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THE ACOUSTIC PERFORMANCE OF LONG-SPAN HOLLOW MASSIVE TIMBER FLOOR CASSETTES DESIGNED FOR CIRCULARITY

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ABSTRACT: Targeting long spans, building systems integration, low-embodied carbon, and end-of-life circularity, a hollow massive timber (HMT) floor cassette system has been developed at Clemson University. Integral to the successful application of this all-timber system is its sound attenuation, particularly in residential flats or in hotels, both of which are subject to strenuous acoustic performance regulations in the United States. This paper details the planning, construction and validation of a new two-story acoustic testing chamber, followed by the results from airborne and structure-borne sound transmission tests performed on assemblies involving the experimental timber floor cassettes.

KEYWORDS: building acoustics, mass timber, floor system

1 – INTRODUCTION

Massive timber structures present a particularly compelling case for circularity in the built environment due to their prefabricated nature, the connections between members, and the importance of retaining sequestered carbon. However, the conventional inclusion of concrete topping slabs atop mass timber floor panels presents a significant barrier to the disassembly and reuse of the panels and supporting framing. A massive timber floor cassette developed and studied at Clemson University aims to combine long spans and systems integration, all while excluding conventional concrete toppings and promoting ease of disassembly and reuse. Critical to this low-carbon, timber-only approach is the acoustic performance of the system, as sound attenuation has often been a motivator for the inclusion of a concrete floor topping.

2 – BACKGROUND

2.1 EXPERIMENTAL HOLLOW MASSIVE TIMBER (HMT) FLOOR CASSETTE

The experimental hollow massive timber (HMT) floor cassette which is the subject of this paper includes two 3-ply cross-laminated timber flanges and two glue-laminated timber beams as web members. The system was first conceived and studied at Clemson University in 2013 as a long-span alternative to conventional CLT floor plates. The flange-to-web connections were the subject of the first developmental testing and analysis, as it was determined that connector stiffness at those junctions has the greatest impact on the system's overall structural performance [1].

Full-scale testing of the HMT system later followed in 2016-17 using a 1.52m wide by 12.19m long (5ft x 40ft) specimen. Non-destructive modal vibration tests revealed

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that the bare floor cassette experienced vibrations within the realm of human sensitivity. Destructive tests examined flexural and shear strengths and proved that the floor system could safely carry the design loads over the 12.19m (40ft) spans [2].

While the structural performance and spanning capacity of the HMT system was promising, the research team understood that system viability / marketability depends on other factors, including the possible integration of building systems (mechanical, electrical, plumbing, fire protection) within the hollow voids of the cassette. This would require a system of access hatches (in the CLT top flange) as well as carefully planned duct penetrations through the glulam web beams. The voids themselves are considered "concealed spaces" within the International Building Code (IBC), and would not require additional fire-stopping measures (beyond the fire-resistance of the mass timber elements themselves) when used within Type III construction. Such concealed spaces are permitted as well by the 2021 IBC for Type IV-HT construction, for example, though they would require more intensive fire-stopping measures. Options in the case of Type IV-HT include sprinklering of the void, filling the void with non-combustible insulation, or sheathing the timber surfaces with fire-resistant Type-X gypsum board.

With the systems integration opportunities in mind, the team imagined the HMT system offering much of the same functionality as a raised-access floor but entirely made up of sustainable timber elements rather than carbon-intensive metal pedestals and cementitious floor tiles. The team also targeted circularity of the HMT panels and their components at the end of service life. Feasible deconstruction and re-use requires reversible connections, as well as the elimination of the concrete topping slabs that typically accompany mass timber floors. These objectives form the basis of the current project titled "An Entirely Wood Floor System Designed for Carbon Negativity, Future Adaptability, and End-of-Life De/Re/Construction", which is supported by the U.S. Department of Energy's ARPA-E agency, under its HESTIA (Harnessing Emissions into Structures Taking Inputs from the Atmosphere) program [3]. In addition to further study on structural performance and connection details, the current project has included analysis of HMT constructability and deconstructability, plus detailed life-cycle assessment of the system, as applied to a hypothetical 3-story baseline office building. Another important area of study focused on the acoustic performance of the HMT cassettes.

2.2 ACOUSTIC PERFORMANCE

Central to the practical functionality of the HMT system, as well as the objective of circularity and the related elimination of concrete topping slabs is the acoustic performance of the floor cassettes. Acoustic performance in buildings depends on the attenuation of both airborne and structure-borne (impact) sound.

Sound transmission across floor or wall partitions is measured in decibels (dB) and varies with sound frequency. It is typically harder for partitions to attenuate low-frequency airborne sounds versus mid and high frequencies. The net sound attenuation is reported in standardized acoustic ratings. The International Building Code [4] imposes its strictest acoustic requirements on multi-family residential structures as well as hospitality structures, such as hotels. In these cases, floor and wall assemblies used between units are required to achieve airborne Sound Transmission Class (STC) ratings of 50 or higher, where tested in accordance with ASTM test standard E90, a laboratory-based test procedure [5]. They could otherwise demonstrate a Normalized Noise Isolation Class (NNIC) rating of 45 or higher for field testing of airborne sound transmission in accordance with ASTM Standard E336 [6]. This difference in rating accounts for some amount of flanking sound transmission in the case of built, field-tested structures. For impact sound performance, these floor and wall assemblies are required to achieve Impact Insulation Class (IIC) ratings of 50 or higher (for lab testing according to ASTM E492) or Normalized Impact Sound Rating (NISR) values of 45 or higher (for field testing according to ASTM E1007) [7] [8].

The mass of concrete, as a material, makes it particularly well-suited for mitigating airborne sound transmission. This is one reason, along with durability and vibration control, that concrete toppings are typically used in mass timber floor assemblies. The reduction of impact sound transmission, on the other hand, often relies on materials which decouple the finish floor surface from the structural slab below. This may include carpeting or impact-absorbing acoustic mats. The research question at the center of our team's acoustic study was whether or not floor assemblies involving the experimental HMT cassette could achieve the code-required acoustic ratings without the inclusion of a concrete topping.

3 – PROJECT DESCRIPTION

3.1 ACOUSTIC CHAMBER AND TESTING

Planning for exploratory and iterative testing and development, the project team elected to design and construct its own acoustic chamber rather than sending floor assemblies out to professional laboratories for testing. The resulting two-story chamber, illustrated in Figure 1, has a footprint of approximately 5.49m x 6.10m (18ft x 20ft), and was built from light frame wood construction in which all cavities were filled with mineral wool insulation. All interior wall surfaces consist of 12.70mm (0.5in.) thick homasote panels on 15.88mm (0.625in.) thick gypsum board on horizontal resilient channels. The resilient channels decouple the wall finishes from the wall framing, an important step for acoustic isolation.

The upper story of the test chamber serves as the "source room", wherein the airborne and impact noise is generated. The lower story serves as the "receiving room", in which transmitted sound is measured. A cut-out in the floor between the source room and receiving room was sized to fit test floor specimens which are 2.44m (8ft) wide by 6.02m (19.75ft) long. The two permanent portions of floor on either side of the opening include 24.13cm (9.5in.) of mineral wool cavity insulation and feature the same layers for the ceiling as were described above for the interior walls. These portions of floor framing are topped with 15.88mm (0.625in) thick gypsum board above 15.88mm (0.625in.) thick OSB. The concept is to have particularly robust, sound attenuating construction around the test floor specimens, such that any airborne sound transmission occurs through the test specimen itself, rather than through the surrounding floor area.

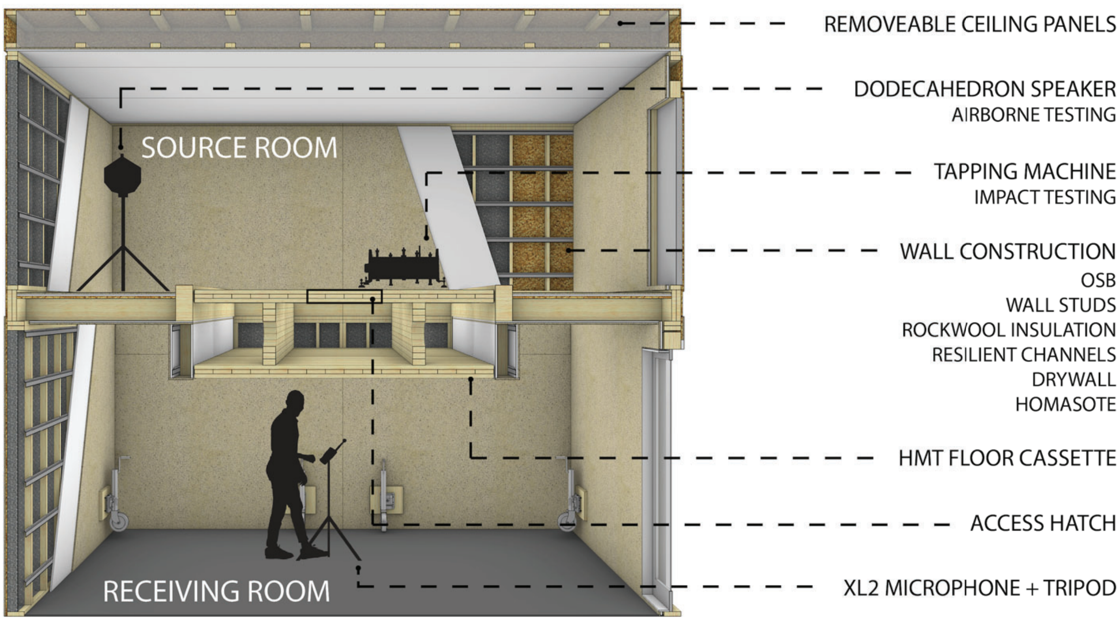

Figure 1. Illustration of Acoustic Chamber and Test Set-up

Tested floor specimens typically bear on walls at either end of their long span. Running along the top plate of these bearing walls is a rubber membrane to limit flanking sound at the floor-to-wall junction. Alternatively, floor specimens, if they are thin enough in their construction, could be supported along their long edges by additional ledger boards.

Through consultation with acoustic testing professionals, it was determined that the research team would follow the field test methods prescribed by ASTM Standards E336-20 (airborne) and E1007-21 (impact) [6] [8]. In part, this is because the geometric volumes of the upper source room ($60.8m^3$) and lower receiving room ($65.7m^3$ for the HMT floor assemblies) fit comfortably within the range required by the ASTM field test standards, while the receiving room volume, in particular, would have been too small to follow the ASTM laboratory test standards. Sound attenuation is measured at a range of prescribed frequencies, from 50Hz at the low end to 5000Hz at the high end. The normalized results are summarized as overall airborne and impact sound ratings. As stated previously, the International Building Code requires minimum NNIC (airborne) and NISR (impact) ratings of 45 for residential and hospitality structures, the most restrictive use cases. These ratings served as the targets for the experimental HMT floor system.

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Professional acoustic testing equipment is used for generating and measuring sound. Airborne "pink" noise (typically around 100dB) is generated in the source room using a specialized amplifier and dodecahedron speaker. Impact noise is generated by a standard tapping machine. Sound levels in both rooms are measured by a hand-held microphone. In particular, our team has used the XL2 microphone / analyzer from NTI audio.

Prior to any acoustic testing of the experimental HMT cassette system, detailed validation testing was first performed on a control floor assembly with known acoustical performance properties. This control floor consisted of a bare 3-ply CLT floor panel, 10.48cm (4-1/8in.) thick, and our measured test data showed high correlation with data previously collected by the professional acoustic testing laboratory of the Maxxon flooring company. This, then, served to validate our experimental set-up, including the new test chamber itself. Throughout this validation testing, various measures were explored and utilized to minimize direct sound leakage from between the source room and receiving room.

3.2 HMT FLOOR CASSETTE DETAILS

Each hollow massive timber floor cassette consists of two 3-ply CLT flanges, each 10.48cm (4.125in.) thick, and two glulam web members at 12.70cm wide x 45.40cm deep (5in. x 17.875in.). The overall width of each cassette is 2.44m (8ft), with web members set symmetrically about the cassette centerline and 1.52m (5ft) from one another. As described above, cassettes of similar depth have been designed and tested for spans of up to 12.19m (40ft). This is more than twice the typical span of conventional mass timber floor systems and promotes greater flexibility in initial space planning for architects and building owners, as well as a greater capacity for adaptation as specific space needs evolve and change. With this being said, and because of the dimensions of the acoustic chamber, the length of the HMT assemblies tested for acoustic performance was limited to 6.02m (19.75ft).

The voids in HMT cassettes are sizeable and can support the integrated passage of mechanical ducts, and electrical, plumbing and fire-suppression lines. Access to these systems is provided at periodic top-down hatches within the upper flange of the cassette. The tested access hatches are 0.61m x 0.76m (2ft x 2.5ft) in size and the hatch door is simply made from the 3-ply CLT rectangle which was cut out for the opening. One edge of the hatch and the hatch door are bevelled so that the hinged door can swing up for access but not swing down into the void.

Figure 2. Photographs of Bare HMT Floor Assembly Before and After Installation within Acoustic Chamber

4 – EXPERIMENTAL SETUP

Six different HMT floor assemblies were tested for acoustic performance. The first was the bare assembly, which was tested in order to establish a baseline. This was followed by tests which examined the relative effects of carpet tiles, as well as the combination of an acoustic membrane and OSB subfloor. The addition of blown-in

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cellulose insulation in the HMT cavities was also studied. The carpet tiles were from the "Concrete Mix" collection from Interface, and featured a carbon-neutral backing [9]. Maxxon's 9.53mm (3/8in.) thick Acousti-Mat® was used for the acoustic membrane, while the OSB layers were each 19.05mm (3/4in.) thick [10]. See Figure 3 for depictions of the tested HMT assemblies. For each tested assembly, at least two full sets of airborne sound tests and two full sets of impact sound tests were performed, with the results in each case being averaged.

Due to the overall depth of the HMT cassette, two suspended wall partitions were added in the receiving room in order to close off the long open sides of the cassette (see Figures 1 and 2). These "enclosure walls" were 34.93cm (13.75in.) in depth and were attached to the bottom face of the glulam beams that comprise the long sides of the floor opening in the acoustic chamber.

As a first step in each round of testing, background noise levels in the receiving room were measured for frequencies meeting and exceeding the demands of ASTM E336-20 and ASTM E1007-21. Six microphone locations at least 1.5m apart and at least 1m from room surfaces were used. A 30-second measurement was conducted at each microphone location, with the six results being averaged. The measurement of background noise is important because it must be subtracted out of the later sound transmission values for the tested assemblies.

Next, to determine absorption, reverberation times in the receiving room were measured in accordance with ASTM E2235-04 using interrupted noise. One speaker position was used and three microphone positions, each at least 1.5m apart, were selected. A total of 15 decays were measured.

When it came to airborne sound testing, the airborne pink noise levels were first measured in the source room. This was followed by the measurements in the receiving room. Airborne sound transmission loss through the floor system is calculated by subtracting the average sound levels recorded in the receiving room from those recorded in the source room. The measurements in both the source room and receiving room were conducted in accordance with ASTM E336-20. Six microphone positions at least 1m apart from each other were used in each room. Due to the height constrictions of the source room, the microphones in that room could not be at least 1m from every one of the room's surfaces. However, the microphone locations were always 1 meter above the source room floor and 0.85m from the source room ceiling, and this was deemed acceptable and in no way unconservative with respect to sound transmission results. Two speaker positions were used in the source room, each over 2m from each other and at least 1.5m above the tested partition. In total, twenty-four 30-second measurements were taken, twelve measuring decibel levels in the source room, and twelve measuring decibel levels in the receiving room. In every case, the sound levels were measured across the prescribed set of frequencies.

Impact sound measurements between the source and receiving rooms were conducted in accordance with ASTM E1007-21 using a standard tapping machine. Four tapping machine positions were used in the source room atop each tested assembly. Since the standard was not written for unorthodox structural floor systems such as the HMT system, tapping positions 3 and 4 were modified from section 6.3 of ASTM E1007-21. Position 3 sat directly atop and in line with one glulam web beam, while position 4 sat along a 45° line from that glulam beam to the center point of the assembly specimen, with the end-most hammer of the tapping machine located over the beam. Four receiving-room microphone positions were used, with each being at least 1m from all surfaces and from one another. In total, sixteen 30-second measurements were taken.

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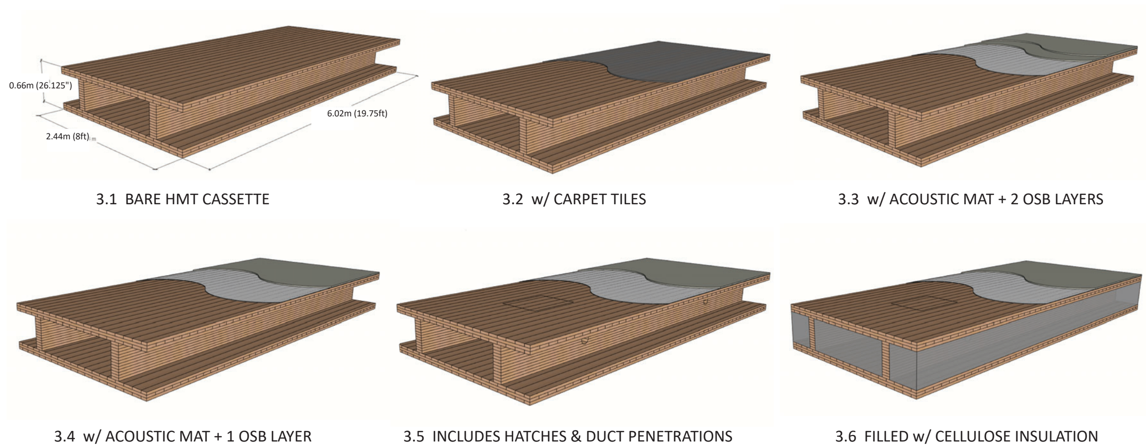

Figure 3. Tested Hollow Massive Timber (HMT) Floor Assemblies

5 – RESULTS

The results of the airborne sound tests are shown below in Table 1 and are plotted in Figure 4. Each measurement reflects the sound transmission loss (in dB) at a given frequency. The higher the value for transmission loss, the more effective the floor assembly was at limiting sound transfer at that given frequency. As expected, sound transfer at the lower frequencies was most difficult to mitigate. The plotted data shows fairly consistent airborne sound performance across the tested assemblies, and this is reflected in the normalized NNIC ratings in Table 3 on the next page.

Table 1: Average Airborne Sound Transmission Losses (in dB)

FREQ (Hz)	TEST 3.1	TEST 3.2	TEST 3.3	TEST 3.4	TEST 3.5	TEST 3.6
50	20	24	21	21	--	22
63	22	23	23	21	24	24
80	26	25	27	25	29	29
100	28	29	29	29	31	32
125	26	28	32	32	32	34
160	31	31	35	34	33	36
200	35	34	38	34	34	36
250	34	35	41	37	37	37
315	33	34	41	35	36	37
400	38	37	43	40	42	44
500	39	38	45	44	45	46
630	40	39	45	45	46	46
800	42	41	45	44	46	46
1000	44	42	47	47	47	47
1250	47	46	48	48	49	49
1600	49	49	51	50	50	50
2000	53	53	55	53	54	54
2500	57	58	59	58	59	58
3150	60	61	63	62	63	63
4000	63	65	66	65	66	66
5000	65	68	70	69	69	69

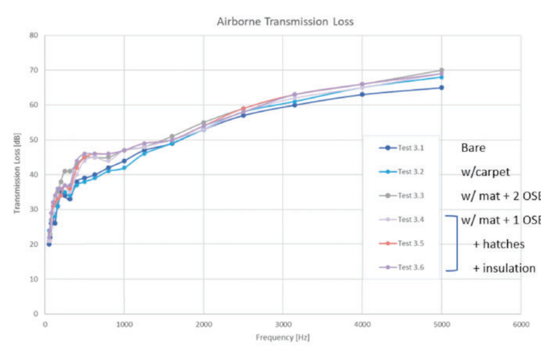

Figure 4. Airborne Transmission Loss Levels Across Test Frequencies

The results of the impact sound testing are shown below in Table 2 and are plotted in Figure 5. Each measurement reflects an impact sound pressure level (in dB) recorded in the receiving room. The lower the value for impact sound pressure level, the more effective the floor assembly was at limiting impact sound transfer at that given frequency. The data clearly shows that a sound-isolation layer (such as carpet or an acoustic membrane) is needed atop the HMT cassette in order to decouple the impact energy from the structural substrate. This is reflected in the normalized NISR ratings in Table 3 on the next page.

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Table 2: Average Impact Sound Pressure Levels (in dB)

FREQ (Hz)	TEST 3.1	TEST 3.2	TEST 3.3	TEST 3.4	TEST 3.5	TEST 3.6
50	66	61	53	56	54	52
63	71	68	65	67	65	64
80	67	63	61	63	60	60
100	72	67	66	66	66	65
125	76	70	67	68	67	66
160	74	67	66	68	67	66
200	74	67	68	73	74	72
250	81	70	68	71	73	72
315	80	68	66	68	69	68
400	79	63	63	67	66	65
500	80	61	61	63	62	60
630	80	57	57	60	57	55
800	75	48	54	57	52	45
1000	72	38	43	47	44	37
1250	70	29	36	41	39	32
1600	66	21	29	34	33	29
2000	60	15	24	27	27	25
2500	51	9	17	19	19	17
3150	38	8	9	11	10	9
4000	30	8	8	10	8	8
5000	24	9	9	9	9	9

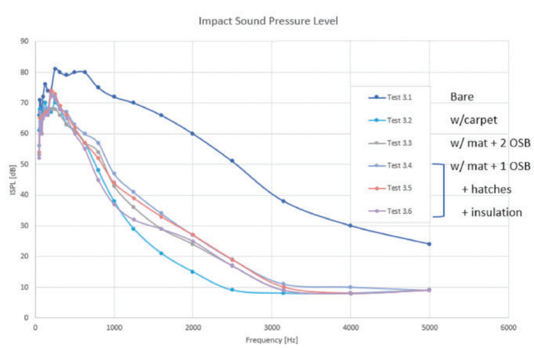

Figure 5. Impact Sound Pressure Levels Across Test Frequencies

Table 3 summarizes the overall, normalized sound attenuation ratings from the various tested HMT floor assemblies. All versions of the HMT floor cassette achieved the required airborne sound rating (NNIC $\geq$ 45). This likely results from the overall mass and geometry of the HMT floor system itself. The tested assemblies that used carpet or an acoustic membrane exceeded impact sound requirements (NISR $\geq$ 45). This is because these layers served to decouple the impact sound from the timber structure of the HMT floor cassette.

The inclusion of access hatches through the CLT top flange and coordinated duct penetration holes through the glulam beams (sized roughly at 0.2m in diameter) had no appreciable effect on acoustic performance. Finally, the addition of blown-in cellulose insulation within the void spaces had only a small effect on performance. The inclusion of this non-combustible insulation does provide a fire-stopping measure suitable for concealed spaces within IBC Construction Type IV-HT. It would probably result in a more discernible effect acoustically were it not for the fact that the HMT system has such robust sound attenuation properties on its own.

Table 3: Average NNIC and NISR Ratings for Tested HMT Assemblies

ASSEMBLY I.D.	ASSEMBLY DETAILS	AVG. NNIC (airborne)	AVG. NISR (impact)
3.1	Bare HMT Cassette	45	37
3.2	w/ Carpet Tile	45	51
3.3	w/ Acoustic Mat + 2 Layers 19mm OSB Subfloor	50	52
3.4	w/ Acoustic Mat + 1 Layer 19mm OSB Subfloor	47	50
3.5	Same as 3.4 but w/ Hatches and Duct Penetrations	49	50
3.6	Same as 3.5 but Filled w/ Cellulose Insulation	49	51

6 – CONCLUSIONS

These test results are encouraging and demonstrate that HMT assemblies can meet or exceed the IBC's most stringent acoustic rating requirements without needing a concrete topping. The resulting elimination of the concrete layer lowers carbon footprint and promotes circularity for the HMT components themselves. This, along with the long-span capacity, and the potential for systems integration, makes the HMT floor cassette a compelling option to consider, depending on the specific needs and opportunities associated with a given building project.

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