Steel Fibers Reinforced Concrete Pipes - Experimental Tests and Numerical Simulation

Zdrenghea Doru 1

1 Technical University of Civil Engineering of Bucharest, Bdv. Lacul Tei, nr. 122-124, Bucharest, Romania
zdrengheadoru@yahoo.com

Abstract. The paper presents in the first part a state of the art review of reinforced concrete pipes used in micro tunnelling realised through pipes jacking method and design methods for steel fibres reinforced concrete. In part two experimental tests are presented on inner pipes with diameters of 1410mm and 2200mm, and specimens (100x100x500mm) of reinforced concrete with metal fibres (35 kg / m³). In part two experimental tests are presented on pipes with inner diameters of 1410mm and 2200mm, and specimens (100x100x500mm) of reinforced concrete with steel fibres (35 kg / m³). The results obtained are analysed and are calculated residual flexural tensile strengths which characterise the post-cracking behaviour of steel fibres reinforced concrete. In the third part are presented numerical simulations of the tests of pipes and specimens. The model adopted for the pipes test was a three-dimensional model and loads considered were those obtained in experimental tests at reaching breaking forces. Tensile stresses determined were compared with mean flexural tensile strength. To validate tensile parameters of steel fibres reinforced concrete, experimental tests of the specimens were modelled with MIDAS program to reproduce the flexural breaking behaviour. To simulate post-cracking behaviour was used the method \( \sigma - \varepsilon \) based on the relationship stress - strain, according to RILEM TC 162-TDF. For the specimens tested were plotted \( F - \delta \) diagrams, which have been superimposed for comparison with the similar diagrams of experimental tests.

The comparison of experimental results with those obtained from numerical simulation leads to the following conclusions: - the maximum forces obtained by numerical calculation have higher values than the experimental values for the same tensile stresses; - forces corresponding of residual strengths have very similar values between the experimental and numerical calculations; - generally the numerical model estimates a breaking force greater than that obtained in the experimental tests. Experimental and numerical studies are used to establish the residual characteristic flexural tensile strength minimum guaranteed and limits of applicability of concrete pipes reinforced with steel fibres used in various field and loading situations.

1. Introduction
The world trend in our days is to concentrate the world’s population into urban centres and to connect them through fast communications ways such as roads and railways.

The development of the urban centres requires the realization of a new nets or refurbishment the existing one of sewers, water supplies, gas or realization of a pedestrian passages or footbridges, in more and more difficult conditions mainly because of explosive grow of road traffic and perturbation of current activities.
The execution of these micro-tunnels by using a method without open-trench, as the method of pipes jacking, reducing considerable this negative impact, making easier the execution of such works by a minimum perturbation on surface and lower costs.

By introducing of such technologies and new solutions (pressurized and mechanized shields, intermediate installations for pushing and lubrication), the pipes jacking method was used for long distances, for different diameters and with different types of reinforcement, becoming one of the most popular method of underground installation of pipes in most of the countries and also in Romania.

The concrete pipes, used for micro-tunnels executed with pipes jacking method, are most likely executed in prefabricated plants.

For pipes reinforcing are used different types of reinforcement:
- Simple circular cage on inner (a);
- Double circular cage on inner, extrados and elliptic (b);
- Simple elliptic reinforcement cage (c);
- Double circular cage on inner and extrados (d);
- Double circular cage on inner and extrados, plus local reinforcements on inner and extrados for stretched areas (e). [1]

![Figure 1. Classical reinforcement of pipes](image)

The actual preoccupation of researchers in the field is to use the steel fibres for reinforcing of pipes. In this context it was necessary substantiation of a conception adequate of conditions, concerning execution of micro tunnels in various ground conditions and loads, as well as clarification of the limits and domains of applicability of such underground structures reinforced with steel fibres, such that to be obtained optimum solutions both on structural and conceptual criteria and also economics criteria in safety and reliability conditions [2].

The most important parameters used for designing of reinforced structure concrete with steel fibres are: the ratio between the fibre length and diameter \((l/d_f)\) and used quantity of fibres reported to one cubic meter of concrete. Both parameters are limited by the fresh concrete workability, which decreases with the increasing of fibres quantity [2].
The concrete reinforced with fibres have a similar behaviour to compression as classic reinforced concrete. The concrete reinforced with fibres have a better behaviour to stretching compare with simple (not-reinforced) concrete [2].

The experimental researches showed that the beginning of cracks and fissures is starts at highest values of load when we are speaking about fibres reinforced concrete. Nevertheless, from a point of view of reaching the ultimate limit status, the steel fibres cannot replace the classic reinforcement.

The fibre reinforced concrete has a series of advantages:

- because of fact that each fibre is contained individual in concrete matrix and is protected by the concrete around it, the propagation of corrosion from a rebar to other it is not possible.
- the steel fibres are slowing down the extend of micro-fissures and prevent the transport of moisture [2].

Also, the studies confirmed that by adding of steel fibres in concrete (dosage increasing) it is increased the residual resistance.

Typical applications in case when the steel fibres can be used as unique reinforcement include concrete slabs and linings for tunnels and micro-tunnels.

In other applications the steel fibres are used as a complement to conventional reinforcement, where, in some cases, the conventional reinforcement can be reduced.

In attempts for previewing the properties of the material for SFRC designing, were proposed different approaches by the technical committees. The proposals can be classified in two main approaches as follows:

- The $\sigma - \varepsilon$ method, based on relation and diagram stress-strain, in which the testing of release to a relationship load-deflection or load-fissure opening (CMOD) it is the base to establish the residual or equivalent flexural strengths;
- The $\sigma - w$ method, based on relation and diagram stress-fissure opening; [2]

When it is compared these two base approaches ($\sigma - \varepsilon$ and $\sigma - w$) it is obviously from the point of view of practical simplicity designing that the stress-strain method it is faster and less complicated.

All investigated proposals are available for FRC with a behaviour to deformation fragile and are designated mainly for designing with steel fibres, even if the Italian proposal it is available also for FRC which represent a ductile deformation and can be applied also to other types of fibres, not only to steel fibres [2].

The fibre reinforced concrete it is classified using two parameters which are determined with residual flexural strengths $f_{R,1}$ and $f_{R,4}$. The first parameter FL0.5 it is given by the $f_{R,1}$ reduced to the nearest multiple of 0.5 MPa, and can vary between 1 and 6 MPa. The second parameter FL3.5 it is given by the value $f_{R,4}$ reduced to the nearest multiple of 0.5 MPa, and can vary between 0 and 4 MPa [3].

These two parameters denote the minimum guaranteed characteristic residual strengths at CMOD values of 0,5 and 3,5 mm, respectively. The residual strengths class is represented as FL, FL0.5 / FL3.5, with the corresponding values of the two parameters [3].

Although, the usage of steel fibres reinforced concrete it is already a common practice in construction field, not yet been established designing norms to be general accepted.

To understand the behaviours of steel fibre reinforced concrete pipes were taken researches consist of testing of pipes with diameters by 1410 mm and 2200 mm accompanied by the testing of some samples with dimensions of 100x100x500 mm.

The experimental tests were accompanied by numerical simulations.

2. The bending test for pipes and samples.
The test of moulded pipes having inner diameters 1400 mm and 2200 mm it was done according with SR EN 1916 for determination of breaking force.
Figure 2. Testing scheme

Figure 3. Pipe mounted on stand

Table 1. The testing results for both pipes

|                         | Diameter pipe D_i=1410mm De=1690 mm, L = 1.50 m | Diameter pipe D_i=2200mm De= 2520 mm, L = 2.00 m |
|-------------------------|-------------------------------------------------|--------------------------------------------------|
| Force for fissure of 1 mm appearing | P_1=92 KN                                          | P_1=100 KN                                        |
| Ultimate load (breaking force)       | P_2=92 KN                                          | P_2=100 KN                                        |
| Total load uniform distributed       | F=75.69 KN/m                                        | F=58.69 KN/m                                      |
| Horizontal deformation (diameter elongation) | d_7 = 11,6 mm                                      | d_7 = 8,8 mm                                      |
| Vertical deformation (diameter shortage) | d_8 = 10,8 mm                                      | d_8 = 9 mm                                        |

In figures 4 are represented the diagrams of elongation force for both pipes after stand test.

Figure 4. Force-elongation diagrams (a) pipe D_i=1410, (b) pipe D_i=2200
The testing of samples was done according with SR EN 12390-5 Testing on mature concrete. Part 5.

To verify the flexural strength needed a continuous series by minimum three samples. The flexural strength resulted from testing of those three samples are presented in table below.

**Table 2. Flexural strength**

| Samples       | Flexural strength |
|---------------|-------------------|
| Sample no. 1  | 5,902 N/mm²       |
| Sample no. 2  | 6,725 N/mm²       |
| Sample no. 3  | 5,907 N/mm²       |

The diagrams strength-deformation for these three samples is presented in figure 6.

According RILEM TC 162-TDF, the residual flexural tensile strength $f_{R,i}$ it is an important parameter which define the behaviour post-cracking of the concrete reinforced with steel fibres.

The residual flexural tensile strength $f_{R,i}$ respectively $f_{R,4}$ are defined at the following crack mouth opening displacement ($\delta_{i}$) or mid span deflections ($\delta_{i,1}$):

- CMOD 1 = 0.5 mm, $\delta_{R,1} = 0.46$ mm
- CMOD 4 = 3.5 mm, $\delta_{R,4} = 3.00$ mm

and can be determined by means of the following expression:

$$f_{R,i} = \frac{3F_{R,i}L}{2bh_{sp}^2}$$ (N/mm²)

where

- $b$ – width of the sample (mm)
- $h_{sp}$ – the distance between fissure’s peak and upper part of section (mm)
- $L$ = span of the sample (mm). [3]

The values of the residual flexural tensile strength resulted from testing of those three samples are presented in table below.
Table 3. Tensile stress from bending ($\sigma_m$) and residual flexural tensile strengths $f_{R,1}$ respectively $f_{R,4}$

| Samples  | $\sigma_m$ [N/mm²] | $f_{R,1}$ [N/mm²] | $f_{R,4}$ [N/mm²] |
|----------|---------------------|--------------------|--------------------|
| Sample 1 | 5,902               | 4,132              | 2,374              |
| Sample 2 | 6,725               | 5,144              | 4,203              |
| Sample 3 | 5,907               | 3,804              | 1,752              |
| Average value | 6,178 | 4,36              | 2,776              |

Average value $f_{R,4} = 2,776 N / mm^2$.

For calculation at ultimate load capacity, the residual flexural tensile strengths, ($f_{R,4}$) is divided to partial safety coefficient $\gamma = 1,3$ resulting the residual characteristic flexural tensile strength minimum guaranteed $f_{ctd} = 2,135 N/mm^2$

3. Numerical simulations of tested pipes and samples.

For simulation of tear test for these two pipes, these were modelled with program MIDAS GTS-NX, having the real dimensions and load scheme, according with SR EN 1916.

The 3D adopted model taken into account the loads which were obtained in the experimental tests shown in Table 1.

Numerical simulation takes into consideration an elastic linear behaviour of the steel fibre reinforced concrete, until when are achieved the breaking forces from experimental tests.

The uniform distributed force (which is a result from concentrate force and support weight) applied on pipe is $F = 75.69 KN/m$.

![Figure 7. Pipe model](image)

The values of unitary stress $s$ as results of calculation with program MIDAS GTS-NX are presented below.

| PIPE  | $\sigma_1$ [N/mm²] | $\sigma_2$ [N/mm²] |
|-------|--------------------|--------------------|
| Di=1400mm inner | +4,87 | -4,78 |
| Di=1400mm outer  | +2,45 | -3,14 |

| PIPE  | $\sigma_1$ [N/mm²] | $\sigma_2$ [N/mm²] |
|-------|--------------------|--------------------|
| Di=2200mm inner | +5,63 | -5,47 |
| Di=2200mm outer  | +3,13 | -3,77 |

Maximum tensile stress for both pipes are having lower values than medium tensile stress from bending (6,178 N/mm²) which correspond to forces for appearance of first fissure from sample’s tests.

For validation of tensile parameters of steel fibre reinforced concrete, the experimental tests of samples were modelled with program MIDAS, in idea to reproduce the breaking behaviour from flexure of samples.

For simulation of testing for these 3 samples, these were modelled according with dimensions and scheme from the real test.
For all three models, the initial response is linear elastic until the tensile stress are achieved, corresponding with the appearance of first fissure from experimental test, after this starting the post-cracking behaviour.

To simulate the post-cracking behaviour, was used the method \( \sigma - \epsilon \) method based on relation stress – deformation, according with RILEM TC 162-TDF.

The points which define the diagram \( \sigma - \epsilon \) were determinate according with the formulas from RILEM TC 162-TDF.

\[
\sigma_1 = \sigma_m \\
\sigma_2 = 0.45 \cdot f_{R1} \cdot k_h, \text{ where } k_h=1 \\
\sigma_3 = 0.37 \cdot f_{R4} \\
\epsilon_1 = \frac{\sigma_1}{E_c} \\
\epsilon_2 = \epsilon_1 + 0.0001 \\
\epsilon_3 = 0.025 \\
\text{Ec} = 33500 \text{ N/mm}^2
\]

Table 6. The values \( \sigma_m, \sigma_2 \) and \( \sigma_3 \) for drawing the diagram \( \sigma - \epsilon \)

| Sample no. 1 | Sample no. 2 | Sample no. 3 |
|--------------|--------------|--------------|
| \( \sigma_m \) | 5,902        | 6,725        | 5,907        |
| \( \sigma_2 \) | 1,859        | 2,315        | 1,712        |
| \( \sigma_3 \) | 0,878        | 1,550        | 0,650        |

For all three tested samples were drawn the diagrams \( \sigma - \epsilon \) (figure 9).

Figure 9. The stress-deformation diagram

4. The comparison of experimental results with those obtained from numerical simulation.
By the help of calculation formulas from RILEM TC 162-TDF were determinate the forces \( F_{R,1} \) and \( F_{R,4} \) needed for drawing the stress-deformation diagrams:

\[
M = b \cdot 0.66 \cdot h_p \cdot 0.56 \cdot h_p \cdot \sigma_2 \\
F_{R,1} = \frac{M \times 4}{l}
\]

Similar for \( F_{R,4} \)

\[
M = b \cdot 0.9 \cdot h_p \cdot 0.5 \cdot h_p \cdot \sigma_3 \\
F_{R,4} = \frac{M \times 4}{l}
\]
### Table 7. Comparison table with the experimental and numerical values for $F_{\text{max}}$, $F_{R,1}$ and $F_{R,4}$

|                      | Experimental values | Numerical values |
|----------------------|---------------------|------------------|
|                      | Sample no. 1 | Sample no. 2 | Sample no. 3 | Sample no. 1 | Sample no. 2 | Sample no. 3 |
| $F_{\text{max}}$ (breaking) | 13112 | 14946 | 13126 | 17843 | 20334 | 17859 |
| $F_{R,1}$            | 9183 | 11432 | 8452 | 9163.1 | 11407.3 | 8453.7 |
| $F_{R,4}$            | 5277 | 9339 | 3894 | 5270 | 9330.6 | 3899.4 |

For all three tested samples were drawn the diagrams $F - \delta$, which were overlapped, for drawing comparison, with the similar diagrams from the experimental tests (figure 10).

![Diagram](image)

**Figure 10.** The comparison between the experimental and numerical diagrams $F - \delta$, when is used the method $\sigma - \varepsilon$.

The comparison of experimental results with those obtained from numerical simulation highlights the following aspects:

- The maximum forces obtained from numerical calculation are having bigger values than those obtained from experimental calculation for the same values of tensile stresses;
- The forces $F_{R,1}$ and $F_{R,4}$ appropriate to residual resistances $f_{R,1}$ and $f_{R,4}$ are having very close values between numerical and experimental calculations.
- Generally, the numerical model estimates a breaking force bigger than the force obtained in experimental tests.

### 5. Conclusions

The reinforcement with steel fibre of concrete pipes represents a viable solution used more and more often because of incontestable advantages:

- reduction of manpower designated to manufacture the classic reinforced cages;
- reduction of fabrication time;
- costs reduction.

Presented studies consisting from experimental tests and numerical simulations have served to establishing of control parameters, which will be used for calculation of steel fibres reinforced concrete pipes, in different soil situation, loads and depths, with setting limits and areas of applicability.
References

[1] Concrete Pipe Design Manual - Copyright © 1997- Ontario Concrete Pipe Association- http://www.ocpa.com/_resources/OCPA_DesignManual.pdf;
[2] Annette Jansson, Kent Gylltoft "Design methods for fibre-reinforced concrete: a state-of-the-art review".
[3] RILEM TC 162-TDF: Test and design methods for steel fibre reinforced concrete. Materials and Structures / Matériaux et Constructions, Vol. 36, October 2003, pp. 560-567.
[4] De la Fuente Albert, Antonio Domingues de Figueiredo, Antonio Aguado, Climent Molins and Pedro Jorge Chama Neto - Experimentation and numerical simulation of steel fibre reinforced concrete pipes.
[5] De la Fuente Albert, Antonio D. de Figueiredo, Antonio Aguado - Substituing the traditional reinforcement in concrete pipes by using structural fibres. (www.cpi-worldwide.com/en/journals/artikel/36844)
[6] J.A.O. Barros, V.M.C.F. Cunha, A.F. Ribeiro and J.A.B. Antunes - Post-cracking behaviour of steel fibre reinforced concrete, Materials and Structures 38 (January-February 2005) 47-56.