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3D FE Modelling and Simulation of Reinforced Concrete Bridge Superstructure for Fatigue Analysis in ANSYS Workbench

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Abstract*—*Simulating and analyzing complex Reinforced Concrete (RC) structures in ANSYS Workbench has been a complex and tedious task to most users, prior to the introduction of "REINFORCEMENT" workflow in ANSYS 2020 R2. This study utilized this new feature to simulate a 3D modelof a single span, 11.3m span by 10.8m width from the 12-span Tamburawa Bridge Kano, Nigeria, using a standard Fatigue load model (FLM) specified in ASSHTO LRFD code. ANSYS Design Modeler was used to develop the Bridge Superstructure 3D model to specifications, material properties were modeled in ANSYS Engineering Data, while stress and fatigue analysis were achieved in Transient Structural Module of the ANSYS Workbench. The study found that the service stresses of the deck and critical Longitudinal Girder are 1.75N/mm^2 and 29.42N/mm^2 respectively, which are within the acceptable limit. The deck and Longitudinal Girder critical deflection were found as 3.90mm and 3.89mm respectively, which are also within the (L/1000 – L/600)mm limit specified for Highway bridges. This is an indication that the Bridge Superstructure is serviceable. The Fatigue life of the Deck and critical longitudinal Girder were obtained as 1x10^6 Cycles and 0.48x10^6 Cycles respectively. The new ANSYS Workbench "REINFORCEMENT" workflow has indeed proved useful for simulating complex RC structure, thereby eliminating the need to develop ANSYS parametric design language (APDL) code.

Indexed Terms*—*ANSYS Workbench, Bridge Superstructure, Deflection, Fatigue Analysis, Finite Element Modelling, S-N data, Tamburawa Bridge, Reinforcement Workflow

I. INTRODUCTION

Bridges are structures designed and constructed to provide uninterrupted and continuous passage of traffic (Vehicles, Trucks and pedestrians) over obstacles (water ways and valley). Bridges are made of various materials of construction ranging from wood, concrete, Steel etc. A typical bridge is structurally segmented into substructure and superstructure. The superstructure refers to the bridge structural element above the bearing line.

The primary function of bridges is to support the to and fro (cyclic) movement of traffic. This cyclic transient action of vehicles and heavy trucks wheels inducing variable stresses on the bridge deck and Girders, which over time results into their gradual and progressive detoriation, then eventually failure. Failure of such nature is known as Fatigue failure.

Over the past few decades, researchers have investigated and assessed bridges all over the world for their serviceability, reliability and safety. The methods of assessment ranges from Laboratory experiment, Field test and Analytical approach [1]. In recent times, due to the development in computer technology, the analytical approach has become an important part of Engineering analysis and design. Therefore most researchers found it a useful tool for either calibrating or validating the Laboratory or Field test results.

FE computer programs are used practically in all branches of Engineering, more also, the method has been used to successfully simulate the behaviour of Bridges [2]. Three dimensional FE modelling, probably the most involved and time consuming, still the most general and comprehensive technique for static and dynamic analysis, capturing all aspects affecting the structural response [2].

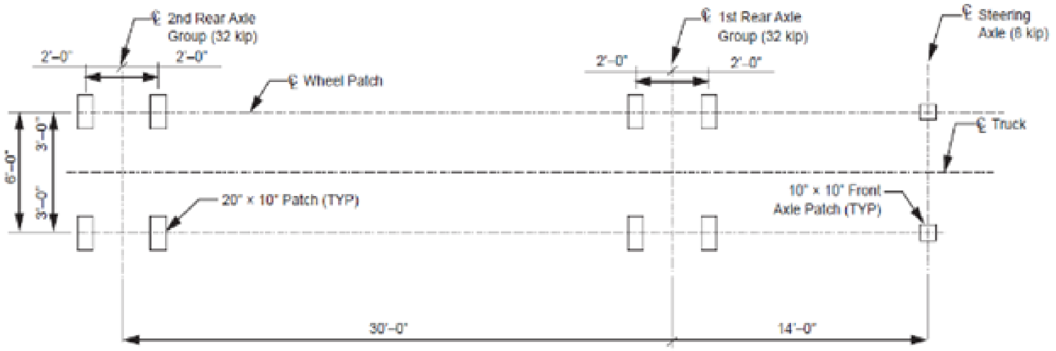


Fig. 1: Plan geometry of the AASHTO FLM

The analytical method accuracy depends upon the ability to simulate the problem [1]. ANSYS a FE program has proved capable to simulate both linearity and non-linearity that exists in material behaviour and geometry of resistance models in nature. ANSYS employs Newton-Rapson technique to solve higher order differential equations [1].

Prior to recent times, simulating the structural response of reinforced concrete elements has been a difficult task in ANSYS Workbench, as it requires a very good experience of FE method and ANSYS Parametric Design Language(APDL) coding to achieve the matrix behaviour of both concrete and rebars especially for large structural models.

This study employed the recently introduced “REINFORCEMENT” workflow in ANSYS 2020 R2 software program to handle the limitation Associated with establishing bond between concrete and rebars in static or transient structural modules of ANSYS Workbench as such eliminating the use of APDL codes.

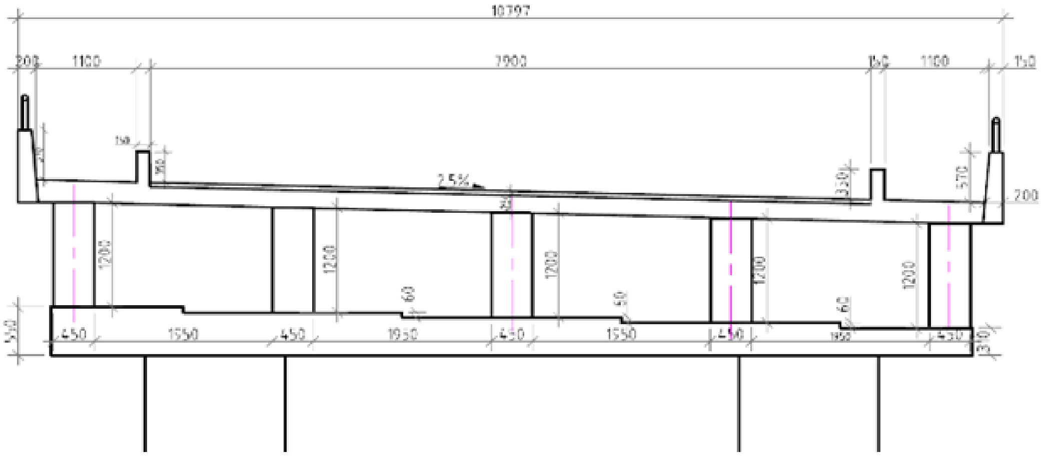


Fig. 2: Tamburawa Bridge Cross Section Detail

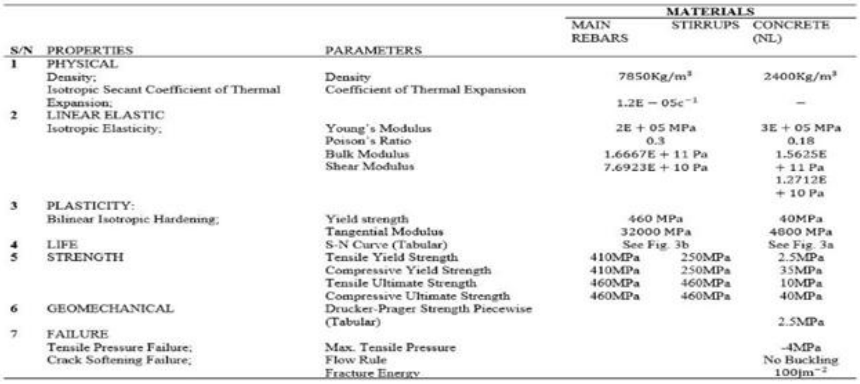
This study was undertaken on Tamburawa Bridge, a RC Highway Bridge, situated along Kano-Zaria road Kano, Nigeria. The bridge was opened to traffic for 35 years precisely now.

The aim of the study is to model, simulate and perform fatigue analysis on critical components of the bridge superstructure (deck and Longitudinal girders), using a standard Fatigue load model (FLM) as specified in AASHTO LRFD [6].

Previously, some related studies have been done using the same program and approach.

Muthanna, *et'al.* [2]. Employed ANSYS software to simulate the structural behaviour of steel-concrete composite box girder bridge and found that the Theoretical 3D FE models developed predicts quite well the elastic behaviour and mode shapes of the bridge, judging from the good agreement of both analytical and experimental test results.

Table I.: Mechanical Properties of Materials



			MATERIALS		
S/N	PROPERTIES	PARAMETERS	MAIN REBARS	STIRRUPS	CONCRETE (NL)
1	PHYSICAL				
	Density;	Density	$7850Kg/m^3$		$2400Kg/m^3$
	Isotropic Secant Coefficient of Thermal Expansion;	Coefficient of Thermal Expansion	$1.2E-05c^{-1}$		–
2	LINEAR ELASTIC				
	Isotropic Elasticity;	Young's Modulus	2E + 05 MPa		3E + 05 MPa
		Poison's Ratio	0.3		0.18
		Bulk Modulus	1.6667E + 11 Pa		1.5625E + 11 Pa
		Shear Modulus	7.6923E + 10 Pa		1.2712E + 10 Pa
3	PLASTICITY:				
	Bilinear Isotropic Hardening;	Yield strength	460 MPa		40MPa
		Tangential Modulus	32000 MPa		4800 MPa
4	LIFE	S-N Curve (Tabular)	See Fig. 3b		See Fig. 3a
5	STRENGTH	Tensile Yield Strength	410MPa	250MPa	2.5MPa
		Compressive Yield Strength	410MPa	250MPa	35MPa
		Tensile Ultimate Strength	460MPa	460MPa	10MPa
		Compressive Ultimate Strength	460MPa	460MPa	40MPa
6	GEOMECHANICAL	Drucker-Prager Strength Piecewise (Tabular)			2.5MPa
7	FAILURE				
	Tensile Pressure Failure;	Max. Tensile Pressure			-4MPa
	Crack Softening Failure;	Flow Rule			No Buckling
		Fracture Energy			$100jm^{-2}$

Habeeba, *et'al.* [1]. Used ANSYS Mechanical APDL and estimated the remaining fatigue life of a RC highway bridge, using S-N curves proposed by AASHTO for RC bridges. Fatigue damages were computed using the Palm-gren Miner's theory of linear damage accumulation.

Rajwanlop and Pannapa [3]. Developed a FE procedure for fatigue evaluation of RC bridge deck under the application of truck wheel load based on smeared crack concept approach, employing the fatigue test data of concrete and reinforcement steel and Palmgren-Miner linear criterion of cumulative damage in the analysis.

Srinivasan and Pradeep [4]. Investigated a hybrid RC beam-column joint under cyclic loading using ANSYS Workbench, performed static stress analysis and a zero-based fatigue analysis on the frame joint and found that the fatigue life increases for both internal and external joints.

II. MATERIALS

The materials used in this study are categorized into three (3) namely:

1) FE program software.
2) Load Model.
3) Resistance Model

A. FE Program (Software)

This study was limited to the modeling and simulation of Tamburawa bridge superstructure (i.e. the Numerical approach) for its investigation, due to it being relatively time and resources conservative.
ANSYS 2020 R2 [5]. Program was released within the Covid-19 period and it incorporated a new workflow known as "*REINFORCEMENT"* implemented in Static and Transient structural analysis modules of the ANSYS Workbench platform. This new feature was expected to cushion the challenges users were faced with in simulating the bond between concrete and steel rebars, leading to the use of APDL codes in previous versions of the program.

Transient structural analysis module of the ANSYS Workbench platform was used for this study.

B. Load Model

Fatigue load model (FLM) specified by AASHTO LRFD [6]. , was used to simulated the fatigue load traversing the study bridge deck system.

This study was limited to FLMs, (i.e. vehicles > 30 tons) since its Numerical approach based and as such the actual traffic loading was not considered.

The plan geometry and footprint of the FLM is as shown in Fig.1.

C. Resistance Model

This refers to the bridge super structure, which in this study is the Tamburawa bride Kano, Nigeria. The cross sectional details of the bridge superstructure was presented in [7]. Detail of the bridge superstructure is presented in Fig.2.

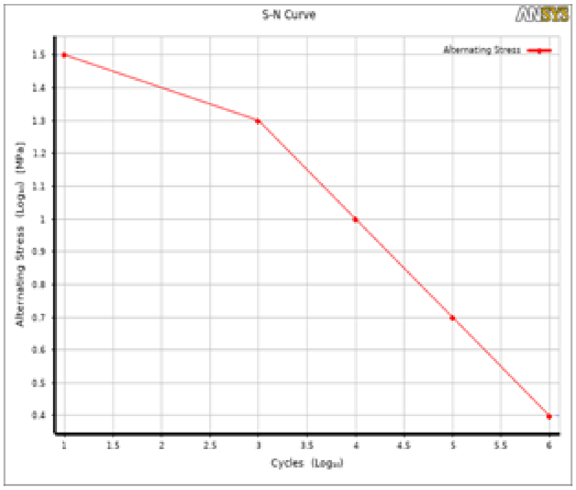
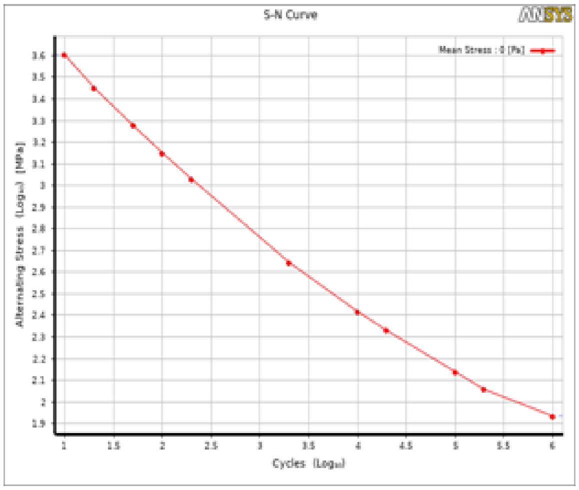


Fig. 3a: Concrete S-N Data

The comprehensive summary of mechanical properties of the concrete and steel rebars used for the materials properties modelling is presented in Table I.

Fatigue data for the concrete and steel rebars are also very pertinent to performing a fatigue analysis. This study adopted fatigue test data presented by [4]. The test data are shown as Fig.3a and b. These are S-N curves which represents the Stress-life of the bridge materials and it was modelled in ANSYS Engineering data module and assigned to the respective materials of the bridge super structure.

Fig. 4: 3D Model of Bridge Super Structure in DM



b. Steel rebars S-N Data

III. METHODOLOGY

This section focuses on the methods and procedures employed to model, simulate and analysis the bridge superstructure in ANSYS Workbench.

A. 3D modelling of bridge super structure

The entire 3D model of the bridge superstructure was modelled to as built specification within *ANSYSDesign Modeler* Graphic user interface (GUI).The steel rebars were modelled with *line bodies* with defined circular cross sections, while the concrete elements were modelled with *solid bodies.*

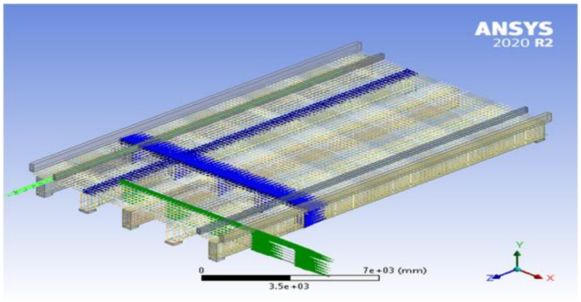
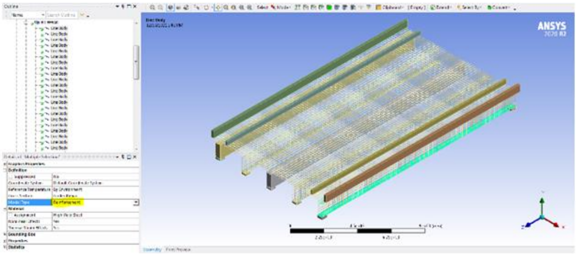


Fig. 5: Reinforcement workflow Application



Add frozen function in Design modeler was used to create separate material interface between the concrete and steel rebars. The Fig.4 above shows the completed 3D model of the embedded steel rebars and the concrete.

B. Property Assignment and REINFORCEMENT

The 3D Bridge model was imported from the Design modeler to the Static structural Analysis system of the Workbench platform for simulation and analysis. Fig.5 shows the use of the *Reinforcement Workflow* to establish the bond between the Steel rebars and concrete elements.

C. Meshing the Model

The mesh Body sizing technique with element size of 300mm was employed to achieve the discrete size for the 933 bodies of the full scale model of a single span of the bridge. The mesh statistics showedthe model has 109,338 Nodes and 46,668 elements. Fig.6 shows the meshed model of the bridge.

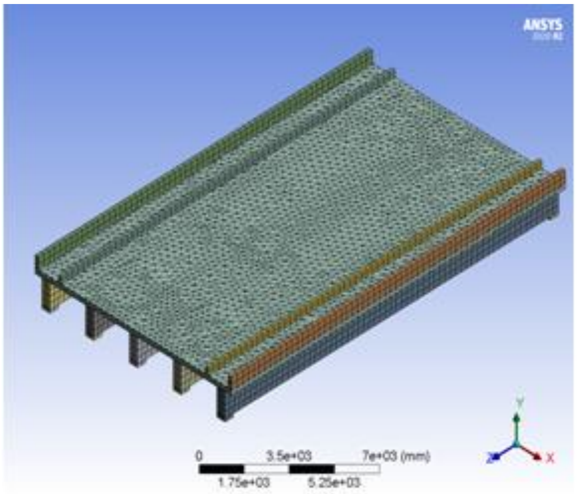


Fig. 6: 3D Meshed model of Bridge SS

D. Loading and Boundary Conditions

The 325kN (32.5Ton) FLM was modeled as Gross weight in motion (GWIM) and loading pattern was simulated for Slow lane (60%), Fast lane (30%) and Both lanes (10%) traffic flow for the 35 years period considered for this study.

The fixed and roller boundary condition at the bridge The fixed and roller boundary condition at the bridge ends were simulated with (0,0,0) and (1,0,0) respectively, i.e. "0" means a restriction of movement, while "1" indicates free movement with respect to the Cartesian coordinate(x, y, z).

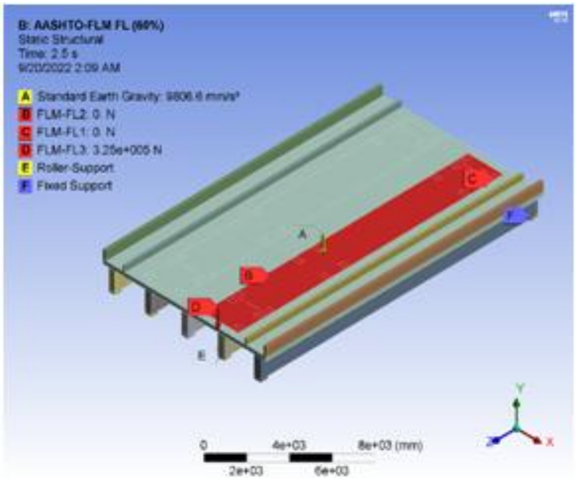


Fig. 7: Load and Boundary Conditions

Fig.7shows the loading and boundary condition of the bridge model.

E. Estimating the FLM cycles

This study assumed that a complete passage of the FLM on a single span of the bridge equals one cycle. The traffic simulation was done to capture the possible numbers of FLMs that has transverse the bridge from inception (1986) to date (2021).

The FLM traffic was estimated in line with the procedure specified in [6].

F. Modelling the FLM as GWIM in ANSYS

The FLM was modelled as GWIM, taking into account the total axle loads and the entire plan area of the fatigue truck (Fig.1).

To simulate the moving (Transient) effect of the fatigue truck on the stationary (Static) bridge deck in ANSYS Workbench static or transient structural Analysis systems, Gross weight of FLM was represented as vertical force component (Y-Component) taking into account the effect of gravity. The tabular data Time-Step function was utilized to simulate the translational movement of the FLM on the deck as shown in Fig.8.

IV. RESULTS AND DISCUSSION

This section presents Serviceability and fatigue analysis results obtained from the analytical study.

1. Serviceability limit state results;
   i. Directional and Total deformations
   ii. Von-Misses Stress and Strains

2. Fatigue limit state results;
   i. Fatigue life
   ii. Fatigue damage

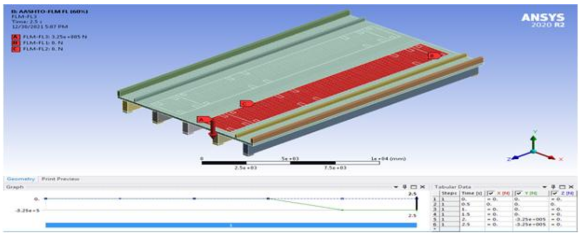


Fig. 8: Simulating Moving FLM

The above results were obtained for three (3) different loading sequences to replicate the possible paths of travel of the FLM on the bridge deck system.

A. *Directional/Total Deformation*

The Y-axis deformation results of the bridge critical components (deck and Girder) in the analysis are presentedin Fig. 9 and 10 respectively. The figures showed the Y-axis deformation of a single span of the bridge super structural components due to a single passage (cycle) of the FLM. The Three (3) sequences of loading simulated had BL FLM passage produce the critical deformation of the deck and girder components.

The maximum deflection at mid-span of the deck and girder are 3.90m and 3.89m respectively, which are both within the limit of [L/1000 – L/800] specified in [6] and [8]for bridges. This showed clearly that the deflection capacity of the bridge under the worst loading condition of the FL, will not be compromised and as such deemed safe in service.

B. *Load-Displacement*

The load-displacement curves of the bridge SS presented in Fig. 12, shows the relationship between the force reactions generated from the bridge due to a single passage of the FLM in sequence defined in the study and the equivalent material response in the form of deformation (displacement) within the specified simulation time frame. The area under the curve represents the work done. The graph clearly indicated that the work done on the bridge is a function of the FLM magnitude or frequency and not the loading sequence. The initial stage of the curves showed a rapid force-displacement (i.e. Elastic), while the second stage showed a gradual force-displacement

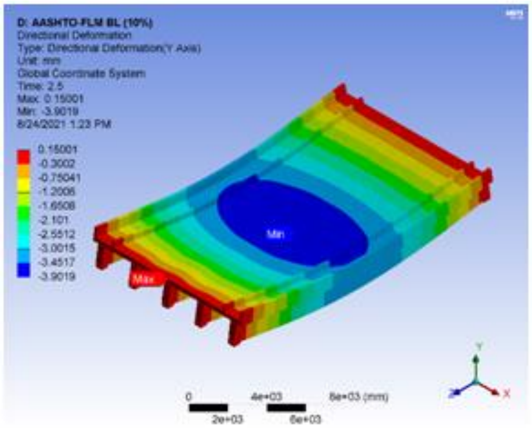


Fig. 9: Bridge deck directional deformation plot.

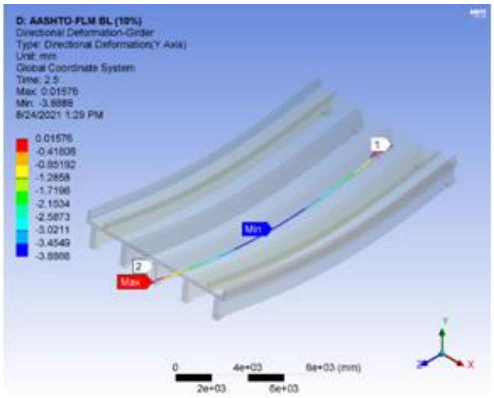


Fig. 10: Girder critical deformation

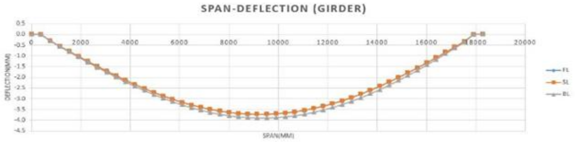


Fig. 11: Girder Span-deflection

(i.e. brittleness). This illustrates the non-linear behaviour of RC model in the simulation.

C. Von-Misses Stress and Strains

The stress-strain plots were obtained from individual Von-Misses stress and strain results of the bridge simulation analysis. The stress results of all the bridge SS components are pertinent to the stress-life fatigue analysis. The critical deck and girder stresses are $1.75\,MPa$ and $29.42\,MPa$ respectively, with a maximum strain value of $3.93x10^4$. The stress-strain relationship (Fig. 13), showed the reaction of the bridge materials upon the application of the FLM and also taking into account the various cross sectional areas of the bridge components.

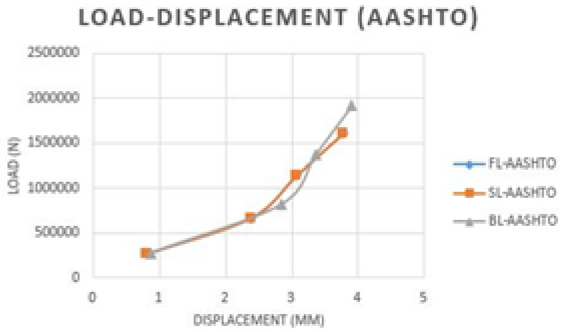


Fig. 12: Bridge Superstructure Load-Displacement

The graphs for three (3) loading sequences were shown and it was visible that the stress-strain curves depends on the loading magnitude more compared to the loading sequence. The curves indicates that the bridge components operates within their limit of proportionality i.e. materials are within their elastic limit and no yield point is visible i.e. point when material deforms plastically.

D. Fatigue Life (FL)

The results of the FL for the study models were presented as contour plots showing the available fatigue life (in cycles) of various components parts of the bridge SS for the given fatigue analysis. Irrespective of the loading sequence simulated,the

Fig. 13: Bridge Superstructure Stress–Strain

Fig. 14: Bridge Superstructure Damage

bridgedeck FL of $1.0x10^6 cycles$remained constant and it corresponds to the maximum FL of both materials as defined in their S-N data. This is because, the material stress produced on the deck ($1.75\,MPa$) falls below the minimum stress defined by the materials S-N data, corresponding to the maximum FL. The deck is said to have an Infinite life. The girders however produced a greater stress value ($29.42\,MPa$) due to contact and boundary condition effect, had the critical girder life was obtained for BL sequence as $0.075169x10^6 cycles$

E. Fatigue Damage(FD)

The results of the FD for the study models were also presented as contour plots showing the fraction of damage sustained by various components due to the FLM passage for the entire simulation. FD is the ratio of the design life (due to loading) to the available life (due to material resistance) after loading, and which according to Miner-Palmgren rule, the cumulative damage greater than one (1) indicates fatigue damage failure. The Fig. 14 showed plot of damages corresponding to the FLM traffic frequencies for the entire bridge life. Generally, the graph indicated that the sustained damage increases with increasing traffic for a constant FLM magnitude. The deck damages corresponding to 10, 30 and 60% loading frequencies are 0.047, 0.120 and 0.240 respectively and, while the critical Girder damage are 0.051, 0.154 and 0.275 respectively. Therefore the cumulative damages for the deck and girder, for the loading sequences simulated are 0.41 and 0.48 respectively. This indicates that the deck and girder components of the bridge SS are deemed safe, since their individual cumulative damages are < 1.0. This implies that only 41% and 48% of the deck and girders respective FL has been expended.

V. CONCLUSSION AND RECOMMENDATIONS

A. CONCLUSION

Judging from the study results of the fatigue analysis and evaluation carried out on Tamburawa bridge super structural components based on the AASHTO LRFD code consideration and using the FE approach, the following conclusion were drawn:

1) The “REINFORCEMENT” workflow introduced in ANSYS 2020 R2 Workbench platform was adequate in simulating the bond between Concrete and Steel rebars in such a complex model and as such has eliminated the need for users to develop APDL codes to achieve same results.
2) The study found that, at Serviceability, the deck and critical girder deflections under the cyclic effect of a standard FLM as defined in ASSHTO LRFD are 3.2mm and 6.4mm respectively, which fell below the limit (L/1000 – L/600) mm specified for highway bridges.
3) The Service stresses of the deck and critical girder were obtained as $1.75\,MPa$ and $29.42\,MPa$ respectively, an indication that the bridge Super structural components are serviceable under the cyclic influence of the FLM specified in AASHTO LRFD code.
4) The damage results obtained from the study showed the bridge girders are more susceptible to greater damages compared to the deck. This was attributed to high contact stresses generated at the support locations. The study found the Cumulative damage in the deck and critical girder as 0.41 and 0.48 respectively and are both < 1.0 limit, as such deemed safe.
5) The deck and critical girder fatigue lives were obtained as $1\text{x}10^6$ cycles and $0.48x10^6\ cycles$, indicating the active numbers of cycles of the FLM the components can sustain before eventually failing.

B. RECOMMENDATIONS

Based on the conclusions highlighted above, the following are recommended for further studies:

1) The ANSYS 2020 R2 and more recent versions with the “REINFORCEMENT” workflow be considered for modeling and simulating large and complex Reinforced concrete systems for Analysis.
2) The study bridge consist of Twelve (12) spans, however only a single span was isolated for detail Fatigue analysis and evaluation, in the long run neglecting components such as Cross-girders and Expansion joints. It is strongly recommended that continuity effect and other limitations highlighted be considered in future studies
3) The study also strongly recommends modelling the bridge bearing effect beneath the girders supports as this was the primary reason the support contact produced high stresses capable of undermining the fatigue life and increased damage of the component.

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