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Hybrid Cross-Laminated Timber Building Case Study Dynamic Identification Under Forced Vibration Tests / Aloisio, A., Rosso, M.M., Pasca, D.P., Gavri, I., Tomasi, R., Šušterši, I., Marano, G.C., Fragiacomo, M.. - 676 - 3:(2025), pp. 564-573. (11th International Conference on Experimental Vibration Analysis for Civil Engineering Structures (EVACES) Porto (Portugal) July 2-4, 2025) [10.1007/978-3-031-96114-4_58].

Availability:
This version is available at: 11583/3006325 since: 2026-01-08T04:40:23Z

Publisher:
Springer

Published
DOI:10.1007/978-3-031-96114-4_58

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09 November 2026

Hybrid cross-laminated timber building case study dynamic identification under forced vibration tests

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Abstract. Timber structures have experienced its revival as a viable structural solution lately, especially thanks to its relatively modern engineered version, i.e. the cross-laminated timber (CLT). Nevertheless, timber constructions are still lightweight and, therefore, inherently prone to experiencing vibration issue phenomena. This challenge motivated research trends within this field lately, in particular, to characterize the dynamical characteristics of hybrid structural solutions. This study presents preliminary findings from the dynamic analysis of a hybrid timber-concrete building case study. The research employs operational modal analysis (OMA) using output-only techniques for ambient vibration recordings and Hilbert Huang transforms (HHT) for forced vibration tests performed during construction stages. Finally, the results of a preliminary finite element model (FEM) updating procedure have been discussed. The current findings evidenced that greater research efforts should be demanded in the next years to better understand the vibration coupling phenomena in these hybrid structural typologies.

Keywords: Timber Buildings · Timber engineering · Finite Element Model Updating · Vibration · Ambient Vibration Tests

1 Introduction

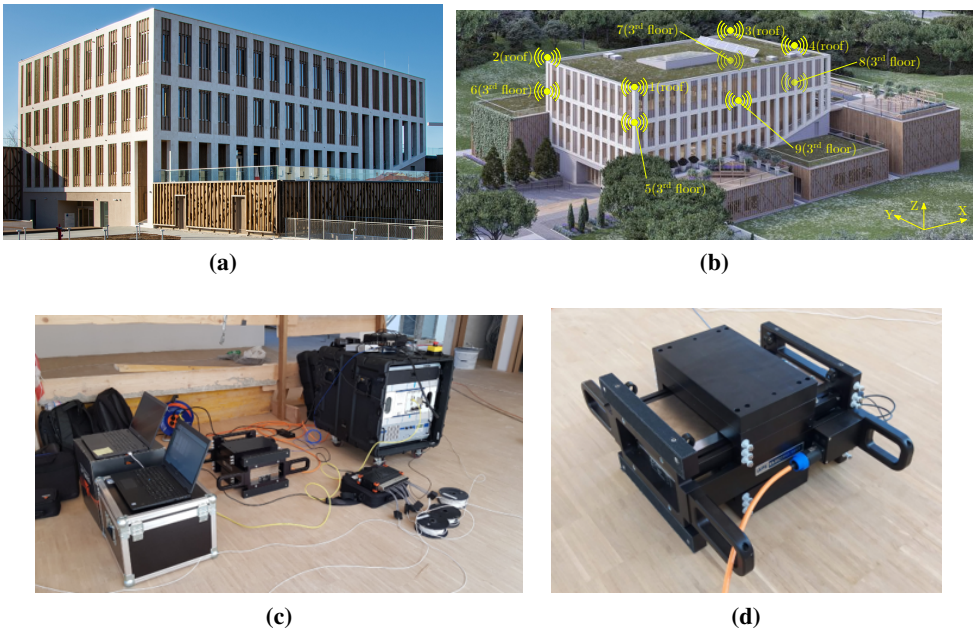
In recent years, timber as a structural material gained again an important role, since its modern engineered version is able to effectively cope with high sustainability standards, satisfactory structural requirements, and low cost. Afterwards its European Technical Approval in 2006, cross-laminated timber (CLT) rapidly expanded across various civil engineering and architectural sectors [1]. Timber structures' lightweight feature provides the possibility for speeding up construction processes, thus lowering their carbon footprint and even reducing labor costs for common residential, commercial, and industrial buildings. Conversely, timber material originates new challenges and complexities for designers when dealing with large-span or high-rise solutions. Moreover, the other side of the coin of this lightweight characteristic is that timber structures are intrinsically prone to vibration issue phenomena, thus affecting the in-service occupant comfort, or even structural integrity in some very serious cases [2].

Over the years, various building typologies have been proposed using CLT as the solely central load-bearing system, or with hybrid solutions such as those ones combined with concrete shear core walls or steel frames besides CLT floors or vertical elements. Moreover, scientific research debates have been focused especially on the dynamic characterization also of these hybrid solutions in the last decades [2]. Nonetheless, several aspects of the dynamic response of hybrid timber buildings still remain highly uncertain, e.g. the vibration response coupling effects between timber and concrete elements, strongly dependent on the degree of interconnection as well. Consequently, experimental vibration testing is invaluable, since it offers vital insights into the mechanical properties of its main components. Indeed, the stiffness of tall CLT buildings is not solely dependent on the properties of the CLT panels but is also significantly influenced by the connection system [3]. Furthermore, due to their lightweight and flexible nature, timber structures may be more vulnerable to excessive vibrations [4]. Nowadays, a still low number of studies deal with very long-term monitoring of this kind of structures, whereas the great majority of them were referred to a limited time span [5,6]. Furthermore, the base assumptions of operational modal analysis (OMA) dealing with natural ambient vibrations, and few studies focused on the possible amplitude-dependent behavior under forced vibration tests campaigns [7]. This is justified also by the observed phenomenon of modal interference of the floor-whipping [8], which introduces additional uncertainty and deviation of the forced results than ambient vibrations traditional OMA.

This current document explores in Section 3 traditional stationary OMA and forced dynamic characterization for a hybrid timber building case study in Slovenia, previously described in Section 2. Eventually, some preliminary results are illustrated related to a finite element model (FEM) of the case study which underwent a model updating process based on OMA results. These latter preliminary results demonstrated that much more effort should be earmarked to provide a more comprehensive understanding of the complex dynamics characterization of this hybrid case study building.

2 Hybrid concrete-timber building description

The herein-analyzed case study is located in Slovenia country and it is a 30×20 m^2 hybrid CLT-concrete building (see Fig. 1). The vertical structural elements are primarily composed of CLT shear walls on the second, third, and fourth floors, while the first floor utilizes concrete walls. On the other hand, horizontal structural components are composed of CLT floors except for the first and second floors which are made of reinforced concrete (RC) slabs. A steel frame is also present in the central part of the building, as better illustrated in Fig. 4, providing a central core for the building. In addition, a staircase is located in one corner of the building plan and is made of concrete core walls. Figs. 1 (b), (c) and (d) illustrate the vibration acquisition system and the deployed sensor layout, and the shaker device used for the forced vibration tests.



(a) **(b)**

(c) **(d)**

Fig. 1. Case study overview. (a) a photo of the monitored building; (b) the deployed accelerometer layout; (c) a photo of the vibration monitoring system; (d) a photo of the shaker used for forced vibration tests.

3 Dynamic characterization under ambient and forced vibration tests

The dynamic characterization of the building is based on ambient and forced vibration tests, conducted in March 2021 and August 2021. As depicted in the sensor layout of Fig.1 (b), it is worth noting that only the second and third floors have been monitored, focusing the standpoint over the dynamics on the CLT part only, and therefore disregarding the stiffening effects possibly provided by the low-rise portions of the adjacent surrounding buildings.

Regarding the natural excitation ambient vibration tests, the modal parameters were estimated using the most well-established OMA techniques implemented in PyOMA software [9,10]. Specifically, the Enhanced Frequency Domain Decomposition (EFDD) [11] and the Stochastic Subspace Identification with its covariance-based version (SSI-cov) [12], have been adopted to identify the actual modal parameters with a mutual validation of the outcomes obtained with two different uncorrelated approaches. The OMA results are reported in Fig.2, illustrating that three main modes are visible on the stabilization diagram and on the singular value graph of the cross-power spectral densities (PSD) at about 4.8, 6.3, and 7.1 Hz. However, the mode shapes visualization is quite unclear, also caused by using an insufficient number of monitored points to provide an extended spatial resolution of the building. Moreover, the vertical components appear quite important in the mode shape visualization, which may lead to thinking that some measurement error appeared. Nevertheless, despite being quite unusual for such types of buildings, these results have been also observed in the subsequent FEM model updating procedure, confirming the relevance of the vertical modal components in this specific case study.

The second monitoring campaign relates to forced vibration tests, conducted employing a shaker varying input excitation with varying frequency with a rate of 5 Hz/h in the range of 2-22 Hz. The dynamic characterization in this latter case has been conducted using the Hilbert-Huang Transform (HHT) technique [13]searching for the analytic form of a vibration recording signal. Foremost, the empirical mode decomposition (EMD), also known as the sifting process, permits decomposing the input signal into a reduced number of time-domain mono-frequency signals denoted as intrinsic mode shapes (IMFs). Afterward, the Hilbert Transform (HT) can be applied to each IMF to characterize their instantaneous properties. Indeed, the HHT provides an instantaneous description of the dynamics of the building, in terms of instantaneous frequency (IF) and instantaneous amplitude (IA), allowing also the analysis of amplitude-dependent behaviors. Fig.3 presents all the most meaningful results obtained with the forced vibration campaign. Fig.3 (a) illustrates the power spectrum recorded by a reference sensor, where the spectral analysis reveals peaks that align with those identified in ambient vibration OMA tests. The excitation signal applied as input to the shaker is depicted in Fig. 3 (b), while Fig. 3 (c) presents the superimposed measured signals from all channels. The average root mean square error is $1.15\times10^{-}4$g, which is comparable to the values obtained during ambient vibration tests (3.13×10^{-4}g). The recorded maximum acceleration reaches 0.011g, approximately ten times higher than the peak acceleration observed during operational conditions (0.001g).

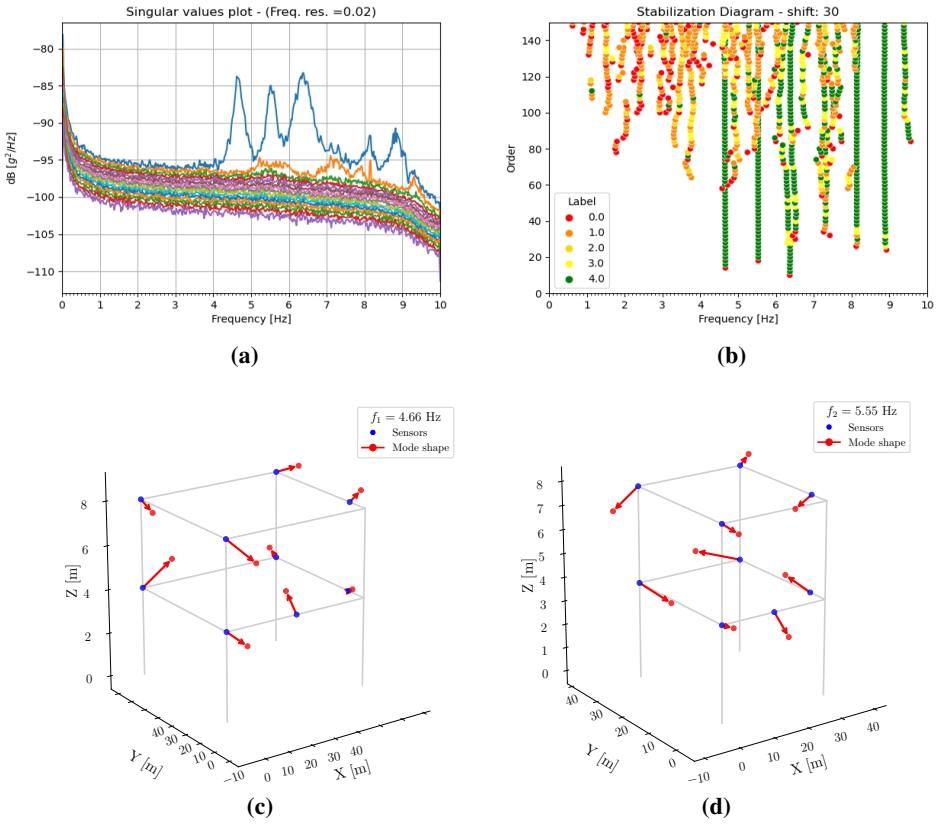


Fig. 2. Ambient vibration OMA results. (a) EFDD results; (b) SSI-cov results; (c) Mode shape simplified visualization at 4.8 Hz; (d) Mode shape simplified visualization at 6.3 Hz.

Table 1. Natural frequencies results for the first three modes retrieved by OMA ambient vibration and forced vibration tests.

Year 2021	Test	Mode 1 [Hz]	Mode 2 [Hz]	Mode 3 [Hz]
March	Ambient	4.81	6.27	7.08
March	Ambient	4.58	5.8	6.71
August	Forced	4.65	5.77	6.67

The IF description for the first three modes of interest is illustrated in Figs.3 (d) and (e). The modal assurance criterion (MAC) illustrates the correlation degree between the

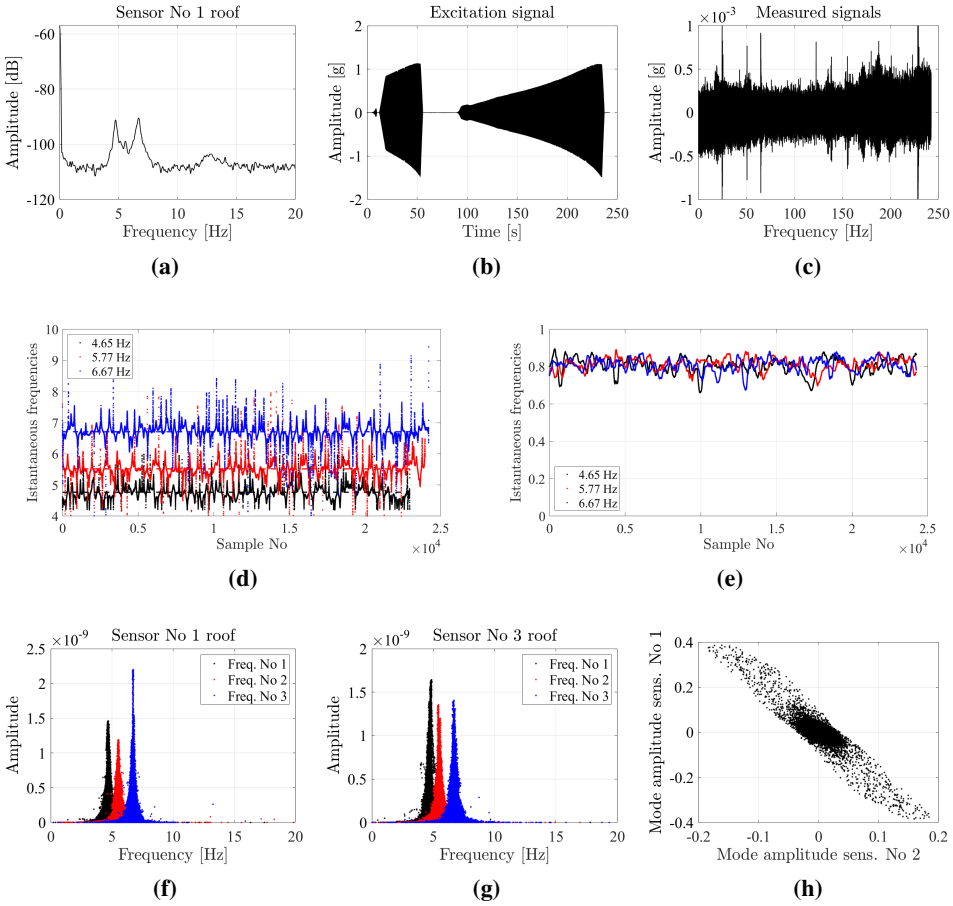


Fig. 3. Forced vibration test results. (a) PSD of a reference sensor; (b) shaker input excitation signal; (c) sensors measured signals during forced tests; (d) IF for the first three modes; (e) Modal Assurance Criterion metric among the IF of the first three modes; (f) IA vs IF graphs for sensor No 1 on the roof; (g) IA vs IF graphs for sensor No 3 on the roof; (h) correlation between IA of sensors No 1 vs No 2 .

estimated averaged mode shapes, yielding a value close to 0.8 for all modes. These outcomes demonstrate the averaged mode shapes cannot be considered physical modes, and therefore it is not advisable to use these results for performing the FEM model updating process. Despite this, the minimal variation in the MAC values demonstrates that the mode shapes are

relatively insensitive to vibration amplitude. However, IF values exhibit greater sensitivity, since larger discrepancies compared to the averaged frequencies are observed during periods of lower vibration amplitude, i.e. when the signal provides less information. In any case, as depicted in Figs.3 (f)-(g)-(h), despite the nonstationary nature of the forced tests, the imposed highest excitation levels are still not sufficient to activate any nonlinear phenomena [14], since a linear correlation is still evident between sensors No 1 and 2, and also the IA is quite vertically aligned at the central frequencies characterizing the three mode shapes of interest.

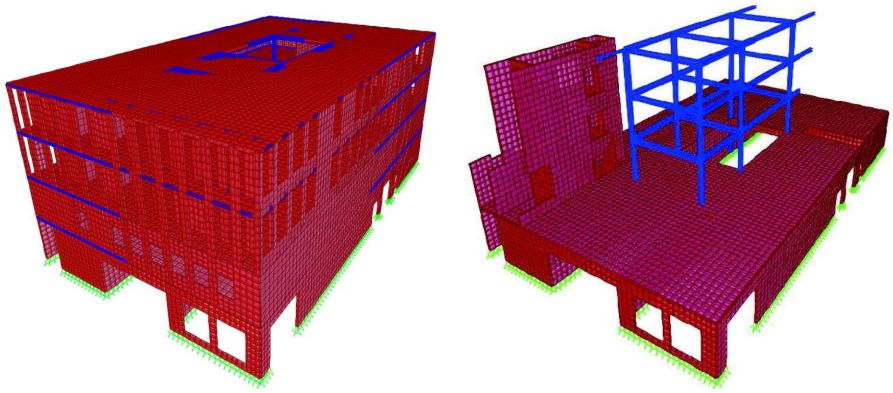
4 Preliminary results of the model updating procedure

Finally, as depicted in Fig.4, the authors developed a FEM model in SAP2000 of the hybrid case study building for performing an initial model updating procedure and calibrating the numerical model based on the experimental in-field vibration campaigns. The geometry of the FE model is based on a 3D model of the actual structure. The CLT panels are defined as orthotropic thin shell sections. The concrete walls are defined as isotropic thin shell sections with the same isotropic material for each section. The wood and steel framing are modeled as frame elements with cross-section and material properties of the specific parts. It is worth noting that SAP2000 has a limitation: two elements do not connect unless the two share at least two nodes. This problem was solved by assigning edge constraints to all area elements, making them connect without sharing corner nodes. Restraints are placed at each node to restrain the bottom of the concrete walls to the basement. The restraints are created with a finer mesh of the base of the wall elements on the first floor. This makes the model restrained at the ground level with a consistent distance that is the same as the meshing size. All restraints prevent displacement in the three translational degrees of freedom and are free to rotate. The mesh size was obtained by setting a trade-off between accuracy and computational effort.

FEM model updating process is utilized to analyze the dynamic behavior of structural systems. The goal of updating is to tighten the gap between the simulated and experimental dynamic response during the in-service conditions. This optimization procedure can be formalized into the minimization of the following objective function [15]:

$$\min \mathcal{F} = \sum_{i=1}^{M} \gamma_i \left(\frac{\omega_i^m - \omega_i^c}{\omega_i^m} \right)^2 + \beta \sum_{i=1}^{M} \left(1 - \mathrm{diag}(\mathrm{MAC}(\Phi_i^m, \Phi_i^c)) \right) \tag{1}$$

where the superscript $(*)^m$ indicates a measured variable, the superscript $(*)^c$ a calculated variable, Φ_i is the mode shape vector, M is the number of modes, MAC is the Modal Assurance Criterion, while γ_i and β are weighting factors. A convergence criterion in Eq.1 is used to evaluate the difference between experimental and numerical data. The two contributing factors are the MAC and the deviation between the numerical and experimental eigenfrequencies. The value of the objective function expresses the accuracy of the numerical model compared



(a) (b)

Fig. 4. Numerical global FEM implemented model. (a) a visualization of the FEM model in CSI SAP2000 software; (b) the FEM detailing of an internal steel framing system into the central part of the building.

to the experimental measurements. The closer Eq.1 is to zero, the higher the agreement with the experimental estimates.

The model updating task has been carried out using the metaheuristic algorithm denoted as differential evolution (DE) developed in Python and using the SAP2000 Open Application Programming Interface (OAPI). The input parameters of the DE are: a population size of 60, a mutation constant of 0.9, and a recombination constant of 0.8. The authors only possess unscaled mode shapes. Therefore, it is necessary to select either the mass or stiffness parameters to avoid an ill-conditioned inverse problem. According to the authors, the most uncertain parameters are the nonstructural masses. Therefore, the parameters chosen in the update are: The nonstructural roof mass, acting as a uniformly distributed load; the mass of the facade, considered as a uniformly distributed load along the perimeter of the building; the nonstructural mass of the floors. The load is considered a mass source to observe effects on the modal analysis. The range of the parameters is 0-2 kN/m^2 for the roof and the floors, while 0-4 kN/m to 4 kN/m for the facade. The initial set of parameters is zero for the three values. Tab.2 shows the optimal values of the structural masses from the updating.

Tab.3 shows the comparison between experimental, initial, and updated modal parameters in terms of frequencies and MAC. The updating led to a significant improvement in the agreement, especially for the second mode. The first and second exhibit a higher discrepancy. Conversely, the MAC between experimental and numerical models is relatively high for the first two modes, 0.96 and 0.85, respectively. However, it does not improve significantly for the third mode, from the initial 0.448 to the optimal 0.728.

Table 2. Updated values of the nonstructural masses.

Floors [kN/m^2]	Roof [kN/m^2]	Facades [kN/m]
0.054	1.88	0

Table 3. Experimental and numerical modal parameters in terms of frequency (f), MAC and relative variation of the natural frequencies (δ), where $_e$ $_i$ and $_u$ indicate the experimantal, initial and updated values respectively.

Mode	f_e	f_i	f_u	δ_i	MAC$_i$	OF$_i$	δ_u	MAC$_u$	OF$_u$
1	4.630	5.199	4.024	0.123	0.954	1.277	0.131	0.967	0.705
2	5.566	7.014	5.566	0.260	0.849		0.000	0.850	
3	6.363	7.286	7.121	0.145	0.448		0.119	0.728	

5 Conclusions and Future Remarks

This preliminary study focused on the experimental dynamic characterization of a hybrid timber-concrete building located in Slovenia. A comparison between ambient and forced vibration tests revealed a strong consistency in modal parameters. Using the Hilbert-Huang Transform (HHT) in the forced tests, the resulting intrinsic mode functions (IMFs) showed good agreement with the identified modal properties in ambient vibration. Furthermore, to investigate potential nonlinear effects, HHT applied to forced vibration test data permitted analyzing instantaneous frequencies and amplitude properties. The results demonstrated that the applied excitation levels were insufficient to induce the activation of noticeable nonlinear dynamical behavior. As a result, forced vibration tests did not provide additional insights beyond those obtained from ambient vibration tests. In conclusion, the preliminary results of a finite element model updating procedure revealed that in the specific case, the vertical mode shape components are particularly relevant. Future insights should be addressed to understand why these vertical components are particularly relevant in this case study, and possibly better explore how the coupling effects between concrete and timber structural components affect the dynamics of the entire system.

Acknowledgments

Giuseppe Carlo Marano acknowledge the support from PNRR MUR project PE0000013-FAIR (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3, NextGenerationEU – D.D. 341 15/3/2022 and D.D. 1555 11/10/2022, PE0000013).

Marco Martino Rosso acknowledges the support received through the project ‘Artificial Intelligence for SUstainable seismic risk reduction of STructures (AI-SUST)” (project code:

2022LEFKHS) funded by European Union – NextGeneration EU through the PRIN 2022 program of the Italian Ministry of University and Research (MUR) (D. D. n. 104, 02-02-2022). This work reflects only the authors' views and opinions whereas the MUR cannot be considered responsible for them.

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