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VIBRATION RESPONSE OF CROSS-LAMINATED TIMBER-STEEL COMPOSITE FLOORS WITH SAND INFILL

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ABSTRACT: The sensitivity of lightweight timber-based floors to serviceability limit state considerations such as deflection and vibration due to human activity is well documented in the literature. Mitigation measures such as concrete topping, active damping mechanisms, breaking floor spans, thick floor profiles have been proffered in the literature, with varied results. In this study, the vibration response of a modular prefabricated cross-laminated timber-steel composite floor was investigated, considering sand-infill as a passive damping solution. Improvements in the vibration serviceability metrics of the floor were observed. On average, 2% additional damping was recorded in floor specimens with sand infill, with damping values peaking at 7%. The study demonstrated the potential of sand in mitigating objectionable vibration in light weight floors.

KEYWORDS: Passive damping; Cross-laminated timber (CLT); Hybrid structures; Modular composite floor

1 – INTRODUCTION

With the increased adoption of timber-based building solutions has come the need to tackle inherent challenges in building with wood, one of which is its greater susceptibility to vibration when used in floors, compared to conventional concrete. Vibration control methods for floors are in three broad categories: active, semi-active and passive techniques. Active vibration control techniques for floors include the application of electro-magnetic actuators [1] and active mass dampers [2]. Semi-active systems employ variable actuators with minimal operating power requirement [3, 4], while passive strategies include construction features such as walls, partitions, floorings, ceilings [5, 6] and tuned mass dampers which perform best in a narrow frequency range and are not ideal when the natural frequencies of a floor are closely spaced [7].

Inspired by previous applications in combustion engines [8] and light wood framing [9], in this research, the efficacy of loose sand as a passive vibration-damping mechanism was studied in a cross-laminated timber (CLT)-steel composite floor system. This involved the introduction of sand into the hollow regions of the steel beams. The underlying hypothesis is that walking actions on the floor would activate friction among the sand particles which would improve the damping of the floor and result in a faster decay of the vibration response. Also, the added weight of sand is expected to contribute to the reduction in the vibration response of the floor. As the unbound sand grains can be easily retrieved at the end-of-life of the structure, the solution fosters designing for deconstruction and circular economy.

2 –FLOOR DESCRIPTION AND DESIGN

The examined floor, illustrated in Fig. 1, consists of 2.4 × 6 m CLT panels fastened to two omega-shaped cold-formed beams (see Fig. 2), made of 44W steel [10], spaced 1.6 m apart with ø 11 mm self-tapping screws inclined at 30° to the floor plane in the beam extremities for efficient shear transmission and at 90° in the middle region.

The floor design was based on the effective flexural stiffness method. The distance between the composite beams was selected to minimize the overhangs of the CLT panel beyond the beams while ensuring that the shear strength and transverse bending capacity of the CLT component was not exceeded at ultimate limit-state loading condition. The decision to limit panel overhangs

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was based on a prior study by Owolabi *et al.* [11], which revealed that floor modules with longer overhangs are more susceptible to objectionable vibration. The spacing of the self-tapping screws was varied based on the shear stress distribution along the longitudinal section, while guidelines in Eurocode 5 [12] and ETA-11/0030 [13] were used to estimate the stiffness of the floor. The serviceability limits state deflection of the floor was also checked to be less than span/180, as required in CSA O86 [14].

In the floor variations with sand, the hollow regions of the beams were filled with round mono-crystalline silica sand (12/20 particle grade [15]), or angular finely graded paving sand (4/200 particle grade [15]). The sand particles were mixed with 20 % sawdust by volume to keep them loose. The average proportion of the mass of sand to that of the overall floor system was 17.3% for those with paving sand and 16.4% for variants with silica sand.

The dry assembly process of the floor, depicted in Fig. 3, reduces construction time and fosters deconstruction, recycling, and reuse of the floor components. The floor system enables capacity-protected CLT design as its light-gauge steel beams perform the role of a sacrificial failure component. The floor modularity also makes it adaptable to different floor plans [16, 17].

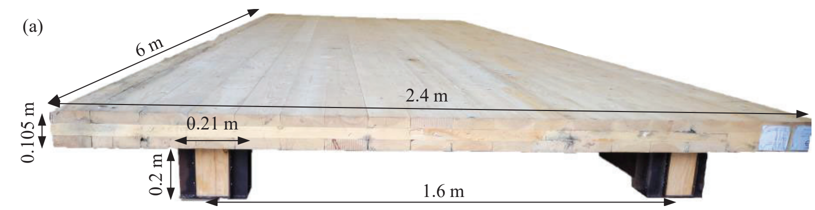
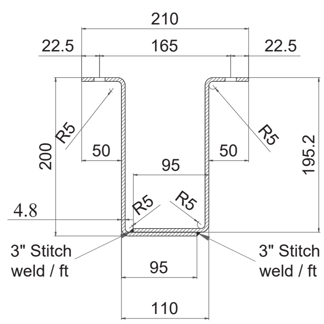


Figure 1. Composite floor module



I_{xx}=17389695.4 mm^4

I_{yy}= 8768230.48 mm^4 ,

Torsional constant= 39944.77mm^4

Cross-sectional area: 3135.05 mm^2

Figure 2. Steel beam cross section dimension (dimensions in mm except stated otherwise)

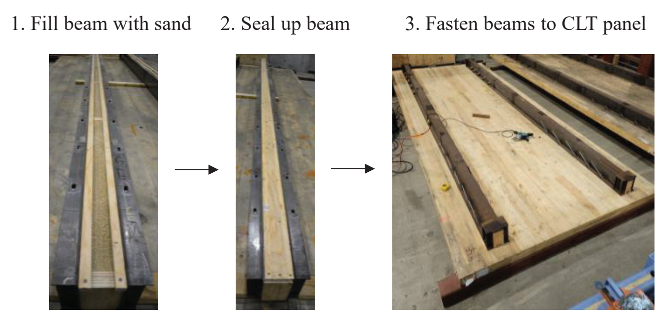


Figure 3. Floor assembly procedure

3 WALKING-INDUCED RESPONSE MEASUREMENTS AND IMPACT HAMMER TESTS

Walking-induced acceleration measurements and modal tests were carried out on floor specimens with and without sand infill, as shown in Fig. 4. The CLT component of the floor and an oversized 245mm thick CLT were also tested. The CLT materials were Canadian spruce-pine-fir (SPF), manufactured in line with ANSI/APA PRG 320 [18]. The test configurations are summarized in Table 1.

The floor modules were simply supported throughout the testing campaign. For the acceleration records, measured at the midspan of the beam region and at the centre of the floor, walking movements induced by a 60-kg human along the middle, side, and diagonal of the floor, at 1.2Hz, 1.6Hz, 2.0Hz and 2.4Hz were considered. In total, 24 acceleration time histories per floor, consisting of 2 accelerometer records and 12 walking activities were obtained via a National Instruments data acquisition system with a sampling frequency of 2000Hz. A low-pass filter with a cut-off frequency of 200Hz was also applied.

Table 1: Modal and walking test configurations

Configuration	Specimen	Samples
CLT	V-grade CLT (105mm thick)	2
	E-grade CLT (245mm thick)	1
Floor module (without sand)	V-grade CLT + 2 beams	2
Floor module (with sand)	V-grade CLT + 2 beams + paving sand + saw dust	2
	V-grade CLT + 2 beams + silica sand + saw dust	2

The logged data was processed to obtain peak acceleration (a_{peak}), root-mean-square acceleration (a_{rms}), vibration dose value (VDV) and response factor (R). VDV and R are defined as:

$$VDV = \int_0^T a_w^4(t)dt \tag{1}$$

$$R = \frac{a_{w,rms}}{0.005} \tag{2}$$

where $a_w(t)$ is the frequency-weighted acceleration per BS 6472 [19], $a_{w,rms}$ is the root-mean-square of the weighted acceleration records, and T is the total duration of vibration.

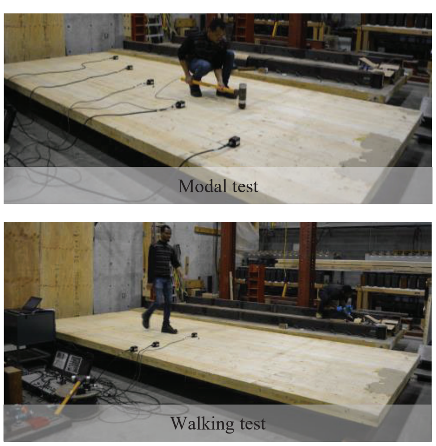


Figure 4. Modal and walking test demonstrations

Experimental modal tests were carried out using an instrumented impact hammer and a data acquisition system, considering 49 impact points and 5 accelerometer locations, and the same sampling frequency and filter as in the walking test. The modal parameters, natural frequencies (f), damping ratios (ξ) and mode shapes were obtained via the rational fraction polynomial curve-fitting method using ARTeMIS Modal software package by Structural Vibration Solutions. Time-history-based damping was also obtained using the logarithmic decrement method [20], considering the walking time histories.

4 – RESULTS

4.1 MODAL CHARACTERISTICS OF TESTED FLOOR SAMPLES

The first three vibration modes of the tested floor specimens, obtained via the rational fraction polynomial curve-fitting method, are shown in Fig. 4. The vibration modes consist of longitudinal bending (first and third modes of the 105mm CLT panels), dome-shaped bending (first mode of the 245mm CLT panel and composite floors), transverse bending (third mode of the composite floors), combined longitudinal and transverse bending (third mode of the 245mm CLT panel) and torsional mode (second mode across all floor types). The mode shapes of the composite floor modules were similar irrespective of the presence or absence of sand, hence their grouping together in Fig. 5.

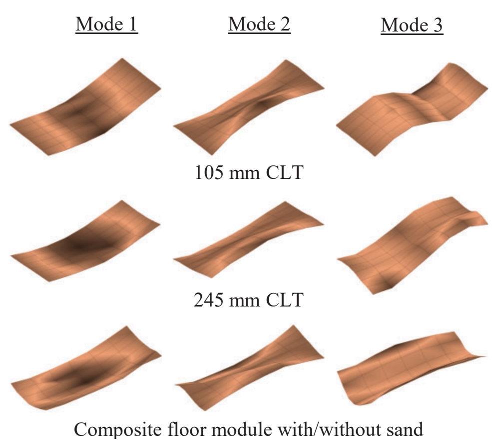


Figure 5. Mode shapes of studied CLT and composite floor specimens

The fundamental frequencies (f_1) and fundamental damping ratios (ξ_1), summarized in Table 2 reveal that the modal properties of the 105mm CLT panels were very similar (2% difference in f_1, 6% difference in ξ_1). The f_1 of composite floors with loose sand was a little lower than

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those without sand (5% decrease on average) due to the higher mass of the former. Composite floor modules with paving sand had a similar range of ξ_1 with those without sand, while those with silica sand had superior ξ_1 values (47% increase on average), similar to the results for the 245mm CLT panel.

Table 2: Modal properties of the tested configurations obtained via rational fraction polynomial curve-fitting technique

Configuration	$f_{1,\,mean}$ (Hz)	$\xi_{1,\,mean}$ (%)
CLT (105 mm)	6.2 (6.2–6.3)	1.6 (1.5–1.7)
CLT (245 mm)	11.7	2.3
Single module	15.5 (15.3–15.6)	1.7 (1.6–1.7)
Single module + silica sand	15.1 (14.7–15.5)	2.5 (2.4–2.6)
Single module + paving sand	14.5 (14.2-14.7)	1.7 (1.6-1.7)

The effect of sand particles in dampening vibration due to human walking activity was deemed not to have been adequately captured by the modal test results due to the brevity of the applied impact hammer loads, which could not sufficiently initiate the inter-particle sand motion like a walking activity would. Consequently, damping values were computed using the logarithmic decrement time history approach based on the walking time histories, and the results are given in Table 3. The table indicates a non-stationary damping phenomenon for the hybrid composite floors, peaking at 6-7% damping at some acceleration amplitudes. A damping gap of about 2% was observed between floor modules with and without sand, around approximately 0.4-1m/s^2, indicating the impact of sand in improving damping characteristics.

Table 3: Average damping ratio for tested floors at various peak acceleration amplitudes

Floor variant	Damping at different acceleration amplitudes (%)							
	0.20 m/s^2	0.40 m/s^2	0.60 m/s^2	0.80 m/s^2	1.00 m/s^2	1.20 m/s^2	1.40 m/s^2	1.60 m/s^2
Module A	3.28	3.00	3.33	3.34	3.18	3.40	2.74	2.56
Module B	4.09	3.16	3.38	3.07	3.55	3.35	3.70	2.06
Module A + paving sand	4.72	5.20	5.15	5.14	5.41	5.17	5.89	3.84
Module B + paving sand	4.70	5.07	6.33	5.21	7.63	4.85	0.76	4.52
Module A + silica sand	5.33	5.86	6.23	6.74	4.27	3.70	7.24	2.23
Module B + silica sand	3.39	4.79	4.93	4.90	5.57	7.05	5.79	4.00
Average (without sand)	3.69	3.08	3.36	3.20	3.37	3.37	3.22	2.31
Average (with sand)	4.47	5.24	5.83	5.62	5.82	5.20	4.60	3.58
Difference	0.78	2.16	2.47	2.41	2.45	1.83	1.38	1.27

4.2 VIBRATION RESPONSE OF TESTED FLOOR SAMPLES

The variation of vibration response metrics (a_{peak}, a_{rms}, VDV and R) of the tested floor specimens with walking frequencies are shown in Fig. 6. The plots indicate that the responses of the composite floor modules were below those of the 105mm CLT but higher than those of the oversized 245 mm CLT, with the exception of a_{peak} plots which did not have a distinct trend.

In the beam region, the response of hybrid composite floor modules with loose sand infill was reduced compared to those without sand, demonstrating the vibration-attenuation effect of loose sand. Considering the average value of each metric for all walking activities carried out on each floor configuration as shown in Fig. 7, hybrid composite floor modules with sand experienced 13% to 17% reduction in a_{rms}, 18% to 22% in a_{peak}, 8% to 9% in VDV and 8% to 11% in R.

The vibration attenuation effect of sand dissipated at the centre of the floor specimens, leading to comparable vibration responses irrespective of the composite floor specimen. The significant loss of stiffness in the transverse direction, beyond the composite beam region housing the sand particles is a plausible reason for this. The 3-ply CLT panels in the tested floor modules have a single transverse laminate with boards that are not edge-glued. Moreover, as sand particles cannot sustain shear, their location in high-shear regions in the transverse plane resulted in more energy dissipation than the central regions.

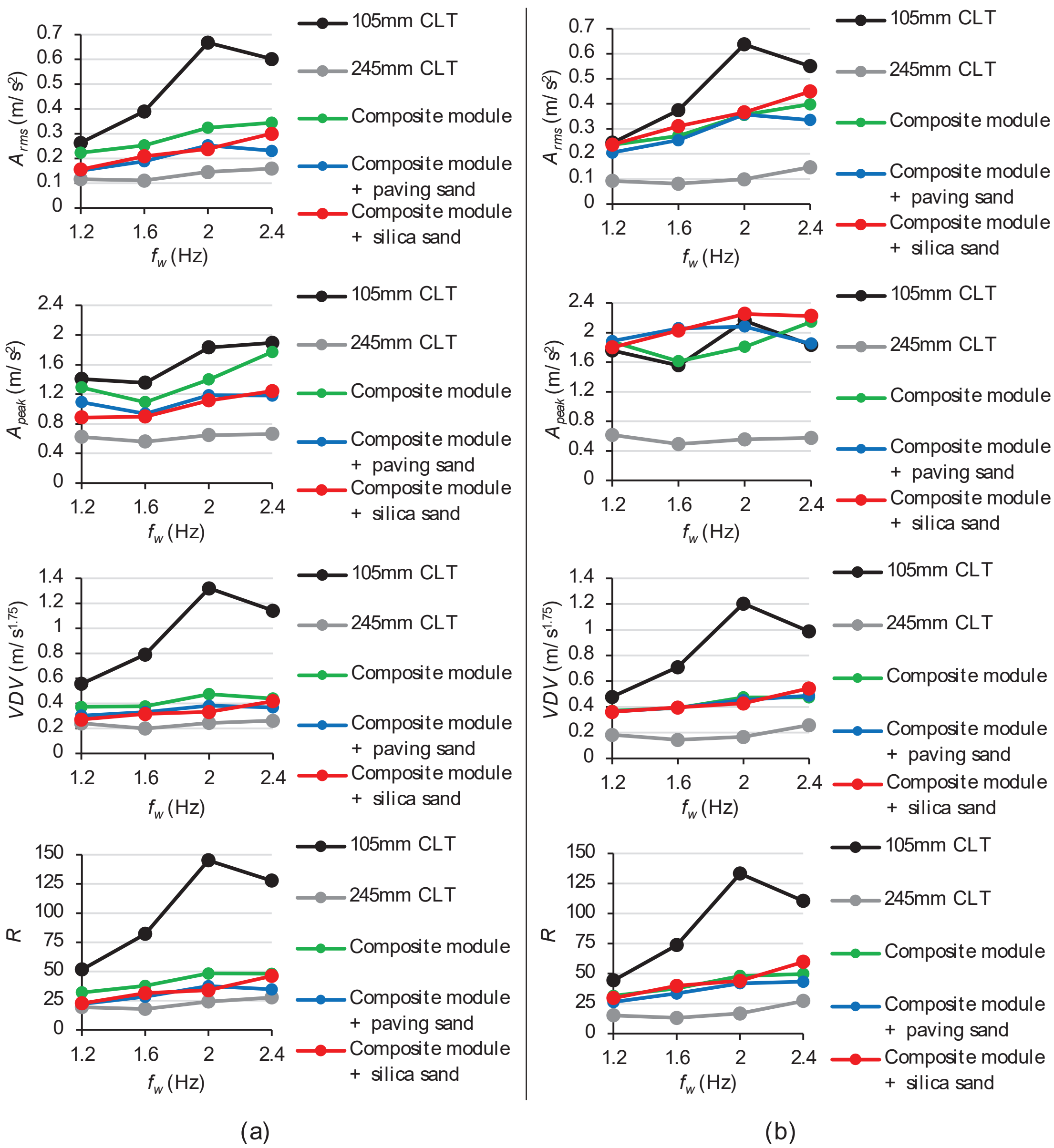

Figure 6. Variation of acceleration metrics with walking frequency (f_w): at midspan in the beam region (a), at the centre of the floor (b)

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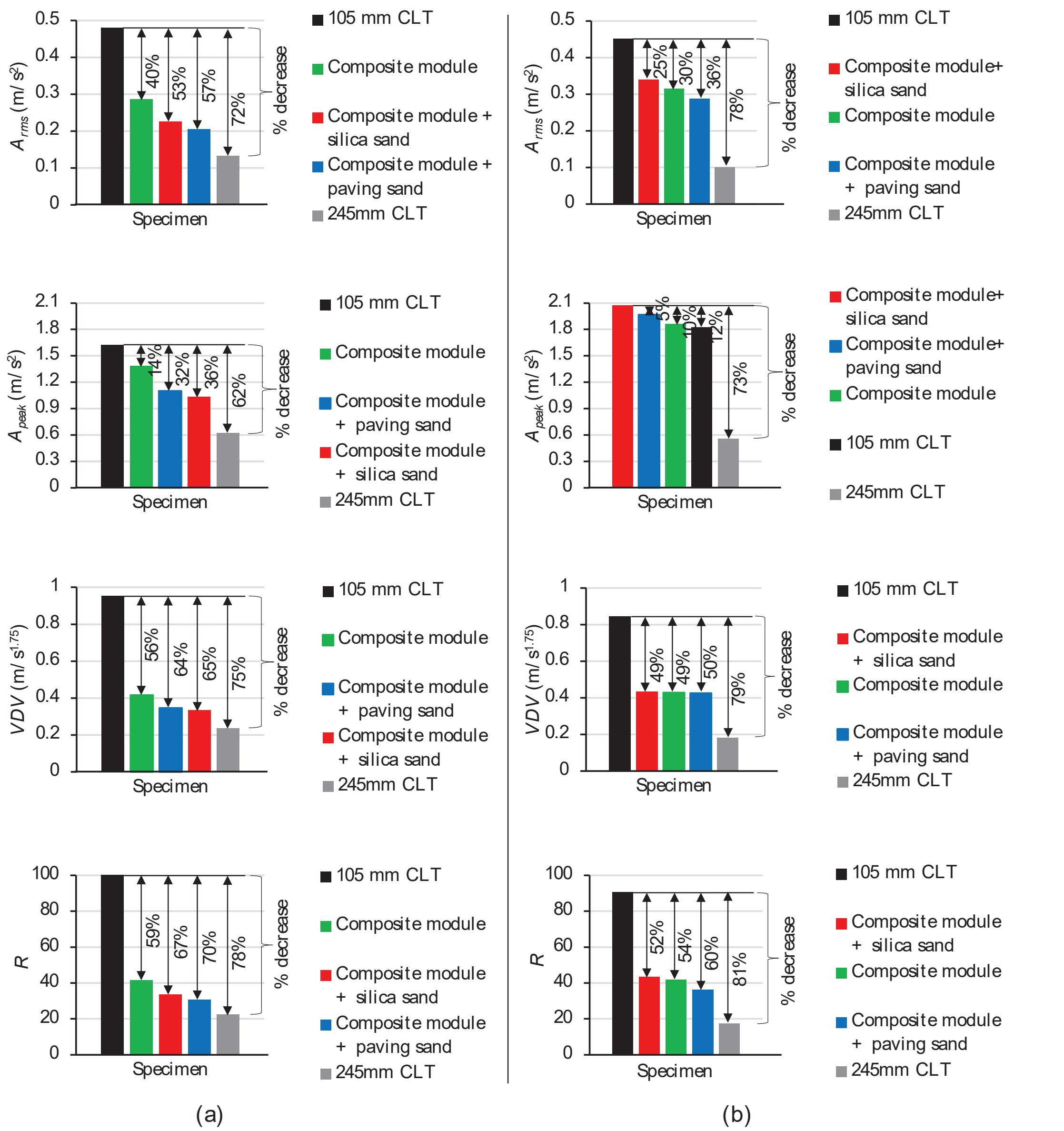

Figure 7. Average values of response metrics: in the beam region (a) at the centre of the floor (b)

While the composite floor specimens with loose sand infill had a better performance than those without, there was only a slight distinction between the responses of the floors with the two types of sand tested. Increasing the proportion of the weight of sand would potentially improve the performance of the floor system by reducing the vibration response. However, beyond an optimal proportion of sand, the floor would become vulnerable to resonance due to a substantial reduction in f_l caused by the weight increase.

5 – CONCLUSION

This study demonstrates that the vibration serviceability metrics of a CLT-steel composite floor can be improved using sand as a passive damping mechanism. Time-history analysis of the walking activities helped capture the vibration-attenuating effect of loose sand particles better than the modal test analysis based on brief impact, loads which were unable to effectively activate the inter-particle sand motion like a walking activity.

The analysis showed that up to 7% damping was achieved in floors with loose sand-infill, revealing an added 2% damping than bare floors on average. However, there was a noticeable variation in damping values obtained among similar specimens due to the intrinsic uncertainties within the system. The sand-damped floor variants recorded lower vibration responses and a slight decrease in fundamental frequency (5% on average) but retained similar vibration modes to the undamped floor variants.

Improved damping ratios and reduced acceleration values are a pointer to better overall vibration serviceability performance of the floor system. Future studies will focus on optimizing the studied vibration-attenuation technique and the application of high-damping materials as potential substitutes for sand.

6 – REFERENCES

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