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The Influence of CBR Value and Overloading on Flexible Pavement Mechanistic Response

Anissa N. Tajudin, Ni Luh P.S.E. Setyarini, and Devy S. Darmawati

***Abstract*— Flexible pavement distresses are often caused by overloading with the combination of other factors, such as subgrade strength. Therefore, this study was conducted to investigate and analyze the effect of subgrade strength on flexible pavement mechanistic response with normal traffic loading and overloading scenario (25% to 100%) using KENPAVE software. CBR was varied from the range 3% to 10% with an increase of every 0,5%. Horizontal tensile strain was then used to estimate pavement fatigue life (Nf) and vertical tensile strain was then used to estimate pavement rutting life (Nr). The results of mechanistic responses reveal that the horizontal tensile strain and vertical compressive strain all decrease with increasing subgrade CBR value. The addition of load will increase the pressure that the vehicle distributes to the pavement, so that the horizontal tensile strain and vertical compressive strain will be higher. Nf and Nd all increase with decreasing of horizontal tensile strain and vertical compressive strain, which implies that higher CBR value will increase Nf and Nd. Rutting occurs at CBR 3% to 7,5% with the overloading of 75% and 100% while fatigue cracking occurs at CBR 3% to 9,5% with the overloading of 50, 75%, and 100%.**

***Index Terms*— CBR, flexible pavement, horizontal tensile strain, overloading, vertical compressive strain.**

I. INTRODUCTION

Pavement quality is one of the most crucial elements in the efficiency of land transportation activities, both in structural and functional. In designing flexible pavement, it is necessary for engineer to consider the specific conditions of a particular location, such as material availability, subgrade strength, rainfall, and traffic load. Differences characteristic of each location will cause differences in calculation result and decision making for choosing the best design. Pavement distress is often caused by overloading with the combination of other factors. Inaccuracy in the design can also cause the road to failure before the expected design life. Therefore, this study is conducted to investigate and analyze the effect of subgrade strength on flexible pavement mechanistic response with normal traffic loading (0% overloaded) and overloading scenario (25%, 50%, 75%, and 100%).

A. Subgrade

Subgrade takes an important role of pavement's overall structure performance. Subgrade materials should adequately provide a stable platform of road construction, limit progressive settlement as a result of repeated traffic loading, and prevent massive slope failure [1].

The material property used to characterize roadbed soil strength for pavement design in AASHTO 1993 which was then adopted to Bina Marga Pt T-01-2002-B is the resilient modulus (M_R). The resilient modulus is a measure of the elastic property of soil recognizing certain nonlinear characteristics. In case that resilient modulus test can't be performed, suitable factors can be used to estimate resilient modulus from standard CBR, R-value, and soil index test results or values [2].

Heukelom and Klomp [3] developed equation to make correlation between CBR value to M_R value which is showed in equation (1) [3].

$$MR = 1500 \times CBR \qquad (1)$$

with :

M_R : Resilient modulus (psi)
CBR : California Bearing Ratio

B. Mechanistic Empirics Response for Layered System

The basic aim of the structural design process is to combine the different layers in such way as to result in the most cost-effective functional pavement structure. This can be achieved by primarily two different methods, first is by using empirical methods, which is charts and equations developed from experimental studies carried out with a set of traffic, environment, and pavements or second is by using a mechanistic method, in which concepts of mechanics are used to predict responses and performance of the pavement. Such an empirically based specification is unlikely to result in an efficient use of construction equipment or materials and does not allow the use of analytical design procedures. A purely mechanistic approach is not possible at this time because the responses can be predicted by employing concepts of mechanics, but the performance has to be predicted by empirical models. Hence, it is more appropriate to say that pavements can be designed either by using the

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A.N. Tajudin is with the [1]Department of Civil Engineering, Tarumanagara University, 11470, West Jakarta, Jakarta, Indonesia (e-mail: anissat@ft.untar.ac.id)

N.L.P.S.E. Setyarini is with the [1]Department of Civil Engineering, Tarumanagara University, 11470, West Jakarta, Jakarta, Indonesia

D.S. Darmawati is with the [1]Department of Civil Engineering, Tarumanagara University, 11470, West Jakarta, Jakarta, Indonesia.

empirical approach or by using the mechanistic-empirical approach (ME) [4][5].

Flexible pavements are constructed by layered systems with better materials on top and cannot be represented by a homogeneous mass. Burmister first developed solutions for a two-layer system and then extended them to a three-layer system. With the advent of computers, the theory can be applied to a multilayer system with any number of layers by using various software available, such as KENPAVE. The basic assumptions to be satisfied are [6][7]:

1. Each layer is homogeneous, isotropic, and linearly elastic with an elastic modulus E and a Poisson ratio v.
2. The material is weightless and infinite in areal extent.
3. Each layer has a finite thickness h, except that the lowest layer is infinite in thickness.
4. A uniform pressure q is applied on the surface over a circular area of radius a
5. Continuity conditions are satisfied at the layer interfaces, as indicated by the same vertical stress, shear stress, vertical displacement, and radial displacement. For frictionless interface, the continuity of shear stress and radial displacement is replaced by zero shear stress at each side of the interface.

C. Fatigue and Rutting Distress Modelling

Traffic load working on the surface of flexible pavement is assumed as evenly distributed static load that the material of pavement will give response which is believed to be critical for design purposes are: Horizontal tensile strain (εt) bottom of the asphalt layer and vertical compressive strain value (εc) on the surface of subgrade [8]. Strain is the unit displacement due to stress, usually expressed as a ratio of the change in dimension to the original dimension (mm/mm or in/in). Since the strains in pavements are very small, they are normally expressed in terms of microstrain (10^{-6}) [9]. Excessive horizontal tensile strain will create cracking on the surface due to fatigue while excessive vertical compressive strain will make pavement distress occurs due to rutting [10].

Several fatigue and rutting models have been developed to relate the asphalt modulus and/or the measured strains to the number of load repetitions. These models are developed to predict pavement fatigue and rutting life. One of the most common of the fatigue and rutting failure model is developed by Asphalt Institute as equation (2) and (3) [11].

$$Nf = 0{,}0796 \left(\frac{1}{\varepsilon t}\right)^{3{,}291} \left(\frac{1}{E1}\right)^{0{,}854} \qquad (2)$$

$$Nd = 1{,}365\, x\, 10^{-9} \left(\frac{1}{\varepsilon c}\right)^{4{,}477} \qquad (3)$$

Where horizontal tensile strain on the bottom of asphalt layer (εt) and asphaltic layer modulus (E1) are used to estimate the allowable number of load repetitions to prevent pavement from fatigue cracking failure (Nf) and vertical tensile strain on the surface of subgrade (εc) is used to estimate the allowable number of load repetitions to prevent rutting failure (Nr). Any value lower than the actual number of designed traffic repetitions will cause distress.

II. EXPERIMENTAL METHODS

To study the influence of CBR subgrade values and traffic overloading to flexible pavement mechanistic response, this order of research methodology was carried out:

1. Obtain actual number of design traffic repetitions data from average daily traffic (ADT) on Cipularang Toll Km 97, West Java Indonesia which is then presented by equivalent single axle loads.
2. Determine pavement requirements for KENPAVE input parameters in terms of layer thickness, elastic modulus, resilient modulus, and poison's ratio.
3. Determine load configuration for pavement response analysis in KENPAVE with traffic scenarios of normal loaded (0%) and overloaded (25%, 50%, 75%, 100%).
4. Run KENPAVE to obtain horizontal tensile strain and vertical compressive strain for various CBR values (3% to 10% with an increase of every 0,5%).
5. Calculate pavement fatigue and rutting life using Asphalt Institute failure model to get allowable repetitions to failure.

Analyze the result of pavement response.

III. INPUT PARAMETERS

The pavement thickness used in this study is presented in Table I and developed by using Bina Marga 2002 method which is based on AASHTO 1993 with traffic parameters obtained from traffic survey in Cipularang Toll km 97, West Java, Indonesia.

TABLE I
PAVEMENT THICKNESS FOR VARIOUS CBR VALUES

CBR	Subbase Course Thickness (inch)	Base Course Thickness (inch)	Surface Course Thickness (inch)	Total Thickness (inch)
3	16	13,5	4,5	34
3,5	14	13,5	4,5	32
4	12	13,5	4,5	30
4,5	11,5	13,5	4,5	29,5
5	9	13,5	4,5	27
5,5	8	13,5	4,5	26
6	6,5	13,5	4,5	24,5
6,5	6	13,5	4,5	24
7	6	13,5	4,5	24
7,5	6	13,5	4,5	24
8	6	13,5	4,5	24
8,5	6	13,5	4,5	24
9	6	13,5	4,5	24
9,5	6	13,5	4,5	24
10	6	13,5	4,5	24

Material characteristics is presented in Table II. Because Poisson ratio has a relatively small effect on pavement responses, it is customary to assume a reasonable value for use in design, rather than to determine it from actual tests [6].

TABLE II
PAVEMENT THICKNESS FOR VARIOUS CBR VALUES

Layer	Material	Elastic Modulus (psi)	Poisson's Ratio
Surface	Asphalt concrete	350.000	0,35
Base	Bituminous treated	230.000	0,35
Subbase	Granular	16.000	0,4
Subgrade	Soil	Based on each CBR	0,45

Load characteristics is presented in Table III. Actual number of design traffic repetitions data from average daily traffic (ADT) on Cipularang Toll Km 97, West Java Indonesia which is then presented by equivalent single axle loads (ESAL). Thus, load characteristics used in this study is based on standard axle load which is single axle dual wheels.

TABLE III
PAVEMENT THICKNESS FOR VARIOUS CBR VALUES

Parameters	Units	Values
Contact radius	inch	4,51
Contact pressure	psi	70 for normal load (0%), 87,5 for overloading of 25%; 105 for 50%, 122,5 for 75%, and 140 for 100%
Inter wheel spacing	inch	16.000
ESAL	repetitions	23.947.797
ESAL	repetitions	23.947.797

IV. RESULTS AND DISCUSSION

CBR values are varied from the range 3% to 10% with an increase of every 0.5%, thus create 15 pavement variations. Pavement structure consists of asphalt concrete surface course, bituminous treated base, and granular subbase. Loading scenarios are represented by contact pressure which is one of the input parameters in KENPAVE. Normal loading indicates standard pressure from standard axle and overloading scenarios are carried out by increasing the amount of that contact pressure. Vertical compressive strains, horizontal tensile strains, and predicted life for rutting and fatigue resulted due to variation of subgrade CBR values and loading scenarios from normal, over 25%, 50%, 75%, and 100% are presented in Table IV to Table VII.

TABLE IV
VERTICAL COMPRESSIVE STRAIN FOR VARIOUS CBR VALUES AND LOADING SCENARIOS

CBR	Vertical Compressive Strain				
(%)	Normal	+25%	+50%	+75%	+100%
3	1,52E-04	1,90E-04	2,28E-04	2,65E-04	3,03E-04
3,5	1,50E-04	1,87E-04	2,25E-04	2,62E-04	3,00E-04
4	1,50E-04	1,87E-04	2,24E-04	2,62E-04	2,99E-04
4,5	1,44E-04	1,80E-04	2,16E-04	2,52E-04	2,88E-04
5	1,47E-04	1,84E-04	2,21E-04	2,58E-04	2,95E-04
5,5	1,46E-04	1,82E-04	2,18E-04	2,55E-04	2,91E-04
6	1,47E-04	1,84E-04	2,16E-04	2,57E-04	2,94E-04
6,5	1,44E-04	1,80E-04	2,16E-04	2,51E-04	2,87E-04
7	1,39E-04	1,73E-04	2,08E-04	2,42E-04	2,77E-04
7,5	1,35E-04	1,69E-04	2,02E-04	2,36E-04	2,70E-04
8	1,29E-04	1,62E-04	1,94E-04	2,26E-04	2,58E-04
8,5	1,26E-04	1,57E-04	1,88E-04	2,20E-04	2,51E-04
9	1,22E-04	1,52E-04	1,83E-04	2,13E-04	2,44E-04
9,5	1,18E-04	1,48E-04	1,77E-04	2,07E-04	2,36E-04
10	1,14E-04	1,43E-04	1,71E-04	2,00E-04	2,29E-04

TABLE V
HORIZONTAL TENSILE STRAIN FOR VARIOUS CBR VALUES AND LOADING SCENARIOS

CBR	Horizontal Tensile Strain				
(%)	Normal	+25%	+50%	+75%	+100%
3	7,32E-05	9,15E-05	1,10E-04	1,28E-04	1,46E-04
3,5	7,28E-05	9,10E-05	1,09E-04	1,27E-04	1,46E-04
4	7,24E-05	9,06E-05	1,09E-04	1,27E-04	1,45E-04
4,5	7,15E-05	8,94E-05	1,07E-04	1,25E-04	1,43E-04
5	7,12E-05	8,90E-05	1,07E-04	1,25E-04	1,42E-04
5,5	7,06E-05	8,82E-05	1,06E-04	1,24E-04	1,41E-04
6	7,02E-05	8,77E-05	1,05E-04	1,23E-04	1,40E-04
6,5	6,94E-05	8,68E-05	1,04E-04	1,22E-04	1,39E-04
7	6,85E-05	8,56E-05	1,03E-04	1,20E-04	1,37E-04
7,5	6,82E-05	8,53E-05	1,02E-04	1,19E-04	1,36E-04
8	6,69E-05	8,36E-05	1,00E-04	1,17E-04	1,34E-04
8,5	6,64E-05	8,30E-05	9,97E-05	1,16E-04	1,33E-04
9	6,58E-05	8,22E-05	9,86E-05	1,15E-04	1,32E-04
9,5	6,51E-05	8,14E-05	9,77E-05	1,14E-04	1,30E-04
10	6,43E-05	8,04E-05	9,64E-05	1,13E-04	1,29E-04

TABLE VI
PREDICTED RUTTING LIFE FOR VARIOUS CBR VALUES AND LOADING SCENARIOS

CBR (%)	Nd				
	Normal	+25%	+50%	+75%	+100%
3	171.451.910	63.135.874	27.856.524	13.974.241	7.687.584
3,5	180.330.315	66.365.629	29.386.008	14.728.981	8.097.621
4	181.954.964	67.003.545	29.621.247	14.855.339	8.170.575
4,5	217.193.147	80.079.418	35.357.826	17.748.070	9.768.120
5	195.024.401	71.685.447	31.716.733	15.887.845	8.744.154
5,5	206.060.633	76.020.523	33.579.943	16.830.794	9.253.025
6	198.015.917	72.917.870	35.504.974	16.166.602	8.891.782
6,5	217.870.636	80.279.231	35.504.974	17.811.370	9.798.601
7	256.957.925	94.684.018	41.876.411	21.007.889	11.557.204
7,5	290.075.470	106.818.107	47.222.659	23.682.615	13.004.051
8	350.760.255	129.164.822	57.101.802	28.637.100	15.750.672
8,5	398.066.872	146.585.127	64.803.053	32.499.351	17.843.123
9	456.761.764	168.446.601	74.540.738	37.330.564	20.548.342
9,5	524.408.666	192.670.921	85.262.996	42.791.089	23.503.664
10	609.482.870	224.085.867	99.220.392	49.704.278	27.314.869

TABLE VII
PREDICTED FATIGUE LIFE (NF) FOR VARIOUS CBR VALUES AND LOADING SCENARIOS

CBR (%)	Nf				
	Normal	+25%	+50%	+75%	+100%
3	59.834.852	28.709.351	15.774.621	9.494.038	6.115.893
3,5	60.896.691	29.232.049	16.061.929	9.666.932	6.227.258
4	61.814.435	29.659.174	16.257.267	9.792.949	6.312.522
4,5	64.529.422	30.967.552	17.017.976	10.237.765	6.592.772
5	65.489.072	31.416.490	17.228.639	10.373.590	6.684.633
5,5	67.433.433	32.352.206	17.770.376	10.680.781	6.889.466
6	68.610.531	32.913.833	18.049.584	10.882.461	7.003.156
6,5	71.181.140	34.153.411	18.743.410	11.270.377	7.272.358
7	74.341.266	35.686.816	19.597.498	11.805.315	7.591.569
7,5	75.313.964	36.143.354	19.850.811	11.935.970	7.702.024
8	80.434.557	38.604.690	21.183.494	12.760.841	8.225.845
8,5	82.201.209	39.437.041	21.641.639	13.015.358	8.389.928
9	84.989.771	40.778.928	22.379.497	13.467.286	8.687.490
9,5	87.725.415	42.078.758	23.095.956	13.899.689	8.953.583
10	91.601.224	43.951.168	24.120.424	14.518.977	9.349.038

The highlighted values in Table VI and Table VII shows the repetitions value are below actual number of design traffic repetitions which is 23.947.797.

A. Subgrade CBR and Strain Response Relationship

The outputs calculated by KENPAVE used in this study are horizontal tensile strain at the bottom of asphalt layer which will give critical value to cause fatigue cracking and vertical compressive strain at the top of the subgrade which will give critical value to cause rutting distress. The relationship between CBR value and vertical compressive strain is shown in Fig. 1 and the relationship between CBR value and horizontal tensile strain is shown in Fig. 2.

Fig. 1 shows that for normal traffic loading scenario, as the CBR value increased from 3% to 10%, the vertical compressive strain decrease from 1,52 x 10-4 to 1,14 x 10-4 while for 100% of traffic overloading scenario, the vertical compressive strain decrease from 3,03 x 10-4 to 2,09 x 10-4. For all traffic loading scenarios, every 0,5% increase of CBR value will reduce the horizontal tensile strain around 1,986%. The slightly horizontal tensile strain escalation from CBR value of 4,5% to 5% may occurs due to the difference of each pavement thickness. What can also be seen from Fig. 1 is that higher CBR value will lower vertical compressive strain which is occurred on subgrade. The result is also implied that higher traffic load will increase vertical compressive strain as much as the increase of traffic load percentage which shows the linear relationship between vertical compressive strain and overloading traffic.

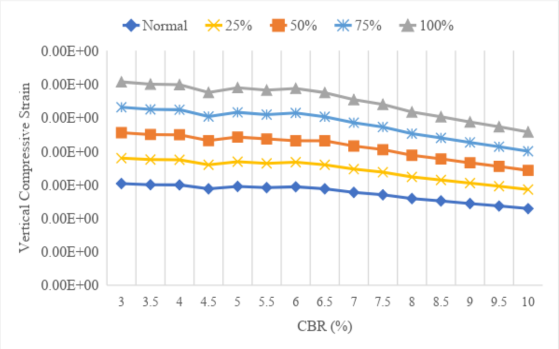

Fig. 1. CBR value and vertical compressive strain relationship

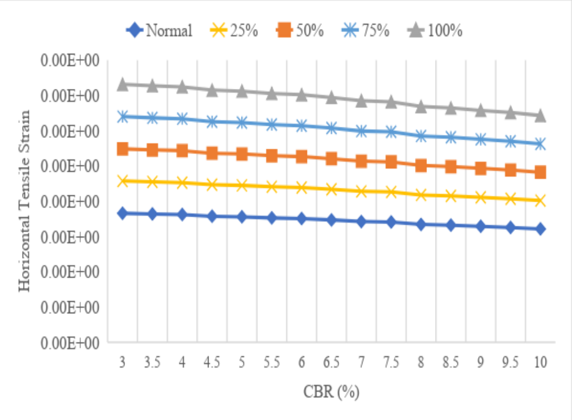

Fig. 2. CBR value and horizontal tensile strain relationship

Fig. 2 shows that for normal traffic loading scenario, as the CBR value increased from 3% to 10%, the horizontal tensile strain decrease from 7,32 x 10-5 to 6,43 x 10-5 while for 100% of traffic overloading scenario, the vertical compressive strain decrease from 1,46 x 10-4 to 1,29 x 10-4. For all traffic loading scenarios, every 0.5% increase of CBR value will reduce the horizontal tensile strain around 0,917%, lower than the percentage resulted in vertical compressive strain. What can also be seen from Fig. 2 is that higher CBR value will lower horizontal tensile strain which is occurred below the asphaltic layer. The result is also implied that higher traffic load will increase horizontal tensile strain as much as the increase of traffic loads percentage which shows the linear relationship between horizontal tensile strain and overloading traffic.

The results of mechanistic response reveal that the horizontal tensile strain and vertical compressive strain all decrease with increasing subgrade CBR value. Higher CBR value represents stronger subgrade, thus the subgrade will receive lower strain value. The addition of load will increase the pressure that the vehicle distributes to the pavement, so that the horizontal tensile strain and vertical compressive strain will be higher.

B. Subgrade CBR and Pavement Life Relationship

Horizontal tensile strain is then used to estimate the allowable number of load repetitions to prevent fatigue cracking failure, which called by pavement fatigue life (Nf) while vertical tensile strain is then used to estimate the allowable number of load repetitions to prevent rutting failure, which called by pavement rutting life (Nr). The relationship between CBR value and Nd is shown in Fig. 3 and the relationship between CBR value and Nf is shown in Fig. 4.

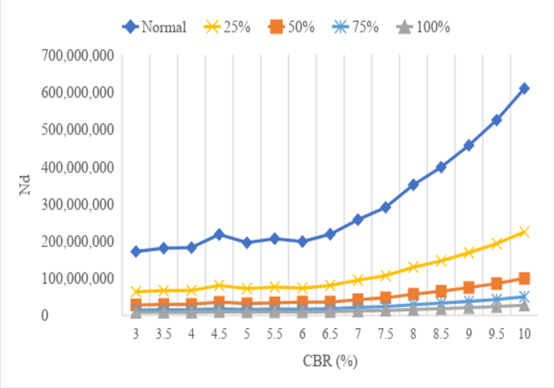

Fig.3. CBR value and Nd relationship

Fig. 3 shows that for normal traffic loading scenario, as the CBR value increased from 3% to 10%, the allowable repetitions to prevent rutting (Nd) is also increase from 171.451.910 to 609.482.870 while for 100% of traffic overloading scenario, the Nd values increase from 7.687.584 to 27.314.869.

The result is also implied that higher traffic load will lower Nd values which means rutting will occur faster because allowable repetitions will be less than those with lower traffic load. Nd decrease significantly in overloading scenarios compared to normal traffic loading with the values of 63%, 227%, 565%, and 1172% for 25%, 50%, 75%, and 100% of overloading respectively.

Any value lower than the actual number of designed traffic repetitions will cause distress. It can be implied that rutting occurs at CBR 3% to 7,5% with the overloading of 75% and 100%.

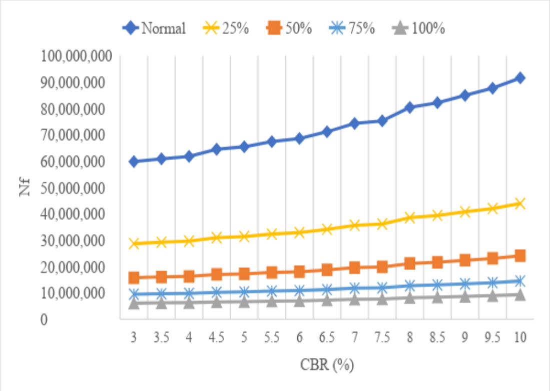

Fig. 4. CBR value and Nf relationship

Fig. 3 shows that for normal traffic loading scenario, as the CBR value increased from 3% to 10%, the allowable repetitions to prevent fatigue (Nf) is also increase from 59.834.852 to 91.601.224 while for 100% of traffic overloading scenario, the Nd values increase from 6.115.893 to 9.349.038.

The result is also implied that higher traffic load will lower Nf values which means fatigue cracking will occur faster because allowable repetitions will be less than those with lower traffic load. Nf decrease significantly in overloading scenarios compared to normal traffic loading with the values of 52%, 153%, 319%, and 566% for 25%, 50%, 75%, and 100% of overloading respectively but less significant than those in Nd values.

Any value lower than the actual number of designed traffic repetitions will cause distress. It can be implied fatigue cracking occurs at CBR 3% to 9,5% with the overloading of 50, 75%, and 100%.

V. CONCLUSIONS

The findings of this study are important for pavement designer and regulator to consider the sensitivity of pavement mechanistic response to the variations of subgrade strength and overloaded traffic for the pavement design and code.

According to the result and analysis in this study, the following conclusions are drawn:

1. The results of mechanistic response reveal that the horizontal tensile strain and vertical compressive strain all decrease with increasing subgrade CBR value. Higher CBR value represents stronger subgrade, thus the subgrade will receive lower strain value.
2. The addition of load will increase the pressure that the vehicle distributes to the pavement, so that the horizontal tensile strain and vertical compressive strain will be higher.
3. Nf and Nd all increase with decreasing of horizontal tensile strain and vertical compressive strain, which implies that higher CBR value will increase Nf and Nd.
4. Rutting occurs at CBR 3% to 7,5% with the overloading of 75% and 100% while fatigue cracking occurs at CBR 3% to 9,5% with the overloading of 50, 75%, and 100%.

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