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SEISMIC ANALYSIS OF A TYPICAL FRAME OF A PREFABRICATED MULTI-STOREY CLT BUILDING

Summary: The increasing use of cross laminated timber (CLT) in modern construction is driven by its sustainability and favorable structural properties compared to concrete and steel. This paper investigates the seismic performance of a typical frame of a prefabricated four storey CLT building in a seismic region. The study assesses the dissipative behavior of structural connections and the overall seismic resistance of multi storey CLT systems. A Finite Element (FE) numerical analysis was conducted using experimental data on the nonlinear behavior of structural connections. CLT wall panels were modeled as elastic orthotropic surfaces, while floor slabs were represented as equivalent beams. Wall to foundation and wall to floor connections were modeled with nonlinear springs. Pushover analysis evaluated seismic response. Results indicate that four storey prefabricated CLT buildings can achieve satisfactory seismic performance under moderate seismic hazard.

Keywords: CLT buildings, earthquake engineering, pushover analysis, N2 method

SEIZMIČKA ANALIZA TIPSKOG RAMA CLT VIŠESPRATNICE MONTAŽNOG TIPA GRADNJE

Rezime: Sve šira primena unakrsno lepljenog lameliranog drveta (CLT – Cross Laminated Timber) u savremenom građevinarstvu posledica je njegove održivosti i povoljnih konstrukcijskih karakteristika u poređenju sa tradicionalnim građevinskim materijalima, kao što su beton i čelik. U ovom radu analizirane su seizmičke performanse tipičnog okvira prefabrikovane četvorospratne CLT zgrade smeštene u seizmički aktivnom području. Istraživanje je usmereno na procenu disipativnog ponašanja konstruktivnih spojeva i ukupne seizmičke otpornosti višespratnih CLT konstrukcija. Numerička analiza metodom konačnih elemenata sprovedena je korišćenjem eksperimentalnih podataka o nelinearnom ponašanju konstruktivnih spojeva. Zidni CLT paneli modelirani su kao elastične ortotropne površine, dok su međuspratne konstrukcije predstavljene ekvivalentnim grednim elementima. Veze zid–temelj i zid–međuspratna konstrukcija modelirane su pomoću nelinearnih opruga. Za procenu seizmičkog odgovora konstrukcije primenjena je pushover analiza. Dobijeni rezultati pokazuju da prefabrikovane četvorospratne CLT zgrade mogu ostvariti zadovoljavajuće seizmičke performanse pri umerenim nivoima seizmičke izloženosti.

Ključne reči: CLT zgrade, zemljotresno inženjerstvo, pushover analiza, N2 metoda

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1. INTRODUCTION

The application of Cross-Laminated Timber (CLT) panels in low- and mid-rise multi-storey buildings has expanded considerably due to their suitability as an alternative to conventional structural systems, particularly in earthquake-prone regions [1]. As a renewable material, wood has the ability to store carbon dioxide during its lifespan, which gives wood-based products, such as CLT, superior environmental characteristics. In addition to environmental advantages, CLT structures possess a high stiffness-to-mass ratio, as well as bearing capacity comparable to reinforced concrete, which makes them suitable for application in seismically active areas [2], [3]. However, despite increasing popularity, the design and calculation of CLT structures, especially concerning seismic action, remain a challenge due to the lack of regulations in Europe. The application of traditional design methods developed for other types of structures is not the most adequate way to assess the actual seismic response and resistance of multi-storey CLT buildings. A significant limitation in the design of innovative building systems, especially prefabricated timber structures such as CLT, is the use of empirical design approaches originally developed for simple structural cases, which are not always suitable for these modern structural systems [2].

Prior testing established that the stiffness of CLT structures, and therefore their dynamic behavior, is mostly determined by how flexible (deformable) the panel connections are [4]. This deformability directly influences the fundamental period of oscillation of the structure (T1), which is the most important parameter for determining seismic forces within the equivalent static load method [4]. Beyond the connections, the structure's stiffness is also significantly influenced by the material's nonlinear behavior, the contribution of non-structural elements, and foundation interaction. These factors significantly complicate the calculation process for CLT structures [5]. Therefore, precise numerical analysis is crucial for understanding the behavior of multi-storey CLT buildings.

This paper provides fundamental information on the behavior of prefabricated multi-storey CLT buildings exposed to seismic action. The 2D model of the typical frame of a prefabricated four-storey CLT building was developed and analyzed using the RFEM 6 Finite Element software. CLT wall panels were modeled as orthotropic shell elements according to the material properties given in [5], while CLT floor slabs were replaced by equivalent beam elements. The inelastic response of the structural connections was simulated based on experimental results of cyclic shear resistance reported in the literature [4]. Two connection systems were implemented in the model to prevent wall uplift and shear: hold-downs (HD connections) and angle brackets (AB connections), as shown in Figure 1 [4]. The connection properties adopted in the model were based on the results reported in [4]. Furthermore, a nonlinear static ("pushover") analysis was performed to investigate the structural response beyond the elastic limit, while the seismic response of the observed typical frame was determined using the N2 method.

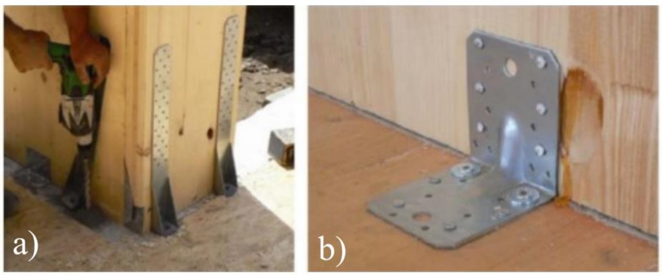


Figure 1: Connection systems used to prevent wall uplift and shear: a) angle-brackets, b) hold-downs [1]

2. ANALYSED STRUCTURE AND CASE STUDY

The case study corresponds to a prefabricated four-storey CLT building with a rectangular floor plan measuring 21.1 × 14.7 m, a total height of 14.8 m, and storey heights of 2.8 m and 3.0 m for the ground floor and upper floors, respectively [2]. The main load-bearing system consists of prefabricated CLT wall and floor panels. Both wall and floor elements are composed of five orthogonal timber layers with a total thickness of 120 mm. The configuration and thickness of the individual layers are presented in Figure 2. The structure was assumed to be founded on Type C soil in accordance with Eurocode 8 [3]. The structural response was subsequently evaluated by means of a nonlinear finite element model described in the following section.

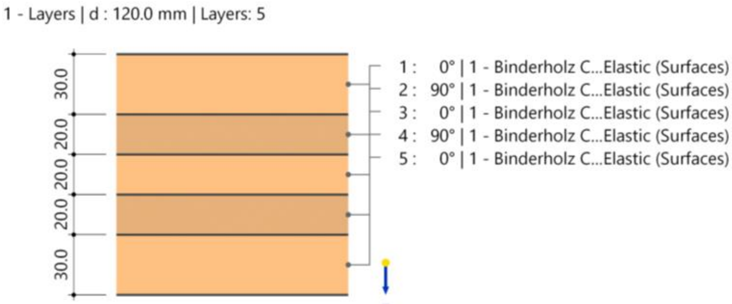


Figure 2: Configuration and thickness of CLT wall and floor panel layers

3. NUMERICAL MODEL AND ADOPTED ASSUMPTIONS

A two-dimensional finite element model representing the typical frame of the analysed building was developed in RFEM 6. CLT wall panels were modelled as orthotropic shell elements, whereas floor slabs were represented by equivalent beam elements with calibrated axial stiffness to reproduce the behaviour of the corresponding CLT floor slabs, as shown in Figure 3.

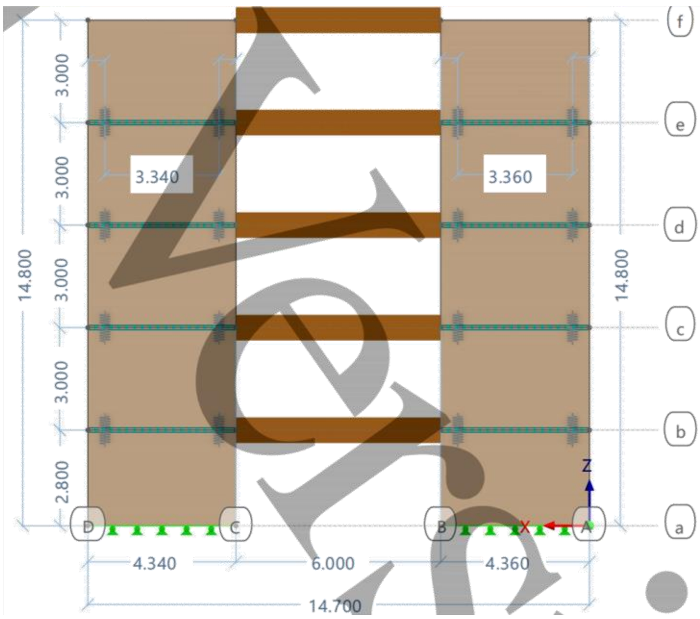


Figure 3: Two-dimensional finite element model developed in RFEM 6

The nonlinear behaviour of the numerical model was primarily governed by the mechanical response of the structural connections. Hold-down (HD) connections resisting uplift were represented by nonlinear spring elements positioned at the wall corners, whereas angle-bracket (AB) connections transferring shear forces were modelled using nonlinear boundary conditions along the wall interfaces, as shown in Figure 4. The constitutive relationships of both connection types were adopted from experimentally validated models reported in the literature, as shown in Figure 5 [4]. Following the methodology proposed by Yasumura and Follesa, nonlinear link elements of negligible length were used to directly incorporate the experimental load–displacement relationships into the numerical model [4].

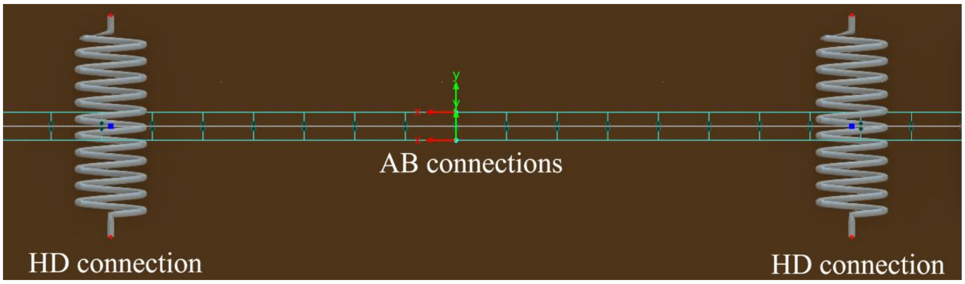


Figure 4: Connection elements of CLT wall panels for tensile force transfer - hold-downs (HD connections) and for shear force transfer - angle-brackets (AB connections)

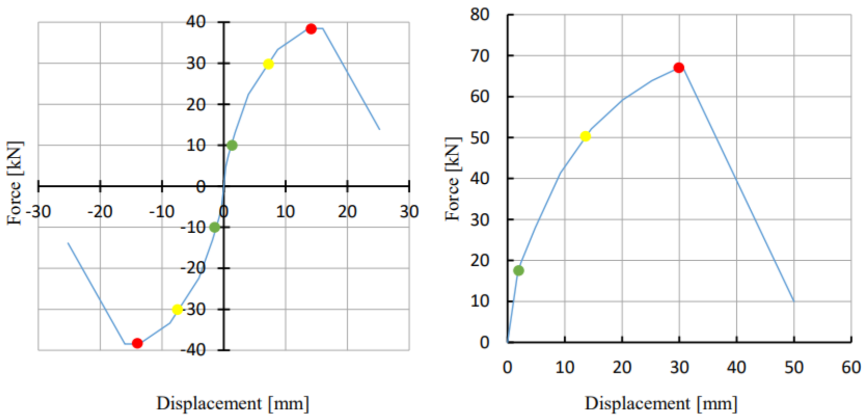


Figure 5: Constitutive relationships adopted for a) HD connections ; b) AB connections [1]

The foundation slab was not modelled explicitly. Instead, wall-to-foundation connections were represented by boundary conditions restraining horizontal and vertical displacements. The interaction between axial and shear forces in the connectors and friction effects were neglected. Vertical loads obtained from linear analysis were applied directly to the wall panels, while floor masses were concentrated at the storey centres of mass and rigid diaphragm behaviour was assumed. The model was subjected to gravity loading and seismic actions.

Six analysis configurations were defined by combining different levels of horizontal ground acceleration acting in the X direction ($a_{g,max}$) with two lateral load distribution patterns: modal (M) and uniform (U). The analysed loading configurations are summarized in Table 1.

Table 1: Analysis configurations for different values of horizontal ground acceleration and different load distribution patterns

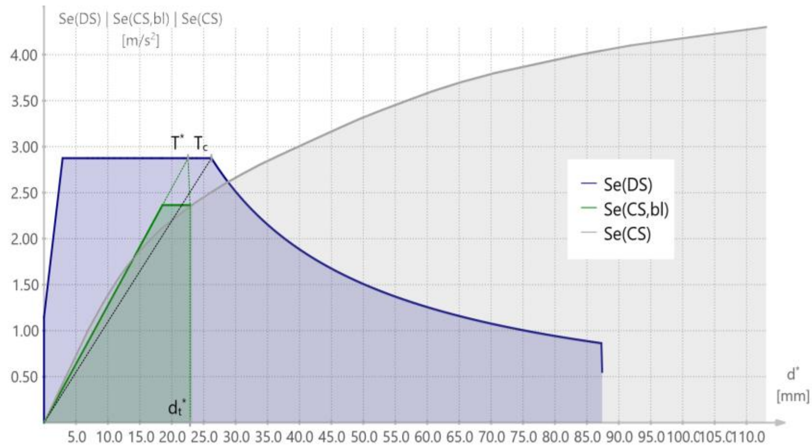
$a_{g,max}$	X direction	
0.1g	M0.1g	U0.1g
0.2g	M0.2g	U0.2g
0.4g	M0.4g	U0.4g

A modal analysis was first performed using the "Root of Characteristic Polynomial" sub-option in RFEM 6 to determine the fundamental and higher modes of oscillation of the structure. Subsequently, nonlinear static analysis, "pushover" analysis, were carried out for all six loading configurations. The developed numerical model, together with the adopted material properties and connection characteristics, was used to evaluate the seismic response of the typical frame of the four-storey CLT building.

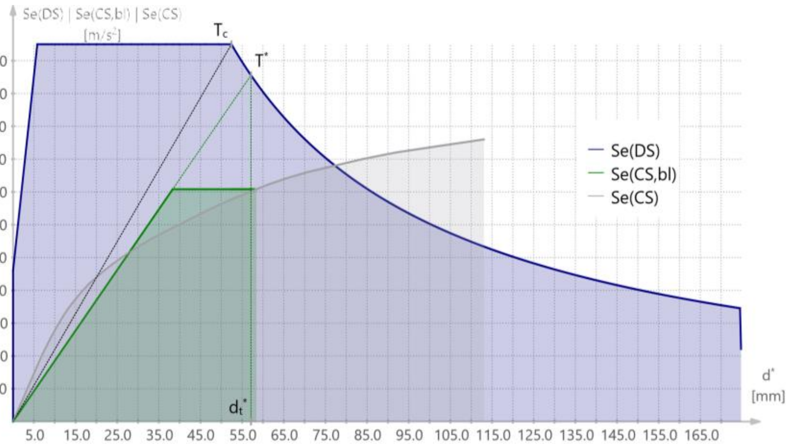
4. RESULTS

Nonlinear static (pushover) analyses were performed by monotonically increasing the horizontal displacements at the centres of mass of each floor in the X direction while considering gravity loads. Two lateral load distribution patterns were adopted: modal and uniform. The resulting capacity curves, describing the relationship between the base shear and the roof displacement, were subsequently transformed into equivalent acceleration–displacement (AD) capacity spectra using the N2 method [6]. The target displacement for each loading configuration was determined using the N2 method, while the seismic performance was evaluated at the performance point, defined as the intersection of the capacity and demand spectra. Figures 6 and 7 present the pushover curves obtained for all six analysis configurations. The capacity spectra were then bilinearized according to the equal-energy principle prescribed in Eurocode 8, as required by the N2 method [3], [6].

a)



b)



c)

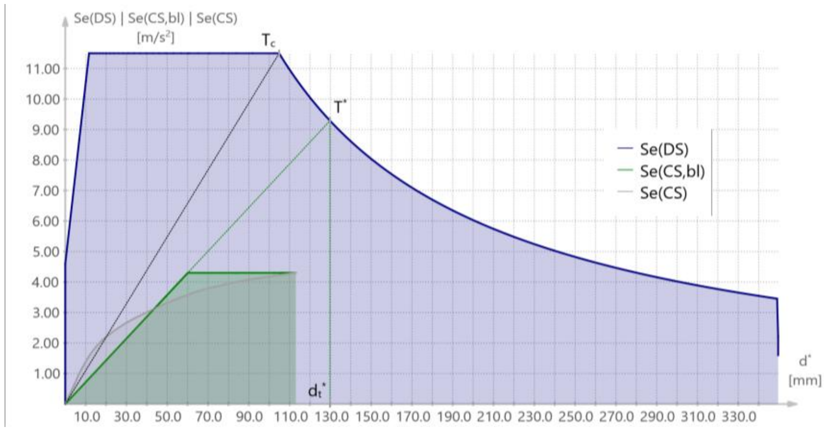
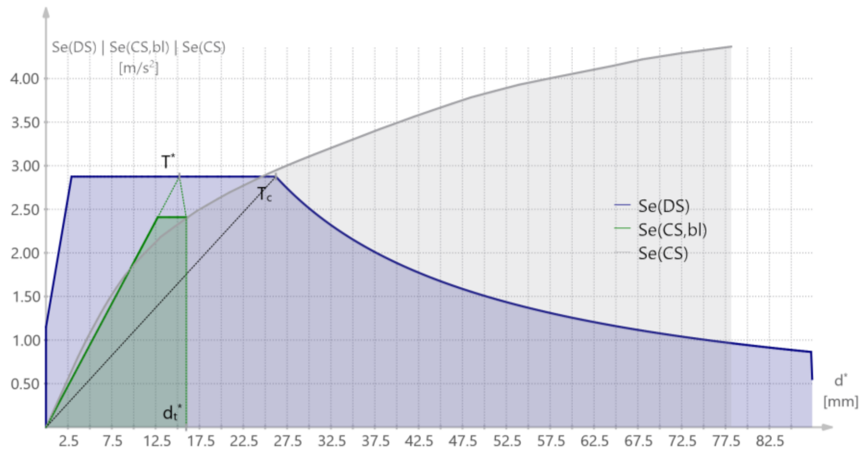


Figure 6: The results of the pushover analysis for the uniform lateral load distribution pattern under horizontal ground accelerations of a) 0.1g, b) 0.2g, c) 0.4g

a)



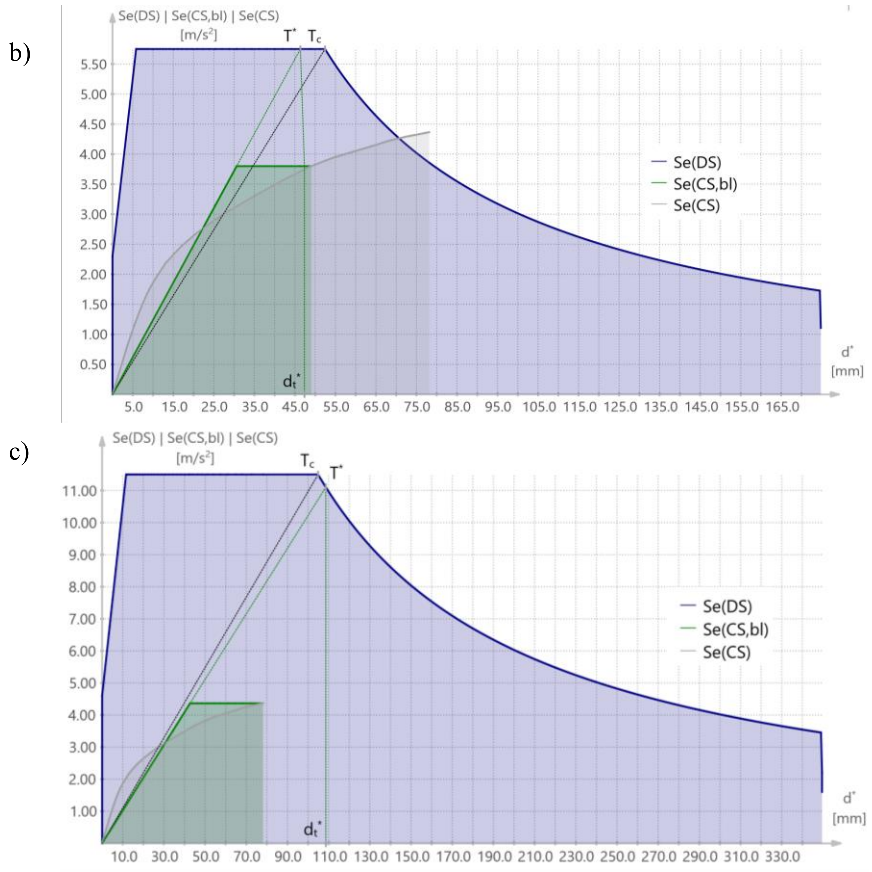


Figure 7: The results of the pushover analysis for the modal lateral load distribution pattern under horizontal ground accelerations of a) 0.1g, b) 0.2g, c) 0.4g

The obtained capacity curves indicate that the adopted lateral load distribution significantly affects the global nonlinear response of the structure. In all analysed cases, the uniform load distribution produced a larger area enclosed by the capacity curve than the modal distribution, indicating greater deformation capacity. The calculated performance point displacements are summarized in Table 2. As expected, the performance point roof displacement increased with increasing ground acceleration. At the maximum horizontal ground acceleration of 0.4g, structural collapse occurred, indicating that the analysed structure lacked sufficient capacity to withstand this level of seismic loading. Future improvements may include the use of mechanical fasteners with higher stiffness and load-bearing capacity. For all acceleration levels, the uniform load distribution resulted in larger performance point displacements than the modal distribution. The observed differences between the modal and uniform load distribution patterns can be explained by the different distribution of lateral forces over the building height. The uniform load pattern mobilizes a larger portion of the structural system simultaneously, resulting in greater global deformation capacity and larger performance point displacements. In contrast, the modal load pattern concentrates the seismic demand according to the fundamental vibration mode, leading to a stiffer global response. These observations are consistent with previous numerical studies on multi-storey CLT buildings reported in the literature [1], [4], [8].

Table 2: Performance point displacements for the six analysis configurations

$a_{g,max}$	X direction	
	M	U
0.1g	16.2 mm	23.2 mm
0.2g	47.4 mm	57.1 mm
0.4g	78.2 mm	113.1 mm

5. CONCLUSIONS

A nonlinear finite element model of a typical frame of a prefabricated four-storey Cross-Laminated Timber (CLT) building was developed to evaluate its seismic performance under different seismic intensity levels. The numerical model incorporated experimentally validated constitutive relationships for the structural connections and was analysed using nonlinear static (pushover) analysis in combination with the N2 method. Six analysis configurations were considered by combining three horizontal ground acceleration levels with two lateral load distribution patterns. The obtained results provide valuable insight into the influence of connection behaviour and loading pattern on the global seismic response of multi-storey CLT buildings.

The results led to the following conclusions:

- the nonlinear behaviour of the structural connections significantly influenced the global seismic response of the analysed CLT frame, confirming the importance of accurately representing connection behaviour in numerical models,
- the adopted lateral load distribution pattern affected the overall structural response. Both the modal and uniform load distributions should therefore be considered during the seismic assessment of CLT buildings, as each may govern different aspects of structural behaviour,
- the uniform lateral load distribution pattern resulted in larger performance point displacements under all analysed seismic intensity levels, indicating greater deformation capacity than the modal load distribution pattern,
- the numerical results for horizontal ground accelerations of 0.1g and 0.2g suggest that the prefabricated four-storey CLT structure is suitable for regions with moderate seismic action. At the maximum horizontal ground acceleration of 0.4g, structural collapse occurred, indicating that it is necessary to adopt mechanical fasteners with greater stiffness and load-bearing capacity to ensure structural stability and prevent collapse under severe seismic loading.

Future research should focus on improving the existing building regulations for CLT structures through additional experimental investigations of connection behaviour, validation of numerical models against experimental results, and the development of more advanced modelling approaches capable of representing the complex nonlinear response of CLT structures.

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SUSTAINABLE DEVELOPMENT GOALS

Sustainable Cities and Communities, Industry, innovation and infrastructure

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