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Structural Durability Assessment of the Benin Sagamu Bypass Overhead Bridge by Reliability Theory

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ABSTRACT :

The structural durability of key structural elements of the Benin-Sagamu overhead bypass bridge located at Oluku, Benin City, Edo state, was determined by the use of reliability theory. The bridge dimensions were measured to determine its dead load while manual traffic count was used to estimate the traffic live loads by calculating the Annual Average Daily Traffic and simulating the total number of vehicles that would use the bridge in 120 years similar to methods used in EN 1991-2 (2003). From the traffic survey data, the mean vehicle load was used as the representation of assessment vehicle live load. The assessment vehicle model closest to those in CS 454 was used as the assessment vehicle and its axle loads and dimensions adopted for structural analysis using the influence line theory. Moments from the analysis resulting from dead and live loads represented the bridge strength model. The resistance model of the bridge was derived from concrete strength by Non-Destructive testing and from the section properties. The reliability theory was applied to determine the reliability and probability of failure of the transverse and longitudinal girders of the bridge. The reliability index of the transverse girder and longitudinal girders were 3.9 and 5.2 respectively and compares favorably to target reliabilities of EN 1990 (2002). The reliability theory was found to be efficient in determining the structural durability by the use of manual traffic counts.

I. INTRODUCTION

Structural durability assessment of bridges determines their current structural safety and this is the most important factor taken into consideration when determining investment budgets intended for bridge maintenance and repair (Bayrak and Akgul, 2020). Two methods adopted to verify structural safety are the condition-based performance prediction approach and the safety-based performance prediction approach (Bayrak and Akgul, 2020). The condition-based assessment method is generally performed by visual inspection whereas the safety-based performance prediction method employs the use of structural engineering formulations and determination of quantified value of resistance degradation and load increase in a bridge member (Bayrak and Akgul, 2020). In the safety-based performance prediction method, the reliability index β or probability of failure P_f can be used to quantify the structural safety (Bayrak and Akgul, 2020).

The term 'reliability' is often oversimplified, used loosely and inaccurately because it is approached in an absolute way such that the structure is either reliable or it is not reliable and in accordance with this approach, it is understood that when the structure is deemed reliable, "the failure of the structure will never occur" (Holicky, 2009). This is an incorrect oversimplification, as failure may occur even when the structure has been

correctly declared to be reliable (Holicky, 2009). A structure could collapse at any time due to the possibility that the structure could be overloaded, inadequately maintained or sabotaged during its service life, and hence, the term 'absolute reliability'' cannot be applied to engineering structures (Stanojev and Stojic, 2014). The basic requirement of reliability is that a structure is to be designed and executed in a manner in which, during its intended life (with appropriate degrees of assurances and in an economic way), it will remain fit for the use for which it was required and sustain all actions and influences likely to occur during execution and use (Holicky, 2009). ISO 2394 (2013) further describes reliability as the ability of a structure to fulfil the specified requirements, including the working life, for which it has been designed and is often expressed in terms of probability.

Methods that directly applied the reliability theory to a reinforced concrete bridge under moving loads were described by Bayrak and Akgul (2020). Though the results were compared to target reliabilities, reliability analysis techniques should take into cognizance rationality when comparing levels of safety of different bridge stock and enables individual assessment to be more bridge specific (Lark and Flaig, 2005). In a reliability-based probabilistic assessment procedure, the uncertainty of each parameter that influences the failure mode under consideration is modelled using an appropriate probability distribution function (PDF), (Lark and Flaig, 2005). The reliability analysis then gives an estimate of the P_f or β of the element or structure under consideration (Lark and Flaig, 2005).

Weigh-In-Motion (WIM) data (includes axle weights measured in WIM sensors) and load model derivation are continuous random variables therefore, the reliability theory in durability assessment can be used to predict loads and uncertainties over long periods and it is also used to quantify the uncertainty associated with a new traffic load model at serviceability (SLS) and ultimate limit states (ULS) (Francois, 2009). In the absence of data from WIM sensors, traffic counts from traffic survey have been adopted in this research, while axle loads were estimated based on CS 454 (2022) vehicle classifications to predict the reliability of a bridge, the focus being on the ULS of the moment carrying capacity.

The focus of this study is the Benin Sagamu Bypass overhead twin bridge. One portion of the bridge has 4 bridge deck spans that are simply supported covering an effective span of 50m. The critical spans considered in this assessment are the two middle spans which covers a length of 19.2m each. The width of the bridge including walkway and abutment is 9.6m. The height of each pier (of 1.2m diameter) above the ground level is 4.5m. Each deck is characterized by an open cross section composed of six (6 numbers) precast reinforced concrete longitudinal girders of flange thickness 0.3m, web thickness of 0.4m and depth of 1.5m set at constant spacing of 1.2m. Distance between the twin bridges is 0.6m. Pictures of the location are as shown below.

Figure 1. Benin-Sagamu By-Pass Bridge showing piers, transverse and longitudinal girders

II.   MATERIALS AND METHDOLOGY

The methods were coined from the Design Manual for Roads and Bridges DMRB 3.4, (2020) and the subsections which include CS 451 and CS 454 formed the basis of the methods adopted for this study. Below is a summary of the procedures adopted to determine the structural durability of the bridge as applied in this study.

1. Bridge structural assessment by physical inspection as prescribed in CS 451.
2. Determination of strength of bridge material using rebound hammer test.
3. Determination of bridge live load through data from traffic count.
4. Calculation of maximum bending moment using influence line theory for moving loads.
5. Calculation of bridge reliability index by First Order Reliability Method (FORM).
6. Estimation of the structural integrity from the probability of failure results.

a. Inspection for Loading and Resistance

The Design Manual for Roads and Bridges, DMRB 3.4, (2020) was adopted for the structural assessment. The structure was inspected to determine the dimensions needed to calculate the nominal dead loads, verify the form of construction, verify lane markings and the nature and condition of the structural components.

b. Dead Load

Dead load items included are the weight of the girders, deck slab, wearing surface and sidewalks and parapets and these were estimated from measurements taken. The self-weight of the components of the bridge were based on the specific weight of for concrete and   for asphalt from table 4.1.1a of CS 454.

c. Live Load

Traffic survey of 5 days was taken and an estimate was made of the annual average daily traffic (AADT) for various vehicle classes. This was simulated for 120years from the year the bridge was in service (2002). The AADT in the year 2002 was estimated from the equation 1 (U.S Department of Transportation, FHA, 2018).

$$AADT(2020) = AADT(2002) \times (1 + r)^n \tag{1}$$

Where is the in year 2020, is the in year 2002, is the number of years projected (18) and is the

Annual Average Change Rate taken as 4% (Ede, 2014).

The total number of various vehicle categories was calculated and then simulated with the traffic model formula of equation 2 (U.S Department of Transportation, FHA, 2018).

$$T = 365 \times AADT\,[(1 + r)^n - 1]/(r) \tag{2}$$

Where is the cumulative number of vehicles and is taken as 120 years.

From the total number of vehicles for each vehicle class projected for 120years (number of years most bridges are designed for), the mean vehicle weight which would ply the bridge route was used as the basis for the live load model. The traffic data naturally represents a lognormal distribution; therefore, the data was converted to a normal distribution by taking the natural logarithm of the cumulative number of vehicles before calculating mean and standard deviation.

This mean vehicle weight representing the vehicle model was compared to the closest vehicle model in CS 454 (2022). After picking the vehicle model, the axle loads and dimensions of the vehicle were taken from CS 454 (2022). These loads formed the actions used in the analysis of the structure.

d. Assessment Resistance Model (R)

Clause 3.10 of CS 454 (2022) reiterates that the assessment resistance can then can be expressed in terms of material strength and section properties. The strength of bridge material therefore was determined through rebound hammer non-destructive test method. The resistance factor R is then expressed (Kohler 2017) as shown in equation 3.

$$R = f_c z \tag{3}$$

Where f_c is the concrete strength factor while Z is section modulus of the structural element. Therefore, mean of resistance μ_R can be expressed as;

$$\mu_R = \mu_{fc} \times z \tag{4}$$

Where μ_{fc} is the mean concrete strength and Z is the section modulus. The standard deviation of resistance σ_R can be expressed as;

$$\sigma_R = \sigma_{fc} \times z \tag{5}$$

Where σ_{fc} is the standard deviation of the mean strength of material.

e. Assessment Strength Model (S)

The bridge's strength was estimated in terms of the maximum moment , of the live loads and dead loads combined. The analysis was done manually using the influence line theory to determine the , that will cause the most adverse effect for a moving load. The becomes the mean of strength while the standard deviation of strength was derived by multiplying the coefficient of variation , from traffic loads analysis and as shown in equation 6.

$$\sigma_S = COV \times M_{max} \tag{6}$$

f. Limit States

This work is focused on the ultimate limit state of the moment carrying capacity and it is expressed in terms of safety margin M, as shown in equation 7.

$$M = R - S < 0 \tag{7}$$

g. Reliability Index (β)

Reliability index **β** is expressed as (Bayrak and Akgul, 2020);

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R{}^2 + \sigma_S{}^2}} \tag{8}$$

The reliability R or probability of safety P_S then (Bayrak and Akgul, 2020) is;

$$R = \phi(\beta) \tag{9}$$

Where Φ is standard normal distribution function.
P_f is given as (Bayrak and Akgul, 2020)

$$P_f = 1 - \phi(\beta) \tag{10}$$

III. RESULTS AND DISCUSSION

A. Traffic Data

Table 1. Traffic count data carried out in year 2020

	CARS	BUSES	LORRIES	TRUCKS	LARGE TRUCKS
MON	12565	4638	615	1296	865
TUE	12736	5788	352	1459	868
THUR	13005	5739	276	1753	1404
SAT	13172	5799	258	1096	1187
SUN	17394	6727	73	405	1012
Total	**68,872**	**28,691**	**1,574**	**6,009**	**5,336**
AVERAGE DAILY TRAFFIC ADT	**13,775**	**5,739**	**315**	**1,202**	**1,068**

B. Total Traffic Volume

From the above traffic data, the *AADT* in the year 2002 estimated from equation (1) gives table 2.

Table 2: AADT estimated for the year 2002

TYPES OF VEHICLES	CARS	BUSES	LORRIES	TRUCKS	LARGE TRUCKS
$AADT$ (2002)	6,800	2,833	1556	594	528

From the table 2, equation (2) is applied for each class of vehicle for 120 years to give table 3.

Table 3: Cumulative number of vehicles for 120 years estimated from equation 2

TYPES OF VEHICLES	CARS (Nos)	BUSES (Nos)	LORRIES (Nos)	TRUCKS (Nos)	LARGE TRUCKS (Nos)
No. of vehicles for 120 years	6,804,561,898	2,834,900,567	1,557,043,870	594,398,495	528,354,218
Total Vehicles TV	12,319,259,048				
No. of vehicles for 120 years (Normal Distribution)	22.641	21.765	21.166	20.203	20.086
Total Vehicles TVN	105.861				

C.   Approximate Vehicle Weights for All Classes of Vehicles
Table 4 Approximate vehicle weights for all classes of vehicles adopted

TYPES OF VEHICLES	CARS	BUSES	LORRIES	TRUCKS	LARGE TRUCKS
TONNAGE (T)	2	20	31	46	51

Source: Federal Highways Regulations (2018)

D.   Relationship Between Vehicular Counts and their weights
The vehicle weights (from table 4) are multiplied to the cumulative number of vehicles estimated for the 120 years (from table 3) for each vehicle class and are as shown in the table below.

Table 5 Table showing relationship between vehicular counts and their weights

TYPES OF VEHICLES	CARS	BUSES	LORRIES	TRUCKS	LARGE TRUCKS
Tonnage (T)	45.282	435.300	656.146	929.338	1,024.386
Total Tonnage TT	3,090.452				
Population Mean [TT/TV] (T)	29.2				
Standard Deviation (T)	20.3				
Coefficient of Variation (*COV*)	0.7				

E.   Analysis of the Longitudinal Girder

From the study, the mean vehicular load which pertains to the bridge is 29.2T. This load is nearest to Vehicle Assessment Load Model A of Table B.1 of CS 454 (2022). The vehicle model dimensions and axle weights are as shown in figure 1. Using Assessment Live Load Model 1 (ALL model 1) of CS 454, the live model for analysis of load can be represented as shown below.
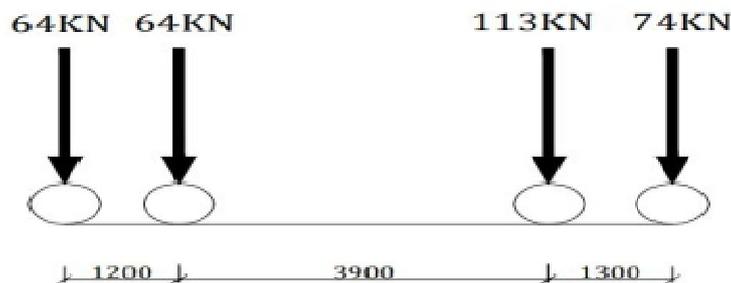

Figure 2. Diagram showing vehicular live loads

F.   Modification of Axle Loads
Table 6 Modification factors for axle loads

	Modification factors	
Modification Factors	Road Surface Classification	Factors
Impact Factor	Poor	1.8 (Table 5.9a of CS 454,multiplied to most critical axle)
Traffic Flow Factor		1.0 (Table 5.9b of CS 454)
Lane Factor		1 (Table 5.9c of CS 454)
Dynamic Modification Factor (DAF) from ARCHES 2010.		1.15

The modified axle loads and their distances for the live load are given below.

$$W_1 = 73.6KN;\ W_2 = 73.6KN;\ W_3 = 233.9KN;\ W_4 = 85.1KN$$

$$O_1 = 1m;\ A_1 = 1.2m;\ A_2 = 3.9m;\ A_3 = 1.3m;\ O_2 = 1m$$

G.   Load Per Longitudinal Girder
Assuming the live load is distributed across three girders (carrying one notional lane) at a time, when divided by 3, the portion of live load which act on a single longitudinal girder can be determined. The axle loads acting on a single longitudinal beam is as shown below.
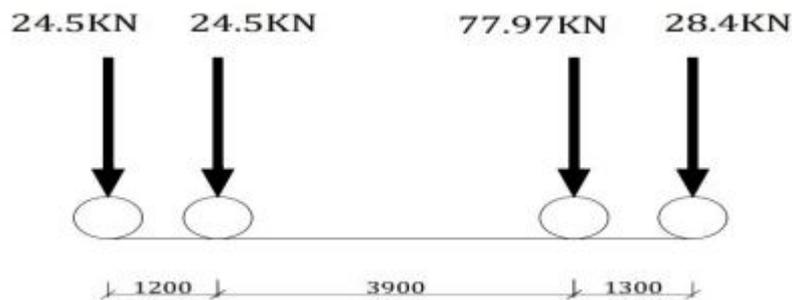

Figure 3. Line diagram of modified Axle Loads per longitudinal girder

A uniformly distributed load of $5KN/m^2$ is added to the remaining portion of the carriageway (CS 454, 2022). This will give 8KN/m^2 across the 19.2m length longitudinally.

H.   Maximum Moments
The live load model together with the bridge dead load would produce M_{max} effects on both the longitudinal and transverse girders as shown in the table 7.

Table 7 Maximum span moments per girder from manual analysis

	Longitudinal Girder	Transverse Girder
	Moment (KNm)	Moment (KNm)
($M_{max} = \mu_S$)	2,732	3,922

I. Section Modulus z of the Longitudinal Girder/ Flange Beam $(z = 0.29 m^3)$
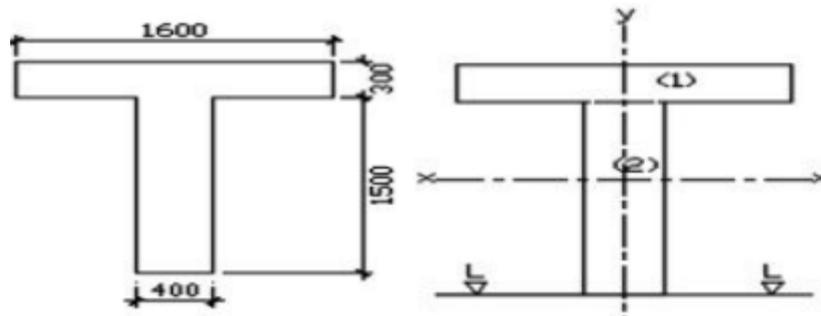

Figure 4. section and components of the longitudinal girder

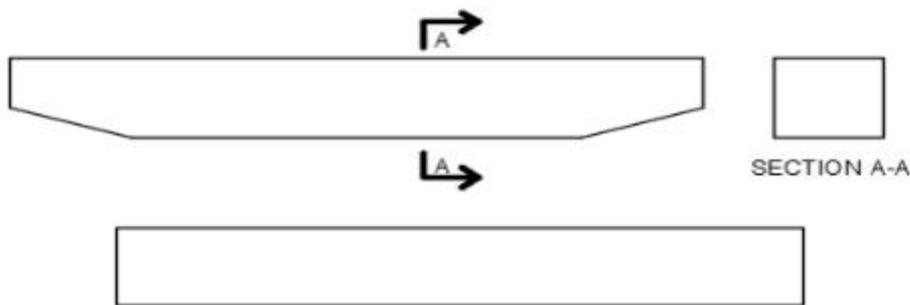### J. Section Modulus of Transverse Girder $(z = 0.324 m^3)$

Figure 5. Transverse girder of the bridge and its Idealized shape

K. Structural Reliability on the Longitudinal Girder
Model Resistance of Longitudinal Girder

$$\mu_R = \mu_{fc} \times z$$

From equation (5), ; $\cdot$ $\mu_R = 47{,}200 \times 0.29 = 13{,}688 KNm; \mu_R$ 13,688KNm

$$\sigma_R = \sigma_{fc} \times z$$

Also, from equation (6), ; $\cdot$
$\sigma_R = 3{,}200 \times 0.29 = 928 KNm; \sigma_R = 928 KNm$

Model Strength of Longitudinal Girder

From equation (6), $\sigma_S = COV \times M_{max}$; $\cdot$
$\sigma_S = 0.7 \times 2{,}732; \sigma_S = 1{,}912 KNm$

L. Reliability index β of Longitudinal Girder Using FORM

From equation (7)

$$\beta = \frac{13688 - 2732}{\sqrt{928^2 + 1912^2}} = \frac{10956}{2125} = 5.2$$

P_f using excel "=NORM.DIST (β),0,1,TRUE)" gives 0.000000123475 = 0.0000001

M. Structural Reliability Using Empirical Method on The Transverse Girder
Model Resistance

Sectional modulus as computed earlier is $0.324 m^3$ The mean concrete strength as calculated is 47,200 KN/m^2 while the Standard deviation of concrete strength is $3{,}200 KN/m^2$.

Therefore $\mu_R = 47{,}200 \times 0.324 = 15{,}292.8 KNm$; and $\sigma_R = 3{,}200 \times 0.324 = 1036.8 KNm$

Model Strength of the Transverse Girder
From equation (7) $\sigma_S = 0.7 \times 3{,}922$; $\sigma_S = 2{,}746 KNm$

N. Reliability index β of Transverse Girder Using Empirical Method

From equation (7
), $\beta = \frac{15293 - 3922}{\sqrt{1037^2 + 2746^2}} = \frac{11371}{2935.3} = 3.9$; P_f using excel 0.0000544177=0.00005

O. DISCUSSIONS

The β of the longitudinal girder ($\beta = 5.2$) is way above the minimum values for a 50 years reference period in table B2 of EN 1990 (2002) which was given as 4.3. This could mean the data used to calculate β were either overestimated (for example concrete strength and traffic data) or the structure is actually durable and reliable requiring minimal maintenance jobs.

The β of the transverse girder ($\beta = 3.9$) is below the minimum values for a 50 years reference period. This would ordinarily mean the reliability of the bridge is in doubt, however, Lark and Flaig (2005) gave a range of variability (0.4 for bending at ULS) that can occur due to level of uncertainties involved in arriving at the β. By conducting a sensitivity analysis, the variability of key factors affecting the reliability can be determined and reliability updated adequately.

IV. CONCLUSION

This paper has shown that the reliability of a bridge not having WIM sensors installed can be determined by the use of traffic survey data to estimate the expected increase in traffic live loads and determine an assessment live load model, coupled with the application of dynamic amplification factor to show vehicle dynamic effects. The reliability indices gives the probability of failure within the period considered and when compared to target reliabilities for similar timeframe, can be used as a measure to quantify the structural safety of a bridge. This in turn shows the structural durability and the current structural integrity of the bridge.

REFERENCES

Assessment and Rehabilitation of Central European Highway Structures, ARCHES (2010). Executive Summary Report May 2010. 6th Framework Programme. Theme: Mobility & Transport, Safety & Security.

Bayrak, H. and Akgul, F. (2020). Reliability Analysis of a Reinforced Concrete Bridge Under Moving Loads. Challenge Journal of Concrete Research Letters Vol. 11. No. 2. Pp 31–38.

BS ISO 2394 (2013). General Principles on Reliability for Structures. BSI Group Headquarters. 39 Chiswick High Road London W4 4AL.

CS 451 (2020). Structural review and assessment of highway structures. Highway Structures & Bridges Inspection & Assessment. Design Manual for Roads and Bridges.

CS 454 (2020). Assessment of highway bridges and structures. Highway Structures & Bridges Inspection & Assessment. Design Manual for Roads and Bridges.

DMRB (2020). Bridges Engineering Division of the Department of Transport. (2020) Design Manual for Roads and Bridges.

Ede, A. N (2014). Cumulative Damage Effects of Truck Overloads on Nigerian Road Pavement. International Journal of Civil and Environmental Engineering IJCEE-IJENS Vol: 14 No: 01, Pp 21-26.

EN 1990 (2002). Eurocode - Basis of Structural Design. The European Union. European Committee for Standardization (CEM), Brussels.

EN 1991 Part 2 (2003). Eurocode 1 - Traffic Loads on Bridges. Actions on Structures. The European Union. European Committee for Standardization (CEM), Brussels.

Federal Highways Act (Control of Dimensions, weights and Axle Loads of Heavy Duty Goods Transport Vehicles) Regulations 2018. Vol. 00. No. 00.

FHA (2018). The Federal Highway Administration. U.S Department of Transportation. Traffic Data Computation Method. Publication No: FHWA-PL-18-027.

Francois, P. V. D. S. (2009). Derivation of a Traffic Load Model for the Structural Design of Highway

Bridges in South Africa. Dissertation presented for the degree of Doctor of Philosophy. Faculty of Engineering at Stellenbosch University. South Africa.

Holicky, M. (2009). Reliability Analysis for Structural Design. SUN MedIA Stellenbosch Ryneveld Street, Stellenbosch, 7600.

Kohler Jochen (2017). Structural Aspects in Structural Engineering TKT4196. Norwegian University of Science and Technology, Norway.

Lark R. J. and Flaig K. D. (2005). The use of reliability analysis to aid bridge management. The Structural Engineer. Vol. 83. Issue 5. Pp27-31.

Pedroni N., Cadini F. and Zio E. (2017). Advanced Monte Carlo Methods and Applications. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems Part A Civil Engineering. Vol. 3 Issue 4.

Roads Liaison Group (2013). Management of Highway Structures - A Code of Practice. The Stationery Office. London.

Stanojev, M. and Stojic, D. (2014). Reliability Analysis of Structures. : Architecture and Civil Engineering Vol. 12, No. 3, Pp. 265 – 272.