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RESEARCH PAPER

Finite element static analysis of polyurethane-sandwiched skewed bridge decks

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Abstract

Bridge decks are the surface structure of bridges that carry the weight of the vehicles. But nowadays, the need for a sustainable approach is required. So, the use of a sustainable material for construction and retrofitting purposes is the need of the hour. In the present study, a novel synthetic material polyurethane has been used in the sandwiched deck of the bridges. The study deals with the variation in skew angles to determine the response of the sandwiched bridge deck under Indian loading conditions. In this study, the response of deflection, equivalent stress, and stresses in X and Y directions on the bridge deck due to the variation in skewness, the thickness of the steel plate and the thickness of polyurethane deck are analysed using finite element method. Further, the bridge deck is sandwiched using steel and polyurethane having different thicknesses, and the responses are recorded. Afterward, a bridge deck is modelled using only polyurethane, to pursue sustainability and justify the RRR (reduce, reuse, and recycle) concept of waste management. The models are developed and analysed using ANSYS workbench. On increasing the skew angle for the sandwiched deck, the deflection and stresses are decreased; so, the skewed deck is more effective than the straight one. It is found that the deflection and stresses are reduced about 8 times and 4 times respectively, when the thickness of polyurethane is increased from 250 mm to 1500 mm. Therefore, it is a good and effective solution for pedestrian bridges and many other such small-scale applications.

Keywords: Sandwiched bridge deck; finite element method; ANSYS workbench; steel; polyurethane

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1 Introduction

Bridge structures are an integral part of the transportation network and are essential for connecting different regions, facilitating economic growth, and improving the overall quality of life. Bridge

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decks are the surface structures of bridges that carry the weight of the vehicles and pedestrians crossing over them. The design of bridge decks varies depending on the span, traffic volume, material availability, etc. The primary function of the bridge deck is to provide a safe and stable surface for the traffic to cross. Bridge decks can be categorised into cable-stayed, arch, box-girder, truss decks, etc., each with its unique characteristics. Isotropic bridge decks, constructed with homogeneous materials, provide a reliable and cost-effective option for small to medium-span bridges, although they require regular maintenance to prevent corrosion as most of such bridges are steel bridges. Orthotropic decks, made of steel or composite materials, provide strength and durability while reducing the weight of the bridge structure. They are commonly used for long-span bridges and offer advantages such as corrosion resistance and excellent skid resistance. However, they require specialised construction skills and equipment and have lower stiffness compared to isotropic decks. Despite the higher construction cost, orthotropic decks are a popular choice for high-traffic areas due to their durability and load-carrying capacity. Despite extensive research on the impact of skew angle on bridge deck behaviour, the dissimilarities in behaviour between isotropic and orthotropic bridge decks at varying skew angles are not well understood. Isotropic decks have uniform steel plate properties, while orthotropic decks consist of a core with steel faceplates exhibiting distinct mechanical properties in different directions. Examining the disparities in behaviour between these deck types, especially in skewed bridge scenarios, is crucial. Several important literature have been discussed in the next paragraph to show the importance of carrying out analysis on the bridge decks by varying the skewness.

The various RC (reinforced concrete) bridges under dynamic loads are analysed and evaluated the "impact factor" to determine their behaviour [1]. The dynamic effects of vehicles on highway bridge decks are analysed. It considers rough pavement surfaces and employs a probabilistic model and finite element approach [2]. The Finite Prism method for dynamic bridge analysis under moving vehicles, utilising explicit time integration and uncoupled equations is employed [3]. The trapezoidal rib orthotropic bridge deck systems are analysed using the finite element method and found that a non-uniform stress pattern should be employed to address local buckling concerns under negative bending moment and axial forces [4]. The AASHTO (American Association of State Highway and Transportation Officials) specifications and LRFD (Load and Resistance Factor Design) procedures with finite-element analysis results for skewed reinforced concrete bridges are compared and are shown overestimation of the maximum moment and differences in longitudinal moment ratios [5]. Stress concentration found at rib intersections in orthotropic steel bridge decks, with high-stress levels in cut-outs [6].

The effect of skew angle is analysed on bridge deck behaviour, observing changes in reaction force, bending moment, torsional moment, and transverse moment [7]. The steel plate reinforcement systems are studied for orthotropic decks, identifying fatigue damage caused by shear stresses in adhesive and core interfaces [8]. Authors found that deflection and bending moments decrease with increasing skew angle in reinforced concrete bridges [9], also the impact of cross-frame stiffness and spacing on fatigue damage in steel bridges are highlighted [10]. The stiffened plates are analysed using the finite element method, conducting a parametric study on stiffener geometry's influence on deflection and stress while keeping the material volume constant, and verifying results with reported data [11]. The versatile steel bridge alternatives are proposed based on span length [12]. The dynamic behaviour of a hybrid girder bridge is analysed with concrete-filled steel tube arches under moving vehicles. The study highlights the impact effects, ride comfort, and the need for further research on this bridge type [13]. Authors have applied semi-analytical GBT (Generalised Beam Theory) formulation to analyse dynamic behaviour of high-speed railway bridge decks. It investigates a real viaduct, capturing enhanced response due to resonance during high-speed train crossings [14]. The buckling behaviour of steel-polyurethane sandwiched bridge decks is studied to determine the stress variations across the deck for recommending a specification for deck thickness and stiffening rib spacing [15]. A new orthotropic steel-concrete composite deck system with improved crack control is investigated for high load capacity [16].

The fluid-structure interaction of stiffened lock gates is investigated using free vibration analysis and numerical simulations [17]. The dynamic pressure distribution of rectangular lock gates is studied under harmonic ground acceleration considering fluid effects [18]. The effect of skew angle on reinforced concrete slab bridges is analysed and observed changes in longitudinal and transverse moments [19]. The UHPC (Ultrahigh Performance Concrete)-orthotropic steel composite decks are studied and noted cracks in rib web and shear connection failure [20]. The effect of fluid on the natural frequencies of a vertical lock gate is analysed using computational analysis [21]. The skewness effect on RC box-girder bridge is investigated subjected to IRC loading [22]. The dynamic behaviour of reinforced concrete bridges is analysed with T-beam and I-girder systems. Seismic, soil, and vehicular factors are considered, using response spectrum analysis in CSiBridge software [23]. A response surface methodology-based optimisation approach is proposed for steel bridge deck systems to simplify the design process [24]. Bridges with high skew angles may lead to performance issues [25]. Skew slab bridges are analysed using ANSYS [26]. The flexural performance of pultruded glass fibre reinforced polymer (P-GFRP) composite beams is investigated in this work by combining experimental, theoretical, and finite element analytic techniques, and the results show good agreement between the numerical and experimental approaches [27]. The multiscale analysis of pultruded fiber-reinforced polymer composite beams is presented, demonstrating remarkable consistency between numerical, experimental, and analytical results, therefore confirming the suggested formulations [28]. Finite element analysis is performed to explore the behaviour of dapped end prefabricated concrete purlins (PCPs), proposing a carbon fiber reinforced polymer (CFRP) reinforcement strategy, particularly highlighting the crucial role of CFRP ply orientation in enhancing shear capacity [29].

A parametric study on skewed composite bridges is conducted [30], and the performance of isotropic and orthotropic sandwiched bridge decks under wheel loading is investigated [31]. The dynamic response of stiffened bridge decks is considered under moving loads. Different stiffeners, load velocities, and traversing paths are considered [32]. The effect of surrounding fluid in a dam-reservoir system on a stiffened lock gate structure subjected to external acceleration is investigated [33]. Fibre Metal Laminate (FML) machining technique is used and identifies the optimal parameters to improve hole quality for the benefit of industry and research [34]. The impact of wrapping with GFRP and CFRP composites on the flexural performance of reinforced concrete-filled pultruded GFRP profile hybrid beams is studied. The results demonstrate notable improvements in load-carrying capacities and structural performance ratios [35]. The effects of fatigue cracks on vibration characteristics are studied [36]. Authors have compared the analysis and results of a two-lane simply supported RC T-frame bridge deck. Dynamic analysis is performed at various span lengths, considering different vehicle databases [37]. The free vibration characteristics of box-girder bridges are evaluated [38]. The natural frequencies of a stiffened lock gate structure interacting with an inviscid fluid are determined. Results are compared with an unstiffened lock gate, considering different geometries and fluid extents [39]. An arc-shaped stiffener is proposed for enhanced fatigue resistance in long-span steel bridges [40]. The static behaviour of steel-concrete-steel sandwiched plates is analysed under different loads using ANSYS Workbench [41]. The effect of skewness on prestressed box-girder bridges is studied [42]. The static and dynamic responses of eccentrically stiffened plates are evaluated [43]. The effect of fluid on a locked gate in a dam-reservoir system using Mindlin's plate theory and the method of separation of variables is investigated. The study has considered sinusoidal excitation and examined the dynamic pressure variation [44].

The understanding of the differences between steel and sandwiched decks for different skew angles is very limited. The use of polyurethane in conjunction with steel for deck construction is an innovative method. The manuscript investigates the structural consequences and advantages of this hybrid material, so contributing to a better knowledge of new materials in structural engineering. Also, very few studies are available on Indian loading conditions. The manuscript tackles a specific and critical issue of structural design by focusing on Indian loading conditions. The numerical technique enables a complete analysis of the structural behaviour of the polyurethane steel deck under various loading situations, providing a comprehensive insight that goes beyond what typical analytical methods can provide. So, in this study, steel and sandwiched decks are analysed and compared for various skew angles, viz., 0°, 10°, 20°, 30°, 40°, 50°, and 60° under Indian loading conditions. Also, decks are modelled and analysed using only polyurethane for a better understanding of the material and its usage considering the sustainability and RRR concepts. The displacement and stresses under Indian loading conditions are determined for all bridge models using the finite element method. This comparison gives an insight into the relative advantages and disadvantages of the new material, assisting in structural design project decision-making. The study has been conducted according to the flow diagram as shown in Figure 1.

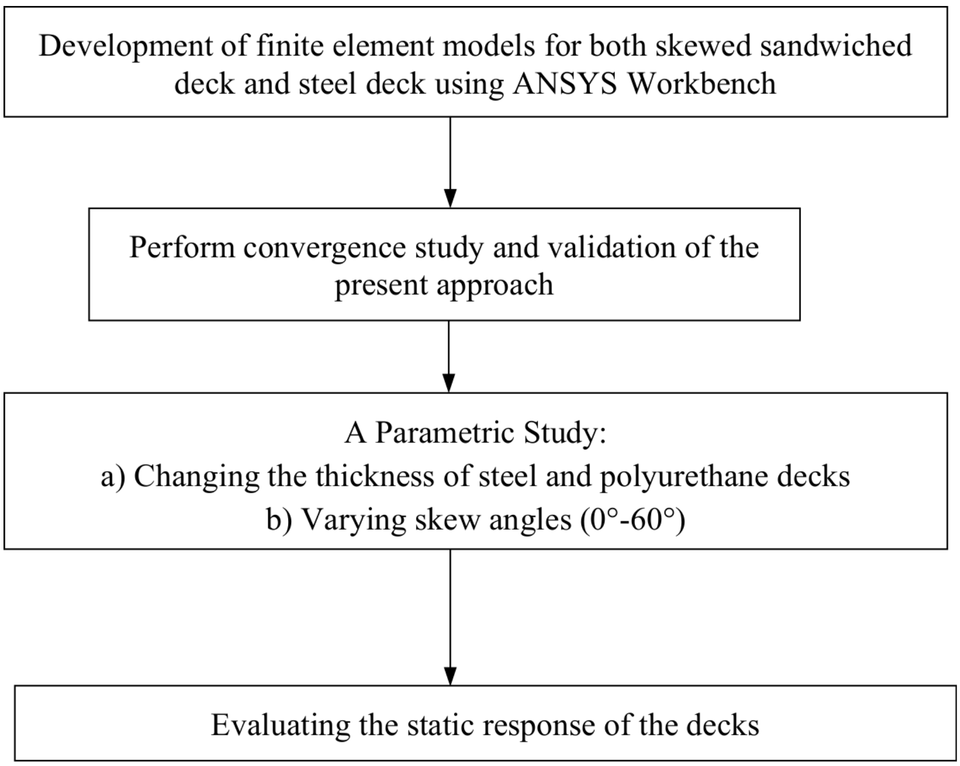


Figure 1. Flow diagram of the study

2 Modelling process and validation

The finite element method (FEM) is used for the analysis with the help of ANSYS Workbench. FEM involves dividing a structure into discrete elements interconnected at nodal points, with individual element stiffness matrices assembled based on assumed displacement or stress patterns. A model considered by Agarwal et al. [31] is reproduced for validating the present approach, as shown in Figure 2. The model of the bridge deck considered is of length 720 mm, width 350 mm and thickness 4 mm for steel isotropic deck, and for sandwiched deck, t_s = 2 mm (both lower and upper steel plates) and t_p = 10 mm, i.e., total thickness = 14 mm. The results obtained from the present study are validated with the experimental and numerical results of Shan and Yi (2016) [14], and Agarwal et al. (2021) [31], respectively. The deck is simply supported on all four edges,

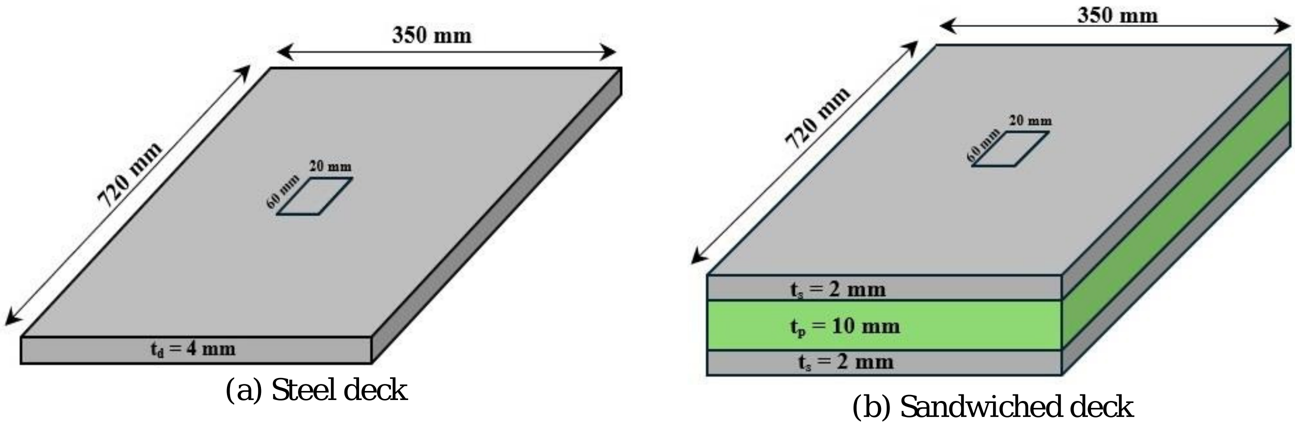


Figure 2. Plan of the deck for validation

and a uniformly distributed area load of 1.667 MPa is applied on 60 mm × 20 mm area at the centre, as specified in Agarwal et al. (2021) [31]. The mesh size of the element is taken as 10 mm after the conduction of a convergence study. The stresses are evaluated at regular intervals of 10 mm in both the longitudinal and transverse orientations and the location of the points are shown in Figure 3. The results obtained are compared with Agarwal et al. (2021) [31], and Shan and Yi

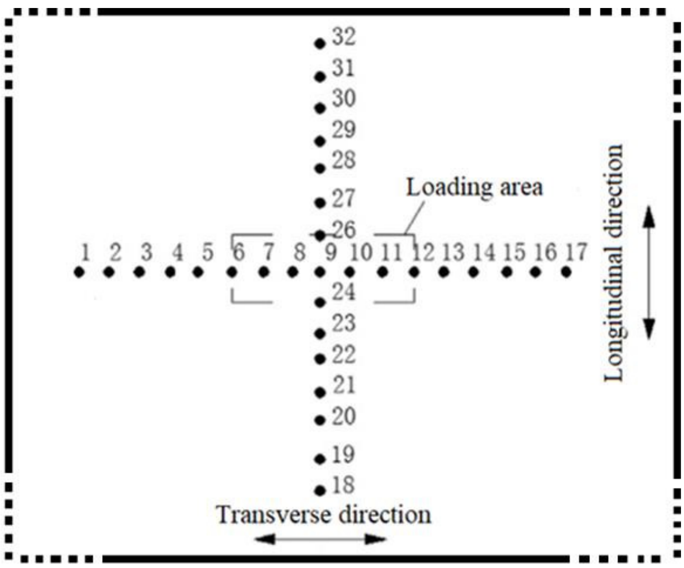
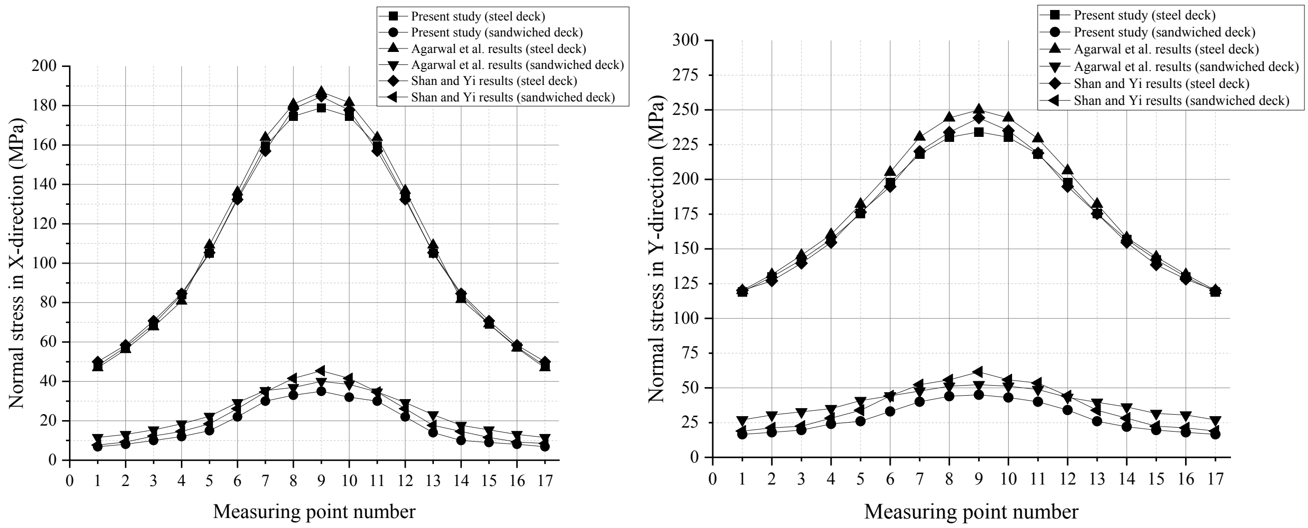


Figure 3. Points of stress calculation on the deck

(2016) [14] and are demonstrated in Figure 4 and Figure 5. The present results were found to be in close agreement with the results reported by Agarwal et al. (2021) [31], and Shan and Yi (2016) [14].

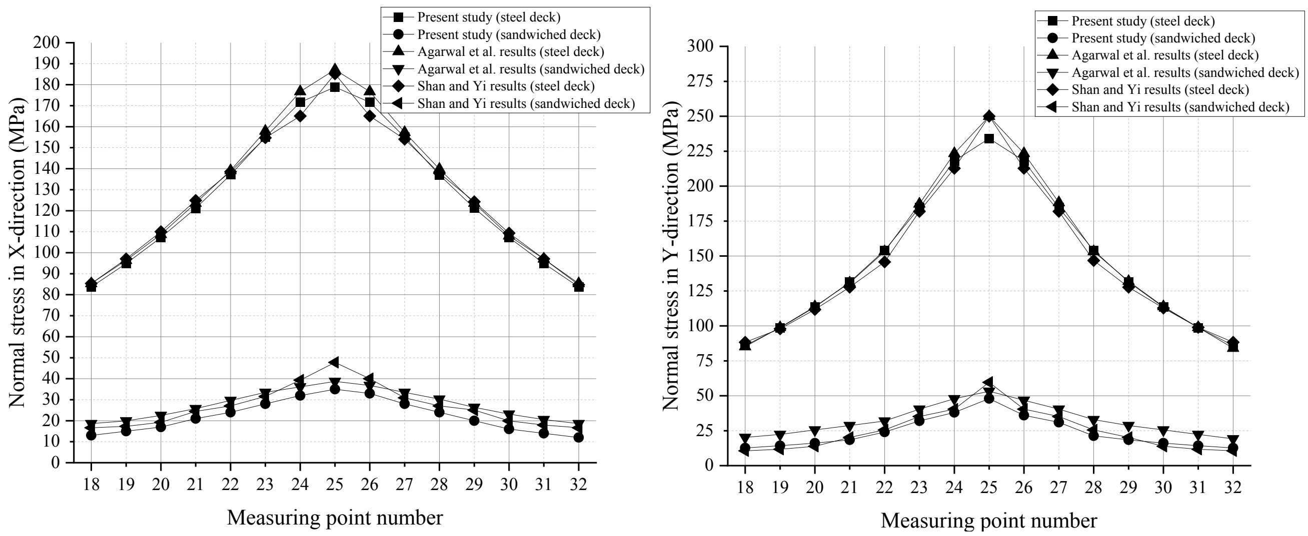
3 Bridge deck model

Deflection and stresses are evaluated for simply supported isotropic and sandwiched decks. A bridge deck of length 20 m, and width 5.76 m is modelled for analysis. Then convergence study is carried out to find the optimum mesh size for the present study. It is performed on an isotropic



(a) Points 1-17 in X-direction (b) Points 1-17 in Y-direction

Figure 4. Stresses in X-direction and Y-direction



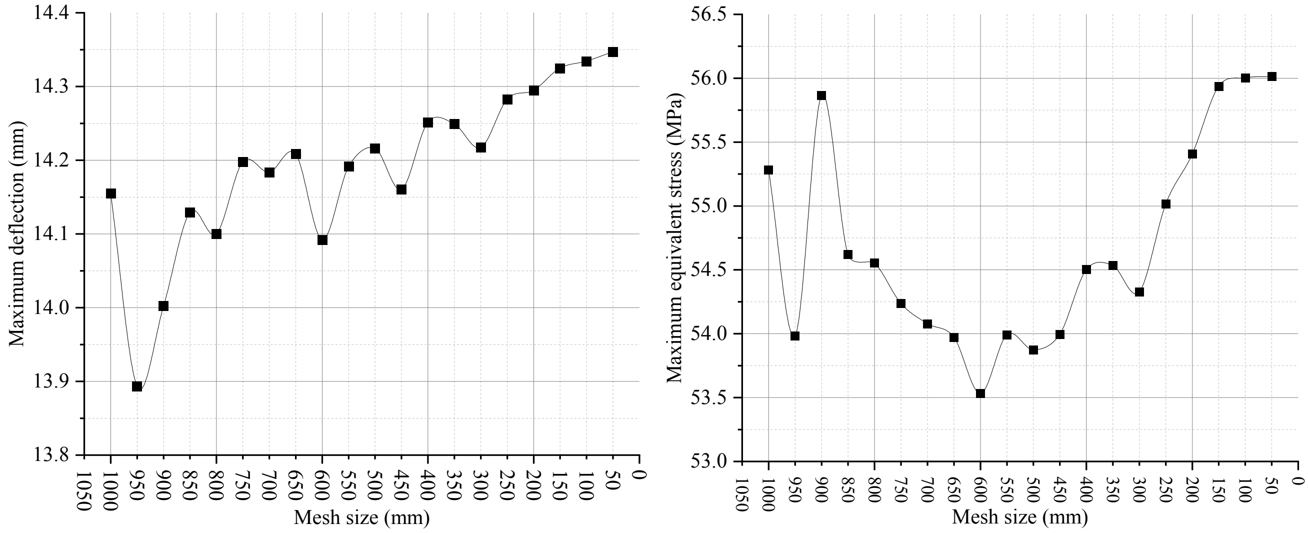
(a) Points 18-32 in X-direction (b) Points 18-32 in Y-direction

Figure 5. Stresses in X-direction and Y-direction

steel bridge deck of length 20 m, width 5.76 m, and thickness 150 mm, with the evaluation of maximum deflection and maximum equivalent stress by applying 70R wheeled load 'L' type (IRC:6-2017) [45]. Maximum deflection and maximum equivalent stress are plotted against mesh size as shown in Figure 6(a), and Figure 6(b), respectively. It is observed that the results converge after the mesh size of 100 mm. So, the mesh size of 100 mm is considered for further analysis. In this study, 3-noded triangular elements and 4-noded rectangular elements with 6 degrees of freedom at each node are used for discretisation. The presence of 4-noded rectangular elements is more, as 3-noded triangular elements accommodate due to the skewness. The details of these elements are shown in Figure 7.

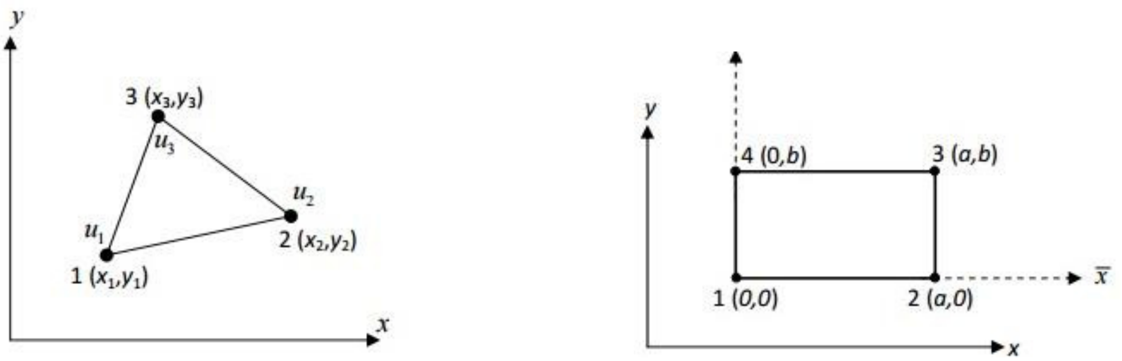
4 Numerical results and discussions

A parametric study has been performed using several examples to estimate the effect of varying skewness in isotropic and sandwiched bridge decks. The materials used in the study are steel and polyurethane, and the properties of these materials are tabulated in Table 1.



(a) Maximum deflection (b) Maximum equivalent stress

Figure 6. Convergence study



(a) 3-noded triangular element (b) 4-noded rectangular elements
(source: https://www.brainkart.com/article/2,3-Noded-Linear-Triangular-Element_5951/#google_vignette)

Figure 7. Elements used in the study

Table 1. Properties of steel and polyurethane

Material	Steel	Polyurethane
Density (kg/m^3)	7850	1150
Yield strength (MPa)	335	0.1 – 0.8 (approx.)
Poisson's ratio	0.3	0.46
Elastic modulus (MPa)	2x10^5	800

The study starts with the selection of load case for the analysis which is further used to analyse deflection and stresses. The anatomies of the steel and sandwiched bridge deck are shown in Figure 8.

Selection of load case

In this section, the different live loads available in the Indian Codal provisions are applied on the deck to select the load that will provide the maximum effect on the deck. Different live loads specified in IRC:6-2017 are considered on the decks, which are class 70R wheeled load 'L' type, class 70R wheeled load 'M' type, class 70R wheeled load 'N' type, class 70R tracked load, class A load, class B load, class AA wheeled load, and class AA tracked load. Further, the steel bridge

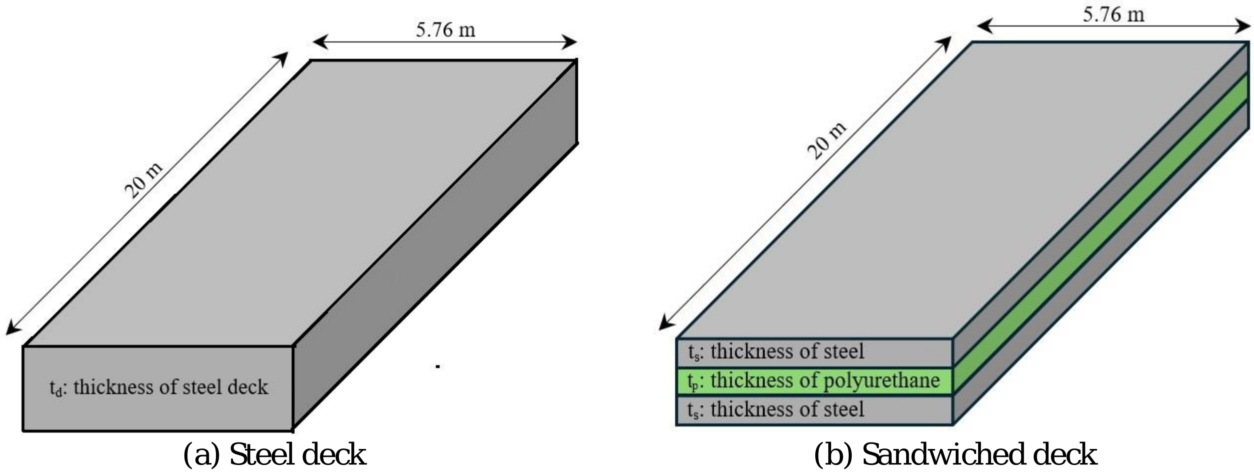


Figure 8. Steel deck anatomy and Sandwiched deck anatomy

deck of length 20 m, width 5.76 m, and 150 mm thick is considered and, analyzed for different live loads mentioned above. The deck is simply supported on all four edges. The results of maximum deflection and stresses are shown in Figure 9. It is clearly observed from the figures that 70R wheeled load 'N' type is giving the maximum effect of deflection and stresses. So, the same load will be considered for further analyses and depicted in Figure 10 for a better understanding.

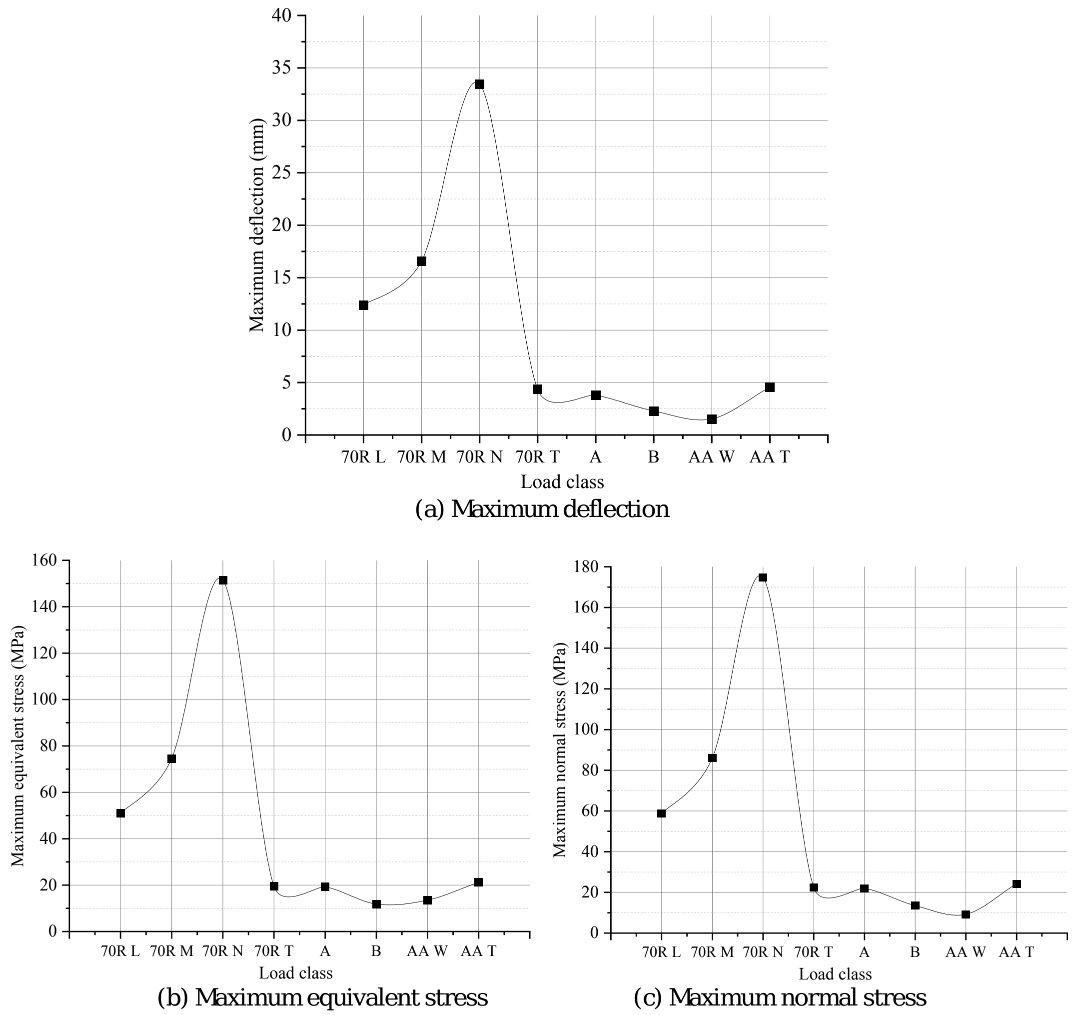


Figure 9. Results on steel deck for different live load cases (IRC:6-2017)

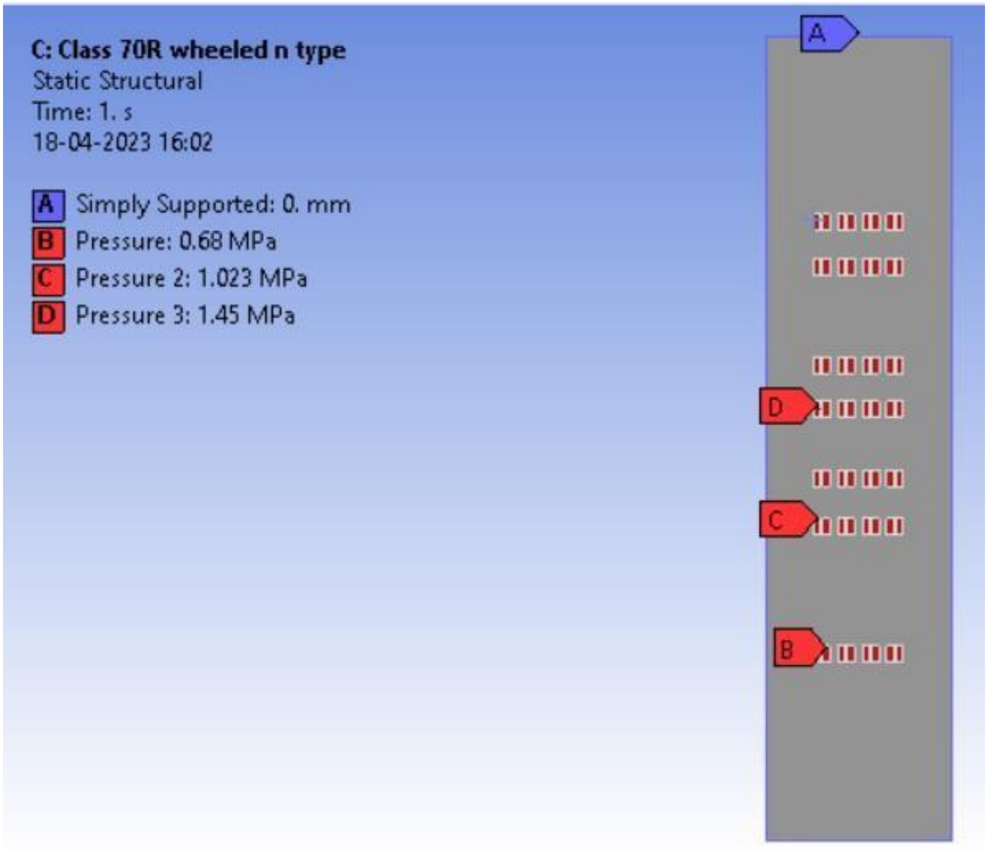


Figure 10. 70R wheeled load 'N' type

Effect of skew angle on isotropic bridge deck

In this section, the isotropic steel deck is analysed to determine maximum deflection and stresses by varying thickness and skewness. The thickness of the deck is varied from 150 mm to 200 mm, with a 10 mm difference and the skewness from 0° to 60° to find one of the most optimum thicknesses. The thicknesses must be chosen based on the maximum deflection criteria of L/800 (where L is span) specified in IRC:112-2011, clause 12.4.1 [46] and AASHTO LRFD Bridge Design Specifications 8th edition (2017), clause 2.5.2.6.2 [47]. The results are presented in Figure 11 for deflection and stresses. The variation in maximum equivalent stress and maximum normal stress along Y-axis is quite large for variation in skew angles. They become almost double from 0° to 60°. As obtained in the results, when the thickness of the deck is more than 170 mm, the maximum deflection criteria are fulfilled. So, the 200 mm thickness, i.e., a rounded value is considered for further analyses of steel decks.

Effect of thickness on sandwiched bridge deck

Now, the sandwiched decks are modelled using steel and polyurethane by varying the thickness of steel and polyurethane. The sandwiched decks are analysed for maximum deflection and maximum stress. The sandwiched decks comprise steel plates above and below of a polyurethane layer. For the sake of simplicity, both layers of steel are taken equal in thickness. The sandwiched deck combinations are first made by reducing the amount of steel and increasing the amount of polyurethane while keeping the total thickness of the deck constant. Further, the amount of steel is kept constant while increasing the amount of polyurethane, which increases the total thickness of the deck. The annotation of the sandwiched cases is tabulated in Table 2 stated in Appendix.

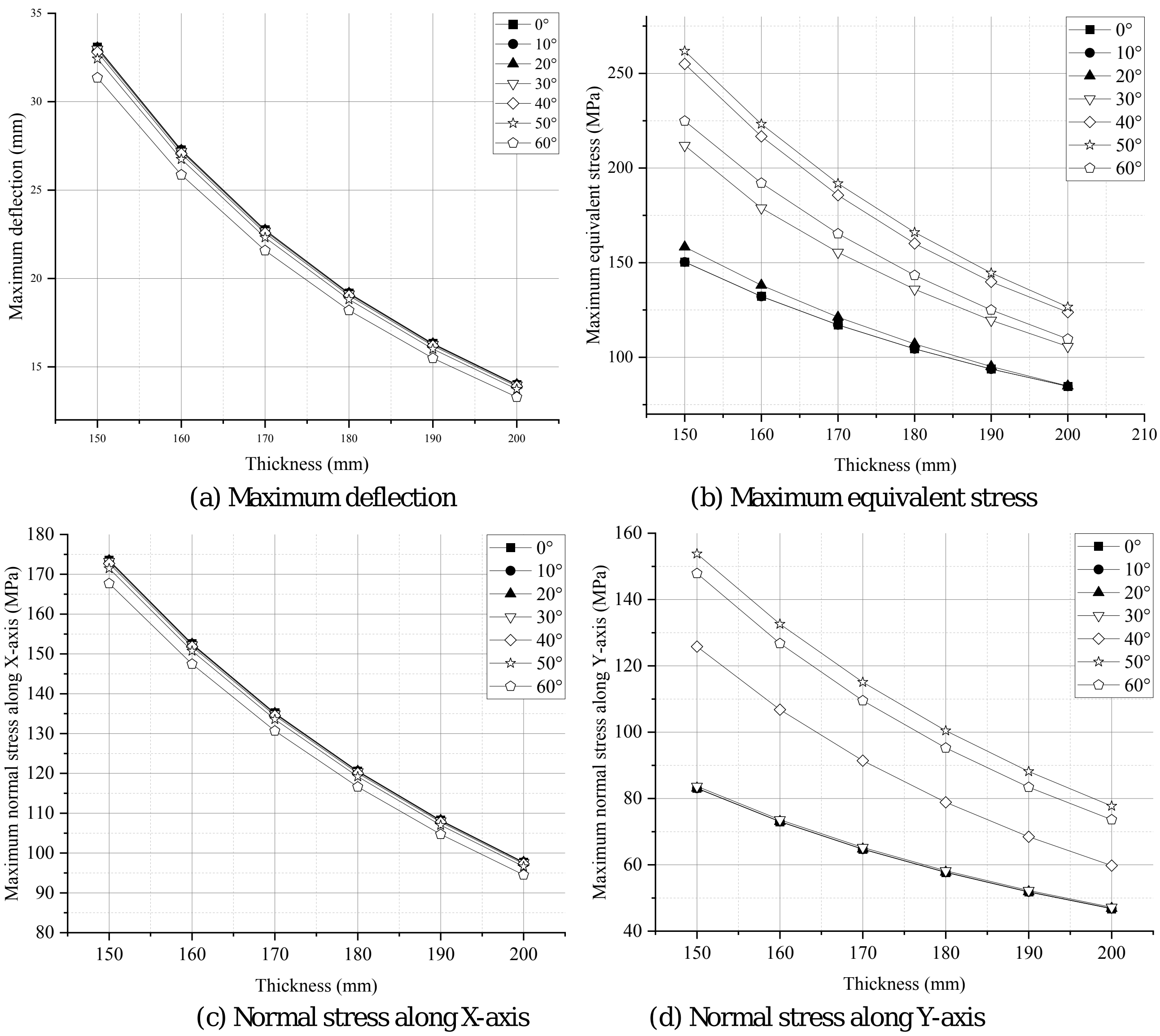
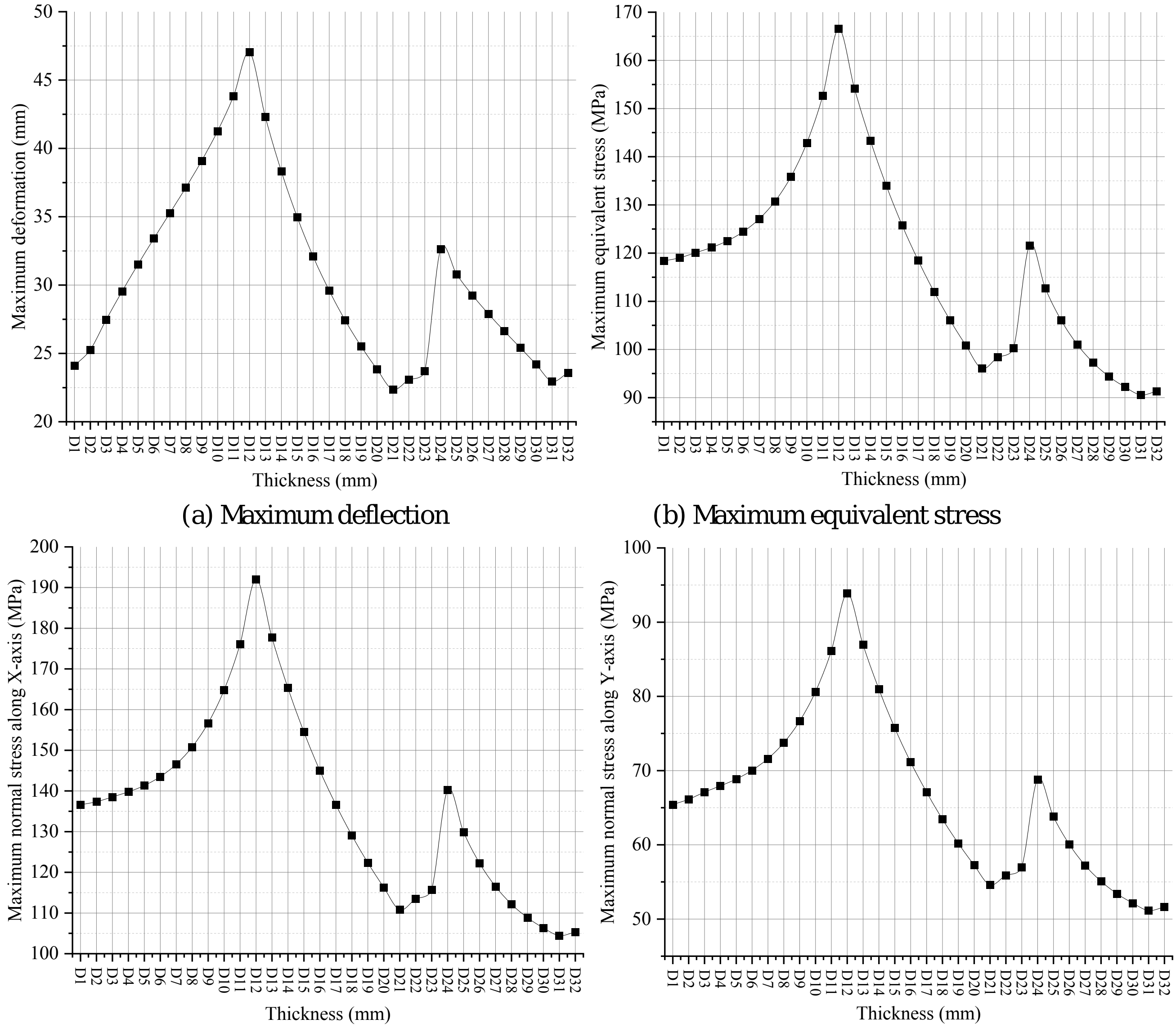


Figure 11. Variation of maximum values of deflection and stresses

Figure 12 shows the results of the analysis. As expected, the value of maximum deflection and stresses increase as we go on decreasing the amount of steel and adding the same amount of polyurethane. But, if we keep on increasing the polyurethane on keeping the steel constant, we see a decrease in those parameters but the total thickness of the deck increases. Also, some combinations, allow for low stresses and deflection but the amount of steel required for those is still higher than the increased thickness ones. Among the presented sandwiched deck combinations, a few are selected for the analysis by varying the skew angles, as per the pattern shown in Figure 13.

Effect of skewness on sandwiched deck

In this section, sandwiched decks are analysed by varying the skew angles. The combinations are selected based on the sustainability and RRR concept of waste management. The decks are selected to show the effect of decreasing the amount of steel while simultaneously increasing amount of polyurethane, while keeping the total thickness constant on the behaviour of the deck. Also, two more combinations are selected, one of which has the lowest deflection and stresses, and the other is one of the best combinations of steel and polyurethane sandwiched deck for 200 mm thickness (which will be used in the subsequent sections for comparison with steel isotropic



(a) Maximum deflection

(b) Maximum equivalent stress

(c) Maximum normal stress along X-axis, i.e., transverse axis

(d) Maximum normal stress along Y-axis, i.e., longitudinal axis

Figure 12. Results of different sandwiched decks

deck of 200 mm thickness). The combinations are selected from Table 2, D1 to D12, D20, D21 and D31 and taken for this analysis. The results of deflection and stresses are shown in Figure 14. The deflection and stresses are relatively comparable on increasing the skew angle. However, as the trend suggests, on increasing the skew angle, the deflection and stresses decrease slightly, and may be considered while designing sandwiched decks.

Comparison between steel and sandwiched decks

In this section, the steel deck of thickness 200 mm is compared with two sandwiched deck combinations (D31 and D21), which are as follows:

- $t_s = 70$ mm, $t_p = 60$ mm,
- $t_s = 30$ mm, $t_p = 200$ mm.

The combination D31 leads to a total thickness of 200 mm and has low values of deflection and stresses. The combination D21 has values even lesser compared to D31 but it has more thickness compared to the former. D21 has a total thickness of 260 mm but only 60 mm of steel, on the

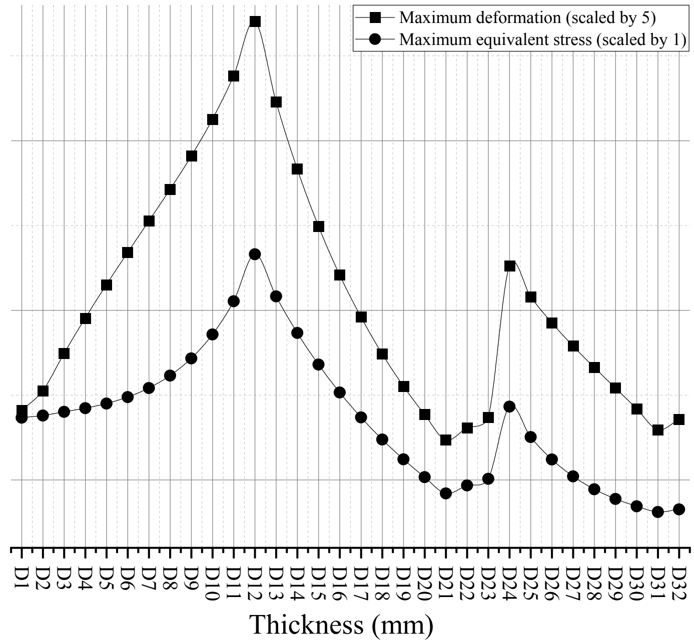


Figure 13. Trend line for the sandwiched decks maximum deflection (scaled by 5)

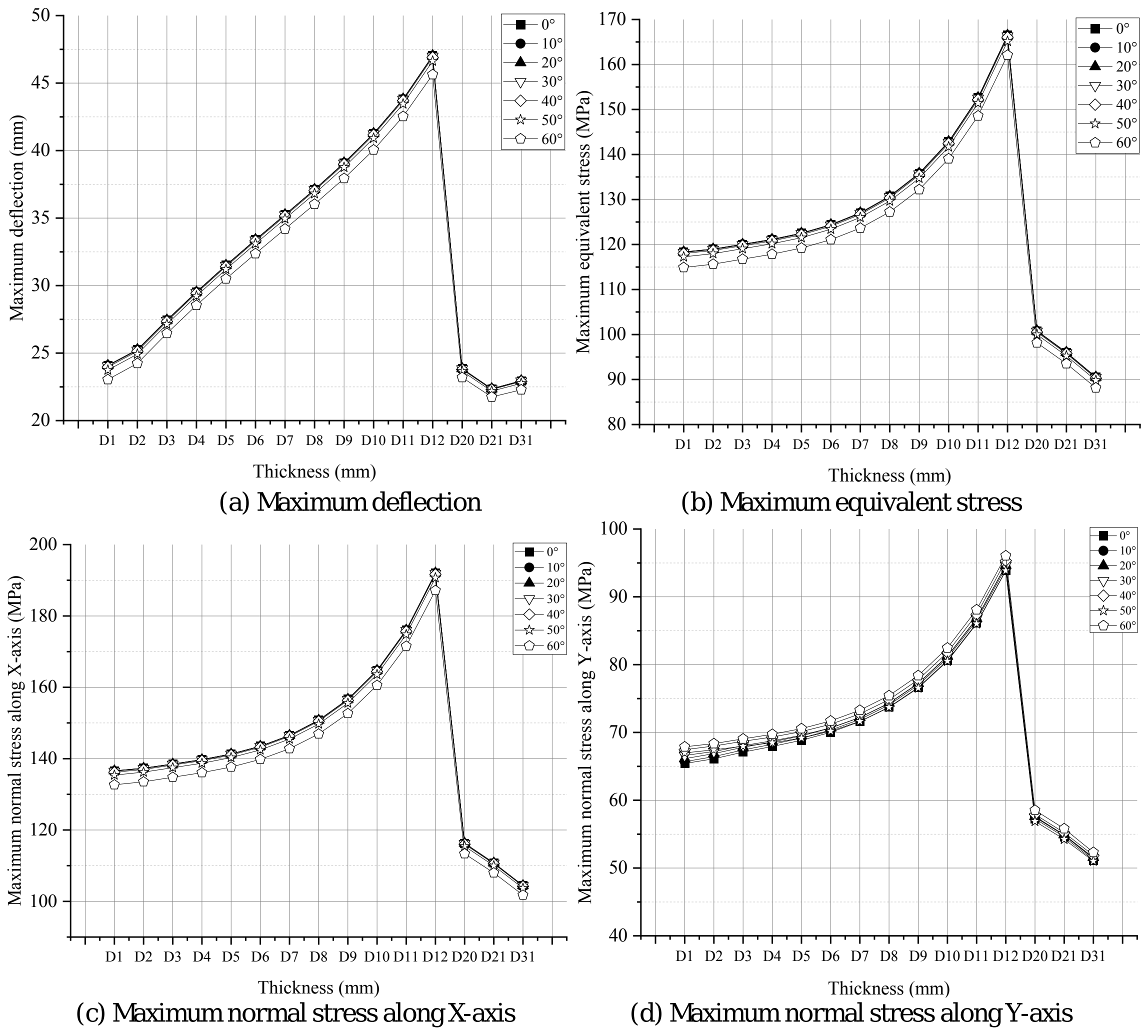
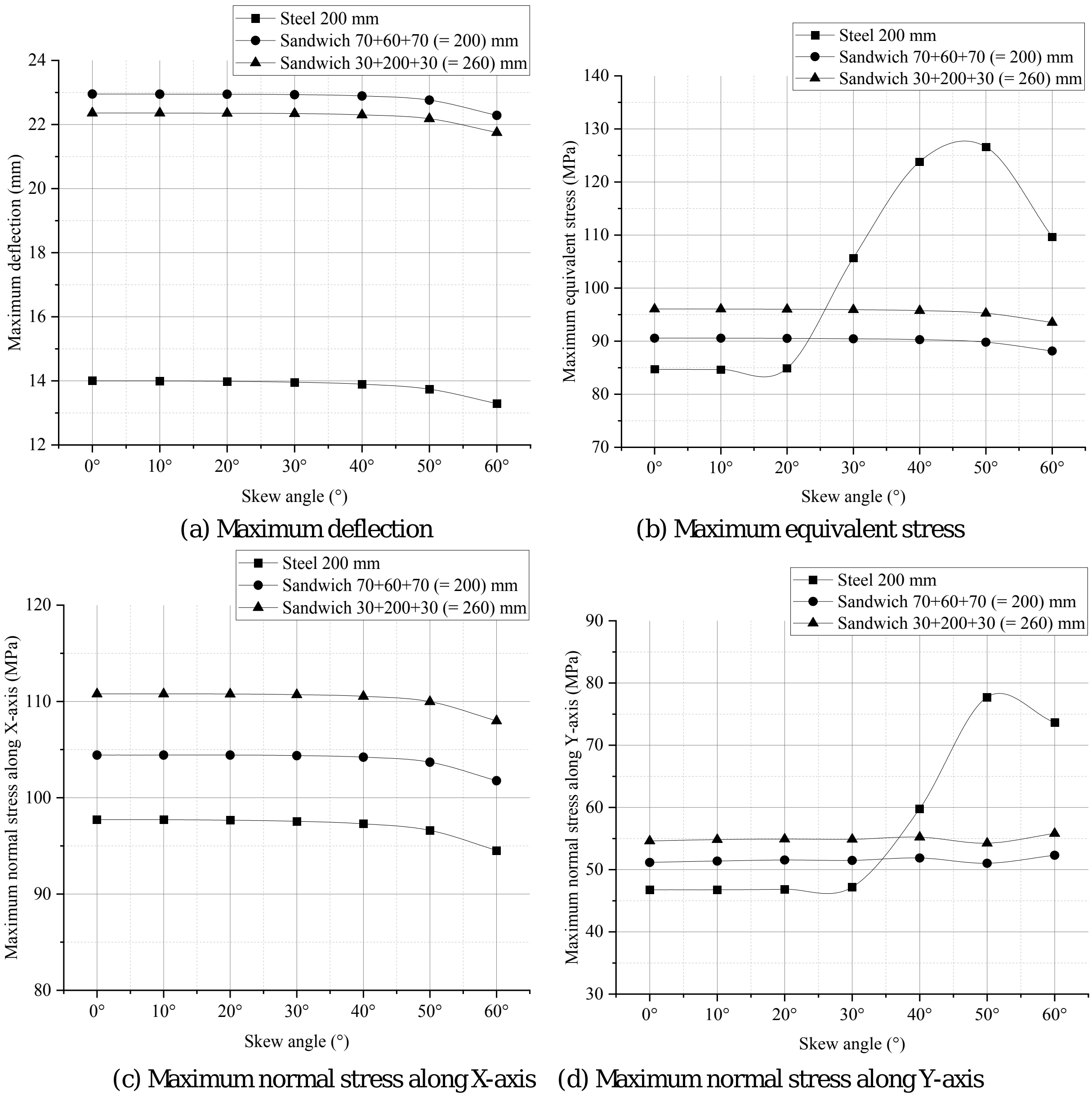


Figure 14. Variation of results of sandwiched decks for different skew angles

other hand, D31 has 140 mm of steel. The results of maximum deflection, maximum equivalent stress, maximum normal stress along X-axis, i.e., the transverse axis, and maximum normal stress along Y-axis, i.e., the longitudinal axis are compared. The findings are presented in Figure 15. It is observed that the three decks have comparable deflections and stresses. Interestingly the maximum equivalent stress of steel isotropic deck turns sharply greater than the sandwiched combinations after skew angle 20°, also the maximum normal stress along Y- axis, i.e., longitudinal axis of steel isotropic deck becomes greater than the sandwiched combination after 30°. However, the maximum deflection of steel isotropic deck remains significantly less than the sandwiched combinations, viz., about 8 mm less for both combinations 1 and 2. For the clarity of the readers, some results are depicted in the form of contours and shown in Figure 16, Figure 17, and Figure 18, for 0° skewed deck, 30° skewed deck, and 60° skewed deck, respectively.



(a) Maximum deflection (b) Maximum equivalent stress

(c) Maximum normal stress along X-axis (d) Maximum normal stress along Y-axis

Figure 15. Results of isotropic and sandwiched decks

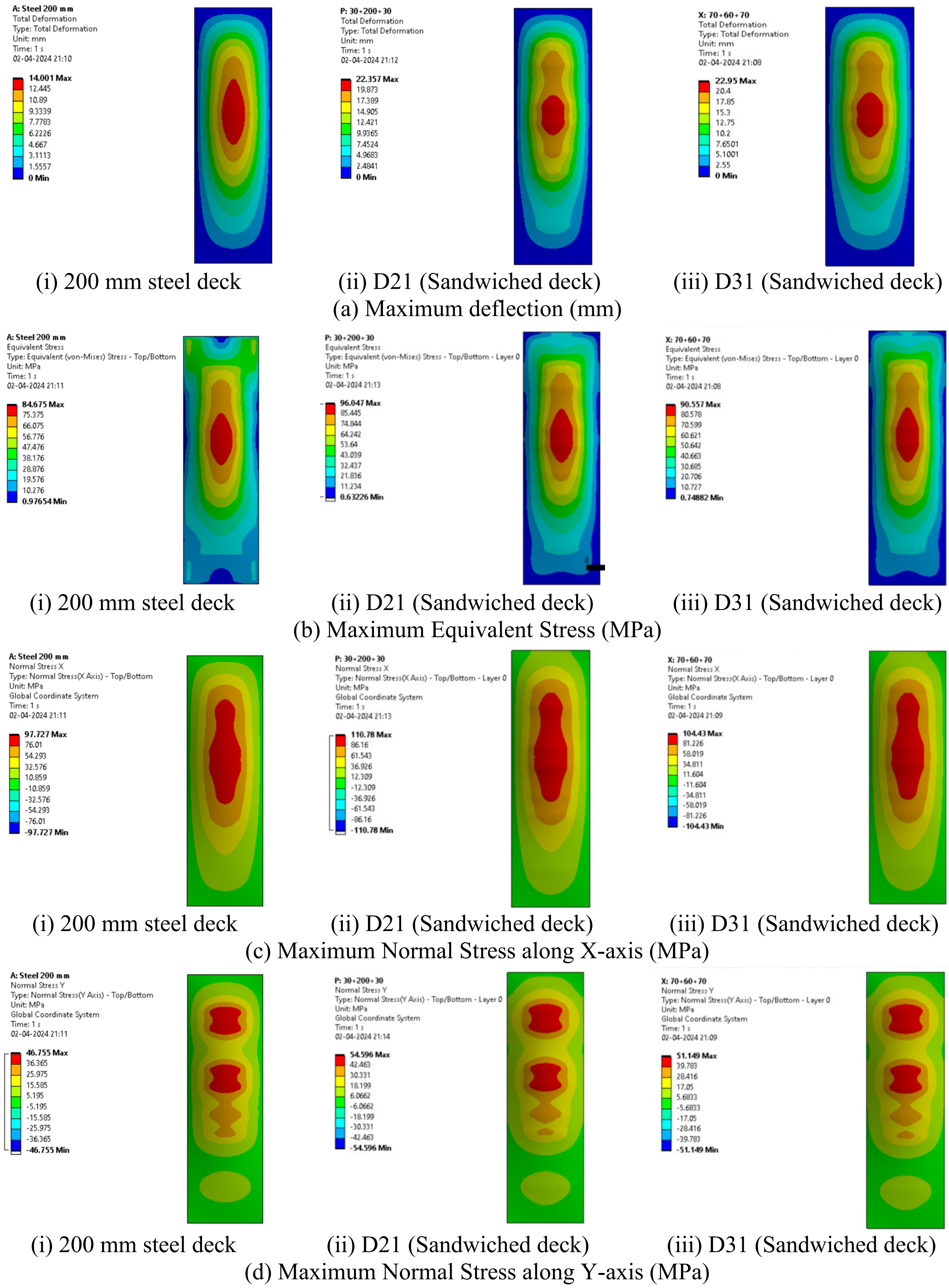
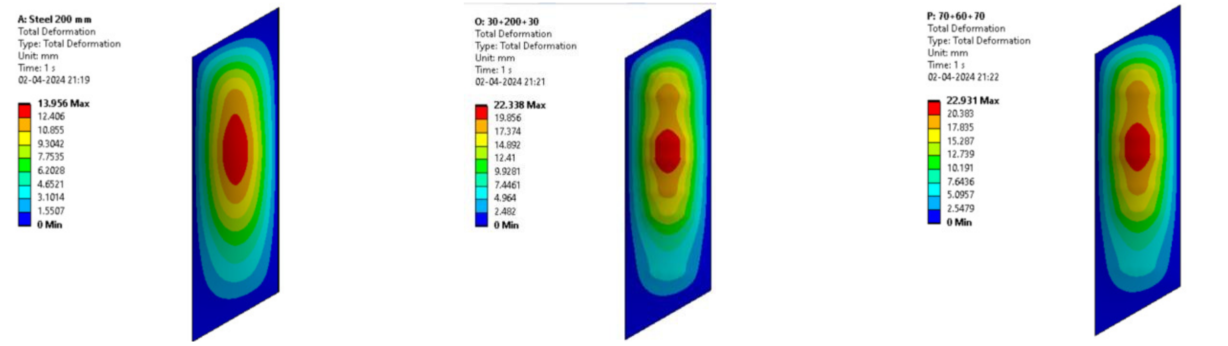


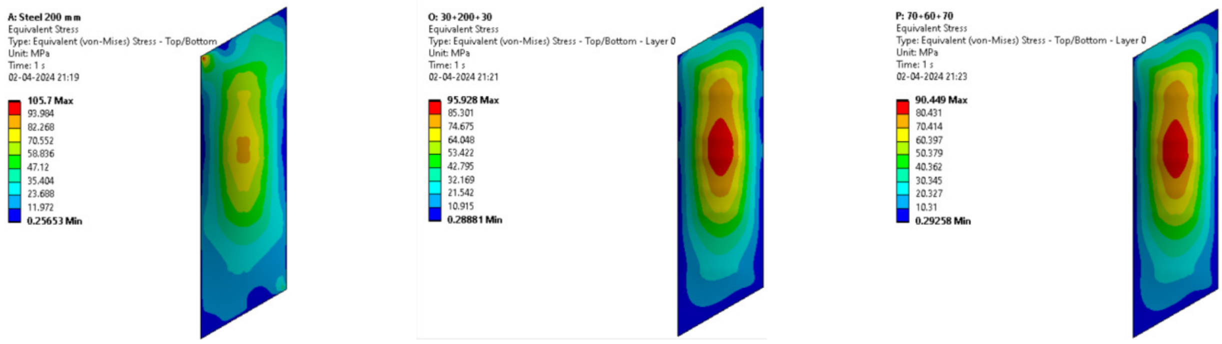
Figure 16. Variation of deflection and stresses on 0° skewed deck

A special case: polyurethane

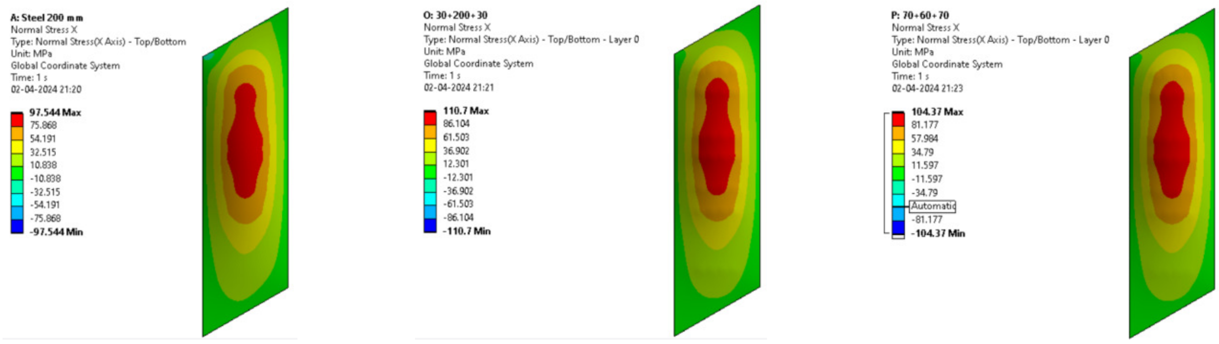
A special case is considered in this section where only polyurethane is used. A bridge of similar dimensions, i.e., length 20 m, and width 5.76 m, is used for this analysis. The thickness of the deck



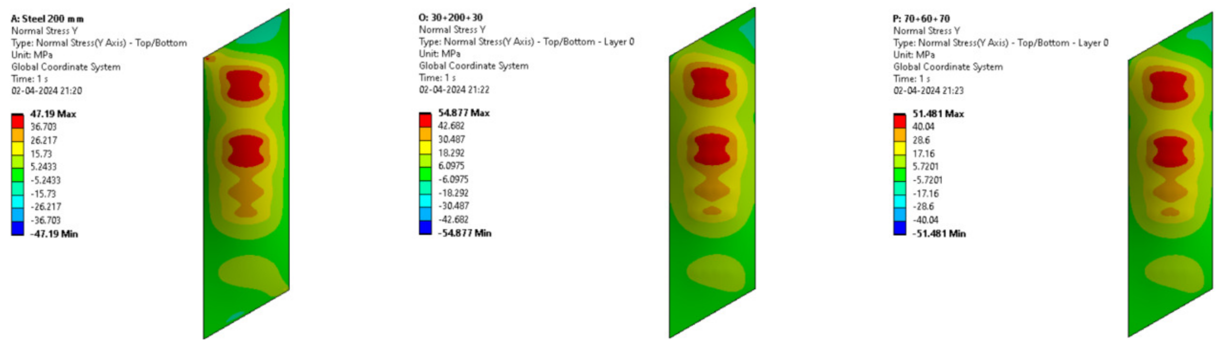
(i) 200 mm steel deck (ii) D21 (Sandwiched deck) (iii) D31 (Sandwiched deck)
(a) Maximum deflection (mm)



(i) 200 mm steel deck (ii) D21 (Sandwiched deck) (iii) D31 (Sandwiched deck)
(b) Maximum Equivalent Stress (MPa)



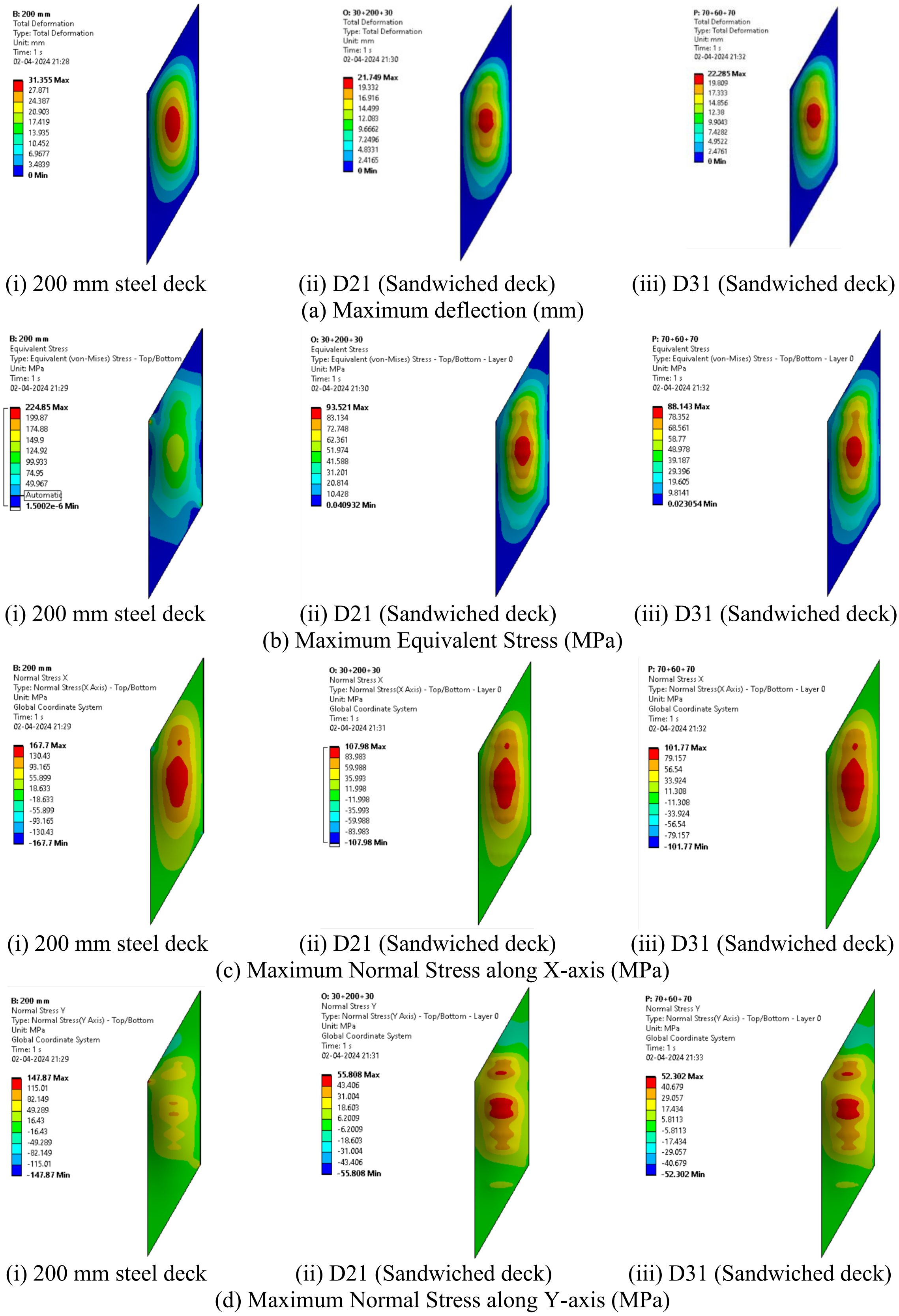
(i) 200 mm steel deck (ii) D21 (Sandwiched deck) (iii) D31 (Sandwiched deck)
(c) Maximum Normal Stress along X-axis (MPa)



(i) 200 mm steel deck (ii) D21 (Sandwiched deck) (iii) D31 (Sandwiched deck)
(d) Maximum Normal Stress along Y-axis (MPa)

Figure 17. Variation of deflection and stresses on 30° skewed deck

is increased from 250 mm to 1500 mm along with the change in skew angle, to understand the response of the deck to the applied load. The results are presented as shown in Figure 19.
As the result suggests, the stresses and the maximum deflection decrease substantially as thickness



(i) 200 mm steel deck (ii) D21 (Sandwiched deck) (iii) D31 (Sandwiched deck)
(a) Maximum deflection (mm)

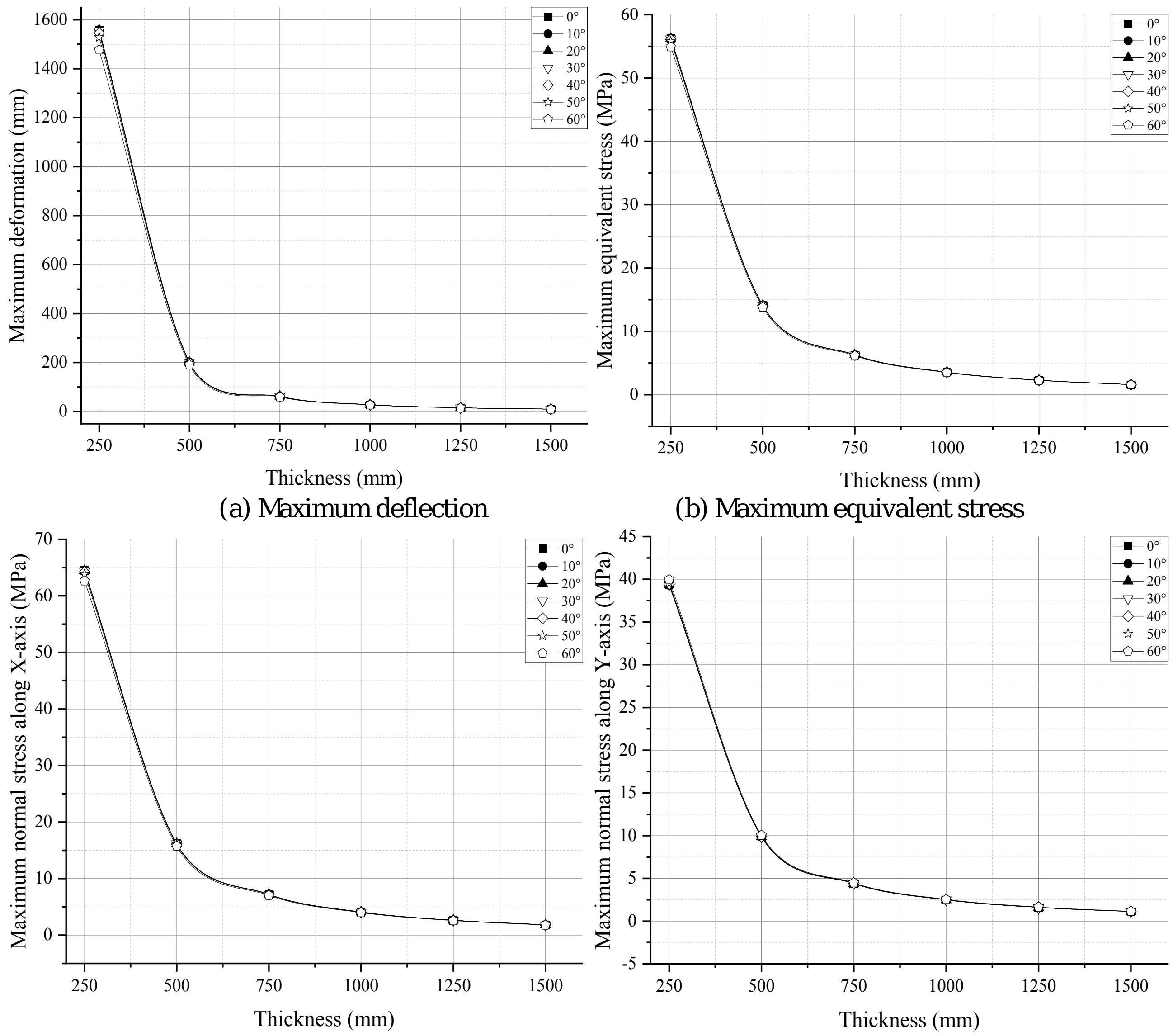
(i) 200 mm steel deck (ii) D21 (Sandwiched deck) (iii) D31 (Sandwiched deck)
(b) Maximum Equivalent Stress (MPa)

(i) 200 mm steel deck (ii) D21 (Sandwiched deck) (iii) D31 (Sandwiched deck)
(c) Maximum Normal Stress along X-axis (MPa)

(i) 200 mm steel deck (ii) D21 (Sandwiched deck) (iii) D31 (Sandwiched deck)
(d) Maximum Normal Stress along Y-axis (MPa)

Figure 18. Variation of deflection and stresses on 60° skewed deck

increases. The percentage decrease in the maximum deflection from 250 mm to 500 mm is of 677% and from 250 mm to 1500 mm is of 772%. The percentage decrease in the stresses from 250 mm to 500 mm is of 298% and from 250 mm to 1500 mm is of 387%. The variation with the skew angle, however, is very small, almost insignificant. Hence, if the design constraints permit, only polyurethane bridge deck can be a good alternative for steel, or even sandwiched deck. Also, it can be used for pedestrian bridges and many other such small-scale applications, or footpaths, or roads as a cover of potholes, etc.



(a) Maximum deflection (b) Maximum equivalent stress

(a) Maximum normal stress along X-axis (b) Maximum normal stress along Y-axis

Figure 19. Results of bridge deck modelled using polyurethane

5 Conclusion

The sandwiched decks are analysed in the present study along with isotropic steel decks and make a comparative study as well. The following conclusions may be drawn from the study and are as follows:

- For a span of deck that can include all the loads completely (for one cycle), 70R wheeled load 'N' type gives the largest deflection and stresses among the live loads listed in IRC:6-2017.
- For a deck length of 20 m of steel, thickness over 170 mm is suitable as per the L/800 deflection criteria.
- For a steel deck, on increasing the skew angle, the deflection decreases slightly, and the equiv-

alent stress decreases for 10° skew angle and then increases significantly. The normal stress along transverse direction decreases slightly and along the longitudinal direction increases significantly.
- On increasing the polyurethane thickness and reducing the steel thickness (to keep total thickness constant), led to an increase in deflection and stresses. Though on increasing the total thickness by increasing the polyurethane amount, deflection and stresses have decreased.
- On increasing the skew angle for the sandwiched deck, the deflection and stresses are decreased; so, the skewed deck is more effective than the straight bridge deck.
- The deflection in one of the most optimum sandwiched combinations (in this study) is 9 mm more than the steel counterpart. The stresses however increase by only 4-7 MPa.
- Only polyurethane deck of 1250 mm is the functional equivalent of steel deck of 200 mm. However, the stresses in the former are significantly lesser than the later. The equivalent stress being almost 37 times less.

Future scope

The future studies, suggestions and academic opportunities are summarised as follows:

- The analysis may be extended for dynamic loading conditions such as traffic-induced vibrations, wind loads, and seismic events.
- Soil structure interaction can be modelled and studied to predict the behaviour of soil and its interaction with the structure.
- Detailed multi-scale modelling may be developed to facilitate global structural predictions.
- Field testing and long-term monitoring may be conducted to provide feedback for further improvement.
- The impact on the environment may be ascertained after the long-term monitoring, which would also predict the sustainability and adaptability of such structures.

The above points may also be considered for academic projects to be conducted in laboratories on the prototype to predict the behaviour of such structures.

Appendix

Table 2. Combinations used for sandwiched deck analysis

Annotation	Steel layers thickness, t_s (mm)	Polyurethane layer thickness, t_p (mm)
D1	82.5	5
D2	80	10
D3	75	20
D4	70	30
D5	65	40
D6	60	50
D7	55	60
D8	50	70
D9	45	80
D10	40	90
D11	35	100
D12	30	110
D13	30	120
D14	30	130
D15	30	140

Table 2. Combinations used for sandwiched deck analysis - continued

Annotation	Steel layers thickness, t_s (mm)	Polyurethane layer thickness, t_p (mm)
D16	30	150
D17	30	160
D18	30	170
D19	30	180
D20	30	190
D21	30	200
D22	30	195
D23	30	191
D24	35	130
D25	40	120
D26	45	110
D27	50	100
D28	55	90
D29	60	80
D30	65	70
D31	70	60
D32	67.5	65

Declarations

Use of AI tools

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

Data availability statement

No Data associated with the manuscript.

Ethical approval (optional)

The authors state that this research complies with ethical standards. This research does not involve either human participants or animals.

Consent for publication

Not applicable

Conflicts of interest

The authors declare that they have no conflict of interest.

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Author's contributions

A.A.: Methodology, Software, Validation, Writing - Review & Editing, Visualization. D.K.S.: Validation, Formal Analysis, Supervision, Writing - Original Draft, Writing - Review & Editing, Visualization. P.A.: Supervision, Writing - Review & Editing, Visualization. All authors discussed the results and contributed to the final manuscript.

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