Dynamic Serviceability of Lightweight Composite Deck as Floor System Under Human Excitation

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Abstract. Lightweight composite deck is widely used as floor system due to the advantage of minimum weight as well as to speedy the construction process. There are numerous investigations on the structural behaviour of lightweight composite deck, but its reliability and understanding on dynamic serviceability remain ambiguous. Therefore, this study intents to numerically investigate the dynamic serviceability of lightweight composite deck as floor system. The lightweight composite deck with dimension of 2900 mm span and 900 mm was modelled in STAAD.Pro. The thickness of lightweight composite deck varied from 100 mm to 225 mm. The isotropic equivalent plate model and effective homogenous criterion were adopted for the geometry and material properties. Dynamic serviceability in term of natural frequency and displacement were analysed in corresponds to the thickness of lightweight composite deck. It is noticeable that by increasing the thickness led to the improvement in the natural frequency. In contrast, the displacement become smaller as the thickness become larger. It was identified that only the lightweight composite deck with thickness 200 mm and 225 mm comply the allowable limit.

1. Introduction
Composite construction has been popular over the last twenty years and has largely accounted for the dominance of steel frames in multi-storey building. This type of construction is structurally efficient because it exploits the tensile resistance of the steel and the compressive resistance of concrete. Applications include commercial, industrial and residential building. As the evolution of construction industry goes by, the current interest on new design of human floor has been discovered. Which is using the lightweight composite deck. This renowned design consists of steel structure and bondeck slab made of lightweight concrete with profiled steel sheet. By using these materials, the construction of floor system evolves significant exploitation since concrete is good in compression while steel shows better performance in tension. It became a new solution in reducing the selfweight of structure and the pedestrian bridge can be constructed in a short time. Besides that, lightweight composite deck is versatile since it can be adapted in many cases, located in between any buildings or elevated from busy road. The good resistance and architectural apparel are also another added value.

Lasheen et al. [1] and Yardim et al. [2] emphasized that lightweight concrete has total weight reduction in term of dead load around 20% to 35%. Even up to 50% as in the latest report by Waldmann
et al. [3]. The thickness is normally in the range 100 mm to 250 mm for shallow decking, and in the range 250 mm to 300 mm for deep decking [4]. In the design consideration, the serviceability of composite slab in term of vibration and deflection must be checked to provide safety and to prevent outright structural failure. Penza [5] reported that composite slab with shorter span will give a good performance in vertical shear capacity. There are numerous experimental tests that have been conducted to study the behaviour of composite slab and the comparison with reinforced concrete slab such as by Zhou et al. [6], Holomek and Bajer [7], Mohamed and Sidky [8] and Cifuentes and Medina [9]. It was measured that the load carrying capacity and stiffness for the composite slab and reinforced concrete slab are almost insignificant different. Meanwhile, the dynamic behaviour of composite slab was investigated based on two variables; the thickness and grade of concrete. The findings revealed that by increasing the thickness of composite slab, the natural frequency increases up to 25% [10].

Unfortunately, lightweight composite deck has less stiffness than normal concrete slab. Concurrently, the reduction on selfweight may cause the transient state being dominant, subsequently lead to the high discomfort level. Although, Yardim et al. [2] and Jaini et al. [11] developed lightweight composite deck that achieve acceptable limit of vibration higher than 10Hz, the understanding on real situation for pedestrian bridge is still need to be developed. Lack of prove on its reliability must be tackled to further enhance the acceptance of lightweight composite deck in construction industry, especially for the pedestrian bridge. Since there are demand on the application of lightweight composite deck, but lack of knowledge and established procedures, the numerical modelling using STAAD.Pro will definitely contribute to a rational and robust prediction of vibration responses, including the structural behaviour under ambient and transient states. Moreover, this study will help in the improvement of construction process by taking optimum consideration of thickness, span and others specification of lightweight composite deck.

2. Numerical modelling

2.1. Specification

Figure 1 shows the schematic design of lightweight composite deck that has been implemented from the deck design of floor system in Parlimen Malaysia [12]. The size is 2900 mm span and 900 mm width with various thicknesses from 100 mm to 225 mm. The lightweight composite deck is supported by universal steel beams at both ends with the size of UB 553 x 312 x 150, where the perfect bond was assumed as presence of shear studs. Fixed supports were assigned at each of end-corner of universal steel beams to create the fully constrains at Fx, Fy, Fz, Mx, My and Mz. So that, the movement in lightweight composite deck will significantly affecting the supports and behave globally.

![Figure 1. Cross-section of lightweight composite deck](image)

The loads that imposed on the lightweight composite deck are based on the static action and human walking activity. The static action includes selfweight, finishes and services of 1.5 kN/m² and variable action for the two-way walkway space. The value of variable action is 3 kN/m² as accordance to Class 37 structure category on BS EN 1992-1-1 [13]. On the other hand, human walking activity acts as dynamic excitation in the form of force-time history. Equation (1) as suggested by Gandomkar et al. [14] was used to calculate the load that induced by the human walking activity.

\[
F(t) = P_{ai} \cos(2\pi f_{st} t)
\]
where, $P$ is individual’s weight taken as 800 N, $a_i$ is dynamic coefficient for the $i$th harmonic force component, $i$ is harmonic multiple of the step frequency, $f_s$ is step frequency and $t$ is time in seconds.

2.2. Geometric properties
Numerical modelling in STAAD.Pro was conducted through linear-elastic analysis. Since the lightweight composite deck has the corrugated shape, a special technique so-called isotropic equivalent plate model as established by El-Dardiry and Ji [15] was employed to model the lightweight composite deck. This is due to fact that STAAD.Pro not permitting the corrugated shape to be modelled with the condition of two separated components. In the isotropic equivalent plate model, the corrugated shape was transformed to the flat layer. Therefore, the orthotropic manner of lightweight concrete and profiled sheet was merged to form an isotropic system. Although, the position of neutral axis and second moment of area are changed, the geometric stiffness and mass of lightweight composite deck can be upheld as original. Figure 2 illustrates the transformation of lightweight composite deck from corrugated shape to the isotropic equivalent plate model.

![Figure 2](image)

**Figure 2.** Isotropic equivalent plate model in numerical modelling.

2.3. Discretization
The lightweight composite deck was modelled as plate elements while the universal steel beams were created as beam elements. In term of meshing, STAAD.Pro provides two different selection which are three-noded polygonal element and four-noded quadrilateral element. In this study, the four-noded quadrilateral element was employed to discretize the lightweight composite deck as this type of meshing provide accurate deformation since it can be interpolated to a higher degree. In addition, the four-noded quadrilateral element is more suitable to form uniform meshing. The size of mesh is 20 mm x 20 mm based on convergency obtained from the mesh sensitivity test. Figure 3 shows the discretization of lightweight composite deck in the interface and rendering views.

![Figure 3](image)

**Figure 3.** Meshing of lightweight composite deck in the interface and rendering views.
2.4. Material properties

The lightweight composite deck consists of foamed concrete and profiled sheet of ComFlor46. The density of foamed concrete was controlled at 1600 kg/m³ which found suitable to be used as structural component. Meanwhile, ComFlor46 has 0.9 mm thickness. The material properties of Young’s modulus, Poisson’s ratio, density, thermal coefficient, critical damping, shear modulus, yield stress, tensile strength, yield strength ratio, tensile strength ratio and compressive strength can be referred in Table 1. The material properties of foamed concrete and profiled sheet are based on BS EN 1992-1-1 [13], and the standard manufacturer respectively. When the isotropic equivalent plate model is adopted, the material properties should be changed to the homogenous effective criterion. Therefore, a general rule of mixtures was used to predict the material properties. Therefore, when the thickness changes and hence the material properties alternated as can be referred in Table 2. It should be noted here that the material properties adopted in this study is predominantly by the brittle material model.

| Table 1. Material properties of foamed concrete and profiled steel sheet. |
|--------------------------|--------------------------|--------------------------|
| Properties               | Foamed Concrete          | ComFlor46                |
| Young’s modulus, \(E\) (kN/m²) | 19.2×10⁶                 | 210×10⁶                  |
| Poisson’s ratio, \(\nu\)   | 0.17                     | 0.3                     |
| Density, \(\rho\) (kN/m³)  | 15.69                    | 76.82                   |
| Thermal coefficient, \(\alpha\) (°C) | 8×10⁻⁶                 | 10×10⁻⁶                |
| Critical damping, \(\zeta\) | 0.05                     | 0.03                    |
| Shear modulus, \(G\) (kN/m²) | 8×10⁶                    | 81×10⁶                  |
| Yield stress, \(F_y\) (kN/m²) | -                       | 280×10³                |
| Tensile strength, \(F_t\) (kN/m²) | 1.84×10⁶               | 0.41×10⁶                |
| Yield strength ratio, \(R_y\) | -                       | 1.5                    |
| Tensile strength ratio, \(R_t\) | -                       | 1.2                    |
| Compressive strength, \(F_c\) (kN/m²) | 20×10³               | -                      |

| Table 2. Material properties based on homogenous effective criterion. |
|--------------------------|--------------------------|--------------------------|
| Properties               | Thickness of lightweight composite deck (mm) |
|                          | 100 mm | 125 mm | 150 mm | 175 mm | 200 mm | 225 mm |
| \(E\) (kN/m²)            | 21.67×10⁶ | 21.11×10⁶ | 20.80×10⁶ | 20.56×10⁶ | 20.39×10⁶ | 20.25×10⁶ |
| \(\nu\)                  | 0.1717  | 0.1713  | 0.1711  | 0.1709  | 0.1708  | 0.1707  |
| \(\rho\) (kN/m³)         | 16.49   | 16.31   | 16.20   | 16.13   | 16.07   | 16.03   |
| \(\alpha\) (°C)          | 8.03×10⁻⁶ | 8.02×10⁻⁶ | 8.02×10⁻⁶ | 8.01×10⁻⁶ | 8.01×10⁻⁶ | 8.01×10⁻⁶ |
| \(\zeta\)                | 0.0497  | 0.0498  | 0.0498  | 0.0499  | 0.0499  | 0.0499  |
| \(G\) (kN/m²)            | 8.94×10⁶ | 8.74×10⁶ | 8.61×10⁶ | 8.52×10⁶ | 8.45×10⁶ | 8.40×10⁶ |
| \(F_y\) (kN/m²)          | 3.62×10⁻³ | 2.85×10⁻³ | 2.35×10⁻³ | 2.00×10⁻³ | 1.74×10⁻³ | 1.54×10⁻³ |
| \(F_t\) (kN/m²)          | 1.82×10⁶ | 1.83×10⁶ | 1.83×10⁶ | 1.83×10⁶ | 1.83×10⁶ | 1.83×10⁶ |
| \(R_y\)                  | 0.0194  | 0.0153  | 0.0126  | 0.0107  | 0.0093  | 0.0083  |
| \(R_t\)                  | 0.0150  | 0.0120  | 0.0101  | 0.0086  | 0.0075  | 0.0066  |
| \(F_c\) (kN/m²)          | 19.74×10³ | 19.8×10³ | 19.83×10³ | 19.86×10³ | 19.88×10³ | 19.89×10³ |

3. Result and discussions

3.1. Acceleration-time history

The overview of plotted acceleration-time history for lightweight composite deck is shown in Figure 4. This acceleration-time history can be converted to the vibration spectrum domain using fast Fourier transform. Therefore, the natural frequency that cause the lightweight composite deck to experience resonant can be easily identified. Figure 5 shows the vibration spectrum domain where the amplitude of
vibration is plotted against the natural frequency. The oscillation gives the range of maximum and minimum amplitudes, where it will reduce to the static state. The highest acceleration-time history can be observed at the point of imposed load. For the lightweight composite deck, it was observed that the maximum acceleration is around 1.42 m/s^2 to 4.31 m/s^2 for thickness 100 mm to 225 mm. According to Saidi et. al [16], walking pedestrians can induce considerable vertical and horizontal rhythmic impulsive dynamic loads that are dominated by the pacing rate and by having a higher pacing rate, the vibration responses including frequency, amplitude and duration will be increased.

![Figure 4](image1.png)

**Figure 4.** Acceleration-time history of lightweight composite deck.

![Figure 5](image2.png)

**Figure 5.** Vibration spectrum domain of lightweight composite deck.

### 3.2. Natural frequency

It should be emphasized that the natural frequency presented here is based on the first mode shape. In this study, the natural frequency was captured under ambient and transient states. The ambient state is fully depending on the selfweight and service load of lightweight composite deck itself. Meanwhile, the transient state is based on the impose load of human walking activity in the form of harmonic-sinusoidal function. Figure 6 shows the natural frequency in corresponds to the thickness of lightweight composite deck. The natural frequency under the ambient state is plotted together with the natural frequency obtained from analytical approach. It can be observed that the natural frequency of ambient state is slightly close to the analytical approach. The lightweight composite deck with thickness 100 mm has the natural frequency of 23.99Hz and 24.30Hz for the ambient state and analytical approach, respectively. This indicate relatively small difference around 1.28%. Similarly, lightweight composite deck with thickness 125 mm has 1.29% error. Meanwhile, for thickness 125 mm to 225 mm, the natural frequency has the gap less than 7.5%.

It can be observed that by increasing the thickness of lightweight composite deck will eventually lead to the higher value natural frequency. Thickness has direct relationship with the selfweight where it will be increased if the thickness enlarged. Hence, it will increase the moment of inertia and consequently increase the natural frequency. Howard and Hansen [17] agreed that as the equivalent
thickness of the floor increased, which corresponds to a greater cross-sectional moment of inertia and cause the first resonance frequency increased. On the other hand, Jaini et al. [11] reported that the natural frequency of foamed concrete composite slab decreases due to the thickness ranging from 100 mm to 150 mm but gradually increased as the thickness reached 175 mm. This can be explained as the presence of the shear bond has been ignored in the modelling process. The lightweight composite deck was modelled as an isotropic equivalent plate model that merged the orthotropic manner of lightweight concrete and profiled sheet to form an isotropic system.

3.3. Displacement

In the real scenario of design, serviceability aspect become predominant factor that need to be checked carefully. Under dynamic loading, especially vibration, serviceability must be referred to both natural frequency and displacement. Figure 7 shows the displacement in corresponds to the thickness of lightweight composite deck under ambient and transient states. A comparison with analytical approach indicates insignificant difference. The maximum error between ambient state and analytical approach is 37.04%, which happen on the lightweight composite deck with thickness 100 mm. The displacement for lightweight composite deck with thickness 100 mm to 150 mm under ambient state is upper bound of analytical approach. However, the ambient state become lower bound when the thickness increases from 175 mm to 225 mm. It can be observed that the displacement is decreased when the thickness become larger. The deformation of structure and supports begins almost simultaneously. As a result, the energy of external load which is absorbed by yielding supports is fully redistributed to the slab.

For a lightweight composite deck that has effective span of 2900 mm, it was computed that the displacement limit is 8.25 mm [13]. Basically, the trend of displacement of lightweight composite deck is almost similar. It can be clearly observed that by increasing the thickness of lightweight composite deck, the displacement is gradually decreased. It is affirmed that the stiffness of lightweight composite deck governs its structural behaviour. By comparing with displacement limit, only lightweight
composite deck with thickness 175 mm, 220 mm and 225 mm accomplish the serviceability requirement. The displacement of lightweight composite deck under transient state is 39.01 mm, 21.54 mm, 13.06 mm, 8.62 mm, 5.77 mm and 4.23 mm for thickness 100 mm, 125 mm, 150 mm, 175 mm, 200 mm and 225 mm, respectively. Under human walking activity, the displacement of lightweight composite deck become obviously larger compared to which under the selfweight and service load. The corresponding reaction as the human walking activity generates higher dynamic forces than the quasi-permanent load [13]. The high dynamic forces together with the quasi-permanent load contribute to a higher magnitude of load, thus the reaction forces and vibration responses under human walking activity is higher than under the selfweight and service load.

3.4. Effective thickness
In order to determine the effective thickness of lightweight composite deck for the pedestrian bridge, the natural frequency is plotted against the displacement. Figure 8 shows the correlation between the natural frequency and displacement under transient state. In respect to Murray et al. [18] and BS EN 1992-1-1 [13], the lightweight composite deck must fulfil the natural frequency and displacement limits. Principally, the natural frequency must bigger than 10Hz while the displacement must lower than 8.25 mm. Although all thicknesses in lightweight composite deck satisfied the vibration limit, only lightweight composite deck with thickness 200 mm and 225 mm pass the displacement control.

In this study, the displacement results are more dominant than the natural frequency when the lightweight composite deck is subjected under human excitation. All the thicknesses passed the natural frequency limit but not the displacement limit. These corresponding results were influenced by the increasing stiffness as the thickness increased. However, different situation might happen if the span of the lightweight composite deck is longer. The natural frequency and displacement will have an equal role in terms of serviceability stage.

![Figure 8. Correlation between natural frequency and displacement.](image)

4. Conclusion
The lightweight composite deck was numerically modelled in STAAD.Pro with various thickness from 100 mm to 225 mm. The isotropic equivalent plate model was employed to construct the lightweight composite deck that originally in the form of corrugated shape. Meanwhile, the material properties of lightweight composite deck were converted from anisotropic to homogenous effective criterion using a general rule of mixtures. The loads that imposed on the lightweight composite deck are based on the static action and human walking activity (in the form of harmonic-sinusoidal function as force-time history). It was discovered that STAAD.Pro able to produce the acceleration-time history and vibration spectrum domain. A comparison of natural frequency and displacement between ambient state and analytical approach provide convincing agreement. It is noticeable that the thickness of lightweight composite deck governs the natural frequency and displacement. When the thickness of lightweight composite deck is increased, the natural frequency is increased as well. On the other hand, the displacement reduces as the thickness become larger from 100 mm to 225 mm.
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