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REINFORCED CONCRETE PIPE DESIGN WITH SINGLE ELLIPTICAL STEEL CAGE REINFORCEMENT

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Abstract: Reinforced Concrete Pipe (RCP) industry has been experiencing declining market share for several years due to competition from the emerging pipe materials. Despite the century historic performance, limited technological advancement was made to the market place in the past decades. This project is to explore the behaviour of the pipe with a single elliptical shape cage in lieu of a conventional double circular cage for primary reinforcement where the layer of the reinforcing steel can be positioned effectively at the tension face under loading. The structural performance of such reinforcing configuration is presented based on the full scale tests using Linear Variable Displacement Transducers (LVDT). The preliminary conclusion showed that the single cage requires at least 10%, possibly 15% more steel than the inner cage from the conventional design. With elimination of outer cage, the overall steel requirement is reduced leading to a potential cost saving.

Keywords: Reinforced, Concrete, Pipe, Three-Edge Bearing Test, Design, Elliptical Reinforcement, Structure.

1 Introduction

1.1 History of Reinforced Concrete Pipe

Following the research conducted by the American Concrete Pipe Association (ACPA) in the early twentieth century, Reinforced Concrete Pipe (RCP) technological advancements have stagnated relative to other research areas. The industry has been experiencing declining market shares over the past few years due to competition from the lightweight flexible pipe industry and tepid technological advancements. This is reflected in the 2017 IBISWorld Industry report about the state of the concrete pipe and block manufacturing industry in Canada. The industry has been at an annual revenue decline of 6.9% since 2012, with an expected annual loss of revenue of 2.7% between the years 2017 and 2022 (Masterson, 2017).

RCP is a rigid pipe which relies primarily on its own structural strength rather than the surrounding soil. On the other hand, flexible pipe relies on the surrounding material to support the overburden loads due to its relative stiffness, and thus cannot structurally support themselves. Consequently, rigid pipes can be buried in soil with less effort in preparation of the bedding and fill material. Structural benefits of RCP are slowly being taken over by technological advancement from other emerging pipe materials (Wong and Nehdi, 2018). Despite the questionable short-term and long-term engineering performance, up to 2100 mm steel reinforced HDPE pipe has been promoted as an alternative to RCP for storm and sanitary drainage which is alarming to the RCP industry (AQUA Q, 2018)

1.2 Manufacturing of Reinforced Concrete Pipe

Standards such as the ASTM C76 and CSA A257.2 govern the manufacturing quality of RCP. In addition to the geometric requirements, these specifications prescribe the reinforcing steel, but require validation through a destructive test known as three edge bearing test (TEBT). Conventionally, manufacturing of RCP commences by fabrication of the steel reinforcing cage, consisting of both circumferential and longitudinal bars. Cold drawn wires and welded wire fabric (WWF) are mainly used for reinforcement. However, much of the recent research for RCP has been on the use of steel fiber reinforced concrete (SFRC) as reinforcement for RCP (Mohamed, et. al., 2015), potentially eliminating the need for the steel cage fabrication process and thus making manufacturing less labor intensive. Considering the research conducted on SFRC, the application of SFRC has not been widespread in RCP due mainly to complications with attaining adequate quantity and dispersal of fibers needed to obtain the desired improvements in performance. Manufacturing process of SFRC pipes in achieving desire hydrostatic performance was also reported as a challenge (Wong, 2016). Furthermore, the fibers are relatively expensive compared to traditional reinforcement (Van Chanh, n.d.).

1.3 D-Load Strength by Three-Edge Bearing-Test

RCP strength is classified according to its design crack load, the load producing a 0.3 mm wide and 300 mm long crack, and its ultimate load using the Three-Edge Bearing-Test (TEBT).. The test is destructive by applying a concentrated load along the crown of the pipe. The pipe is supported by two strips at the invert along the full length of the barrel. (Figure 1). The distance between the lower bearing strips is a function of the internal diameter of the RCP. The concentrated load is applied at a uniform load rate between 7 to 37 kN/min/m. Furthermore, the class of the pipe is determined by the minimum of the design crack load or the ultimate load divided by the safety factor whichever is smaller. The value is normalized to newton per meter long per millimeter internal diameter (D).

Figure 1: TEBT setup

1.4 Research Scope

Current Canadian and American standards allow for the use of a single elliptical steel-cage reinforcement as an alternative to the double cage configuration (CSA, 2009) (ASTM, 2014). However, a single elliptical reinforcing steel-cage is not commonly used in the industry as the structural performance is not fully understood, coupled with manufacturing limitations of the steel cage. Manufacturing an elliptical reinforcing steel-cage requires specialized machinery. Circular steel cage reinforcement can also be manipulated into an elliptical cage by holding it in place using rods or chairs throughout the casting process, however this process can induce stresses in the steel cage leading to stability issue in wet concrete. Cage and concrete debonding may compromise the sectional capacity.

Single elliptical steel-cage design can offer a more effective design since the steel is more favorably positioned at the tensile faces of the pipe under the loading condition. The single elliptical cage is positioned in such a manner where the steel would resist the tension stresses in the inner surface of the pipe invert and crown, and the stresses in the outer surface of the spring-lines. According to studies on the behavior of RCP under the TEBT (Heger, 1963), the outer steel cage reinforcement in a double cage reinforcement does not significantly contribute to the ultimate flexural strength of the RCP since the outer cage at each critical section of the pipe is not in the tension zone and is usually 75% of the steel area of the inner cage). Standards require the steel reinforcement for a single elliptical cage to be about 10% more in comparison to the inner cage in a double cage design. Therefore, theoretically the structural performance should be similar between the traditional double and single elliptical steel configurations. The objective of this study is to explore the structural performance of RCP reinforced with single elliptical reinforcing steel cage in comparison with conventional reinforcement.

Figure 2 shows a typical reinforcing cage design. Single cage design can be found in smaller diameter pipes such as 750 mm or smaller. Double circular cages are commonly used in pipes that have sufficient wall thickness. An additional elliptical cage is supplemented to the double caged design for large diameter pipe with higher design class.

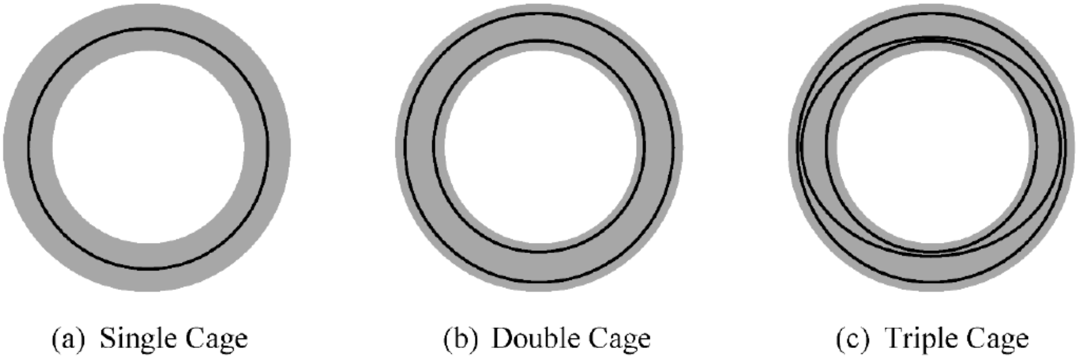
(a) Single Cage (b) Double Cage (c) Triple Cage

Figure 2: RCP reinforcing cage configuration (Wong and Nehdi, 2018)

2 Experimental Program

2.1 Experimental Setup

Quality control of the 0.3 mm design crack load using the TEBT is conducted manually by visual inspection using a crack gauge. To better understand the behavior of RCP under TEBT in accordance with CSA A257.2, Linear Variable Inductive Transducers (LVIT's) were used to measure the deflection of the RCP against the applied loads. The vertical deflection of the crown towards the invert was measured by positioning two LVIT's 610 mm into the pipe at the crown and invert of the RCP spigot, which is believed to be the weakest area of the pipe where the 0.3 mm usually occurs first. The LVIT's used were manufactured by Alliance Sensors Group and had a stroke of 50.8 mm and a linearity error of ±0.15%. The setup of the LVIT's is shown in Figure 3.

Figure 1: Setup of LVIT's when testing vertical deflection under TEBT

2.2 Pipe Manufacturing

Full scale pipe specimens were produced by Con Cast Pipe in their facility located in Oakville, Ontario. The concrete for all specimens was made from a typical dry cast mix with a water-cement ratio of 0.4. Concrete was consolidated through vibrations in the mould, and immediately stripped from the formwork after enough vibrations due to the zero-slump characteristics of the concrete. The elliptical reinforcing steel cage was manufactured using the automatic cage welding machine manufactured by MBK Maschinenbau GmbH in Germany. The machine is capable of manufacture the cage to a truly elliptical shape. However, welding limitations require the cage to have 200 mm transition zones at both ends where the steel cage goes from round to elliptical then to round again configuration.

2.3 Pipe Sample Selection

The testing program covers nominal diameters between 975mm to 1500 mm where the double cage design configuration governs the flexural capacity of the pipe. 1200 mm was selected for this report because of the availability of the test results. A total of five specimens were tested. Two single elliptical steel cage pipe samples with different design class and area of reinforcing steel were compared against two traditional pipe samples with the equivalent area equal to the inner steel reinforcement. Since design standards require additional steel reinforcement in comparison to the inner cage in a double cage configuration, a reduction of design class was expected. Furthermore, a single elliptical steel cage pipe sample with additional steel reinforcement was tested to compare the effect of added steel on the strength for the 100D design class. Table 1 lists the properties of the tested pipe specimens.

Table 1: Properties of tested RCP specimens

Pipe Designation	Cage Config.	Design Class	Area of Steel (mm^2/m)	Compressive Strength of Concrete (f_c')	Yield Strength of Steel (f_y)	Age Tested (Days)
TRCP 1200-1	Double Circular	100D	822	40	485	8
TRCP 1200-2	Double Circular	140D	1549	40	485	7
ERCP 1200-1	Single Elliptical	100D	822	40	485	8
ERCP 1200-2	Single Elliptical	100D	904	40	485	24
ERCP 1200-3	Single Elliptical	140D	1549	40	485	7

3 Results

3.1 Failure Mechanisms and Cracking Patterns

Four main criteria define the structural behavior and failure of RCP under the TEBT including flexural strength, radial tension, diagonal tension, and crack control, according to a study conducted by Heger in 1980 (Heger, 1980). The steel content and the cage configuration at the tension zone of RCP are the main parameters that influence the failure mechanism of the pipe. The governing failure mechanism exhibited in the single elliptical reinforced pipe was flexural failure, which was characterized by the occurrence longitudinal cracks at the invert, crown, and spring-lines as shown in Figure 4. Diagonal and radial tension cracks were exhibited in some pipes but were not the governing mode of failure. The following cracking pattern was also exhibited in double cage configuration; however, the cracking was less severe as shown in Figure 5.

During loading, the first crack always developed at the spigot at the inner face of the invert of the pipe, followed by cracks at the outer face of the spring-lines of the pipe at the spigot. The cracks increased in width and length with increased loading. This failure mechanism is also typical in a traditionally reinforced double steel cage pipe. However, a noticeable difference between the single elliptical and double circular steel cage reinforced pipes was the development of multiple cracks in the double cage configuration at the invert inner face of the pipe spigot prior to the identification of the 0.3 mm design crack load as opposed to

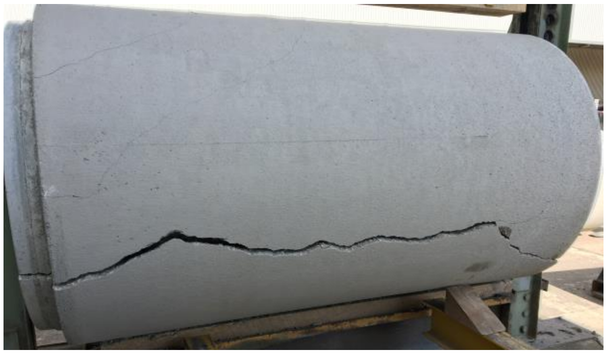

Figure 4: Single elliptical cage longitudinal cracking

Figure 5: Double circular cage longitudinal cracking

a single crack in the single cage which was later identified as the 0.3 mm design crack load in the single cage configuration.

3.2 Single Cage vs Double Cage Configuration

It was observed that the performance of the single cage configuration specimens was inferior to double cage configuration specimens with of the equivalent design class and amount of reinforcement. Table 2 exhibits the tested specimens with the load values for the 0.3 mm crack load and ultimate load with the percent difference between them. Table 3 exhibits the normalized load values per meter length per millimeter of pipe diameter in addition to the equivalent design class of the specimen indicating how the specimen performed relative to the desired strength target.

According to CSA A257.2 standards, the 0.3 mm crack load for 1200 mm 100D and 140D is 293 kN and 410 kN respectively. As expected, specimens with the single elliptical cage configuration did not reach the design class of 100D as there was a reduction in area of reinforcement relative to the standards. The double cage configuration met the design class standards and were in fact exceeded the requirement. Increasing the area of steel reinforcement for 100-D design class (ERCP 1200-2) led to an improved structural performance which indicates that the area of steel is an important parameter to the structural performance. Furthermore, the results indicate that designing a single cage configuration by using an equivalent area of steel to the inner cage in a double cage configuration is insufficient to achieve the required performance, thus a safety factor must be introduced.

Table 2: Tested RCP specimens with cracking and ultimate loads

Pipe Designation	Number of Cage Reinforcements	Design Class	Area of Steel (mm^2/m)	0.3-mm crack load (kN)	Ultimate load (kN)	Ultimate load as percentage of 0.3-mm crack load
TRCP 1200-1	Double Circular	100D	822	341	494	144.9%
TRCP 1200-2	Double Circular	140D	1549	485	582	120.0%
ERCP 1200-1	Single Elliptical	100D	822	261	341	130.7%
ERCP1200-2	Single Elliptical	100D	904	359	404	112.5%
ERCP1200-3	Single Elliptical	140D	1549	414	445	107.5%

Table 3: Tested RCP specimens with normalized and cracking load

Pipe Designation	Number of Cage Reinforcements	Design Class	Area of Steel (mm^2/m)	0.3-mm crack load (kN/m/mm)	Ultimate load (kN/m/mm)	Equivalent Design Class
TRCP 1200-1	Double Circular	100D	822	341	494	113D
TRCP 1200-2	Double Circular	140D	1549	485	582	159D
ERCP 1200-1	Single Elliptical	100D	822	261	341	78D
ERCP 1200-2	Single Elliptical	100D	904	359	404	92D
ERCP 1200-3	Single Elliptical	140D	1549	414	445	122D

3.3 Load-Deflection Curves

Normalized load- deflection curves of the tested specimens under the TEBT were also analyzed to better understand the structural behavior from the effect of the cage configuration. Figure 6 and Figure 7 represent the load- deflection curves for 1200 mm nominal diameter pipes with 100D and 140D design class respectively. All specimens exhibited a linear increase in deflection as the load increased, followed by non-linear behavior once the specimen reaches the 0.3 mm crack load. It was observed through the curves that the ultimate strength of the single elliptical cage configuration was lower than that of the double cage configuration. This implies a strength reduction due to the decreased amount of overall steel reinforcement, although the specimens have an equivalent area of inner steel reinforcement for the same class.

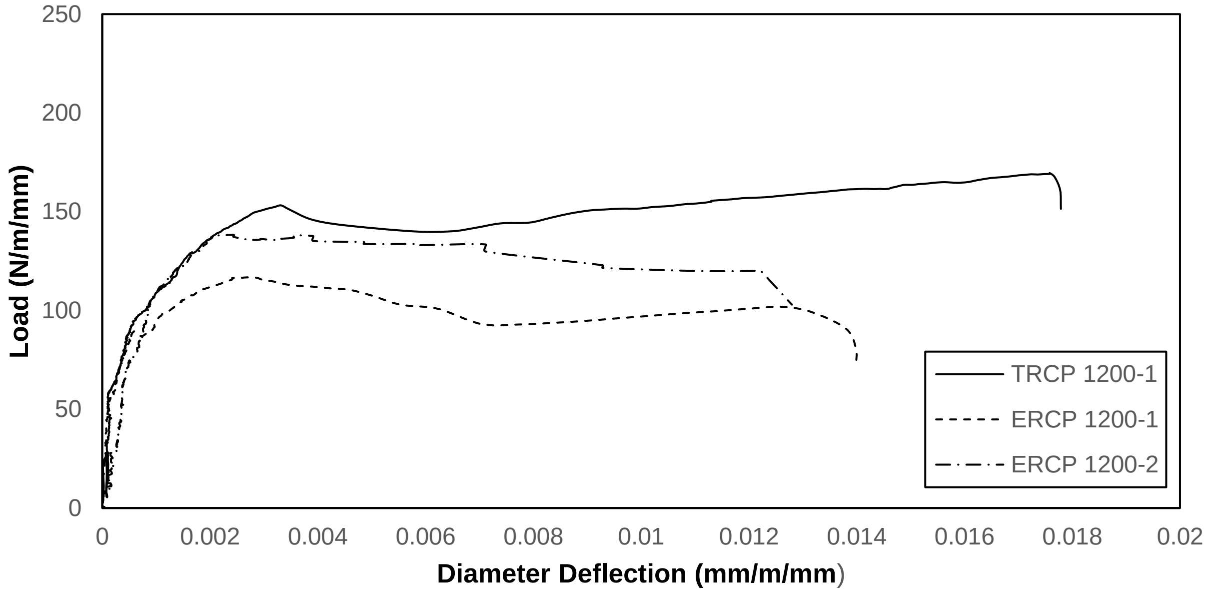

Figure 6: Load-Deflection curve for 1200-100D specimens

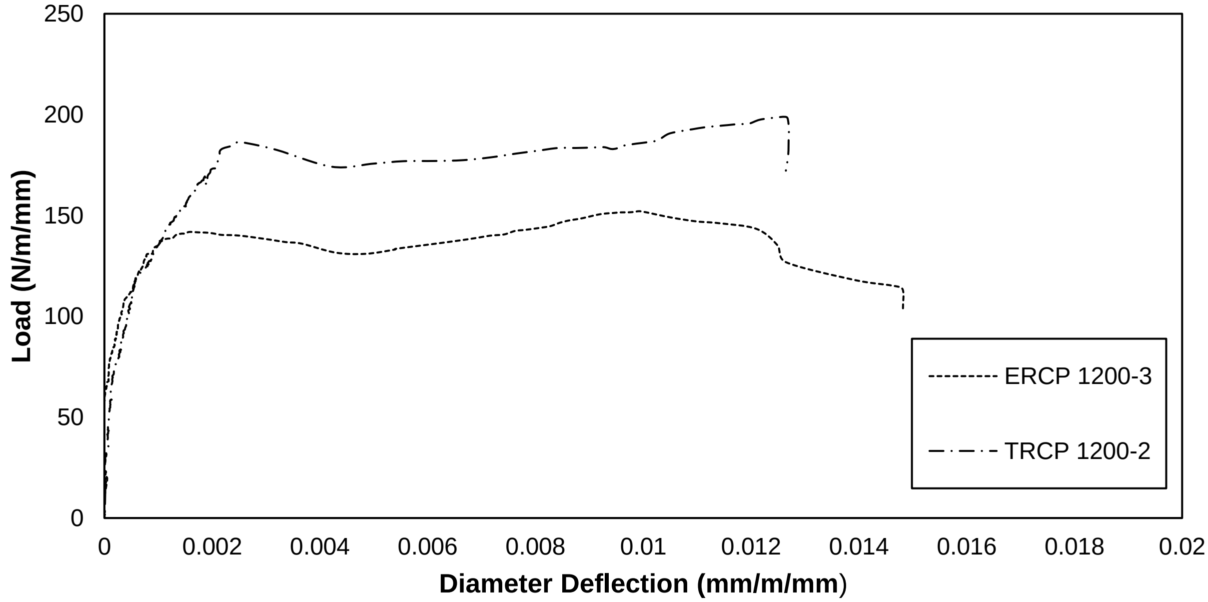

Figure 7: Load-Deflection curve for 1200-140D specimens

All specimens experienced an abrupt decrease in load carrying capacity followed by a very large increase in deflection as the steel reinforcement becomes effective during high cracking and deflections (Mohamed and Soliman and Nehdi, 2014). Single elliptical cage specimens, ERCP 1200-2 and ERCP 1200-3, experienced a sudden ultimate failure under the TEBT at very close proximity to the 0.3 mm crack load. This is shown in ultimate load as a percentage of the 0.3 mm crack load in Table, where the ultimate load was only 12.5% and 7.5% higher than the 0.3 mm crack load in addition to load-deflection curves which show a sudden drop of the curve close to ultimate failure. This phenomenon could be due to the stresses and weak points that the shape of the elliptical steel cage reinforcement exerts on the specimen under loading especially on the inner face of the invert and crown outer face of the spring-line of the pipe as shown in Figure 8.

Figure 8: Cracking of specimen with single elliptical steel cage

4 Conclusion and Recommendations

The scope of the following research was to study the structural behaviour of RCP specimens with single elliptical steel cage reinforcements and compare them to double (inner and outer) steel cage reinforcements. The conclusion of the report can be summarized as follows:

1. It was expected that the structural performance of the single elliptical cage would be inferior to the double configuration for the tested samples since there was a reduction of reinforcement area from the standard design. This was found to be the case for tests conducted.
2. Adding additional inner steel area reinforcement in one of the specimens did improve the structural behaviour. However, the area of steel was greater then 10% in comparison to the inner cage in a double cage configuration. Additional area of steel is needed in order to achieve the design class.
3. It was found that the failure of RCP with single elliptical cage configuration was more sudden and severe than the double cage configuration. The effect of the shape of the single elliptical cage configuration on the performance of RCP in addition to the effect of eliminating the outer steel cage reinforcement needs to be examined in future studies.

4. The single cage requires at least 10%, possibly 15% more steel than the inner cage from the conventional design. With elimination of outer cage, the overall steel requirement is reduced leading to a potential cost saving.

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2. NSERC: Financial sponsor
3. Western University: primary researcher

References

Wong, Lui, and Moncef Nehdi. "Critical Analysis of International Precast Concrete Pipe Standards." *Infrastructures*3, no. 3 (2018): 18. doi:10.3390/infrastructures3030018.

AQUA Q. *BOSS 3000-Large Diameter Steel Reinforced Polyethylene Pipe*. AQUA Q, 2018.

Mohamed, Nedal, Ahmed M. Soliman, and Moncef L. Nehdi. "Mechanical Performance of Full-scale Precast Steel Fibre-reinforced Concrete Pipes." *Engineering Structures*84 (2015): 287-99. doi: 10.1016/j.engstruct.2014.11.033.

Wong, Lui, “Full-scale manufacturing of steel fibre reinforced concrete pipe.” Canadian Society of Civil Engineering, Annual Conference (2016): London Ontario

Nguyen Van Chanh, “Steel fibre reinforced concrete”, Advances in concrete technology volume 3-Gordon and Breach Science publishes

ASTM C76-16, Standard specification for Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe

CSA A257.2-2014, Reinforced circular concrete culvert, storm drain, sewer pipe and fittings

Heger, Frank "Structural Behavior of Circular Reinforced Concrete Pipe-Development of Theory." *ACI Journal Proceedings* 60, no. 11 (1963): 1567-613. doi:10.14359/7905.

Heger, Frank. (1980). *Design Method for Reinforced Concrete Pipe and Box Section.*

Masterson, R. (2017). *IBISWorld Industry Report Concrete Pipe and Blockk Manufacturing in Canada.* Rory Masterson.