Design and construction of pile-supported concrete industrial floors

Piled floors in distribution centres are attracting unfavourable attention among developers and building owners and there is some nervousness about the commonly used steel-fibre-reinforced concrete (SFRC) designs. Many floors are cracked to some degree. In perhaps most cases, the cracking does not lead to serious problems but in others, the severity of the cracking is such that the floors may not give the expected long-term service. Tony Hulett of Face Consultants proposes measures in design and construction required to minimise the incidence of cracks in steel-fibre-reinforced piled floors. First, it is useful to understand what can be expected from floors.

Pile-supported slabs are designed on the assumption that at working loads they are in a cracked state, ie, the load-induced stresses are being resisted by reinforcement. It follows that cracking of the upper surface can be anticipated when loaded, although applied safety factors mean that this may not necessarily be the case.

This tends to surprise owners and tenants who do not expect to see cracks in floors. Pile-supported ground floors are similar to suspended floors in, say, office developments. The difference is in use. Office floors are covered on top by raised computer floors and by ceilings below. Cracking is therefore rarely observed. Floors in distribution centres are quite different, where cracks are highly visible.

Avoiding cracks is therefore an important objective. This is not the same as limiting crack widths as would be expected in structural design. Deliberate reduction of crack widths by increasing reinforcement can lead to considerably more, albeit very fine, cracking. Such cracking may be too fine to repair and yet will still break down under the actions of pallet trucks. The risks of this approach can be seen in Figure 1.

Recent history

Anecdotal evidence suggests that many such floors are cracked and some are cracked to a large extent.

Cracking occurs in two basic patterns: first in nominally straight lines coincident with pile grids, sometimes in one direction only but in other cases in both orthogonal directions.

It seems that this linear cracking occurs early in the life of the floor and is initiated by drying shrinkage. Over the piles, load-induced stresses are at their highest and shrinkage-induced stresses are additive such that the cracking strength of the plain concrete is exceeded.

Second, in some cases, crack patterns develop over the piles, commonly of an annulus with cracks radiating away as can be seen in Figure 2. This cracking tends to develop more slowly as the floor is used, suggesting that it is more load related, although drying shrinkage may well play a part. It has also been observed that this form of cracking is sometimes associated with excessive deflections as can be seen in Figure 3.

It is not understood whether this is the development of fan pattern yield lines or punching or a combination of both.

Over time, cracking tends to develop as shown in Figure 4, with the familiar 'islands' along crack lines. These are difficult to repair effectively and where this is the case, there is doubt concerning the long-term serviceability of the floor, with consequent effects on the value of buildings.

The solution is to use SFRC in such a way as to maximise the construction benefits while minimising the risks of cracking. It would be unwise to suggest that cracking can be totally eliminated but evidence suggests that it is possible to considerably reduce it. The starting point is to insist on a comprehensive specification in order that loads are correctly assessed.

Developers' specifications

Specifications often give inadequate detail on loads anticipated. To interpret loads correctly, the following are needed in the specification. In the absence of these data, loads are commonly understated:

- leg loads and spacing, including aisle spacing*

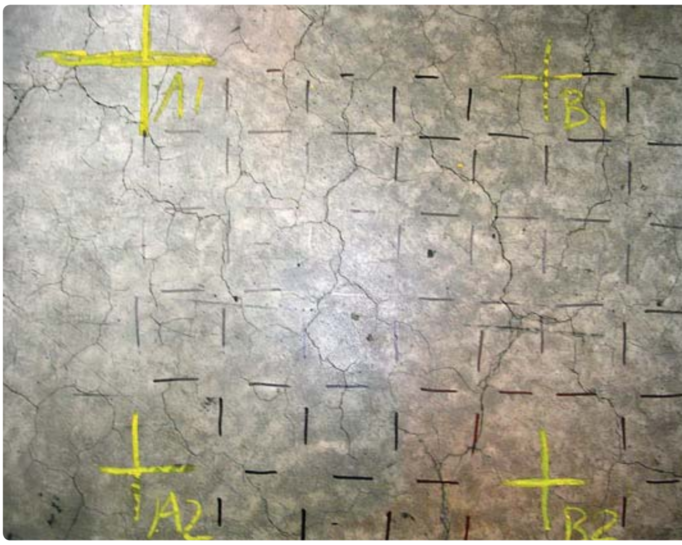

Figure 1 top: Excessive cracking in a conventionally reinforced floor.
Figure 2 above: Cracking over a pile.

Figure 3: Deflections at mid span.

Figure 4: Breakdown of surface at cracks

- truck loads showing maximum axle and wheel loads
- plans for wire guidance saw cuts *
- uniformly distributed loads
- other loads such as mezzanine columns.

* Unlike ground-supported floors, the thickness of a piled slab is a function of the proximity of the racking and the aisle spacing. There is a strong case for specifying the most onerous racking formation and for the provision of saw cuts as the floor may be used for very narrow aisle (VNA) racking at some stage in its life.

Design with SFRC

Yield line analysis is generally used to assess imposed moments in folding plate and fan-type patterns. In addition, punching shear stresses are checked.

It is suggested that there is a strong correlation between the poor performance of floors and slab thickness, although construction detailing is of considerable importance, as discussed later. The lack of robustness arises from two basic factors as follows.

Effective spans

Many designs use an assumption that the folding plate yield lines are formed at a distance of half the slab depth away from the edge of the supports. This may be a reasonable assumption for continuous supports but not for round pile heads, as illustrated in Figure 5. The red hashed line is a more rational position for the yield line and reflects the commonly observed crack pattern shown on the left of the illustration.

Pile heads must be correctly designed and installed so that the effective spans are not increased by loss of structural support at their edges.

This approach would increase effective spans by around 25%, which will result in an increase in slab thickness of the order of 10–15%.

SFRC performance

SFRC performance has generally been poorly documented and there has been a lack of traceable test results data, although there is evidence that this is changing. SFRC designs

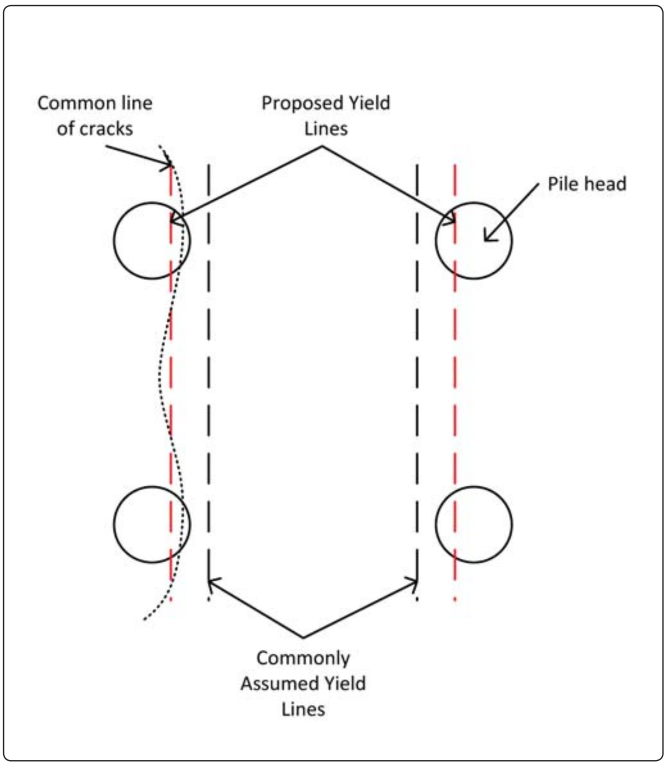

Figure 5: Yield line positions.

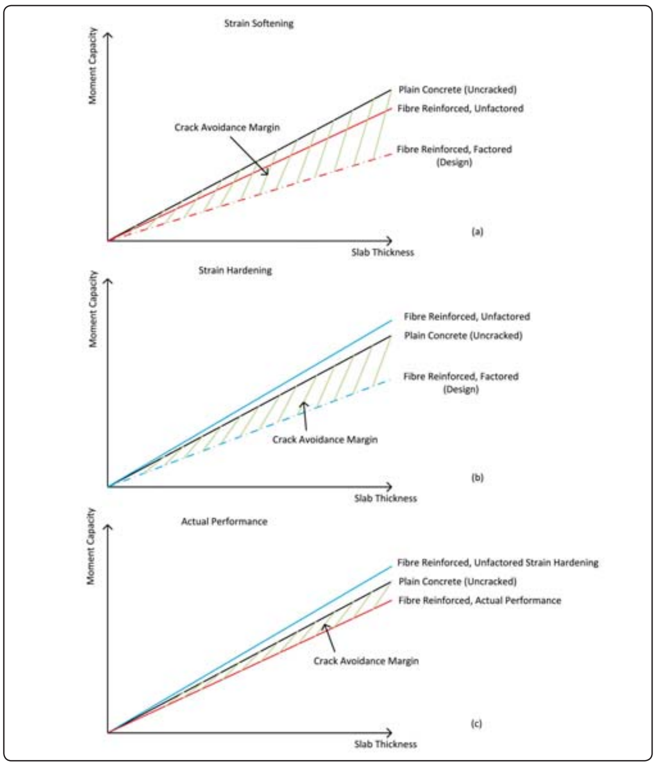

Figure 6: Crack avoidance margins.

also tend to be opaque and not easily verified.

Engineers should be able to validate designs using accepted test methods for SFRC performance and this can now be done using test data based on the notched beam tests in BS EN 14651(1). There has been prolonged debate on the method of testing. As mentioned in Concrete Society Technical Report 63(2), "The respective merits of beam and plate tests to determine the flexural capacity of SFRC are keenly debated by steel fibre suppliers."

The flooring industry now needs to move on with an accepted and transparent test method. The beam test is already codified and yields results that can be interpreted directly for floor design. Through its use, the public knowledge base on SFRC can be expected to develop.

It is commonly accepted in the literature that for fibre types and dosages used in floors, the fibres will provide a strain-softening response to loads. However, it is common to find designs assuming apparent strain-hardening responses with cracked resistance of 10% or more over the uncracked section.

It is believed that reliance on the beam tests with a common form of stress block analysis will lead to increases in slab thickness of about 10%.

Overall, changes to effective spans and to the assessment of SFRC performance could lead to increases in slab thickness of around 20%.

Designing for shrinkage stresses

To give certainty on elimination of surface cracks, it would be necessary to analyse the slab elastically. In theory, the permissible stress could be reduced by an allowance for shrinkage-induced stress. This would have the effect of very significantly increasing slab thickness without a guarantee that shrinkage-induced cracking would be avoided. A similar approach was introduced for ground-supported slabs in the third edition of TR34(3) and then later withdrawn.

The only practical method of dealing with shrinkage stresses is to minimise them by reducing shrinkage and restraint. This can be done by attention to the shrinkage potential of the concrete and by careful attention to the tolerances of the pile heads and construction platform. The spacing between free movement joints can also be reduced.

This approach cannot be validated by calculation but relies on a common sense approach to dealing with known potential problems. As a starting point, the designer should avoid designing to the limit where the factored SFRC yield moment is of a similar magnitude to the unfactored moment of the plain concrete.

Figures 6a–c show conceptually the relationship between the moment capacities of plain concrete and fibre-reinforced concrete. Clearly the actual moment–depth relationship is not linear.

Figure 6a shows a fibre performance that is considered to be typically strain softening.

Figure 7: Pile heads and sub-base.

The unfactored fibre capacity is close to that of plain concrete and the factored fibre capacity is lower by a factor of 1.5. The hatched area then forms what can be considered the crack avoidance margin.

Figure 6b shows a fibre performance that is strain hardening. The unfactored fibre capacity is greater than that of plain concrete and the factored fibre capacity is again lowered by a factor of 1.5. The crack avoidance margin is considerably reduced.

If it is accepted that the fibres do not give a strain-hardening performance then the crack avoidance margin will be significantly reduced as shown in Figure 6c. It follows that the more ambitious the claim for the SFRC performance, the greater the likelihood that the elastic limit of the concrete will be exceeded, resulting in cracking. It is suggested that this is a common scenario.

The obvious conclusion is that to avoid cracking, stress levels should be within the elastic limit of the plain concrete. Formally designing to this limit with partial safety factors applied would lead to considerably thicker floors which cannot be justified; therefore, working within the elastic limit demands that great care is taken to avoid shrinkage restraint as discussed below.

Reducing shrinkage stresses

The strategies for reducing stresses are well established in ground-supported floor construction. They are the reduction of shrinkage potential by avoiding high cement and water contents and by reduction in restraint by good-quality sub-base construction and adequate provision of joints. These same principles can be applied to pile-supported floors although with some limitations.

In particular, pile heads need more careful attention than is often found. They must be flat and level and must not protrude above the finished level of the sub-base, which itself should also be level as seen in Figure 7.

Concluding remarks

Present concerns about steel-fibre-reinforced floors on piles are justified as many are in poor condition because of cracking. With robust design, appropriate material performance testing and careful attention to construction methods, it is believed that cracking can be greatly reduced.

The use of SFRC should not be rejected but should be developed, not least because there are significant economic benefits when compared to construction with conventional reinforcement.

There is a good future for floor construction on piles using steel-fibre-reinforced concrete. ●

References

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