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1. Development for Thermomechanical Analysis
2. Development for Heat Transfer Analysis
3. Development for SIFBuilder
4. Extra exercise
Day 3:
Development for Thermo-mechanical Analysis
### Thermo-mechanical Analysis

**Finite Element Model**
- Nodes
- Elements
- Boundary conditions
- Load

**Domain**
- Analysis
- Recorder

**Element**
- Thermal Action
- Temperature History
- Location
- Displacement
- Residual force
- Temperature field
- Tangent stiffness

**Section**
- Deformation
- Resisting force
- Temperature
- Section stiffness

**Material**
- Stress
- Strain
- Temperature
- Modulus
Thermo-mechanical Analysis

Class Name
- attributes
+ operations()

Class structure

Class1

Class2

Association

Assembly Class

Class A

Class B

Aggregation

Base Class

Sub Class

Generalisation

UML Notation
Thermo-mechanical Analysis

Material
  └── UniaxialMaterialThermal
      ├── ElasticMaterialThermal
      │    ├── Steel01Thermal
      │    │    └── Concrete02Thermal
      │    └── Steel02Thermal
      │         └── ConcreteECThermal
      └── SteelECThermal

SectionForceDeformation
  └── Element
      ├── dispBeamColumn2dThermal
      │    └── forceBeamColumn2dThermal
      └── FiberSection2dThermal
          └── FiberSection3dThermal
              └── dispBeamColumn3dThermal
                  └── forceBeamColumn3dThermal

BeamColumn element
BeamColumn element

Different level of state determination
Thermo-mechanical Analysis

Thermal load step $k$
- Calculate thermal force of element
  \[ F_{th} = \sum F_{sl} \cdot w_{si} \]
- Form unbalance force
  \[ R_0^k = F_{ex}^k + F_{th}^k - F_r^{k-1} \]

Iteration step $i$
- Form tangent stiffness
  \[ K_i^k(E_i^k) \]
- Compute displacement increment
  \[ \Delta q_i \]
- Update displacement
  \[ q_i^k = q_i^{k-1} + \Delta q_i \]

Update deformation of section $si$: $e_{si}(q_i^k)$

Update state of fibre $fi$
- $\varepsilon_i(\varepsilon_{si})$, $\varepsilon_m = \varepsilon_i - \varepsilon_{th}$, $\sigma(\varepsilon_m)$, $E_t$

Calculate resultant force of Section $si$
\[ F_{r,si} = [f_{r,si} \ M_{r,si}] \]

Form unbalance force
\[ F_{rl}^i = \sum F_{r,si} \cdot w_{si} \]
\[ R_l^i = F_{ex}^i - F_{rl}^i \]

Convergence check
- Yes
  - Thermal load step $k+1$
- No

BeamColumn Element Flowchart
Thermo-mechanical Analysis

Shell element
Thermo-mechanical Analysis

Shell element

- Nodal points
- 2x2 Gauss integration points
- Interpolation tying points of shear strain

Mid-layer of Shell
Concrete layer
Smeared rebar layer
Thermo-mechanical Analysis

Beam-column element

Section $s_i$

Fibre $i \{ y_{f_i}, A_{f_i} \}$

$(Y_9, T_9)$

$(Y_n, T_n)$

$(Y_1, T_1)$

1D temperature gradient

$(Z_1, T_{11})$

$(Z_5, T_{15})$

$(Y_5, T_5)$

$(Y_4, T_4)$

$(Y_3, T_3)$

$(Y_2, T_2)$

$(Y_1, T_1)$

$(Z_1, T_6)$

$(Z_5, T_{10})$

2D temperature gradients (I-section)
Thermo-mechanical Analysis

Thermal action for beam or column

Thermal action for slab

Beam2dThermalAction (Beam3dThermalAction)
Day 3: Development for Heat Transfer Analysis
Heat Transfer Analysis

Finite Element Model
- Nodes
- Elements
- Boundary conditions
- Load

Structural Analysis

Heat Transfer Analysis

HTNodes
HTElements
TemperatureBC
HeatFluxBC

Finite Element Model

Tcl interpreter

ModelBuilder

Domain

Analysis

Recorder

HTAnalysis

HeatTransfer Domain

HTRecorder
Day 3: Development for SIFBuilder
What fire models?
IDEALISED UNIFORM FIRES

- Initiated in Sweden, used widely in Eurocode oriented design;
- Parameters include fuel load, ventilations and compartment dimensions;
- Limited to 500m² and 4m height by EN1991;
- Beginning to be used in “PERFORMANCE-BASED” approach, often disregarding limits.

Based on tests dating back over 100 years specifies a fixed temperature-time curve;

still remains widely used as a “PRESCRIPTIVE” approach for ALL types of construction.

Non-UNIFORM FIRES

PARAMETRIC FIRES

STANDARD FIRE

IDEALISED UNIFORM FIRES

Design Fires

Initiated in Sweden, used widely in Eurocode based design;
Parameters include fuel load, ventilations and compartment dimensions;
Limited to 500m² and 4m height by EN1991;
Beginning to be used in “PERFORMANCE-BASED” approach, often disregarding limits.
IDEALISED NON-UNIFORM FIRES

Continuous fuel distribution
- Large plan office
- Post-flashover
- Fire spread / Travelling fire

Discontinuous fuel distribution
- Car park, bridge fire
- Unlikely fire spread
- Localised fire

Fuel distribution
OPEN-PLAN OFFICE

Horizontally travelling fires

- Distributed fuel load (office furniture)
- Non-uniform burning
- Travelling fire model (Stern-Gottfried 2012)
- Refinement of the methodology is still ongoing

WTC 1, Floor 94
WTC 1, Floor 97
Tall building fires
--Vertically travelling fires

- Fire spread through adjacent floors
- Delays of ignition associated with compartment fire models
- A sub-structure model of WTC tower subjected to Multi-floor fire (Kotsovinos & Usmani 2013)

- Multi-floor fire model for WTC collapse
Localised fires

- Fuel load controlled
- Sufficient ventilation
- No fast fire spread

- Car park building / atriums/ bridges
- Hasemi fire tests
- Eurocode model / SFPE model
- Ceiling fire plume / steel beam underneath ceiling /smoke layer

Localised fire plume
What is the complexity?

- Localised compartment fire
- Partial exposure
- Mostly ignored in practice

Heat flux distribution from a localised fire (at a single instant)

Typical column X-sections

Fire exposed surface

Typical beam X-sections

Beams

Columns

Typical column X-sections
Modelling structural behaviour in fire using OpenSees

**Beam-column elements**
- Uniaxial materials
- Fibre based sections
- Displacement based / force based

**Shell elements**
- Multi-axial materials
- Multi-layered plate sections

- OpenSees FE model
Integrated computation in OpenSees

**SIFBuilder**
User-friendly interface for creating (regular) structural models and enable consideration of realistic fire action

**Fire**
Models of fire action (only *idealised* fires), i.e., Standard fire, Parametric fire, EC1 Localised fire, Travelling fire

**Heat Transfer**
Heat transfer to the structural members due to fire action

**Thermo-mechanical**
Structural response to the elevated temperatures
- **Tcl** supported
  (Tool command language)
- **SIFBuilderDomain** as main storage
- **SIFModel** created for building info
  (material, section, members)
- Various types of Impose loads
- Various types of fire action
- Automated heat transfer analyses
- Automated implementation of thermal action
SIFBuilder
- Implementation of Fire Action

Strategy for efficient heat transfer modelling
--- Idealised non-uniform fires, $T(x,y,z,t)$

- Heat flux input varies with the location;
- Composite beam: a series of 2D sectional analyses
- Concrete slab: using localised 1D Heat Transfer analyses

- Composite beam
- 2D section with localised BC
- Localised heat flux
- Floor slab
SIFBuilder

- Fire surrounding centre column
- EC1 Localised fire
- Unconfined ceiling
- Horizontally Non-uniform temperature distribution
- Localised structural deformation
SIFBuilder
-Idealised uniform fires

- Compartment fire
- Standard fire curve
- Confined in one corner compartment (111)
- Wall partitions considered

- Structural deformation
- Configuration
Day 3: Extra Exercise?
THANK YOU!