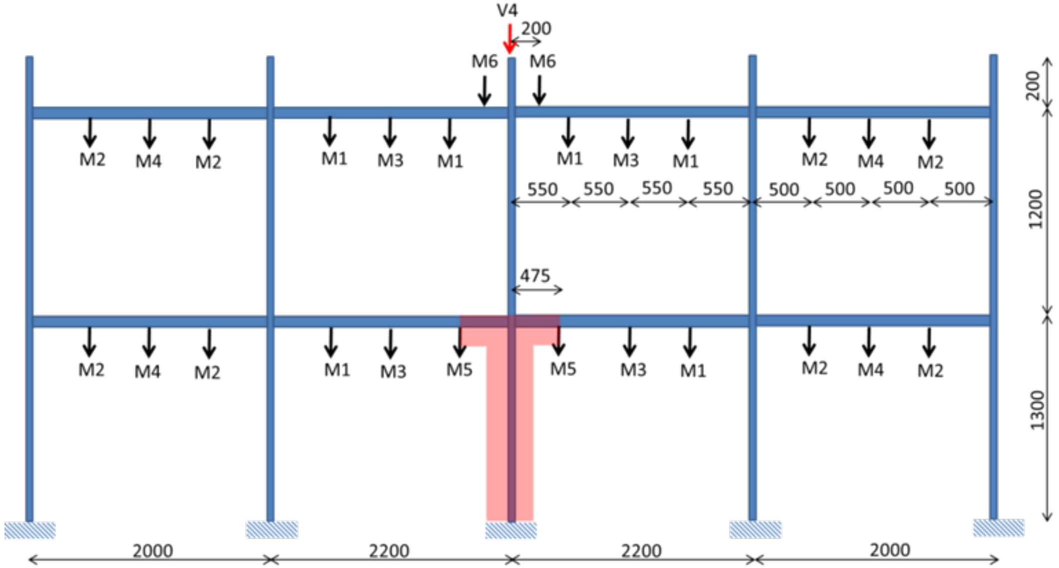
- The finite element software ABAQUS is used to model and analyse the structure
- Steel columns and beams are discretised using 1-D line elements and concrete slabs are modelled using shell elements.
- A tie constraint is use to simulate composite action between the steel beam and the concrete slab.
- Assumptions: beam-to-column and secondary beam-to-primary beam connections behave as rigid and pinned, respectively.



3D model (ABAQUS)

4. Numerical model (validation)

- Progressive collapse analysis of steel moment frame in fire (Jiang et al. 2018)



M1 (N)	M2 (N)	M3 (N)	M4 (N)	M5 (N)	M6 (N)
4667.3	2312.4	751.1	766.0	69.7	81.7

The test frame

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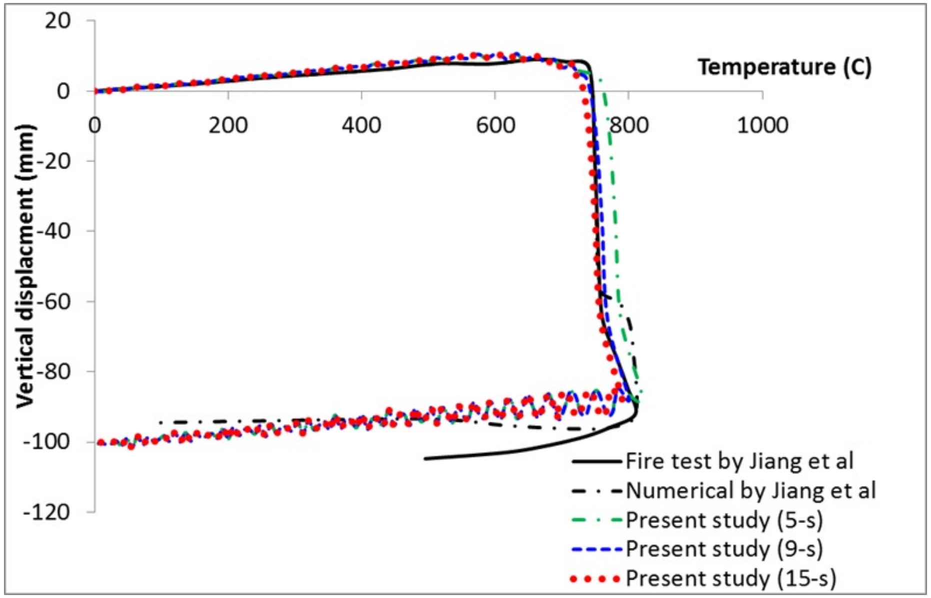
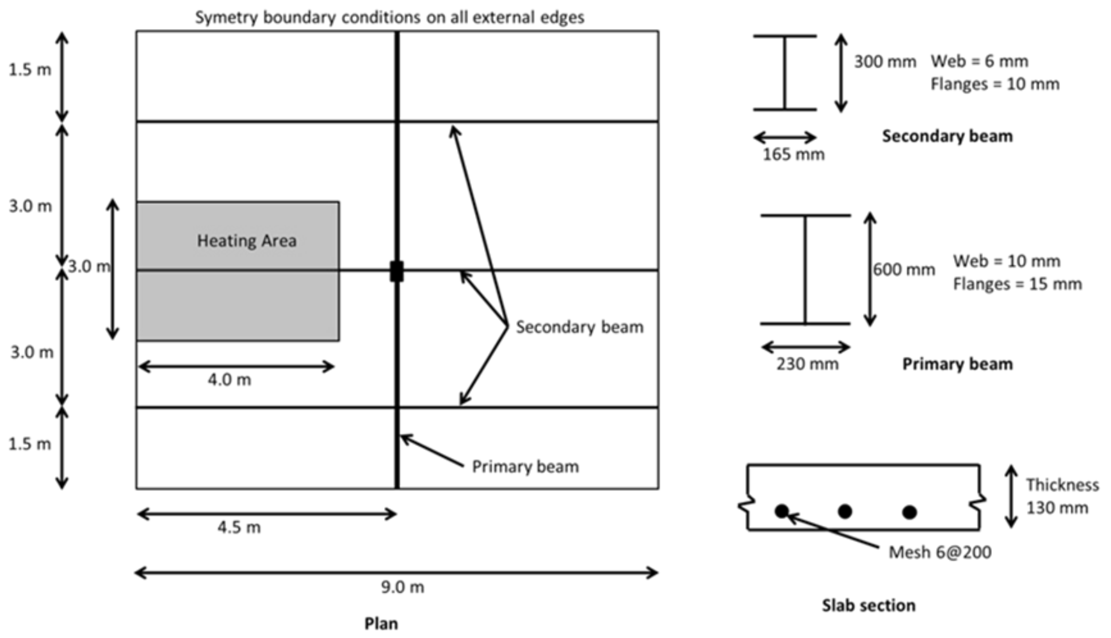
4. Numerical model (validation)

- Progressive collapse analysis of steel moment frame in fire (Jiang et al. 2018)



4. Numerical model (validation)

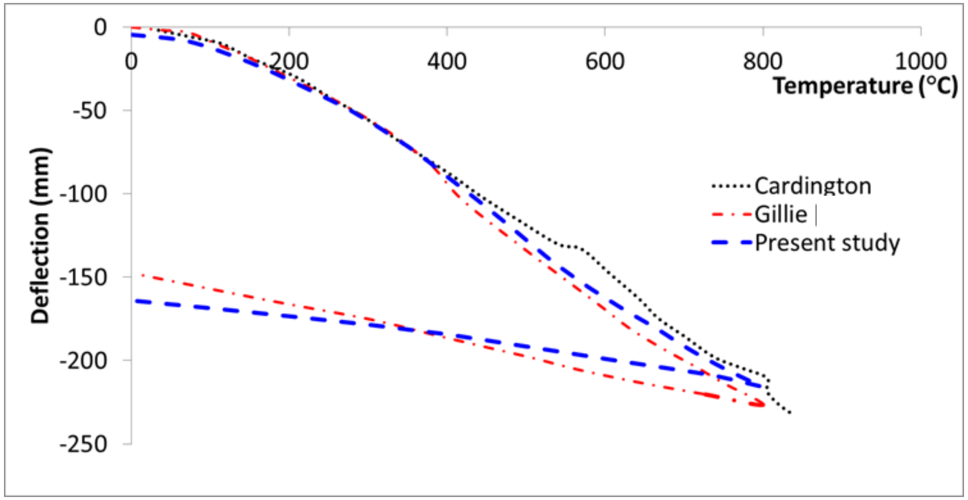
- Fire analysis of a composite steel frame building (Gillie, 2009)



Simplified version of the UK Cardington Test

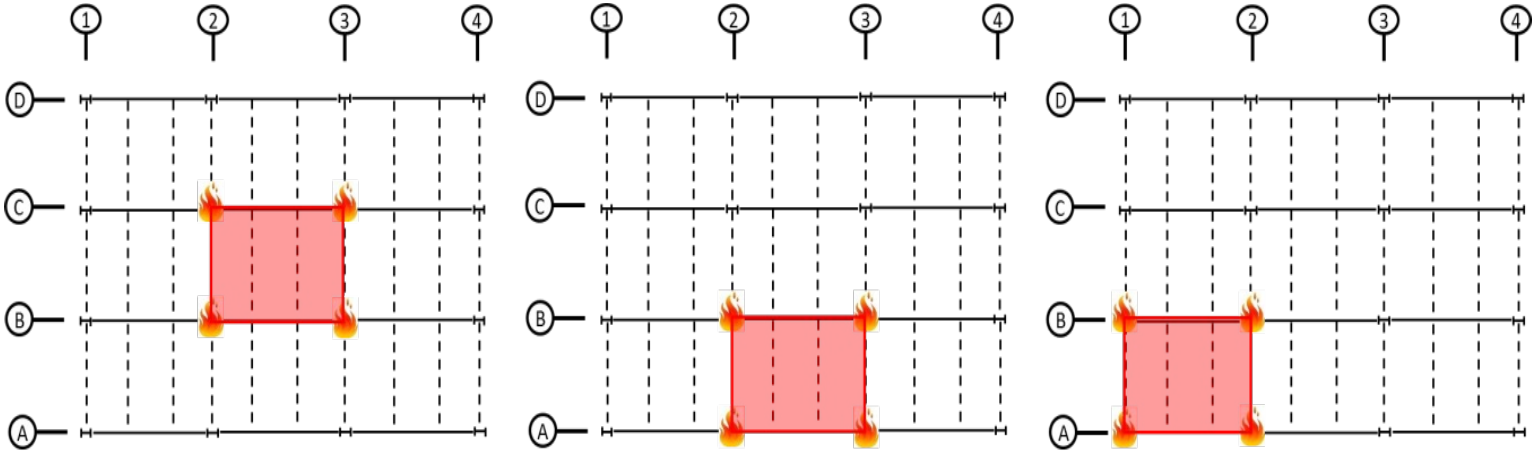
4. Numerical model (validation)

- Fire analysis of a composite steel frame building (Gillie, 2009)



5. Progressive collapse analyses of undamaged structures

- Influence of fire compartment location



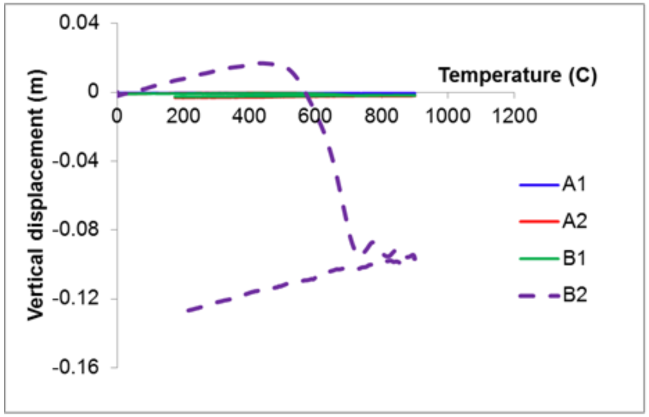
a. Internal bay

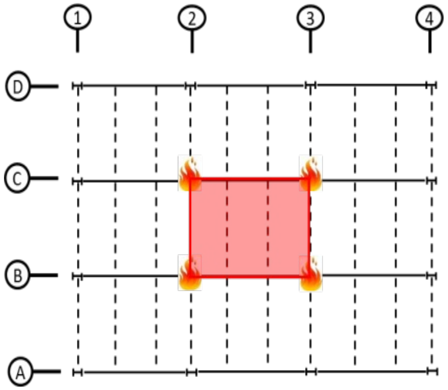
b. Edge bay

c. Corner bay

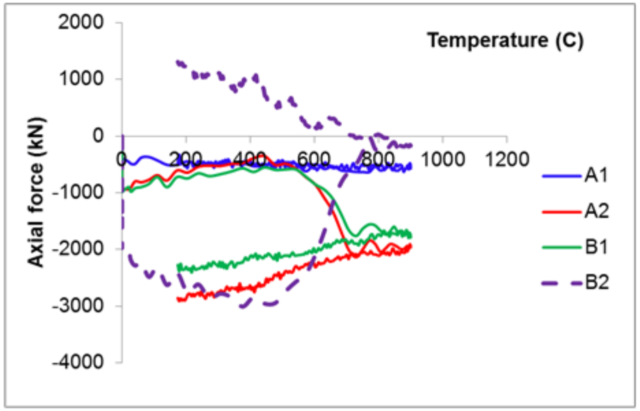
5. Progressive collapse analyses of undamaged structures

- *Internal bay compartment*
  - *the axial force of heated column B2 increases due to thermal expansion and the restraint provided by the surrounding structure*
  - *Once the temperature reaches 520°C, the heated column B2 buckles and suddenly loses load bearing capacity. Then, the loads are transferred to the adjacent columns (A2 and B1)*



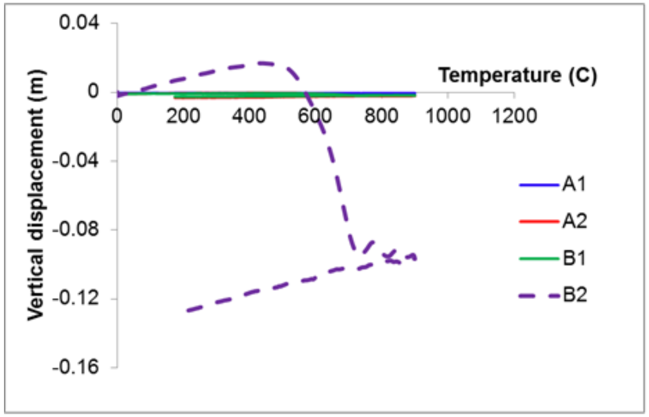


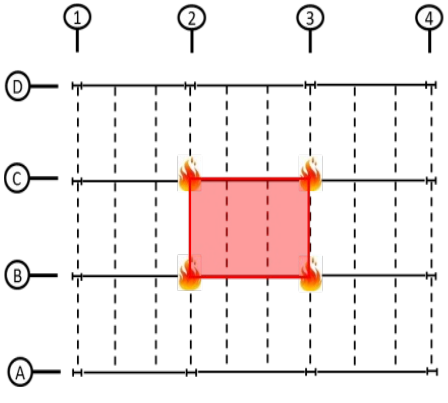
a. Internal bay



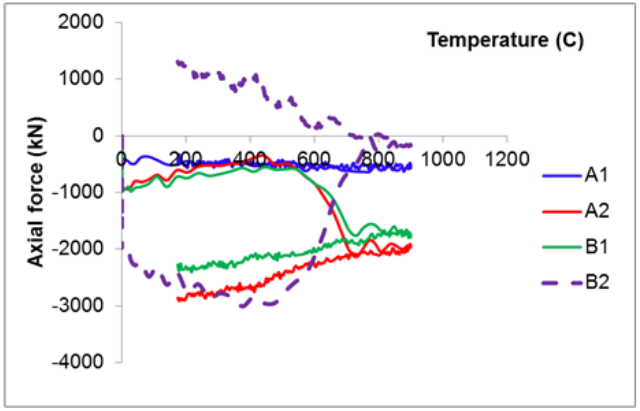
5. Progressive collapse analyses of undamaged structures

- *Internal bay compartment*
  - *The heated columns expand downward during the cooling phase, rather than revert to the initial position.*



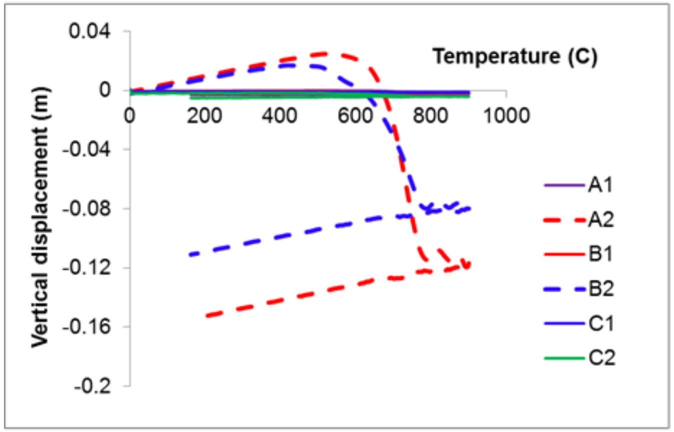


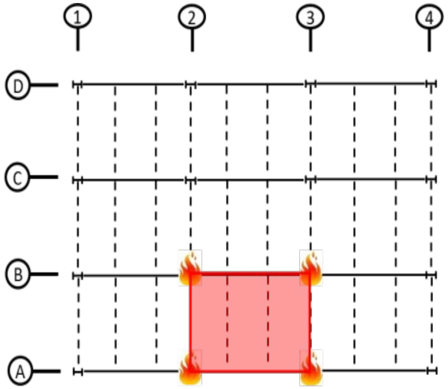
a. Internal bay



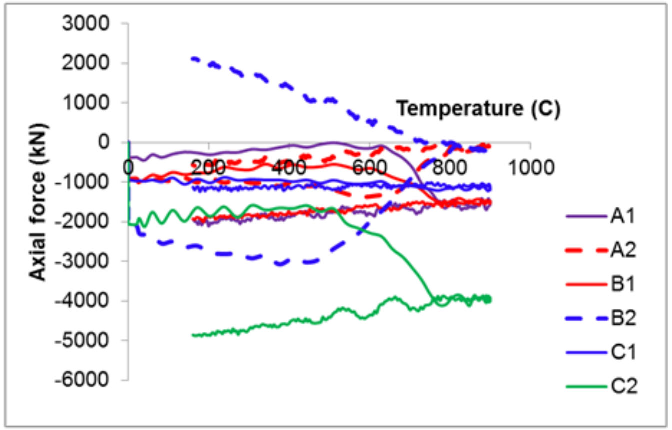
5. Progressive collapse analyses of undamaged structures

- *Edge bay compartment*
  - Similarly, the loads previously sustained by the heated columns are transferred to the surrounding column when buckling at the heated columns occurs.



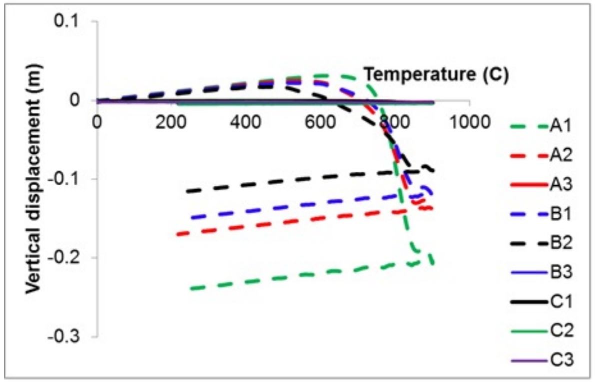


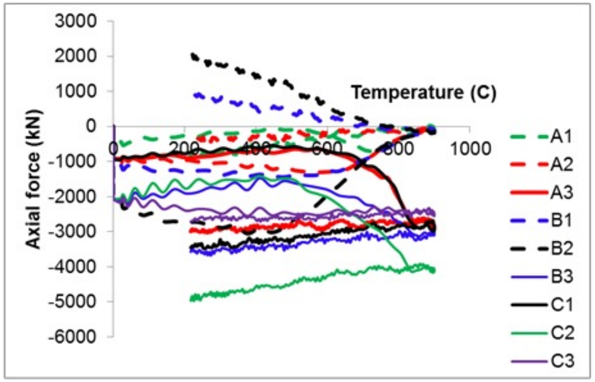
b. Edge bay

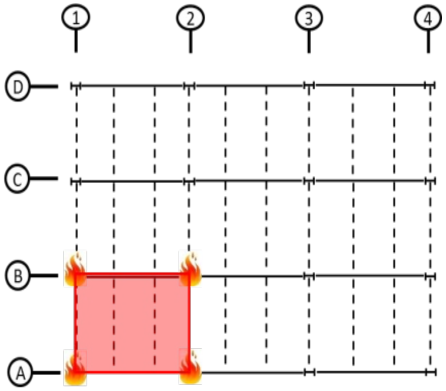


5. Progressive collapse analyses of undamaged structures

- *Corner bay compartment*
  - Runaway failure (rapid increase in the rate of displacement) occurs when the temperature reaches 760°C
  - The frame can be re-stabilised eventually after the column failure so the runaway failure disappears with increasing temperature







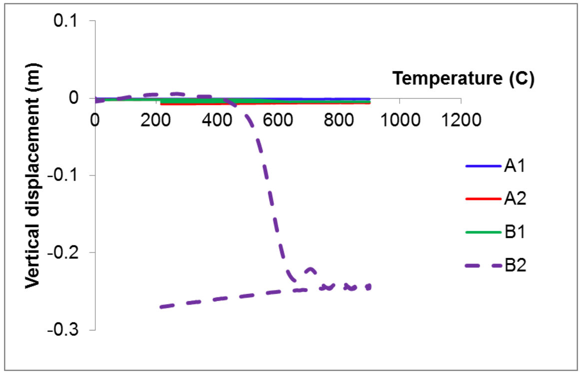
c. Corner bay

5. Progressive collapse analyses of undamaged structures

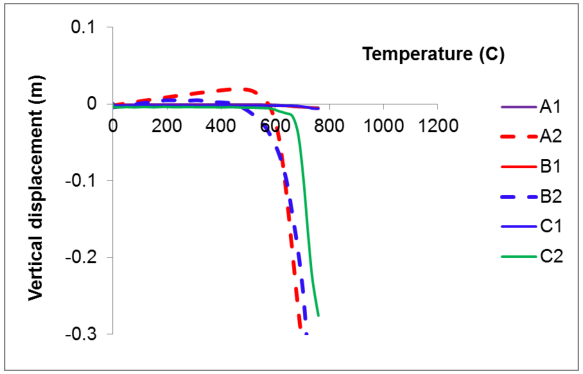
- Influence of load ratio
  - The applied floor load 5.5 kN/m^2 (1 x dead x 0.5 live) taken for fire limit state design seems too low to cause collapse of the whole building.
  - The load was increased to 11 kN/m^2 (1.35 x dead + 1.5 x live) based on the Eurocode ultimate limit state for normal conditions. This led to a load ratio of 0.6 for the internal column

5. Progressive collapse analyses of undamaged structures

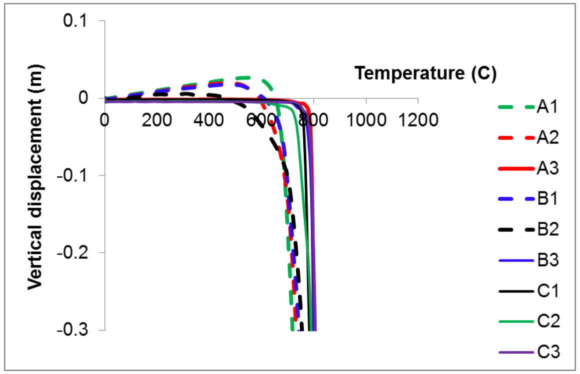
- Influence of load ratio
  - For the internal bay scenario, all heated columns buckle at 500°C, this is earlier in temperature terms compared to the edge bay and corner bay fire scenario.
  - However, there is no collapse of the building subject to the internal bay compartment fire.
  - The adjacent columns still have enough capacity to accommodate the additional load previously sustained by the heated column



Internal



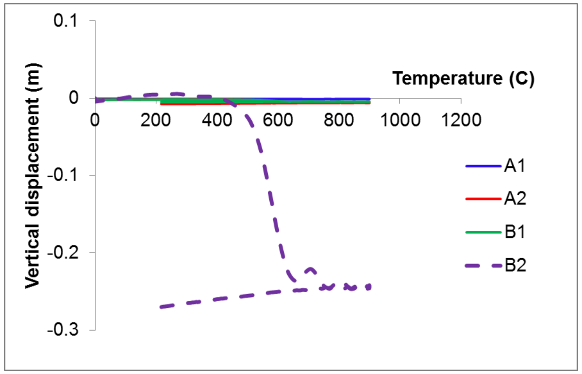
Edge



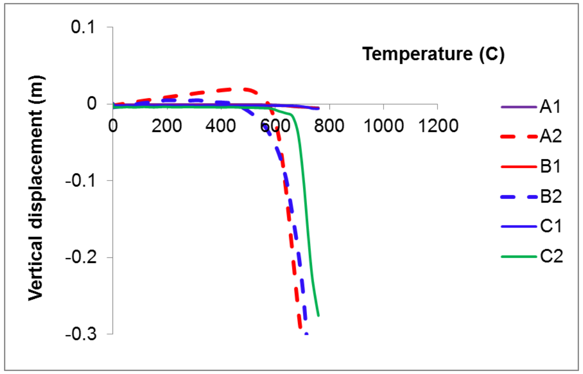
Corner

5. Progressive collapse analyses of undamaged structures

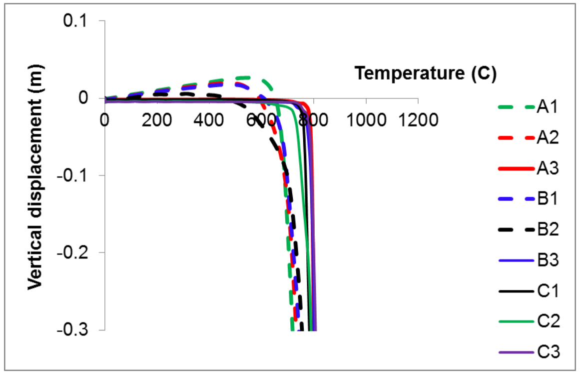
- Influence of load ratio
  - On the other hand, the fire scenarios at the edge bay and corner bay cause collapse of the building.
  - The collapse can be identified when vertical displacement of the top columns continues with no re-stabilisation point



Internal



Edge



Corner

6. Progressive collapse analyses of earthquake damaged structures

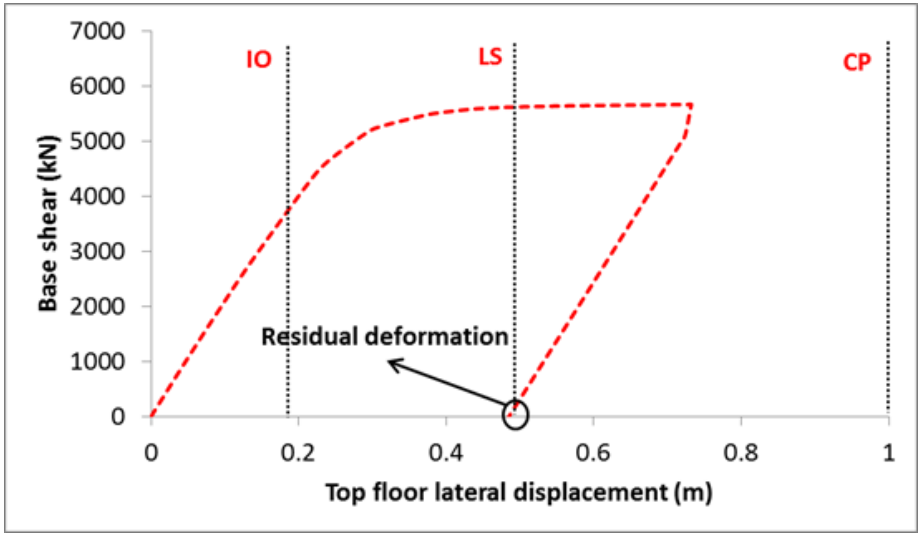
- Two earthquake damage scenarios on the composite building are studied.
  1. Lateral deformation that remains after the earthquake.
  2. Fire compartment damage that can lead to the fire travelling across the floor.

6. Progressive collapse analyses of earthquake damaged structures

- Influence of residual deformation
  - Three step procedure
    - The building is subjected to gravity load
    - Pushover analysis is performed. The building is pushed incrementally using a specific lateral load to arrive at a target displacement. The load is then reduced to zero again
    - Fire analysis of the frame with residual deformation is performed

6. Progressive collapse analyses of earthquake damaged structures

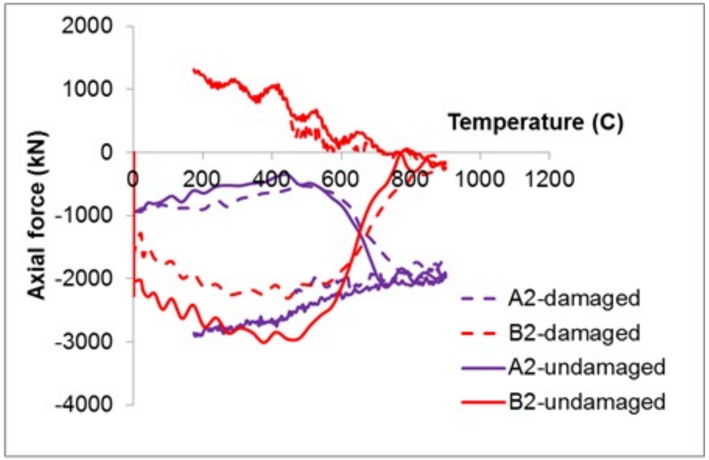
- Influence of residual deformation



Pushover curve

6. Progressive collapse analyses of earthquake damaged structures

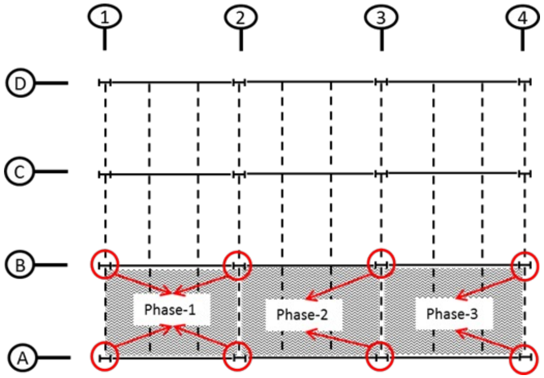
- Influence of residual deformation
  - The load redistribution path in the damaged building is almost identical to that obtained from the undamaged building.
  - This is due to the fact that the building satisfied the earthquake damage limitation and thus has relatively small permanent deformation.
  - Neither the load redistribution path nor the fire resistance of the building are considerably affected by the earthquake damage in this particular case

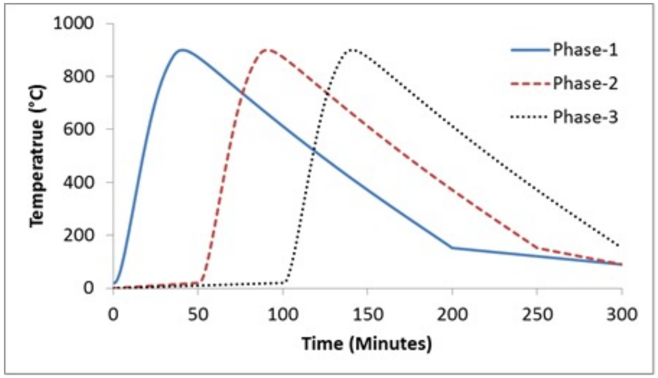


6. Progressive collapse analyses of earthquake damaged structures

- Influence of travelling fire

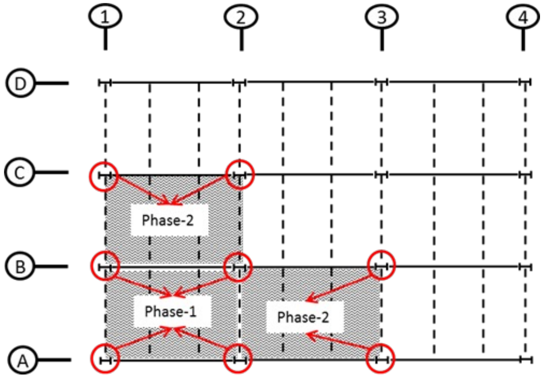
Scenario 1

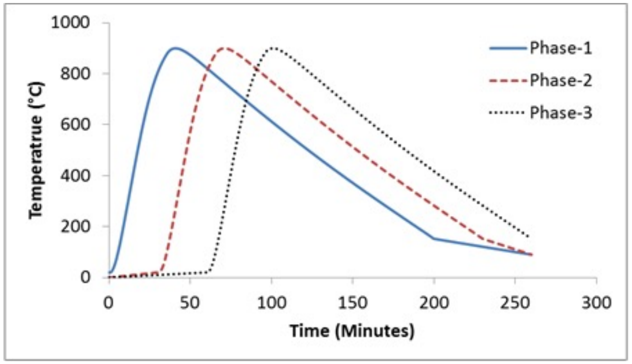




50 minutes inter-zone time delay

Scenario 2

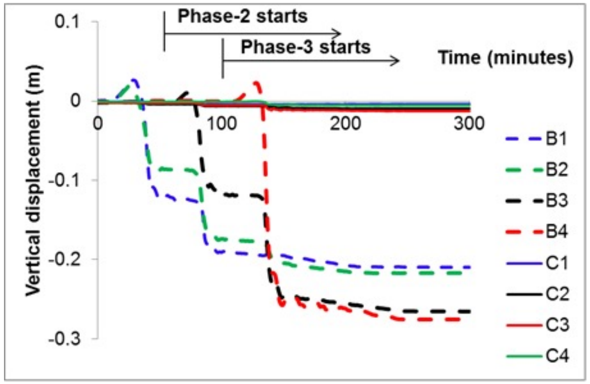




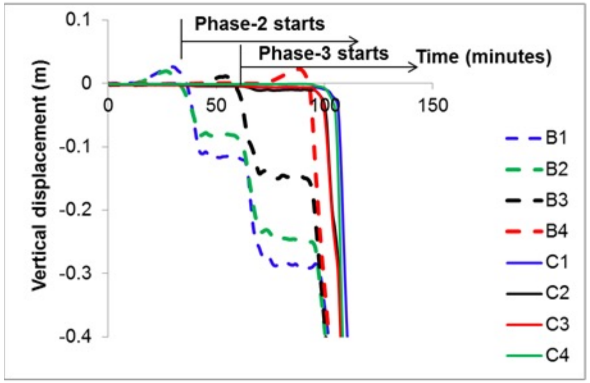
30 minutes inter-zone time delay

6. Progressive collapse analyses of earthquake damaged structures

- Scenario 1
  - For the case with inter-zone time delay of 50 minutes, it can be seen that there is transient instability due to buckling of some columns.
  - However, the frame can resist the travelling fire because of its capacity to distribute loads carried by the failed columns to the neighbouring columns.
  - In contrast, total collapse occurs when the inter-zone time delay escalates to 30 minutes



50 minutes inter-zone time delay



30 minutes inter-zone time delay

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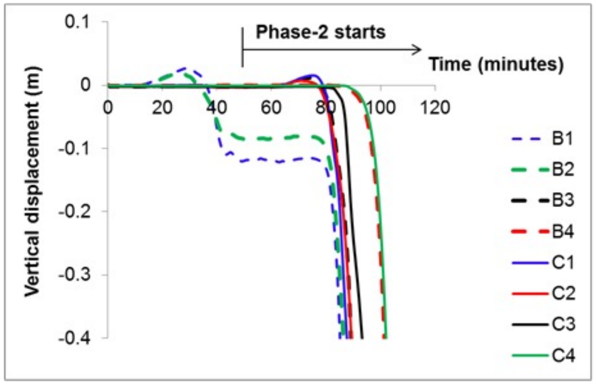
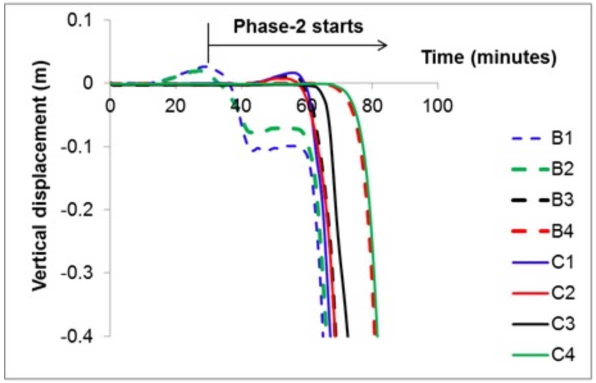
6. Progressive collapse analyses of earthquake damaged structures

- Scenario 2
  - The similar behaviour is noticed for both scenarios of 50 minutes and 30 minutes of inter-zone time delay
  - For 30 minutes inter-zone time delay, the collapse occurs earlier (52 minutes) and more columns failed in the same time compared to that of the scenario with 50 minutes inter-zone time delay
  - The study above showed that travelling fire and inter-zone time delay greatly affect the collapse resistance of the building. This demonstrates the importance of fire containment particularly during an extreme event such as an earthquake.



50 minutes inter-zone time delay



30 minutes inter-zone time delay

7. Conclusions

- The 3D models are required simulate load redistribution between columns as a result of heating. The loads supported by the heated columns are redistributed to the adjacent columns along two horizontal directions which cannot be captured in 2D models.
- There is a possibility that collapse may occur during the cooling phase as extra loads are transferred to adjacent columns. Hence, the cooling phase should be considered in the robustness analysis of the building (and also during fire-fighting or search operations).
- The travelling fire scenario and inter-zone time delay significantly affect the collapse resistance of the building. This shows the importance of fire containment to prevent building collapse in a multi-hazard event such as fire following an earthquake.

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