SOME SOLUTIONS FOR THE REHABILITATION OF TWO METHANE TANKS

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ABSTRACT
The paper deals with the rehabilitation of two methane tanks with Carbon Fiber wraps and Glass Fiber wraps by partial wrapping. The reason for strengthening these tanks is primarily lack of compliance with new code requirements regarding the concrete compressive strength. The concrete compressive strength of these tanks is determined using the combination of ultrasonic pulse velocity method and rebound hammer test. The characteristics of confined concrete are calculated according with FIB Bulletin 14/2001 and ACI 440.2R-02 (2002) code and then the results are compared. The results reveal that the rehabilitation solution with Glass Fiber wraps is more effective than the rehabilitation with Carbon Fiber wraps in terms of ductility and the rehabilitation solution with CFRP fabrics is more effective than the other one in terms of concrete compressive strength.

Keywords: non-destructive tests, rehabilitation, CFRP, GFRP, confinement, methane tanks

INTRODUCTION
Confinement of concrete is an efficient technique used to increase the compressive strength and ductility of reinforced concrete members. In the case of circular cross sections, confinement can be achieved by applying external FRP wraps continuously all over the surface or discontinuously as strips. The paper aims to compare the characteristics of confined concrete in the case of partial wrapping of two methane tanks with CFRP and GFRP fabrics. The concrete compressive strength of the tanks is determined using the results of ultrasonic pulse velocity method and rebound hammer test. The characteristics of confined concrete are calculated according with FIB Bulletin 14/2001 and ACI 440.2R-02 (2002) code and then the results are compared.

MATERIALS AND METHODS
1. Degradations of the tanks and their causes
In a previous work [1] there are presented the deficiencies of two methane tanks from Wastewater Treatment Plants Oradea. These tanks are cylindrical structures 10.75 m in height and 19 m in diameter. The main deficiency consists in concrete degradation caused by the action of temperature variation, inefficient use of insulating materials and an inefficient fluoride silicatization of the inner surface of the tanks. This degradation decreases the sustainability of these types of structures. The main reason for rehabilitation of these tanks is lack of compliance with new code requirements regarding the concrete compressive strength.

2. Determination of concrete compressive strength
The non-destructive testing is the most practical and widely used because it estimates the strength of concrete without destroying the structure. Some combined methods were developed, in order to estimate concrete strength by using the results of two or more non-destructive tests.

The concrete compressive strength of the methane tanks was determined using the combination of ultrasonic pulse velocity method and rebound hammer test.
The ultrasonic pulse velocity method involves measuring the travel time over a known path length of a pulse of ultrasonic waves. The pulses are introduced into the concrete by a piezoelectric transducer and a similar transducer acts as receiver to monitor the surface vibration caused by the arrival of the pulse [2]. The ultrasonic pulse velocity measurement were conducted using an ultrasonic instrument from PROCEQ company with transducers with 50 mm in diameter, and had maximum resonant frequency of 54 kHz (fig. 1).

The rebound hammer test involves measuring the rebound height of a hammer, that is dropped from a fixed height above the test surface. The degree of rebound is an indicator of the hardness of the concrete. The rebound number was determined using Digi-Schmidt 2000 rebound hammer ND/LD model (fig. 2).

The results of non-destructive tests are presented in the table 1.

<table>
<thead>
<tr>
<th>Structural element</th>
<th>Cross section</th>
<th>n</th>
<th>d (cm)</th>
<th>t (µs)</th>
<th>v (m/s)</th>
<th>$R_{c,ref}$ (N/mm²)</th>
<th>$R_{c,med}$ (N/mm²)</th>
<th>Concrete class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane tank</td>
<td>1</td>
<td>41.33</td>
<td>30</td>
<td>86.7</td>
<td>3460</td>
<td>17.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>43.66</td>
<td>30</td>
<td>84.7</td>
<td>3540</td>
<td>22.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>44.3</td>
<td>30</td>
<td>83.1</td>
<td>3610</td>
<td>23.9</td>
<td>25.52</td>
<td>C16/20</td>
</tr>
</tbody>
</table>

where: n – rebound number, 
d – distance between transducers, 
t – travel time of a pulse of ultrasonic waves,
v - ultrasonic pulse velocity,
\( R_{c_{\text{ref}}} \) – reference value of concrete compressive strength,
\( R_{c_{\text{med}}} \) – medium value of concrete compressive strength.

3. Rehabilitation solution

Fiber reinforced polymer (FRP) composites are widely used in strengthening solutions due to some advantages such as their features in terms of strength, corrosion resistance, lightness and ease of application. FRP composites can consist of epoxy, polyester or vinyl-ester matrices and carbon, glass or aramid fibers. These composites can be manufactured as flexible sheets or fabrics (wraps) with fibers in one or at least two different directions.

CFRP fabrics consist of two components, epoxy based impregnating resin and carbon fiber fabric and can be used to strengthen reinforced concrete structures or to confine concrete.

GFRP wrap is an unidirectional woven glass fiber fabric for structural strengthening. GFRP wrap can be used for every kind of strengthening requirement; it has an excellent cost performance and it is non conductive [3].

The rehabilitation solution proposed for these tanks is partial wrapping with CFRP and GFRP fabrics. The CFRP and GFRP dimensions that were calculated according with FIB Bulletin 14/2001 and ACI 440.2R-02 (2002) are as follow:

**FIB Bulletin 14/2001**
- SikaWrap Hex 100C: thickness 0.76 mm, width 150 mm, centre-to-centre distance 450 mm and thickness 0.38 mm, width 150 mm, centre-to-centre distance 225 mm;
- SikaWrap Hex 100G: thickness 1.08 mm, width 150 mm, centre-to-centre distance 450 mm and thickness 0.72 mm, width 150 mm, centre-to-centre distance 225 mm

**ACI 440.2R-02**
- SikaWrap Hex 100C: thickness 0.76 mm, width 150 mm, centre-to-centre distance 450 mm and thickness 0.38 mm, width 150 mm, centre-to-centre distance 225 mm;
- SikaWrap Hex 100G: thickness 1.44 mm, width 150 mm, centre-to-centre distance 300 mm and thickness 1.08 mm, width 150 mm, centre-to-centre distance 225 mm.

Arrangements of strips is shown in figure 4.
The characteristics of confined concrete were calculated according with FIB Bulletin 14/2001 [4] and ACI 440.2R-02 (2002) code [5].

The calculus according with FIB Bulletin 14/2001:
The volumetric ratio of FRP jacket \( \rho_j \) is given in Equation (1):

\[
\rho_j = \frac{4 \cdot d_{e} \cdot t_j}{(d_{e}^2 - d_{i}^2) \cdot s} \cdot \frac{b_f}{s}
\]  

where: \( t_j \) – FRP jacket thickness,
\( d_{e} \) – outer diameter of the tank,
\( d_{i} \) – inner diameter of the tank,
\( b_f \) - width of FRP strip in partial wrapping,
\( s \) – pitch in partial wrapping.
The lateral confining pressure $\sigma_l$ was determined using Equation (2):

$$\sigma_l = k_{conf} \cdot \varepsilon_l = k_{conf} \cdot \varepsilon_{fu}$$

(2)

where: $k_{conf}$ – stiffness of the FRP confinement (see Eq. 3),
$\varepsilon_l$ – circumferential strain of the concrete, equal to the strain $\varepsilon_j$ in the FRP jacket,
$\varepsilon_j = 0.017$ (CFRP); $\varepsilon_j = 0.028$ (GFRP).

$$k_{conf} = k_e \cdot \rho_j \cdot \frac{E_{fu}}{2}$$

(3)

where: $E_{fu}$ – modulus of the FRP jacket; $E_{fu} = 230000$ N/mm$^2$ (CFRP),
$E_{fu} = 76000$ N/mm$^2$ (GFRP),
$k_e$ – the confinement effectiveness coefficient that is given in Eq. (4) in case that concrete is partially wrapped:

$$k_e = \left(1 - \frac{s'}{2 \cdot D}\right)^2$$

(4)

where: $s'$ – clear spacing between the FRP wraps,
$D$ – diameter of the tank.
The confined peak strength $f_{cc}$ is expressed with an equation (Mander et al. 1988) that has been extensively tested against experimental data [5]:

$$f_{cc} = f_{co} \left( 2.254 \cdot \sqrt{1+7.94 \cdot \frac{\sigma_l}{f_{co}} - 2 \cdot \frac{\sigma_l}{f_{co}} - 1.254} \right)$$  \hspace{1cm} (5)

where: $f_{co}$ – unconfined concrete strength; $f_{co}=10.67$ N/mm$^2$ (C16/20).

The compressive strain $\varepsilon_{cc}$ at confined peak strength $f_{cc}$ is given in Eq. (6):

$$\varepsilon_{cc} = \varepsilon_{co} \cdot \left[ 1 + 5 \cdot \left( \frac{f_{cc}}{f_{co}} - 1 \right) \right]$$ \hspace{1cm} (6)

where: $\varepsilon_{co}$ – compressive strain of unconfined concrete.

$$\varepsilon_{co} = \frac{f_{co}}{E_c}$$ \hspace{1cm} (7)

where: $E_c$ – modulus of elasticity of concrete; $E_c=27000$N/mm$^2$ (C16/20).

The formula for ultimate axial compressive strain of confined concrete (Spoelstra and Monti, 1999) [6] is:

$$\varepsilon_{cu} = \varepsilon_{co} \cdot \left[ 2 + 1.25 \cdot \frac{E_c}{f_{co}} \cdot \varepsilon_{tu} \cdot \sqrt{\bar{f}_l} \right]$$ \hspace{1cm} (8)

where: $\bar{E}_c$ - concrete tangent modulus:

$$\bar{E}_c = \frac{E_c}{f_{co}}$$ \hspace{1cm} (9)

$\bar{f}_l$ - maximum confining stress:

$$\bar{f}_l = \frac{f_l}{f_{co}}$$ \hspace{1cm} (10)

**The calculus according with ACI 440.2R-02 (2002)**

The design ultimate tensile strength of the FRP material $f_{fu}$ is determined using the environmental-reduction factor for the appropriate fiber type and exposure condition [7].

$$f_{fu} = C_E \cdot f_{fu}^*$$ \hspace{1cm} (11)

where: $f_{fu}^*$ – ultimate tensile strength of the FRP material as reported by the manufacturer,

$C_E$ – environmental-reduction factor.
The design rupture strain can be written as in Eq. (12):

$$\varepsilon_{fu} = C_E \cdot \varepsilon^*_{fu}$$  \hspace{1cm} (12)

where: $\varepsilon^*_{fu}$ – ultimate rupture strain of the FRP reinforcement.

The volumetric ratio of FRP jacket is given in Eq. (13):

$$\rho_f = \frac{4 \cdot d_c \cdot n \cdot t_f \cdot b_f}{d_e^2 - d_i^2} \cdot \frac{s}{2}$$  \hspace{1cm} (13)

where: $t_f$ – FRP jacket thickness,
$n$ – numbers of plies.

The confining pressure $\sigma_l$ is given in Eq. (14):

$$f_l = \frac{k_a \cdot \rho_f \cdot \varepsilon_{fu} \cdot E_f}{2}$$  \hspace{1cm} (14)

where: $E_{fu}$ – modulus of the FRP jacket,
$\varepsilon_{fe}$ – effective strain level in FRP reinforcement, equal to the design rupture strain of FRP reinforcement; $\varepsilon_{fe} = \varepsilon_{fu}$,
$k_a$ – efficiency factor; $k_a=1$ for circular sections.

The apparent confined concrete strength $f'_{cc}$ for a circular concrete member wrapped with an FRP jacket is expressed with Eq. (15):

$$f'_{cc} = f'_c \left( 2.25 \cdot \sqrt{1 + 7.9 \cdot \frac{f_l}{f'_c} - 2 \cdot \frac{f_l}{f'_c} - 1.25} \right)$$  \hspace{1cm} (15)

where: $f'_c$ – specified compressive strength of concrete; $f'_c = 10.67$ N/mm$^2$.

The maximum usable compressive strain in concrete for FRP-confined reinforced concrete members is given in Eq. (16):

$$\varepsilon'_{cc} = \frac{1.71 \cdot (5 \cdot f'_{cc} - 4 \cdot f'_c)}{E_c}$$  \hspace{1cm} (16)

**RESULTS AND DISCUSSIONS**

The results for both rehabilitation solutions are presented in Table 2:
where: \( n \) – number of FRP plies, 
\( b_f \) - width of FRP strip in partial wrapping, 
\( s' \) – clear spacing between FRP wraps, 
\( f_{cc}, f'_{cc} \) – confined concrete compressive strength, 
\( \varepsilon_{cc}, \varepsilon'_{cc} \) – ultimate axial compressive strain of confined concrete.

Based on the results presented in table 2 the following conclusions are drawn:

- In order to provide confinement strengthening it is required a larger amount of GFRP fabrics in the case of calculus according with ACI 440.2R-02 (2002) than in the case of calculus according with FIB Bulletin 14/200. ACI 440.2R-02 (2002) code accounts for environmental degradation and long-term durability by suggesting reduction factors \( C_E \) for various environments. In the case of wastewater treatment plants this reduction factor is less than 1 and that decreases the design rupture strain.

- The ultimate axial compressive strain of confined concrete and the confined concrete compressive strength obtained from the calculus according with FIB Bulletin 14/200 are bigger than in the case of calculus according with ACI 440.2R-02 because ACI code doesn’t specify how the confined concrete modulus changes beside the unconfined one. FIB 14 is taking into account this change by calculating a concrete tangent modulus.

- The number of CFRP plies required to provide confinement strengthening is less than the number of GFRP plies in both cases of calculus.

- In the case of wrapping with CFRP strips the ultimate axial compressive strain of confined concrete calculated according with FIB Bulletin is less than in the case of wrapping with GFRP strips. The compressive strength and ultimate axial compressive strain of confined concrete obtained from the calculus according with ACI 440.2R-02 are bigger in the case of wrapping with CFRP than in the case of wrapping with GFRP.

**CONCLUSIONS**

The rehabilitation solution by partial wrapping with CFRP fabrics is more effective than the solution with GFRP in terms of concrete compressive strength and the solution with GFRP is more effective in terms of ductility. ACI 440.2R-02 code is more restrictive than FIB Bulletin 14/2001. The american code ACI 440.2R-02 accounts for environmental degradation by suggesting a reduction factor \( C_E \) that decreases the design rupture strain.

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