Fibre reinforced concrete tunnel linings – a review of new guidance

In this article, Benoit Jones reviews new guidance available for design of fibre reinforced tunnel linings

IN RECENT YEARS, quite a lot of new guidance has been published on the design of fibre reinforced concrete, the most notable being the fib Model Code 2010, published in 2013. At the World Tunnel Congress in San Francisco this year, the International Tunnelling Association's Working Group 2 (ITA WG2) and ITAtech Activity Group Support also published reports on the subject, which will be the focus of this article.

Introduction

Fibre reinforced concrete tunnel linings are desirable mainly because they are cheaper, but also because when well-designed, specified and constructed they can provide a higher quality product. Although fibres are often significantly more expensive per tonne than reinforcing bars, they can save money in other ways:

- The fibres can be much stronger than reinforcing bars (and hence less kg/m^3 of concrete is needed),
- They are dispersed in the concrete, including near the surface, potentially reducing the number of segments damaged during handling and transportation that need to be repaired or thrown away.
- If there is no reinforcement cage made up of reinforcing bars, then this removes a whole section of a segment factory or, in the case of sprayed concrete, fibre

Figure 1: ITA WG2 Report No.16 and ITAtech Report No.7, both published in April 2016

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reinforcement added to the concrete removes the need to fix steel lattice girders and mesh. This can reduce labour costs and increase production.

It is a testament to the benefits of fibre reinforced concrete tunnel linings that designers have struggled for years to design them on a rational and defensible basis rather than opting for the far simpler and easier to design steel bar reinforced concrete. These pioneers have contended with incomplete design guidance and the need to base designs on extensive testing, often at full-scale. These barriers to adoption are still sometimes a bridge too far for the more conservative clients.

Now, however, the times may be a-changing, with more detailed standards and guidance becoming available, based on experimental research and real case studies amassed over the last 20-30 years. Perhaps in a few years' time, designing a tunnel lining with fibre reinforced concrete will be no more onerous than designing with reinforcing bars.

In April 2016, two new reports were published by the ITA. Both are on precast fibre reinforced concrete segmental linings. One is written by Working Group 2 – Research, and the other is written by ITAtech.

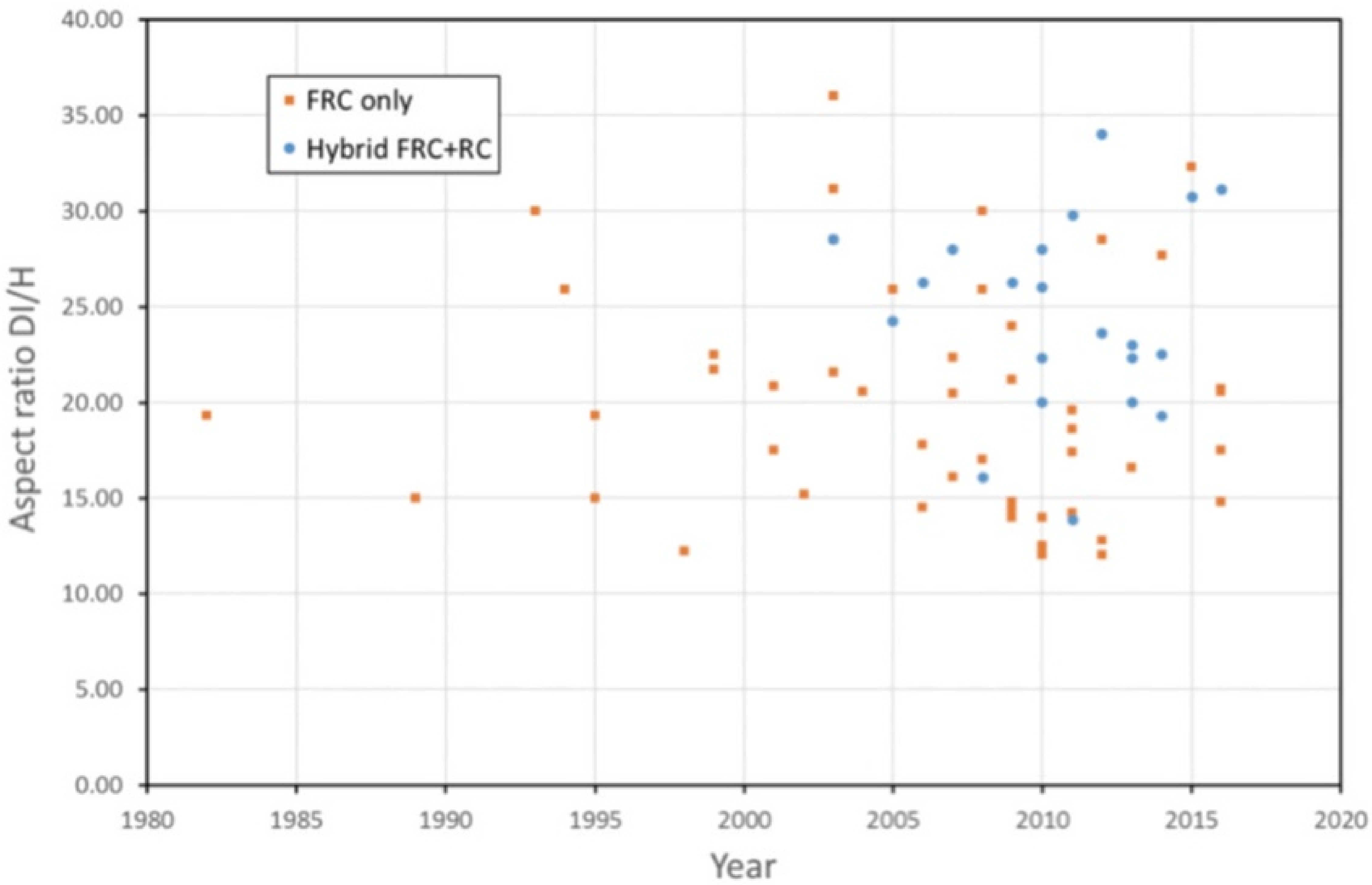
ITA Report No.16 "Twenty years of FRC tunnel segments practice: lessons learnt and proposed design principles", Working Group 2 – Research, April 2016

The stated aim of this report is to bridge the gap between currently available standards and recommendations intended for general FRC design and the actual design of FRC segmental linings. This seems like a useful objective, as tunnel linings have unique requirements and loading conditions compared to standard structural members. It is based on research studies and on 73 case studies from the first use of fibre reinforced concrete tunnel linings in Metrosud subway in Italy in 1982 up to the present day.

What the report actually does is to quickly conclude in the introduction that the fib Model Code 2010 (2013) is the only standard worth using. This is probably a reasonable approach to take as it is probably the most advanced and well-accepted code. It was published in 2013 and covers all aspects of the design of concrete structures. It is a lengthy document of some 402 pages so even though it is a minor part, fibre reinforced concrete design is covered in some detail. It seems likely that the fib Model Code 2010 will remain the most widely-accepted code until an annex to Eurocode 2 on fibre reinforced concrete is published.

The WG2 report doesn't quite deliver on its promises. Sections 9 and 10 summarising the Model Code design approach may be useful for those who can't afford to purchase the Model Code for □□99 (inc. VAT and shipping), but in places it is less clear than the Model Code or it is lacking explanation and I doubt it would be possible to proceed with a design without getting a full copy and reading all the guidance therein.

Figure 2: Aspect ratio DI/H of all 73 case histories presented in ITA WG2 Report No.16 Table 1



Another minor criticism is that there is mention early on that reinforcing bars are better for dealing with "localised stresses" and fibres are better for "diffused stresses", but there is no explanation of these terms until much later. Which is fine if you read it twice. There is frequent, though not usually sense-threatening, international-English language usage, which some may find awkward to read.

Sections 11 and 12 on particular requirements for tunnel linings are useful as an aide-mémoire. In Section 11 a list is made of standard loading conditions for a segmental lining in chronological order:

1. Demoulding of tunnel segments
2. Storage of segments
3. Transportation of segments
4. Positioning of segments by erector
5. Thrust jack forces from TBM
6. Introduction of normal ring force in longitudinal joint
7. Ring behaviour of the tunnel lining during grouting process
8. Ring behaviour of the tunnel lining embedded in the ground
9. Ring behaviour during special event such as fire, explosion, earthquake (fire event only will [be] briefly discussed in this document)

It is then stated that all these are simple to analyse as a ring, except 5 and 6. These special situations are where forces are being transferred across the joints and special attention is needed. It could be argued that 7, 8 and 9 also require knowledge of how forces are transferred across the joints, since this determines the rotational stiffness of the longitudinal joints needed for any model of a complete ring. Suggestions are made in Section 11.2 for how this rotational stiffness could be estimated by plotting moments against curvature as the joint rotates, but the role of packers is ignored. Since the properties of the packer in the joint have direct influence on the stress distribution and hence the eccentricity of the normal force and hence the rotational stiffness, this seems a strange omission.

For analysis of ring behaviour, another key aspect is the role of interaction between adjacent rings. This is especially important when the longitudinal joints of adjacent rings are not aligned but stepped, which is usual practice nowadays. This means that longitudinal joints cannot rotate without transferring forces to adjacent rings. Therefore, rings often do not behave independently and rotational stiffness is further affected. WG2 haven't gotten to the bottom of this problem, which is understandable as it is complicated, but it would be useful to know more detail about how this problem can be tackled by designers and researchers alike.

The report ends with brief summaries of 14 of the case studies, giving basic facts about their design and construction. This is a useful resource for designers wishing to persuade clients of the track record of fibre reinforced concrete. 71% are fibre only, and 29% are a hybrid design of fibres and reinforcing bars. As shown in Figure 2, the hybrid designs tend to be more common at larger diameters and tend to result in a slenderer lining. Hybrid designs are also a more recent invention, the first recorded use being the Oenzberg Tunnel in Switzerland in 2003.

If there is a future revision of this report, providing some examples of design calculations and detailing in an appendix would be very useful, similar to the examples provided by the 2001 WG2 Report on seismic design of underground structures (Hashash et al., 2001). At present the report's recommendations lack too much detail to be of much use except as signposts for designers to find detail elsewhere or to work it out for themselves. There is much richness in the detail and examples would be an excellent way of communicating the different possible approaches.

ITAtech Report No.7 "ITAtech guidance for precast fibre reinforced concrete segments – Vol.1: Design aspects", ITAtech Activity Group – Support, April 2016.

The stated aims of this document are very similar to those of the WG2 Report. Another report is planned in future by ITAtech to cover production aspects of fibre reinforced concrete segments.

The introduction lists information about the behaviour of fibres and fibre reinforced concrete, presumably based on research. It would be useful if references were given to these studies, otherwise as the state-of-the-art changes it will be difficult to know how new understanding fits in, and also because without citations it reads like a series of statements without scientific basis rather than a proper literature review. Apart from this failing, it is well-written and clear and seems right up to date with current understanding of strain softening and strain hardening behaviour and how this affects cracking patterns.

ITAtech Report No.7 assumes the reader has an in-depth knowledge of design using the fib Model Code 2010. This is certainly necessary, but the strength of this report is that it doesn't repeat information in the Model Code but concentrates on clearly explaining the possible design approaches relevant to a segmental lining with commentary on their validity.

The main body of the report describes design procedures, performance specification and sustainability. Again the lack of references is conspicuous. The report is full of statements like this: "FRC segments have been demonstrated to be durable and, when fibres are used with bar reinforcement, the fibres reduce the risk of corrosion of the bars". Factual statements like this require evidence in the form of empirical data, deduction or a reference to empirical data or deduction done by others, otherwise they are not scientific. I am sure these references exist and that the vast majority, if not all, of the statements in the report are correct, but people need references so they can follow the same logic if they want to. Very occasionally, the authors get this right, for example: "It has been found that, when exposed to conditions conducive to reduced alkalinity, good quality SFRC will only carbonate to a depth of a couple of millimetres over a period of many years (Nemegeer et al., 2000)". A reader can look up the reference and decide whether she agrees with the statement. Perhaps references can be added to a future revision.

The section on performance specification, and in particular the discussion of testing methods, is an excellent and much-needed review. There are several beam tests available, with different loading conditions (3-point and 4-point) and some have a sawn notch and some do not. Un-notched beams with 4-point loading tend to have lower mean flexural strengths than notched beams because a crack is allowed to form anywhere in the constant moment region and hence will occur at the weakest point.

The report also discusses the high coefficient of variation found in beam tests, which can be as high as 25%. When statistical rules are applied, this can result in a characteristic strength that is well below the mean strength. The authors report that careful testing by a single well-trained operator of at least 12 specimens can reduce the coefficient of variation to around 10%. There then follows a detailed description of how to interpret the ASTM C1609 beam test and the EN 14651 beam test.

The last section on sustainability gives values for embodied CO_2 of constituent materials, and for examples of concrete reinforced with steel bars, steel fibres and synthetic fibres. Now that designers and clients are becoming more concerned with carbon footprint as well as cost, it is interesting to see that fibre reinforced concrete will result in a smaller carbon footprint than bar reinforcement. In the case of steel fibres, this is mainly due to the lower volume fraction needed as they have a higher embodied CO_2/tonne than steel bars. It would be interesting to compare the 9 case studies in Appendix D of this report or even the ones in the ITA WG2 report with this model, as thickness of the lining will have a big effect on sustainability in terms of volume of excavated material and volume of concrete, and the WG2 report showed that hybrid linings tended to be slenderer, particularly at larger diameters.

"FRC segments have been demonstrated to be durable and, when fibres are used with bar reinforcement, the fibres reduce the risk of corrosion of the bars"

Conclusions

One wonders whether ITAtech and WG2 could work together to produce a single document, as they both have strengths – ITAtech is particularly good on design procedure and testing methods, whereas WG2 is good on background, has more case studies and is quite good on loading conditions (which are not covered at all in the ITAtech report).

One way in which both reports could be improved is to include, perhaps in an Appendix, example calculations. These would be far easier to follow and would reinforce the message. Perhaps more than one example calculation could be included to demonstrate different approaches to specification, testing, determination of parameters, load combinations and design.