ADHESION AT HIGH TEMPERATURE OF FRP BARS STRAIGHT OR BENT AT THE END OF CONCRETE SLABS

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• The paper deals with the structural behaviour of concrete slabs reinforced with FRP bars or grids in the case of high temperatures, due to fire event.

• The mechanical properties of FRPs deteriorate when high temperatures arise in those materials, resulting in a significant decrease of performances of the FRP-reinforced structural members.

• Even if several international codes are available for the design of concrete structures reinforced with FRP bars, few provisions and calculation models taking account of fire condition are suggested.

Within a research program the authors have already tested in fire condition six concrete slabs reinforced with GFRP bars, characterized by different values of concrete cover and anchoring length, by exposing them to heat in a furnace according to the time-temperature curve ISO834.

Based on such results, three further fire tests have been recently carried out on three slabs reinforced with GFRP bars bent at the end of the member, in order to improve the anchorage of the bars within the short zone not directly exposed to fire.

In the following the results of all the fire tests are summarized making possible a comparison between the different anchorage efficiency.
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**Background**

over 40 thermocouples for each slab

**Instrumentation**

- Thermocouples on bars
- Thermocouples in concrete
- Strain gauges

**Experimental program**

**Experimental results**

**Conclusions**

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**Image:**

- Top view of FRP bars in a concrete slab with thermocouple locations marked.
- Thermocouple locations labeled A to M.
- Instrumentation diagram showing bar and concrete locations.

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**Diagram:**

- Grid representation of a concrete slab with bar and thermocouple placements.
- Thermocouple locations marked with circles.
- Bar and concrete details shown in the lower left corner of the diagram.

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**Chart:**

- Thermocouple numbers: 15 to 21.
Parameters

- Concrete cover
- Length of zone outside the furnace
- Bars type (straight or bent)
- Fire load level $\eta_{fi} = \frac{M_{Ed,fi}}{M_{Rd}}$

Note: A continuous reinforcement from side to side of the concrete element is used.
## Background

**Geometrical properties**
- Slabs thickness = 180 mm
- Slabs width = 1250 mm
- Span length = 3200 mm

## Experimental program

<table>
<thead>
<tr>
<th>Set</th>
<th>Slab</th>
<th>Concrete cover [mm]</th>
<th>Anchorage length [mm]</th>
<th>Longitudinal (diameter/spacing) [mm/mm]</th>
<th>Bars no.</th>
<th>M_{Rd} [kNm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>S1</td>
<td>32</td>
<td>250 straight bars</td>
<td>Φ12/150</td>
<td>9</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td></td>
<td></td>
<td>Φ12/225</td>
<td>6</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>S4</td>
<td>51</td>
<td>500 straight bars</td>
<td>Φ12/125</td>
<td>10</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>S5</td>
<td></td>
<td></td>
<td>Φ12/200</td>
<td>7</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>S6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>S7</td>
<td>32</td>
<td>250 bent bars</td>
<td>Φ12/150</td>
<td>9</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>S8</td>
<td></td>
<td></td>
<td>Φ12/225</td>
<td>6</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>S9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Test matrix

### Materials
- Concrete C35/45
- GFRP bars (E glass fibers and orthophthalic polyester resin, T_{g} = 100°C)

### Geometrical properties
- Slabs thickness = 180 mm
- Slabs width = 1250 mm
- Span length = 3200 mm

### Experimental results
- Set Slab
- Concrete cover
- Anchorage length
- Longitudinal (diameter/spacing)
- Bars no.
- M_{Rd}

### Background
- Not exposed to fire
- ISO834

### Test matrix
- Straight bars
- Bent bars

### Conclusions
- Adhesion at high temperature of FRP bars straight or bent at the end of concrete slabs

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Experimental results

Load

Zone of slab un-exposed to fire

Zone of slab exposed to fire

ISO834

Fire Load level

\[ \eta_{fi} = \frac{M_{Ed,fi,t}}{M_{Rd}} \]

S1, S4, S7 \[ \rightarrow 10\% \text{ of } M_{Rd} \text{ (own weight)} \]

S2, S5, S8 \[ \rightarrow 40\% \text{ of } M_{Rd} \text{ (F=17.5kN)} \]

S3, S6, S9 \[ \rightarrow 60\% \text{ of } M_{Rd} \text{ (F=17.5kN)} \]
**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*
Observations after tests concerning the anchorage zone – STRAIGHT BARS

Slabs S1-S2-S3: Pull out of bars

\[ c = 32\text{mm}, \quad L_{\text{unexp}} = 250\text{mm} \]

Section: end of slab

- Holes after bars pulled out
- Cracks on transverse section at the end of the slab (correspondence crack/bar)

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Observations after tests concerning the anchorage zone – BENT BARS

Slabs S7-S8-S9: no pull out of bars
\[ c = 32\text{mm}, \ L_{\text{unexp}} = 250\text{mm} \]

Cracks on transverse section at the end of the slab in correspondence of each bar without pull out.
**Background**

**Experimental program**

**Experimental results**

**Conclusions**

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**ADHESION AT HIGH TEMPERATURE OF FRP BARS STRAIGHT OR BENT AT THE END OF CONCRETE SLABS**


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**Time-deflection diagram**

**Set I**

![Graph showing deflection and load increment for Set I with Slabs S1, S2, S3.](image)

**Set II**

![Graph showing deflection and load increment for Set II with Slabs S4, S5, S6.](image)

**Set III**

![Graph showing deflection and load increment for Set III with Slabs S7, S8, S9.](image)

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<table>
<thead>
<tr>
<th>Set</th>
<th>Slab</th>
<th>c [mm]</th>
<th>(L_{unexp} [mm])</th>
<th>Bar’s end</th>
<th>STAGE 1</th>
<th>STAGE 2</th>
<th>Type of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>S1</td>
<td>32</td>
<td>250</td>
<td>Straight</td>
<td>(\eta_{fi} = 50%)</td>
<td>(t_e = 10 \text{ min})</td>
<td>(\eta_{fail} = 55 %)</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>32</td>
<td>250</td>
<td>Straight</td>
<td>(\eta_{fi} = 60%)</td>
<td>(t_e = 40 \text{ min})</td>
<td>(\eta_{fail} = 50 %)</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>32</td>
<td>250</td>
<td>Straight</td>
<td>(\eta_{fi} = 60%)</td>
<td>(t_e = 60 \text{ min})</td>
<td>-</td>
</tr>
<tr>
<td>II</td>
<td>S4</td>
<td>51</td>
<td>500</td>
<td>Straight</td>
<td>(\eta_{fi} = 10%)</td>
<td>(t_e = 10 \text{ min})</td>
<td>(\eta_{fail} = 100 %)</td>
</tr>
<tr>
<td></td>
<td>S5</td>
<td>51</td>
<td>500</td>
<td>Straight</td>
<td>(\eta_{fi} = 40%)</td>
<td>(t_e = 120 \text{ min})</td>
<td>(\eta_{fail} = 85 %)</td>
</tr>
<tr>
<td></td>
<td>S6</td>
<td>51</td>
<td>500</td>
<td>Straight</td>
<td>(\eta_{fi} = 60%)</td>
<td>(t_e = 120 \text{ min})</td>
<td>100 *</td>
</tr>
<tr>
<td>III</td>
<td>S7</td>
<td>32</td>
<td>250</td>
<td>Bent</td>
<td>(\eta_{fi} = 10%)</td>
<td>(t_e = 10 \text{ min})</td>
<td>(\eta_{fail} = 60 %)</td>
</tr>
<tr>
<td></td>
<td>S8</td>
<td>32</td>
<td>250</td>
<td>Bent</td>
<td>(\eta_{fi} = 40%)</td>
<td>(t_e = 180 \text{ min})</td>
<td>45 *</td>
</tr>
<tr>
<td></td>
<td>S9</td>
<td>32</td>
<td>250</td>
<td>Bent</td>
<td>(\eta_{fi} = 60%)</td>
<td>(t_e = 180 \text{ min})</td>
<td>90</td>
</tr>
</tbody>
</table>

**STAGE 1: constant load**

**STAGE 2: increasing load**

\(\eta_{fi} = M_{Ed,fi,t}/M_{Rd}\) (constant load)

\(\eta_{fail} = M_{Ed,fi,t}/M_{Rd}\) (at failure)

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\(*\) Residual strength

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**At the end of concrete slabs**

Main remarks on temperature levels and concrete cover

Comparison between thermal field in two typologies of slabs

- **Cover**
  - T_g after about 15min for S2
  - T_g after about 25min for S5

- **Cover thickness affects the time needed to achieve T_g in the bars**

- **In the unexposed zone T_g in the bars is not achieved**

- **In the zone exposed to fire the overlapping of bars cannot be used**

- **T_g = 100°C**
**Background**

**Experimental program**

**Experimental results**

**Conclusions**

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**Thermal behaviour**

- **Concrete cover** was confirmed particularly meaningful for the protection provided to FRP bars, allowing to delay the attainment of high temperature values in the bars.

- In a part of the **zone not directly exposed** to fire (as a function of fire exposure time) the bars didn’t attain the **glass transition temperature** $T_g$.

**Mechanical behaviour**

- When the bars temperature achieves the glass transition value, there is a significant **reduction of bond** between FRP bars and concrete.

- The mechanical behaviour of tested slabs has been characterized by the migration of bars stresses from the zone directly exposed to fire to the anchorage zone *(i.e. the zone not directly exposed to fire action)*.

- When the glass transition temperature is achieved in the zone directly exposed to fire, the structural behaviour depends mainly on the length of unexposed zone (anchorage length) and on the bars type (straight or bent).

**Structural details**

- **The anchorage obtained simply by bending bars at the end of member in a short zone (250mm) allowed to attain a good structural behavior in case of fire, equivalent to that shown by slabs characterized by a large anchoring length (500mm).**

- **The production process allowing the bar to be bent is easily implemented by FRP bars manufacturers owing technologically advanced systems.**