INVESTIGATING VIBRATION EFFECTS ON WOODEN FRAME BUILDINGS: A FOCUS ON CLT RESPONSE TO TRAFFIC-INDUCED VIBRATION

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1 INTRODUCTION

Wooden frame buildings, especially those constructed with Cross-Laminated Timber (CLT), have become increasingly popular due to their sustainable nature and structural efficiency. Nevertheless, there are ongoing concerns about their vulnerability to environmental vibration, particularly those caused by nearby traffic, which may pose risks to the building's serviceability.

CLT is a complex material to be modelled as it relies on multi-layer with anisotropic properties. This study will evaluate the effectiveness when employing a simplified CLT modelling strategy. And will evaluate the environmental vibration impact on a mix construction (concrete and wooden frame).

2 BUILDING RESPONSE TO ENVIRONMENTAL VIBRATION

When vibration transfers from open ground (free-field) into a building, its magnitude and phase will change at the surface-building interaction due to impedance mismatch between propagation media (ground structure) and the building structure.

To simplify the modelling process when assessing building response from environmental vibration, a set of ground-to-building transfer functions, empirically derived, has been compiled by previous publication[1,2,3]. These transfer function curves indicate that conventional residential buildings with spread footings up to 4 stories high can experience vibration attenuation of up to 12 dB around the 63 Hz 1/3 octave-band. They also suggest that heavier building constructions generally exhibit greater coupling loss.

Once the vibration reaches the foundation, it propagates through the building's primary structure, including load-bearing external walls, structural columns, and floor slabs, typically losing some energy along the way. Figure 1 presents the generalized empirical curves typically used when carrying out an environmental impact assessment to establish the vibration impact on building from passing trains. The foundation coupling loss has been derived from measurements on heavy masonry buildings. The floor resonances are measured on typical mid-size rooms (in the 1970s) from city apartment buildings. The overall transfer function is the combining effect from both the coupling loss and the floor resonance.

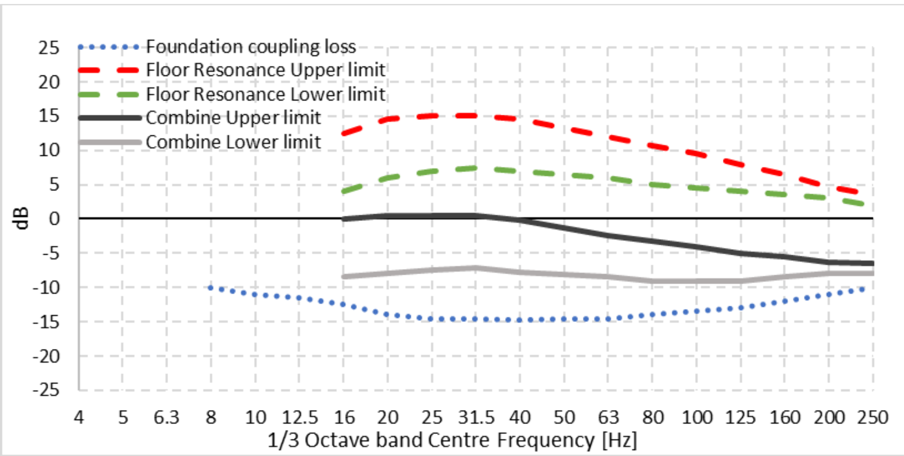

Figure 1: Generalised empirical curves[2].

Recent years have witnessed significant changes in construction methods, particularly in internal structures where lightweight construction materials like CLT floor plates.

3 MODELLING PROCESS

3.1 Modelling Tool

To evaluate the building response from traffic-induced vibration, FINDWAVE®[4], a well-established three-dimensional finite difference time-domain numerical model (FDTD) which computes the propagation of waves in elastic media, has been used.

The vehicle module, forcing function, represents the train as a stack of damped masses and springs. The dynamic excitation is provided from an input file containing an assumed vertical rail profile.

The environment module (e.g. rail/ground/building) models the dynamic behaviour of the rail surface supporting the vibration source (e.g. train), and the medium surrounding it, e.g. soil or air, together with structures below or above ground level. The structures of concern are represented by cells in a 3-dimensional orthogonal grid; and to each cell is assigned density, Lamé constants and loss factor.

By creating a representation of the system of elastic materials as a three-dimensional array of discrete cells, each possessing the four fundamental properties of an elastic medium, namely shear modulus, compression modulus, density and loss factor, and applying the rules of wave propagation in elastic media, it is possible to represent the real-life behaviour of the system, subject only to the accuracy of the parameters used and the limitations of the size of the cells in the array.

To account for complex geometries the cell parameters (density and Lamé constants) are scaled accordingly to capture the static and dynamic behaviour of the elements being modelled. For example, with the appropriate scaling a rectangular element, which is defined by a cell, will be able to approximate the dynamic behaviour of an I-beam. Given the small level of vibrations, it is assumed that the connections between beams and columns are rigid (e.g. beams and columns use the clamped boundary condition).

3.2 Test Building Design

For this study a prototype building of a mixed construction (see Figure 2) will be assessed under the influence of rail traffic using the above mentioned FDTD method.

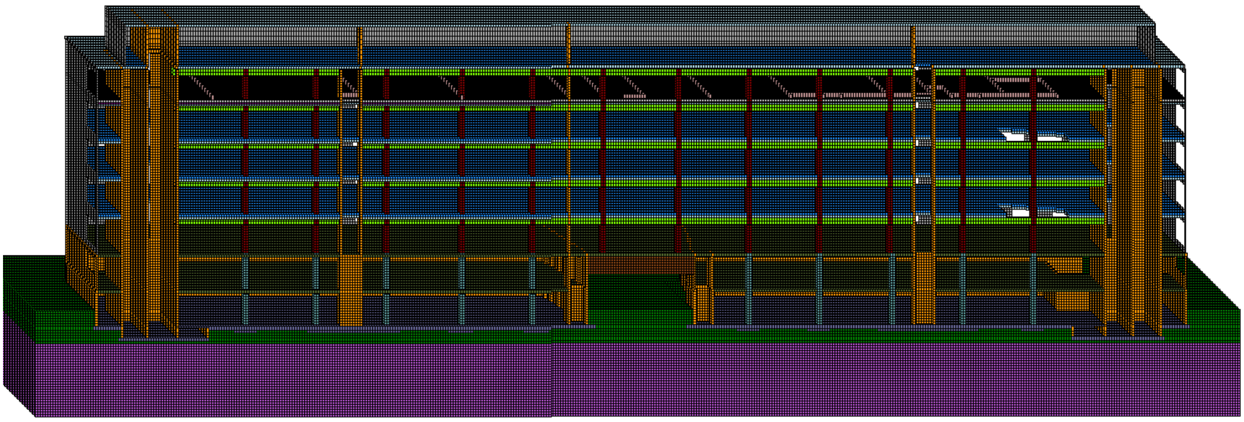

Figure 2: Isotropic view taken from the numerical model showing the building under evaluation.

The building, which is supported by a reinforced concrete foundation, spans a footprint measuring 100 m in length and 17 m in width. Concrete structures, such as columns and floorplates, forms the building structure from the basement up to the first-floor level. Transitioning from the second floor upward, wooden structural elements such as façades, floors, columns, and beams are utilized. There are five core structures (elevators and staircase shafts) rising from basement up to the sixth-floor level providing adequate constrain to the wooden frame. From the ground floor to the first level, the floor structure comprises concrete slabs upheld by concrete columns arranged on a 7 by 5.5 m gride. The perimeters of these floor structures are securely fastened to the concrete façade (clamped). This layout remains uniform across all levels, with only the materials varying. Starting from the second floor and extending upwards, wooden columns are utilized exclusively. Moreover, all CLT floorplates are further supported by two parallel beams fixed to the columns, running along the building's length (see Figure 3). For each floor level the following build-up is assumed:

- Basement Raft-foundation slab: 400 mm concrete slab.
- Ground-floor and first floor slab: 300 mm concrete slab.
- Second floor level: CLT 250 mm panel
- Third floor level: CLT 300 mm panel
- Fourth floor level: CLT 350 mm panel
- Fifth floor level: CLT160 + 120 mm concrete. On top of this mixed panels the model assumes an acoustic resilient layer and screed 60 mm (125 kg/m²) as shown in Figure 4.

This proposed floorplate layout, incorporating various materials and thicknesses, introduces diversity into the investigation. The fifth-floor level hybrid floor build-up has been assumed to test a mixed floor plate. The sixth-floor level, which has not been analysed, is being modelled to load the fifth-floor level. The façade which constitutes load bearing walls are as such:

- Basement: 300 mm concrete walls, with façade openings
- Ground floor: 200 mm concrete walls, with façade openings
- Floors level 1 to 6: CLT 160 mm walls, with façade openings

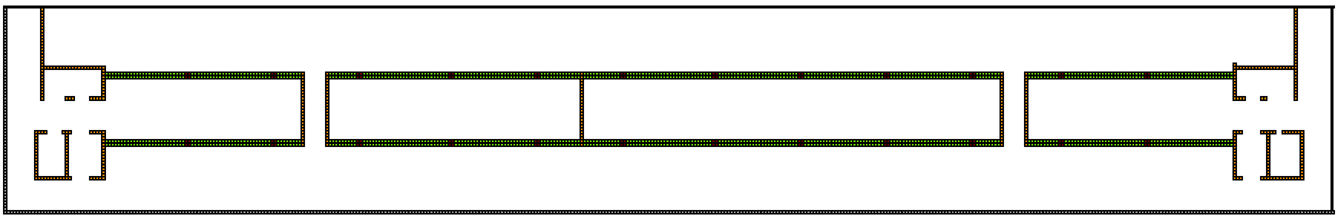

Figure 3: Plane view of the floorplate supports showing the beams and columns layout of the wooden frame.

3.3 Material Properties

The floorplates of the wooden part of the building consists of CLT panels formed of 5 to 7 (depending on the floor level) layered lumber boards stacked at 90 degrees angle and glued into one piece. Each layer constituting the CLT panel exhibits a specific grain direction, which is combined by alternating between the longitudinal and transverse directions (i.e., along the x-axis and y-axis) on the horizontal plane. The elastic modulus for the major axis is assumed to be 11 GPa and for the minor axis is around 0.40 GPa.

The CLT panel of the fifth-floor level floorplate, which makes up the most complex floorplate of the building, consists of 5 layers of different thicknesses and orientations as depicted in Figure 4.

To effectively model a CLT panel, which is composed of thin wooden layers, the use of "shell elements" within the Finite Element Method (FEM) is common practice. However, considering the scope of the issue at hand, which necessitates capturing the dynamic interaction between the building, ground, and rail system, this study opts for the FDTD method to evaluate the impact of rail-induced vibration on the building. Consequently, simplifying the CLT modelling becomes imperative by amalgamating its properties into a single layer. To achieve this, the CLT panels are simplified to exhibit isotropic behavior. This assumes that the CLT slabs will mainly be affected by vertical-bending deformation resulting from the vertical-shear waves, induced by the ground-borne vibration of nearby traffic. As a result, the FDTD model assumes that the axial modulus on the grain direction aligns with the perpendicularly horizontal direction and vertical direction. Since the constituent layers share identical materials and are stacked at 90-degrees angles, this adjustment effectively reduces the axial moduli of the CLT panel on the two horizontal directions.

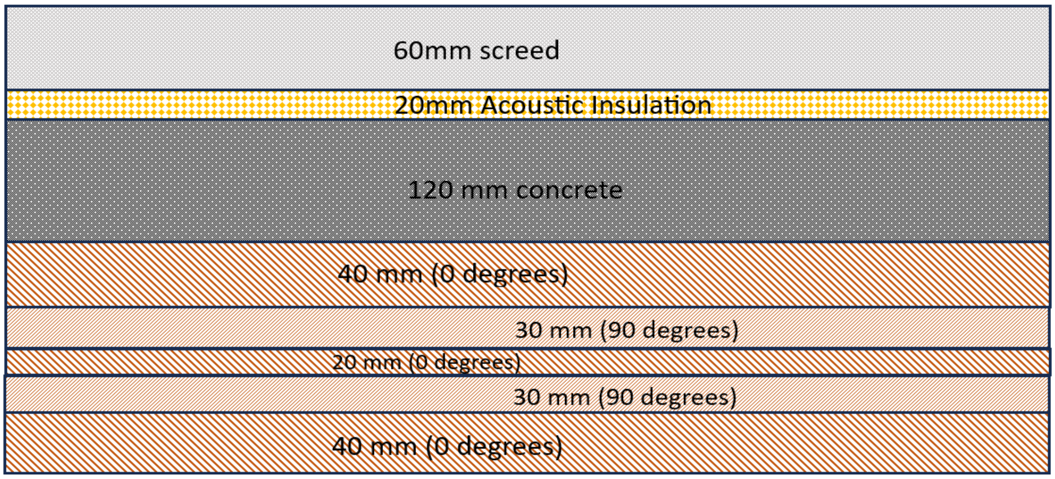

Figure 4: Fifth floor level floorplate hybrid floor panel buildup.

To ensure the effectiveness of such modelling assumptions (CLT as a single panel), a verification stage is employed, contrasting the multilayer CLT system (evaluated using "composite shell elements") with the single-layer panel to verify consistency in terms of response between both systems. Table 1 summarizes the mechanical properties of the structural elements used for the numerical model.

Table 1: Mechanical properties used on the Finite Difference Method

Material	Density [kg/m^3]	Young's Modulus [GPa]	Poisson ration	Loss factor
Concrete	2400	28	0.2	5%
Screed	1900	28	0.2	5%
CLT panel and wooden beams	420	0.4	0.43	5%
Wooden columns and wooden façade	420	11	0.43	5%

The 20mm acoustic insulation depicted in Figure 4 has been modelled as a glass fiber mat with a bedding stiffness of 11 MPa. This insulation is expected to provide isolation at a frequency of approximately 50 Hz. Lightweight partition walls are not generally included as structural elements as they are assumed to not greatly affect main dynamic behavior e.g., mode shapes although they can contribute to overall damping. The ground has been modelled with two layers, each having the following properties. The top layer assumes a Vs=154 m/s Vp=306 m/s and a density of 1700 kg/m^3; the bottom layer assumes Gravel with a Vs of 180m/s, Vp of 280 m/s and a density of 1600 kg/m^3.

4 RESULTS

4.1 Verification

The verification process will compare the response of the fifth-floor hybrid floorplate, modelled as a single-layer panel using FDTD, to the one modelled as a multi-layer panel using FEM.

For the FEM analysis, the fifth-floor hybrid floor panel made from CLT and concrete is modelled using composite shell elements composed of a series of plies that account for both bending and membrane terms as per the grain orientation and material. The density of CLT is assumed to be 420 kg/m^3 and the mechanical properties (Young's modulus, Shear modulus and Poisson's ratio) in the three directions are those of C24 timber. The concrete is C25/30 grade with a density of 2500 kg/m^3 and mechanical properties as per the Eurocode. The FDTD analysis uses the material properties given in Table 1.

4.1.1 Panel Modelling Strategy Comparison

Figure 5 displays the outcome of the hybrid floorplate FEM modal analysis (CLT modelled as multi-layer panel) presented in narrow bands. Only the most relevant modes are depicted here. It's evident that the modes are predominantly concentrated within the 10 Hz and 12.5 Hz one-third octave bands.

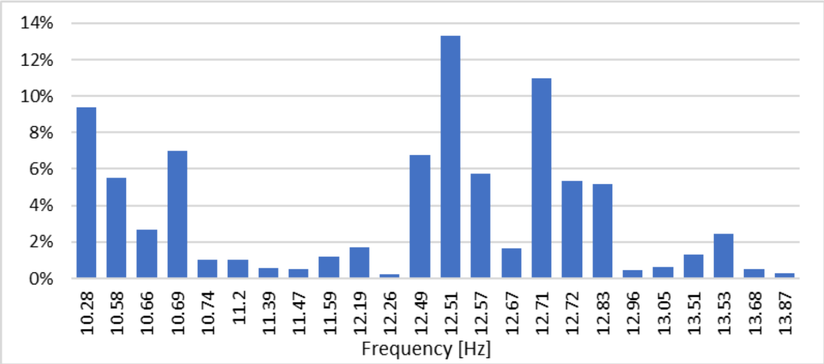

Figure 5: Percentage distribution of the most representative modes evaluated on the 5th floor slab modelled using a CLT multi-layer.

To assess the modal characteristics of the hybrid floorplate, where the CLT is represented as a single layer using the FDTD method, the entire floorplate was impacted on a 250 mm grid.

The response shown in Figure 6 has been taken at the floorplate surface on the longitudinal center line (between the two beams shown in Figure 3). The results show that the main modes are within the 10 Hz and 12 Hz 1/3 octave bands with a distribution of roughly 25% and 12% respectively. However, given that there is a higher percentage of model distribution around the 10 Hz, as opposed to the distribution in Figure 5 which shows a higher distribution around the 12.5 Hz, the analysis suggest that the single isotropic panel modelling scheme produces a slightly softer floorplate when compared to the multilayer CLT.

The rise around the 63Hz frequency range can be partly attributed to the 20mm acoustic insulation which has its isolation frequency at 50Hz.

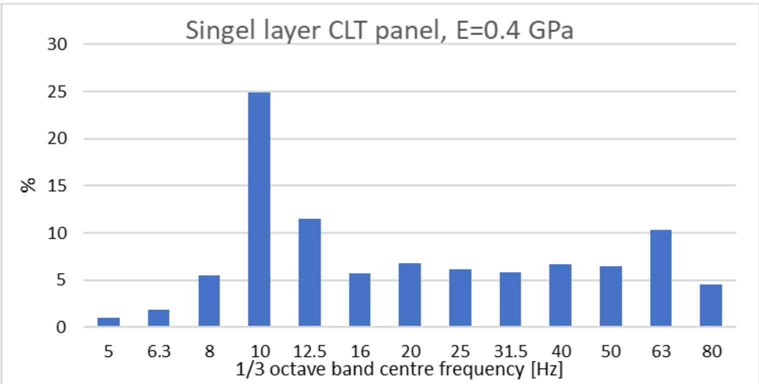

Figure 6: One-third octave band modal distribution evaluated along the center line of the single layer CLT panel.

4.2 Sensitive Analysis

Two sensitivity analyses have been carried out:

- Assessing the impact which the timber grain orientation has on the simplified modelling process. This has been done by contrasting the elastic modulus of 11GPa, which represents the axial modulus along timber grain to 0.4 GPa (perpendicular to the timber grain).
- A decrease of a 40% floorplate stiffness is also carried out to establish an uncertainty margin.

Figure 7 shows the 1/3 octave band modal distribution along the centre line of the hybrid floorplate of the fifth-floor level for the following scenarios: *E*=0.4 GPa representing the CLT model using the minor axis material properties; *E*=11 GPa representing the CLT model using the major axis material properties; and, *E*=0.24 GPa which represents the CLT model minor axis material properties with a 40% reduction in vertical stiffness; all other layers (see Figure 4) are kept as originally modelled. The vertical stiffness of the *E*=0.4 GPa CLT panel is around 0.285 N/m. A reduction in vertical stiffness by 40% yields an elasticity modulus of 0.24 GPa (from 0.285 N/m to 0.171 N/m). Figure 7 shows the resulting hybrid floorplate response for the three scenarios.

Comparing the *E*=11 to *E*=0.4 GPa scenarios, an upward modal distribution in frequency shift can be observed. However, given that the relationship between the 10 Hz and 12.5 Hz becomes disproportionally skewed to the 12.5 Hz octave band. This suggests that the adoption of the E=11 to represent the elasticity modulus when modelling the CLT as a single panel would yield a stiffer floorplate compared to reality. This could produce over optimistic results when assessing the response of the building.

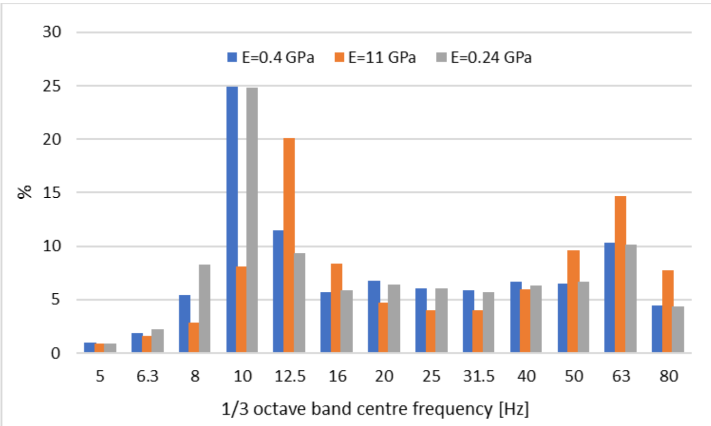

Figure 7: One-third octave band modal distribution along the center line of the floorplate of the fifth-floor level for the three scenarios: *E*=0.4 GPa; 11 GPa and 0.24 GPa.

A 40% stiffness reduction (*E*=0.24 GPa) does not show to have any major impact on the modal distribution. There is an ever so slightly decrease in frequency response which can only be noticeable by observed the 12.5 Hz 1/3 octave band.

It can be inferred, from this sensitivity analysis, that the material properties corresponding to the minor axis (*E*=0.4 GPa) have proven to be a conservative representation of the multi-layer CLT panel.

4.3 Rail-induced vibration impact assessment

The goal of the rail-induced vibration impact assessment is to contrast the generalized transfer functions to wooden frame transfer functions evaluated herein. The transfer function describing the building response takes as its input the vibration levels assessed along a line running along the longitudinal facade of the building at the ground surface. Note that given the proximity the input to the system will be influenced by the reflection form the foundation. This aligns with the convention way of carrying out transfer function measurements. The forcing function is a moving line source using typical Electric Motor Unit (EMU) train mechanical properties.

The output of the system is assessed along a line running along the centerline of the building's length on each floorplate. Additionally, a secondary analysis has been performed to determine the floorplate response. In this analysis, the input to the system is obtained at the centerline on the top of the raft foundation, corresponding to the basement level.

Figure 8 left contrasts the evaluated building response to the generalized curve; Figure 8 right contrasts the evaluated transfer function for each floor level floorplate to the generalized floor curves.

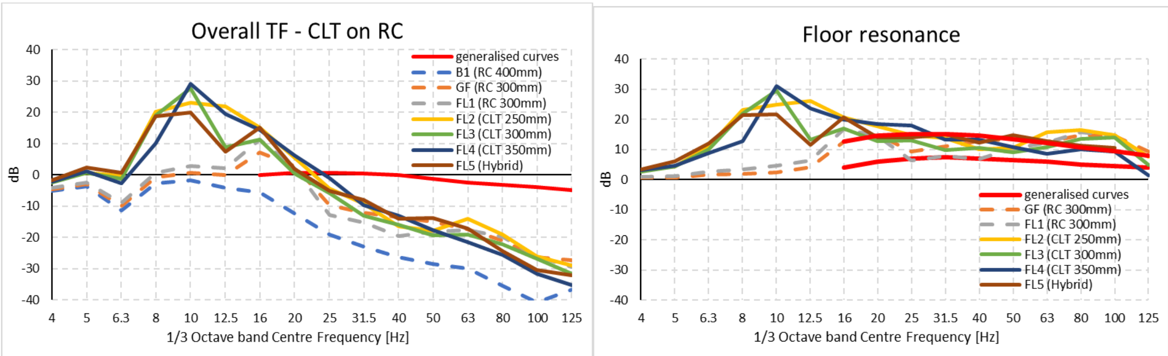

Figure 8: Comparison of the evaluated and generalized transfer functions: left, the building response (surface ground to floor level); right, the floor response (basement to floor level).

In general, when comparing to conventional masonry buildings the wooden structure response provided in Figure 8 left shows a shift in the frequency content, the modelled building emphasizes the low frequencies whereas high frequencies are attenuated. This could be attributed to the lighter weight characteristics of the wooden frame building and to the fact that the foundations rely on a thin raft.

Figure 8 right shows that the concrete portion of the building (see dashed line in Figure 8) to be within the expected floor response range, however the CLT floorplates show a significant increase in response around the low frequency region. It is also worthwhile noting that this result will not impact on the structural borne noise.

5 CONCLUSION

The study presented herein, which aims to utilize the Finite-Difference Time-Domain (FDTD) method to assess a wooden frame building's response to rail-induced vibration, has assessed the effectiveness of employing a simplified CLT modelling strategy based on a single layer with isotropic characteristics.

The sensitivity analysis conducted revealed that modelling a single layer using material properties corresponding to the CLT minor axis provided a reasonable conservative representation of the multi-layer CLT panel.

By comparing the response of a conventional reinforced concrete building to the modelled wooden frame structure, the study highlighted a substantial difference. The wooden frame structure exhibited a significant increase in response, up to 20dB, at significantly lower frequencies, albeit outside the audible range.

6 REFERENCES

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