Structural Engineering and Mechanics, *Vol. 61, No. 3 (2017) 389-396*
DOI: https://doi.org/10.12989/sem.2017.61.3.389

Simplified approach for the evaluation of critical stresses in concrete pavement

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(Received February 9, 2016, Revised November 15, 2016, Accepted November 16, 2016)

Abstract. Concrete pavements are subjected to traffic and environmental loadings. Repetitive type of such loading cause fatigue distress which leads to failure by forming cracks in pavement. Fatigue life of concrete pavement is calculated from the stress ratio (i.e. the ratio of applied flexural stress to the flexural strength of concrete). For the correct estimation of fatigue life, it is necessary to determine the maximum flexural tensile stress developed for practical loading conditions. Portland cement association PCA (1984) and Indian road congress IRC 58 (2015) has given charts and tables to determine maximum edge stresses for particular loading and subgrade conditions. It is difficult to determine maximum stresses for intermediate loading and subgrade conditions. The main purpose of this study is to simplify the analysis of rigid pavement without compromising the accuracy. Equations proposed for determination of maximum flexural tensile stress of pavement are verified by finite element analysis.

Keywords: concrete pavement; flexural stress; edge stress; slab thickness; radius of relative stiffness; simplified approach

1. Introduction

Rigid pavements are primarily subjected to vehicle load and temperature load. Pavement slab may be subjected to very high traffic loading along with the environmental loading (i.e. temperature) which develops large amount of stresses. Critical stresses vary mainly with the modulus of subgrade reaction, material properties, slab thickness and axle load configuration. Pavements are directly supported on foundation soil/subbase and hence it is necessary to maintain uniform and good subgrade. Maitra *et al*. (2014) developed method for prediction of crack propagation in concrete pavement under cyclic loading and reported that slab on higher subgrade strength withstands higher peak load as well as higher crack length when compared to weaker subgrade. Support condition affect cracking performance of slab, Roesler *et al*. (2012) conducted accelerated pavement full scale testing on slab panels on different subgrade. It was observed by Roesler *et al*. (2012) that for thin slab pavements, lower subgrade stiffness lead to large deformations. However, the effect of subgrade stiffness has less influence on the slabs with thicker sections. From many researchers it is observed that maximum stress for axle loads occur when placed at edge of the slab. PCA (1984) guideline as well as IRC 58 (2015) calculate fatigue life from the stress ratio. Hence, it is necessary to determine correct value of critical stress developed for applied axle load configuration under actual site conditions.

Correct estimation of critical stress helps to determine fatigue life precisely.

Presently many researchers use finite element tools for the realistic determination of stresses in the pavement. Maitra *et al*. (2013) used ANSYS for the determination of critical stress in jointed concrete pavement. Finite element analysis is rigorous for modeling structure and also needs expert to use particular FE tool.

2. Methods to calculate flexural stress in rigid pavement

Maximum edge stress developed in the pavement due to vehicle axle load can be determined by various methods. Some important and widely used methods such as method suggested in IRC 58 (2002), IRC 58 (2011), IRC 58 (2015), PCA (1984) and Finite element method are briefed below.

2.1 Indian road congress (IRC) method

IRC 58 (1974) guidelines for the design of rigid pavements for highways were first published in 1974 with Westergaard's formulae modified by Teller and Sutherland to calculate stresses in the concrete pavement. Temperature stresses were calculated using Bradbury's coefficient at critical edge region. First revision of the guideline came in 1988 with the modification of legal axle load limit from 8.2 tonnes to 10.2 tonnes. IRC 58 (2002) is the second revision of guideline for plain jointed rigid pavements which suggest calculation of flexural stresses either by using charts or by

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http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

equations. Fatigue analysis of pavement was introduced in this revision. Charts given in Appendix-I of IRC 58 (2002) are for single and tandem axle load with different magnitudes in the edge region. Stress calculation is based on fundamental concept of Westergaard and Picket & Ray's work. The load stress may also be calculated for critical edge region for single and tandem axle load from Westergaard's equation modified by Teller and Sutherland given in Appendix-VI of IRC 58 (2002). Stresses calculated by Westergaard's equation are based on the assumption that slab is infinite or semifinite, with circular or semicircular type of loading. In practice the slab is casted in some finite size and joints are provided in between panels. Bradbury's coefficients are used to calculate thermal stresses developed in finite slab. IRC 58 (2002) recommends providing hard shoulder to reduce the load stresses but does not account the effect of shoulder in calculation of flexural stress. IRC 58 (2002) is silent about tridem axle load stresses.

Finite element analysis was first used in the third revision of IRC 58 guideline which came in 2011. Flexural stress due to combined action of load (single, tandem or tridem axles) and temperature differentials are given. Finite element analysis was carried out for pavement panel size 4.5×3.5 m and subjected to various combinations of axle loads and temperature differentials. Results of analysis were plotted and can be used to determine maximum flexural stress. These charts are given in Appendix-IV of IRC 58 (2011) for single and tandem axle for bottom up cracking with and without the combination of temperature difference in slab. These finite element analysis results are also used to develop regression equations in guideline for the estimation of maximum flexural tensile stress for bottom-up and top-down cracking case. Regression equations are given in Appendix-V of IRC 58 (2011) for single, tandem as well as tridem axle. These regression equations can be used to determine maximum tensile stresses developed in the slab edge region at the bottom of slab for bottom up cracking and at the top of slab for top down cracking. IRC 58 (2011) recommends constructing tied concrete shoulder to protect the edge of high volume pavements and reduce the flexural stresses in the wheel path region. Analysis of pavement for same loading with and without monolithic concrete shoulder shows pavement with shoulder produces less flexural stress as compared to without shoulder as per Clause 6.6.1 of IRC 58 (2011). 50% Load transfer efficiency (LTE) at transverse joint was considered when slab is provided with dowel bars, however, LTE reduces to 10% when transverse joint is without dowel bars. When the slab is without dowel bars LTE depends on aggregate interlock in concrete pavement at joint. Maitra *et al*. (2010) suggested use of new parameter modulus of interlocking joint which depends on aggregate size and joint opening to account aggregate interlocking at joints. Vandenbossche *et al*. (2011) specified that LTE at joint is dependent on aggregate interlock at joint, base support and shoulder if any. LTE at joint can be greatly improved by the use of tie/dowel bars. Increasing LTE at joint also improves the performance of the pavement.

In the recent revision IRC 58 (2015), design of concrete pavement depends on cumulative fatigue damages caused by action of axle loads due to tensile flexural stresses at top and bottom of pavement. As per Appendix-I (IRC 58 2015) strength requirement of dry lean concrete (DLC) reduced to 7 MPa from 10 MPa. Calculation of flexural stresses is same as in the previous revision. Stress charts for bottom up cracking case are given in Appendix-IV (IRC 58 2015) for single and tandem axle load with the combination of different temperature differential.

2.2 Portland cement association (PCA) method

PCA (1984) document "thickness design for concrete highway and street pavements", determines thickness from fatigue analysis and erosion analysis. PCA method developed mechanistic approach for design is widely adopted. Pavement thickness is determined based on flexural strength of concrete, modulus of subgrade reaction, vehicle axle load and design period. Charts and Tables are provided by PCA document to determine the design thickness. Critical case for determining maximum stress is when vehicle load is placed at the edge of slab panel. Critical edge stress can be determined for single, tandem and tridem axle load. Only bottom up cracking load conditions are taken into account while calculating critical edge stresses by PCA. Design thickness can be calculated for slab with and without tied concrete shoulder. PCA does not consider the effect of thermal loading on slab. However, various researchers observed that thermal loading may create large amount of curling stresses in slab and cracks may develop due to temperature differential through slab thickness. PCA design procedure suggests that stress increase due to loss of support may vary from 5% to 15%. PCA considers the coefficient of variation 15% for the realistic addition to design procedure. Concrete strength calculation is at 28 days strength; however in procedure it considers the concrete strength gain with the age. In addition to fatigue damage due to load repetition, erosion analysis is also given in the PCA for determining the minimum thickness of slab. Erosion of foundation is more due to deflections than stresses. Critical location of load for maximum deflection is slab corner, due to discontinuity in two directions. Lee and Carpenter (2001) had implemented PCA thickness design equations in a window based program. Maximum edge stress calculation can be done for different axle loads (single and dual) considering slab with or without tied concrete shoulder by using the edge stress equations provided by them. Fatigue analysis was also done in PCAWIN program using stress ratio.

PCA method is based on some assumptions like fixed slab length 4.572 m (180 in), slab width 3.666 m (144 in), slab modulus of elasticity 27579 MPa (4 Mpsi), Poisson's ratio 0.15, constant wheel contact area 0.178×0.254 m^2 (7×10 in2), wheel spacing 0.305 m (12 in), axle spacing 1.273 m (50 in), axle width 1.833 m (72 in) and aggregate interlock factor of 172.25 MPa (25000 psi) for slab with tied concrete shoulder. Standard single axle (dual wheel) load 80 kN (18 kip) and tandem axle (dual wheel) load 160 kN (36 kip) is considered. Thus the flexural stress developed will be same disregarding the joint spacing, wheel spacing, axle spacing, wheel contact area and actual load transfer capability of slab.

Westergaard’s equations are based on many assumptions and hence many guidelines adopting finite element method for the pavement analysis. There are many software available to analyze the structures using finite element method. Yang and Dai (2013) had modeled pavement with semi rigid base layer in ANSYS and obtained stresses and strain for dynamic loading. Finite element method gives flexibility of modelling slab with realistic properties of material and assigning complex load. Comprehensive 3D finite element pavement slab is modeled to obtain critical response of slab for different axle loading, the method is explained in detail below.

2.3 Fınıte element method

Finite element method is powerful tool used currently for the precise structural analysis with simple as well as complicated geometry and loading conditions. SAP2000 computer software is used to determine the critical stresses developed in the concrete pavement for traffic loading. Analysis of plain concrete pavement is done using 2D area element as well as 3D solid element. Four noded shell element is used to model concrete slab that combines separate membrane and plate-bending behavior. Each node has 6 degrees of freedom at connected joint that is, translation and rotation in *x*, *y* and *z* direction. To achieve best results, aspect ratio of element is maintained by refining mesh size near to unity. Material and geometric properties were assigned as per the requirement. Uniform area load in gravity direction was assigned on the top face (face 6) of shell element. Face definitions of four noded quadrilateral element is shown in Fig. 1.

Eight node hexahedral solid element (block element) is also used to model 3D concrete slab that combines separate membrane and plate-bending behavior. Each node has 3 degrees of freedom that is translation in *x*, *y* and *z* direction. To achieve best results, aspect ratio of element is maintained by refining mesh size near to unity. Material and geometric properties were assigned as per the requirement. Uniform load in gravity direction was assigned on the top face (face 6) of brick element. Face definitions and joint connectivity of eight noded hexahedral solid element is shown in Fig. 2.

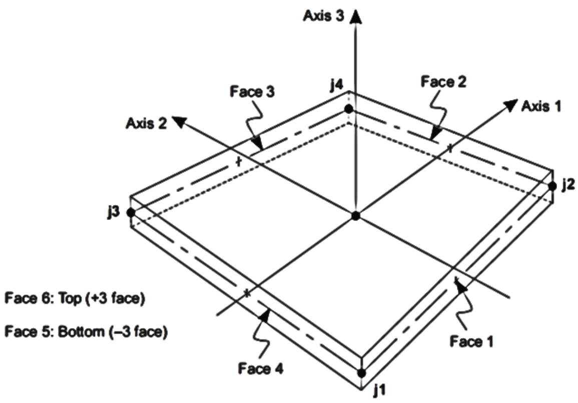

Fig. 1 Quadrilateral shell element and face definitions (Source SAP2000 analysis reference manual)

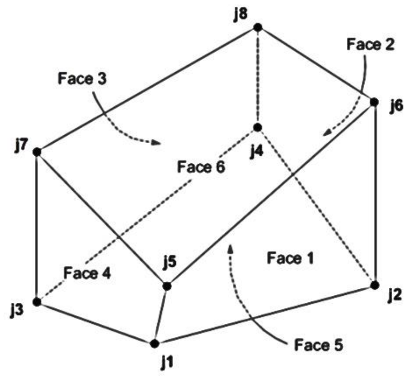

Fig. 2 Solid element joint connectivity and face definitions (Source SAP2000 analysis reference manual)

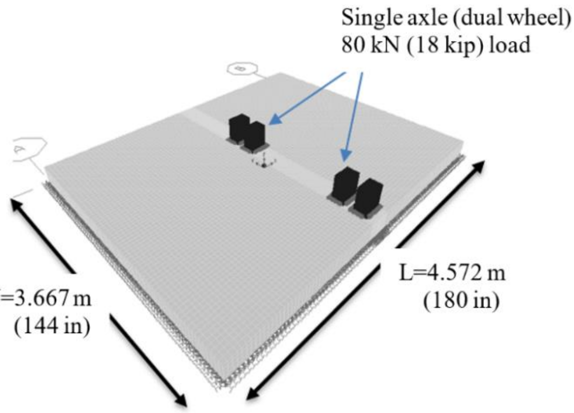

Fig. 3 Finite element model of slab with 80 kN (18 kip) single axle (dual wheel) load

Subbase or foundation for concrete slab was modeled by using spring element for shell as well as solid element model. These springs elastically connect the joint of shell or solid element to the ground. Spring stiffness was calculated by considering the mesh size of slab and assigned at bottom nodes. Single, tandem and tridem axle loads are assigned as per PCA document.

3. Validatıon of 3D fınıte element model

3D comprehensive models were prepared in SAP2000 by using shell as well as solid element and finite element analysis is carried out for static axle loads. Single axle load of 80 kN (18 kip) and 240 kN (54 kip), tandem axle load of 160 kN (36 kip) and 480 kN (108 kip) were applied on mathematical model with same geometric and loading arrangements. Slab thickness 241.3 mm (9.5 in) considered for both cases of axle loads.

Figs. 3-5 shows mathematical model of slab on springs and carrying single, tandem and tridem axle (dual wheel) load respectively.

Slab geometry and loading configurations considered by IRC 58 (2015) and PCA (1984) guideline are given in Table 1. Panel size and axle load configurations are nearly same by IRC 58 (2015) and PCA (1984).

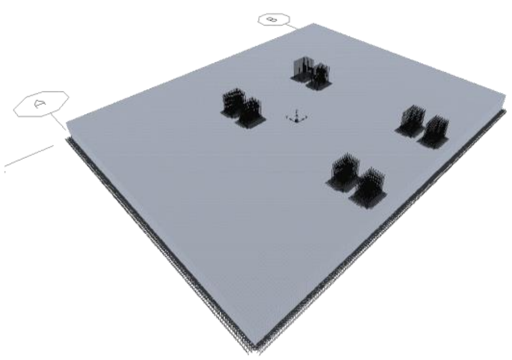

Fig. 4 Finite element model of slab with Tandem axle (dual wheel) load

Table 1 Loading and geometric configurations considered by IRC and PCA Guidelines

Parameter	IRC 58 (2015)	PCA (1984)
Slab length (mm)	4500	4572
Slab width (mm)	3500	3667
Modulus of elasticity (MPa)	30000	27579
Poisson's ratio	0.15	0.15
Transverse wheel spacing (mm)	1800	1833
Distance between center of dual wheel (mm)	310	305
Longitudinal axle spacing (mm)	1300	1273
Offset distance between outer face of wheel and slab edge (mm)	0.00	102
Contact area of single wheel (mm^2)	160×234 mm	178×254 mm

To validate the results obtained from software, model considered by PCA is prepared and same loading and support conditions were assigned.

Realistic finite element model without concrete shoulder was prepared as per PCA document. Analysis results obtained from finite element method are compared with the results obtained from Lee and Carpenter (2001) expressions based on PCA method. These expressions are used to determine maximum flexural tensile stresses developed in slab for single as well as tandem axle load.

It is observed from Table 2 that the results by finite element method and PCA method are in good agreement for the above considered cases. Maximum difference observed was within 10% for single as well as tandem axle load for above considered problems

Results obtained from the models prepared by shell element and solid elements are almost same and hence to analyze this type of problems shell element can be used effectively. New simple approach developed from 3D Finite element analysis using shell element is explained below.

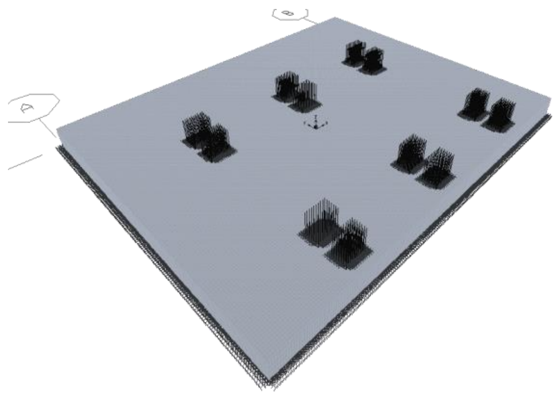

Fig. 5 Finite element model of slab with Tridem axle (dual wheel) load

Table 2 Comparison of analysis results for slab by Finite element method and PCA method

Axle Type	Load (kN)	*K* MPa/m (pci)	Maximum flexural tensile stress *S* (MPa) PCA	3D FE Analysis by SAP2000 Shell element	3D FE Analysis by SAP2000 Solid element	% Difference with PCA Shell Element	% Difference with PCA Solid Element
Single	80	35 (130)	1.41	1.39	1.40	2.1	1.1
		68 (250)	1.26	1.20	1.22	4.1	3.3
		136 (500)	1.11	1.02	1.03	7.7	6.9
		271 (1000)	0.98	0.87	0.88	10.7	9.9
	240	35 (130)	3.97	4.16	4.20	-4.7	-5.7
		68 (250)	3.53	3.61	3.65	-2.3	-3.3
		136 (500)	3.11	3.07	3.10	1.3	0.5
		271 (1000)	2.74	2.62	2.64	4.6	3.9
Tandem	160	35 (130)	1.31	1.27	1.28	3.0	2.2
		68 (250)	1.10	1.06	1.07	3.6	3.0
		136 (500)	0.93	0.87	0.87	6.6	6.3
		271 (1000)	0.79	0.72	0.72	9.6	9.4
	480	35 (130)	3.69	3.82	3.85	-3.6	-4.4
		68 (250)	3.10	3.19	3.21	-3.0	-3.7
		136 (500)	2.60	2.60	2.61	0.2	-0.2
		271 (1000)	2.22	2.15	2.15	3.5	3.2

4. New simplified approach

Flexural tensile stress developed in the slab due to vehicle loading or temperature differential through thickness are the main cause of the failure of concrete pavement. Closed form solutions provided by Westergaard and modified by many authors were used to determine critical stresses in the pavement, however these solutions are based on assumptions like infinite slab size, full contact between slab and foundation, circular or semicircular type of load contact and uniform pressure distribution. Westergaard's stress equations are no more used by the recent guidelines without modifications. Nowadays many

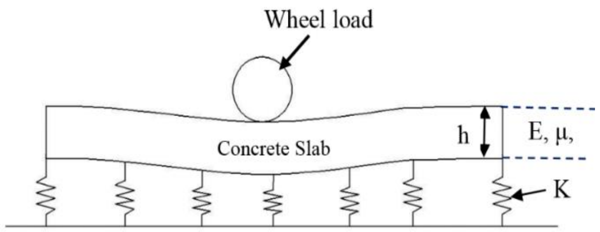

Fig. 6 Deflection of concrete slab on subgrade soil due to wheel load

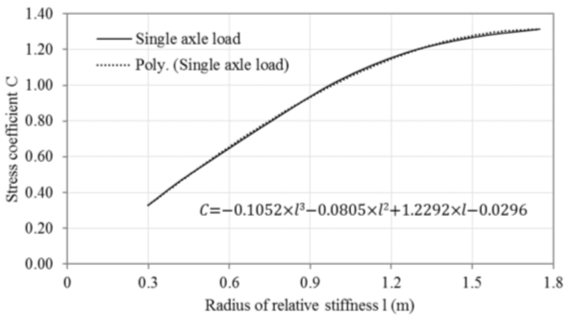

Fig. 7 Relation between radius of relative stiffness with stress coefficient for single axle load

structural analysis software's are available which can model realistic 3D model with specific loading conditions. Finite element analysis needs expert to model and analyze the practical problems; one with inadequate knowledge may yields the wrong result. Closed form solutions available from different guidelines are also tedious to solve. Charts given by IRC 58 (2015) guideline and PCA (1984) document are for some particular loading and subgrade conditions, however for intermediate values one need to interpolate in between the available values. Modulus of elasticity of concrete was taken as constant value by PCA as well as IRC guideline. To avoid such difficulties, simplified approach based on simple calculation is proposed.

Slab deflection is resisted by the subbase foundation on which slab is directly rested as shown in Fig. 6. Slab deflection is also dependent on thickness and elastic modulus of concrete slab. Yoder and Witczak (2012) specified that resistance to deformation depends upon the subgrade stiffness and the flexural stiffness of the concrete slab. Fig. 6 shows the deflection of concrete slab resisted by concrete properties and subgrade strength. Radius of relative stiffness represents all these terms, calculated as Eq. (1). Where radius of relative stiffness is in m, modulus of elasticity of concrete slab in MPa, thickness of slab is in m and subgrade strength is represented by modulus of subgrade reaction in MPa/m.

Radius of relative stiffness $$l=\left[\frac{Eh^3}{12K\left(1-\mu^2\right)}\right]^{0.25} \quad (1)$$

After analyzing some problems, it is found that for concrete slab without shoulder, relation between radius of relative stiffness and stress coefficient can be established and used to determine maximum flexural tensile stress. Normally for concrete pavement radius of relative stiffness lies in between 0.3 m to 1.750 m accounting possible practical variation in *E*, *h* and *K*.

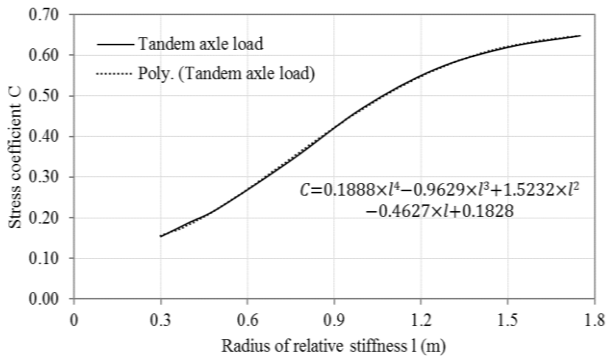

Fig. 8 Relation between radius of relative stiffness with stress coefficient for tandem axle load

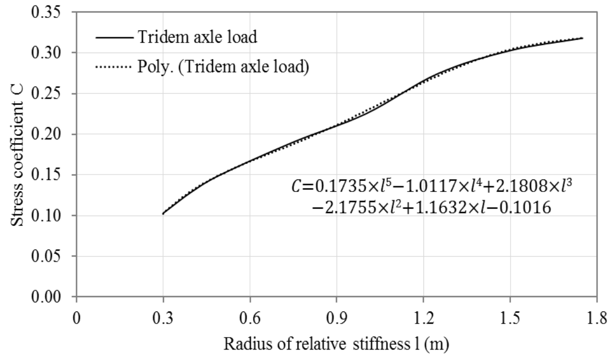

Fig. 9 Relation between radius of relative stiffness with stress coefficient for tridem axle load

Table 3 Regression equations to calculate stress coefficient from radius of relative stiffness

Axle Type	Stress Coefficient (C)
Single	$C=-0.1052\times l^3-0.0805\times l^2+1.2292\times l-0.0296$
Tandem	$C=0.1888\times l^4-0.9629\times l^3+1.5232\times l^2-0.4627\times l+0.1828$
Tridem	$C=0.1735\times l^5-1.0117\times l^4+2.1808\times l^3$ $-2.1755\times l^2+1.1632\times l-0.1016$

Maximum flexural tensile stress in MPa can easily be calculated from Eq. (2), for single, tandem as well as tridem axle load conditions when axle load *P* (kN) is placed at the critical edge location of slab of thickness *h* (m). Stress coefficient depends on radius of relative stiffness value, which can be determined from Figs. 7-9 for single, tandem and tridem axle respectively. Stress coefficients are developed for most commonly used panel size and axle load configurations as given by PCA. IRC also suggest nearly similar dimensions of panel and geometric configurations.

Maximum flexural tensile stress

$$S=Stress\ Coefficient\ (C)\times\frac{P}{1000\times h^2} \quad (2)$$

Stress coefficients developed for different thicknesses (100, 150, 225 and 300 mm) of slab by varying subgrade strength of foundation soil. It was observed that the stress coefficients are showing nearly same stress coefficients for

Table 4 Comparison of Simplified method with 3D finite element method

Axle Type	Load (kN)	l (m)	h (m)	K (MPa/m)	Coefficient of S.A (C)	Maximum flexural tensile stress (S) MPa		% Difference
						3D FE Analysis	Simplified Approach	
Single	80	0.30	0.15	978	0.330	1.17	1.17	0.1
		0.40	0.20	734	0.446	0.89	0.89	-0.6
		0.50	0.25	587	0.549	0.70	0.70	-0.9
		1.25	0.30	26	1.180	1.05	1.05	-0.2
		1.75	0.35	11	1.315	0.86	0.86	-0.1
	240	0.30	0.15	978	0.330	3.52	3.52	0.1
		0.40	0.20	734	0.446	2.66	2.67	-0.6
		0.50	0.25	587	0.549	2.09	2.11	-0.9
		1.25	0.30	26	1.180	3.14	3.15	-0.1
		1.75	0.35	11	1.315	2.57	2.58	-0.1
Tandem	160	0.30	0.15	978	0.154	1.09	1.09	0.0
		0.40	0.20	734	0.189	0.75	0.76	-0.5
		0.50	0.25	587	0.224	0.57	0.57	-0.7
		1.25	0.30	26	0.566	1.01	1.01	-0.1
		1.75	0.35	11	0.648	0.85	0.85	-0.1
	480	0.30	0.15	978	0.154	3.28	3.28	0.0
		0.40	0.20	734	0.189	2.26	2.27	-0.5
		0.50	0.25	587	0.224	1.71	1.72	-0.6
		1.25	0.30	26	0.566	3.01	3.02	-0.2
		1.75	0.35	11	0.648	2.54	2.54	-0.1
Tridem	240	0.30	0.15	978	0.103	1.10	1.10	0.0
		0.40	0.20	734	0.130	0.78	0.78	-0.5
		0.50	0.25	587	0.151	0.58	0.58	-0.7
		1.25	0.30	26	0.275	0.73	0.73	-0.1
		1.75	0.35	11	0.318	0.62	0.62	0.0
	720	0.30	0.15	978	0.103	3.31	3.30	0.0
		0.40	0.20	734	0.130	2.32	2.34	-0.6
		0.50	0.25	587	0.151	1.73	1.74	-0.7
		1.25	0.30	26	0.275	2.20	2.20	-0.1
		1.75	0.35	11	0.318	1.87	1.87	-0.1

respective radius of relative stiffness for specific axle load case. Coefficients developed are then optimized to get best results for all thicknesses varying from 100 mm to 350 mm. Maximum flexural tensile stress can be calculated from given stress coefficients for any practically occurring axle load intensities on pavement, however gives best results for single axle load (80 to 240 kN), tandem axle load (160 to 480 kN) and tridem axle (240 to 720 kN).

Flexural edge stress is calculated easily for axle loads with the help of above simple method using Eq. (2). Regression equations generated from Figs. 7-9 represents the relation between radius of relative stiffness and stress coefficient are given in Table 3, and also shown on respective figure by dotted line with polynomial equation. These equations can be used instead of using charts for calculation of stress coefficient from radius of relative stiffness. Coefficient of determination (R^2) for these equations is above 0.999 which is near to unity thus indicates stress coefficients can be predicted without error from the radius of relative stiffness values.

Stress calculated with this new method and stresses obtained from 3D finite element results were compared in Table 4 for different thickness of slab and loading intensities.

Table 4 shows that the maximum flexural tensile stresses obtained by simplified approach are close to the 3D finite element results. Percentage difference for these problems is within 1%.

Charts given by PCA (1984) to determine equivalent stress for single, tandem as well as for tridem axle are based on constant modulus of elasticity (E) 27579 MPa. IRC 58 (2015) recommends 30000 MPa modulus of elasticity when information is not available, charts provided by IRC 58 (2015) are based on the assumption of constant E (30000 MPa). Concrete with different mix design may have different modulus of elasticity. Eurocode 2 (2004) has given values of modulus of elasticity based on characteristic compressive cylinder strength of concrete, E increases with the increase in the grade of concrete. Concrete with characteristic compressive cylinder strength 12 MPa and 70 MPa shows modulus of elasticity 27000 and 41000 MPa respectively as per Eurocode 2 (2004). While designing concrete pavement E value should always be determined from testing. PCA (1984) and IRC 58 (2015) consider

Table 5 Comparison of FE results with simplified approach for 40000 MPa modulus of elasticity

Axle Type	Load *P* (kN)	*K* (MPa/m)	*h* (m)	*E*=40000 MPa			
				l (m)	*S* (MPa) FE Analysis	*S* (MPa) S.A.	% Difference
Single	60	2322	0.20	0.33	0.54	0.54	0.5
		15	0.25	1.37	1.18	1.18	0.4
		63	0.30	1.10	0.73	0.72	-0.7
		319	0.35	0.82	0.421	0.43	1.1
	260	19	0.20	1.10	7.10	7.04	-0.8
		588	0.25	0.55	2.46	2.51	2.0
		13	0.30	1.65	3.75	3.77	0.8
		319	0.35	0.82	1.82	1.84	1.1
Tandem	140	2322	0.20	0.33	0.57	0.57	0.0
		588	0.25	0.55	0.54	0.55	1.7
		63	0.30	1.10	0.80	0.79	-0.3
		319	0.35	0.82	0.43	0.44	1.5
	500	19	0.20	1.10	6.41	6.38	-0.5
		15	0.25	1.37	4.76	4.78	0.4
		13	0.30	1.65	3.54	3.55	0.4
		11	0.35	1.92	2.69	2.69	0.2
Tridem	220	19	0.20	1.10	1.36	1.35	-0.4
		15	0.25	1.37	1.02	1.02	0.0
		13	0.30	1.65	0.76	0.77	0.6
		319	0.35	0.82	0.36	0.36	-0.6
	750	2322	0.20	0.33	2.07	2.10	1.5
		588	0.25	0.55	1.90	1.91	0.3
		63	0.30	1.10	2.06	2.05	-0.3
		11	0.35	1.92	1.98	2.00	0.7

constant value of modulus of elasticity. To understand the effect of change in modulus of elasticity on concrete edge stresses, some problems were considered and analyzed by changing only *E* and keeping other parameters same. From the analysis it was observed that for *E* (27000 to 40000 MPa) the stress results shows variation around 10 %. For higher subgrade modulus value, the difference is also higher. It is important to assign practically obtained material properties while developing FE model, Dehdezi (2013) had shown that change in the properties of concrete influence the critical stress results in pavement.

While deriving stress coefficients for simplified approach of analysis, modulus of elasticity was considered 27579 MPa and 0.15 Poisson's ratio as per PCA guideline. Simplified approach analysis procedure basically depends on the radius of relative stiffness, and hence change in modulus of elasticity does not affect the stress coefficient if subgrade or other parameters adjusted to get required radius of relative stiffness. Simplified approach provides flexibility to assume any practical value of modulus of elasticity. To observe the effect of change in modulus of elasticity (other than 27579 MPa) on the maximum flexural tensile stress, results shown by FE analysis are compared with the simplified approach (regression equations Table 3) and presented in Table 5.

From the Table 5, it is clear that simplified approach can be used effectively with the flexibility in modulus of elasticity, modulus of subgrade reaction as well as thickness of slab. Maximum percent variation in the results of FE analysis by SAP2000 and simplified approach is 2%.

5. Conclusions

Following are the broad conclusions from the study of different methods of concrete pavement analysis and proposed simplified approach for determining critical stresses in concrete slab without shoulder.

- Simplified approach can be used to determine maximum flexural tensile stress developed for critical edge loading condition using simple equation.
- Normally radius of relative stiffness lies in between 0.3 to 1.75 m for the practical problems and hence simplified approach covers almost all problems.
- Many guidelines consider constant modulus of elasticity for analysis of concrete pavement, simplified approach provides flexibility to consider any practically obtained value of modulus of elasticity for realistic and better solution. Maximum variation of results with finite element are found to be 2%.
- Use of simplified approach is easy and time saving approach to determine maximum flexural tensile stress in the slab, with great accuracy without performing FE analysis.

Acknowledgments

The work described in this paper has been supported by the Technical Education Quality Improvement Program (TEQIP-II). The authors are thankful to The Director, Visvesvaraya National Institute of Technology (VNIT), Nagpur.

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PL

Notations

C	Stress coefficient
DLC	Dry lean concrete
E	Modulus of Elasticity of Concrete (MPa)
FE	Finite element
h	Pavement thickness (m)
IRC	Indian Road Congress
K	Modulus of subgrade reaction (MPa/m)/(pci)
l	Radius of relative stiffness (m)
LTE	Load transfer efficiency
P	Single/Tandem/Tridem rear axle load (kN)
PCA	Portland Cement Association
S	Maximum tensile stress at bottom of slab (MPa)
S.A	Simplified approach
μ	Poisson's ratio of concrete