Journal of Infrastructure Planning and Engineering (JIPE)

Journal homepage: https://ejournal.warmadewa.ac.id/index.php/jipe

Composite structure in the Kutus-kutus factory building, Gianyar, Bali

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Received on 6 September 2022, accepted on 18 October 2022, published on 26 October 2022

ABSTRACT

This study focuses on the design implementation and performance analysis of concrete-steel composite structure of a four-story Kutus-Kutus Factory, a facility for the production of herbal oils, built in the seismically active Gianyar district of Bali. In order to create an efficient, fully composite cross section, the design process uses an analytical approach that emphasizes the relationship between the concrete slab and steel beams as well as the design of each of these components. The structure was designed and assessed in accordance with Indonesia Building Standard guidelines for minimum load, earthquake-resistant, and concrete and steel-based material requirements. The final results of the design confirmed that the composite performance is strong enough to withstand enormous loads combined in industrial buildings, particularly in seismically active areas, and can operate within the recommended safety margins and restrictions. This paper ends with a call for more research on the real application of composite structure design in Indonesia, which can then assist the rapidly expanding Indonesian construction industry in maximizing the advantages of using composite construction techniques.

Keywords: composite; dynamic analysis; shear connector; structure

1 Introduction

A composite structure is made up of two or more types of construction materials, each with its own strength, that work together to form a stronger structural component [1], [2]. Composite structures are typically stronger than non-composite structures because each of their constituent materials has unique advantages in supporting the structure's strength [3]. The structural design incorporates steel beams that are combined with concrete slabs via shear connectors, as well as steel columns. The benefits of composite design include steel weight savings of 20% to 30%, which are frequently obtained by utilizing all of the benefits of composite systems [4]–[6]. Due to their effective use of materials, steel-concrete composite structural systems are being used more frequently in the construction industry and are the focus of intense research at top universities and corporations around the world [7], [8].

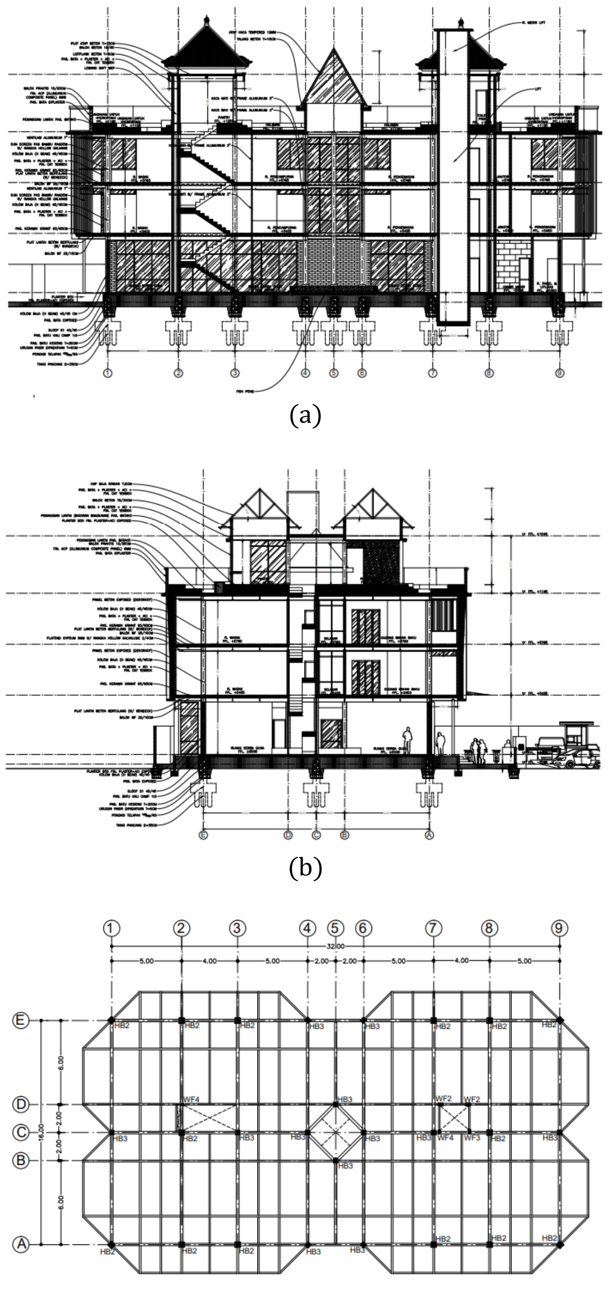
This study focuses on the design application and performance investigation, which emphasize an analytical approach to the connection between the concrete slab with steel deck and the steel beams, as well as the design of each of these elements to create an effective, and completely composite cross section capable of withstanding the heavy load combination in seismically active sites and industrial buildings. Both the design philosophy and the limitations of the current design are presented. This paper ends with a call for more research on the design guidelines, which can then assist the rapidly expanding construction industry in maximizing the advantages of safe implementation of composite construction techniques.

The design techniques were used in real construction plan of the Kutus-Kutus Factory in Gianyar, Bali, which designed with a length of 36 m, a 20m width, and a building height of 4 floors, requiring a fast and slim fabrication. Realistic and accurate loadings were simulated through finite element analysis. The design results were assessed to be within guideline limitations for serviceability of the building.

https://doi.org/10.22225/jipe.1.2.2022.81-86

2 Data and Methods

Figure 1 depicts the four-story, composite-material-built Kutus-Kutus Factory, a facility for the manufacture of herbal oils. This factory was built in Gianyar, Bali, which is a seismically active area. The structure was designed in accordance with SNI-1727-2020, minimum load requirements for buildings [9], SNI-1726-2019 guidelines for designing earthquake-resistant buildings [10], SNI-2847-2019's requirements for structural concrete in buildings [11], and SNI-1729- 2020's requirements for structural steel buildings [12].



(a)

(b)

(c)

Figure 1. Kutus-kutus factory: (a) side portal view; (b) front portal view; (c) plan view.

The design process employs an analytical approach that focuses on the connection between the concrete slab and the steel beams, as well as the design of each of these elements to produce an effective, fully composite cross section capable of withstanding shear force.

2.1 Composite slab strength design.

The composite slab was designed with concrete in a metal deck and a one-way slab system. The minimum thickness of the slab and can be determined as [12]: Nominal rib height (h_r) is not greater than 75 mm ($h_r \leq 75$). The average width of the ribs or concrete haunches (w_r), shall be not less than 50 mm ($w_r > 50$), but shall not be taken in the calculations as more than the minimum clear width near the top of the steel deck. And the slab thickness over can be taken as <50mm.

The composite slab bending strength can be expressed as follows[12]:

$$M_{n+} = T_d\ (D_p - \tfrac{a}{2}) \quad \text{......} \quad (1)$$

$$M_{n-} = A_s\,.\,f_{yd}\,.\left(d - \tfrac{a}{2}\right) \quad \text{......} \quad (2)$$

In which, D_p, T_d, a, and M_{n+} are slab effective thickness, steel deck tensile strength, concrete compression thickness, and slab positive bending nominal strength, respectively. Furthermore the slab negative bending nominal strength, M_{n-}, were governed by, A_s, f_{yd} and d, which are rebar area, rebar strength, reversed effective slab effective thickness, respectively, as depicted in **Figure 2**.

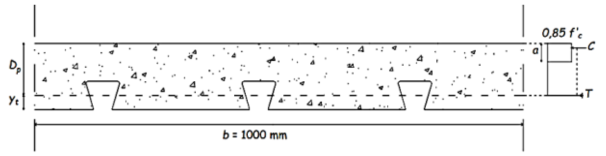


Figure 2. Concrete slab with steel deck cross section.

In addition, the slab shear strength, V_c, were governed by its dimensions and concrete material strength, which can expressed as follow:

$$V_c = 0.17\lambda\sqrt{f'_c}.\,b.\,d \quad \text{......} \quad (3)$$

Where λ equal to 1 according to SNI-2847-2019 [11].

2.2 Shear connector design

The shear connector is critical for integration of the slabs and the beams, visualized in **Figure 3**. The diameter of the stud, shear connector, considered based on the base plate thickness, not more than 2.5times, while its length can be taken as 4 times of the diameter. The nominal shear strength of a steel stud embedded in a solid concrete slab or a composite slab with a deck, Q_n, can be calculated and need to comply following expression[12]:

$$Q_n = 0{,}5A_{sa}\sqrt{f'_c E_c} \leq R_g R_p A_{sa} F_u \quad \text{......} \quad (4)$$

In which, A_{sa}, E_c, and F_u are cross section area of stud, concrete young's modulus, and stud tensile strength, respectively. R_g and R_p are installation orientation factors that can be determined using **Table 1.**

Table 1. Installation orientation factors [11].

Condition	R_g	R_p
Without steel deck	1.0	0.75
Deck parallel to beam steel section		
$\frac{w_r}{h_r} \geq 1.5$	1.0	0.75
$\frac{w_r}{h_r} \leq 1.5$	0.85	0.75
Deck perpendicular to beam steel section; Number of stud in same deck rib		
1	1.0	0.6
2	0.85	0.6
3 or more	0.7	0.6

Furthermore, the number of stud can be determined from the sections with the greatest positive or negative bending moment, and shall be equal to the horizontal shear divided by the nominal shear strength of one steel anchor.

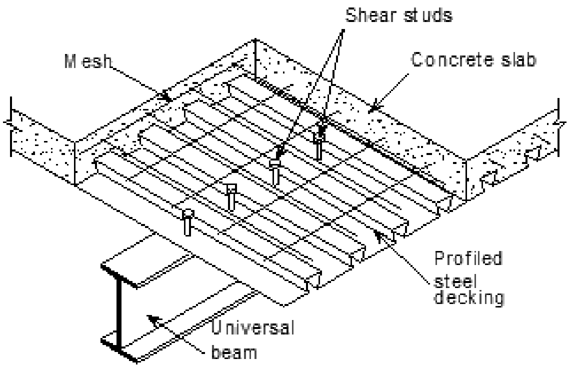


Figure 3. Shear stud connecting slabs and beams [13]

2.3 Composite beams design

The strength of the composite beam is governed by the stress distribution, and it's depend to plastic neutral axis which influenced by compression in concrete, *C*, and tensile in steel, *T*, resultant force. Therefore, the positive bending strength can be vary based on following conditions (for compact profile) [12]:

For T≤C, plastic neutral axis is within concrete slab,

$$M_n = M_p = F_y A_s (Y_2 + \tfrac{1}{2} d_b) \tag{5}$$

For T>C, plastic neutral axis is in steel beam flange,

$$M_n = M_p = C(Y_2 + \tfrac{1}{2} d_b) + C_{sf}\,(d_b - y)\tfrac{1}{2} \tag{6}$$

For T>C, plastic neutral axis is in steel beam web,

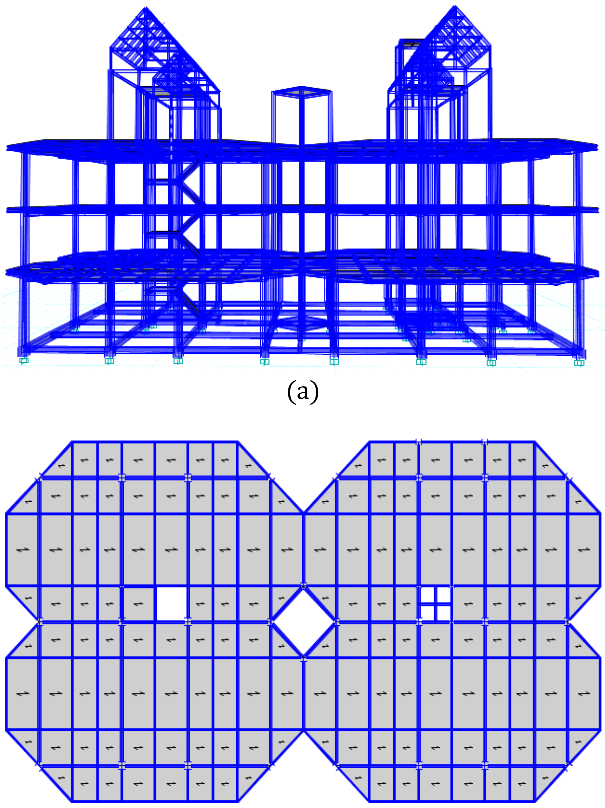
$$M_n = M_p = C(Y_2 + \tfrac{1}{2} d_b) + C_{sf} y_f + C_{sw} y_w \tag{7}$$

In which, Y_2, and d_b is the distance from compression resultant to beam section upper fiber and the beam height, respectively. Furthermore, C_{sf}, and C_{sw}, are the compression occurs in steel beam flange, and web respectively. While, y_f, and y_w are the distance to plastic neutral axis from C_{sf}, and C_{sw}, respectively.

In addition, the negative bending and shear strength of the composite beam can be determined based on the steel beam shear capacity alone.

2.4 Finite element analysis of the structure

The Kutus-Kutus Factory in Gianyar, Bali, was modelled using ETABS software [14], as shown in **Figure 4.** The structure modeled thoroughly and into a single unit and loaded realistically from the roof to the frame for more accurate internal forces [15].


(a)

(b)

Figure 4. Structure model: (a) front view; (b) typical plan view of the model.

The material strength for composite structural design is 25MPa for concrete and 240MPa for both beams and deck material, with young's modulus of $4700\sqrt{f'_c}$ MPa and 200GPa for concrete and steel, respectively. The floor slab received dead and live loads of 152 kg/m^2 and 245 kg/m^2, respectively. The earthquake load is calculated using following factors, which correspond to the construction site; $I_e = 1.5$, $S_{D1} = 0.501$, $S_{DS} = 0.724$, S_D location class and $R = 8$, $C_d = 4.5$, resulting in a spectrum that determines the structure responses.

3 Results and Discussion

3.1 Composite slabs performance

The moment demand were quite uniformly distributed on the composite slabs, as shown in **Figure 5** and listed in **Table 2.** Equations (1), (2), and (3) yield the 75mm, 50mm, and 50mm rib height, width, and concrete thickness over the rib, respectively, for the composite slab design, which also uses wire mesh with an 8mm- diameter and 150mm-space in between. As a result, the strength inherent in the composite slabs was 28.7kN.m for positive bending capacity and 4.5kN.m for negative bending capacity, which were sufficient to resist the moment demand.

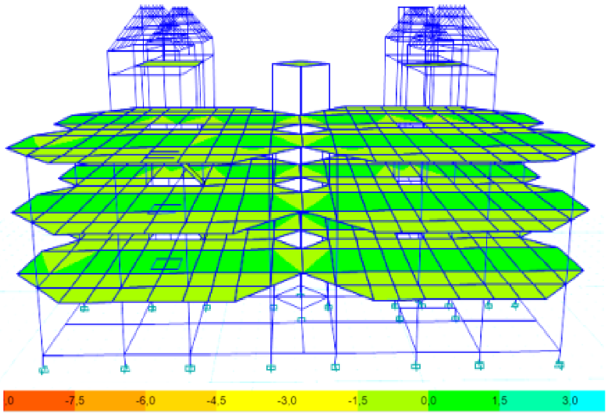


Figure 5. Moment distribution in composite slabs.

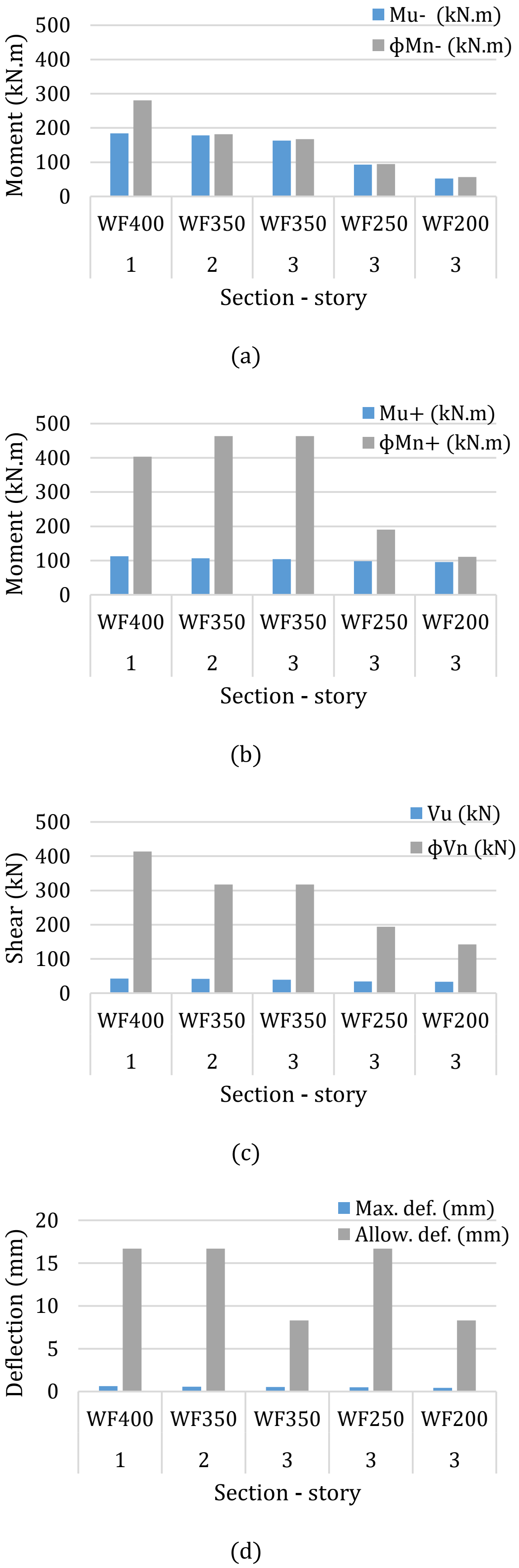
The composite slab has also been assessed to be within the allowable deflection, *L/240*=16.7mm, which reflects the slab element's serviceability. Note that *L* is the slab span.

Table 2. Ultimate moment demand and maximum deflection in composite slab.

Story	M_{u+} (kN.m/m)	M_{u-} (kN.m/m)	Maximum deflection (mm)
1	5.9	4.4	15.0
2	5.7	4.2	14.6
3	4.2	2.6	14.3

3.2 Performance of composite beams with shear connectors

The demand for composite beams was much more uniform in the positive moment than in the negative moment. Based on this demand and the design method described in section 2, the steel beam section used in this structure can be obtained, as shown in **Table 3.** The design was controlled by the negative moment, as can be seen in **Figure 6**(a), and the nominal capacity of the beam efficiently resists the negative moment demand, while the positive moment and shear demand are significantly outweighed by its nominal capacities, as shown in **Figure 6**(b) and (c). Additionally, the beams' deflection was significantly less than the limit set by the building regulations [12].



(a)

(b)

(c)

(d)

Figure 6. Composite beams performance: (a) positive moment; (b) negative moment; (c) shear; (d) deflection.

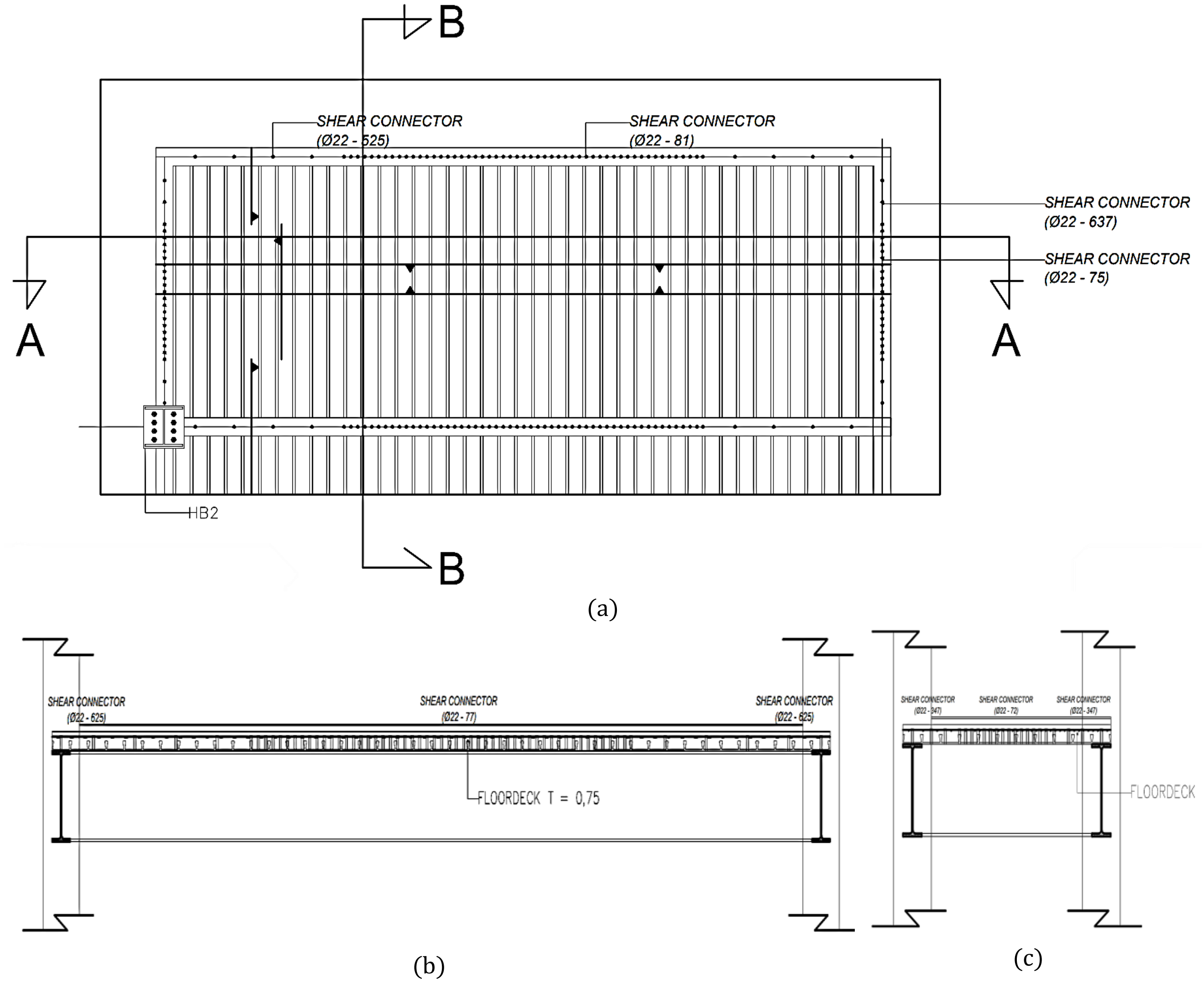
Table 3. Moment demand-capacity and maximum deflection in composite beams.

Story	Section	M_{u+} (kN.m)	ϕM_{n+} (kN.m)	M_{u-} (kN.m)	ϕM_{n-} (kN.m)	V_u (kN)	ϕV_n (kN)	Max. def. (mm)	Allow. def. (mm)
1	WF400	113	403	184	281	43	414	0.64	16.7
2	WF350	107	463	178	182	42	317	0.56	16.7
3	WF350	104	463	163	167	39	317	0.53	8.3
	WF250	98	190	93	95	34	194	0.48	16.7
	WF200	96	111	52	57	33	142	0.43	8.3

Such performance of the composite beams can be achieved due to the influence of the shear connector. The procedure mentioned in section 2 results in 22mm-diameter with 100mm length stud. The detail number of the stud for each beams were listed in **Table 4**. As can be seen, the number of studs required in the middle of the beams was greater than those required at the ends of the beams, reflecting the design proportion to the relative shear and deflection demand at the beam-slab interface. The final design of the composite element were shown in **Figure 7**.

Table 4. Shear connector design.

Story	Section	Number of stud		Space (mm)	
		Mid	End	Mid	End
1	WF400	24	4	84	250
2	WF350	26	4	77	264
3	WF350	14	2	72	637
	WF250	16	2	125	347
	WF200	12	2	84	625



(a)

(b)

(c)

Figure 7. Typical detail of design: (a) plan view; (b) A-A view; (c) B-B view.

4 Conclusion

The composite construction of Kutus-Kutus Factory utilizing composite structure was presented. In this application, the composite designed using concrete slab with steel deck connected to the steel beam via shear connectors. The construction techniques assessment verified the performance are provides sufficient strength to resist the heavy load combination in industrial building, especially in seismically active area, and can perform within the guideline safety margins and limitations.

Due to the composite slabs' complete unification with the steel beams and the increased rigidity provided by the concrete and steel combination, resulting in a successful design outcome. It should be noted that the design in this study may be identical to future construction, despite the dimensions being determined by the specific conditions of the individual project, such as the construction budget and schedule. This type of construction technology and design will most likely be advancing in the future.

Acknowledgement

The architectural drawings and soil test data used in the design were provided by Agora Design Bali, and thus it is acknowledged.

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