MACRO SYNTHETIC FIBRE REINFORCEMENT FOR SEGMENTAL LININGS DESIGN

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ABSTRACT

The concrete, which is fibre-reinforced, it is becoming one of the most widely used items within the segmental linings because of its improved durability and performance of segments. Also, the significant cost saving, it can be achieved by traditional rebar cages replacement with the fibres. The macro synthetic fibres, or the MSF, it is completely non-corrosive and is ideal for the critical environment. Some of the recent publications are giving a basis for the design and much more credibility to this kind of reinforcement type. In this given paper, there will be presented design methodology for the precast tunnel segment and particularly the task which is associated with MSF reinforcement usage. One of the case history from Santoña- Laredo interceptor collector general that is currently under the process of construction in the northern section of Spain has also been provided, and illustrations have been given about the specific benefits which are brought in by MSF reinforcement for the segmental linings.

Keyword: - Structural fibre, Concrete segment, Fibre reinforced concrete, Etc.

1. INTRODUCTION

While the usage of the structural fibres within the initial and the final or permanent linings around the world is showing the importance of the fibres within underground construction, and this has brought in the growing interest in the designers along with the ingenious and the referring authorities. In the past 20 years, the fibre-reinforced concrete or FRC segmental tunnel lining, it has been highly adopted in many projects worldwide. A comprehensive overview of such projects has been given in the ITA WG2 report of 2015.

The structural fibres can easily replace or can even lessen the ordinary rebar gauges as they will then be acting within the reinforcement as one of the primary structures. Cost savings at a significant level also gets achieved by the use of the fibres, mostly through partial or the entire replacement within the production of the ordinary reinforcement, but also through the improvement of robustness, durability, and serviceability, and hence this helps to reduce the maintenance cost.

The macro synthetic fibre-reinforced shotcrete or MSFRS, it has also risen in the maturity as a re-engineered material, and it is getting widely used in many forms of the sprayed tunnel linings, and the same is done for not just temporary but also for permanent ground support in the mining and the civil tunnel applications too (Nitschke and Winterberg, 2016).

Application within the precast tunnel segment, it is new. However, one cannot ignore the fact that The MSF has very distinct advantages over the steel reinforcements. For example, non-corrosive, and this doesn't suffer from the embrittlement of the matrix and even the inherent performance laws with the age as proved (Bernard, 2014). Also, the continuous research and development are yielding high-performing fibres that are able to meet some of the

particular specifications of the project of the tunnels. The reference to it can be found within ITAtech report 7 of 2016.

The replacement of the steel rebar cage of the tunnel segment by the use of non-coercive reinforcement of the fibre will help to yield higher durability. Apart from the same fibres that are near the reinforcement of the surface, which is quite vulnerable to concrete coverage and also provides the crack control and the resistance to the impact, repair minimization and reject rates and this, in turn, the total project cost.

A rebar cage, that got used traditionally, The replacement of it with the macro synthetic fibres also allows the change of the crack control, which is governed by design for the durability or SLS for the ULS design that is purely structural with much more freedom in the process of detailing and for the potential of the cost savings.

Definitely, the usage of MSF reinforcement for the segments of the tunnel is relatively very new, and the recent publications, including ITAtech report 7 of 2016 or British PAS 8810 of 2016, they are now giving much more credibility to the reinforcement type and also for the basis of such a design.

2. Design - Segmental lining

Introduction

Currently, there does not exist any particular design standard or the guidelines for the MSFRC. There are some regular design methodologies for the steel fibre reinforced concrete or SFRC applicable. The micro synthetic fibre, it can be used wherein the project performance, and specification criteria can be easily met- If the concrete reinforcement with the fibrous synthetic reinforcement can be exhibited and it provides adequate strength of post cracking residual, in such a case, it has been said to be considered as suitable for the structural purposes and the SFRC (ITA WG2, 2015).

There were global standards for the steel fibres' absence in the past, but this did not come in the way of its acceptance as well as its usage of it in different applications. There have been continuous developments and many successfully completed projects, which are a clear indication that the same is currently applicable to very high-performance synthetic fibres.

3. Concrete segments with fibre reinforcements

FRC design is completely based upon the performance of tensile, which means the capacity of crack bridging that has been provided by the use of the fibres. There have been several experimental tests that have been carried out for the determination of the tensile characteristics. The behaviour of the fibre reinforcement in terms of post cracking, it can be easily determined in an indirect manner upon the bending beams using the displacement control machines. Model code 2010 of 2012 has been today one of the most recognized standards internationally for FRC design. The characterization of the performance of post-crack is known for following European harmonized standard EN 14651.

The design of the segment, it aims typically at the largely compressed section with very little to moderate bending moments. Apart from the same, the reinforcement might only be required for the load cases that are temporary and are typically for the propulsion of TBM at the joints in the form of the bursting ladders.

The reinforcement of traditional steel is still required in some of the large tunnels or the tunnels that are present within the soft grounds because of the high bending movements within the permanent or the temporary condition. In such cases, the hybrid reinforcement, which includes the combination of the cage and fibre, it has been considered as much more durable as well as a solution that is caused efficiently because of the partial replacement of the rebar by the fibres (Plizzari and Cominoli, 2005).

4. Segmentation of ring

For the better accomplishment of a solution that includes fibre only, The smaller segments are required to be adopted for limiting the segment aspect ratio, which is the ratio of the developed length over the thickness. Did exist a very large number of the smaller segments that reduce the stiffness of the given ring and, in return, that act as the bending moments upon the segments. Also, the damage risk while handling and the temporary load conditions, all of the same gets minimized.

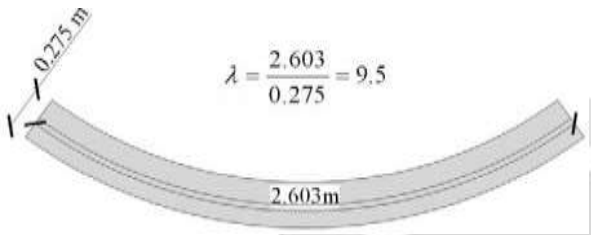

Figure: Segment Aspect Ratio Definition

Varied executed tunnels of FRC experience, they suggest that within the aspect ratio, the value that does not exceed 10, it safely permits FRC usage only as per ITAtech, 2016. But there exist some or the other parameters, including tunnel diameter, ground conditions, and the overburden, and all of these must allow the replacement of rebars by the use of fibres that have been verified by the structural design.

5. SLS Design

The segments which have been reinforced with the use of rebar cage made of traditional steel, they require very tight service limits so ask to protect the reinforcement of steel from the corrosion. The control over crack width that is given by the reinforcement of fibre can easily change the crack control, which is governed by the design of SLS in the pure design, which is required structurally. This helps in eating the economic benefits and also creating significant freedom within the detailing and the design. The FRC, without any conventional reinforcement, It can easily limit the development of the crack width wherein the load re-distribution is completely possible as it has been given within the indeterminate statistical elements like the rotation capacity, including tunnel segment within axial thrust, DBV 2001.

According to recent research, it can be seen that by the addition of macro synthetic fibres that are high performing to the concrete that is reinforced by steel rebar, it reduces the width of the crack along with the spacing of the crack by around 30% within the bending of the beams that are simply supported (Bernard, 2015). This is why MSF can easily add a significant gain of the design life to the concrete structures that are still reinforced, like the segments that are hybrid reinforced.

6. Design of ULS

FRC segmental linings, the approach of typical design, is a use of the force that is Moment-Normal interaction diagrams or the Moment-Normal capacity limit curve. The design load couples which is factored acting upon the section, they must completely remain within the envelope of M-N.

The material properties of FRC are therefore derived from beam tests that are then eventually used as a basis for the determination of the relationship of stress-strain of concrete upon the tension side. The idealized diagram of stress-strain enables the setup of capacity limit curves that get obtained by the equilibrium iterations upon the cross-section which has been given.

7. Project of Santoña-Laredo

Santoña-Laredo General interceptor collector, It is a subsea tunnel of around 1.5 km that is currently under construction in the northern part of Spain. Santoña marshland's sanitation project, The given tunnel is the part of the same, and it has been constructed with mixshield TBM 4.30 m, that is across Santoña bay and is using the macro synthetic fibre which is reinforced for the concrete segments. The manufacturing process review, and specifically the design of the given tunnel segment, It has led to words decision for replacement of the rebar cages that are conventional, with the macro synthetic fibre.

8. Design of segmental lining

It is not just the cost savings within the production but also the design review of the segment of the tunnel for meeting up the aggressive marine environment, that has led to the decision for replacing rebar cages that are very used conventionally, with the BarChip macro synthetic fibres of EPC.

To better accommodating this concrete solution which is fibre-reinforced, some of the smaller segments got adopted from meeting up the limit of the segment aspect ratio. The diameter internally of the tunnel is 3.50 m, along with the segment thickness of around 250 mm. The selection was made for the segmentation to be around 5+1, together with the three rectangular segments apart from the two counter keys and the keystone, which is half size. This has been known for yielding the segment aspect ratio of around 8.6, and this is below the limit of 10, which was mentioned before.

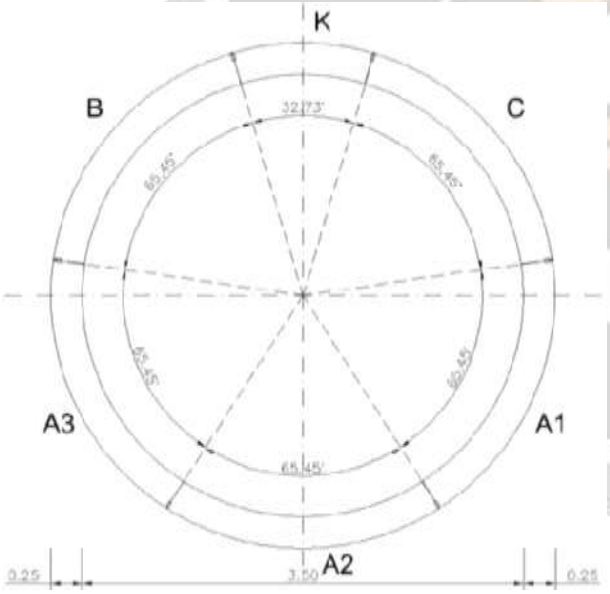

Figure: Ring Segmentation

The FRC segments structural design, by employing the concrete class of C45/55, It is completely based upon the EHE-08, 2008 (Spanish) along with the 2010 fib model code. The FRC is required for making compliance with the other two ductility criteria that follows EHE-08, Annex 18. Here in the flexural performance, It gets determined as per the testing standard that is European harmonized, EN 14651. It simply means that the minimum ductility requirement within different displacements that has to retain a minimum of 40% of the total flexural strength or the cracking stress as a part of the residual performance in the SLS, 0.5 mm crack mouth opening displacement, and the minimum of the 20% with a ULS that includes CMOD of 2.5 mm.

According to the experience that has been gained from the previous projects that used BarChip MSF, some of the characteristic values which got determined include,

- $f_{R1k} \geq 0.4\ f_{ctk,fl}$ and
- $f_{R3k} \geq 0.2\ f_{ctk,fl}$
- $f_{ctk,fl} = 3.60$ MPa
- $f_{R1k} = 1.50$ MPa
- $f_{R3k} = 1.50$ MPa

Wherein the value of the residual strength can easily be reached with the 5kg/m^3 of the BarChip BC48. There were conducted many testing trials at the Polytechnic University of Catalunya laboratory that is in Barcelona, Spain, for corroborating values. Apart from what has been considered as the test of the standard beam that exists within the trials frame, the parallel testing also got executed, and it employs the double punching test or the Barcelona test. This methodology test is known for using the smaller specimens, and also it reduces any efforts which are related to the quality control in comparison to the beam testing (UNE 83515, 2010). The correlation of R2 is 0.9, and this got attained between two of the test methods so as to ensure that the frequency of complex beam test, it can be reduced.

9. Permanent conditions design

For the permanent condition structural design due to the geostatic loadings, It has been carried out for some seven critical chainages, wherein the ground conditions, in particular, got expected for yielding critical load combinations. Such conditions have been known for comprising the maximum or the minimum overburden and maximum water pressure in the combinations therein.

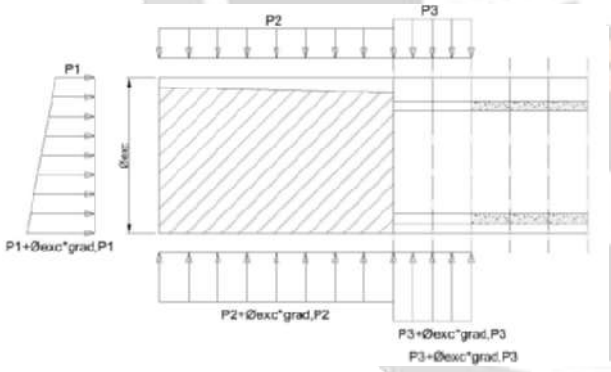

Figure: FEA derived Load model

Within the slurry shield drive to assume the machine's normal operating conditions and terrain deformations that can help in a determination of the load up on the ring, It is completely dependent upon seven factors, and the summary of the same can be found below,

- Ahead of the front, the deformation
- The radical deformation that exists all around the shield
- The radical deformation within the trail of shield
- The pressure adjustment of the poor and the drainage within the long run

Such analyses, It gets carried out by the use of FLAC3D FEA or finite element analysis.

With the use of the formula of Muir-Wood, for determination of the stiffness of the ring along with the model that is experimentally based, for the determination of this strength development of a given injection mortar in the given advance rate which has been assumed of the eight rings every day, The lord combinations ruling as the M-N couples, that acts upon the segmental lining got found the US structural design uses the capacity envelope of M-N. Also, the interaction diagrams of the axial force bending moment, they are a common tool for the final linings design (Nitschke and Winterberg, 2016).

The properties of FRC material which was given earlier didn't mention some of the flexural values characteristics, and the same gets corroborated by the test results of the experiment. Such values become the basis for the relationship of stress-strain of the concrete upon the tension side by the use of the stress block that is simplified. The diagram of stress-strain enables the setup of the capacity limit curve that is then obtained by the equilibrium iterations that are upon the given cross-section.

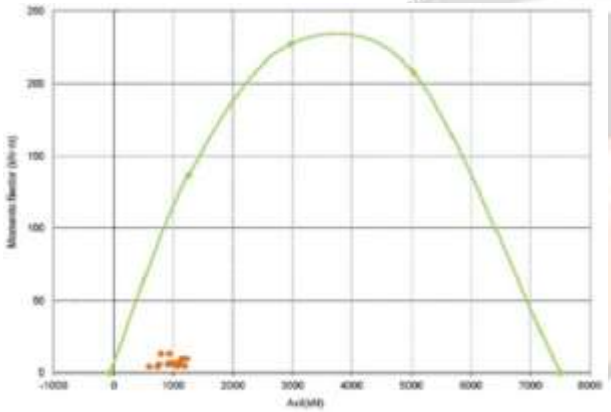

Figure: FRC section M-N capacity Envelope

The given figure completely shows factored design load couples that have been plotted in the capacity envelope of M-N. This design is quite adequate for C45/55 chosen concrete glass and the 5 kg/m^3 of the BarChip BC48 fibre, which will be acting as the primary reinforcement. The given ring, it will be under the axial compression because of the normal forces that govern. The bending moment which is very moderate, it acts upon the ring so that there gets minimized the tensile stress. It shows that the detailing of the ring, it did get well designed for accommodating the fibre-only solution in the given load conditions that are permanent.

The international diagram of M-N also shows some remarkable provisions within the capacity of load-bearing that is given by the concrete section that has been fibre-reinforced.

The radical joints, or such joints that exist between ring segments, they get checked against the max bursting and the compressive stress. A ground settlement has also been found for being minimal so that the birdsmouthing because of the ovalization of the ring, does not get considered. Also, the guiding rods within the radical joint make sure that segments remain connected with a very minimal offset that, in turn, can help in the production of the additional stress and eccentricity. A comprehensive capacity design of around 5.37 MN/m of a given section, it exceeds the maximum acting load by far, that is 1.22MN/m. A check was also made over the busting stresses with the use of FLAC3D, and the same remained at 0.89 MPa, that is quite below the capacity of the design tensile of the plain concrete, which is 1.77 MPa. This is why there was no requirement for additional reinforcement.

10. Temporary conditions design

The loads that result from segment handling, that includes demoulding, stacking, and turning, they also get checked against the strength of the design tensile of the plane concrete at referring ages. The performance of post crack can be given by fibre reinforcement, the same has not been taken into account in this given case, and this has been done for avoiding any cracking of the segments at any stages.

There was a check made for the ring joints against the load that came in from the jacking forces during the TBM propulsion. The maximum force of the trust of the mixshield TBM was 16275 kN, and it was distributed on the 11 Jacks, which means two jacks were there for the MD segment and one was for the keystone. Any comprehensive stress that was under jacking pads, it was seen well below admissible stress. But bursting stresses also require special attention, and they got modeled and better analyzed with the FLAC3D. There is a requirement for distinguishing the two cases, including tangential stress that was along with the ring joint phase and can lead to the spelling, and the other was stressing upon the segment depth, which can lead easily to splitting. The figure shows the given model, which has been adopted within the FEA kind of the tangential spalling, which resulted there in stressed under the jacking thrust.

The max of the spalling stress, It was determined for being around 4.07 MPa, and this exceeded the capacity of tensile of the concrete and the residual tensile strength of post crack strength provided by fibres. When the stresses got integrated, it yielded the tensile force, which was 50.8 kN, and it needed 1.17-cm^2 additional reinforcements, which were required at the given ring joints. This has been provided as the bursting ladders that consisted of the three dia. 8mm that got connected with the dia. 6mm stagger-bar, which was continuous.

The figure shows a bursting ladder that got placed in the mould. Due to the stiffness reason of the ladder and some of the related eases which were associated with placing the same within the mould, It got continued within the radical joints and was then just connecting at the edge of the trailing segment. It is to be noted that radical joints by no means required any additional reinforcement, and it was just a measure for easing as well as reducing the manual handling in regards to the times of the production cycle.

The stress distribution gradient upon jacking face, it is shallow when considering the perpendicular direction. This is why there was not seen an exceeding of splitting stresses within the design tensile strength of the plane concrete, and this is why there was no requirement for any additional reinforcement.

During TBM propulsions, The segment gapping effect because of imperfect ring build, it also got verified with the FLAC3D. The existing gap of the 3mm in width between the last installed ring and the offset segment got also analyzed. Apart from the same, in the load case, the stress which was a result of the same, it remained completely below the design tensile strength of the plane concrete, and there was no requirement for any additional reinforcement.

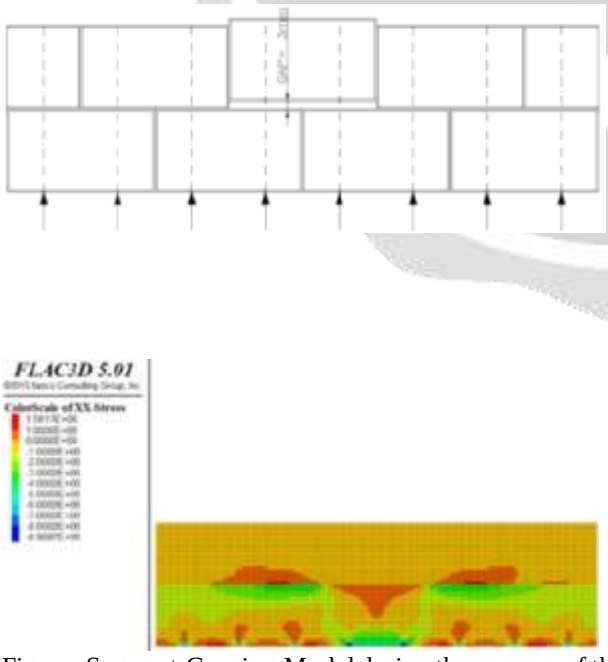

Figure: Segment Gapping Model during the process of thrusting and the resulting stresses on segments at bottom

11. Economic aspects

The design of the initial segment was seen yielding the conventional steel reinforcement cage of the 95 kg/m^3. Within the precast operations, in regards to the improvement as well as the related cost savings, Acciona Construcción, The main contractor, also reviewed the design with the Ingemey Consultores, who will be the final design consultant. Taking a switch to the BarChip fibre reinforcement of EPC, it eliminated 80% + steel reinforcement. The remaining of the bursting ladders, which were 16 kg per m^3, the same got solely for the jacking forces, wherein synthetic fibre was the primary reinforcement for the segment.

Apart from advantages which included saving over the direct cost, the micro synthetic fibres switch also eliminated rebar cage and the inherent labor. It also reduced to the production cycle time by around 50%.

In regards to the cost assessments, that included the segment manufacturing and the reduced repair, all the rejection rate because of the FRC segment's robustness that was significantly improved, that was reviewed cost savings in a total of around 40% for rings in comparison to rebar cage design which was traditional.

12. Conclusion

Based upon the ongoing research, as well as the continuous development of the macro synthetic fibre and the reinforced concrete of macro synthetic fibre, did make it as of today as a modern and the cost-efficient construction material.

Apart from eliminating the durability issues in regards to the primary reinforcement corrosion, yields have been there that are providing significant advantages for the designs as the same does not get covered any longer by the serviceability limits.

The saving of substantial cost and the time can get attained by The fibres used by the reduction within the cost-intensive labor for preparation, placing, and the control of the rebar reinforcement that is standard. Now, this is applicable specifically within the complex reinforcement cages that are of the tunnel Segments that are precast. Apart from the same cost, which is related to the maintenance by the replacement of the rejected or by making the repair of the damaged segment, even the same can be reduced significantly.

The experience which has been gained in the Santoña-Laredo project is a clear indication that the macro synthetic fibre reinforcement segments will be performing very robustly, and it will be very satisfactory even when there exist some difficult conditions (Orfila Farræs et al. 2017).

Such types of tunneling projects which include sewage irrigation or the underground hydropower pipelines, they are in the world market widely present, and they can bring in a huge opportunity for the segmental linings made of macro synthetic fibre reinforced concrete, and it will help to profit from the advantages.

With the project's successful completion will help to build up much more confidence within the macro synthetic fibre we enforcement segmental linings. The gained experience in the success of the given project will also lead to towards the implementation of the technology in some of the other tunnel projects.

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