Flexural Behaviour of Cold Formed Steel-Timber Composite Flooring Systems

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Abstract: Composite flooring systems comprising cold-formed steel beams and timber floorboards have been proposed recently for building flooring as efficient, economical, durable and sustainable solutions. In this study, a parameterised 3D finite element model for analysing the performance of such flooring systems has been developed and validated against experimental data reported for a specific steel/Particle Boards (PB) flooring system in the literature. Once validated, the model was used to investigate the flexural behaviour of various composite floors by replacing the Particle Boards (PB) with a range of sustainable engineered products with known mechanical properties. The results of this study provided insights into the usage of various sustainable engineered board products in novel composite flooring systems and the importance of their elastic constants. It has also become apparent that the flexural behaviour of the studied composite flooring systems is mainly governed by the connections between cold-formed steel beams and the floorboards.

Keywords*: Cold-Formed Steel Beams, Composite Floors, Finite Element Method, Engineered Timber Products, Flexural Behaviour*

1. Introduction and Background

Composite structures have been used extensively in the construction industry since the beginning of the 20th Century and have significantly and rapidly evolved over the years (Pelke & Kurrer 2015). The recent trend in structural engineering has been to implement steel and concrete composite slab systems in building construction in order to reduce the time and costs associated with traditional concrete flooring systems. Whilst innovative, this technique has been around for over twenty-years and is generally limited to profiled steel sheeting and reinforced concrete (Hsu et al. 2014). In the past few years, composite flooring systems comprising cold-formed steel beams and timber-based floorboards have been proposed for building flooring since they provide efficient, economical, durable and sustainable solutions (Kyvelou et al. 2018). A typical set out of the cold-formed steel and engineered timber composite flooring system is illustrated in Figure 1. This system can be simply installed above the larger structural hot rolled steel beams. Structural material properties and characteristics significantly influence the performance of structures (Samali et al. 2011; Tabatabaiefar et al. 2012; Fatahi & Tabatabaiefar 2014; Tabatabaiefar & Clifton 2016) and recent studies (e.g. Far et al. 2017; Saleh et al. 2018) have highlighted the merits of using cold-formed steel in building industry. Xu and Tangorra (2007) conducted an experimental investigation on vibration characteristics of typical flooring systems comprising cold-formed steel C-shaped joists and timber floorboards. However, their experimental investigation did not take into account the possibility of composite action mobilisation between the cold-formed steel C-shape joists and timber panels in the system. Li et al. (2012) examined the potential of using light weight bamboo–steel composite slabs as flooring systems and their results showed that the bamboo–steel composite slabs have the potential to replace concrete slabs in low-rise buildings. Zhu et al. (2016) studied the structural behaviour of composite light-gauge steel truss girders and oriented strand boards. After series of experimental tests, they realised that the spacing of the fasteners can significantly influence the overall stiffness and capacity of the composite system.

Even though the above mentioned experimental studies showed promising results, in order to better understand the main features of the structural behaviour and to further develop the existing pool of data, further investigations seem to be needed in order to more precisely quantify the potential benefits derived due to development of composite action within cold-formed steel flooring systems. Developing innovative composite flooring systems requires developing an extensive testing program to examine and verify the reliability of these systems under various loadings which could be quite time consuming and expensive. Having accurate finite element tools for simulating the structural response of such systems could accelerate such systems development. Hence, a parameterised finite element model is developed in this study to numerically investigate flexural behaviour of various composite floor systems consisting of floorboards with a range mechanical properties. It should be highlighted that Kyvelou et al. (2018) carried out numerical studies only on the structural behaviour of flooring systems composed of cold-formed steel beams and PB. As there is a wide range of engineered wood and bamboo products available in the market, this study explores the potentials of using other sustainable products (such as OSB (Oriented Strand Board), LSL (Laminated Strand Lumber), LVL (Laminated Veneer Lumber) and Laminated Bamboo boards) as alternatives to PB in composite flooring systems. Therefore, this paper complements the previous studies by investigating the effects of using different types of floorboards on the structural response of composite floors in order to achieve a better understanding of the structural behaviour of various sustainable products when used in conjunction with cold-formed steel.

2. Numerical Approach

Several studies (e.g. Queiroz et al. 2007; Vasdravellis and Uy 2014; Kyvelou et al. 2018) have utilised commercial finite element software to simulate the nonlinear behaviour of composite systems. Queiroz et al. (2007) developed numerical simulations of composite beams with full and partial shear connection and highlighted the importance of developing finite element models able to predict the behaviour of structural systems in order to complement experimental investigations. Pavlović et al. (2013) presented finite element models capable of accurately simulating push-out tests on composite steel-concrete members while Vasdravellis and Uy (2014) developed numerical simulations which successfully replicated bending tests on composite systems comprising steel beams and concrete slabs.

In this study, the finite element software package SAP2000 v20 has been utilised for the numerical investigation. SAP2000 is a versatile commercial finite element software which enables users to consider various boundary conditions and connection systems with high accuracy. The comprehensive set of experimental data of Kyvelou et al. 2017 has enabled the author to validate the model based on various types of boundary conditions. Once validated, the model was used for conducting parametric studies and exploring the effects of variation in floorboard mechanical properties on the structural response of composite floors. The main features and details of the developed finite element model have been described in the following sub-sections.

2.1. Material Inputs

The material properties are obtained from measurements reported in the literature. Cold-formed steel sections are assumed to exhibit nonlinear behaviour represented by the modified Ramberg and Osgood as described in Kyvelou et al. (2018). The parameters used in the modified Ramberg and Osgood material model are similar to those reported in the literature and the summary of stiffness and strength properties are given in Table 1.

For floorboards, similar to Kyvelou et al. (2018), the elastic properties of PB are adopted from coupon test data conducted by Kyvelou et al. (2017). It should be highlighted that the same mechanical properties of PB were chosen in this study so that the predicted structural response of cold-formed steel and PB systems could be compared with experimental data in Kyvelou et al. (2017) as well as their numerical predictions reported in Kyvelou et al. (2018). Such comparisons enabled the author to assess the accuracy of his numerical model and validate it for the next steps. Once validated, the cold-formed steel and PB system can be used as a benchmark case to investigate the effects of using floorboards with different stiffness and strength values. Material properties of engineered wood and bamboo products considered for numerical investigation in this study have been tabulated in Tables 2 and 3. These properties were collected from the literature based on the data reported by various researchers (e.g. Bai et al. 1999; Janowiak et al. 2001; Sharma et al. 2015; Chen & He 2017; Moradpour et al. 2018).

2.2. Contacts and Boundary Conditions

The 6 m floor has a total width of 1200 mm and is supported across a 5800 mm span. The floor has simple supports at one end while the other end is supported by roller supports in order to create a statically determinate flooring system. A frictionless contact between floorboards and steel was considered using nonlinear GAP elements in SAP2000 for simulating the behaviour of composite systems with no connections (zero shear connection). To simulate the behaviour of the most efficient case (ideal case), full (perfect) bonding instead of frictionless contact has been also considered. For partially connected systems (practical case), 2-joint Link/Spring objects have been introduced between the nodes of the bottom surface of the floorboards and the top surface of steel (at equal intervals). Incorporating various contacts between the floorboards and the steel in the developed parameterised model has enabled the author to demonstrate the range of possible cases and structural responses that could occur in practice. Figure 2 illustrates an overview of the developed numerical model geometry and boundary conditions.

2.3. Modelling of Screws

The load-slip responses of screws were determined experimentally by Kyvelou (2017). Such response is incorporated into the SAP2000 model using 2-joint Link/Spring objects with known stiffness values to simulate the behaviour of screws (Figure 2). For this purpose, the initial slope of the experimental curve from push-out tests, described empirically in Kyvelou (2017) is adopted. In other words, Link/Spring objects with similar stiffness and spacing were employed to represent the shear connections between the cold-formed steel and timber floorboards. For parametric studies, constant parameters were adopted to simulate the behaviour of partially connected floor systems. More realistic models could be incorporated based on a series of connection tests that are envisioned to be conducted in the future.

2.4. Element Type and Meshing

The model has been discretised using quadratic Solid elements in SAP2000 software. Fine mesh was generated for both the floorboard and cold-formed steel beams along the longitudinal axis of the floorboards (Figure 2). Additionally, the mesh was generated such that the nodes of the bottom surface of the floorboard and those of the top surface of steel beams match with each other. Solid elements were used for steel and floorboard to capture the true thickness stress and strain distribution in both components accurately. Nonlinear, large-deformation analysis has been conducted using various mesh sizes until convergence was achieved.

3. Validation of the Developed Numerical Model

To validate the accuracy of the numerical model developed in this study, the numerical results have been validated against the results of physical tests performed by Kyvlou (2017). The validated model was then employed in Section 4 to predict the behaviour of various steel/timber composite floors by replacing the wood-based Particle Boards (PB) with various engineered wood and bamboo products with known mechanical properties reported in the literature. The thickness of floorboards (38 mm), width of the floorboards (1200 mm), and the height of the steel section (250 mm) were kept constant.

Kyvlou (2017) carried out 12 physical tests on flooring systems comprising cold-formed steel beams and wood-based Particle Boards (PB). The mentioned experimental data were provided for floors with various spacing between the shear connectors (self-tapping screws). Amongst those 12 tested cases, load-deflection responses from tests and numerical analyses for two cases, namely, case B15-2 and case B30-2 were presented in Kyvlou (2018). Since case B30-2 comprises 3-mm thick cold-formed steel sections, which are similar to cold-formed steel sections available in Australia market, case B30-2 composite floor has been selected for numerical validation in this study.

Load-deflection responses of 5 distinct composite floor systems with various screw spacing (from 600 mm to 75 mm) reported in Kyvlou (2017) have been digitised and illustrated in Figure 3 (highlighted in colours for various screw spacing (B30-1 to B30-5)). For clarity purposes, numerical predictions are only given for three cases; i.e. composite floor systems with: (i) no connection (dotted line), (ii) partial connection with screw spacing of 600 mm (solid black line), and (iii) full connection between PB and cold-formed steel beam (dotted-dashed line). The reported experimental data lie between the upper (full connection) and lower (no connection) bounds. Figure 3 also shows that by increasing the efficiency of connections, the stiffness (slope of the curve) and the ultimate load (P_u) increase. In addition, it can be observed that the mid-span deflection also increases significantly. Similar trends could be observed in the experiments of Kyvelou (2018).

Figure 4 compares load-deflection curves estimated by the numerical model developed in this study (solid black line) with the experimental data reported by Kyvlou (2017) (solid orange line) and the numerical predictions of Kyvelou et al. (2018) model (dashed grey line). It should be noted that predictions of load-displacement curves are only reported for B15-2 and BD30-2 (screw spacing of 600 mm) in Kyvelou et al. (2018). Therefore, BD30-2 was selected as a benchmark example of partially connected composite floor system in the present study. In addition to load-deflection curves, the typical observed failure mode from Kyvlou (2017) experiments were compared with the failure mode predicted by the numerical model developed in this study. As shown in Figure 5, the numerical model can replicate the observed typical failure mode presented in Figure 16 of Kyvelou et al. (2018) with acceptable accuracy.

Considering the reported results in Figures 3 and 4 as well as the failure mode predicted by the numerical model in Figure 5, it has become apparent that the trends and the values of the numerical responses as well as the shape of the failure mode, predicted by the developed SAP2000 numerical model in this study, are in good agreement and consistent with the experimental data reported in Kyvlou (2017) and Kyvelou et al. (2018). Therefore, the developed numerical model in this study can replicate the behaviour of real flooring systems comprising cold-formed steel beams and wood-based Particle Boards (PB) with acceptable accuracy.

To highlight the validity of the numerical model predictions, the ultimate moment capacities of the flooring systems were examined and compared in Table 4. The good agreement between the numerical predictions and the experimental data proves the validity of the current developed numerical model. As a result, predictions provide confidence in the practical utility of the developed model for exploring the usage of other sustainable products in composite floor systems and conducting several parametric studies before developing such products.

To better understand the effect of shear connection between PB floorboards and steel, the normal strain (ϵ_x) distributions throughout the beam height and at the mid-span are plotted in Figure 6. Results are presented for three different conditions, namely, no connection considering frictionless contact between PB floorboards and steel (Figure 6a), partial connection between PB floorboards and steel using fasteners with 600mm spacing (Figure 6b), and full connection considering B30-2 and PB floorboards are bonded to steel section top flange (Figure 6c). The three mentioned conditions have been analysed under two load conditions, namely, ultimate load P_u (solid line) and half of the ultimate load 0.5 P_u (dashed line). The results presented in Figure 6 clearly show that connection between floorboards and steel has significant effect on the local strain and therefore the failure response of the studied composite floors. It should be noted that in the floors with weak connections, the timber may actually fail in tension rather than compression according to Figure (6b). As wood products are brittle in tension and often have lower tensile strength than compressive strength, the failure behaviour of such floor systems is expected to be governed by the tensile strength of the wood product.

4. Results and Discussion

Several engineered wood products are available to the construction industry. The validated numerical model was employed to investigate the potential use of such sustainable materials as alternatives to replace PB in cold-formed steel/PB composite flooring systems. For this purpose, this study explores replacing PB with several commercially available wood products in constructing cold-formed steel composites floor systems. As highlighted in Section 3, the mechanical properties of floorboards can influence the failure response of such systems. Therefore, the orthotropic elastic and strength properties of these products given in Tables 2 and 3, respectively, were employed. These properties were collected from literature based on the data reported by various researchers (e.g. Bai et al. 1999; Janowiak et al. 2001; Sharma et al. 2015; Chen & He 2017; Moradpour et al. 2018).

As described in Section 3, nonlinear large-deformation analyses have been performed using the mechanical properties listed in Table 2 and distinct connection types. Predicted numerical ultimate moment capacities of various composite floor systems are tabulated in Table 5. Comparing the results in Table 5, it has become apparent that Laminated Bamboo, LVL and LSL products yield the highest moment capacity values for all different connection systems while PB and OSB products have the lowest capacities. The overall behaviour of the studied composite systems is mainly governed by the type of the connection between cold-formed steel beams and the floorboards.

Considering the mechanical properties listed in Table 2 and the full connection results in Table 5, it is evident that despite having a relatively high longitudinal Young's modulus (E_1), the LSL composite floor has a slightly lower (80 MPa) bending moment capacity compared to the floor systems made from LVL (80.2 MPa) or Laminated Bamboo products (81 MPa). Parametric studies were conducted to investigate the effect of individual elastic constants on the moment capacity of composite floor systems. It has become apparent that the transverse Young's (E_3) and out-of-plane shear modulus (G_{23}) of the floorboard can influence the structural behaviour of the fully connected composite floor in addition to the floorboard longitudinal Young's modulus (E_1). It is understood that the higher transverse Young's and shear moduli of LSL and Laminated Bamboo compared to LVL are compensating for their relatively lower longitudinal Young's moduli. Therefore, replacing PB (an isotropic material) with other orthotropic products should be done carefully. Comparing the predicted ultimate moment capacities of various composite flooring systems with partial connections (practical case) in Table 5 showed that by replacing PB with Laminated Bamboo, LVL, LSL and OSB, the ultimate moment capacity of composite floor systems can be improved by 7.5%, 5.9%, 4.5% and 1.5%, respectively. Very low increase was observed for OSB probably due to the very low out-of-plane shear modulus (G_{23}) of OSB (170 MPa) compared to PB (958 MPa). Thus, LVL, LSL and bamboo products, in addition to PB, may be considered for designing composite floor systems in conjunction with cold-formed steel beams. Optimising the layered structure of such bio-based panel products are recommended for developing damage-tolerant composite floors in the future.

5. Conclusions and Recommendations

In this study a finite element model of composite flooring systems comprising cold-formed steel beams and timber-based floorboards has been developed and validated against available testing data. Once validated, the model was employed to analyse the flexural behaviour of various steel/wood and bamboo composite floors. The potential use of engineered wood products including OSB, LSL, LVL and Laminated Bamboo in constructing composite flooring systems was addressed in terms of their estimated ultimate moment capacities.

The results provided insights into the usage of various sustainable engineered board products in novel composite flooring systems and the importance of their elastic constants. The connection between floorboards and cold-formed steel beams was found to have significant effect on the local strain fields and therefore the failure response of the studied composite floors. In addition to the type of the connection between cold-formed steel beams, determining the orthotropic elastic constants of wood and bamboo products is important in describing the performance of such systems. Small differences in shear and Young's moduli of different products, with the same panel thickness and the same connection system, could lead to variations in the ultimate moment capacity of flooring systems. Comparing the predicted ultimate moment capacities of various composite flooring systems with partial connections (practical case) showed that by replacing PB with Laminated Bamboo, LVL, LSL and OSB, the ultimate moment capacity of composite floor systems can be improved by 7.5%, 5.9%, 4.5% and 1.5%, respectively. Therefore, it can be concluded that LVL, LSL and bamboo products, in addition to PB, can be considered for designing composite floor systems in conjunction with cold-formed steel beams in order to improve flexural capacity of the studied flooring systems.

Composite flooring systems should be designed and optimised based on the availability of steel sections as well as natural resources in local regions around the world. Since the design procedure of composite flooring systems has not been developed for practicing engineers, it is recommended that design tables covering various span lengths and loading arrangements be established to facilitate the use of composite flooring systems made from sustainable bio-based products in the building industry. The author of this paper is developing such design tables for Australian cold-formed steel and wood products and the results will be published in the near future.

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Figure 1 : Typical set out of a cold-formed steel and timber composite flooring system

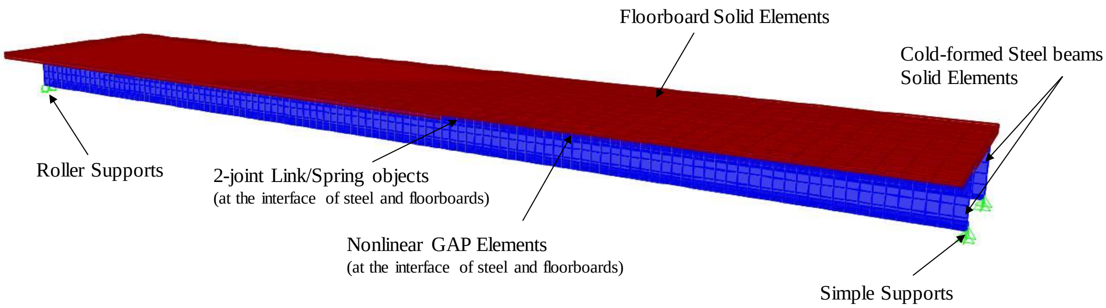


Figure 2: Geometry and boundary conditions of the developed SAP2000 numerical model

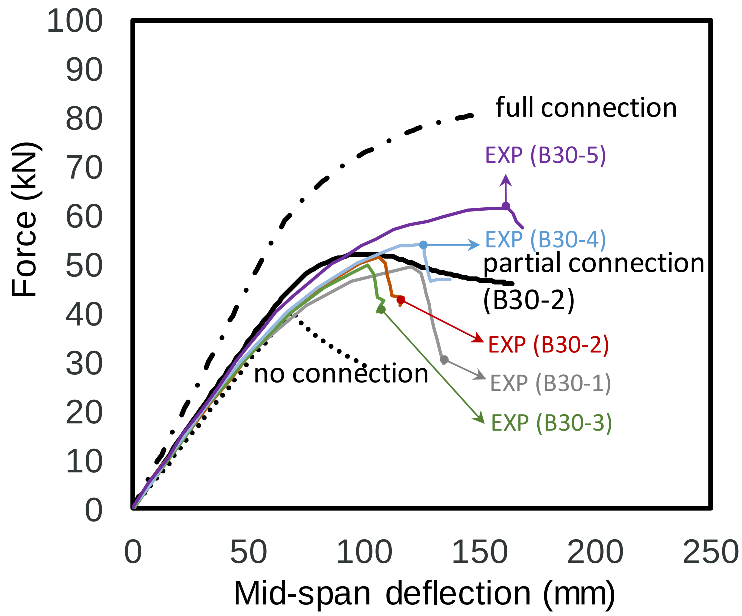


Figure 3: Load-deflection responses of different composite floor systems

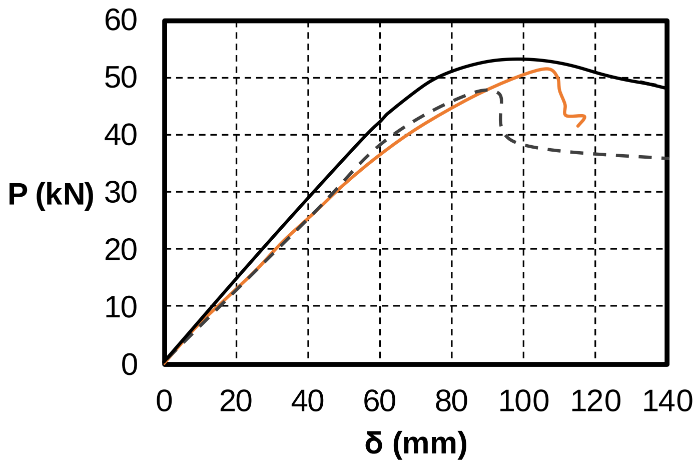


Figure 4: Comparison between experimental data (solid orange line - Kyvelou et al. 2017), FE predictions of Kyvelou et al. (2018) (dashed grey line) and the current numerical model predictions (solid black line)

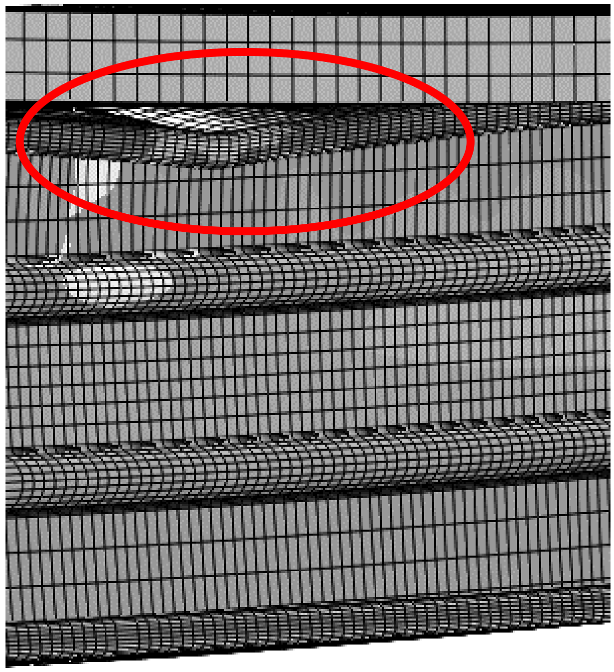
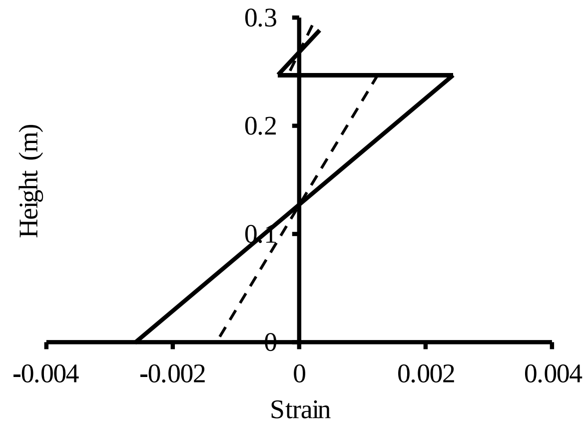
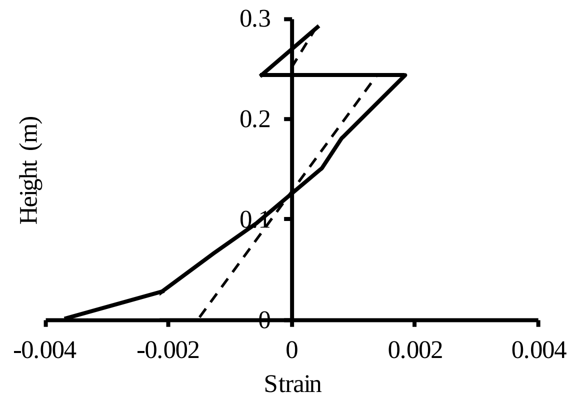


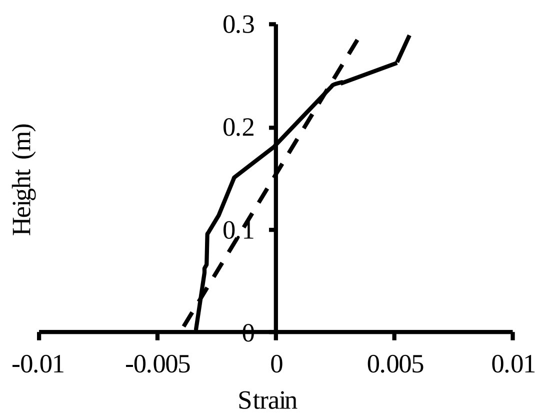
Figure 5: Typical failure mode predicted by the numerical model in this study



(a)



(b)



(c)

Figure 6: Effect of shear connection between PB floorboards and steel on mid-span strain distribution throughout the beam height; (a) no connection, (b) partial connection, (c) full connection

Table 1: Mechanical properties of cold-formed steel (Kyvelou et al. 2017)

Young's Modulus E (MPa)	Poisson's Ratio υ	Flat Yield Strength $\sigma_{0.2}$ (MPa)	Corner Yield Strength $\sigma_{0.2}$ (MPa)	Tensile Strength σ_u (MPa)
201000	0.3	491	574	561

Table 2: Orthotropic elastic constants of composite materials considered for numerical investigation

Product	Young's Modulus (MPa)			Shear Modulus (MPa)			Poisson's ratio		
	E_1	E_2	E_3	G_{12}	G_{13}	G_{23}	υ_{12}	υ_{13}	υ_{23}
PB (Kyvelou et al. 2017)	2300	2300	2300	958	958	958	0.20	0.20	0.20
Southern Pine OSB (Bai et al. 1999)	4000	2400	690	690	207	170	0.15	0.30	0.30
Yellow Poplar LSL (Janowiak et al. 2001)	12500	1380	650	719	675	196	0.45	0.40	0.7
Southern Pine LVL (Janowiak et al. 2001)	16100	1600	570	754	403	120	0.52	0.35	0.40
Laminated Moso Bamboo (Bai et al. 1999)	10350	500	690	830	900	290	0.39	0.34	0.31

Table 3: Strength properties of composite materials considered for numerical investigation

Product	Compressive Strength (MPa)	Tensile Strength (MPa)
	f_c	f_t
PB (Kyvelou et al. 2017)	12.9	5.8
OSB (Chen & He 2017)	13.6	12.1
LSL (Moradpour et al. 2018)	46	10
LVL (Sharma et al. 2015)	57	49
Laminated Bamboo (Sharma et al. 2015)	77	90

Table 4: Ultimate moment capacities of steel/PB systems. Comparison between numerical results and experimental data at different levels of shear connections

Connection System	M_u^{Model} (kN.m)	M_u^{Model}/M_u^{Exp}
Partial connection (Kyvelou et al. 2017)	46.6	0.96
Partial connection (current study)	49.2	1.01
Full connection (current study)	76.8	-
No connection (current study)	42.2	-

Table 5: Predicted ultimate moment capacities (kN.m) of various composite flooring systems using the developed numerical model in SAP2000

Connection System	Engineered Board Products				
	PB	OSB	LSL	LVL	Laminated Bamboo
No connection	42.2	42.0	42.9	43.1	43.7
Partial connection	49.1	49.8	51.3	52.0	52.8
Full connection	76.8	79.6	80.0	80.2	81.0