TMP UNIVERSAL JOURNAL OF RESEARCH AND REVIEW ARCHIVES

VOLUME 3 | ISSUE 4 | YEAR 2024 | OCT-DEC 2024

RECEIVED DATE	ACCEPTED DATE	PUBLISHED DATE
28/10/2024	29/11/2024	23/12/2024

Article Type: Research Article

Available online: www.tmp.twistingmemoirs.com

ISSN 2583-7214

AN EMPIRICAL ASSESSMENT OF THE MECHANICAL PROPERTIES OF COMPOSITE DECKS CONSTRUCTED VIA THE LAYERING METHOD AS COMPARED TO A FOREIGN SPECIMEN

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ABSTRACT

This research investigated the mechanical properties of a composite deck and determined the maximum percentage of its components. A foreign specimen (L: 29 cm, W: 14.5 cm, and T: 2 cm) was first prepared and validated for its components by weighing and then placing it in 30 steps of one and two hours in a 200 °C and a 500 °C oven. The composite deck's components were partially disassembled at each step, and the identified parts were weighted and compared with the currently available industrial materials. Overall, identifying the main components allows for the feasibility study of composite deck construction. In this research, the proposed composite was first constructed by imitating the foreign specimen and then evaluated by relevant tests to compare it with the foreign counterpart for its mechanical properties.

Keywords: Composite deck, Profile sheet, Mechanical properties, Sliding, Deflection

INTRODUCTION

In the modern world, breakthroughs in engineering require a mixture of material properties, as a single material having all the desired properties is currently lacking. Due to the paucity of such a versatile material, research needs to explore methods to merge the properties of the materials. The solution for this is to construct composites made up of multi-component materials that maintain properties much stronger than the properties of each single component while delivering a superb performance attained by the synergy between all the constituents.

Composite decks are constructed from wood of any shape, natural and chemical fibers, diverse types of resins, and special additives. The constructed composites differ widely depending on how (and at which percentages) the constituting compounds are used in the composite.

The marine industries in the Persian Gulf and Northern Iran need lightweight materials that possess high strength and superb resistance to moisture and ultraviolet (UV) irradiation and retain their strength at elevated temperatures. Due to the lack of such a versatile material, research needs to explore methods to merge the properties of the materials. The solution for this is to construct composites made up of multi-component materials that possess properties that are much stronger than the properties of each single component while delivering a superb performance attained by the synergy between all the constituents.

Regarding foreign composite specimens and according to the current documents and literature on the functional materials used in the composite decks constructed worldwide, the main components used for making such decks are natural fibers, resins, polymers, fillers, stabilizers, lubricants, and controllers.

Composite decks are increasingly used in modern construction, particularly in steel-concrete structures in large bridges with upper concrete plates of over 25 meters [1, 2].

When assessing composite decks, the strength and cross-sectional area of these structures need to be strictly reflected. Similarly, strain concentration in the areas surrounding steel beams needs to be particularly stressed in designs and final approvals [3].

Composite decks can potentially be impacted by shear lag caused by intentional loading, as well as other strains imposed on the deck's main plane due to the application of longitudinal loads [4].

Modeling bridges widened with composite decks entails specialized knowledge and should be carried out by expert designers. In recent decades, the impacts of shear lag have been a subject of concern in many studies. Von Karman et al. [5] proposed the concept of "effective width" in composite structures developed for the aviation industry. Reissner et al. [6] proposed "shear lag" in structural engineering and studied box beams by defining a parabolic function to describe transverse strength.

Jelsvik et al. [7] studied the impact of shear lag using the analog-beam method. Next, Zari et al. operated the method proposed by Reissner et al. to complete the Newmark model that is specially dedicated to composite beams with partial shear connection.

There are currently numerous methods to solve equations governing this problem. However, the finite element method (FEM) is the most employed technique, as defining special elements with the ability to reflect shear lag impacts is of paramount importance.

Concerning composite decking with shear-flexible connections, several Newmark-based FEM analyses have been proposed in studies, including polynomial functions, force-based elements, and mixed elements.

Composite decks function similarly to traditional reinforced concrete (RC) decks. However, the main difference comes from the fact that, in composite decks, the profiled steel sheet is effectively utilized with a higher significant cross-sectional area. The design load is the same for both conventional RC decks and composite decks. Likewise, the bending stresses on the profiled steel sheeting in composite decks are low due to the high moment of inertia. Accordingly, composite decks can more effectively carry higher load when compared to conventional RC decks. Furthermore, the high load-carrying capacity of composite decks has been justified by the literature mentioned below. Profiled steel sheet decking has low ductility and high strength which is a relatively new trend in the construction sector.

The strength of such decking is studied under combined flexure, web crippling, and moment-rotation capability. This allows using such type of profiled steel sheet decking economically. Akhand et al. [2] used cold-formed sheeting (Bondek-II sheeting) of nominal thickness 1.0 mm to conduct experiments on the dovetailed or re-entrant profiles. The test results showed that such kind of decking possesses high buckling sensitivity. Deck failure is caused by the yield of the profile ribs. After reaching the ultimate load, the profiled steel sheet delaminates from the concrete which gradually reduces the load on the profiled steel sheeting until load failure. After reaching its maximum load, the profile sheeting will fail due to yielding. Thus, profiled steel sheet decking has low ductility, high strength, and high load-carrying capacity.

Hyeong Yeol Kim and Youn Ju Jeong [3] proposed a new bridge girder with a longer and light-weight span compared to conventional RC decks. They experimentally investigated full-scale composite decks (700 mm × 1000 mm) and compared them with traditional RC decks of the same size. The proposed neutral axis of the deck systems was nearly located at half their depth. However, compared to the neutral axis, traditional RC decks were two-thirds of their depth. Likewise, the flexural rigidity of the composite decks was nearly twice that of the RC decks. The load borne by the composite decks was 2.5 times that of the traditional RC decks.

According to Wright et al. [4], the composite decks with steel sheets display load-deflection responses that follow a linear elastic path until the profiled steel sheet buckles. However, at the start of buckling, the load-deflection response follows a non-linear path. The profile starts yielding in the elastic state. Accordingly, composite decks have a higher load-carrying responses than conventional RC decks.

Baskar and Antony Jeyasehar [5] reported that providing frictional and mechanical interlocking in the profiled steel sheet allows for enhancing the composite behavior between concrete decks and the profiled steel sheet. Indeed, by using interlocking devices, the shear in the composite decks can be transferred longitudinally. As reported, this interlocking system provides higher interaction between the steel and the concrete. Bashar et al. [6] produced lightweight concrete by using the palm oil clinker aggregates (POC) as a full replacement for normal aggregates. They cast eight full-scale composite-deck specimens, of which six were made of palm oil clinker concrete (POCC) and two were made of traditional concrete. The results revealed that POCC is suitable to be used for structural applications with a weight reduction of 18.3% compared to traditional concrete composite decks.

Prajapati et al. [7] employed trapezoidal profiled stainless steel decking sheets to study the behavior of composite decks. They obtained a failure load at a maximum of 68 kN with a 135 mm shear span and noticed a corresponding maximum mid-span deflection of 12.28 mm. They further reported a load of 57.14 kN at the first crack, which was 84% of the failure load. It was found that shorter shear span specimens fail in shear bond mode, while longer shear span specimens fail in flexure mode. In another study, Shiming Chen and Xiaoyu Shi [8] worked with dovetailed and trapezoidal profile sheets. The results from the bending test obtained by Redzuan Abdullah and Samuel Easterling W. [9] and Chen S. [10] were taken for finite element (FE) validation. Likewise, Eldib M.E et al. [11] developed a new FEM including profile shapes and concrete crushing failure considering the contact mechanism between concrete and steel due to the profiled sheet form. They found that slips and deflections obtained by FE agree with similar values obtained from experimental results. Similarly, the FE research focusing on the interface contact model agreed well with the test results when comparing the experimental and FE analytical results. Ultimately, the performance and load-carrying capacity of composite decks were predicted.

Taking note of the above topics, this research explores a method to merge materials and construct a composite with certain properties such as lightness, high strength, and resistance to moisture and UV irradiation.

1. Raw materials with the highest percentage of purity available in the market were used to prepare the prototype. It was assumed that the layering process is impacted by the least volume of impurity.

2. The specimens were dried and decomposed at different stages in ovens and furnaces with very high thermal stability. The furnaces were provided with the maximum temperature required for the decomposition of the components of the foreign specimen.

The obtained optimized prototype was subjected to the foreign specimen to compressive strength, tensile strength, water absorption, and fire resistance tests, followed by comparing the results.

The proposed method

Tensile, compressive, water permeability, and fire resistance tests were conducted at Iran Polymer and Petrochemical Institute (IPPI), which holds highly accurate devices and equipment.

1. Structure

Based on the documents, the materials and components of the composite deck are the following:

1) Natural or chemical fibers such as glass fibers, straw fibers, and other natural fibers
2) Resins and polymers such as polyester and phenolic resins, propylene, and polyvinyl chloride polymers
3) Fillers such as calcium carbonate, talc, and fumed silica
4) Stabilizers such as antioxidants, titanium dioxide, and glass flake
5) Lubricants and controllers such as calcium stearate, paraffin ester lubricant
6) Compatibilizers such as polyolefin 1 and 4 DL glycidyl ether

The validity of the above components was assessed after the prototype was designed by imitating the foreign specimen with a length of 29 cm, a width of 14.5 cm, and a thickness of 2 cm. The specimen was first weighed.

Figure 1. The prototype

The prototype was then placed in 30 steps of one and two hours in a 200 °C and a 500 °C oven, respectively.

At each step, parts of the composite deck components were separated, and the identifiable components were compared with the existing and available industrial materials after weighing. Then, the main components were identified, including, by frequency, resin, fiber, wood fiber, and lubricants. These data were then used for the feasibility study and fabrication of the mold by imitating the foreign specimen.

2. Properties of the profiled steel sheeting

Cold-formed steel sheets (thickness: 1 mm) were purchased from the market. They were then rendered into the appropriate profile form through the press-breaking process. The profile sheets had a length of 1600 mm and a width of 750 mm. The cross-sectional area and its moment of inertia vary between the different profiles. Coupon tests were conducted on the cold-formed steel sheet to assess the structural properties. Table 1 presents the test results regarding the mechanical properties of the steel sheet.

Table 1. Mechanical properties of the steel sheet

Specimen ID	A_{sb} (mm^2)	Yield Strength, f_y (MPa)	Yield Strain, ε_y (μmm/mm)	Ultimate Strength, f_u (MPa)	Elongation, ε_u (%)
Ø8	52.6	459.0	2300	578.4	18.0
S	750	266.12	1520	324.79	27.4

Figure 2 shows the geometric variation of profiles of steel sheeting used for choosing the specimens.

By varying the br/bf ratio, the variation in the generic profile of the sheet is obtained. Likewise, it is possible to transform the profile from a dovetailed profile, rectangular profile, or trapezoidal profile by varying the br/bf ratio. The various profiles adopted and their corresponding cross-sectional dimensions are depicted in Figure 3. In a study, Burnet and Oehlers used a new form of push-out test with different rib shear connectors to investigate the parameters influencing the mechanical bond characteristics. They proposed a new design procedure with different profiled geometry with embossments, profile thickness, and cross-section area of composite decks.

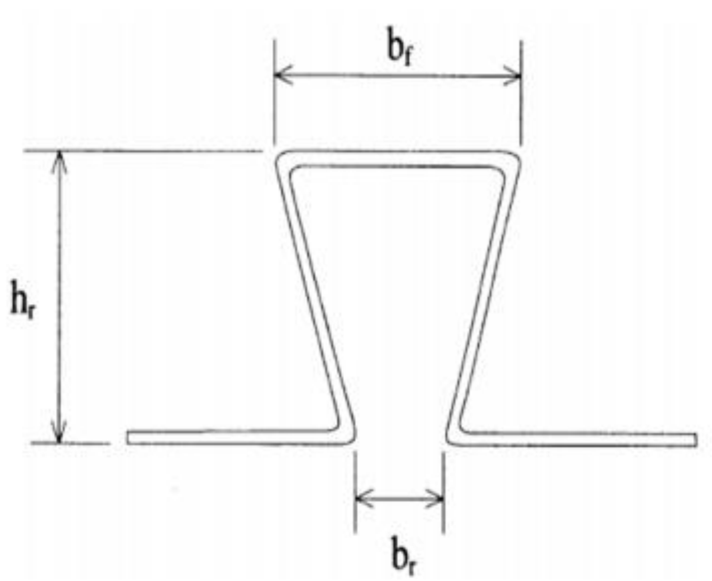

Figure 3. Generic shape of the profiled sheet rib. hr: height of rib, bf: width of flange, and br: width opening of ribs.

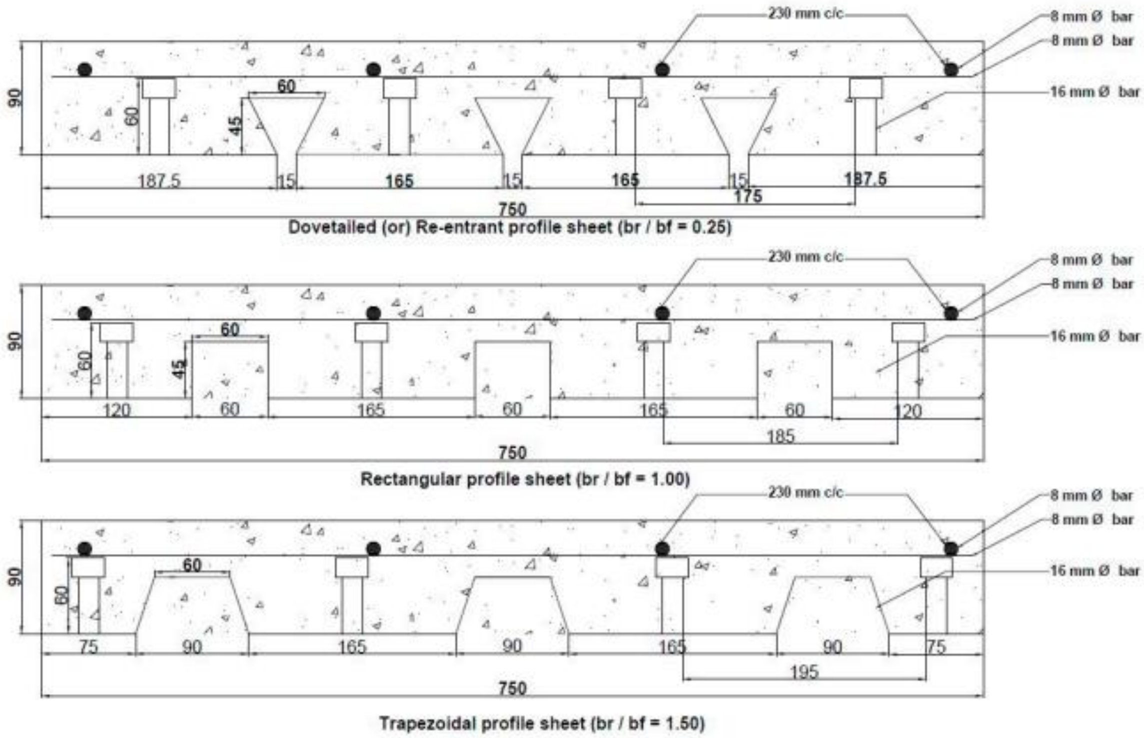

Figure 4. Cross sectional dimensions of profiled sheet

Figure 4 depicts the specimens fabricated from dovetailed, rectangular, and trapezoidal profiles, respectively, adopted for the present research. When measuring the actual dimensions of the fabricated profiled sheets and then comparing them with that of the ideal one, it was found that the dimensions vary in the maximum range of ±2%. Table 2 presents the geometric properties of profiled sheeting.

Table 2. Geometric properties of the profiled sheeting

Specimen Type	Area (mm^2)	Perimeter (mm)	Moment of Inertia (1 × 106 mm^4)		Radius of Gyration (mm)	
			Ix	Iy	Rx	Ry
Dovetailed	1224.87	2451.74	0.6	222.36	22.11	426.1
Rectangular	1048	2098	0.57	195.8	23.32	432.27
Trapezoidal	982.6	1967.2	0.581	187.4	24.32	436.7

Figure 4. Dovetailed, rectangular, and trapezoidal profiled sheet

(All the dimensions are in mm)

3. Mild steel bars

Cold-formed profiled sheets in composite decks serve to reinforce tension. A minimum reinforcement was provided to counteract the shrinkage and temperature effect. This research used mild steel reinforcement (diameter: 8 mm) spaced apart at 230 mm in both directions. The arrangement of bolted shear connectors on a profiled sheet and the arrangement of mild steel reinforcement are shown in Figure 5.

Figure 5. 6. Cold-formed sheet with bolted shear connectors and mild steel

4. Preparation

1. Cleaning of the mold with acetone
2. Drying the mold in six 45-min steps
3. Applying polyvinyl alcohol separating film

4. After one hour, layering of resin mixture and Vinyl ester with silica and glass flake compounds
5. Polyester resin layering with 450 grams of glass fibers and then mixing wood fiber with polyester resin
6. Vinyl ester resin layering with 600 grams of rattan fibers
7. Vinyl ester resin mixed with 150 grams of glass fibers

The fabricated prototype was weighed, and its weight was lower than that of the foreign specimen. After analyzing the materials obtained from ovens and furnaces while stressing high strength, less water absorption, and fire retardant (retardant), the percentage of wood fiber, silica, and fiber (450 grams) was minimized and replaced with calcium carbonate, aerosol, titanium, and fibers (150 grams). Then, the optimum specimen was fabricated by altering the formulation, following the steps below.

1. Cleaning of the mold with acetone
2. Drying the mold in six 45-min steps
3. Applying polyvinyl alcohol separating film
4. After one hour, layering of resin mixture and Vinyl ester with silica and glass flake compounds
5. Polyester resin layering with 450 grams of glass fibers and then mixing wood fiber with polyester resin
6. Vinyl ester resin layering with 600 grams of rattan fibers
7. Vinyl ester resin mixed with 150 grams of glass fibers
8. Layering of mix resin and phenyl ester with calcium carbonate, titanium, erucyl alcohol, aluminum hydroxide, talc, and 1 and 4 DL glycidyl ether after.

The fabricated prototype was weighed and its weight was lower than that of the foreign specimen.Then, both the optimized and foreign specimens were tested in the laboratory in IPPI regarding compressive strength, tensile strength, fireproofing, and water permeability (Figure 6).

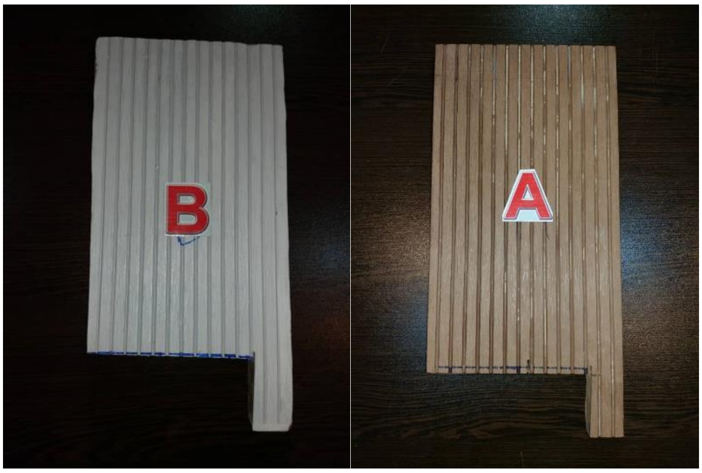

Figure 6. The optimized specimen

Findings

1. Compressive and tensile tests were conducted by a universal test system: The foreign and optimized specimens are shown in B and A, respectively.

Figure 7. Compressive and tensile tests

The foreign specimen (A) tolerates 77,270 Newton and has a tensile strength of 38.6 MPa. The corresponding values for the optimized specimens are 132,000 Newton and 1.56 MPa. These results are shown in Figure 2-4.

2) For the water permeability results, the mean water absorption values for foreign and optimized specimens are, respectively, 0.812 and 0.557.

3) Burning test results were the same for both specimens.

Deflection

Based on the linear variable differential transducer (LVDT), the deflection curve at mid-span at the central trough of the profiled sheeting in rectangular and trapezoidal composites was linear. Figure 8 depicts the load versus deflection curve. Composite decks with rectangular and trapezoidal profiles are experimental.

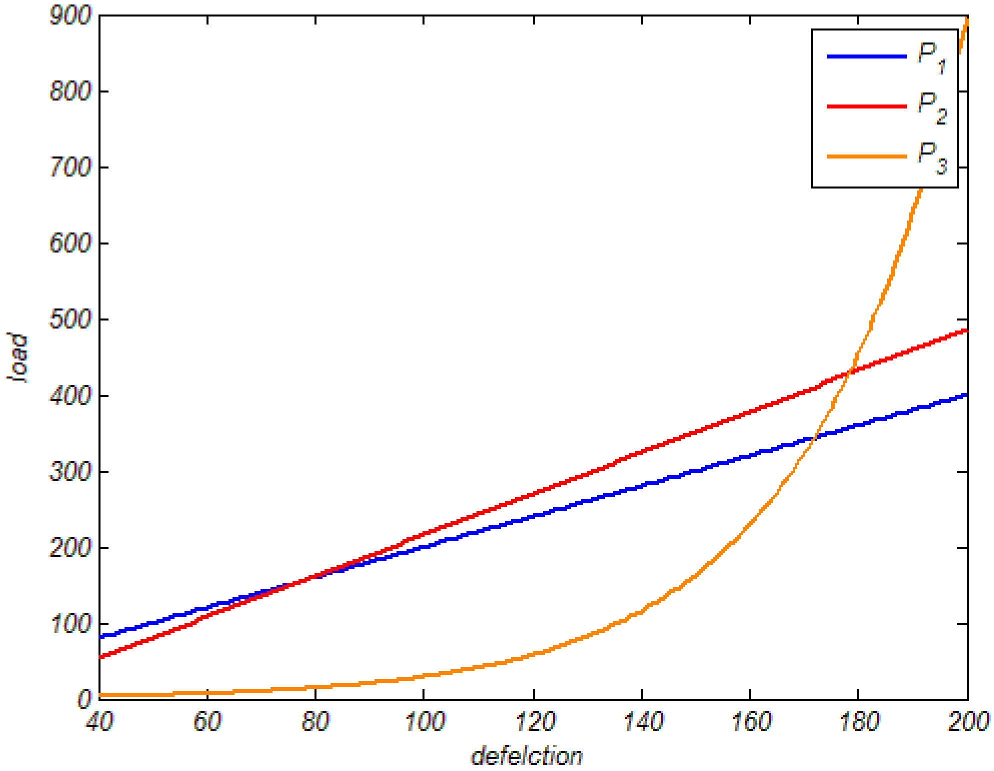

Figure 8. Load versus deflection curve of profiled composite decks in all trials

In all the profile shapes, a linear elastic path follows the load-deflection behavior until the steel sheet starts to buckle. After that, the nonlinear load-deflection behavior of the linear elastic path follows the load-deflection behavior of all profile shapes until yielding. Thus, the ultimate strength is much greater than the strength at the first buckling of the steel sheet. This is due to the nonlinear load-deflection behavior of the material. Thus, the ultimate strength is much higher than the initial strength, and several profiles are made in the linear, non-linear part of the load-carrying range to carry the loads. Figure 8 shows that the range of carrying loads is up to working loads. As shown, in the decks with the span, the linear profile carries maximum loads of 93.5 kN, while the deflector, a profile, carries maximum loads of 993.5 kN.

The deflection is 28.53 mm, which is minimal compared to other profiles such as 28.53 mm, which was minimal compared to trapezoid and rectangular profile decks.

End slip

Slip is the relative horizontal displacement between concrete decks and the profiled steel sheeting and is measured using dial gauges. Figure 9 shows end slips of rectangular profiled composite decks.

Figure 9. Slip of rectangular profiled composite decks

Figure 10 shows the load versus slip curve of dovetailed. Rectangular and trapezoidal profiled composite decks of trial I and trial II.

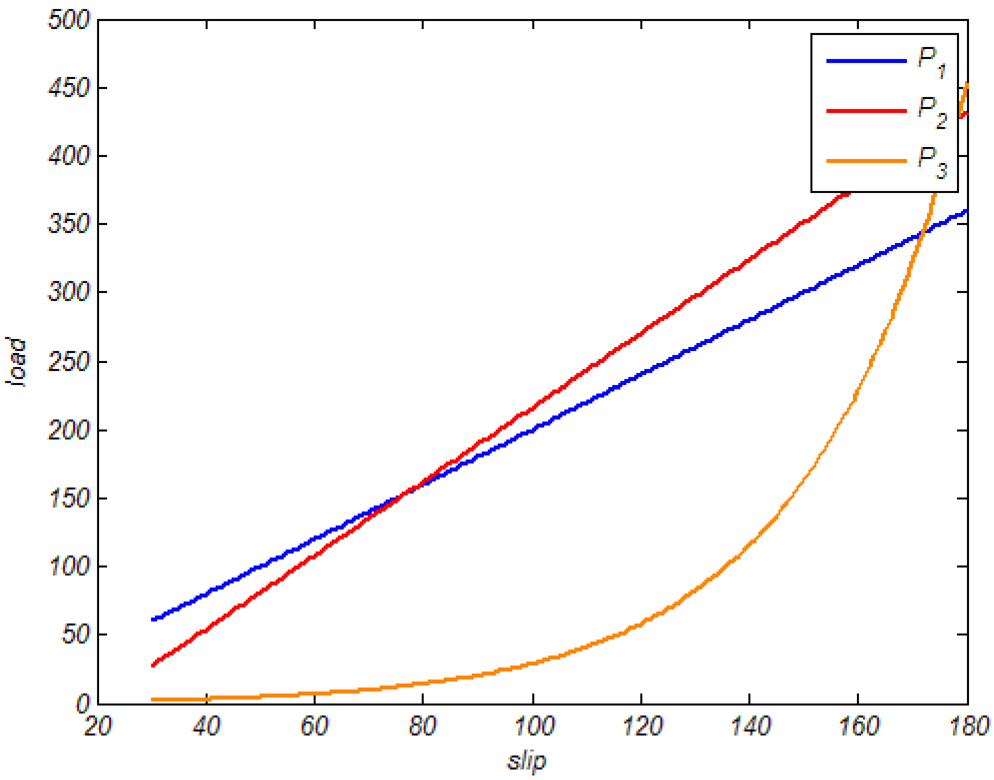

Figure 10. Load versus slip curve of profiled composite decks for trials I and II

Strain energy

The total energy stored by the composite decks under static flexural load was determined. The area plotted between the load and deflection is the total strain energy stored by the material. The strain energy was calculated for all three shapes of profiling in the composite decks. It was found that rectangular and dovetailed profiled composite decks have attained the strain energy of 2.86 kNm and 2.1 kNm, respectively. Likewise, the maximum strain energy obtained for the trapezoidal profiled composite decks was 2.98 kNm. However, the load-carrying capacity of the trapezoidal profiled decks was 22.03% lower than that of the dovetailed profiled composite decks.

The higher deflection in the trapezoidal profiled composite decks results in higher strain energy carrying capacity of the sections. Energy stored in the composite decks is shown in Figures 11 to 13.

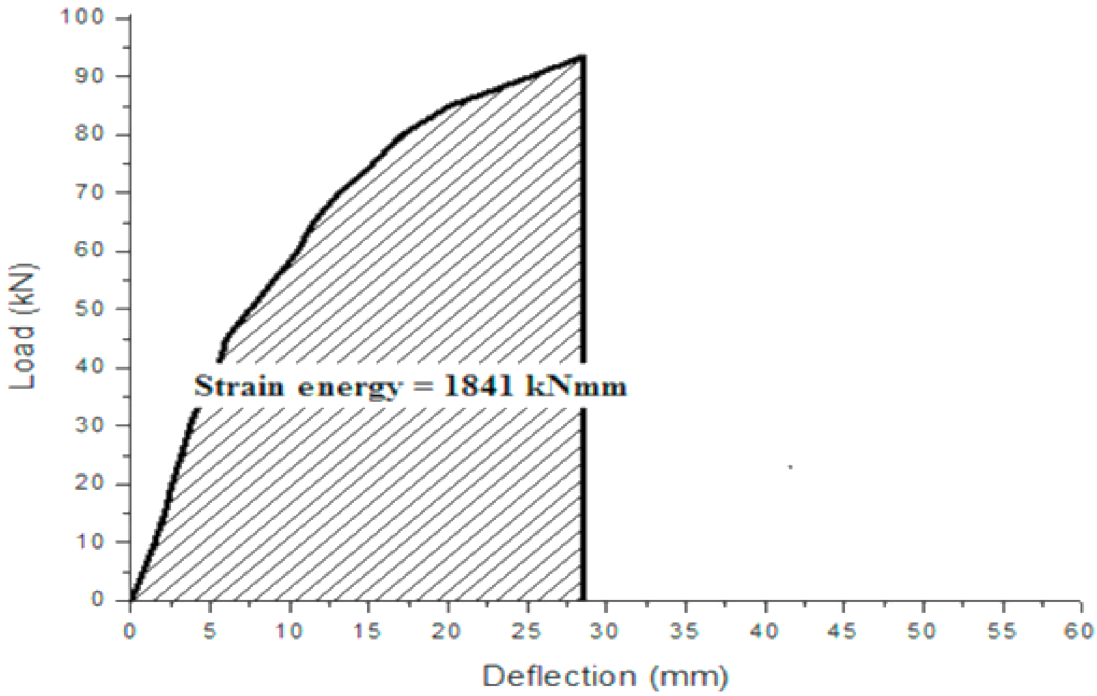

Figure 11. Strain energy of dovetailed profiled composite decks in trial 1

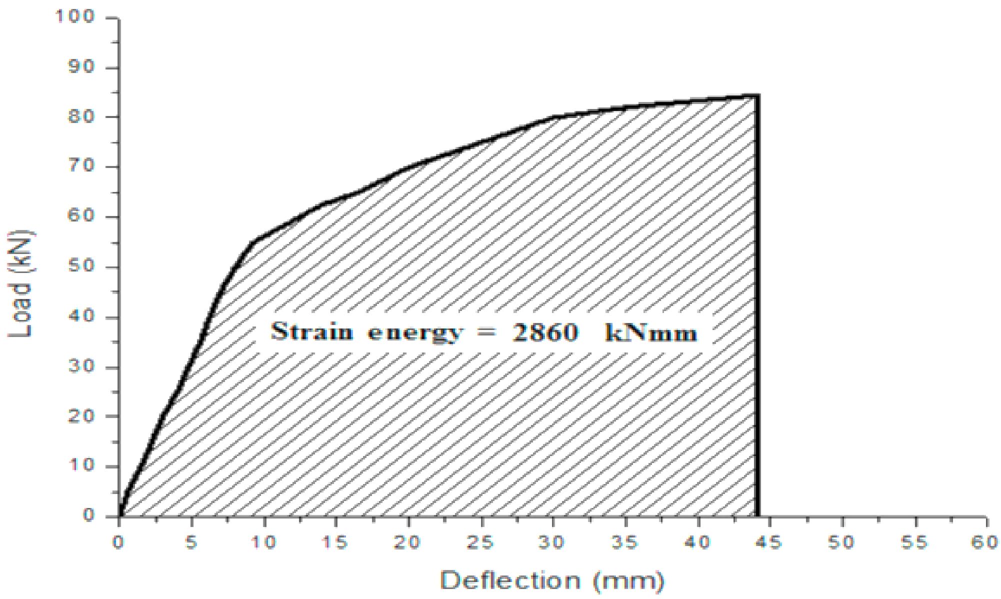

Figure 12. Strain energy of rectangular profiled composite decks in trial 1

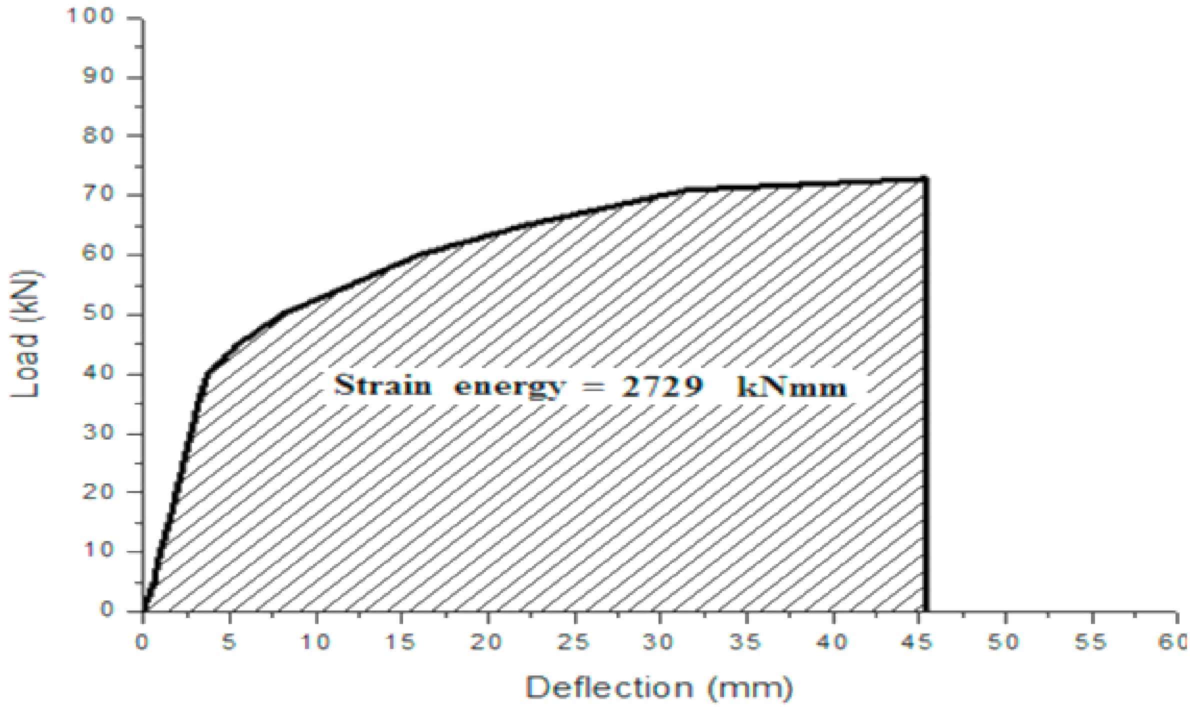

Figure 13. Strain energy of trapezoidal profiled composite decks in trial

The compressive and tensile strength values for the optimized specimen are 1.7 and 1.5 times higher than that of the foreign specimen, respectively. Likewise, the water permeability of the optimized sample has decreased by 1.46 times compared to the foreign specimen. Based on these, the final formulation for fabricating the optimized specimen is as follows:

1) Layering vinyl ester resin mix with 1% calcium carbonate, 3% 4-DL glycidyl ether, 4% aerosil, 2% titanium, 2% talc, 20% aluminum hydroxide, and 2% glass flake

2) Polyester resin layering with 150-gram glass fibers

3) Layering of polyester resin with 600-gram rattan fibers

4) Polyester resin layering with 150-gram needle fibers

5) Layering mixed resin and vinyl ester with 20% aluminum hydroxide, 4% aerosol, 2% talc, 1% calcium carbonate, 2% titanium, 1 and 4 DL glycidyl ether 3%, and glass flake 2%.

CONCLUSION

Based on experimental studies, this research investigated the behavior of the composite decks with different profiled sheeting. The best cold-formed sheeting profile that suits the composite decks was chosen. Collectively, the results obtained are as follows:

- The behavior of the shear connector composite decks largely depends on the ratio of the opening width at the rib to the opening width at the top flange (br/bf).

- The load-carrying capacities of the dovetailed composite decks are 5.35% and 22.03% greater than rectangular and trapezoidal profiled composite decks, respectively.

- Deflection and slips of dovetailed, or re-entrant, profiled decks are lower than that of rectangular and trapezoidal profiled decks.
- Dovetailed, or re-entrant, profiled decks have high resistance to vertical separation.
- The trapezoidal profiled composite decks attain the maximum strain energy of 2.98 kNm.
- Compared to rectangular and trapezoidal profiled composite decks, the strain energy stored by the material is lower for the dovetailed profiled composite decks.
- A rise in the ratio of the opening width of ribs to flange width enhances the ductility ratio.
- The ductility ratio for trapezoidal profile is 36.3% and 55% higher than that for rectangular and dovetailed profiled composite decks, respectively.
- Trapezoidal profiled decks fail by shear bond mode. This is the predominant failure in composite decks and needs to be minimized.
- The slip at early stages was negligible for all the specimens. In the plastic stage, the magnitude of slip enhanced significantly with loading.
- The specimen's elastic and plastic behavior largely depends on shear span and loading. Thus, if the investigation highlights the elastic behavior and long shear span for plastic behavior, a short shear span is then recommended.
- For all the composite decks failing in flexure, the ductility ratio can be defined as the ratio of curvature at ultimate to yield moment capacity.
- After yielding, ductility indicates that the deformation capacity of trapezoidal composite decks is higher than its energy dissipation ability when compared to other composite decks.

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