Design of Heavily Loaded Continuously Reinforced Concrete Pavements

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Abstract

Industrial pavements are subjected to very large loads, e.g., axle loads exceeding 1000 kN and containers stacked in height and blocks equaling single loads of even higher magnitude. Often, industrial pavements are located in harbors where the subgrade may consist of the previous bottom of the sea and fillings. It is necessary to make the concrete pavement competitive and as thin as possible without jeopardizing safety. Continuous reinforced concrete pavements (CRCP) may be one possibility. Prof. A. Losberg used yield line theory (YLT) for the design of CRCP. The YLT is described in the paper through some simple and practical cases. The YLT allows considerably higher ultimate loads than the theory of elasticity. One problem is how to handle fatigue. It is illustrated by tests found in the literature. Finally, a new Swedish design concept for industrial CRCP based on YLT and containing a high safety factor to prevent fatigue failure is described.

Background

Industrial pavements are subjected to very large loads, e.g., axle loads exceeding 1000 kN and containers stacked in height and blocks equaling single loads of even higher magnitude. Often, industrial pavements are located in harbors where the subgrade may consist of the previous bottom of the sea and fillings. Plain concrete pavements meeting these demands have to be very thick. The client may select a weaker but less expensive alternative accepting reduced design life and increased maintenance costs but keeping the investment budget. Consequently, it is necessary to make the concrete pavement competitive and as thin as possible without jeopardizing safety. Continuous reinforcement may be one possibility.

In Europe, continuously reinforced concrete pavements (CRCP) are usually given the same or negligibly less thickness as the jointed plain concrete pavement (JPCP). This practice always surprises structural engineers used to the benefit of reinforcement. The theoretical reasons for this practice are that the thickness is needed (i) to provide flexural rigidity to distribute and limit the strain in the subgrade and (ii) to hold tightly cracks that may occur due to environmental loading, e.g. restrained shrinkage and restrained thermal movements. The demands on industrial pavements are, however, different from those on highway pavements. The evenness does not have to be the same and a higher degree of cracking may be accepted. The number of load repetitions is only a fraction of the one on the highway. The shape of the pavement and the traffic pattern differ from the longitudinal one characterizing the road. Finally, the load magnitude may be ten times larger on the industrial pavement. Consequently, it may be appropriate

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to find other design methods for an industrial CRCP than the ones developed for CRCP in the road network.

The Swedish professor A. Losberg made in the 1960s a pioneer work on the design of CRCP using the yield line theory developed by his Scandinavian colleague K. W. Johansen. Losberg designed the reinforced concrete pavements for the Arlanda airport of the Swedish capital in the same decade. Losberg's design method does not cover fatigue. The yield line theory is developed for the ultimate limit state, whereas fatigue loading is connected to the repetition of the maximum load of the serviceability limit state. In Sweden, an engineering design method combining yield line theory and fatigue has been developed recently. Design tables have been suggested and industrial pavements, designed using these tables, have been constructed and found to behave satisfactorily.

Research Significance

Properly designed continuously reinforced concrete pavements constitute a cost-effective solution for heavy-duty pavements in harbors and other areas with poor subgrade. Compared with highway pavements, a higher degree of cracking may be accepted when the maximum possible load that may occur very seldom or more frequently loads the industrial pavement. Consequently, there is a need of developing design methods both for the ultimate limit state and for fatigue loading. This paper deals with yield line theory, especially in combination with fatigue.

An Introduction to Yield Line Theory for Slabs on Grade

The yield line theory (YLT) for reinforced concrete (RC) slabs was developed by the Danish researcher K. W. Johansen in the 1940s (Johansen 1943). The Swedish professor A. Losberg introduced the YLT to RC slabs on grade (Losberg 1960). The idea behind the YLT is that a constant flexural moment equal to the positive moment capacity *m* develops in positive yield lines (visible on the bottom side of the slab) and that a constant flexural moment equal to the negative moment capacity *m*' develops in negative yield lines (visible on the top side of the slab). The moment capacities may be computed by the following equations:

$$m = 0.9 \cdot \rho \cdot f_{\mathrm{st}} \cdot d^2 \qquad (1)$$

$$m' = 0.9 \cdot \rho' \cdot f_{\mathrm{st}} \cdot (d')^2 \qquad (2)$$

where ρ and ρ' are the reinforcement ratio in the bottom and top of the slab, respectively, f_{st} is the yield strength of the reinforcement, and *d* and *d*' are the effective depth for positive and negative bending, respectively. *m* and *m´* are both assumed to be equal in two perpendicular directions, e.g., welded wire fabrics with same reinforcement area in both directions.

The relationship between moment capacity and ultimate load can either be derived using energy conditions or equilibrium equations. Let us consider a single load *F* on a RC slab on grade. Assume a circular yield line pattern consisting of radial positive yield lines and a negative yield line at a circumference with radius

r_0 (Figure 1). The angle between two radial yield lines is dϕ. The difficulty is to determine the subgrade reaction $p = p(r)$. The equilibrium demands that

$$F = 2\pi \cdot \int p(r) \cdot r \cdot \mathrm{d}r \tag{3}$$

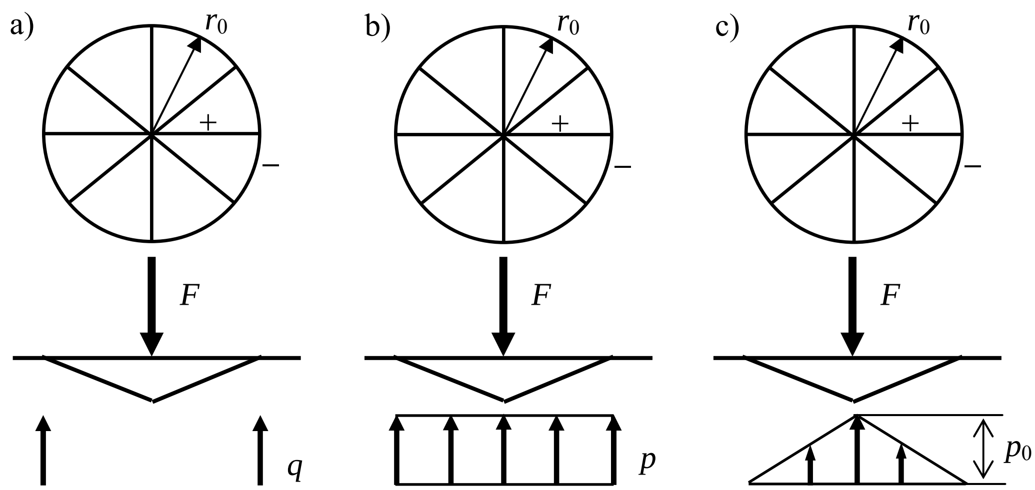

Figure 1. Yield line pattern and three possible subgrade reaction distributions.

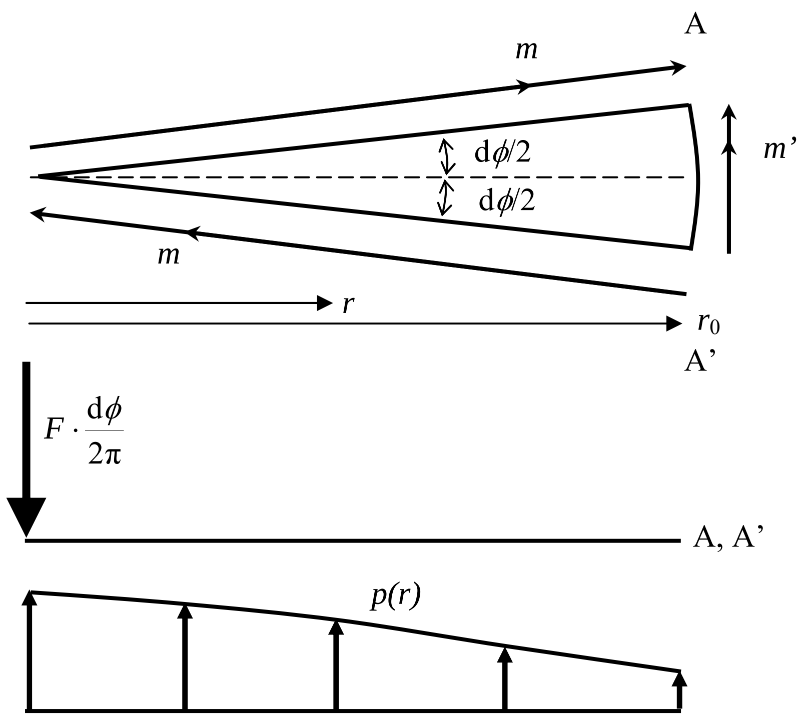

Figure 2. Equilibrium for a small sector of the circular yield line pattern.

Figure 1 shows three possibilities: (a) $F = 2\pi \cdot q$, (b) $F = \pi \cdot p \cdot r_0^2$, and (c) $F = \pi \cdot p_0 \cdot r_0^2/3$. The relationship between moment capacity and ultimate load can be determined by studying the moment equilibrium at the periphery (A-A') of a small sector (Figure 2). We obtain F for case (a) by considering small angles ($\sin \mathrm{d}\phi \approx \mathrm{d}\phi$):

$$F \cdot \frac{\mathrm{d}\phi}{2\pi} \cdot r_0 = m' \cdot r_0 \cdot \mathrm{d}\phi + 2 \cdot m \cdot r_0 \cdot \sin\frac{\mathrm{d}\phi}{2} = m' \cdot r_0 \cdot \mathrm{d}\phi + 2 \cdot m \cdot r_0 \cdot \frac{\mathrm{d}\phi}{2} \tag{4}$$

and, hence,

$$F = 2\pi \cdot (m + m') \tag{5}$$

This is the well-known expression for an elevated slab (see, e.g., Nylander & Kinnunen 1974). The subgrade reaction does not contribute. For slabs on grade, usually some part of the load is supported by the subgrade within the circular yield line. The load carrying capacity F increases with the concentration of the subgrade reaction. For a general case, we obtain:

$$F \cdot \frac{\mathrm{d}\phi}{2\pi} \cdot r_0 - \left[\int_0^{r_0} p(r) \cdot r \cdot (r_0 - r) \cdot \mathrm{d}r\right] \cdot \mathrm{d}\phi = (m + m') \cdot r_0 \cdot \mathrm{d}\phi \tag{6}$$

For case (b), we obtain:

$$F \cdot \frac{\mathrm{d}\phi}{2\pi} \cdot r_0 - \left[\int_0^{r_0} p \cdot r \cdot (r_0 - r) \cdot \mathrm{d}r\right] \cdot \mathrm{d}\phi = F \cdot \frac{\mathrm{d}\phi}{2\pi} \cdot r_0 - p \cdot \frac{r_0^{\,3}}{6} \cdot \mathrm{d}\phi = (m + m') \cdot r_0 \cdot \mathrm{d}\phi \tag{7}$$

$$\Rightarrow \qquad F = 3\pi \cdot (m + m') \tag{8}$$

since $p = F/(\pi \cdot r_0^2)$. For case (c), we obtain:

$$\begin{aligned} &F \cdot \frac{\mathrm{d}\phi}{2\pi} \cdot r_0 - \left[\int_0^{r_0} p_0 \cdot \left(1 - \frac{r}{r_0}\right) \cdot r \cdot (r_0 - r) \cdot \mathrm{d}r\right] \cdot \mathrm{d}\phi = \\ &= F \cdot \frac{\mathrm{d}\phi}{2\pi} \cdot r_0 - p_0 \cdot \frac{r_0^{\,3}}{12} \cdot \mathrm{d}\phi = (m + m') \cdot r_0 \cdot \mathrm{d}\phi \end{aligned} \tag{9}$$

$$\Rightarrow \qquad F = 4\pi \cdot (m + m') \tag{10}$$

since $p_0 = 3F/(\pi \cdot r_0^2)$. We see that the load carrying capacity F increases when the uniform load distribution is replaced by a conical load distribution, i.e., with an increased subgrade reaction concentration. We may summarize the three cases by the equation

$$F = \kappa \cdot 2\pi \cdot (m + m') \tag{11}$$

where κ = 1, 1.5, and 2 for cases (a), (b), and (c), respectively. A. Losberg investigated further concentration, see next section.

Losberg's Solutions to Some Important Cases

Losberg (1961) developed solutions for, e.g., (1) single load on the interior of a slab, (2) twin loads of the interior of a slab, and (3) single load on a free edge. He developed solutions for both resilient subgrade (Winkler foundation, defined by the modulus of subgrade reaction *k*) and elastic subgrade (elastic, isotropic, homogeneous body of semi-infinite extent). Here, only the solutions for resilient subgrade are given (Figures 3-5). The load carrying capacity *F* is given by Eq. (11). The coefficient κ is dependent on the ratio between the load distribution radius *c* (assuming a circular loading area) and the elastic radius of rigidity *l* defined as

$$l = \sqrt[4]{D/k} \tag{12}$$

where $D = Eh^3/\left(12[1-\nu^2]\right)$ = flexural rigidity of the pavement, h = pavement thickness, E = modulus of elasticity of concrete, and ν = Poisson's ratio of concrete. κ increases with increasing *c/l* and reaches $\kappa = 2$, which is the same as for the triangularly distributed subgrade reaction in case (c) above, for *c/l* = 0.7 (single load, Figure 3). The twin loads constitute a more beneficial loading case with increased load carrying capacity at the same *c/l* values (Figure 4). The edge loading (Figure 5) is more severe leading to lower load carrying capacity. Theoretically, κ approaches $\kappa = ½$ when *c/l* approaches infinity, i.e., the subgrade reaction vanishes.

Fatigue Strength of CRCP

As indicated above, continuously reinforced concrete pavements (CRCP) are often designed as plain concrete pavements. In a recent paper, Kang et al. (2004) study the fatigue strength of CRCP both theoretically and experimentally. They summarize previous research and conclude that the number of allowable load repetitions *N* may be determined by the following equation:

$$N = A \cdot \left(\frac{f}{\sigma}\right)^B \tag{13}$$

where f = flexural strength, σ = flexural stress, and A and B are two experimentally determined constants. The researchers performed laboratory tests in ¼ scale of a CRCP in the Korean highway system. They concluded that Eq. (13) with A = 225 000 and B = 4 according to Vesic & Saxena (1970) could be used to describe the test results. This means that Kang et al. neglected the reinforcement.

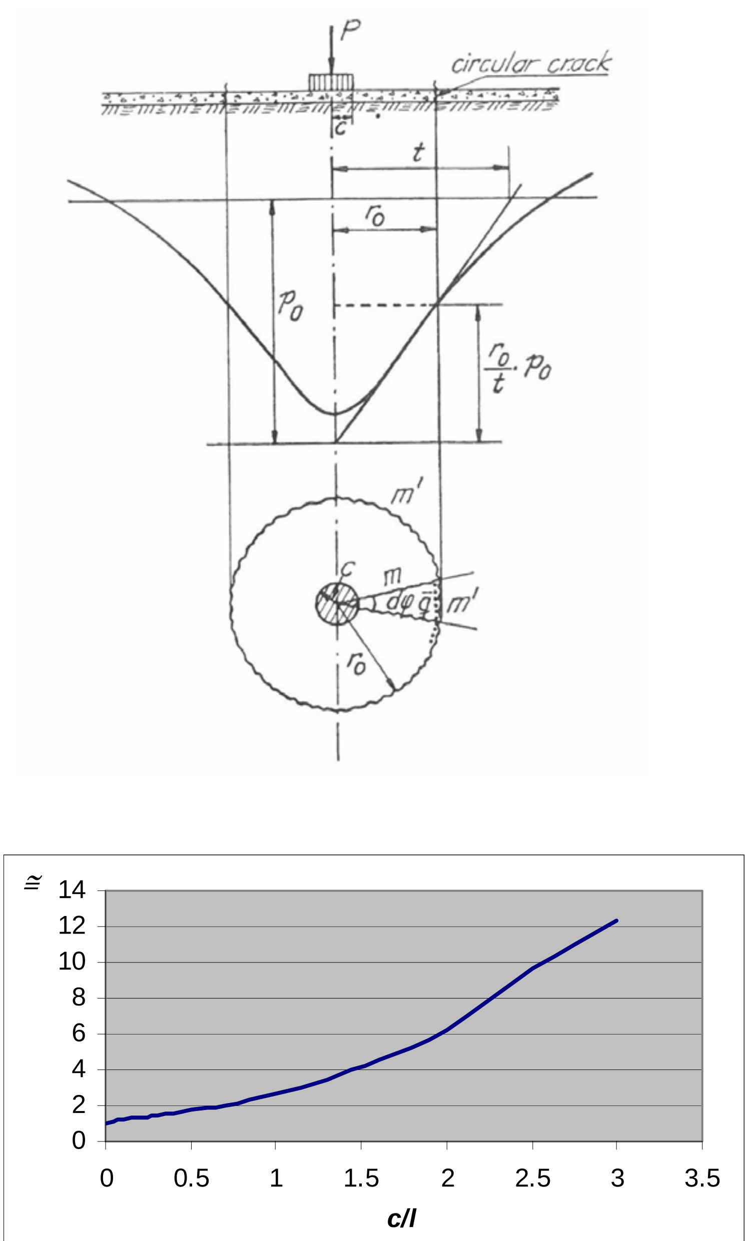

Figure 3. YL pattern and assumed subgrade reaction distribution (top; Losberg 1961) and coefficient κ (bottom) for a single load on the interior of a slab.

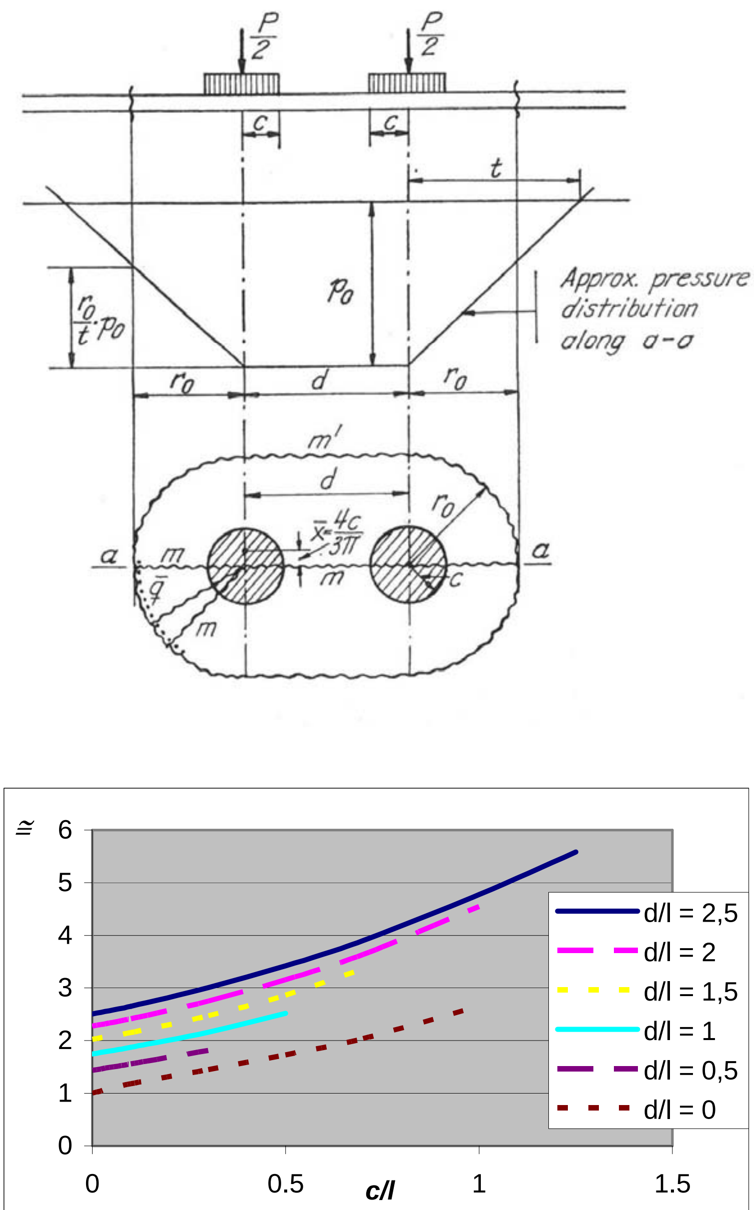

Figure 4. YL pattern and assumed subgrade reaction distribution (top; Losberg 1961) and coefficient κ (bottom) for twin loads on the interior of a slab.

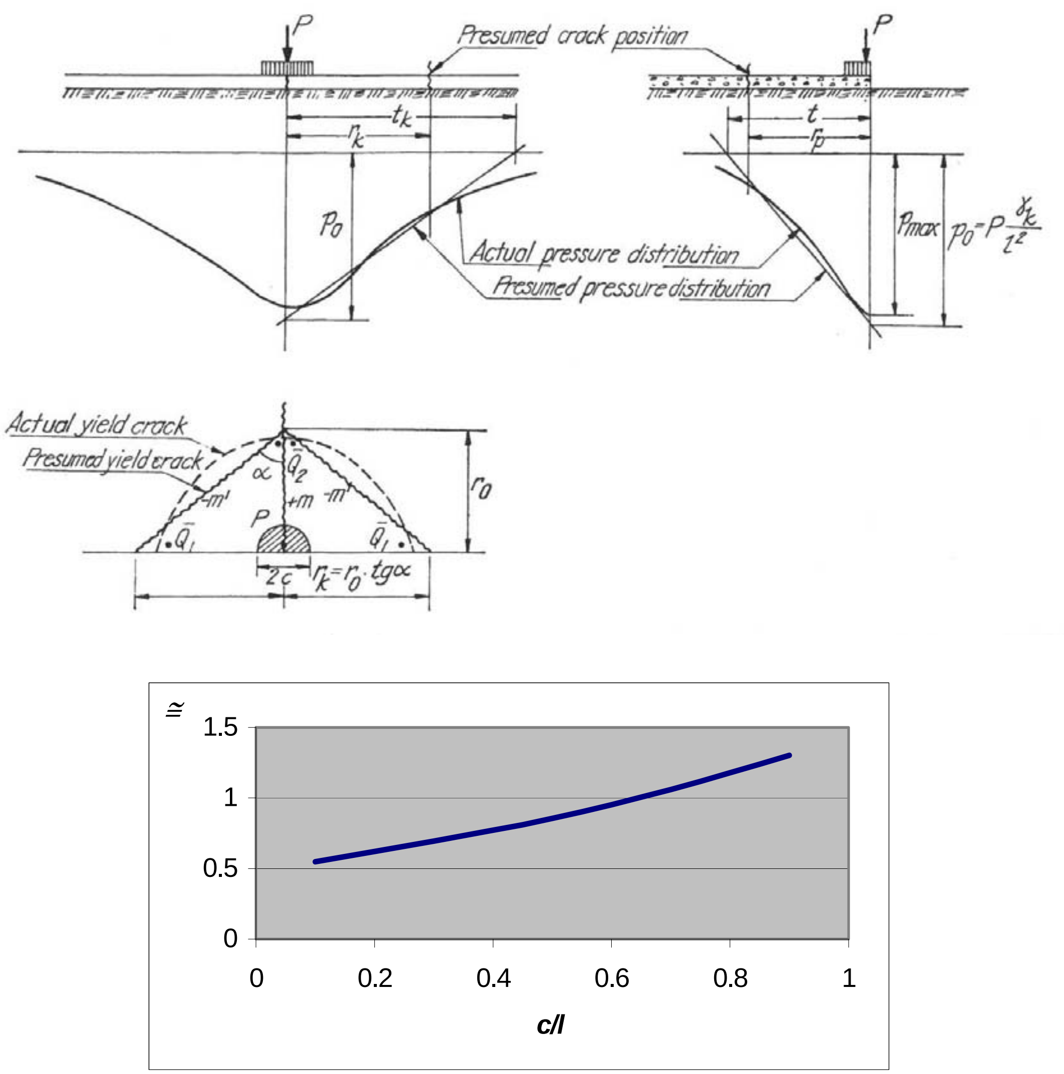

Figure 5. YL pattern and assumed subgrade reaction distribution (top; Losberg 1961) and coefficient κ (bottom) for a single load on a free edge ($m = m'$).

Since Kang's tests are well described, we may reanalyze them. They conducted static and fatigue tests on concrete slabs with length × width × height = 1400×1000×75 mm. To simulate the cement-treated base and the subgrade below, rubber plates were used below the specimens giving a modulus of subgrade reaction k = 706 MN/m^3. The reinforcement mesh was centrically placed (i.e., at mid height). The longitudinal and transverse reinforcement ratios were 0.57 and 0.05 percent, respectively. The transverse reinforcement is negligible. If the reinforcement in two perpendicular directions is very different, Losberg's circular yield line pattern will not develop. Instead, we might assume a yield line pattern composed by three parallel yield lines (Figure 6).

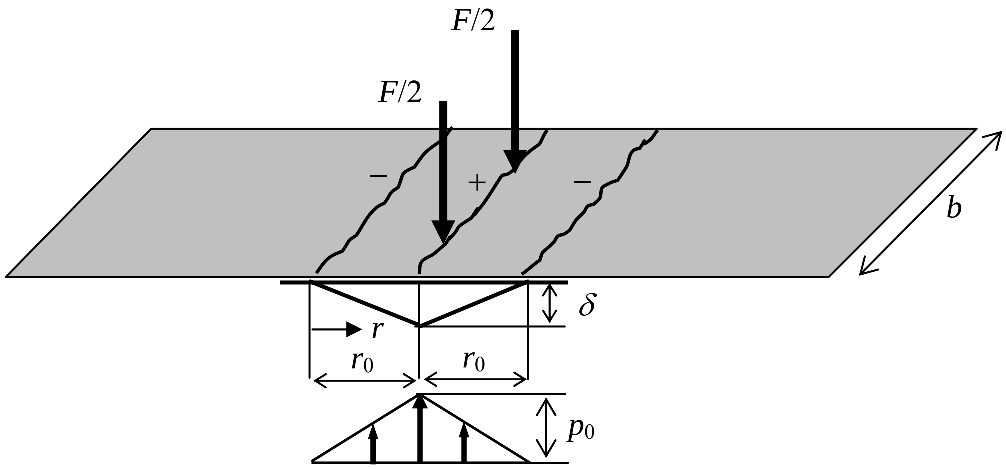

Figure 6. Assumed yield line pattern for CRCP with predominant longitudinal reinforcement and possible subgrade reaction distribution.

The load carrying capacity for the RC slab in Figure 6 may be determined using energy equations. The internal and external energy W_{i} and W_{e} are given by the following equations:

$$W_{\mathrm{i}} = 2 \cdot m' \cdot b \cdot \Theta + m \cdot b \cdot 2\Theta = 2 \cdot \left(m + m'\right) \cdot b \cdot \Theta \tag{14}$$

$$W_{\mathrm{e}} = F \cdot r_0 \cdot \Theta - 2 \cdot b \cdot \int_0^{r_0} p(r) \cdot r \cdot \Theta \cdot \mathrm{d}r \tag{15}$$

where m and m' are the positive and negative moment capacity, respectively, and the mid span deflection $\delta = r_0 \cdot \Theta$.

Let us consider three possible subgrade reaction possibilities (cf., Figure 1):

(a) linear subgrade reaction q at $r = r_0$ ($F = 2 \cdot q \cdot b$)
(b) constant subgrade reaction $p(r) = p$ = constant ($F = 2 \cdot p \cdot r_0 \cdot b$)
(c) linearly varying subgrade reaction $p(r) = p_0 \cdot (r/r_0)$ ($F = p_0 \cdot r_0 \cdot b$)

By setting $W_{\mathrm{i}} = W_{\mathrm{e}}$, the load carrying capacity for the three cases can be determined. We obtain

$$F = \begin{cases} 2 \cdot \dfrac{b}{r_0} \cdot \left(m + m'\right) & \text{(a)} \\ 4 \cdot \dfrac{b}{r_0} \cdot \left(m + m'\right) & \text{(b)} \\ 6 \cdot \dfrac{b}{r_0} \cdot \left(m + m'\right) & \text{(c)} \end{cases} \tag{16}$$

By analyzing Kang's obtained crack pattern (Figure 7, left), we may assume that $b/r_0 = 4$. The moment capacity $m = m' = 7.2$ kNm/m by assuming $f_{\mathrm{st}} = 500$ MPa and utilizing Eqs. (1) and (2) setting $d = d' = h/2 = 37.5$ mm and $\rho = 0.011$ (computed on the effective depth). Thus, the load carrying capacity F = 115 kN, F = 231, and F = 346 kN for cases (a), (b), and (c), respectively. The subgrade reaction was not measured so we must be satisfied by stating that the load carrying capacity ought to be somewhere between 100 and 350 kN. The measured failure load was 128 kN, i.e., within this range.

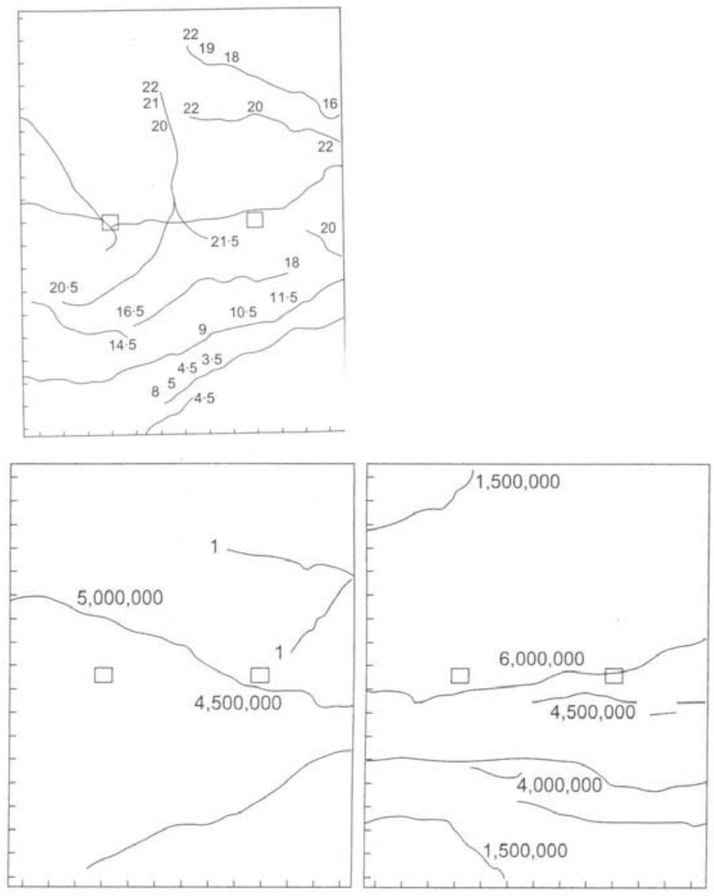

Figure 7. Crack propagation during static test (far left) and fatigue tests performed by Kang et al. (2004). The length and width of the test specimens are 1.4 and 1.0 m, respectively. The squares indicate the loading points. The figures correspond to the crack propagation at a certain load level (unit: metric ton) or number of load repetitions.

Kang et al. (2004) conducted also fatigue tests (Figure 7, middle and right). Three test specimens were subjected to two centrically placed fatigue loads (principally shown in Figure 6). The maximum load was 48, 40, and 16 % of the static load, respectively. Failure, defined as a crack through the loading points, was obtained after 5 million and 6 million load repetitions, respectively, for the two specimens with highest loads. The specimen exposed to 16 % of the static load sustained 10 million load repetitions without cracking. The number of tests was far too small to develop YLT for fatigue loading, but the test result show that the CRCP investigated withstood 40 % of the static load under 5 million load repetitions.

The Swedish Method to Consider Fatigue

The YLT was originally developed for the ultimate limit state considering the maximum possible load including safety factors or partial coefficients. If YLT is used for a bridge slab, e.g., the annual failure probability might be 10^{-5}. Consequently, the probability that the assumed yield line pattern develops during the service life of the bridge is limited. The traffic load that might contribute to fatigue is usually much less than the dead load. Consequently, fatigue is not considered when using the YLT. In a concrete pavement, the traffic load is the predominant load. Fatigue is considered in the design of plain jointed concrete pavements. This design constitutes also the basis for the design of CRCP given the same or slightly smaller thickness. But how should we consider fatigue when using the YLT?

Prof. A. Losberg did not discuss fatigue in his design guide (Losberg 1961). Arlanda airport 45 km north of Stockholm, Sweden, was constructed in the late 1950's and the early 1960's. The airport pavements consisted of CRCP and were designed by A. Losberg. They behaved satisfactorily during more than 35 years but have subsequently showed substantial cracking due to traffic loads with both number and magnitude exceeding the design values (Stig Jansson, Cementa AB, Danderyd, Sweden, personal communication, Jan. 11, 2005). The concrete pavements have successively been replaced with asphalt, but they remain still in some minor areas. The author has not had access to the original design but through knowledge of the current traffic the number of departures of the design aircraft ought to have been limited to 450 000 during the airport's first 30 years.

As far as the author knows, no research has been devoted to YLT and fatigue. One reason might be the complexity and costs of performing fatigue tests on CRCP. Another cause might be that the use of YLT for concrete pavement design is restricted primarily to Sweden that is a country with more than 99 percent flexible pavements. The Swedish use of concrete pavements on harbors, container terminals, and for other industrial purposes has, however, increased during recent years. In cases with a combination of heavy loads and poor subgrade, there has been a demand of CRCP. Despite the lack of research reports, the designer needs advice.

In a Swedish project gathering the national expertise on concrete pavements, the following concept was chosen:

The YLT might be chosen for design of CRCP if

(i) the safety factor is set to 3.0 and

(ii) the number of load repetitions is limited to 1 million.

The safety factor is defined as the ratio between load carrying capacity and design load. Losberg (1961) proposed a safety factor of 1.6 to 2.0 to avoid permanent deformations under normal loads. He didn't consider fatigue, but these values give a hint of a decent magnitude of suitable safety factors. It is interesting to compare these design conditions with the test results by Kang et al. (2004). The analyses of their test results indicate a safety factor equal to 2.5 and a load repetition limit of 5 million. In comparison with these findings, the Swedish design is conservative.

In practical design, it is quite common that heavy axle loads are replaced by an equivalent standard load axle (ESAL) number. This is a straightforward method when the ratio between the maximum load trafficking the pavement and the standard axle load is limited. For industrial pavements, this ratio may approach 10. The Swedish design guidelines strongly dissuade from such a method if the load ratio is large. Contrary, any standard axle loads or other minor loads may be replaced by an equivalent number of load repetitions by the maximum load. This leads to a minimum number of computed load repetitions and, hence, an increased probability to remain within the load repetition limits of the YLT use.

Contrary to Losberg's design recommendations (1961), the flexural rigidity D of the concrete pavement is computed for the un-cracked state. Losberg computed the flexural rigidity for a cracked concrete section with a completely inactive tension zone ("stage II") and a stiffness ratio between reinforcement steel and concrete $n = E_s/E_c = 15$. Losberg's assumptions are logical and in harmony with those times. YLT is applied to cracked concrete. However, the concrete slab is un-cracked between the cracks. A partially cracked and partially un-cracked concrete slab would be very difficult to model. Using the un-cracked flexural rigidity leads to higher stresses and moments in the concrete pavement and, hence, conservative design. The ratio $n = 15$ was usually used in concrete design at that time, but does not reflect the stiffness ratio at short time loading, e.g., traffic loading.

Punching

If a small area, e.g., a small square with side length b, of a slab on grade is loaded by a large concentrated force F, there is a risk for a punching shear failure. A frustum of a cone is assumed to be punched out of the slab. The slope between the envelope surface and the slab plane is assumed to be 45°. It means that only a tensile stress σ acts in the failure surface. At failure, $\sigma = f_v$, where f_v is the shear strength of the concrete slab.

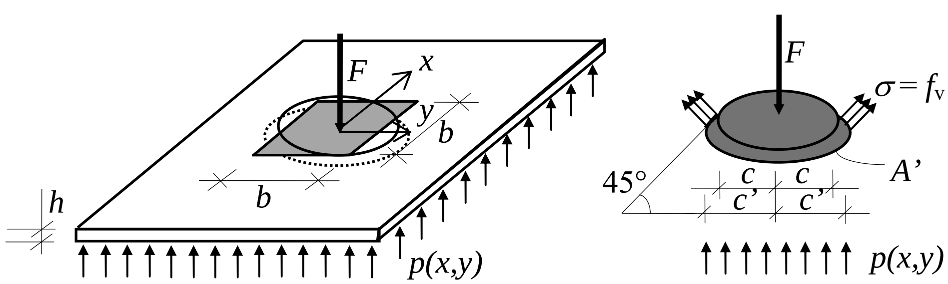

Figure 8. Assumed failure mode at punching shear failure.

According to the Swedish handbook for concrete structures (2004), the load carrying capacity of a reinforced concrete slab subjected to punching may be computed by the following equation:

$$V_u = \eta \cdot u_1 \cdot d \cdot f_{v1} \tag{17}$$

where η = eccentricity (usually, $\eta = 1$), u_1 = the average perimeter of the punching cone, and d = effective depth of the slab. For a circular loading surface with radius c, $u_1 = 2\pi(c + d/2)$. For a rectangular loading surface with side lengths b_1 and b_2, $u_1 = 2(b_1 + b_2) + \pi d$. The formal shear strength f_{v1} of concrete is given by the following equation:

$$f_{v1} = 0.45 \cdot \xi \cdot (1 + 50 \cdot \rho) \cdot f_{ct} \tag{18}$$

where ρ is the reinforcement ratio in the bottom of the slab, f_{ct} = design value of the tensile concrete strength, and ξ = height dependent parameter defined as

$$\xi = \begin{cases} 1.4;\ \text{if } d \leq 0.2 \text{ m} \\ 1.6 - d(\text{m});\ \text{if } 0.2 \text{ m} < d \leq 0.5 \text{ m} \\ 1.3 - 0.4 \cdot d(\text{m});\ \text{if } 0.5 \text{ m} < d \leq 1.0 \text{ m} \\ 0.9;\ \text{if } 1.0 \text{ m} < d \end{cases} \tag{19}$$

In a refined analysis, the beneficial effect of the subgrade reaction on the underside of the punching cone (Figure 8) might be considered. If the resultant to the subgrade reaction on the underside of the punching cone is denoted Q, the load carrying capacity V_u according to Eq. (17) may be magnified by a factor $\Gamma = \frac{1}{1 - Q/F}$, where F is the applied punching load ($F = V_u$ at punching failure). The magnitude of Q/F is, however, usually small, i.e., less than 10 percent.

Practical Design

A 2001 Swedish R&D project developed design tables for industrial concrete pavements (Silfwerbrand, 2001). Solutions are given for the following pavement systems: (1) jointed plain concrete pavements (JPCP) , (2) roller compacted concrete (RCC), (3) continuously reinforced concrete pavements (CRCP), (4) JPCP on cement treated base, (5) JPCP on asphalt treated base, (6) RCC on asphalt treated base, and (7) steel fiber reinforced concrete pavements. The design of the CRCP followed the following steps:

1. In both longitudinal and transversal direction, the reinforcement ratio ρ is determined as the minimum reinforcement for crack control.
2. The pavement thickness h is determined by using YLT and fixing the ratio between load carrying capacity and design load equal to 3.0.
3. Knowing reinforcement ratio ρ and thickness h, the spacing s between reinforcement bars can be determined as soon as the bar diameter has been selected.

The design is based on the following assumptions:

1. The safety factor of 3.0 is considered to contain fatigue effects limited to 1 million load repetitions.
2. The flexural rigidity of the concrete pavement is determined for un-cracked state.
3. Losberg's hypothesis (1961) stating that stresses caused by temperature and shrinkage (restraint stresses) disappear as soon as the reinforcement stress has reached the yield point (i.e., after cracking).
4. Edge loading is prevented either by obstacles against traffic or through tapered pavements.

The reinforcement ratio is designed to secure crack distribution in the CRCP. According to the Swedish handbook for concrete structures (2004), the minimum reinforcement ratio $\rho_{\min}$ for a RC slab on grade is given by the following equation:

$$\rho_{\min} = \frac{A_s}{A_{c,ef}} = 0.7 \cdot \frac{f_{cth}}{\sigma_s} \qquad (20)$$

where A_s = reinforcement area, σ_s = reinforcement steel stress ($\leq$ 420 MPa), $A_{c,ef}$ = effective concrete area, and f_{cth} = high value of tensile concrete strength (= 1.5· f_{ctk}, f_{ctk} = characteristic tensile strength). The minimum reinforcement is assumed to give a tensile force in the reinforcement exceeding the tensile force in the concrete. The beneficial effect of subgrade friction on the crack distribution is considered by the factor 0.7. In a project developing Swedish design tables (2001), σ_s = 420 MPa, f_{cth} = 1.5·1.95 = 2.92 MPa, and $\rho_{\min}$ = 0.49 %. We selected ρ = 0.50 %. Corresponding reinforcement area can either be centrically placed (at mid height) or evenly distributed between bottom and top. The first solution means that $A_s = \rho{\cdot}s{\cdot}h$, the second one that $A_s = A_s' = ½\rho{\cdot}s{\cdot}h$, where h = slab thickness and s = spacing between reinforcement bars in a welded wire fabric (WWF). Assuming a bar diameter Φ = 16 mm, the bar area A_s = 201 mm^2. Consequently, s = 40200/h and s = 80400/h (mm) for the centrically placed and distributed reinforcement, respectively.

The solutions for the case with centrically placed reinforcement are given in Figure 9. Solutions for evenly distributed reinforcement in bottom and top can be found in Silfwerbrand (2001) as well as solutions for container loading. The solutions for CRCP have been compared with solutions for JPCP with dowelled joints with an even spacing of 5 m. The CRCP thickness is 70 to 80 percent of the JPCP thickness at 10 000 load repetitions and 60 to 70 percent at 1 million load repetitions. If Swedish design practice for concrete roads had been used instead, the CRCP thickness had approached 90 to 100 percent of the JPCP thickness. The benefit of using YLT in design of CRCP is obvious.

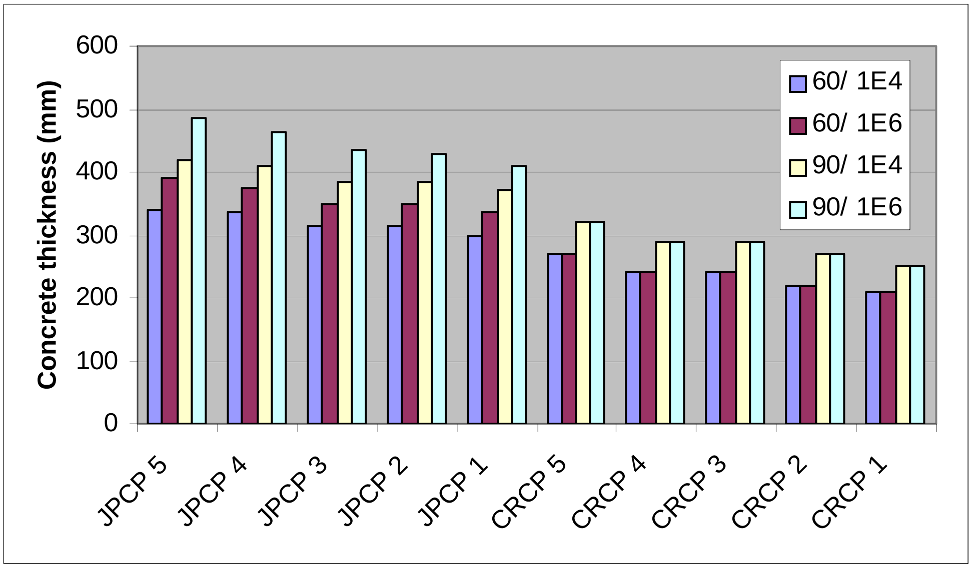

Figure 9. Recommended concrete thickness for CRCP and JPCP solutions for four different load cases (axle load = 60 kN or 90 kN, number of load repetitions = $1\cdot10^{-4}$ or $1\cdot10^{-6}$) and five different subgrade material types (5 = silt, 4 = clay, 3 = silty sand, 2 = sand, 1 = crushed rock) according to Silfwerbrand (2001).

Concluding Remarks

Continuously reinforced concrete pavements (CRCP) constitute a versatile alternative for industrial pavements subjected to very large loads. The paper reuses the yield line theory (YLT) developed by the Scandinavian researchers K.W. Johansen and A. Losberg and summarizes modern Swedish design of CRCP based on YLT. One key issue is to consider fatigue effects. Here, an engineering approach using a considerably high safety factor of 3.0 and a load repetition limit of 1 million has been adopted. Comparison between available test data shows that this approach is conservative. However, CRCP subjected to fatigue loading is a challenging research area. Fracture mechanics might be one method to analyze the crack development, especially in the low cycle area. Issues like the development of crack width and the degradation of load transfer efficiency in the cracks have also to be investigated.

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