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Steel-Fibre-Reinforcement and Increasing the Load-Bearing Capacity of Concrete Pavements

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Abstract

Elastic theories form the basic concept used in most of the existing design codes for industrial or transportation plain and conventionally reinforced concrete ground slabs. The post-cracking load bearing capacity of slabs-on-ground is not taken into account in most of these codes. Therefore, these codes (e.g. PCA, ACI) cannot be used directly for steel fibre reinforced concrete (SFRC). Guidelines for SFRC (e.g. Concrete Society) use the ultimate limit state concept for fibre reinforced ground floors, but only partially, since cracking is only allowed to occur on the bottom surface of the slab. The highly repetitive nature of the loads which may cause considerable degradation in the mechanical properties of the pavement and foundation also is not considered in this method. The aim of this paper is to evaluate the load-bearing capacity of SFRC pavements through numerical simulations, and to assess the accuracy of the analytical methods used in different design codes,

Keywords: SFRC, numerical analysis, load-bearing, concrete pavements.

1. INTRODUCTION

Due to considerable differences between the strength of concrete in tension and compression, the tensile strength of rigid pavements usually dominates the design. Therefore, in plain concrete pavements, the compressive capacity of the slab remains largely unused. The material in general remains in the elastic domain until cracking takes place, hence, its behaviour could be predicted by elastic analysis.

For reinforced concrete (RC) pavements a significant part of load bearing capacity is developed after cracking and mobilization of the force in the reinforcement. Therefore, the slab enters the non-linear domain of structural behaviour and using elastic assumptions leads to a significant underestimation of the slab capacity. SFRC pavements behave similar to reinforced concrete, though the effective amount of reinforcement is much less, and hence also require non-linear analysis for predicting their behaviour.

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Existing design codes, for industrial or transportation slabs, rely on elastic or basic elasto-plastic theories and methods of analysis. This paper begins by a review of the various theories used. However, these methods are not perfect for general analysis and numerical methods are more flexible in the range of problems they can solve.

Load bearing capacity of concrete pavements may be reduced due to considerable degradation in the strength properties of the material caused by fatigue effects. Steel fibres increase the fatigue resistance of concrete significantly (ACI 544.4R 1999). However, the effect of fatigue on SFRC pavements has not been sufficiently studied in the published literature and requires comprehensive research.

The elastic and inelastic behaviour of SFRC pavements are studied in this paper using FE models. The load-bearing capacity of SFRC pavements is evaluated for a typical road slab, considering the issue of fatigue. The results are compared with analytical methods. In the absence of test results for investigating the effect of fatigue on SFRC pavements, at this stage, the fatigue effect is simulated by a reduction factor in the strength of concrete.

2. EXISTING THEORIES FOR ANALYSING RIGID PAVEMENT

The first complete design method for rigid pavements was developed around 1920, based on Westergaard's theory (ACI 360R, 1997). Westergaard assumed that the slab is a homogeneous, isotropic and elastic material resting on a perfect subgrade. Westergaard's equations are still widely used for computing stresses in pavements and validating models developed using different techniques, In spite of overestimating the required slab thickness. In 1943, Burmister (1943) proposed the theory of stresses and displacements in layered systems. This theory was never developed enough for engineering design practices, because it is not applicable for limited-length slabs under edge and corner loads. Later, Losberg (1961) and Meyerhof (1962) developed similar strength theories based on the yield line concept. However, these theories are not able to predict the deformational behaviour of the slab-foundation system.

The classical differential equations are often used to predict the structural behaviour of rigid pavements. Solving these equations by conventional methods is feasible only for simplified models with homogeneous materials and continuous geometry for slab and subgrade. Therefore, the use of this approach for a real rigid pavement, which may contain discontinuities and be supported by a non-uniform subgrade, is quite limited. However, it is possible to use them as a bench-mark for validating other numerical models, by comparing the results under similar assumptions. Considering an infinitely extended plate carrying a load "P" which is distributed over a small area, the maximum tensile stress can be computed by closed-form equations. In this case, Timoshenko (1952) developed equations, using the same assumptions as in the Westergaard's theory. In the case of a highly concentrated load, Timoshenko's equations corrected by means of the thick-plate theory using Westergaard's equations.

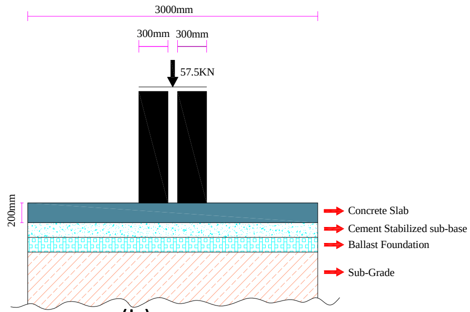
In the existing theories two models have been used for the subgrade: Winkler (or dense liquid) subgrade and elastic-isotropic solid subgrade (ACI 360R, 1997). Winkler foundation is assumed to deflect under an applied vertical force in direct proportion to the force, without shear transmission to adjacent areas of the foundation. In the elastic-isotropic solid model the applied load to the surface of the foundation is assumed to produce a continuous basin. The elastic response of real soils is located somewhere between these two extremes.

3. NUMERICAL METHOD

A good numerical tool for analysing the behaviour of rigid pavements is the "Finite Element" (FE) method. The FE method offers good potential to solve complex problems and can be used to analyse rigid pavements having many different boundary conditions. Two different approaches are examined for analysing a concrete pavement carrying a single concentrated load. In the first approach, materials are assumed to behave elastically. In the second, the non-linear behaviour of concrete is considered and the smeared crack model is used for simulating the post-cracking behaviour of the SFRC pavement. Winkler model is used for simulating the foundation. The ABAQUS finite element package (Hibbitt, Karlsson and Sorensen 2004) is used to perform the analysis.

The chosen slab to be analysed in one that will be tested as part of a large European funded project called "Ecolanes". The slab will be subjected to accelerated load testing at the TUI, Romania. A general description of this test is summarised in Figure 1 as well as in Table 1.

(a)



(b)

Figure 1 (a) Circular accelerated loading test, TUI Romania (b) Layers and the loading

Table 1 Slab details

Slab:	Track width	: 3.00 m
	Slab thickness	: 200 mm
	Elastic modulus	: 32GPa
Load:	Double wheel load	: 57.5 kN
	Position	: Moving
along the centre line		
	Number of load cycles	: 1.5 million
Supporting layers:	Equivalent modulus of reaction	: 0.4 N/mm^3

Two models were analysed: (1) Infinite slab, to compare the results with existing closed form equations (A slab size of 6×6m was found to sufficiently simulate a large slab). (2) Finite width slab of 3m (A 3×6m slab was found to be sufficient in this case).

Shell elements were used for modelling the slab, in which the thickness is significantly smaller than the other dimensions. Shell elements have displacement and rotational degrees of freedom at each node.

3.1 Reliability Assessment and Mesh Sensitivity Analysis of the Elastic FE Model (Infinite Slab)

4 element dimensions were used for mesh sensitivity analysis, to compare the results and to evaluate the sensitivity of the model to mesh refinement. The results of FE analysis for an infinitely extended slab are compared with two closed form equations (Table 2).

Figure 2 shows the percentage difference between the maximum tensile stresses calculated by FE analysis and closed form equations, for different element sizes. This figure clearly shows the sensitivity of the model to the element size. Using finer meshes, the numerical solution tends to converge and get closer to the results of the closed-form solutions.

Table 2 Element dimensions and results of elastic analysis for an infinite slab

Method	Mesh No.	Element Size (mm)	Maximum tensile stress at the bottom face (MPa)
FE Analysis	1	300	0.711
	2	150	1.159
	3	50	1.339
	4	25	1.363

Closed-Form Solution	Timoshenko's equation	1.36
	Westergaard's equation	1.423

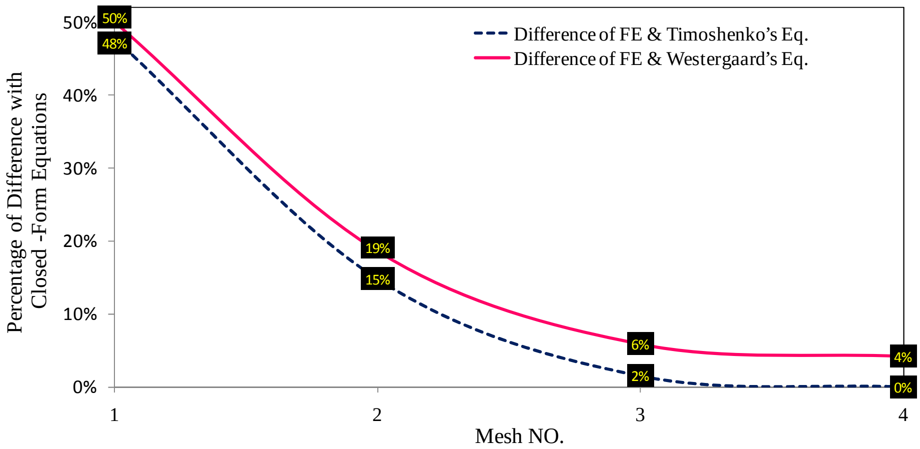


Figure 2 FE elastic analysis, compared with closed-form solutions

The results indicate that the developed finite element model used is conceptually reliable and can be used for analysing other slab geometries and loading configurations. Due to acceptable accuracy, 50 mm element size is used for future analysis.

3.2 Non-Linear FE Analysis of the Finite Width Slab

FE analysis of the slab was performed under the service load, (double wheel load with two contact areas, each 110×300mm) which was applied centrally on the slab. Under this load the stresses created in the slab were much less than the cracking stress. Therefore, the load was increased gradually, to monitor the post-cracking behaviour of the slab until complete collapse. The post-cracking tensile strength of SFRC increases the load bearing capacity of the structural member beyond the plain concrete capacity. The tension softening diagram of concrete, which represents the relationship between tensile stress and tensile strain in the fracture zone, describes the post-cracking behaviour of concrete. Figure 3 shows the concrete material properties used in the analysis. The ratio of ultimate biaxial compressive stress to ultimate uniaxial compressive stress (Kupfer et al. 1973) was assumed to be 1.15. The approach used for simulating the non-linear behaviour of the concrete is the smeared crack approach.

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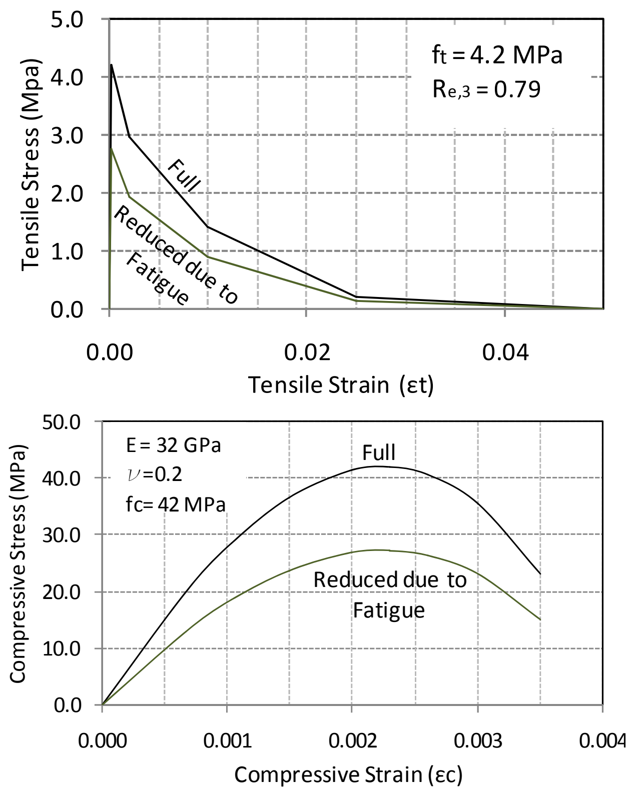

Figure 3 Concrete material properties

As the load increased, the flexural stresses at the bottom of the slab reached the flexural strength of the concrete, leading to a transversal tension crack caused by positive moments. Further increases in the load led to a longitudinal tension crack in the bottom of the slab. After that further increase in the load did not cause further increase in positive moments, but the moments were redistributed. This resulted in a substantial increase in circumferential negative moments some distance away from the loaded area, resulting in circumferential tensile cracks at the top of the slab. The ultimate load occurred when the transversal crack reached the edges of the slab which was split into two. The load versus central displacement curve of the slab is presented in the next section, Figure 4.

3.3 The Fatigue Effect

Due to traffic and cyclic environmental conditions concrete pavements are subjected to repetitive loading. Generally, fatigue strengths for SFRC are 65 to 95 percent at one to two million cycles of non-reversed load, as compared to typical

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values of 50 to 55 percent for slabs without fibres. For properly proportioned high-quality SFRC, a fatigue value of 85 percent is often used in pavement design (ACI 544.4R 1999).

To account for the fatigue effects in numerical analysis in this paper, the material capacity was reduced to 65% of the static strength, and the structure was analysed as for static loading. Figure 4 shows the load-displacement curve at the centre of the slab with and without consideration of the fatigue effect. The loads corresponding to initiation of transversal, longitudinal and circumferential cracks are illustrated on the curves.

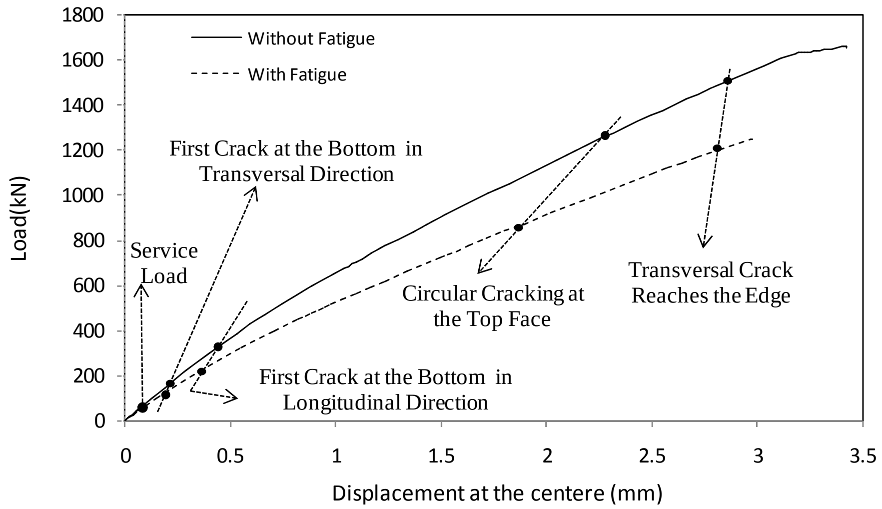

Figure 4 Load-displacement curve at the centre of the slab.

Results of the numerical non-linear analysis are compared with the non-linear method of the Concrete Society (2003).

4. CONCRETE SOCIETY METHOD FOR SFRC SLABS

The method presented in TR34 of the Concrete Society (2003) for fibre reinforced ground floors is based on the elasto-plastic theory developed by Meyerhof (1962) using the ultimate limit state concept, but only partially, since cracking is only allowed to occur on the bottom surface of the slab.

Using the Concrete Society method for dual point loads acting centrally, the total collapse load can be approximated. According to the Concrete Society definition, collapse load is reached immediately before the development of visible circumferential cracks on the top of the slab. In this method, the contribution of the

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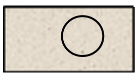
subgrade reaction is ignored. Using the above calculations and ignoring the partial safety factor, the ultimate load of the slab with the characteristics presented in section 3, is estimated at 790kN. This is the maximum load carried by the slab immediately before the cracks form at the top face.

5. DISCUSSION

A comparison of results for each crack mode and corresponding loads is shown in Table 3. For fatigue loads, this table shows that the load corresponding to the first crack reduces proportionally to the reduction in material property. Deterioration has less impact on the final capacity.

Table 3 Loading capacity, with and without considering fatigue effect

Cracking stage		Numerical Model			Concrete Society
		Central load (kN)		Load bearing ratio (Fatigue/No fatigue)	Central load (kN)
		No fatigue	With fatigue		No fatigue
First transversal crack at the bottom		175	115	66 %	-
First longitudinal crack at the bottom		320	215	67 %	-
Circumferential crack at the top face		1250	850	68 %	790
Cracking all over the transversal direction		1500	1200	80 %	-

6. CONCLUSION

Analysis done using FE shows that the slab capacity exceeds the elastic capacity and service load by many times. Therefore, the approaches used in most of the codes for the design of transportation slabs, which are based on classical elastic theories, are not suitable for SFRC pavements.

Numerical analysis showed that the first crack is expected in the transversal direction followed by cracks in the longitudinal direction. Top cracks around the loading surface occur at much higher loads and the slab eventually fails by splitting into two.

The effect of fatigue could be taken into account by reducing the material properties and this has a greater impact on the first crack load than the ultimate capacity.

A comparison with the Concrete Society method for ground slabs shows that more work needs to be done to bring the two approaches together.

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