Case Study

Analysis of a Fiber-Reinforced Bridge Structure Under Dynamic Loading and Thermal Conditions With Ansys Composite PrepPost

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Ansys Software Used

This resource uses Ansys Mechanical™structural finite element analysis software and Ansys Composite PrepPost (ACP).

Summary

The case study investigates the responses of a hollow core Fiber-Reinforced-Polymers (FRP) bridge deck panel with steel girder under transient dynamic load due to the traversal of vehicles on the deck. The detailed study of behavior of FRP deck due to temperature difference between top and bottom surface of the deck is carried out in Ansys Mechanical software and its dedicated composite analysis tool Ansys Composite PrepPost (ACP).

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1. Introduction

1.1 Fiber Reinforced Plastics

Innovation of advanced fiber reinforced plastic (FRP) material has sparked a revolution in the contemporary technology applied to real life structures. In fact, the industry is increasingly focusing on the use of composite materials with aerospace being at the forefront, however, FRPs are also increasingly found in consumer goods [1]. The assembly of layers of fibrous materials (also known as plies) are stacked in a certain way to achieve a specified strength and stiffness criteria to form a composite laminate (Figure 1).

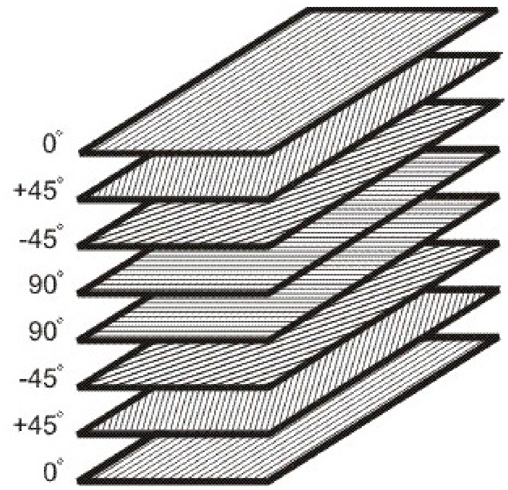


Figure 1: Stacking of plies in composite laminate with different fiber orientation. Displayed here is a quasi-isotropic stacking sequence with the following notation considering its symmetry [90/-45/+45/0]S.

The introduction of decks made predominantly with FRP laminated composite materials are gradually gaining acceptance from civil engineers and has added considerable momentum in the past few decades with successful installation of several composite bridges around the world. The reasons for the wide acceptance are due to several advantages of using FRP over other traditional construction materials. FRPs possess properties like reduced dead load, better weather and corrosion resistance, low thermal conductivity, low coefficient of thermal expansion, radar transparency, non-magnetic, high impact strength, high dielectric strength (insulator), part consolidation, tailored surface finish, ability to be molded into various shapes, low maintenance cost etc. For further background information on composite materials, the reader is kindly referred to the following resources:

1. Understanding Composite Materials | Ansys Innovation Courses
2. Understanding and synthesizing composite material properties: The Synthesizer Tool in Ansys Granta EduPack
3. Understanding the fundamental concepts behind composite shell structures : Theory of Composite Shells | Ansys Courses
4. Understanding the mechanics of FRPs: Mechanics of Fiber Reinforced Polymer Composite Structures | Ansys Courses

1.2 Problem description

The transient dynamic response analysis of glass FRP deck panel with steel girder is carried out for two lane traffic using Ansys Mechanical software. The class B load as per IRC 6:2017 [2] is applied as vehicle load. The wheel loads are modeled as point loads on the deck surface. The deck-girder model with traffic directions is shown in Figure 2. The thicknesses of web and flanges of the girders are taken as 50 mm. The dimensions not mentioned in the current section is varied and the information is included in the relevant subsections under 'Postprocessing' section. The thermal analysis of the deck-girder panel is also carried out at different temperature conditions, whereby the ambient temperature is as assumed to be 20°C. The model is analyzed due to uniform temperatures of 40°C, 60°C and 80°C at the top plate. Two temperature variation cases are also considered (i) uniform variation from 60°C at the top plate to 20°C at the bottom plate and (ii) uniform variation from 20°C at the top plate to 60°C at the bottom plate. The temperature dependent material properties for GFRP are displayed in Table 1. The coefficients of thermal expansion along three principal directions are α_1=α_2=8.6×10^{-6}/°C and α_3=22.1×10^{-6}/°C.

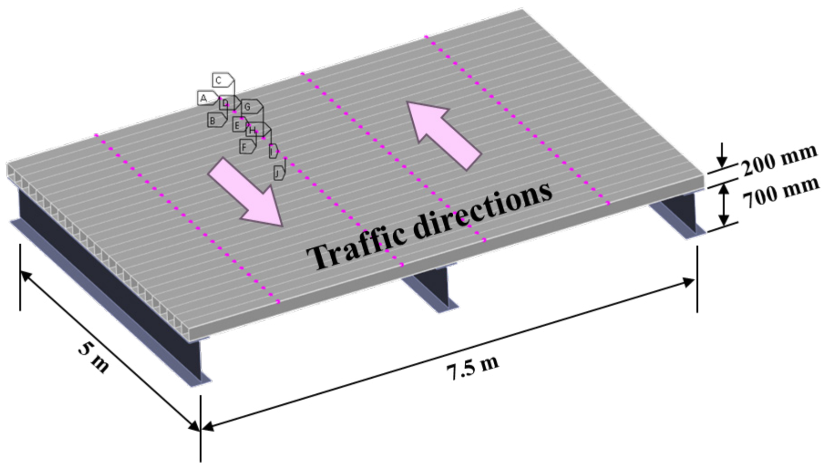


Figure 2: FRP deck steel girder panel dimensions and traffic loads (details see Section 2.2.2 and 2.2.3).

Table 1: Temperature dependent Material Properties for Bi-directional GFRP.

	Material properties									
T (ºC)	*E_1 (GPa)*	*E_2 (GPa)*	*E_3 (GPa)*	*v_{12}*	*v_{23}*	*v_{13}*	*G_{12} (GPa)*	*G_{23} (GPa)*	*G_{13} (GPa)*	*ρ (kg/m³)*
20	30.4	30.4	9.95	0.247	0.301	0.301	3.99	11.7	11.7	2064
40	30.08	30.08	9.87	0.247	0.301	0.301	3.72	11.5	11.5	2064
60	27.86	27.86	9.21	0.246	0.301	0.301	3.69	10.61	10.61	2063
80	22.08	22.08	8.34	0.243	0.3	0.3	3.12	9.5	9.5	2062
100	18.72	18.72	6.83	0.237	0.297	0.297	2.98	8.42	8.42	2058
120	15.0	15.0	5.12	0.232	0.291	0.291	2.69	7.33	7.33	2055

2. Preparing the problem in Ansys Workbench Tool

The model's project schematic, comprised of the component system ACP (Pre) and the analysis systems for the static and transient analyses, is displayed in Figure 3. The geometry and the laminate layup are transferred from the ACP (Pre) to the analysis systems with their individual pre- and post-processing steps. It must be noted that for the transient analysis the thermal loads of the static structural analysis are considered and are thus also linked.

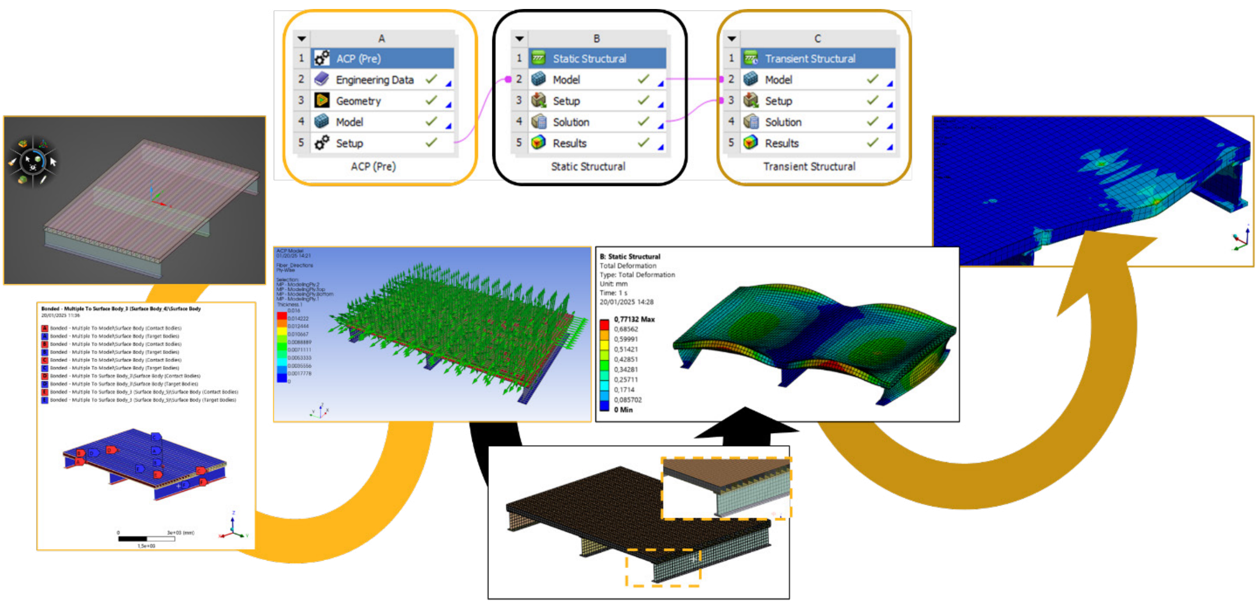


Figure 3: Project schematic in Ansys Workbench tool combining the Ansys ACP component system with the Ansys Mechanical analysis systems for static and transient structural analysis.

2.1 Preprocessing

The preprocessing part is carried out in Ansys Composite PrepPost (ACP) tool to model the composite laminates. The GFRP material properties from Table 1 is entered in the 'Engineering data' section manually.

2.1.1 Preparing the geometry

The GFRP deck steel girder panel is modeled in Ansys Discovery software as shown in Figure 4. The length of the deck panel is chosen as 5 m. The width of the deck panel is chosen considering the minimum width criteria for two lane bridge as per IRC 6:2017 [2].

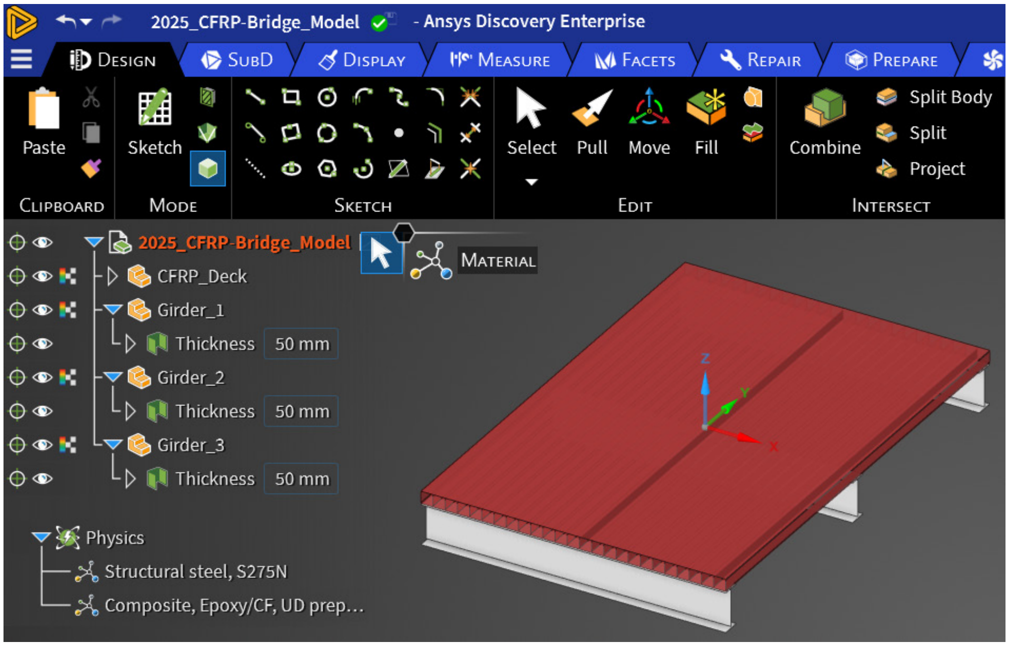
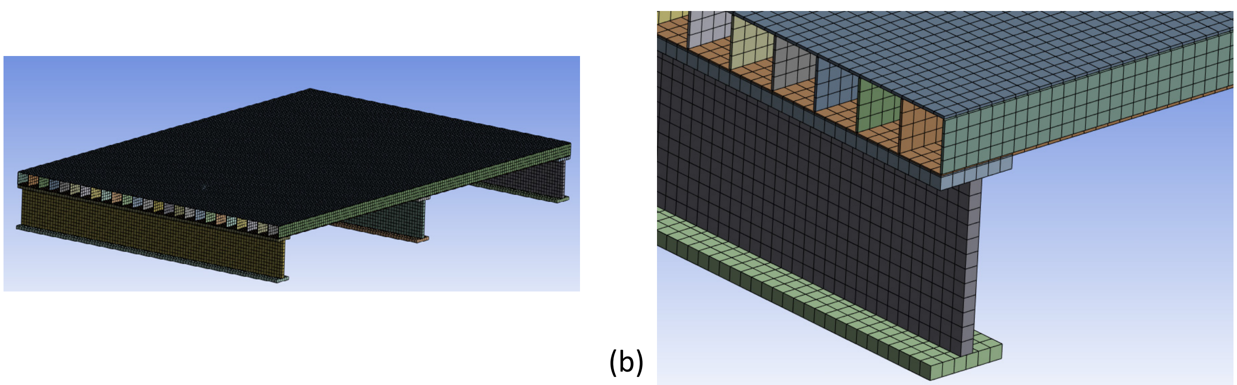


Figure 4: CAD model of the FRP bridge, comprised of surfaces, shown in Ansys Discovery tool.

2.1.2 Meshing

The meshing of the deck model with and without girder is generated using SHELL281 element [3] with element size of 0.1 m as shown in Figure 5. A fully structured mesh with 13200 quadratic elements is generated. The different parts of the model are appointed as different 'Named Selections', e.g., Top, Bottom, -X, +X, GirderFlange and GirderWeb.

(a)



(b)

Figure 5: The discretization of the deck panels, showing (a) the meshed deck panel and (b) the zoomed in view with 'thick' shell elements.

2.1.3 Connections between different parts

The top and bottom plates of the deck are connected to the stiffeners with bonded connection using Multipoint Constraint formulation. The 'Pinball Radius' is taken as 0.1 m (same as the mesh size). Similarly, the bottom plate of the deck to the top flange of the girder and the girder flanges to the web are connected.

2.1.4 *Modeling the composite laminates in Ansys ACP tool setup*

The generation of composite laminates in the top, bottom and stiffener plates of the deck by stacking the laminae is done in Ansys ACP tool. The first step is to create the ply fabric (lamina) of required thickness using the GFRP material property inserted in the 'Engineering data' section. Then the stackup (laminate) is created by stacking the required number of fabrics (20 are chosen here) along specific fiber directions (0°/90°/… anti-symmetric). The Element sets are automatically created as per the Named Selections created in the 'Meshing' section. After that different Rosettes are created as specific coordinate system required for the model parts. The 'Oriented Selection Sets' are created different 'Element Sets'. The final step in this section is to create 'Modeling Ply' for each part of the model using corresponding 'Oriented Selection Set' and 'Stackup'. The fiber orientations for different components of the deck are shown in Figure 6.

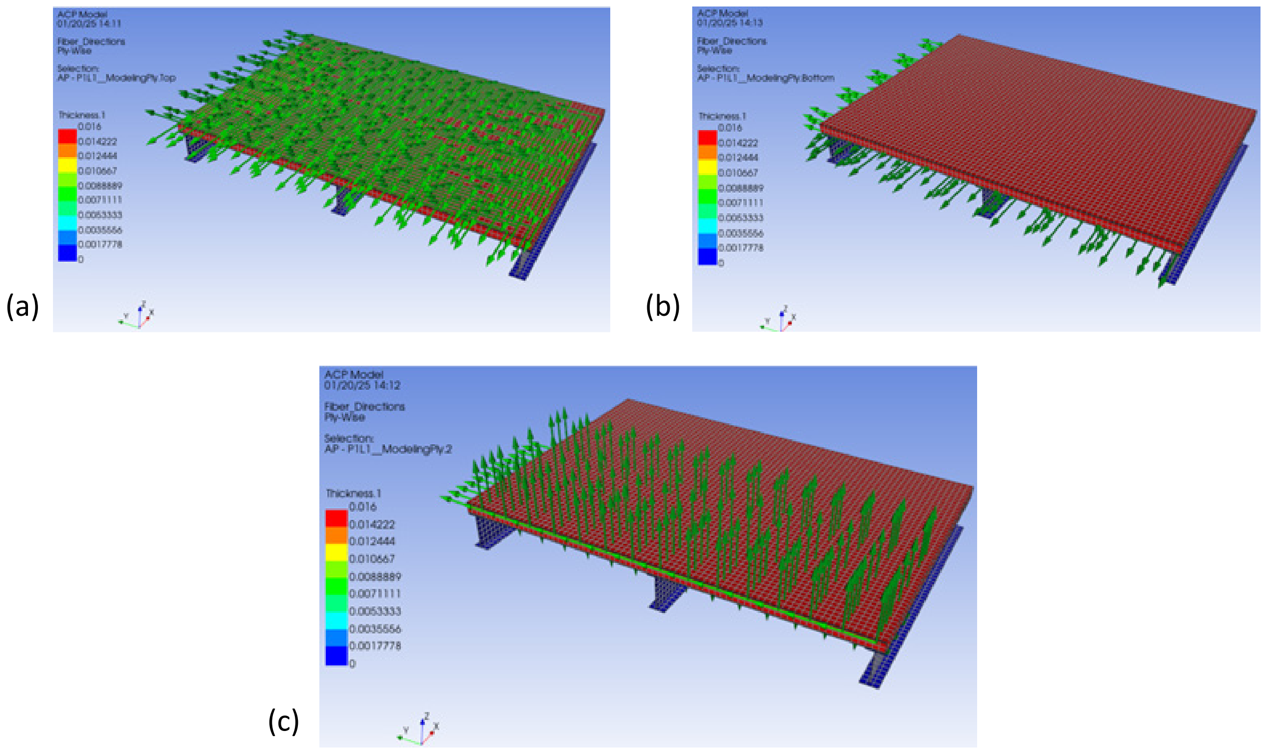


Figure 6: Fiber orientation in (a) the top plate, (b) the bottom plate and (c) the stiffeners of the deck, including a thickness color plot.

After setting up the 'Modeling Plys', Ansys ACP tool allows users to sanity-check the layup and assess the laminate performance such as its stiffness and compliance matrix or the engineering constants, as shown in Figure 7.

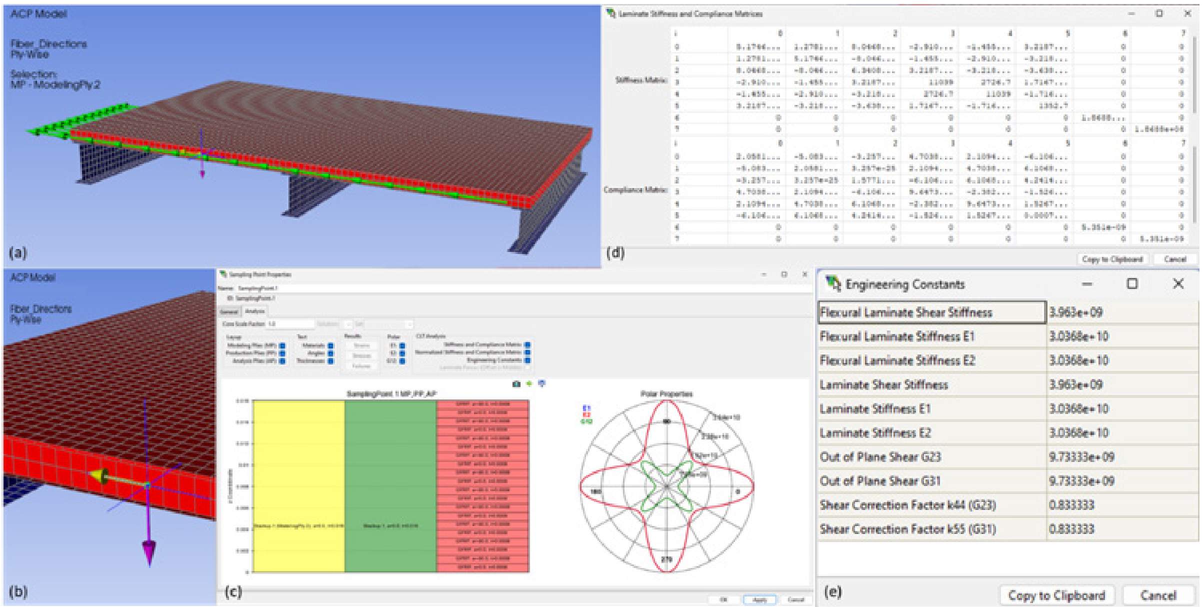


Figure 7: (a) Modeling ply fiber orientation and (b) sampling point within the deck structures, allowing the visualization of the (c) composite layup and assessment of its properties such as (d) laminate stiffness and (e) engineering constants.

2.2 Processing

The next step is to perform the transient dynamic analysis of the deck-girder model under gradient thermal environment. This is a two-step procedure. First, the model is analyzed under thermal environment in the 'Static Structural' analysis system. Then the temperature effect is imported to a 'Transient Structural' analysis system to evaluate the combined effect of the vehicle load under thermal environment. The thermal deflection from the 'static structural' system and the deflection profile under ambient temperature from 'transient structural' system is also evaluated.

2.2.1 Brief Procedure

The shell composite data from the Setup of the Ansys ACP section is imported to the 'Static structural' analysis system. The environment temperature is set as 20°C in the 'static structural' system. The Boundary conditions and the 'thermal condition' is inserted. The 'thermal condition' may be varied as described later in the study. The thermal deformation may be obtained for each case from the 'Directional Deformation' in the results section. The 'Model' and 'Solution' section of the 'Static structural' is imported to a new 'transient structural' system. This action imports the effect of thermal condition as an 'Imported Body Temperature Submodeling'. The values of the 'step end time' and 'time steps' are inserted in the 'Analysis settings' of transient system. The connection between 'static' and 'transient' systems does not import the boundary condition. Thus, the boundary condition and the moving loads are added to the 'transient' system. The resulting solution gives the deflection profiles of the deck-girder model under thermal condition.

2.2.2 Static Structural analysis system

Before starting the analysis validation of the static structural analysis under thermal environment needs to be carried out. A laminated FRP deck panel of dimensions 4000×1000 mm with four unidirectional laminae [0°/90°/90°/0°] for the top and bottom plate and eight laminae [0°/90°/90°/0°/0°/90°/90°/0°]

for intermediate stiffeners has been considered to validate the thermal deflection analysis. The deflection due to uniform thermal load is presented in Table 2 and compared with Sit & Ray [4] which shows quite a good agreement.

Table 2: Deflection of deck panel at the mid-point under uniform thermal load.

Temperature (°C)	Directional Deformation in Z-Direction [mm]	
	Present Study	Sit & Ray [4]
40	2.543	2.724
60	3.814	3.661

The laminated deck plates made of 20 layers with varying fiber orientations are considered for the present study. The ambient temperature is considered as 20°C. The analysis is performed for i) increment of uniform temperature at top surface varied from 40°C to 80°C, ii) differential temperature with 60°C at top and ambient temperature at bottom and iii) ambient temperature at top and 60°C at bottom surface. The laminates are modeled with 20 bi-directional laminae of thickness is 0.8 mm. The element size is considered as approximately 100 mm (default mesh settings applied) for computing the results with adequate accuracy. The simply supported boundary conditions (one end hinged and other end roller) are provided at the ends of the girders. The application of various types of thermal loads may be visualized from Figure 8.

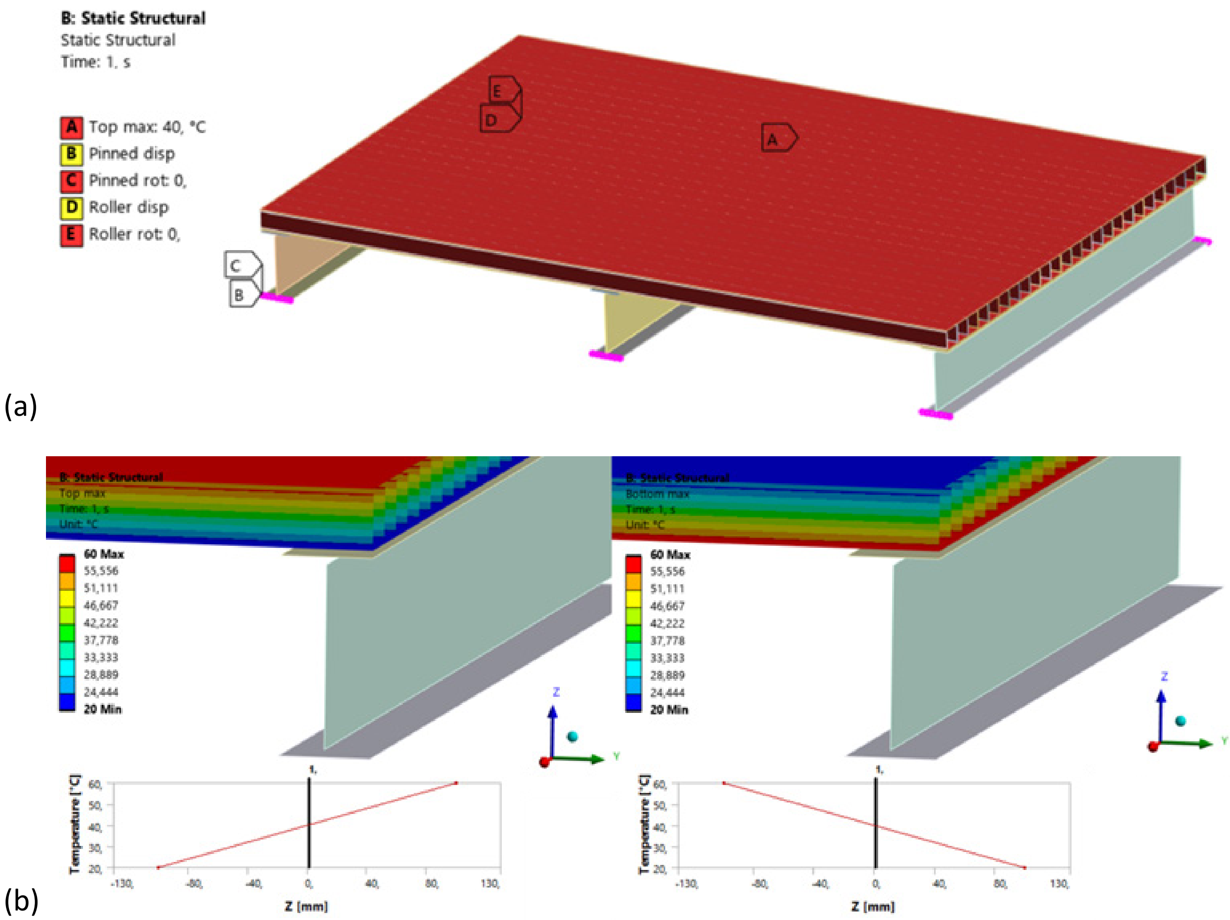


Figure 8: Static structural boundary conditions and thermal load profiles for different cases.
(a) Static structural boundary conditions with a thermal load applied uniformly at the top surface of top plate and pinned and roller supports at the girder edges.
(b) 60°C at top (left) and bottom (right) of the deck with ambient temperature at opposite surface

2.2.3 Transient Structural analysis system

The formulation of moving load in the simulation has been validated from the data obtained from Li and Zhang (2020) [5]. The bridge deck has been modeled as a beam. A bridge deck of length 20m, flexural rigidity EI=10^9 Nm^2 and mass per unit length =3000 kg/m is considered. A single point load of 0.6 ton is moved on the deck at a speed of 100 kmph. The deflection time history curves at the midspan obtained from the literature and the Ansys simulation are compared in Figure 9. Two deflection curves show very good agreement with each other. The average deviation is about 7.3%.

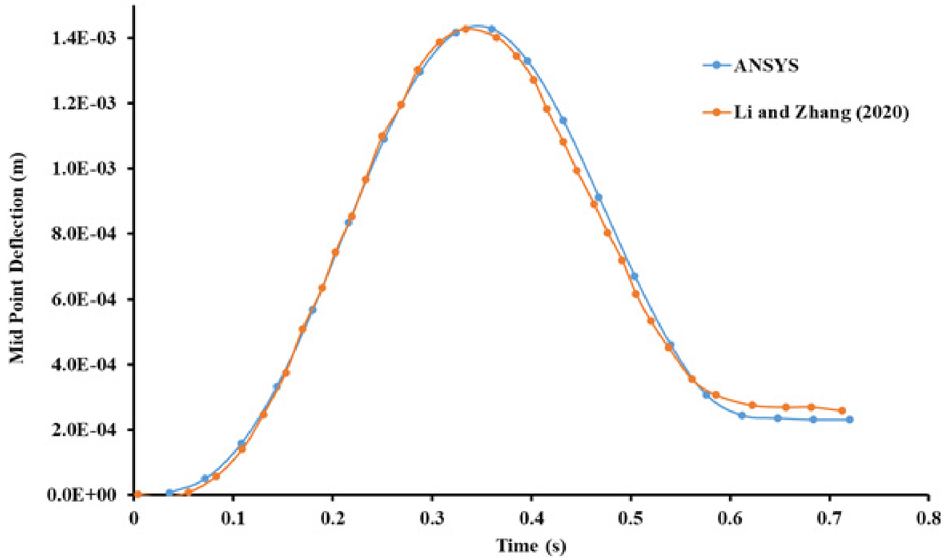


Figure 9: Comparison of time history curve of midspan deflection with scientific literature [5].

An extensive parametric study of the deck is carried out by varying different parameters of the deck and vehicles. The following parameters are considered for the present study:

1. Varying the spacing of the stiffeners
2. Varying the depth of the deck (d in mm)
3. Varying the laminate thickness and speed of the vehicle

2.3 Postprocessing

2.3.1 Thermal deflection

It may be observed from Table 3 that the maximum deflection of deck under differential temperature is of higher magnitude when compared with the conditions of uniform temperature. For all the thermal load cases, the deflection is less for laminates with angle ply fiber orientations (θ/-θ…) than the cross-ply laminates (0°/90°/…). Moreover, the deflection is maximum under thermal load case 4 as observed from Table 3. Figure 10 describes the deflection profiles of the deck under the effects of various thermal load cases. The deflection profiles of the deck do not vary significantly with the change in fiber directions.

Table 3: Deflection of the deck in mm under different thermal load cases with varying fiber orientations

Case	Temperature profile	Fiber orientation			
		(0°/90°/..)	(45°/-45°/..)	(30°/-30°/..)	(15°/-15°/..)
1	Uniform 40°C at top surface of deck	0.029	0.0268	0.0268	0.0273
2	Uniform 60°C at the top surface of deck	0.057	0.0520	0.0519	0.0530
3	Uniform 80°C at the top surface of deck	0.076	0.0711	0.0708	0.0724
4	60°C at top surface and ambient at bottom surface	1.24	1.200	1.210	1.240
5	60°C at bottom surface and ambient at top surface	1.215	1.02	0.992	1.080

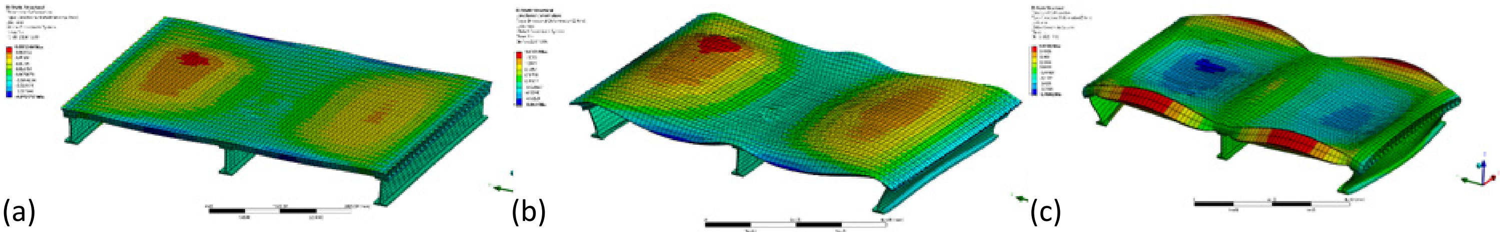

(a) (b) (c)

Figure 10: Typical deflection profiles of the deck with cross-ply laminates under the thermal load case (a) 2, (b) 4 and (c) 5.

The Von-mises stresses due to different temperature load cases have been described in Table 4 for cross ply laminated deck. It can be observed that the maximum stress occurs in the stiffeners near the edge for all the thermal load cases.

Table 4: Temperature-induced stresses in stiffeners in MPa.

Thermal loading Cases	Middle stiffeners	Edge stiffeners
60 °C Uniform at the top surface of the top plate	0.467	0.851
60 °C at top surface and ambient at bottom surface	12.027	20.369
60 °C at bottom surface and ambient at top surface	15.495	17.074

The behavior of the stiffeners under different thermal load cases is shown in Figure 11. The basic behavior remains same for all the cases.

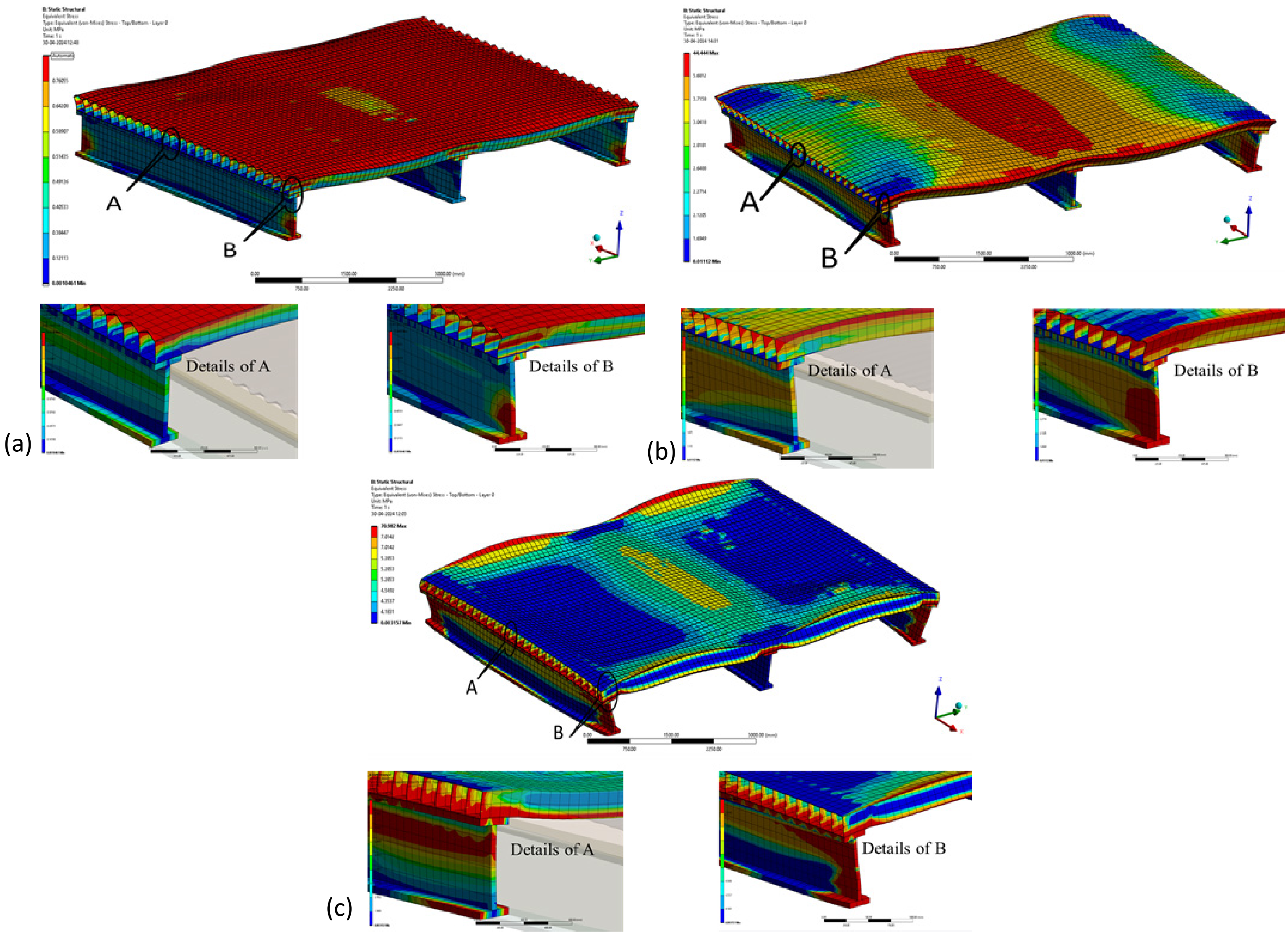


Figure 11: Stress contour of the middle and edge stiffeners under
(a) 60 °C uniform loading at the top surface of the top plate,
(b) 60 °C at top surface and ambient at bottom surface of deck and
(c) 60 °C at bottom surface and ambient temperature at top surface of deck.

It can be observed from Fig. 11 (a) that the application of uniform temperature on the top surface of the deck plate causes maximum stress at the junction of the top plate and the intermediate stiffeners near the middle span of the deck and the maximum stress at mid-depth near the girder support for edge stiffeners. From Fig 11(b), it can be noted that maximum stress occurs at the junction of the top plate for stiffeners when the deck is subjected to differential temperature maximum at top and minimum at bottom of the deck plate. Whereas reverse phenomenon prevails for differential temperature with maximum at bottom and minimum at top of the deck plate. Fig 11(c) shows that maximum stress occurs at the junction of the bottom plate and the stiffeners irrespective of position.

2.3.2 Transient Dynamic Analysis

2.3.3.3 Varying the stiffener spacing

This study is carried out by varying the spacing between the deck stiffener and keeping other parameters constant. For further information on parametrization of you CAD model for design exploration, the reader is kindly referred to:

1. Parametrization Basics
2. Parameterization — Lesson 4 | ANSYS Innovation Courses
3. Parametric Analysis and Optimization | Ansys Courses

Laminates of antisymmetric cross ply having 20 layers are considered for the present study. The velocity of the vehicle for the analysis under moving load is considered as 72 km/h. The Figure 12 depicts the peak deformations and the maximum Von mises stresses for different stiffener spacings of the stiffener under the effect of moving load. The peak deformation and the maximum stress in the system increase with the increase in stiffener spacing as the stiffness of the deck reduces.

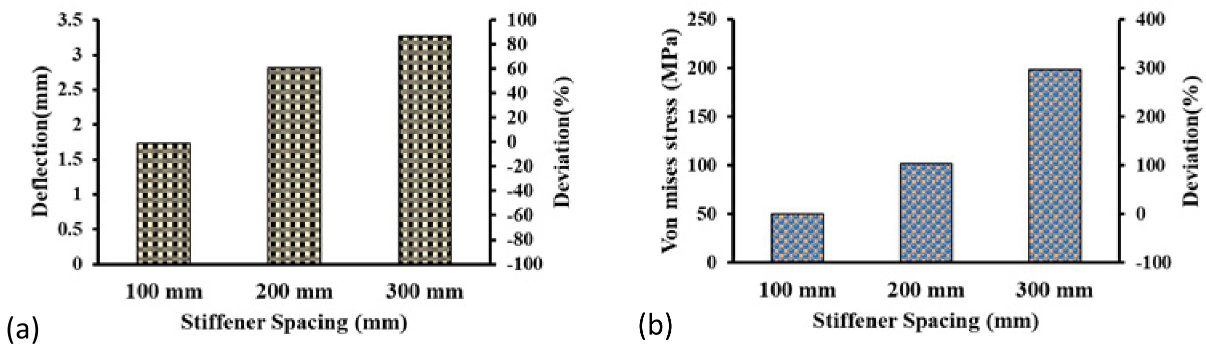


Figure 12: (a) Peak deformation and (b) maximum Von Mises stress responses of the deck with varying stiffener spacing under vehicle load

2.3.4.4 Varying the depth of the deck

This study is carried out by changing the depth of the stiffeners provided in the deck and other parameters remaining constant. The laminates having 20 layers with antisymmetric cross ply lamination scheme are used. Figure 13 shows the peak deformations and the maximum Von mises stresses for varying depth of the deck. The peak deformation and the maximum stress in the system decrease with the increase in the depth of deck. Though the reduction is much more significant between depth 200mm and 250mm. However, the variation becomes insignificant when the depth is increased further beyond 250 mm to 300mm.

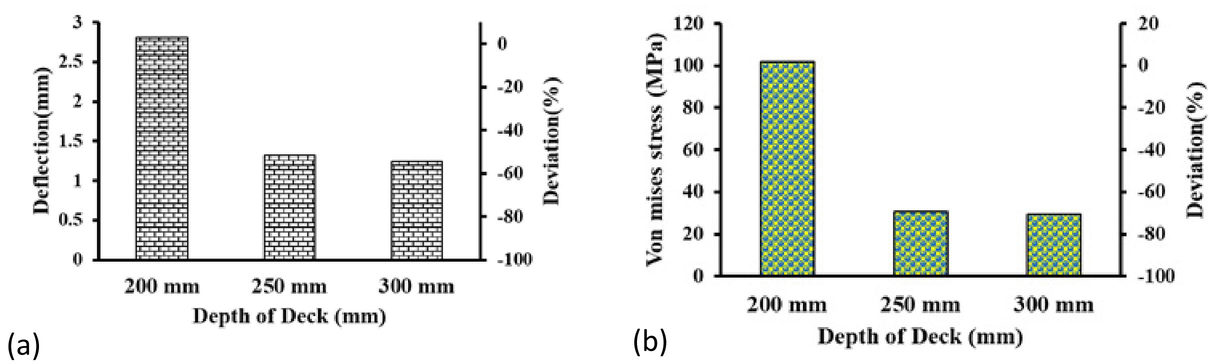


Figure 13: (a) Deformation and (b) pak Von Mises stress responses of the deck with varying depth of the deck under vehicle load.

2.3.5.5 Varying the laminate thickness and speed of the vehicle

The speeds of the vehicles are varied from 36 km/h to 108 km/h. The deck panel is fabricated using laminates of 10 layers and 20 layers of antisymmetric cross-ply (0°/90°/…) with 0.8mm thickness of each lamina. The maximum deflections for each case are evaluated for varying speeds and the variation is shown in Figure 14. The maximum deflection increases and peaks with the increase in the velocity of vehicle up to 72 km/h and a significant reduction is observed thereafter.

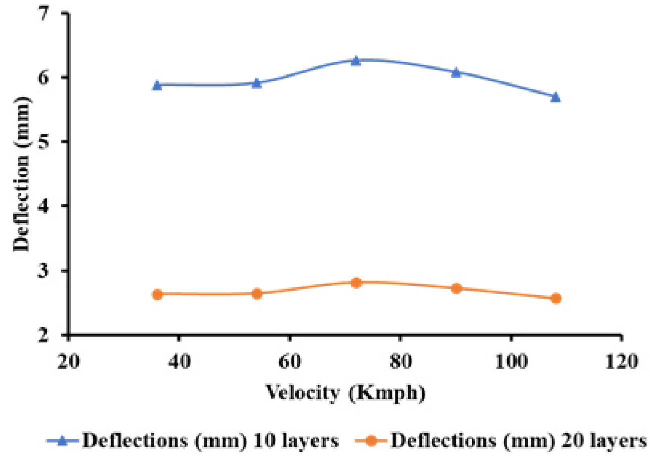


Figure 14: Comparison of deflections for laminates consisting of 10 and 20 layers (different thickness) at different vehicle speeds.

The midpoint deflection profiles for different speeds of the vehicle for laminates with 20 layers are plotted in Figure 15. The maximum deflection occurs when the third and fourth axles enter the deck on both the lanes. The minor depression in the curves after the first peak is due to the introduction of fourth axle on either edge of the deck, which produces a minor upward deflection thus diminishing the peak value. The deflection drops rapidly after departure of the fourth axles from the deck on either lane, thus producing a major trough. A marginal increment of peak is again observed when each of the last four axles of the vehicle enters the deck. It can be observed that the magnitudes of the deflection under vehicles moving with different speeds vary to some extent, however, the overall pattern remains consistent.

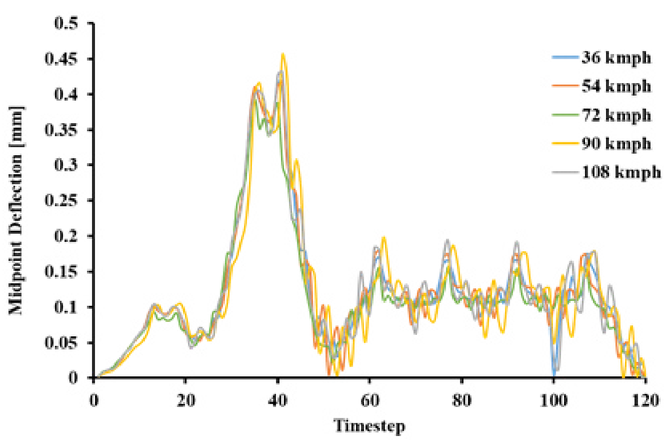


Figure 15: Midpoint deflections of the deck for varying speeds of the vehicles.

The time history for the maximum equivalent stress on the deck for different speeds of the vehicle are plotted in Figure 16. The maximum stress on the deck occurs when the third and fourth set of wheels enter the deck on both the lanes. The four peaks on the plate are due to arrival and departure of the third and fourth axles. The stress diminishes rapidly after departure of these heavier axles from the deck, thus producing a trough. The localized peaks on the trough portions are due to either entrance or exit of the trailing axles. It can be observed that the variation of the maximum stress on the deck with change in speeds are negligible. Figure 17 displays the maximum equivalent stress on the deck for different laminates consisting of 10 and 20 layers for a vehicle speed of 72 km/h. It can be observed that the profile remains same for both the cases, but magnitude of stresses varies significantly. The peak value of stress for 10 layered laminate reaches up to 150 MPa, whereas the peak stress for 20 layered laminate is confined to 50 MPa.

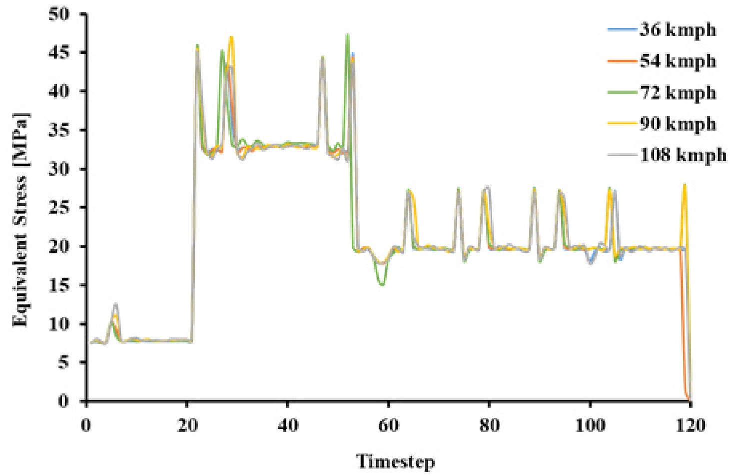


Figure 16: Maximum equivalent stress on the deck under vehicle with varying speeds.

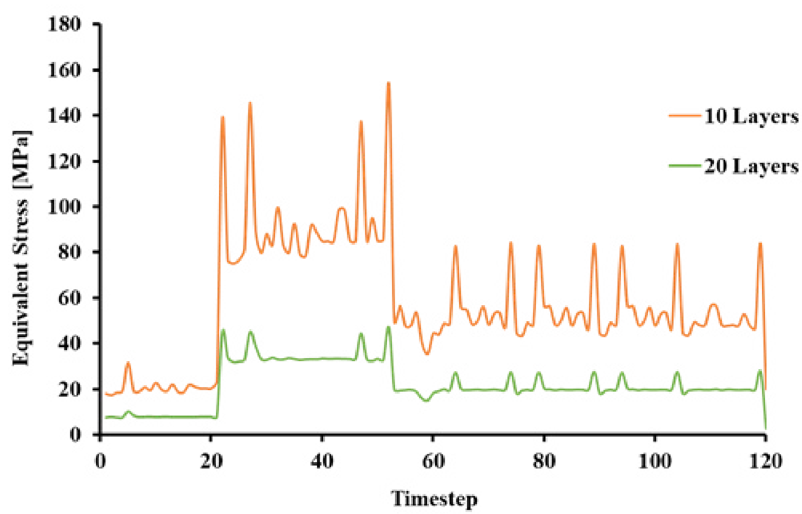


Figure 17: Maximum equivalent stress on the deck for different laminate thickness.

As noted from Figure 16 and Figure 17, the maximum stress on the deck occurs at the arrival of 3rd axle to the departure of 4th axle from the deck. It is observed that a much larger stress is introduced to the system at the arrival of the 3rd or 4th axles than after the respective axles have already entered the deck. The 3rd and 4th axles have the maximum axle. Thus, the stress and deflection are maximum at time when these axles are present on the deck. The maximum equivalent stress contours on the deck having 20-layers of laminates for vehicle velocity of 72 km/h are shown in Figure 18 at different positions of the axles on the deck.

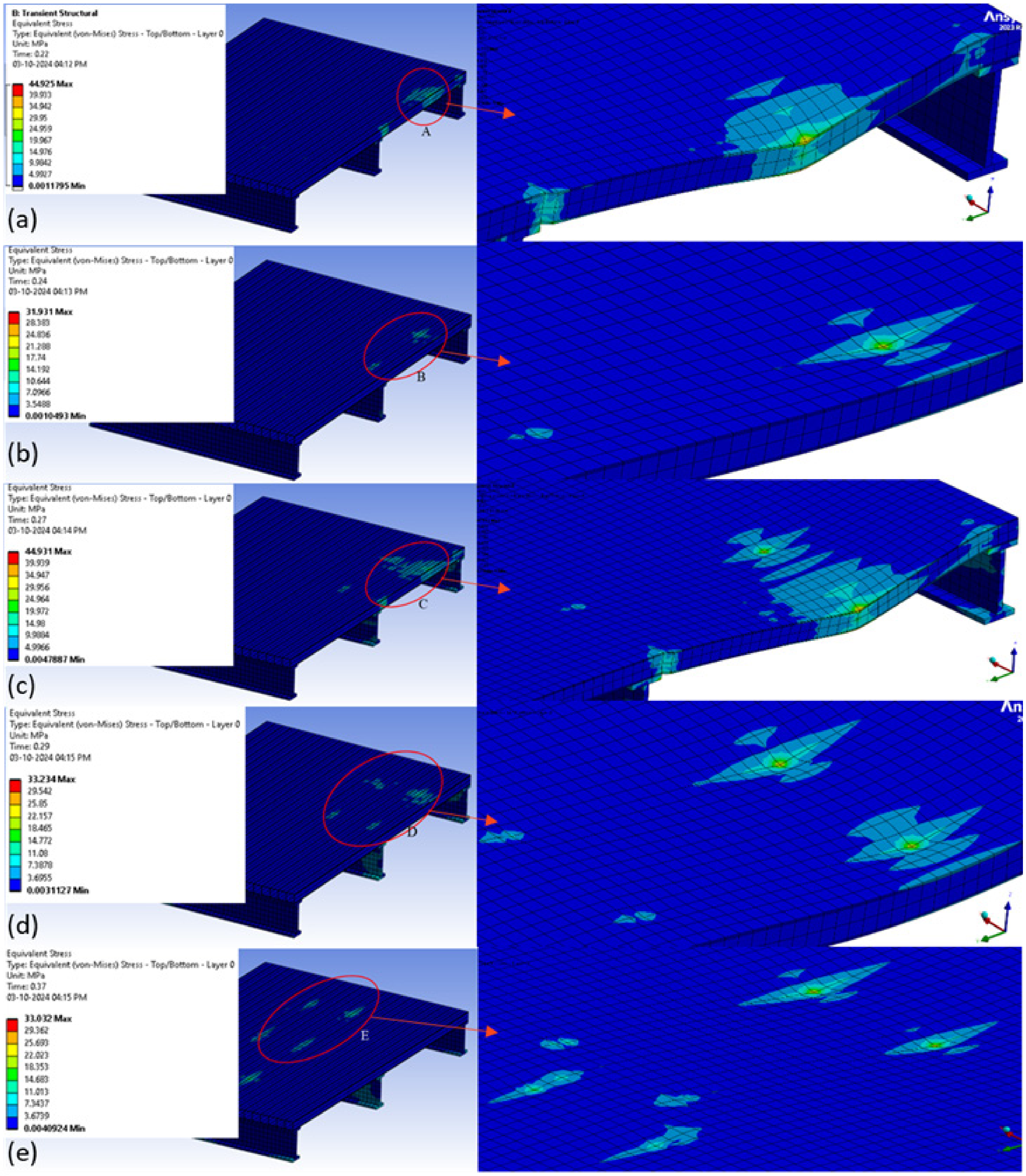


Figure 18: Maximum equivalent stress contour on the deck at (a) arrival of 3rd axle, (b) once the 3rd axle is on deck, (c) at arrival of 4th axle, (d) once the 4th axle is on deck and (e) with the 3rd and 4th axle near midspan.

2.3.6 Transient Dynamic Analysis under thermal condition

The midspan deflection of deck for the combined effect of thermal and Class B train load according to IRC 6:2017 [2] specification is computed by considering the laminates with material properties mentioned in Table 1. The present study has been carried out for vehicle speed 72 km/h. The laminates consist of 20 layers of cross ply laminae. The depth of the deck is considered as 200 mm. The transient dynamic analysis of deck is conducted under Class B train load combined with differential thermal load cases: Case (i) Differential temperature 60 °C at the top and ambient temperature at bottom surface of the deck and Case (ii) Differential temperature 60 °C at the bottom and ambient temperature at the top surface of deck. The deck consists of two lanes carrying two-way traffic. The deflection time history at the middle of lane under different thermal load cases and under ambient temperature 20 °C is a presented in Figure 19. Case (i) Due to the maximum temperature at top surface, the deck deflects in the upward direction and simultaneously downward deflection occurs under the effect of train load. The resultant deflection is downward under the effect of 3rd and 4th axles at the specified location in the deck. Though the deflection is initially upward due to thermal load case (i), downward deflection increases under the effect of wheel loads from the deflection at ambient temperature as the material degrades with the increment of temperature. The deflections remain downward throughout the movement of train load for the case (ii) temperature profile as the temperature is maximum at the bottom of the deck which too produces downward deflection. It may be observed from Figure 16 that the deflection remains downward under combined effect of thermal (case ii) and vehicle load and reaches to maximum under transition effect of 3rd and 4th axles.

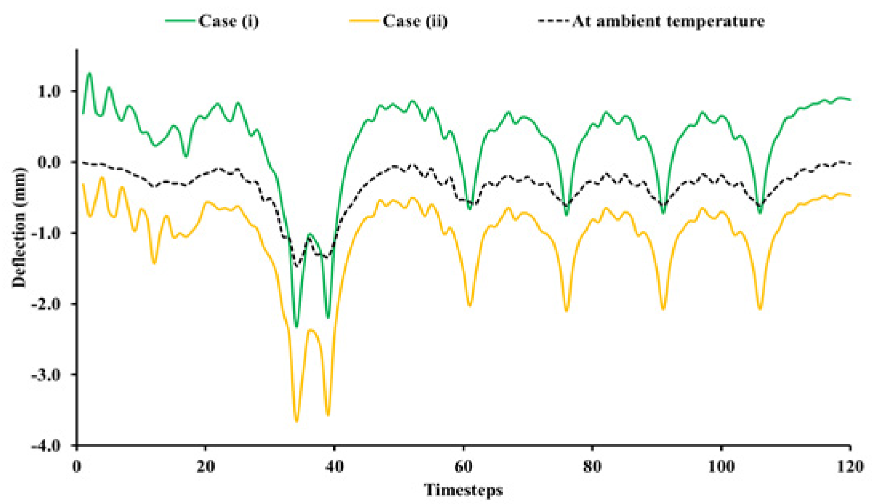


Figure 19: Mid-span deflection in mm under three different thermal load cases.

The study on the dynamic behavior of the deck is further extended for decks with 250 mm and 200 mm depths under the combined effect of the Class B moving train load and thermal interaction (i) variation of temperature from 60°C (at top surface) to ambient temperature (at bottom surface) and (ii) variation of temperature from 60°C (at bottom surface) to ambient temperature (at top surface). The central (mid-lane) deflection time history is presented in Figure 20 for both the temperature profiles with varying depth of the deck panel. It may be observed from that the resultant deflection due to combined effect of wheel load and thermal load is reduced as the stiffness is increased due to increase of deck depth from 200 mm to 250 mm.

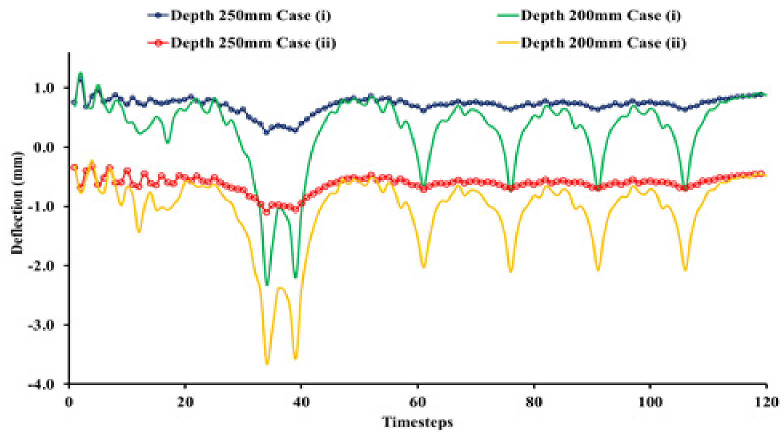


Figure 20: Midspan deflection for decks with 250 mm and 200 mm depth under combined thermal and vehicle loads.

3. Conclusions

This study presents the thermal analysis, transient dynamic response analysis and combined analysis of a GFRP bridge deck with steel girders due to transition of IRC Class B train load at various speeds, as defined by [2]. The Ansys Mechanical software module is used to simulate the thermal environment and the movement of the vehicles. The process of the preparing geometry, modeling of the composite laminates in Ansys Composite PrepPost (ACP), meshing, and post-processing of relevant data is showcased and discussed in the current study. The solutions obtained from the static and dynamic responses produced by varying different parameters of the fiber-reinforced deck are presented and discussed. The study under combined effect of temperature variation and vehicle load with variable speed may be considered as a benchmark problem for further researchers and real-life problems on the analysis and design of FRP bridge decks.

4. References

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