A NEW APPROACH ON CRUSHING STRENGTH TEST FOR FIBRE REINFORCED CONCRETE PIPES

Antonio Figueiredo*, Albert de la Fuente¹, Climent Molins¹ and Antonio Aguado¹

* University of São Paulo, Department of Civil Construction Engineering,
  Caixa Postal 61548. CEP 05424-970. São Paulo, Brazil.
e-mail: antonio.figueiredo@poli.usp.br, web page: www.poli.usp.br

¹ Barcelona Tech (UPC), Department of Construction Engineering.
  C/Jordi Girona Salgado, 1-3, 08034, Barcelona, Spain
  e-mail: antonio.aguado@upc.edu, albert.de.la.fuente@upc.edu, climent.molins@upc.edu, web page: www.upc.edu

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Summary: The fibre reinforced concrete pipes have normally their mechanical behaviour verified through crushing test that follows a cycled procedure. This test is crucial to verify if the pipe fit the mechanical requirements specified in the standards. The conception of this test procedure is based on the premise that no continuous lecture of load and displacement curves will be made. So, only one load value is quantified (maximum load) and two other loads are verified. The first load to be verified is the proof load in the first loading cycle before the peak load. The same load value is verified again at the second loading cycle, at post-peak part of the test when the bearing capacity of the cracked pipe under a fixed load is checked. In that situation, there is no actual determination of the post-crack strength. Thus, a different procedure of testing is proposed, without cycling loading and with continuous data acquisition on load and diameter displacement measurement. A LVDT are used for diametric displacement measurement and it is fixed in a device in order to avoid influence of external deformation. Results published in previous experimental studies focusing in fibre reinforced concrete pipes with different fibre contents were used for the test procedure analysis. A new procedure for the crushing test is proposed based on the approach of the new fib Model Code for structural design of fibre reinforced concrete. The analysis shows that the new test procedure could lead to a better assessment of the pipe during the test, including the post-peak strength, even when the fibres provide a strain hardening behaviour. In this particular case, the cycled test became unfeasible due to the difficulties associated to the evaluation of correct moment of interruption of the first cycle of loading. Another advantage of the proposed test procedure is to turn possible the future association between the level of displacement and the service life conditions of the component.

1 INTRODUCTION

Despite the concrete pipes market is well established in areas like the continents of Europe and North America, there are several countries with different levels of development that require large investments in the sector. For example, the need of sewage collecting and treatment systems in underdevelopment countries is very common. Furthermore, the need of substitution of old sewage collecting pipe lines must be not ignored, because this kind of component is subject to numerous factors affecting their structural stability [1]. On the other hand, concrete pipes producers are facing increasing competition from other products such as plastic pipes. Previous studies had demonstrated that concrete pipes could be an interesting technological alternative, including by sustainability point of view [2]. So, the use of fibre reinforcement could turn this kind of pipes more competitive, especially
for reduced diameters which demand lower fibre content [3]. However, the introduction in the market of fibre reinforced concrete pipes (FRCP) could be considered under progress nowadays due to several factors such as: (1) the risk of damage when manipulating the pipes; (2) the lack of calculation methods for this type of material, and (3) the difficulty to overcome the inertia towards changes in conventional markets [4]. In any case, the quality of the components must be treated with special attention, because this will provide better conditions to fulfill different requirements.

Another important aspect linked to the concrete pipes quality control is the fact that the standard test used to assess these elements is carried out with the entire element, in a full scale test. So, this kind of test could be of interest in studies focusing design models due to the possibility of numerical model validations [5]. One barrier for this development is the too simplistic test procedure established in the standards that cannot provide enough information in order to give a perfect knowledge of the pipe behaviour during the test. So, this paper has the objective of presenting the limitations of the current standard test and proposes a new approach for this test in order to achieve a better accuracy for the results.

2 CONVENTIONAL STANDARD CRUSHING TEST

The mechanical behaviour of concrete pipes is commonly evaluated through the crushing test method, also known as three-edge bearing test, prescribed by the standards EN 1916 [6] and ABNT NBR 8890 [7] (Figure 1). These standards stipulate two different test procedures: one for pipes reinforced with conventional steel wires or bars and the other for FRCP.

![Figure 1: Pipe positioning for the standard crushing test](image)

In the case of pipes with conventional reinforcement, the component is subjected to a continuous loading up to failure in order to determine the proof and ultimate loads. The proof load \( F_p \) is defined as \( 0.67 F_n \), being \( F_n \) the minimum crushing load, which must be equal or greater than the ultimate load reached during the test. For the conventionally reinforced pipes, the standards allows a crack opening of 0.25 mm [8] or 0.3 mm [7] corresponding to the crack load \( F_{cr} \). Due to the different approach of this test in relation with the prescribed to FRCP, the conventionally reinforced pipe qualification will not be focused in this paper.

The standard three-edge bearing test for FRCP requires a cyclic loading procedure [6,7], which is schematically presented in Figure 2. The first cycle consists of loading the pipe until an equal level of the proof load \( F_p \), as specified for the conventionally reinforced concrete pipes. At this instant, the load is sustained for, at least, one minute and the pipe is checked for evidence of any crack or other
damage. The pipe is rejected if any crack or damage is observed. So, it is obligatory to verify if $F_{cr}$ shall be greater than $F_c$ for FRCP. If the FRCP is approved at this first stage, the loading of the pipe is continued until reach the maximum load ($F_u$). When the load start to decrease and reach the value of 95% of $F_u$ the pipe is unloaded finishing the first cycle of the test. On the second loading cycle, the pipe is reloaded up to $F_c$ and the load is held for one more minute. The pipe has to withstand this post-peak proof load in order to be approved. The test procedure established by the European standard [6] is finished at this point. In the specific case of the Brazilian standard [7], the second cycle has an extension (Figure 2) for which the pipe is loaded until achieve the maximum measured post-peak load ($F_{max,pos}$). The obtained $F_{max,pos}$ shall be equal or greater than 1.05$F_c$. In both cases [6,7] the softening behaviour is expected for the pipes because the required post-peak load strength is about two thirds of the peak-load.

![Figure 2: Schematic diagram showing the cycle loading plan for FRCP crushing test [6,7].](image)

One important aspect to be observed is the fact that the standards [6,7] only prescribe the load control, without any concern to the displacement control during the test. The requirements for the apparatus are restricted to the definition of the testing machine as a device “capable of applying the full test load without shock or impact and with an accuracy of 3 % of the specified test load” [6]. The standard requires that the test equipment “shall be equipped with a load-recording facility” [6]. The crack width is only verified for the bar reinforced concrete pipes with bars, “measured on the surface, optically by a magnifier or equivalent” [6]. That condition is quite different in relation with the regular fibre reinforced concrete (FRC) in terms of concepts for test methods and design approach adopted in the new fib Model Code [8]. The purpose of the Code is to provide guidance to design FRC structural elements observing the serviceability (SLS) and ultimate (ULS) limit states simultaneously, “based on the state-of-the-art knowledge on this structural material” [8]. In that sense, it is demanded to perform bending tests in prisms, as the prescribed in the standard EN 14651 [9], in order to provide a load versus deformation diagram. The deformation is generally measured and expressed in terms of Crack Mouth Opening Displacement (CMOD) or mid-span deflection ($\delta$). So, the standard crushing test for FRCP do not observe basic aspects used in the new fib Model Code [8] in order to verify the SLS and ULS.

Actually, by the European Standard [6], even the post-crack load bearing capacity is not quantified,
because the test procedure is interrupted just after the verification of the pipe capacity of maintain the proof load in the second cycle. On the other hand, the Brazilian Standard [7] prescribes the maximum post-peak load determination, although this determination is made without any connection with the level of displacement or crack width. So, there is a need of improvement in this FRCP test method in order to achieve a closer approach to the concepts adopted in the new code.

3 IMPROVEMENTS FOR THE CRUSHING TEST OF CONCRETE PIPES

The proposition of the new configuration for the crushing test for FRCP has to be done aiming to turn this test more reliable and fitted with the new concepts for FRC standardization. In that sense, some improvements are suggested to be incorporated in future standards. The main intention is to discuss possibilities that can be incorporated in future revisions of FRC pipe standards [6,7].

3.1 The use of LVDTs for displacement control

In previous experimental studies [5,10,11,12], the use of LVDTs for displacement control showed to be a very useful tool that permits to obtain a much more complete response from the test result. Tests made with FRCP with 800 mm of nominal diameter provide an enhanced condition to achieve a better understanding of the pipe behaviour during the test [10]. In that sense, devices were fixed to specimens providing a continuous acquisition of the diametrical displacement. This system is based on the use of LVDTs positioned against the upper part of the inner surface of the pipe and attached at supports fixed at the bottom part of the pipe as shown in Figure 3. This set up used for LVDTs positioning allows measuring the diametrical displacements of the pipes without any interference of external strains or dislocations in the results. The device works like a yoke system that supports the LVDTs in the bending tests of beams [9]. This kind of test configuration turns possible to achieve diagrams as the results presented in Figure 4.

Figure 3: (a) Devices used to set the LVDTs at both edges of the pipe during the crushing tests [10] and (b) LVDT positioned at the upper part of the inner surface of the pipe [11].

As the results presented in Figure 4 were obtained using the Brazilian standard [7], there is a demand of maximum post-peak load determination. If the European standard [6] was used, the test will be interrupted after the moment where the load was sustained for a period of one minute during the second cycle. So, the diagrams in Figure 4 are reproduced in Figure 5 as if the tests were carried out using the European standard. It is possible to verify that both fibre consumptions provide a compliance to the proof load (120 kN) and ultimate load (180 kN) requirements [6,7] in both cases for AE2 class. On the other hand, just in Figure 4 is possible to verify that the fibre content of 40 kg/m³ provided an excessive residual strength, much higher than the needed to the standard requirements compliance. So, the LVDTs use in the test leads to a better visualization of the diagrams and, as
consequence, the requirements fulfilment verification could be easier done. More over, this interruption turns unfeasible to apprehend the excess of fibre consumption and to control the actual variability of the post-peak bearing capacity of the pipe.

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**Figure 4:** Diagrams of load versus average diametric displacement obtained in crushing tests made according the Brazilian standard [7] run with pipes with 20 kg/m$^3$ and 40 kg/m$^3$ of steel fibres [10].

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**Figure 5:** Diagrams of load versus average diametric displacement obtained in crushing tests made according the European standard [6] run with pipes with 20 kg/m$^3$ and 40 kg/m$^3$ of steel fibres [10].

Some previous works had pointed the low variability of the crushing test results [8,14], but they only can consider just the first cycle of loading, as presented in Figure 5, where the fibre has as minor influence [10]. The variation of the post-peak strength became impossible when the test is interrupted during the verification of the proof load sustain capacity [6]. So, the variability of the FRCP is partially
underestimated because the first cycle of loading is strongly influenced by the matrix. Consequently, the result of the crushing test could not be directly compared to others obtained in bending tests [8,14]. On the other hand, if the displacement control by LVDTs is not used it will be impossible to determinate a residual strength related for a fixed level of displacement or crack opening, as it occurs for FRC. Therefore, the difference between both test methods was not just restricted to the size of the sample, but related to the test procedure especially in terms of the residual strength evaluation. So, the LVDTs use could amplify the possibilities of analysis of the test itself, providing a better evaluation of the mechanical behaviour of the component.

3.2 Cycled versus continuous test procedure

The same previous study discussed in the last item [10] had shown that there is no major influence on the pipe response during the three-edge bearing test if the loading is made using cycles or not. In order to illustrate this aspect, the results of continuous and cycled tests carried out with EA2 pipes with 800 mm of nominal diameter and 20 kg/m³ of steel fibres are presented in Figure 6. Comparing both group of load versus average diametric displacement is possible to figure out that the basic pattern of the diagrams is very similar. The unique major difference is the cycle of unloading and reloading of the pipe just after the peak, which do not interfere in the residual strengths envelope, even when other fibre contents were used [10].

![Figure 6: Diagrams of load versus average diametric displacement obtained in crushing tests made continuous and cycled procedures run with pipes with 20 kg /m³ of steel fibres [10].](image)

The use of the continuous test brings another advantage that is to approximate the three edge bearing test to the regular beam bending tests, which has normally been performed without cycled procedures. Consequently, the continuous crushing test will be more easily linked to the new general approach of FRC standard parameterization [8]. The use of the continuous test could also provide a much simple condition for modelling and design for this type of elements [5,12].

3.3 Diametric displacement measurement position

FRCP with 600 mm of nominal diameter were tested using two different set ups for the LVDTs positioning [5,11]. In this particular study, the continuous test with just one cycle of loading was used. At the first test arrangement, the measurement of displacement occurred simultaneously at the spigot and the socket (Figure 7a). So, that condition turns possible to obtain the diagram of load by average
diametrical displacement of the pipes. In the second test configuration, only one LVDT was placed at the spigot of the pipe (Figure 7b). Thus, two series of pipes were produced with fibre reinforcement to be tested with each of those test configurations. The fibre consumption used in these examples shown in Figure 8 was 20 kg/m$^3$. There are two average diagrams, each one take from three individual test results.

Comparing both diagrams in Figure 8 is possible to conclude that the load versus displacement measured at the spigot show a much more flexible result, especially at the first part of the curve. On the other hand, the results obtained when the displacement was measured at the spigot and at the socket simultaneously, had presented higher stiffness in the beginning of the curve. The end of the initial elastic part was prolonged by the influence of the socket region where the concrete matrix contributes more strongly [13]. When the displacement was measured only at the spigot, the pipe response presents a more flexible behaviour at this region of the diagram, due to lower rigidity of this part of the pipe. The difference observed in the pattern of the curves obtained in the two series of tests could only be attributed to the geometric factors, because the characteristics of matrix and type of reinforcement are the same. So, the enlargement of the socket is the main factor influencing the pattern of the curves at the elastic region. This fact could affect the compliance of the results to the numerical model output, especially when bidimensional models are used [12]. In that sense, the measurement only at the spigot is a better choice because provide curves that fits better to the numerical result [12]. More than this, the measurement only at the spigot provides better conditions to observe the initialization of the crack, corresponding to the point C at the Figure 8. The spigot is also a critical location because the cracking process starts at the crown at this position. The $F_{cr}$ is a key parameter because define the proof load that characterizes the strength class of the pipe [6, 7].

One aspect that could be observed analysing the diagrams in Figure 8 is the greater post-peak instability presented by the curve of load versus the displacement measured at the spigot. It occurs because the socket helps to stabilize the behaviour when the curve was obtained correlating the load with the average diametric displacement. So, one disadvantage of measuring the displacement only at the spigot is the more unstable response of the test.
4 TEST PARAMETERS UNIFORMIZATION

4.1 Specific loads and displacement

The total load capacity of a pipe is dependent on its diameter and length for each strength class. So, the required proof load \( (F_c) \) will increase proportionally to the length and the diameter of the pipe. The strength class EA2 requires 60 kN/m for a pipe with 1000 mm of nominal inner diameter, and will correspond to 30 kN/m for a pipe with a diameter of 500 mm, for example. If the pipe with a diameter of 500 mm has a length of 2000 mm, the total proof load will be 60 kN. The ultimate load \( (F_u) \) for a pipe with 1000 mm of nominal diameter shall be 90 kN/m and the ultimate load required for a pipe with 500 mm will be 45 kN/m. So, the ordinary solution to turn comparable the results of crushing test made in pipes with different geometries (diameter and length), but the same strength class, is to use the specific load per unit of length multiplied by the nominal diameter.

Logically, the displacement measured at the crushing test is affected by the geometrical characteristics of the pipe. The main factor affecting the displacement is the pipe diameter. In that sense, the most simply way to turn comparable the tests results is to control the specific displacement corresponding to the measured displacement divided by the pipe diameter. It could be expressed as a percentage of the inner diameter.

4.2 Example of application

Some previous published results in steel fibre reinforced concrete pipes (SFRCP) \([10,11]\) are also used here aiming to illustrate the use of the specific values to parameterize the load versus displacement diagrams. In these studies, two different diameters of pipes (600 mm and 800 mm) were analysed. The pipes with both diameters had a same length (2500 mm) and fibre consumptions of 10 kg/m\(^3\), 20 kg/m\(^3\) and 40 kg/m\(^3\). Three pipes were tested for each condition. In Figure 9 the results are presented in terms of average curves of total load versus average diametric displacement. The extra load bearing capacity presented by the pipes with 800 mm in relation with the pipes with 600 mm in Figure 9 is just related to geometric characteristics.

A better condition for comparison of the results was obtained when the specific parameters were used, as presented in Figure 10. When the total load was replaced by the specific load, where the pipe diameter and length is considered, the diagrams show to be very close, especially for the post-peak
part of the curve. Taking into account the fact that a softening behaviour was expected for the pipes due to the standards parameters, the load bearing capacity has a strong influence of the displacement level. Although this, the basic pattern of the curve could be compared when the specific displacement is used as it could be observed in Figure 10 for pipes with fibre contents of 10 kg/m$^3$ and 20 kg/m$^3$.

On the other hand, if a high dosage of fibre is used, as is the case of 40 kg/m$^3$ for both pipes diameters in Figure 10, a hardening behaviour could be obtained. In this case, is much more difficult to observe when the load is reduced up to 95% of the maximum load (peak-load) in order to unload the pipe and start the second load cycle [6,7]. It could occur for a higher level of displacement, in a condition very unfavourable for the fibre reinforcement evaluation.

![Figure 9](image9.png)

**Figure 9**: Average curves of load versus average displacement for SFRCP with diameters of 600 mm and 800 mm [10,11].

![Figure 10](image10.png)

**Figure 10**: Average curves of specific load versus specific average displacement for SFRCP with diameters of 600 mm and 800 mm (results adapted from [10,11]).
5 PROPOSITION FOR THE NEW CRUSHING TEST

The concepts for FRC design adopted by the new fib Model Code [8] for the softening behaviour (Figure 11) was taken as a reference to propose the new crushing test method for FRCP. There are two main stages in the diagram presented in Figure 11. The first stage is the matrix contribution (MC90 – Plain concrete), which is characterized by the maximum flexural strength ($f_{\text{ct}}$). On the second stage, there are two levels of post-peak strength. The first one is the $f_{\text{Fts}}$, related to serviceability residual strength, corresponding to a SLS specific deformation for the ($\varepsilon_{\text{SLS}}$) and significant crack opening. The second level of strength is $f_{\text{Ftu}}$ and is related to the significant crack opening to the ULS and corresponds to a specific deformation $\varepsilon_{\text{ULS}}$. So, a similar approach of the fib Model Code [8] for FRC is adopted as basis for the diagram presented in Figure 12 for FRCP softening behaviour parameterization. This diagram represents the schematic response of a FRCP under the continuous load during the crushing test.

![Figure 11: Stress strain relationship for softening FRC in the new fib Model Code [8].](image1)

![Figure 12: Specific load and specific diametric displacement general relationship to be verified in the FRCP crushing test.](image2)
The main difficult is to establish the level of diametric displacements for the post-peak strengths. The displacement associated to the SLS ($d_{SLS}$) could be related to the maximum post-peak load and has to guarantee that the post-peak instability will not affect this part of the curve. In this case, the value of 0.4% could be suitable, because this value is slightly superior of the values associated to the maximum post-peak load and the instability region [10]. Also, this specific displacement has to be as close as possible to the displacement corresponding to the maximum post-peak load measured in the second cycle of loading as the regular test is carried out, corresponding to $1.05F_c$ in the Brazilian standard [7]. As an example, the results obtained in previous study [10] the maximum post-peak load obtained in the second cycle occurred around 2.6 mm or 0.35% of total or specific diametric displacement, respectively. The same value of total average diametric displacement was observed when pipes with a diameter of 1000 mm were tested [15]. But, in this case, the specific diametric displacement was 0.26%. It had occurred because these last pipes had a shorter length (1.5 m) [15] and the influence of the socket was more intense providing a reduction of the displacement.

Logically, the $d_{SLS}$ value should be better studied in the future in order to evaluate the level of crack opening. The same difficulty appears to establish the level of displacement corresponding to the $d_{ULS}$ value. In this particular case, a first approach to establish $d_{ULS}$ could be use the same proportion observed in the fib Model Code for $\varepsilon_{SLS}$ and $\varepsilon_{ULS}$, where $\varepsilon_{ULS}$ is five times greater than $\varepsilon_{SLS}$ [8]. So, an initial value for $d_{ULS}$ could be around 2%. This could be the limit for the test procedure and, in order to achieve the complete verification of compliance to the standard parameters, the follow steps shall be observed.

One more difficult is the fact that there is no previous parameter for $F_{ULS}$ requirement. So, the fib Model Code [8] is taken as a reference once again. In this Code, the residual strength associated to ULS has to be, at least, 82% of the residual strength corresponding to the SLS in order to guarantee a minimum ductility. Thus, the value of $F_{ULS}$ could be considered, in a first approach, equivalent to 82% of $F_{SLS}$ ($F_{ULS}=0.82F_{SLS}$).

So, in the test procedure, the pipe should be prepared for the test using a LVDT fixed in a support as presented in Figure 7b. This procedure has the intention of provide better conditions to verify the linearity of the first elastic part of the curve and the cracking initialization. The general conditions for the test could be the same established in the nowadays standards [6,7]. The pipe should be loaded up to the specified proof load, sustained for one minute, and the pipe inspected for any crack or other damage. This procedure is the same of the current standards and is very important to verify if the pipe fulfill the crack proof load requirements. After this verification and if no crack is observed, the loading is continued up to a moment when the diametric displacement reach the value corresponding to $d_{ULS}$.

Once the load versus diametric displacement is obtained, some verification has to be done. The first one is to verify if the deflection in the initial part of the curve (related to point C in Figure 8) occurs above the load corresponding to $F_c$. With that condition fulfilled there is a better guarantee that the crack proof load is in accordance with the requirements. The second verification is the total maximum load or peak-load obtained in the test that shall be equal or greater than $F_n$.

The third verification is related to post-peak load bearing capacity of the pipe. The first load to be verified in this condition is the load corresponding to $d_{SLS}$. This load should be equal or greater than the $F_c$ value. In this case, the requirements demanded by the current European standard were totally verified. The last verification to be done is to verify if the load at the displacement of $d_{ULS}$

6 FINAL REMARKS

The main objective of this paper was to present the limitations of the current standard crushing test that do not allow verifying the pipe mechanical behaviour with a good level of reliability. The nowadays procedure presents several limitations as the poor verification of the post-peak load bearing capacity of the FRCP. On example of this condition is the fact that the residual strength was not quantified in the European standard [6], restricting the evaluation of the variability associated to the fibre reinforcement main contribution. Due to the softening behaviour expected for the pipes, if a displacement control is not used in order to fix the level where the residual bearing capacity should be
determinate, another variability factor will be introduced in the process. As the standards do not take in consideration the diametric displacement level during the test, the connection with the new approach of the *fib* Model Code became impossible, turning difficult possible optimizations in the future.

So, the modifications proposed here to the new crushing test procedure has the aim of test optimization and to increase its reliability. However, this is just a proposition and some aspects have to be subjected to further studies in the future in order to achieve more reliable parameters for the test method. Among these parameters that should be verified in future studies are the level of crack opening during the post-peak stage of the test. This is a key parameter to well establish the values corresponding to \(d_{ULS}\) and \(d_{SLS}\) and respective loads. Naturally, the level of crack opening should be correlated to the durability conditions, which is another important aspect that deserves better studies in the future. Another important theme for future works is the study focusing the interaction between pipes and ground during the loading, because the crushing test is carried out without any confinement as it occurs in practical conditions. It could be considered together with the redundant characteristic of the concrete pipes, which is an important factor to establish the control avoiding the use of characteristic strengths values, which is not adequate for FRC elements in that condition [16].

The fact that an entire pipe is used as a specimen turns the current FRCP quality control test more expensive and demanding than the tests used for FRC quality control. So, although the new crushing test procedure FRCP come together with a more complex apparatus, an investment in this test could be justified by the increase on its reliability and the optimization of the FRCP design aligned with the *fib* Model Code [8]. The quality control could be complemented with non-destructive tests in order to reduce the total amount of crushing test [17] and the total costs regarding to this task, without reducing its reliability.

REFERENCES


