PROGRESSIVE COLLAPSE ANALYSIS OF STEEL FRAMES IN FIRE

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Background

- **Member-based structural fire engineering** simply does not work for large, complex buildings (see the NIST report on WTC7).
- **Performance-based SFE design** inevitably has to depend on non-linear numerical modelling of large subframes of the structure.
- If the building is to avoid the possibility of **disproportionate collapse** in fire, this numerical modelling must be capable of predicting real structural collapse, rather than the first loss of stability.

Threads for the Research

- Development of global SFE modelling *(Vulcan).*

Static/dynamic formulation .

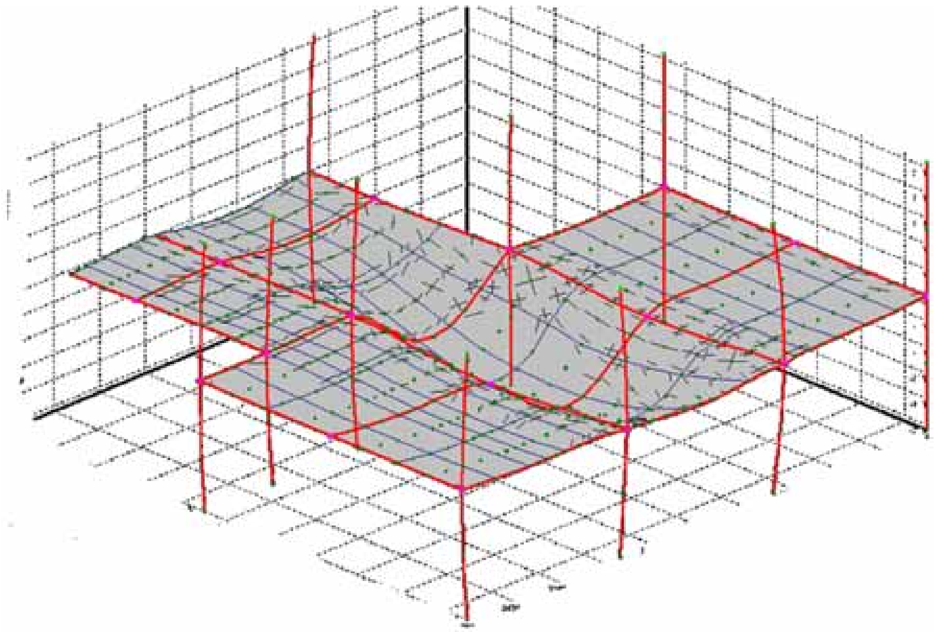
- Interest in scenario-based robustness analysis in fire.
- Different forms of global/severe local failures.

- Development of high-temperature component-based connection element for global analysis

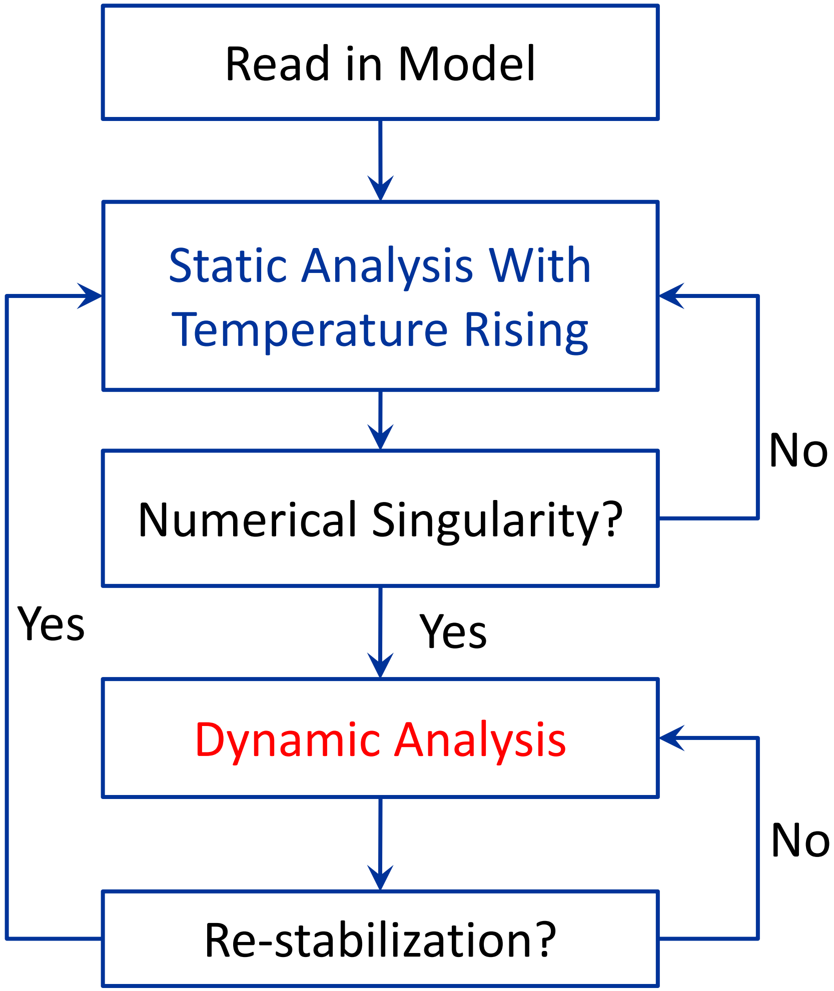
Practical SFE global analysis including collapse

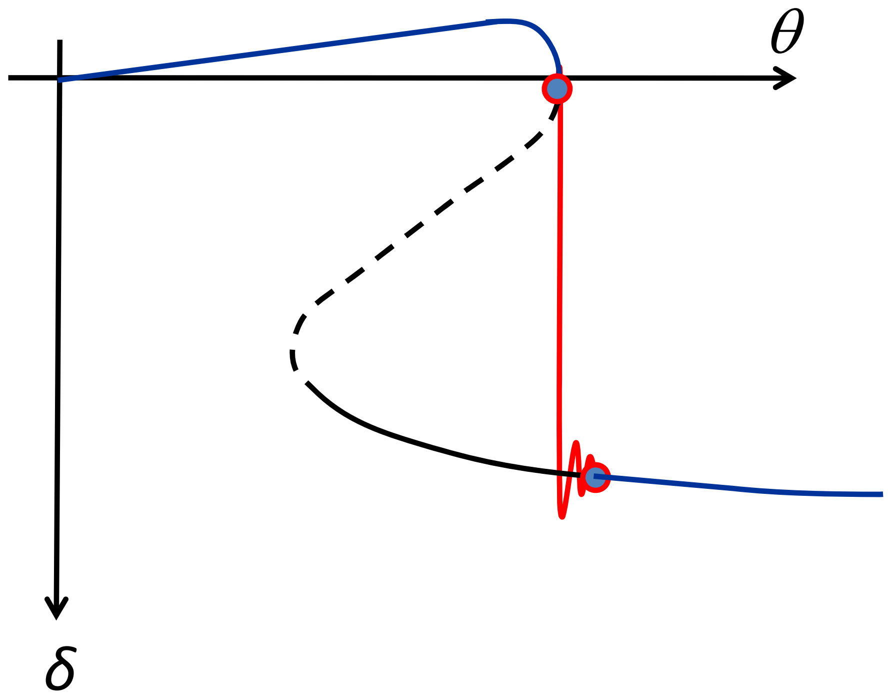
Introduction of *VULCAN*

- Finite element software specialized in Structural Fire Engineering;
- Developed for over ten years;
- The steel-framed composite buildings are modelled as assemblies of finite beam–column, connection and layered floor slab elements;



Static-Dynamic Procedure





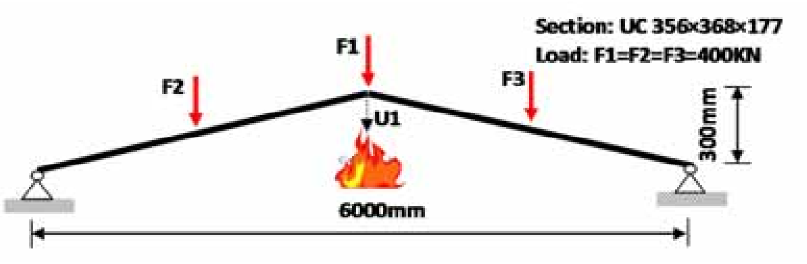
Explicit Dynamic Code

Explicit time integration method is adopted for dynamic analysis. The kinetic conditions, including displacement , velocity and acceleration, is determined by that of the previous step.

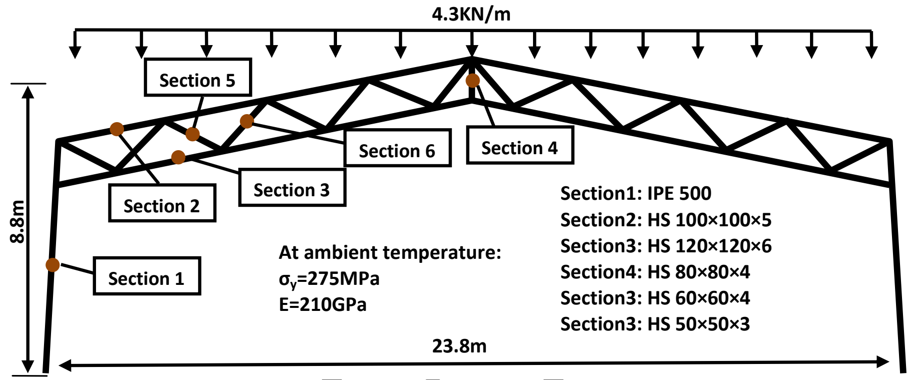
Small time step is required.

1. Initial conditions and initialization:
   Set initial value of material state variables and u_0^n, $\dot{u}_0^n$, compute mass matrix M and initially estimate the time step.
2. Initialise the nodal internal force.
3. Compute the accelerations $\ddot{u}_i^n = (M^n)^{-1}(Q_i^n - F_i^n - D_i^n)$
4. Time update: $t_{i+1} = t_i + \Delta t_i$; $\Delta t_{i+1/2} = (\Delta t_i + \Delta t_{i+1})/2$
5. First partial update nodal velocities: $\dot{u}_{i+1/2}^n = \dot{u}_{i-1/2}^n + \Delta t_i \ddot{u}_i^n$
6. Enforce boundary conditions.
7. Update the nodal displacements: $u_{i+1}^n = u_i^n + \Delta t_{i+1/2} \dot{u}_{i+1/2}^n$
8. Calculate the nodal internal forces.
9. Compute $\ddot{u}_i^n$
10. Second partial update nodal velocities: $\dot{u}_i^n = \dot{u}_{i+1/2}^n + (t_{i+1} - \Delta t_{i+1/2})\ddot{u}_{i+1}^n$
11. Check energy balance at time step $i+1$
12. Adaptive check for variable time step.
13. Update counter: $i=i+1$
14. Output; if simulation not complete, go to 4.

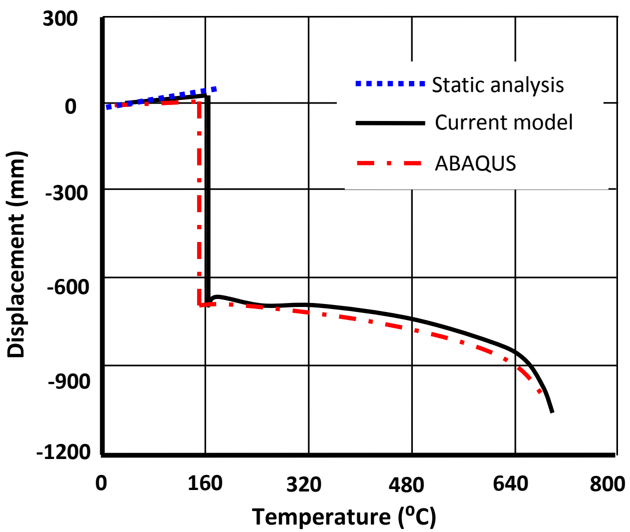
Validation

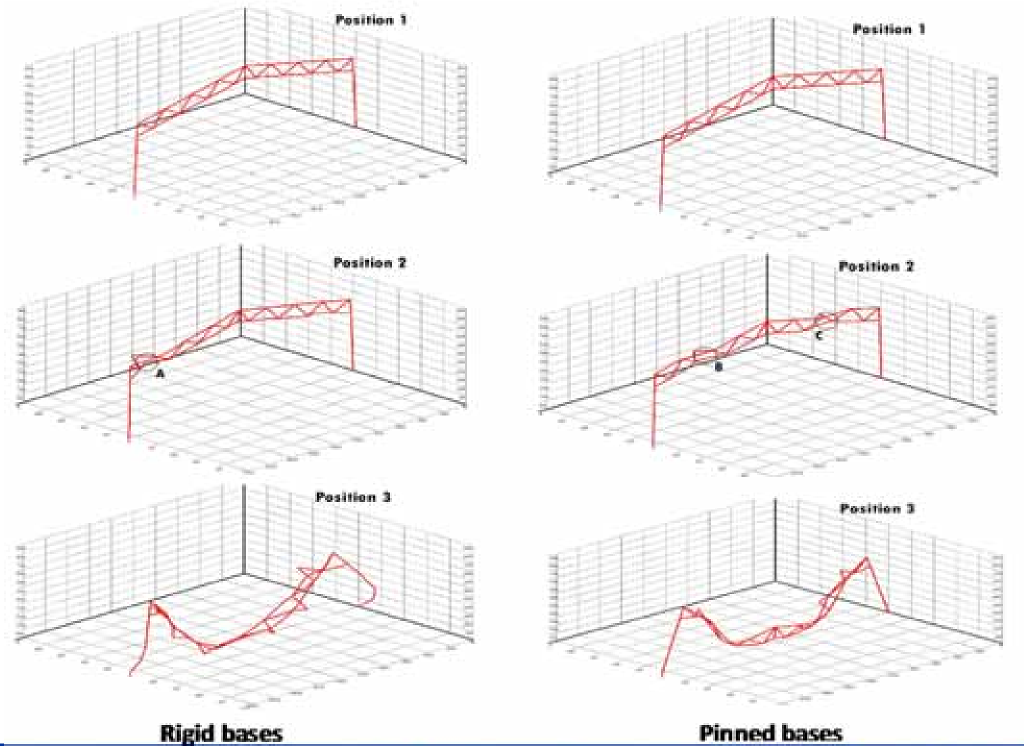


Snap-through Test



Truss Frame Test





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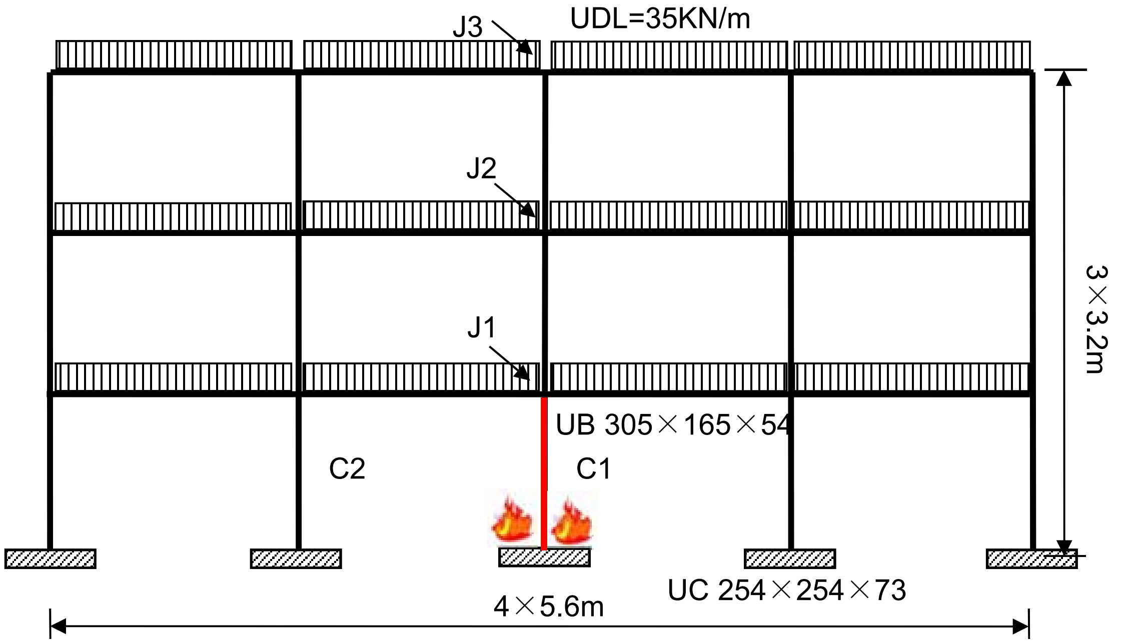
Collapse Mechanism of Frames in Fire



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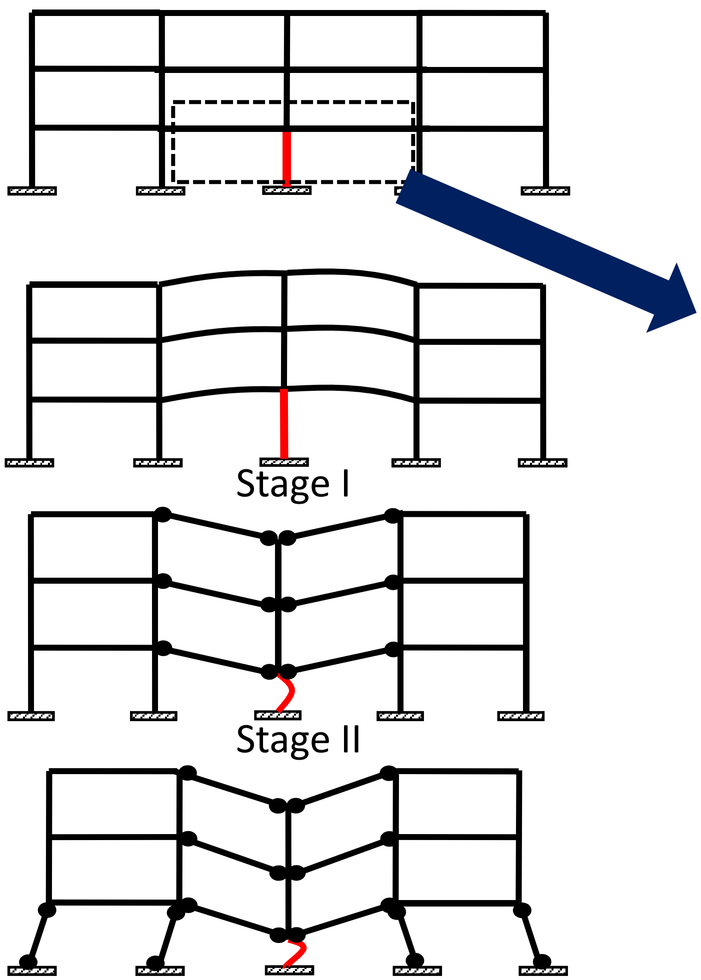

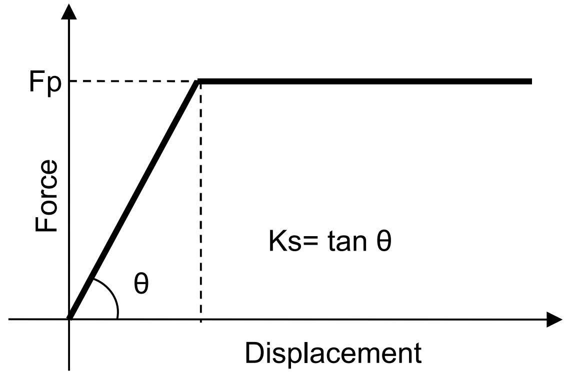

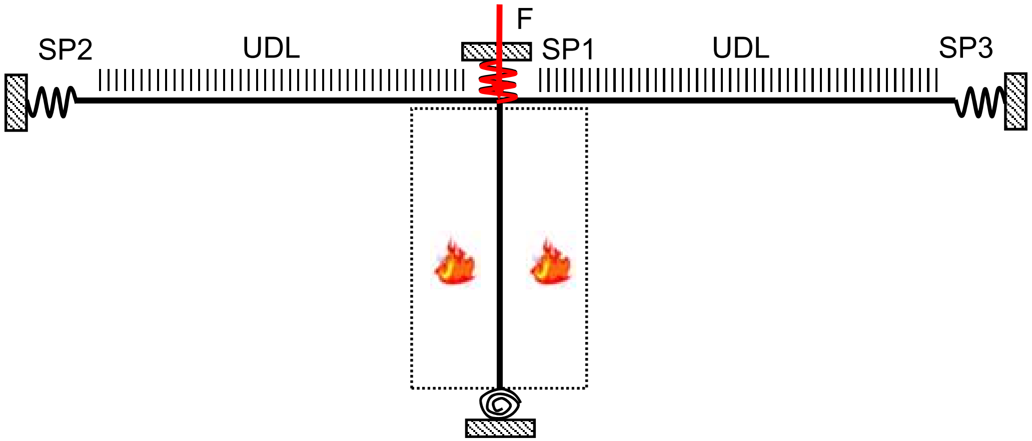

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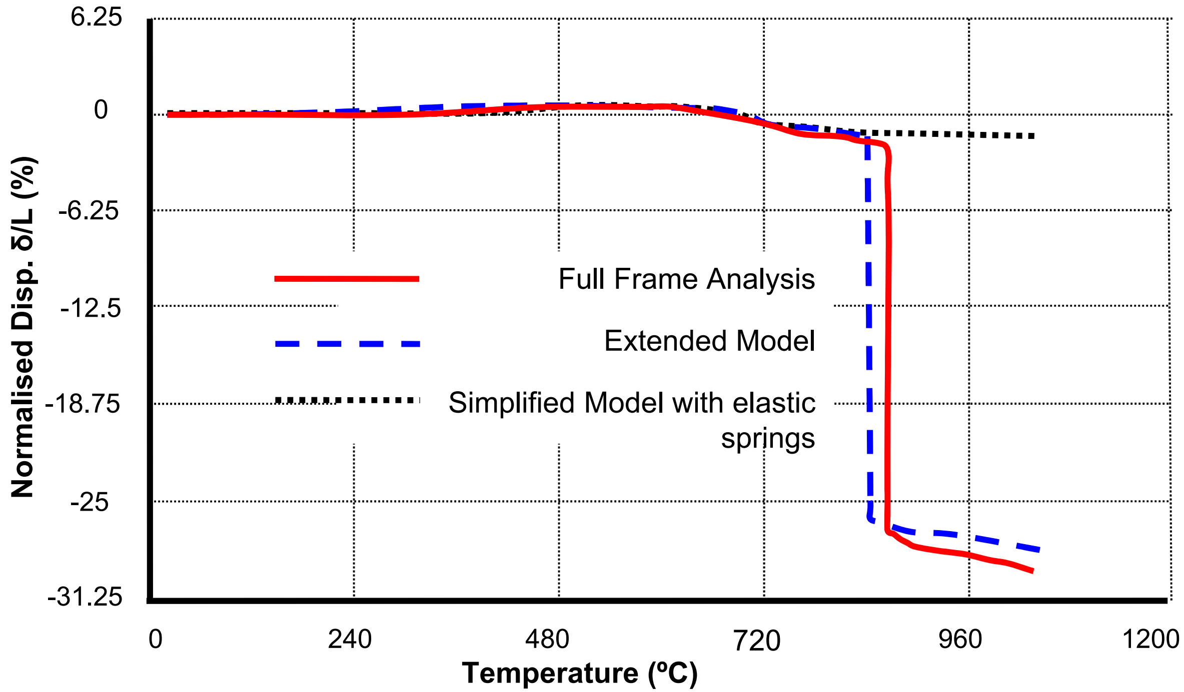

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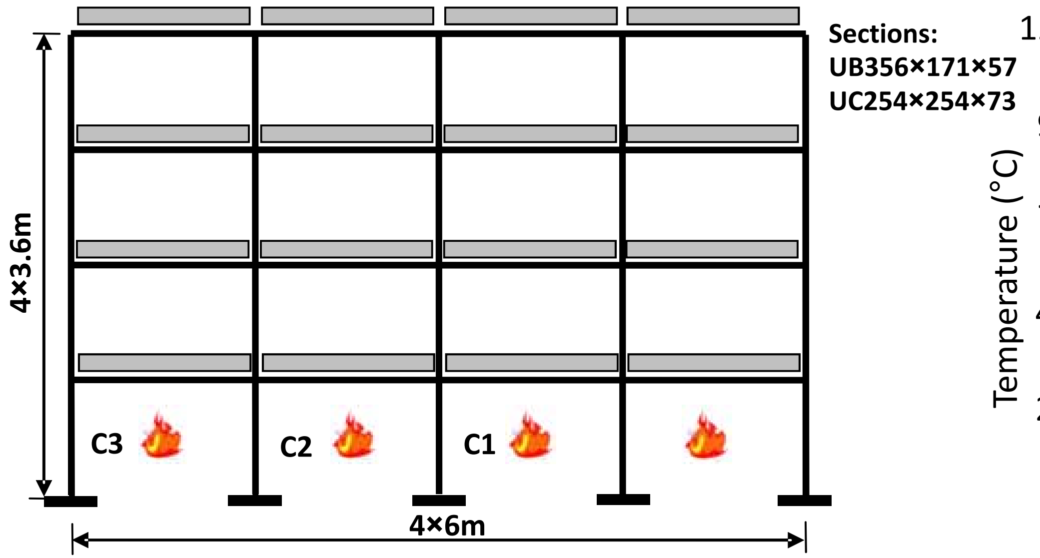
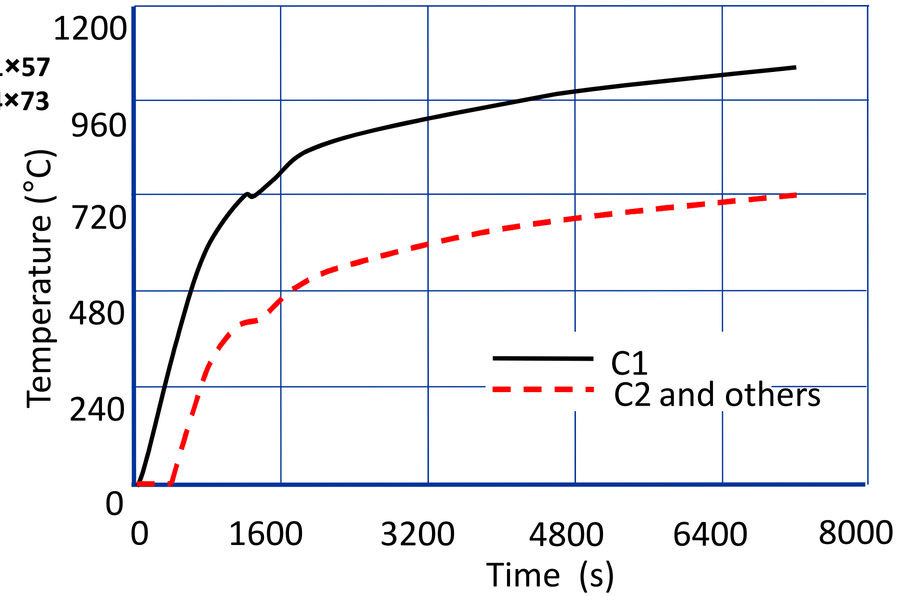




Key issues:

1. Buckling of critical column
2. Yielding of beams connected to heated columns
3. Fracture of connections between beams and columns
4. Load sharing and buckling of adjacent columns
5. Pull-in of adjacent columns

Collapse Mechanism of Frames in Fire

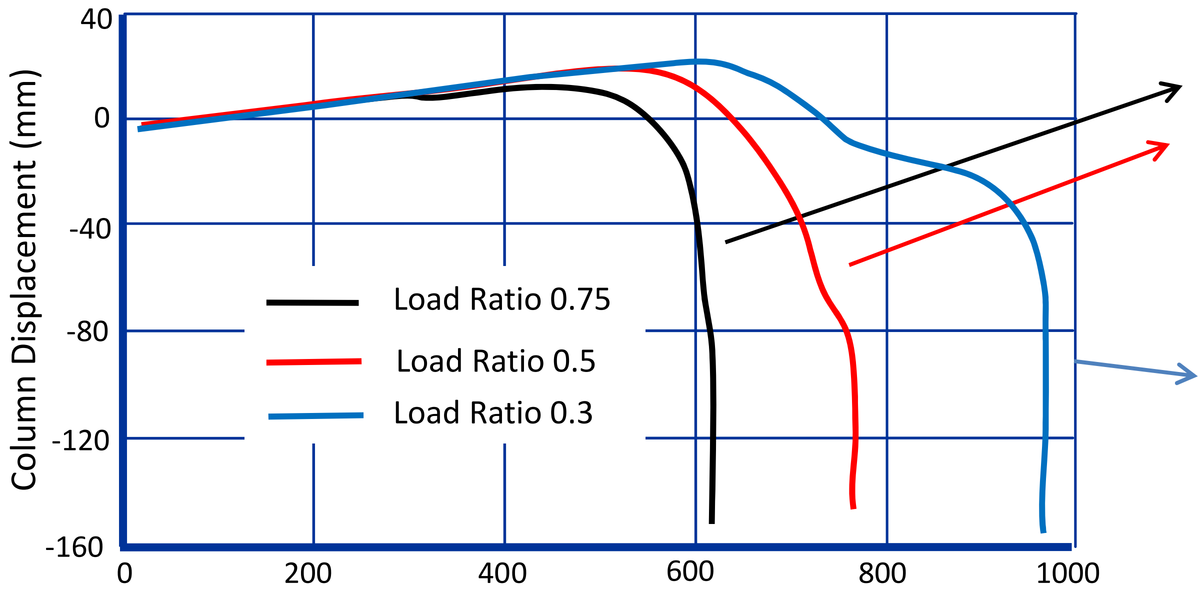
Influence of load ratio

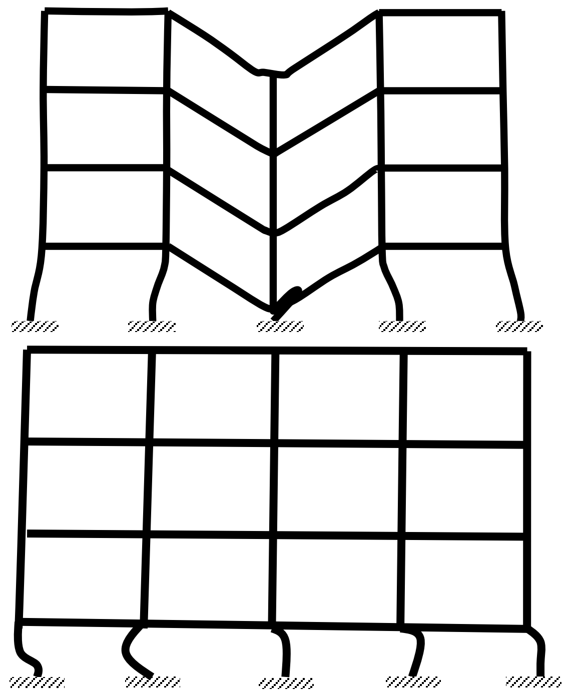
Higher load ratios:

Low buckling temperatures of C1; Lack of lateral restraint.

Lower load ratios:

Higher failure temperature of C1; adjacent columns buckle simultaneously.





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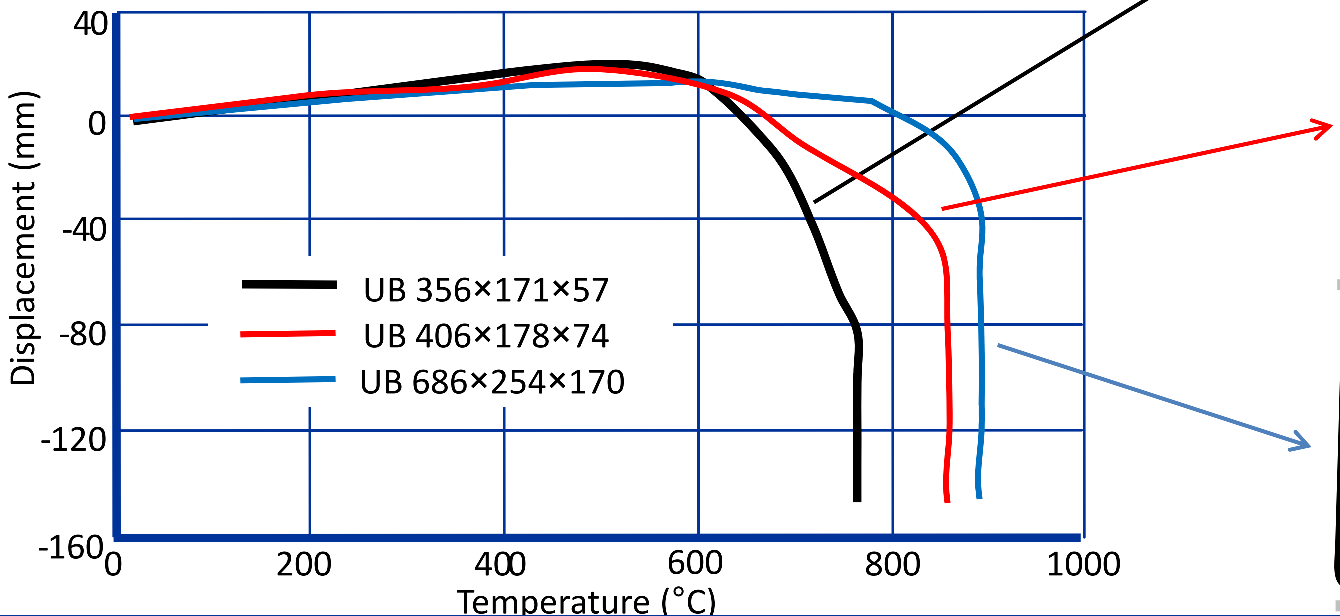
Influence of beam sections

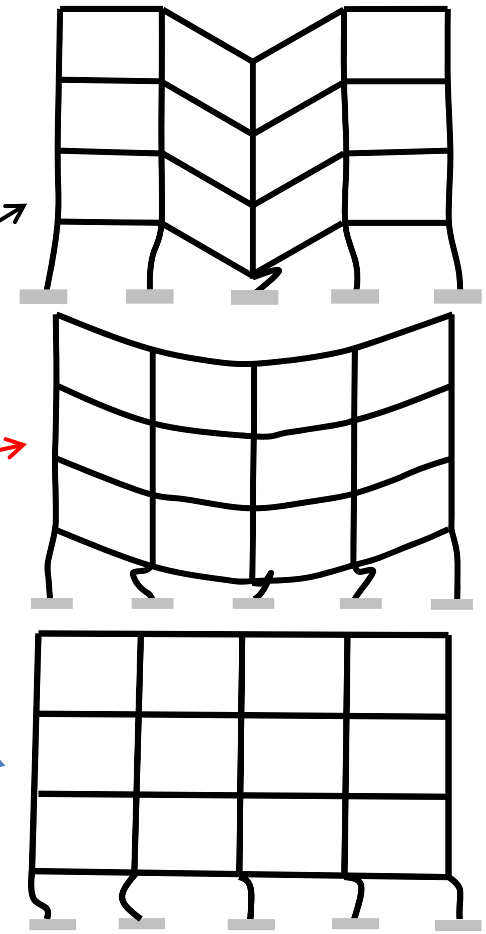
Strongest beam sections:

Stiff restraint to the heated column; high failure temperature; all adjacent columns buckle simultaneously.

Smaller beam sections:

Lower collapse temperature; pull-in of adjacent columns induces total collapse.





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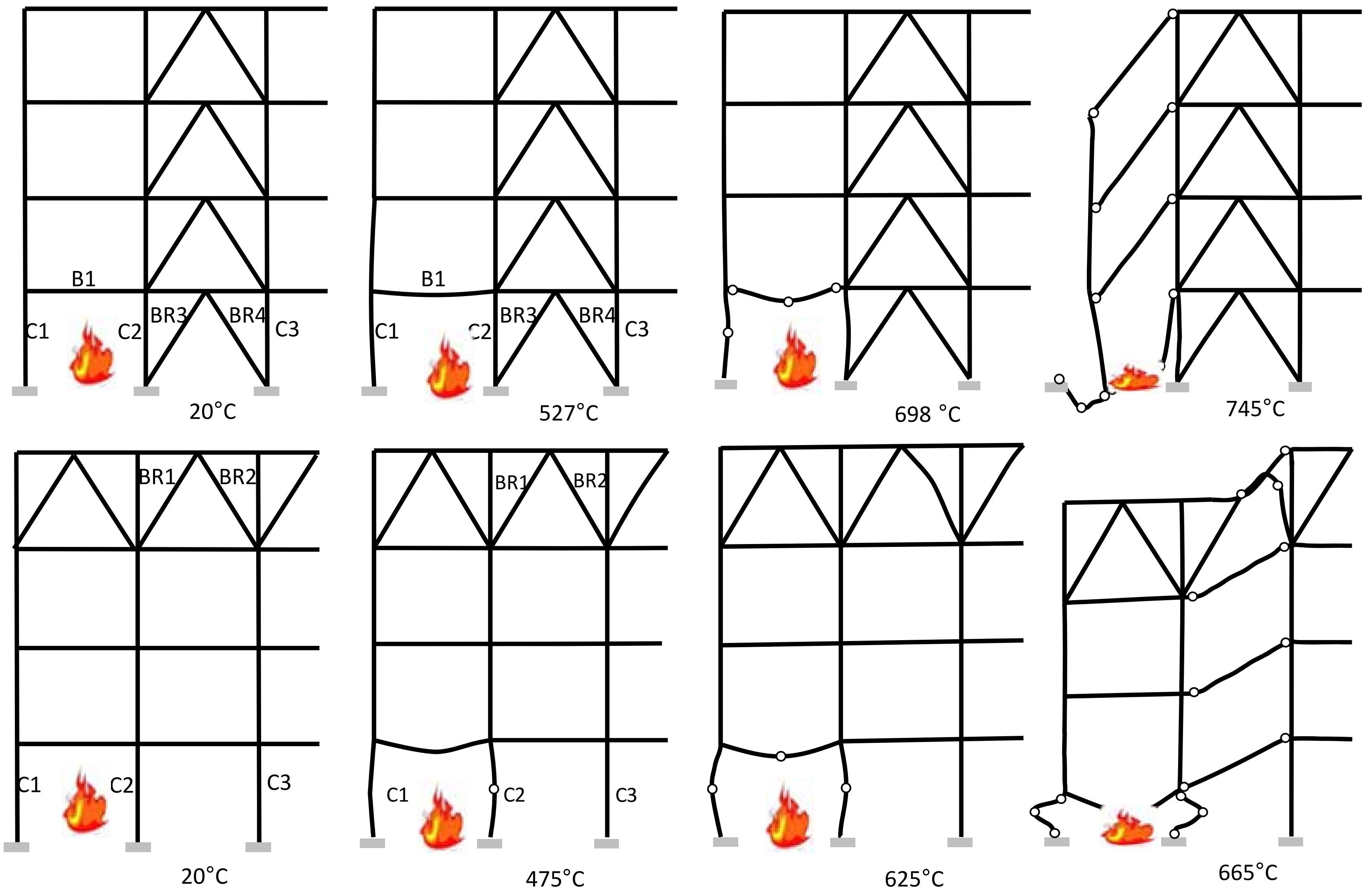

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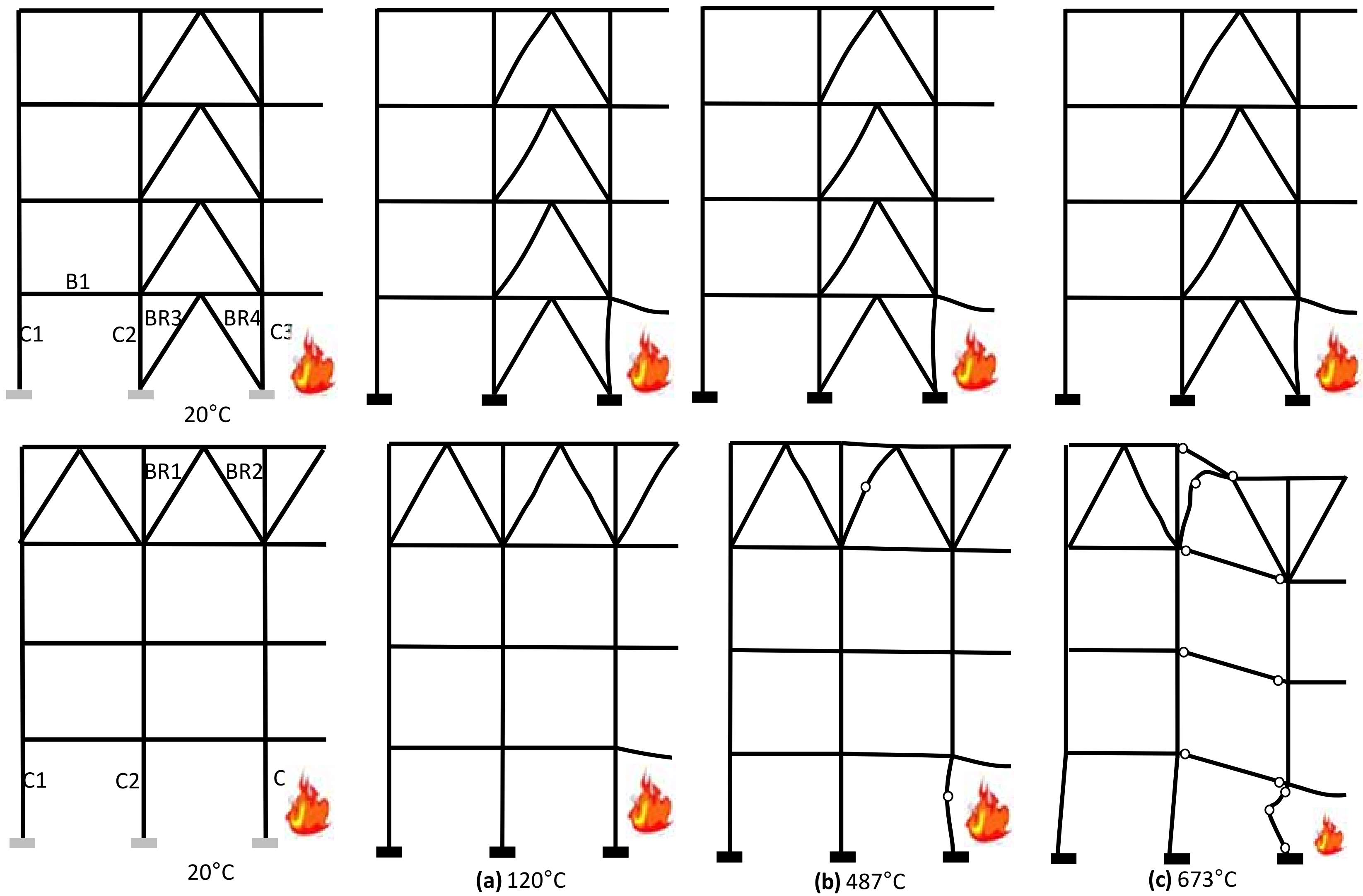

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Progressive collapse analysis of steel structures under fire conditions

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The collapse behaviour of braced steel frames exposed to fire

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Progressive Failure of Connections in Fire

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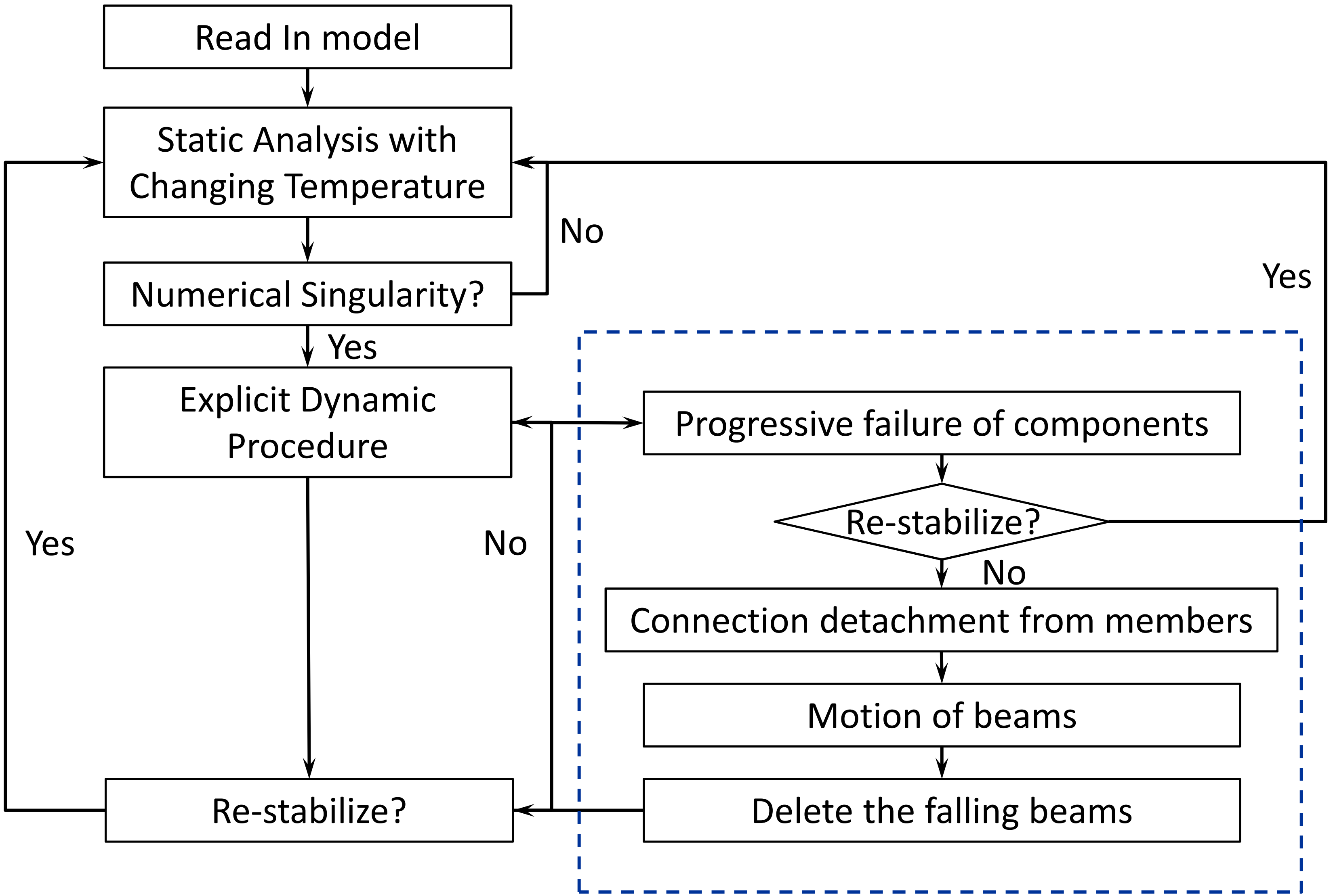
- Connection is important for robustness of steel structure in fire.
- Component-based model is widely developed for modelling the connection behaviour in changed temperature.
- Connection is simulated by assembly of springs with known characteristic.
- Analysis terminates after first component fails due to numerical singularity.

Progressive Failure of Connections in Fire



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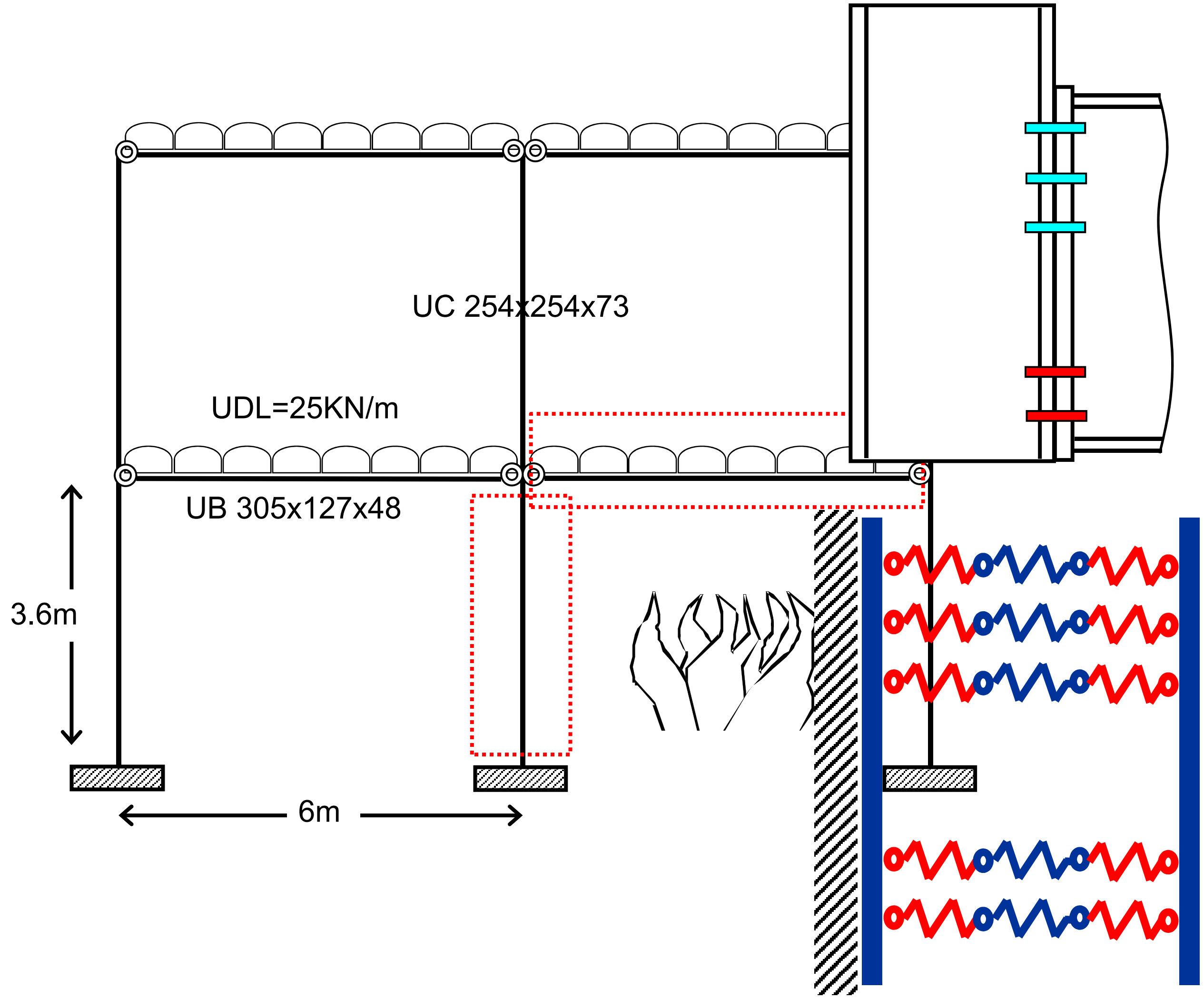

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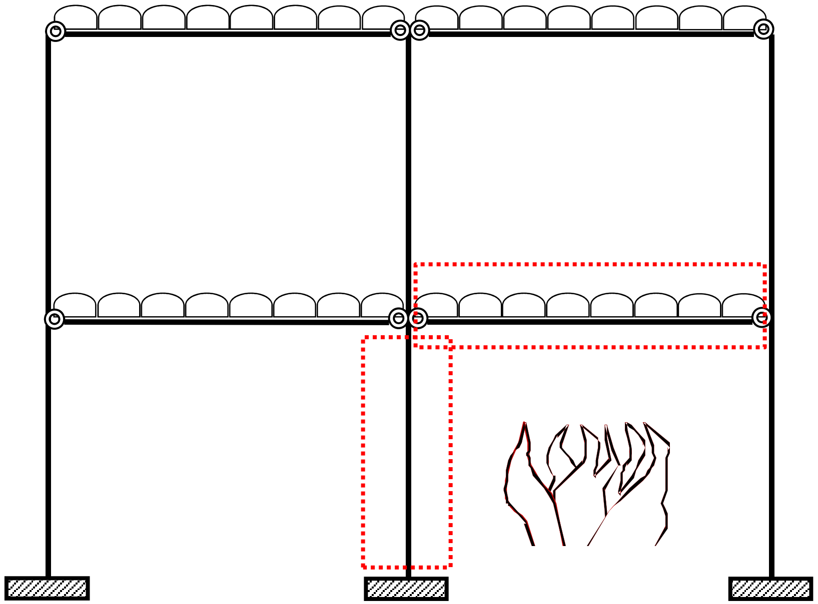

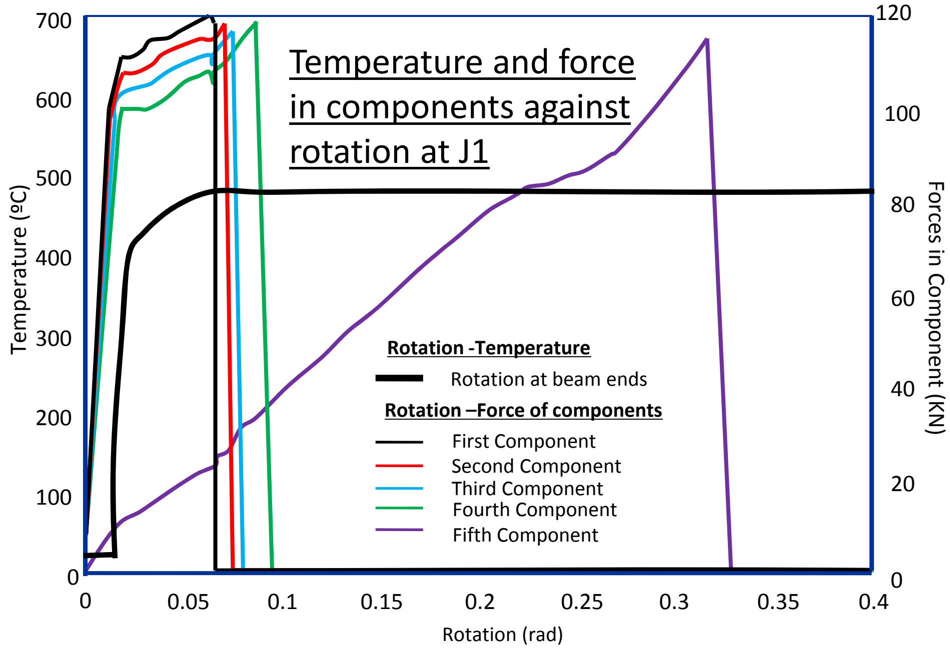

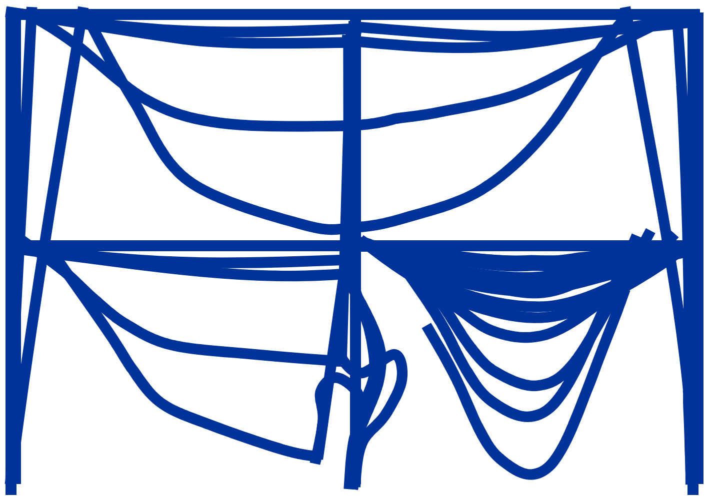

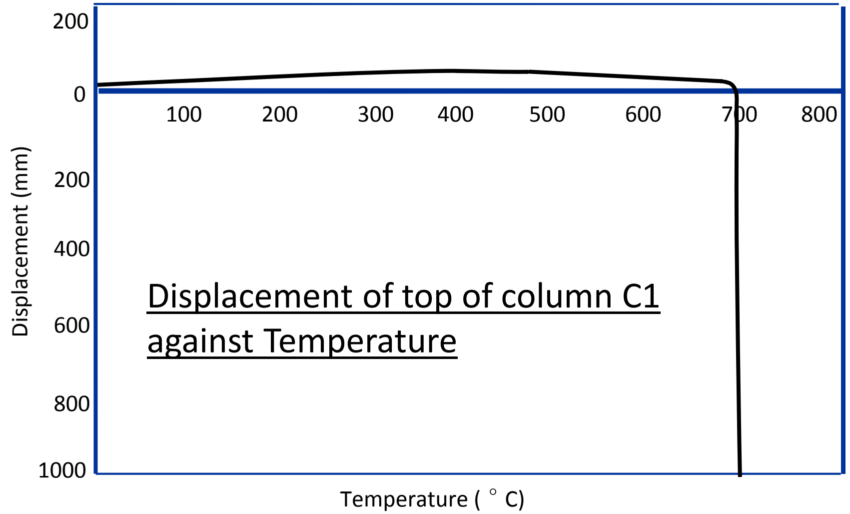

Ductility Demand of Connections in Fire

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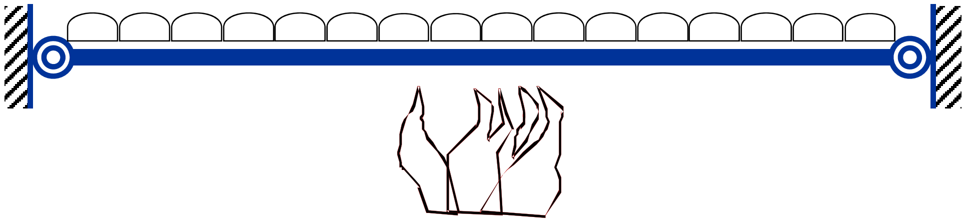
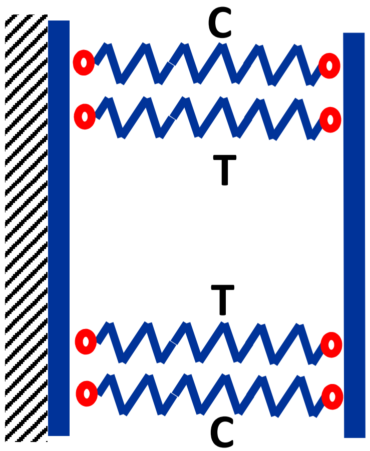
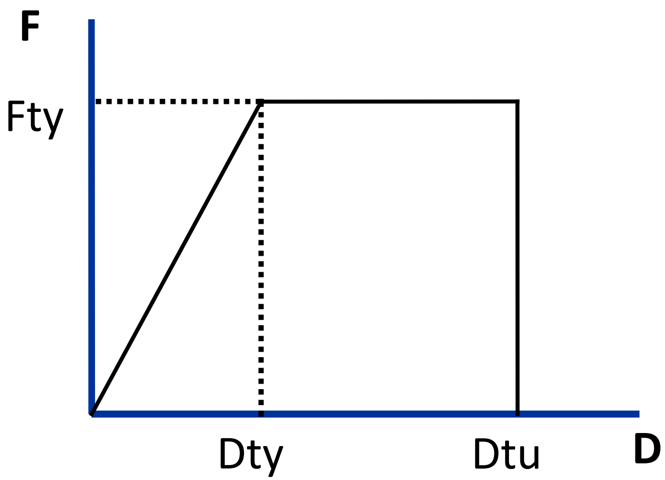


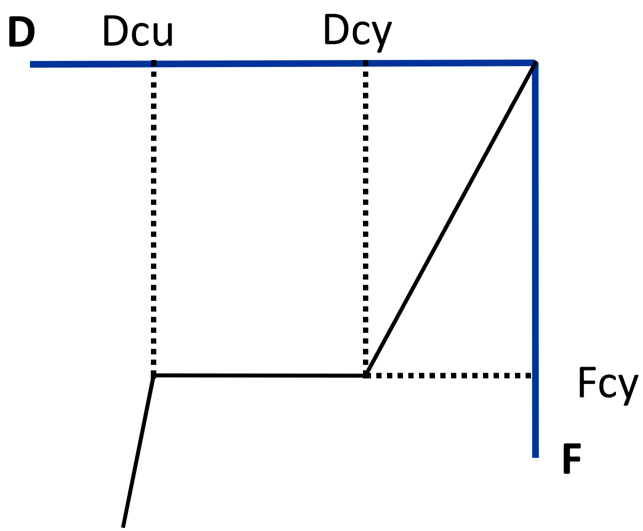
Tested beam with connections



Simplified Connection Model



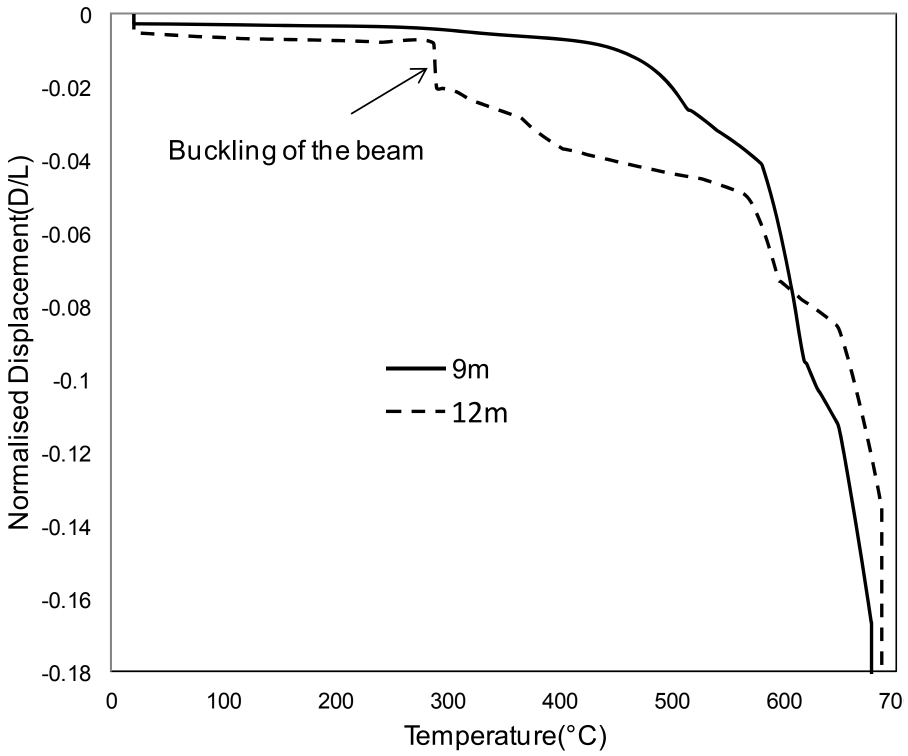
Tension Row



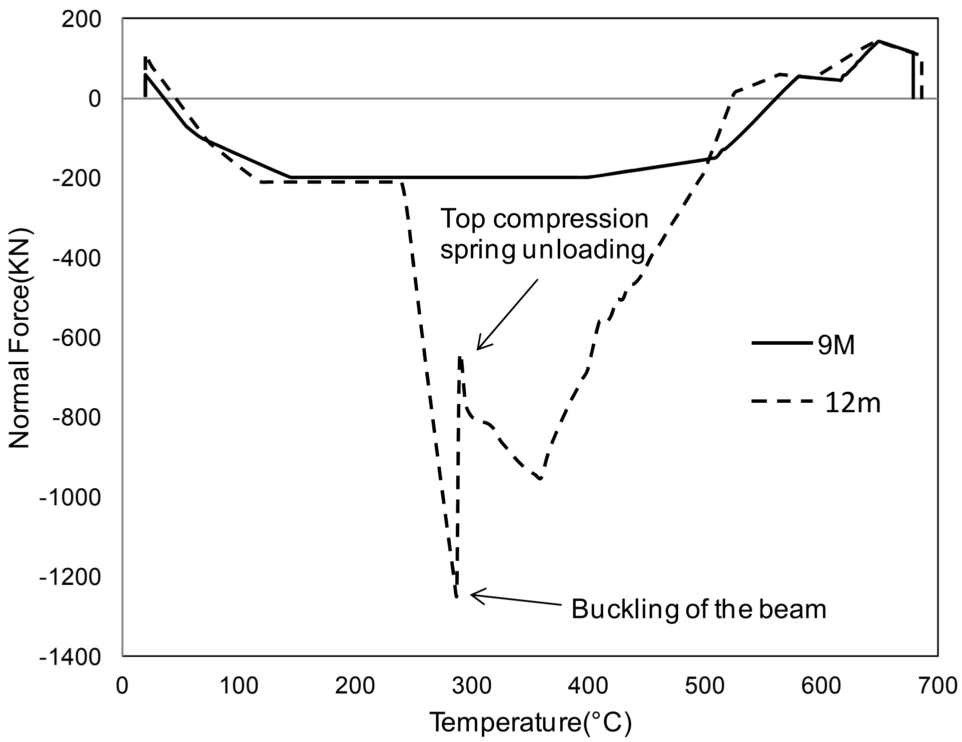
Compression Row

Ductility Demand of Connections in Fire

Beam Span



Mid-span displacement of beam



Normal force in connection

Longer beam---Larger compressive force---Buckling of beams

Little influence on the tensile normal forces

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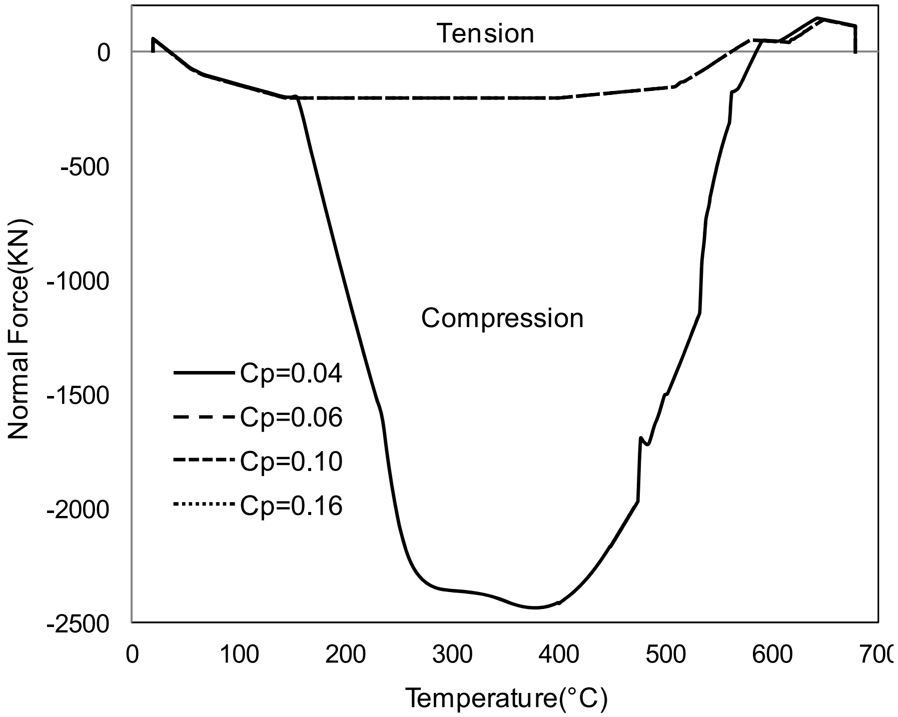
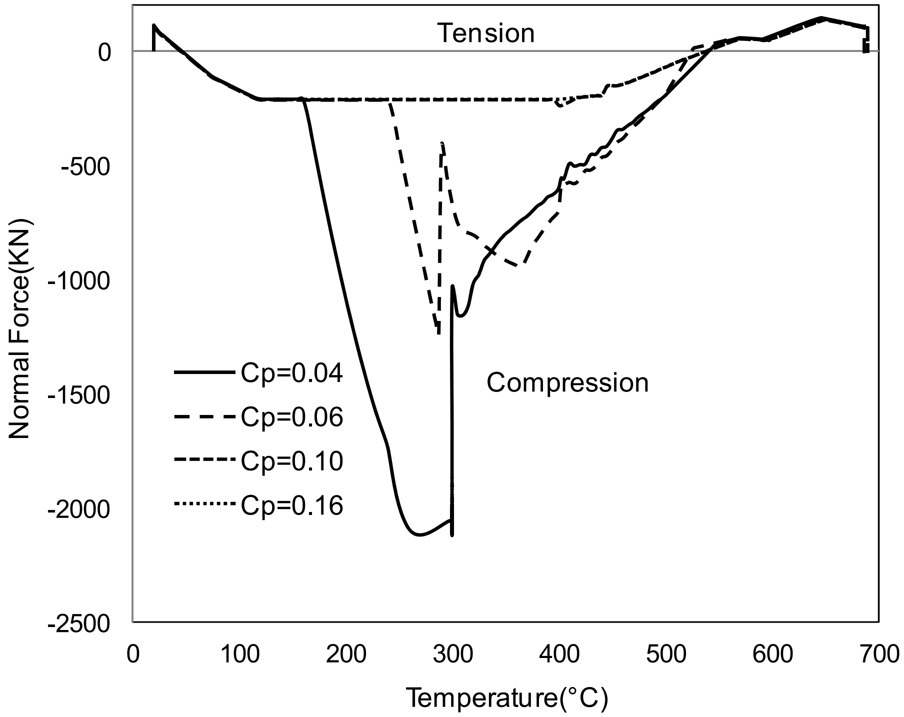
Compressive Ductility



9m Beams



12m Beams

Sufficient compressive ductility avoid large compressive force in beams

No influence on the failure temperature of connections

Ductility Demand of Connections in Fire

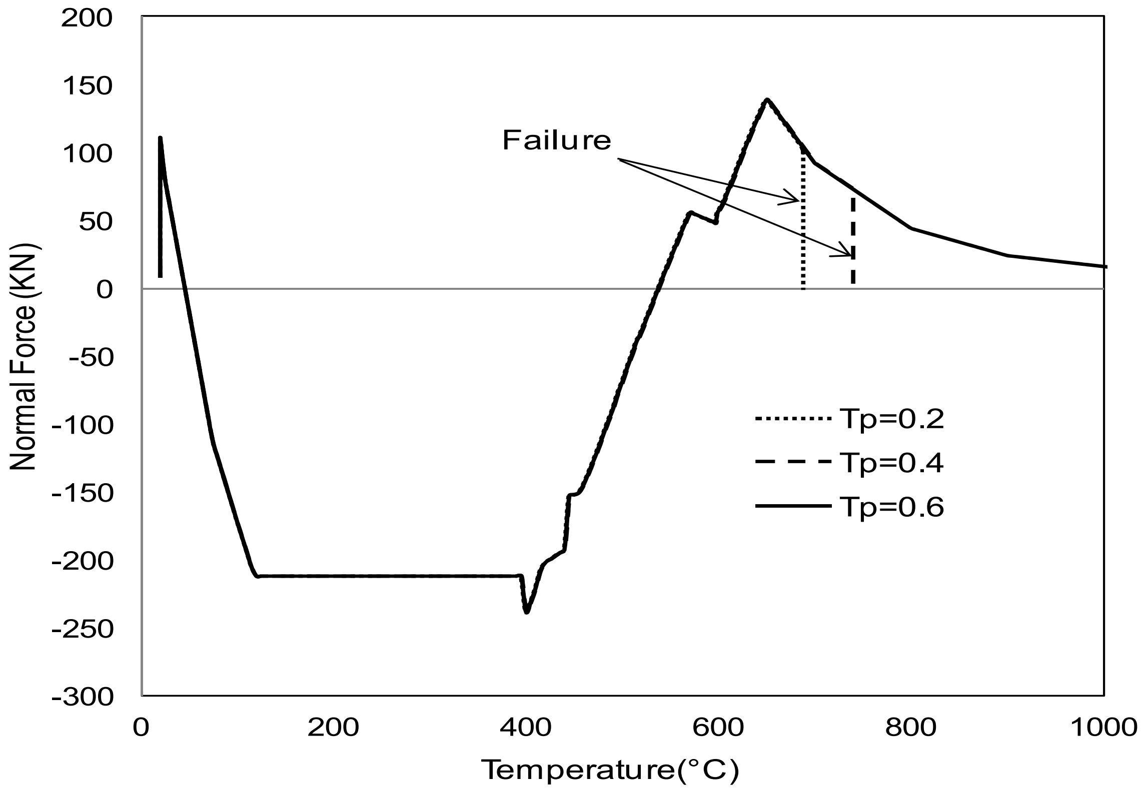
Tensile Ductility

Beam Section	Span	Tensile ductility(T_p)	Rotation Capacity (rad)	Failure Temperature (° C)
UB 533x210x122	9m	0.2	.6099	679
		0.4	.9530	735
		0.6	No Failure	No Failure
UB 533x210x122	12m	0.2	.4659	689
		0.4	.7089	739
		0.6	No Failure	No Failure

Tensile ductility contributes more to avoiding total connection failure and enhancing their rotation capacity, by reducing the catenary force necessary for beams to carry their loads at high temperatures.

Ductility Demand of Connections in Fire

Tensile Ductility



The catenary force decreases as the deflection and temperature increase.

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Ductility Demand of Connections

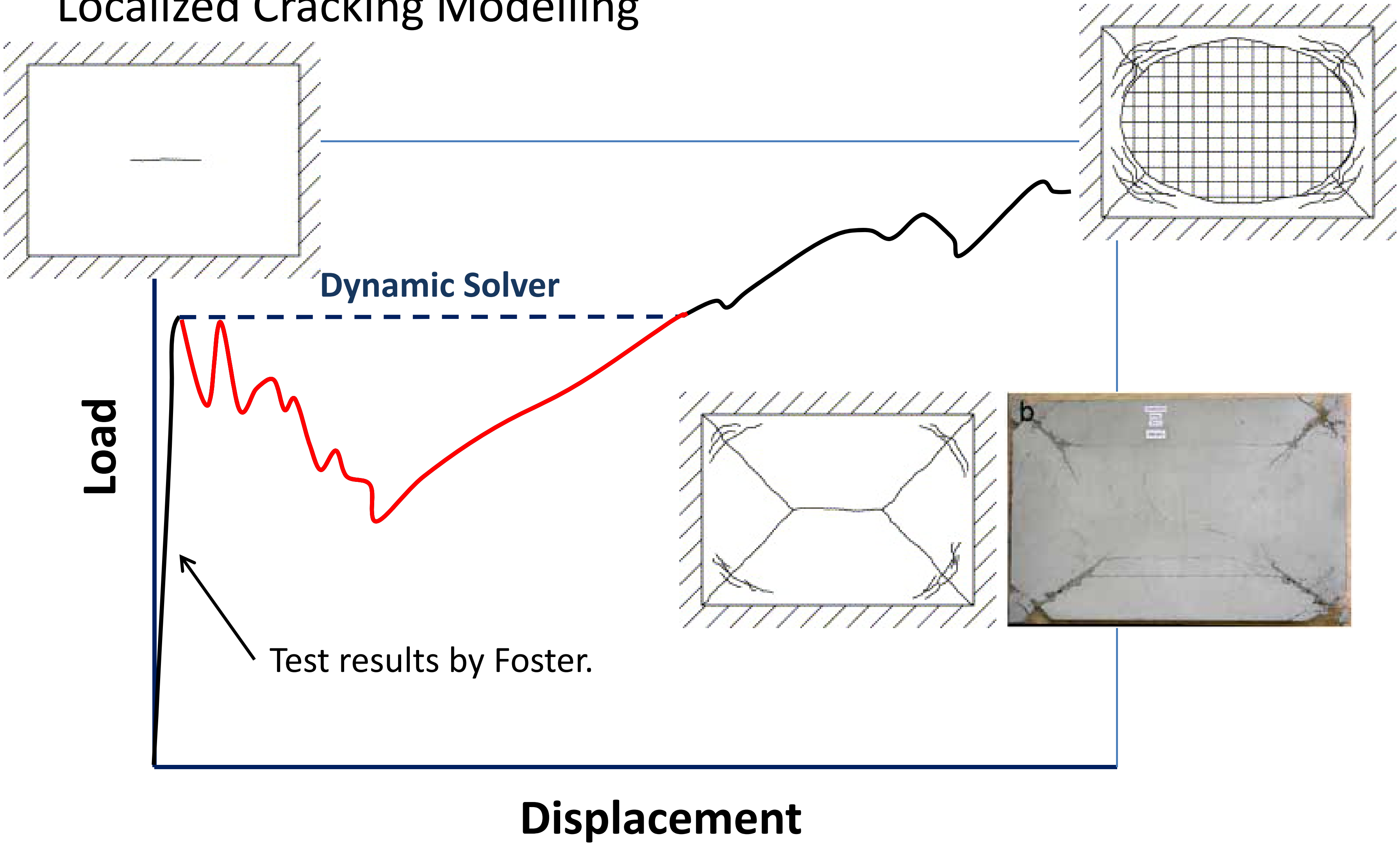
Span (m)	Ultimate limited states (KN/m)	Fire limited states (KN/m)	Cross section	Ductility Index									
				0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
				Failure Temperature(°C)									
6	97.3	62.1	UB406×178×60	633	693	--	--	--	--	--	--	--	--
9	97.3	62.1	UB533×210×101	583	615	647	675	707	751	--	--	--	--
12	97.3	62.1	UB610×305×149	553	571	599	619	639	655	675	703	727	--

No Failure

Beams with larger span require higher ductility of connection to retain the integrity.

Further Application and Discussion

Localized Cracking Modelling



Further Application and Discussion

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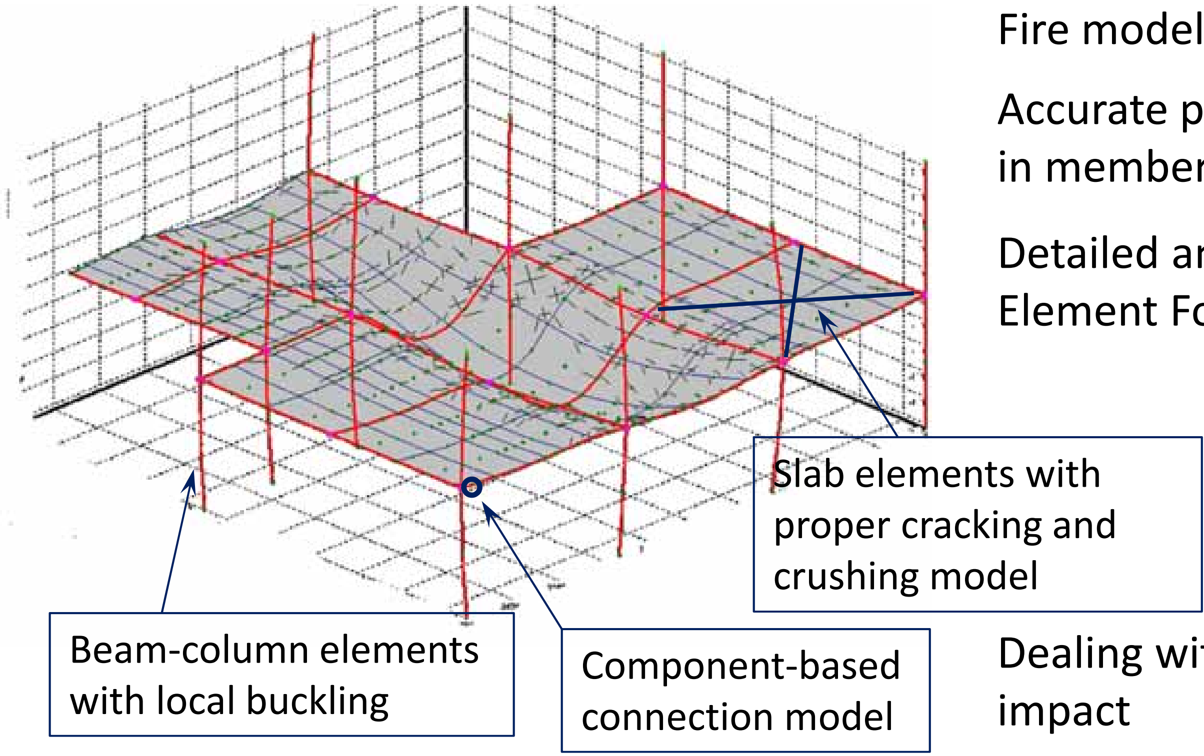
Practical global collapse analysis in fire



Fire modelling

Accurate prediction of temperature in members

Detailed and Comprehensive Element Formulations

Dealing with debris loading and impact

Further Application and Discussion

Computational Efficiency

High non-linearity and complexity slow down the computational speed.

Thank you!