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FINITE ELEMENT ANALYSIS OF REINFORCED CONCRETE BRIDGE DECK SUBJECT TO VEHICULAR VIBRATIONS

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ABSTRACT: In this study, finite element analysis was conducted to evaluate the structural effectiveness of reinforced concrete bridge deck subjected to vehicular vibration. Series of numerical tests using the finite element method as coded in ANSYS Software were carried out. Load case analysis type was selected for this study, which includes modal analysis, transient and vibration analysis. For the various analyses, the load which was used was 24.11kN (2460 kilogram) which is the average weight of a Large Truck as an extreme load condition case. The model results from simulation were compared with the maximum allowable span deflection of a bridge based on the relevant design codes such as BS 5400-3:2000, AASHTO LRFD and Australian Bridge Design Code. The results indicate a maximum span deflection of 2.8974mm which is less than the maximum allowable deflection of the bridge span, 22.5mm by about 676%. The modal analysis result shows the failure mode of the bridge with respect to dynamic movement of the vehicle, that is, the action of the force of the vehicle with respect to the natural frequency of the bridge and also shows the modes of failure due to ground movement and wind force under severe conditions. The former and later had a maximum deflection of 26.354mm and 21.624mm respectively. The result obtained herein shows that the reinforced concrete bridge of span length 18000mm, 220mm thick deck, reinforced with T16/200 of steel is effective to sustain the design load and vehicular vibrations during its design life with little deformation.

KEYWORDS: Vibrations, Modelling, Modal Analysis, Transient Analysis, ANSYS.

1 INTRODUCTION

Civil Engineering is a profession tasked with the design of safe, economical and functional structures. Most studies in recent times have been channeled to determining the dynamic responses of reinforced concrete bridges. With much of the focus on the following: dynamic displacements, moments and on the load distribution to the floor [1].

As the ages of existing structures increases, it becomes imperative for the constant inspection and assessment of these structures. The reasons can be such that there has been changes in intended use of the structure, new rules with higher load demands for the structure, as result of deterioration in the structure, accidents during service life (such as; vehicle impact, fire, earthquakes), inadequate serviceability, detection of design or construction errors [2].

The presence of highway facilities in a country show the extent to which the country is growing or has grown. Due to the scarceness of land and increased traffic in major cities, bridge structures have become an inevitable part of the transportation facilities, for example, highway and railway bridges. Recently, with advancement in the areas of high-performance materials, construction methods and design technologies, bridge architecture has surpassed so many expectations. Also with the passage of time, bridges are becoming more slender and lighter and hence more susceptible to vibrations due to heavy vehicles and high-speed trains passing over them [1].

Vibrations caused by vehicles in motion become enormous when the vehicle velocities are at resonant or critical values. This may have some adverse effect on the overall safety of the bridge and comfort of the passengers. In addition, it may also expose the supporting structures to danger. Hence, there is need to control and if possible curb this undesirable excessive vibrations of bridges under vehicular loads [1].

It is well known that structures can resonate, which means that small forces can lead to important deformations, and possibly damages can be induced in the structure. Historically, on 1st July 1940 the Tacoma Narrows Bridge was opened on 1st July 1940 experienced a massive collapse on 7th November of that very year due to the wind load in the region [3]. This event is presented as an example of elementary forced resonance with the wind providing an external periodic frequency that matched the bridge`s natural structural frequency, though the actual cause of failure was aero elastic flutter. A bridge would possibly suffer from different kinds of loadings and forces during its long-term service period, such as the vehicular loads, wind forces and earthquakes. Deterioration or ageing of bridges and damages due to strong earthquakes or these dynamic loadings may result to collapse of the bridge, sometimes with catastrophic consequences. The Third Mainland Bridge (TMB) in Nigeria is usually subjected to impose heavy dynamic traffic volume from over loaded vehicles, static potholes, and dilapidated expansion joints. This phenomenon instilled fear and panicking on the bridge users due to the effect of vibration and the bridge motion [4].

Vertical vibrations caused by vehicles are the major causes of significant motion of bridge deck with local vibration at the neighborhood of the expansion joint. With the incessant and alarming rate of collapse of bridges due to age and induced mechanical vibrations in Nigeria and globally, extensive research needs to be carried out to know how structurally effective a bridge is after being subjected to constant and intermittent mechanical vibrations. This study covers the modelling of Reinforced Concrete Bridge and the static, modal and transient analysis of the RC bridge. The analysis is conducted using finite element method as packaged in ANSYS software.

2 OVERVIEW OF BRIDGE VIBRATION

Bridge vibration became a serious problem through the manufacturing of high speed vehicles and trains. In response to this problem, a British Royal Committee was formed to look into the problem of vibration and violent concussion. The Committee conducted a number of studies at the Portsmouth dockyards, [5]. Zhang *et al.* [6] studied the Effects of Vehicle-Induced Vibrations on the Tensile Performance of Early-Age Polyvinyl alcohol-engineering cementitious composites (PVA-ECCs). Ja’e *et al*. [7] conducted modal analysis on three Vertically Curved Reinforced Concrete Flyover Bridges (VCRCFB) models using CSiBridge 2013. They concluded that the use of combined geometry precast beams should be encouraged in achieving vertical profiles for this class of bridges. Lakshmi et al. [8] studied the condition monitoring or RCC slab bridge deck by conducting small scale test models and concluded that the frequency, deflection and width of cracks are used as parameters to study the health condition of the bridge. The damage detection is successful in identifying the reduction in frequency on the RCC slab deck. The reduction in stiffness after appearance of the first crack was 23 %. The frequency was significantly decreased from 100 Hz to 80.28Hzdue to flexural cracks that occurred in concrete. The experimental and analytical results are nearly equal and the crack pattern and frequency reduction are adequately simulated using ANSYS. Osumeje *et al.* [9] conducted reliability based study on reinforced concrete bridge decks subject to fatigue. All the failure modes were considered by varying the geometrical and material properties of the system. It was concluded that the reliability index increases as the section depth and grade of concrete increase. Huth et al. [10] in their work, assessed the sensitivity of several damage detection, localization, and quantification methods based on modal parameters. During the modal tests, the bridge vibrated with a servo-hydraulic shaker.

3 FINITE ELEMENT ANALYSIS

The Finite Element method of analysis is a numerical way of solving problems of engineering systems. It is useful for systems with complex geometries, loadings, and material properties. Finite element analysis (FEA) has become commonplace in recent years, and is now the basis of a multibillion dollar per year industry. Numerical solutions are now possible and available for complicated stress problems using FEA, and the method is so necessary that even introductory treatments of Mechanics of Materials such as these modules should outline its principal features. [11].

3.1 Modeling in ANSYS workbench

The analysis in this study was conducted in ANSYS finite element software. The section modeled in this study has a length of 72m making a total of four (4) spans of each 18m and having an expansion joint at the middle of its entire length. Figures 1 and 2 show the section of the modeled bridge structure and the 3D view respectively.

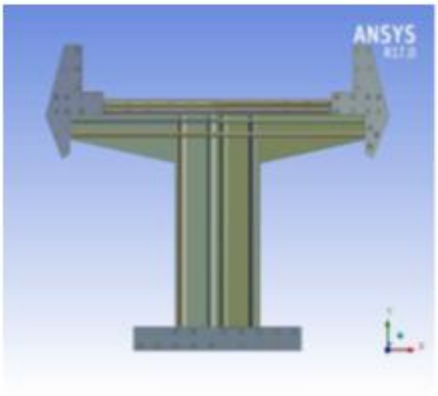


Figure 1. Cross section of bridge model

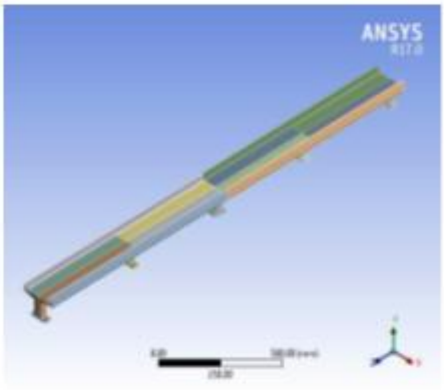


Figure 2. 3D view of the bridge model

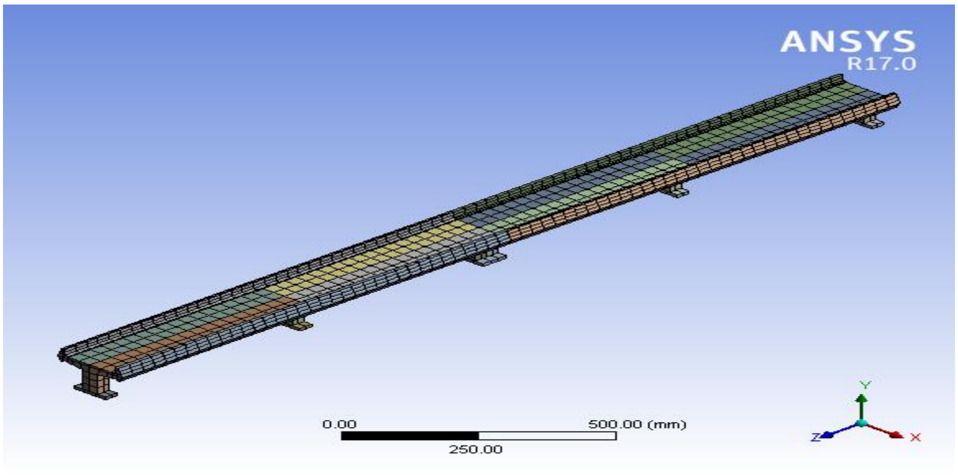


Figure 3. Mesh generation for bridge model

Based on the shape and geometry of the model, ANSYS can automatically select the appropriate meshing size and type for the model. Though the mesh size can be varied from coarse (large mesh) to fine (small mesh), the finer the mesh, the accurate the results. This is because of the number of nodes produced by meshing. Figure 3 depicts the mesh generation for the bridge model. As the number of nodes increases, the number of solutions also increases, thereby resulting into better results (solution). The full bridge consisted of 24,576 nodes.

3.2 Analysis of model

Load case analysis type was selected, which includes modal analysis and transient analysis. For the various analyses, the load considered was 24.11kN (2460 kilogram) which is the average weight of a Large Truck or SUV (sport utility vehicle).

3.2.1 Modal analysis

To evaluate the vibration frequency, modal analysis was carried out on the ANSYS software, based on the subspace iteration as developed from Rayleigh - Ritz method and power method, which is now very efficient in solving large scale structure with little order of vibration frequency and mode [12].

Equations (1) and (2) show the maximum kinetic energy T_{max} and potential energy V_{max} of a system for a given frequency of vibration, ω.

$$T_{max} = \frac{1}{2}\omega^2 \phi^T M \phi \tag{1}$$

$$V_{max} = \frac{1}{2}\phi^T K \phi \tag{2}$$

From $T_{max} = V_{max}$

$$\omega^2 = \frac{\phi^T K \phi}{\phi^T M \phi} = \frac{k^*}{m^*} = \mathrm{R} \tag{3}$$

Where R was the Rayleigh traders. If the given vibration mode is the exact value of the system’s i-order vibration mode, the result would give the exact value of ω_i^2; if the given mode shape, ϕ is similar, the result could only give an approximation of the frequency.

3.2.2 Transient analysis

Transient analysis is based on equation 4, which is motion equation for N degrees of freedom for a linear system.

$$[\mathrm{M}]\ddot{\mathrm{x}}(\mathrm{t}) + [\mathrm{C}]\dot{\mathrm{x}}(\mathrm{t}) + [\mathrm{K}]\mathrm{x}(\mathrm{t}) = \mathrm{f}(\mathrm{t}) \tag{4}$$

Where [M] is the mass matrix,
[C] Is the damping matrix, and

[K] Is the stiffness matrix.

4 RESULTS AND DISCUSSION

4.1 Static analysis of the bridge

The maximum deflection of a bridge is given by, $\frac{L}{800}$, where L = 18,000mm and it is the span of the bridge. This implies that the maximum deflection experienced by the bridge should not exceed the allowable as given by BS1180 [13]. Figure 4 shows the maximum deflection/ deformation as depicted by the simulation. The maximum deflection was found to be 2.8974mm. This is less than, $\frac{L}{800} = \frac{18000}{800}$, = 22.5mm.

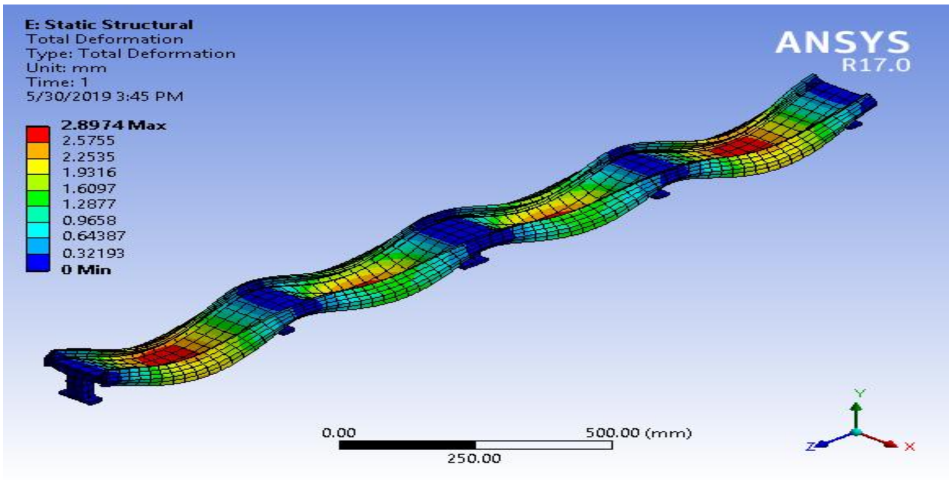


Figure 4. Maximum deformation/deflection

4.2 Results of modal analysis

Modal analysis is the process of determining the inherent dynamic characteristics of a system in forms of natural frequencies, damping factors and mode shapes. In this study, the focus was mainly on natural frequencies and mode shapes. Figure 5 shows the various inherent dynamic responses with respect to natural frequencies and mode shapes.

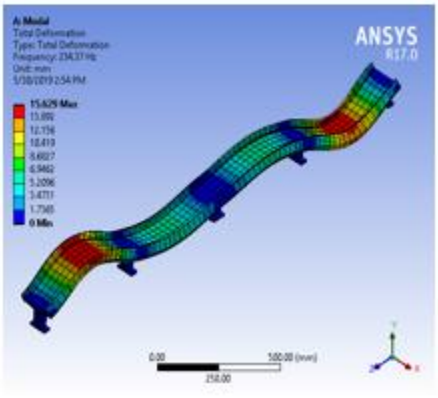


Figure 5a. Failure Mode 1

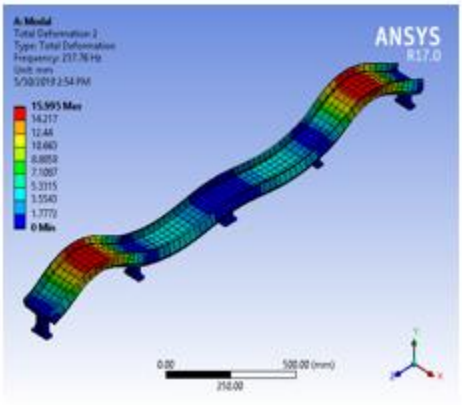


Figure 5b. Failure Mode 2

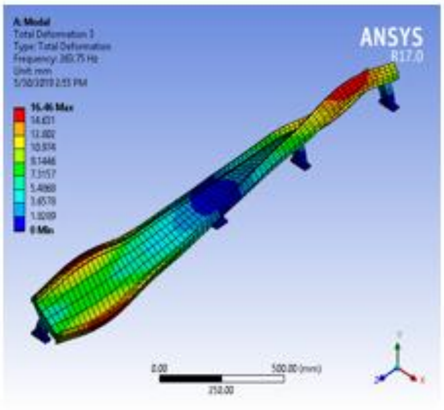


Figure 5c. Failure Mode 3

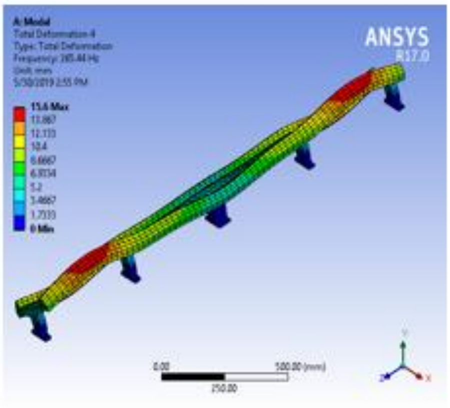


Figure 5d. Failure Mode 4

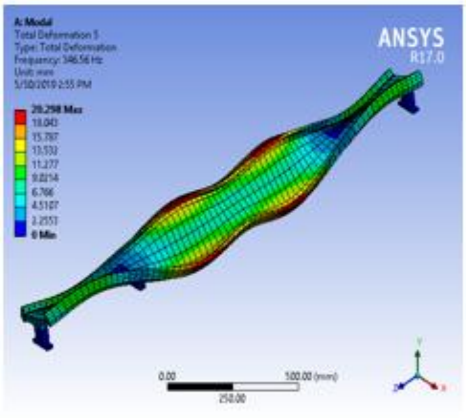


Figure 5e. Failure Mode 5

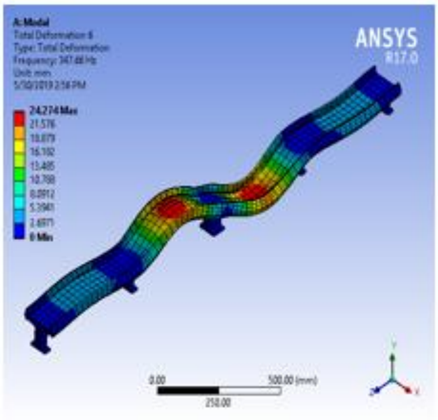


Figure 5f. Failure Mode 6

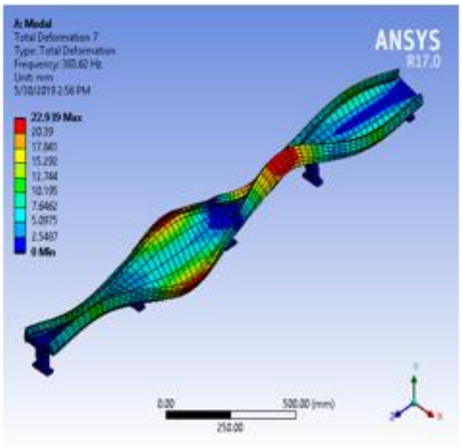


Figure 5g. Failure Mode 7

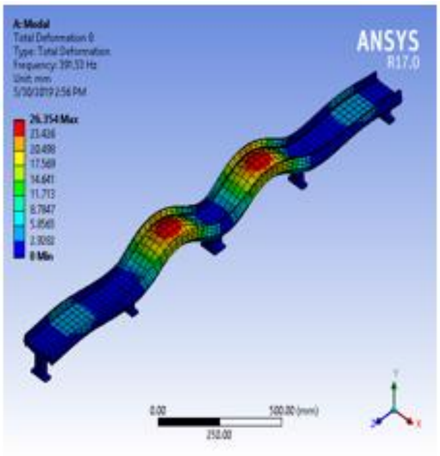


Figure 5h. Failure Mode 8

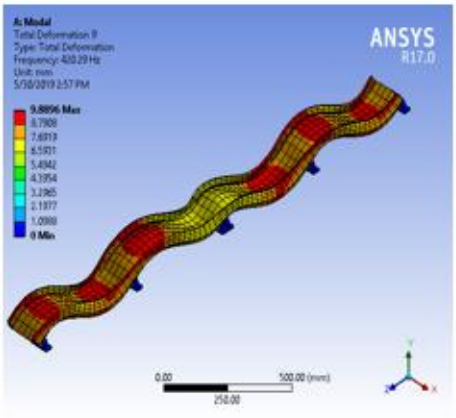


Figure 5i. Failure Mode 9

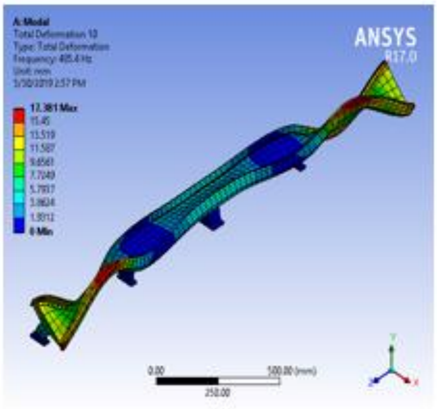


Figure 5j. Failure Mode 10

It must be noted that Figures 5a,5b,5f,5h,5i,5n and 5o show the failure mode of the bridge with respect to dynamic movement of a car, that is, the action of the force of the vehicle with respect to the natural frequency off the bridge. Mode 8 (Figure 5h) has the maximum deformation/deflection of 26.354mm before total failure occurs which is at the two central spans of the bridge considered.

Figures 5c, 5d, 5e, 5g, 5j, 5k,5l and 5m show the modes of failure due to ground movement and wind force under severe conditions, and it can be seen that the maximum deformation/deflection sustained in this modes of failure is at mode 13 (fig 5m) having deformation of 21.624mm.

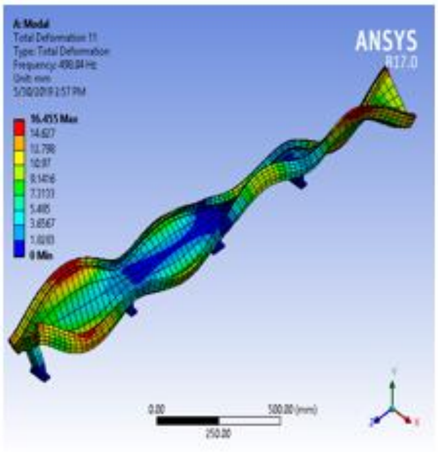


Figure 5k. Failure Mode 11

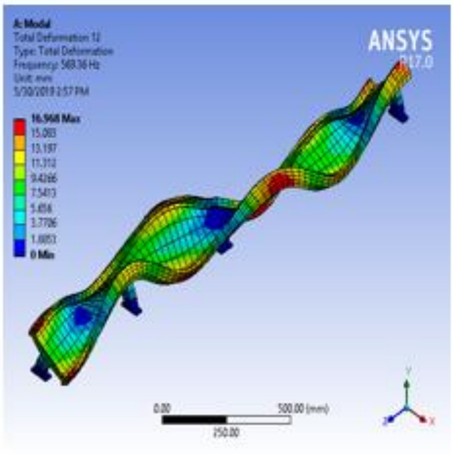
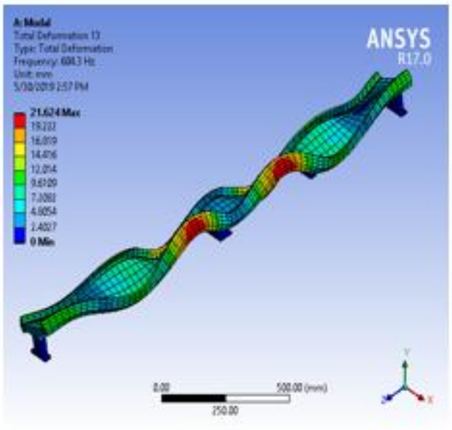


Figure 5l. Failure Mode 12



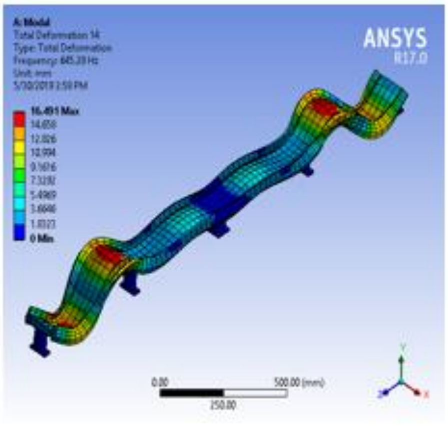


Figure 5m. Failure Mode 13

Figure 5n. Failure Mode 14

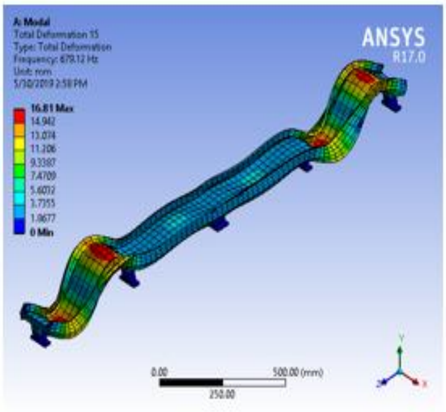


Figure 5o. Failure Mode 15

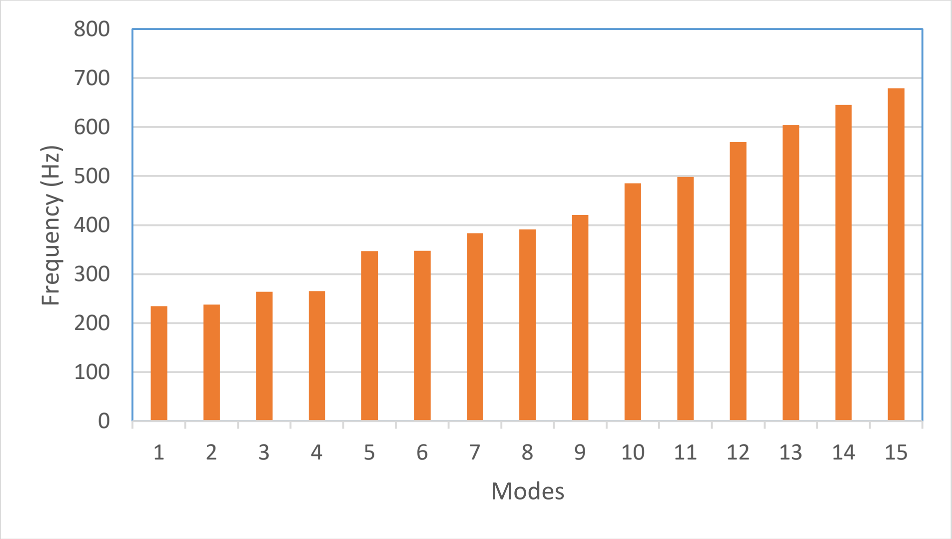


Figure 6. Frequency at each mode

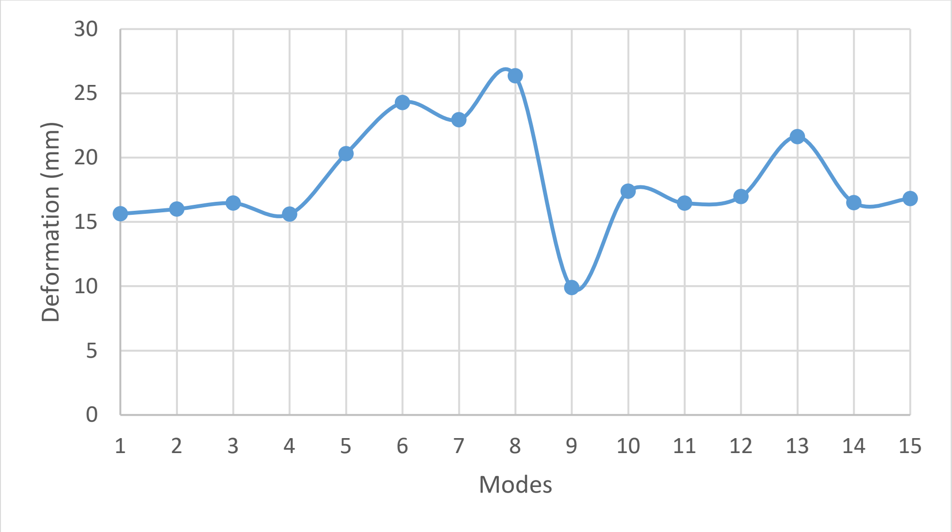


Figure 7. Relationship of deformation to number of modes

This is as a result of the twist of the bridge through the action of ground vibration and high speed winds, which can lead to easy collapse of the bridge. Although in Nigeria, ground vibrations like earthquakes, tremors and high speed winds are not common, but the recent seismic activities in Nigeria, has shown that Nigeria is not immune to such disasters and as such civil engineers must put into consideration the resistance of structures to seismic activities. Figure 6 shows the frequency of the various modes of failure, with the last mode (i.e mode 15) having the highest frequency of 679.12. figure 7 gives the relationship between deformation and the various modes, mode 8 shows the highest deformation of 26.354mm, this is reflected in the mode 8 model as a nearly perfect undulating shape.

4.3.2 Result of transient analysis

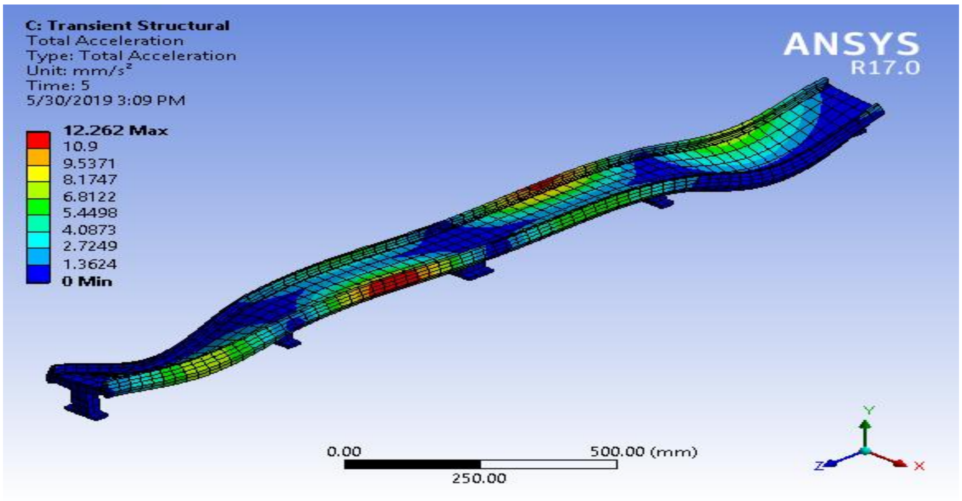


Figure 8a. Transient structural: total acceleration

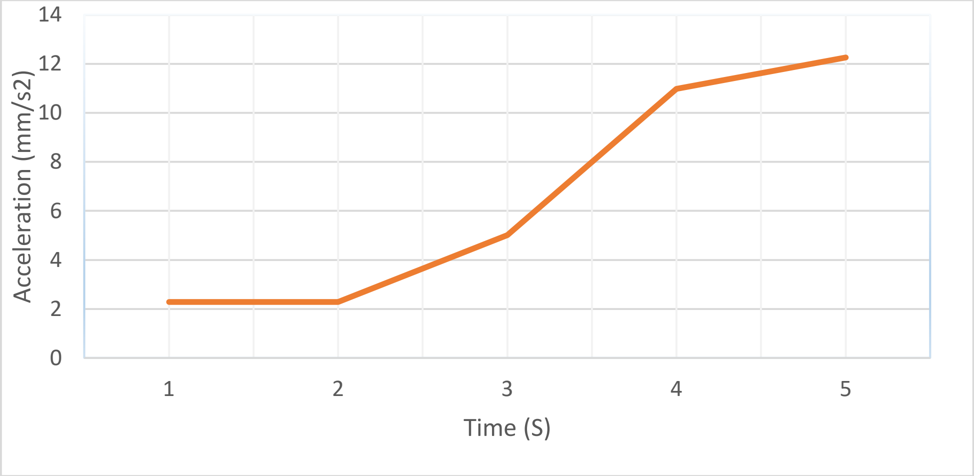


Figure 8b. Relation of acceleration with time of vehicular load on the bridge

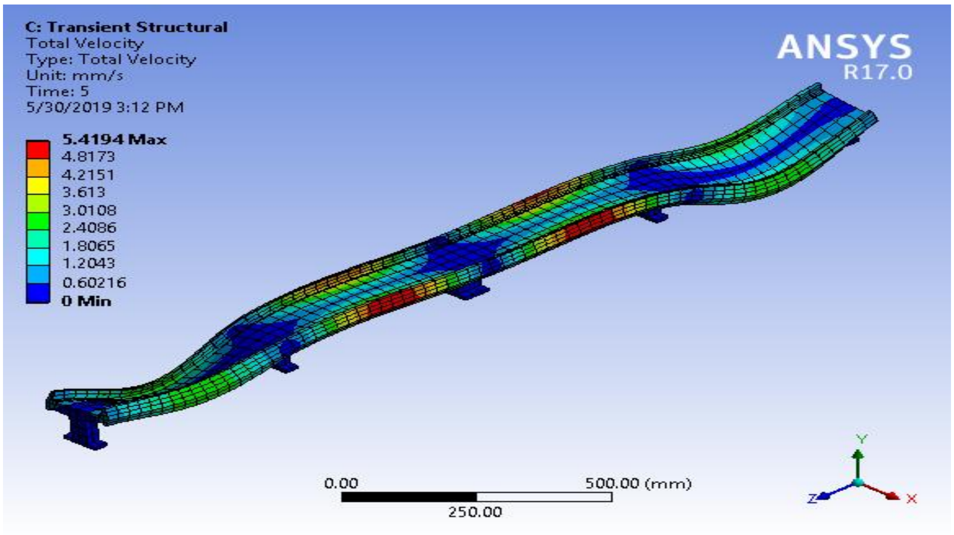


Figure 9a. Transient structural analysis: total velocity

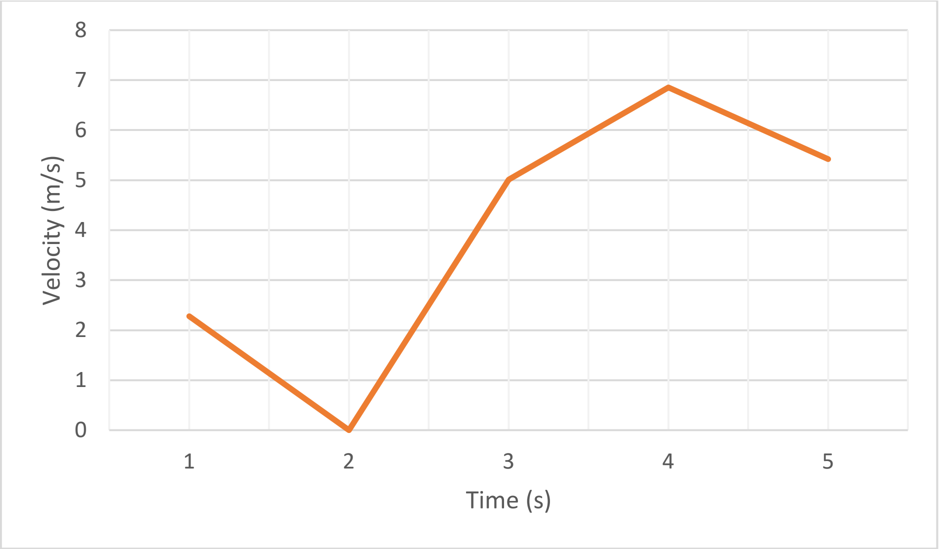


Figure 9b. Relationship of velocity with time of vehicular load on the bridge

Figures 8, 9 and 10 show the acceleration, velocity and stress of the bridge structure, it can be seen that the acceleration is always below the velocity. From the model, maximum deformation or displacements are witnessed at the two extreme ends of the bridge, this is the case for both the acceleration and velocity. From the ends, the velocity is small or rather decreasing so the deformation is large.

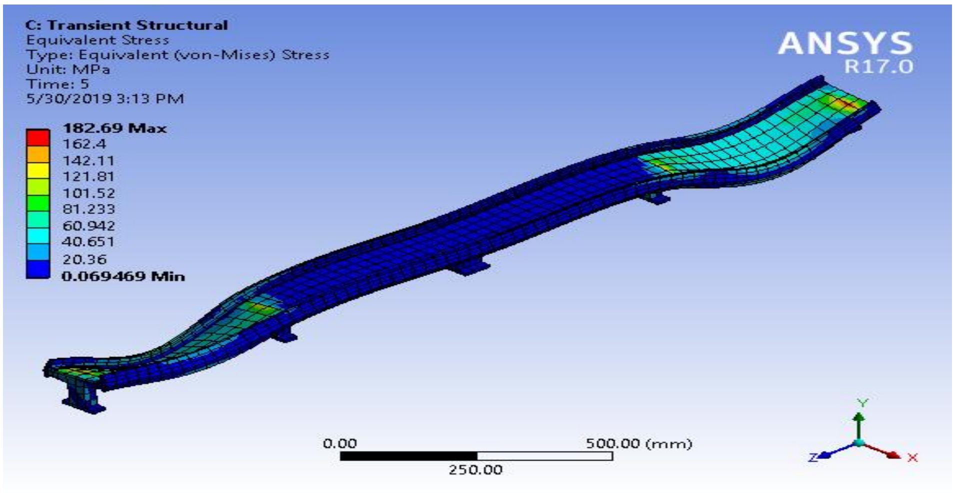


Figure 10a. Transient Structural Analysis: Equivalent (Von-Mises) Stress

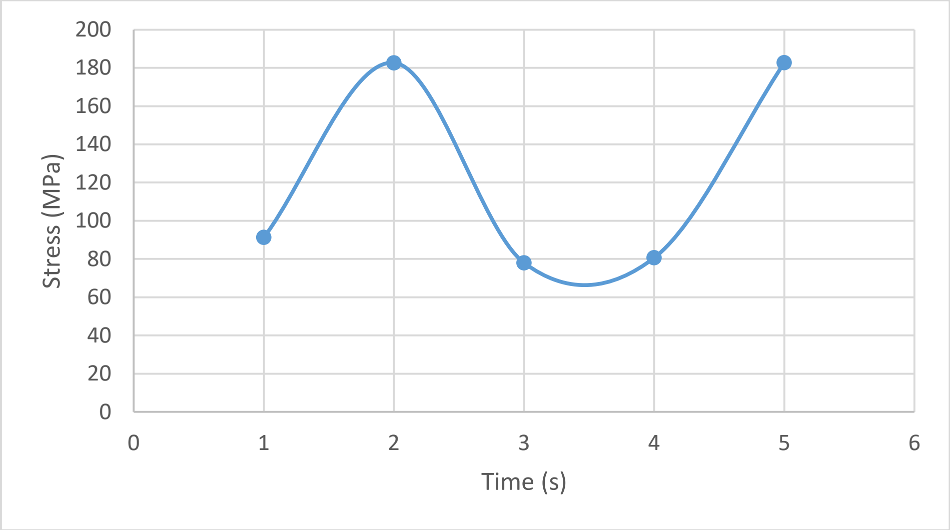


Figure 10b. Relationship of stress to time as developed in the bridge

Upon entering the bridge from both sides, the maximum acceleration and velocity that will yield the deflection is 12.262m/s^2 and 5.4194m/s respectively. While the maximum stress developed within the bridge will be at the entrance and exit, this was found to be182.69MPa.

Considering the stress induced in the bridge structure, the stresses in the two mid spans are 0.069, indicated by the blue colour all over the span. While at the two ends, the model showed some high deformation as indicated by the green, yellow and orange colour. As the velocity began to decrease after about 4 seconds, the stress rose from 80.646 to 182.69MPa. This validates that as velocity on a structure increases the stress decreases and vice versa.

5 CONCLUSION

After the finite element analysis was performed using ANSYS Workbench, the following conclusions were drawn from it

i. Finite element (FE) method as coded in ANSYS software has proven to be a good program for both modelling and analysis of reinforced concrete structures with a fast computational time and user friendly interface
ii. This study resulted in a maximum span deflection of 2.8974mm which is less that the maximum allowable deflection of the bridge span, 22.5mm
iii. The FE of the modal analysis resulted to a maximum deflection/deformation of the reinforced concrete bridge as 21.624mm for sway movement with respective to ground movement and 26.354mm for response of bridge with respect to vehicular movement.
iv. The FE application to the transient analysis resulted in the maximum acceleration, maximum velocity and maximum stress with respective to vehicular movement as 12.262m/s^2, 5.4194m/s and 182.69MPa respectively**.**

REFERENCES

[1] Alka, Y. P., and Jangid, R. S. (2016). Vibration control of bridge subjected to multi-axle vehicle using multiple tuned mass friction dampers. *International Journal of Advanced Structural Engineering (IJASE), Volume 8*(Issue 2,), pp 213–227.

[2] Jansen A.(1996). Research to fatigue behaviour of topping on prefabricated concrete girders. Master thesis, Delft University of Technology, Netherlands., p.128.

[3] Goga, V. (2012). Mechanical vibration on “Structural health monitoring and damage assessment using a novel time series analysis methodology with sensor clustering”. *Journal of Sound and Vibration, 330*((6)), 1196-1210.

[4] Akiije, I., and Omotose, M.F (2012). Lagos Third Mainland Bridge Strengthening Assessment Research *Journal in Engineering and Applied Science*, Vol.1, (No.3), pp. 197-203.

[5] Willis, R. (1867). Extracts from the appendix of the report of the commissioners appointed to inquire into the application of iron to railway structures. In Barlow, P. A treatise on the strength of materials. 6th ed., 326-386

[6] Zhang, X., Liu, S., Yan, C., Wang, X., & Wang, H. (2019). Effects of vehicle-Induced vibrations on the tensile performance of early-Age PVA-ECC. Materials, 12(17), 2652.

[7] Ja’e. I.A., Abubakar, I. and Abejide, O.S (2018). Vibration analysis of vertically curved reinforced concrete flyover bridges: analytical model study. *Jordan Journal of Civil Engineering, Volume 12, No. 2*

[8] Lakshmi, G. P. (2017). VIBRATION TEST ON R MODEL FOR CONDITI. International Journal of Civil Engineering, 8(3).

[9] Osumeje, T.U. (2016). “reliability analysis of reinforced concrete bridge decks subject to fatigue”.*OpenAir@ABU.* dissertation of Ahmadu bello University.

[10] Huth, O., Feltrin, G., Maeck, J., Kilic, N., and Motavalli, M. (2005). “Damage identification using modal data: experiences on prestressed concrete bridge.” *Journal of structural engineering, 131(12),*, 1898-1910.

[11] Subramani, T., Manivannan, R., & Kavitha, M. (2014). Crack identification in reinforced concrete beams using ANSYS software. International Journal of Engineering Research and

Applications, 4(6), 133-141.

[12] Ge, Shuzhi Sam, Shuang Zhang, and Wei He. (2011) "Vibration control of an Euler–Bernoulli beam under unknown spatiotemporally varying disturbance." International Journal of Control 84.5 947-960.

[13] British Standards Institution. (1997). BS 8110 Structural Use of Concrete, Part. 1. Code of Practice for Design and Construction.