### Current Research at University of Naples

- Structural behaviour of composite steel-concrete buildings in fire
- Simplified fire design methods for steel-concrete composite members (e.g. Annex F of EN1994-1-2)
- Fire tests and theoretical analysis of concrete slabs reinforced with FRP bars (will be presented by Antonio Bilotta in TS)
- Applications of Structural Fire Safety Engineering to car parks
- FSE and Fire Risk Assessment approach (will be presented by Iolanda Del Prete in TS, but some general concepts will be given in this presentation)

**WG1 - Emidio Nigro**
**WG2 - Giuseppe Cefarelli**
**WG3 - Antonio Bilotta**
**Iolanda Del Prete**
**Anna Ferraro**
**Domenico Sannino**

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### Structural behaviour of composite steel-concrete buildings in fire

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td><img src="image1" alt="Graph at 0 min" /></td>
</tr>
<tr>
<td>15</td>
<td><img src="image2" alt="Graph at 15 min" /></td>
</tr>
<tr>
<td>54</td>
<td><img src="image3" alt="Graph at 54 min" /></td>
</tr>
</tbody>
</table>
### Structural behaviour of composite steel-concrete buildings in fire

<table>
<thead>
<tr>
<th>Seismic Zone</th>
<th>Section Type</th>
<th>Fire Scenario</th>
<th>Single Member Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beam</td>
<td>Column</td>
<td>Collapse Time</td>
</tr>
<tr>
<td>2</td>
<td>HE260B</td>
<td>HE500B</td>
<td>111 min</td>
</tr>
<tr>
<td>4</td>
<td>HE240B</td>
<td>HE280B</td>
<td>116 min</td>
</tr>
</tbody>
</table>

#### Full-scale experimental fire tests on concrete slabs reinforced with FRP bars

**Instrumentation**

- Over 40 thermocouples for each slab
- Thermocouples on bars
- Thermocouples in concrete
- Strain gauges
**Full-scale experimental fire tests**

**Load**

- Zone of slab un-exposed to fire
- Zone of slab exposed to fire
- Zone of slab un-exposed to fire

**Fire Load level**

\[ \tau_{fl} = \frac{M_{Ed,fl,t}}{M_{Rd}} \]

- S1, S4, S7: 10% of \( M_{Rd} \) (own weight)
- S2, S5, S8: 40% of \( M_{Rd} \) (\( F = 17.5 \text{kN} \))
- S3, S6, S9: 60% of \( M_{Rd} \) (\( F = 17.5 \text{kN} \))

**Observations after tests**

**Slabs S4-S5-S6: Fiber failure at midspan**

**Inside the furnace:** bars \( c = 51 \text{mm} \), \( L_{unexp.} = 500 \text{mm} \)

**Section: end of slab**

- Longitudinal reinforcement
- Glass fibers without resins
Application of FSE to Car Parks of C.A.S.E. Project for L’Aquila

Building description: Analysis of the structural characteristics

Choose of the Safety Performance Levels

Choose of the Active and Passive Fire Protection

Static and fire design load calculation

Fire Model Fire Design Scenario

Design and Structural Model

Thermal and structural analysis (for each fire design scenario)

The model meets the safety levels choose?

Modify of the size or typology of structural elements

YES

NO

Were tested all scenarios?

YES

END

C.A.S.E Project - L’Aquila (Italy)

Open car park

Concrete slab

Isolation device

Unprotected steel column

Design Fire Scenarios

Localised fire (Pre-flashover) From INERIS (2001) guideline

Fire scenario L1

Fire scenario L2

RHR curves From CEC agreement 7215-PP/025

Car (Category 3)

VAN
Structural models

Global analyses with non linear software SAFIR2007

Substructure

Static scheme

3D-Detailed analyses with software ABAQUS/standard

Column

Loads on column corresponding to actions from global analysis

Performance Level 4:
Checks in terms of resistance and limitation of damage (differential vertical displacements in the columns)

Global Analyses Results

Fire scenario L2 - Global Analysis

Temperatures vs time

Axial loads vs time

Displacements vs time

Vertical displacement (mm)

There is not structural collapse

Axial load resistance vs time

Axial load effect

Axial load resistance
Selection of Fire Scenarios and Performance Levels through Fire Risk Assessment Approach

Emidio Nigro

Di.St. - Department of Structures for Engineering and Architecture
University of Naples Federico II
Naples, ITALY

Introduction: Fire Safety Engineering

The “Fire Safety Engineering” (FSE) is the application of engineering principles, rules and expert judgement based on a scientific assessment of the fire phenomena, the effects of fire and both the reaction and behaviour of peoples, in order to:
- save life, protect property and preserve the environment and heritage,
- quantify the hazards and risks of fire and its effects,
- evaluate analytically the optimum protective and prevention measures necessary to limit, within prescribed levels, the consequences of fire (ISO/TR 13387-1).

A branch of Fire Safety Engineering is the Structural Fire Engineering.

Structural Fire Engineering deals with specific aspects of passive fire protection in terms of analysing the thermal effects of fires on buildings and designing members for adequate load bearing resistance and to control the spread of fire (C. Bailey).
Fire Safety Performance Levels

**Fire Safety Goals**
The main objective of fire safety checks concerns the mechanical resistance and stability, in fire situation, of the structure.

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Fire resistance is not required, where consequences are acceptable or where risk is negligible</td>
</tr>
<tr>
<td>II</td>
<td>Maintaining the fire resistance requirements, which ensure the lack of partial and/or complete structural collapse, for a sufficient time with evacuation of occupants</td>
</tr>
<tr>
<td>III</td>
<td>Maintaining the fire resistance requirements, which ensure the lack of partial and/or complete structural collapse, for a sufficient time with emergency management</td>
</tr>
<tr>
<td>IV</td>
<td>Limited damage of the structures after fire exposure</td>
</tr>
<tr>
<td>V</td>
<td>Complete serviceability of structures after fire exposure</td>
</tr>
</tbody>
</table>
Fire Safety Performance Levels

Fire Safety Goals
The main objective of fire safety checks concerns the mechanical resistance and stability, in fire situation, of the tower.

Performance Level III
maintaining the fire resistance requirements, which ensure the lack of partial and/or complete structural collapse, for a sufficient time with emergency management or for the entire duration of the fire.

Performance Level IV
limited damage of the structures after fire exposure.

Selection of Design Fire Scenarios through Fire Risk Assessment

Fire Scenario
qualitative description of the development of a fire with time identifying key events that characterise the fire and differentiate it from other possible fires. It typically defines the ignition and fire growth process, the fully developed stage, decay stage together with the building environment and systems that will impact on the course of the fire (EN1991-1-2)

the choice of the design fire scenarios is carried out by Fire Risk Assessment, that takes into account the probability and consequence of the fire scenario

\[ R = P \times C \]

The Fire Risk Assessment is performed through the Event Tree approach, according to ISO-16732 Guidelines.
Selection of Design Fire Scenarios through Fire Risk Assessment

**Fire Risk Assessment procedure**

1. identification of a comprehensive set of possible fire scenarios;
2. estimation of probability of occurrence of each fire scenario;
3. estimation of the consequence of each fire scenario;
4. estimation of the risk of each fire scenario (combination of the probability of a fire and a quantified measure of its consequence);
5. ranking of the fire scenarios according to their risk.

**Event tree**

A time-sequence path from the initiating condition through a succession of intervening events to an end-event.

**Technical references**


**Selection of Design Fire Scenarios**

**Main events:**

- Fire ignition
- First aid suppression
- Alarm activation
- Sprinkler activation
- Sprinkler suppression
- Barrier effectiveness

**Secondary events:**

- doors state (open or closed)
- windows state (open or closed)

may be taken into account by the fire model

Probability of occurrence of each event and consequence value of each fire scenario are obtained both by direct estimation from available data and engineering judgment.
Available statistic data show that the probability of detecting fire manually and automatically is 69%. By considering that in 4% of cases, there’s no manual or automatic detection system, this probability reaches 72%.

By considering a probability of success equal to 87%,

\[ p(1^{\text{st}} \text{ Event}) = 62\% \]

**2nd Event: smoke detector effectiveness**

Smoke detectors reliability decreases during time, if maintenance operations aren’t provided. In the examined case, by considering that system works for a year, and one maintenance operation is provided for each year, it can be assumed

\[ p(2^{\text{nd}} \text{ Event}) = 70\% \]

**3rd - 4th Event: sprinkler activation and effectiveness**

Statistic analyses, carried out in USA (with reference to time period 2003-2007), show that, during fire event in building with office use, sprinkler activates in 96% of cases, and the system is effectiveness in 99% of cases.

\[ p(3^{\text{rd}} \text{ Event}) = 96\% \quad p(4^{\text{th}} \text{ Event}) = 99\% \]

**5th Event: barrier effectiveness**

Available data show that barrier effectiveness, in building provided by sprinkler, is equal to 99.6%, while is equal to 92.8% in other cases.

\[ p(5^{\text{th}} \text{ Event}) = 99.6\% \]

### Selection of Design Fire Scenarios: Probability of occurrence

**1st Event: first aid suppression**

**2nd Event: smoke detector effectiveness**

**3rd - 4th Event: sprinkler activation and effectiveness**

**5th Event: barrier effectiveness**

### Selection of Design Fire Scenarios: definition of consequences

<table>
<thead>
<tr>
<th>Scenario</th>
<th>1st event</th>
<th>2nd event</th>
<th>3rd event</th>
<th>4th event</th>
<th>5th event</th>
<th>Damage (%)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS1</td>
<td>YES</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0%</td>
<td>Damage is limited to thing involved in fire</td>
</tr>
<tr>
<td>SS2</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td></td>
<td>0.08%</td>
<td>Damage is limited to ½ room</td>
</tr>
<tr>
<td>SS3a</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>0.3%</td>
<td>Damage is limited to 2 rooms</td>
</tr>
<tr>
<td>SS3b</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>0.3%</td>
<td>Damage is limited to 2 rooms</td>
</tr>
<tr>
<td>SS4a</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>2.5%</td>
<td>Damage is limited to the compartment (15 rooms)</td>
</tr>
<tr>
<td>SS4b</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>5.0%</td>
<td>Damage is limited to the entire floor (30 rooms)</td>
</tr>
<tr>
<td>SS5</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td></td>
<td>0.3%</td>
<td>Damage is limited to 2 rooms</td>
</tr>
<tr>
<td>SS6a</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>2.5%</td>
<td>Damage is limited to the compartment (15 rooms)</td>
</tr>
<tr>
<td>SS6b</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>5.0%</td>
<td>Damage is limited to the entire floor (30 rooms)</td>
</tr>
<tr>
<td>SS7a</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>50.0%</td>
<td>Collapse of a part of building</td>
</tr>
<tr>
<td>SS7b</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>100.0%</td>
<td>Collapse of entire building</td>
</tr>
</tbody>
</table>
Case Study: Design Fire Scenarios definition

Fire Risk Assessment and Performance Ranking

<table>
<thead>
<tr>
<th>Consequence</th>
<th>Risk</th>
<th>Risk Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.000</td>
<td>11</td>
</tr>
<tr>
<td>0.06</td>
<td>0.0202</td>
<td>5</td>
</tr>
<tr>
<td>0.30</td>
<td>0.0068</td>
<td>8</td>
</tr>
<tr>
<td>0.30</td>
<td>0.0000</td>
<td>10</td>
</tr>
<tr>
<td>2.50</td>
<td>0.0247</td>
<td>4</td>
</tr>
<tr>
<td>5.00</td>
<td>0.0038</td>
<td>6</td>
</tr>
<tr>
<td>0.30</td>
<td>0.0325</td>
<td>3</td>
</tr>
<tr>
<td>2.50</td>
<td>0.0027</td>
<td>7</td>
</tr>
<tr>
<td>5.00</td>
<td>0.0000</td>
<td>9</td>
</tr>
<tr>
<td>10.00</td>
<td>0.2116</td>
<td>1</td>
</tr>
<tr>
<td>100.00</td>
<td>0.0328</td>
<td>2</td>
</tr>
</tbody>
</table>

Performance Level IV: limited damage
Performance Level III: resistance for all fire exposure time

Fire Safety Performance Levels

Fire Safety Goals

The main objective of fire safety checks concerns the mechanical resistance and stability, in fire situation, of the tower.

STAGE I: Preliminary Analysis
- Project definition
- Definition of fire safety goals
- Definition of fire safety performance levels
- Selection of design fire scenarios
- Approval of design fire scenarios by Italian Fire Brigade (Vigili del Fuoco)

STAGE II: Quantitative Analysis
- Choice of model
- Analyses results
- Selection of final design
- Design documentation

Performance levels

Highest risk scenario
High probability scenario

Performance Level III
- maintaining the fire resistance requirements, which ensure the lack of partial and/or complete structural collapse, for a sufficient time with emergency management or for the entire duration of the fire

Performance Level IV
- limited damage of the structures after fire exposure
Choice of the fire model

The post-flashover fire is obtained through different models:

- One-zone model, which assumes homogeneous temperature, density, internal energy and pressure of the gas in the compartment applying Ozone (provided by University of Liege) and C-FAST (provided by NFPA).
- CFD model applying FDS (provided by NIST).

Case Study: Fire Scenario SS7a - One zone model
Case Study: Fire Scenario SS7a – One zone model

<table>
<thead>
<tr>
<th>Fire Model</th>
<th>First aid suppression</th>
<th>Alarm activation</th>
<th>Sprinkler activation</th>
<th>Sprinkler suppression</th>
<th>Barrier effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>

EN1991-1-2

**RHR (MW)**

\( A_n = 25 \text{ m}^2 \)

**Q = 750 MJ/m²**

**Column check with critical temperature**

\( \theta_{cr} = 630 ^\circ \text{C} \)

**Fire involved in a single room (25m²)**

**Case Study: Fire Scenario SS5**

<table>
<thead>
<tr>
<th>Fire scenario</th>
<th>First aid suppression</th>
<th>Alarm activation</th>
<th>Sprinkler activation</th>
<th>Sprinkler suppression</th>
<th>Barrier effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS5</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>

RHR (MW)

\( A_n = 25 \text{ m}^2 \)

**Q = 750 MJ/m²**

\[ \dot{Q}(t) = \dot{Q}_{act} \cdot e^{-0.02t/\theta_{cr}} \]
Case Study: Fire Scenario SS7a – One zone model

<table>
<thead>
<tr>
<th>Fire Model</th>
<th>First aid suppression</th>
<th>Alarm activation</th>
<th>Sprinkler activation</th>
<th>Sprinkler suppression</th>
<th>Barrier effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire involved in a single room (25m²)</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>-</td>
<td>YES</td>
</tr>
</tbody>
</table>

\[ Q = 1662 \text{ MJ/m}^2 \]
\[ A_{fi} = 25 \text{ m}^2 \]

EN1991-1-2

**RHR (MW)**

**Tempo (min)**

- **OZONE (environment)**
- **void**

**t_R = 13 min**

---

Case Study: Fire Scenario SS5

<table>
<thead>
<tr>
<th>Fire scenario</th>
<th>First aid suppression</th>
<th>Alarm activation</th>
<th>Sprinkler activation</th>
<th>Sprinkler suppression</th>
<th>Barrier effectiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS5</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>

\[ A_{fi} = 25 \text{ m}^2 \]

**RHR (MW)**

**Tempo (min)**

- **OZONE (environment)**
- **void**

---
Fire model: EN1991-1-2 Approach

Table E.5 — Fire growth rate and RHR for different occupancies

<table>
<thead>
<tr>
<th>Occupancy</th>
<th>Fire growth rate</th>
<th>RHR [kW/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>Medium</td>
<td>300</td>
</tr>
<tr>
<td>Hospital (room)</td>
<td>Medium</td>
<td>300</td>
</tr>
<tr>
<td>Hotel (room)</td>
<td>Medium</td>
<td>300</td>
</tr>
<tr>
<td>Library</td>
<td>Medium</td>
<td>60</td>
</tr>
<tr>
<td>Office</td>
<td>Medium</td>
<td>300</td>
</tr>
<tr>
<td>Classroom of a school</td>
<td>Medium</td>
<td>300</td>
</tr>
<tr>
<td>Shopping centre</td>
<td>Fast</td>
<td>150</td>
</tr>
<tr>
<td>Theatre (cinema)</td>
<td>Medium</td>
<td>150</td>
</tr>
<tr>
<td>Transport (public space)</td>
<td>Slow</td>
<td>600</td>
</tr>
</tbody>
</table>

Table E.2 — Factors $A_m$

<table>
<thead>
<tr>
<th>$\delta_m$</th>
<th>Function of Active Fire Fighting Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{m1}$</td>
<td>Independent Water Suppression</td>
</tr>
<tr>
<td>$\delta_{m2}$</td>
<td>Automatic Fire Detection &amp; Alarm</td>
</tr>
<tr>
<td>$\delta_{m3}$</td>
<td>Automatic Alarm Transmission to Fire Brigade</td>
</tr>
<tr>
<td>$\delta_{m4}$</td>
<td>Work Fire Brigade</td>
</tr>
<tr>
<td>$\delta_{m5}$</td>
<td>Off Site Fire Brigade</td>
</tr>
<tr>
<td>$\delta_{m6}$</td>
<td>Safe Access Routes</td>
</tr>
<tr>
<td>$\delta_{m7}$</td>
<td>Fire Fighting Devices</td>
</tr>
<tr>
<td>$\delta_{m8}$</td>
<td>Smoke System</td>
</tr>
<tr>
<td>$\delta_{m9}$</td>
<td>Smoke System</td>
</tr>
<tr>
<td>$\delta_{m10}$</td>
<td>Smoke System</td>
</tr>
</tbody>
</table>

Table E.4 — Fire load densities $q_x$ [MJ/m²] for different occupancies

<table>
<thead>
<tr>
<th>Occupancy</th>
<th>Average $q_x$ [MJ/m²]</th>
<th>80% Fractile $q_x$ [MJ/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dwelling</td>
<td>370</td>
<td>494</td>
</tr>
<tr>
<td>Hospital (room)</td>
<td>230</td>
<td>280</td>
</tr>
<tr>
<td>Hotel (room)</td>
<td>310</td>
<td>377</td>
</tr>
<tr>
<td>Library</td>
<td>1,500</td>
<td>1,824</td>
</tr>
<tr>
<td>Office</td>
<td>420</td>
<td>511</td>
</tr>
<tr>
<td>Classroom of a school</td>
<td>285</td>
<td>347</td>
</tr>
<tr>
<td>Shopping centre</td>
<td>500</td>
<td>730</td>
</tr>
<tr>
<td>Theatre (cinema)</td>
<td>300</td>
<td>365</td>
</tr>
<tr>
<td>Transport (public space)</td>
<td>100</td>
<td>122</td>
</tr>
</tbody>
</table>

NOTE: Gumbel distribution is assumed for the 80% fractile.

Fire model: EN1991-1-2 Approach

RHR (MW)

One-zone fire model

OZONE - $Q=750$ MJ/m²

OZONE - $Q=278$ MJ/m²

$t_R=30$ min
Summary and Conclusions

- Fire Safety Engineering, in accordance with Italian and European standard, allows the definition of safety goals and different performance levels, associated to defined design fire scenarios.

- The identification of design fire scenarios is carried out by means of Fire Risk Assessment, applying the event tree approach and the risk ranking evaluation according to ISO-16732 Guidelines: it has been shown that different design fire scenarios may be related to different fire performance levels (e.g. resistance of structures for highest risk fire scenario and limited damage for the most probable fire scenario).

- The choice of design fire scenarios determines the identification of key events that characterise the fire and differentiate it from other possible fires.

- Traditional Eurocode approach concerns the mechanical resistance and stability of structures, with reference to a single fire event, in which the effective value of fire load is modified in a semi-probabilistic way by means of partial safety factors, in order to take into account the events that can affect fire development.

- A comparison between the two approaches has been proposed.


• E. NIGRO, G. CEFARELLI, A. FERRARO, I. DEL PRETE, D. SANNINO, G. MANFREDI. Application of Structural Fire Engineering to an Italian Tall Office Building. 7th International Conference on Structures in Fire (SIF'2012), Zurich, Switzerland, June 6-8, 2012, p. 13-22. Editors: M Fontana, A. Frangi, M. Knoblach. Printed and bound by ETH Zurich. DOI: 10.3929/eth-a-0070501097.Fire Safety Engineering, in accordance with Italian and European standard, allows the definition of safety goals and different performance levels, associated to defined design fire scenarios.
Thanks for your attention